UNIVERSITAT POLITÈCNICA DE VALÈNCIA
UNIVERSITATEA TRANSILVANIA DIN BRASOV

DEPARTAMENTO DE INGENIERÍA MECÁNICA Y DE MATERIALES
DEPARTAMENT PRODUCT DESIGN, MECHATRONICS AND ENVIRONMENT

METHODS AND TECHNIQUES FOR BIO-SYSTEM`S MATERIALS BEHAVIOUR ANALYSIS

Leonard-Gabriel Mitu

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DOCTORAL THESIS

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TEZĂ DE DOCTORAT

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Ing. Leonard Gabriel MITU

TEZĂ DE DOCTORAT

TITLU (română): Metode şi mijloace de analiză a comportamentului materialelor din structura biosistemelor

TITLU (engleza): Methods and techniques for bio-system's materials behaviour analysis

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ABSTRACT

The PhD. thesis entitled " ***Methods and techniques for bio-system's materials behaviour analysis***", aims, from the start, a systematic study of the biomaterials categories and their mechanical, chemical, thermal, etc. characteristics. The study is completed with methods and means for analysing the behaviour of biocomposites materials. Based on this study, the research work focuses on the analysis of the mechanical and thermal behaviour of layered composites consisting of epoxy prepreg blades reinforced with unidirectional and in diagonal carbon fibre fabrics. These layered categories are used in the construction of prosthetic blades in the form of "J" in order to support dentures worn by runners in the stages of competition and training. In order to identify the characteristics of these layered categories, in the paper were developed two lines of research: developing a method for analyzing the anatomy of the lower limb regarding: the skeletal system, the joint system, gait and running biomechanics on non-amputees, gait and sprint biomechanics on amputees with sports prostheses which contain the prosthetic blades "J"; developing theoretical methods to analyse the layered composite made of epoxy blades reinforced with unidirectional and in diagonal carbon fibres. The research concludes with the development of experimental procedures for determining the mechanical and thermal characteristics of layered composite made of epoxy blades reinforced with unidirectional and in diagonal carbon fibres. The experimental research procedures include compression and bending tests, the analysing method Dynamical Mechanical Analyser DMA and thermal determination tests. The test specimens consist of layered composites with 3, 5 and 7 blades having unidirectional and in diagonal carbon fabrics. The experimental results allow the determination of the real values of lamina, and respectively composite elasticity law and also of the analysis regarding the composite real thermal behaviour. The thesis combines knowledge from different areas: anatomy, biomechanics, biomaterials, layered composite materials, physics, etc. The research paper is of an actual interest with high potential in sports and in improving the comfort and the psychic of the persons that suffered transtibial amputation.

RESUMEN

La tesis titulada "**Métodos y técnicas para el análisis del comportamiento de los materiales de bio–sistema**", tiene como objetivo, inicialmente, realizar un estudio sistemático de diversas categorías de biomateriales y sus características mecánicas, químicas, térmicas, etc. El estudio se completa con métodos y medios para analizar el comportamiento de los materiales biocomposites. Sobre la base de este estudio, el trabajo de investigación se centra en el análisis del comportamiento mecánico y térmico de los materiales compuestos estratificados que consiste en epoxi preimpregnado reforzado con láminas de tejidos de fibra de carbono con orientación unidireccional y en diagonal. Estas tipologías de laminados se utilizan en la construcción de prótesis en forma de "J " con el fin de apoyar a las prótesis usadas por los corredores en las etapas de competición y entrenamiento. Con el fin de identificar las características de estos laminados, en el presente estudio, se desarrollaron dos líneas de investigación:

- el desarrollo de un método de análisis de la anatomía de las extremidades inferiores en relación con: el sistema esquelético, el sistema de unión (articulaciones), la marcha y la biomecánica que se ejecutan en no amputados, la biomecánica de andar y correr sobre los amputados con prótesis deportes que contienen las hojas de prótesis " J ".
- el desarrollo de métodos teóricos para analizar el material compuesto en capas hecha de hojas de epoxi reforzado con fibras de carbono unidireccional y en diagonales. La investigación concluye con el desarrollo de procedimientos experimentales para la determinación de las características mecánicas y térmicas del material compuesto en capas hechas de láminas de epoxi reforzadas con fibras de carbono unidireccionales y diagonales.

Los procedimientos de investigación experimental incluyen pruebas de compresión y de flexión, el análisis mecánico dinámico (DMA) utilizado en estudios de procesos de relajación y en reología y ensayos de determinación térmicas. Las pruebas se realizaron sobre probetas fabricadas en materiales compuestos en capas con 3, 5 y 7 láminas con tejidos de carbono unidireccional y en diagonal. Los resultados experimentales permiten la determinación de los valores reales de elasticidad la lámina, y el material compuesto. También el análisis sobre el comportamiento térmico real de compuesto.

La tesis combina el conocimiento de las diferentes áreas: anatomía, biomecánica, biomateriales, materiales compuestos en capas, física, etc. El trabajo de investigación es de un interés real con un alto potencial en el deporte y en la mejora de la comodidad y el psíquico de las personas que han sufrido una amputación transtibial.

RESUM

La tesi titulada " Mètodes i tècniques per a l'anàlisi del comportament dels materials de bio - sistema", té com a objectiu, inicialment, fer un estudi sistemàtic de diverses categories de biomaterials i les seves característiques mecàniques , químiques , tèrmiques , etc. L'estudi es completa amb mètodes i mitjans per analitzar el comportament dels materials biocomposites . Sobre la base d'aquest estudi, el treball de recerca se centra en l'anàlisi del comportament mecànic i tèrmic dels materials compostos estratificats que consisteix en epoxi preimpregnado reforçat amb làmines de teixits de fibra de carboni amb orientació unidireccional i en diagonal . Aquestes tipologies de laminats s'utilitzen en la construcció de pròtesis en forma de " J " per tal de donar suport a les pròtesis usades pels corredors en les etapes de competició i entrenament . Per tal d'identificar les característiques d'aquests laminats, en el present estudi , es van desenvolupar dues línies d'investigació:

- El desenvolupament d'un mètode d'anàlisi de l'anatomia de les extremitats inferiors en relació amb : el sistema esquelètic, el sistema d'unió (articulacions), la marxa i la biomecànica que s'executen en no amputats, la biomecànica de caminar i córrer sobre els amputats amb pròtesis esports que contenen els fulls de pròtesis "J".

- El desenvolupament de mètodes teòrics per analitzar el material compost en capes feta de fulles de epoxi reforçat amb fibres de carboni unidireccional i en diagonals. La investigació conclou amb el desenvolupament de procediments experimentals per a la determinació de les característiques mecàniques i tèrmiques del material compost en capes fetes de làmines de epoxi reforçades amb fibres de carboni unidireccionals i diagonals.

Els procediments d'investigació experimental inclouen proves de compressió i de flexió , l'anàlisi mecànica dinàmica (DMA) utilitzat en estudis de processos de relaxació i en reologia i assaigs de determinació tèrmiques . Les proves es van realitzar sobre provetes fabricades en materials compostos en capes amb 3, 5 i 7 làmines amb teixits de carboni unidireccional i en diagonal. Els resultats experimentals permeten la determinació dels valors reals d'elasticitat la làmina, i el material compost. També l'anàlisi sobre el comportament tèrmic real compost .

La tesi combina el coneixement de les diferents àrees : anatomia , biomecànica , biomaterials, materials compostos en capes, física, etc. El treball de recerca és d'un interès real amb un alt potencial en l'esport i en la millora de la comoditat i el psíquic de les persones que han patit una amputació transtibial.

Rezumat

Teza de doctorat intitulată ***„Metode şi mijloace de analiză a comportamentului bio materialelor din structura biostemelor”*** îşi propune la început un studiu sistematic al categoriilor de biomateriale şi a caracteristicilor mecanice, chimice, termice etc. ale acestora. Studiul este finalizat cu metode şi mijloacele pentru analiza comportamentului materialelor biocompozite. Pe baza acestui studiu, lucrarea de cercetare se concentrează pe analiza comportamentului mecanic şi termic al compozitelor stratificate formate din lamele epoxi preimpregnate armate cu ţesături din fibre de carbon unidirecţionale şi în diagonală. Aceste categorii se stratificate sunt utilizate în construcţia lamelelor protetice în formă de *„J”* la protezele sportive purtate de alergători în fazele de concurs şi de antranament. Pentru a se identifica caracteristicile de utilizare a acestora stratificate în lucrare s-au dezvoltat două direcţii de cercetare : 1-elaborarea unei metodici de analiză a caracteristicilor anatomice ale membrului inferior privind: sistemul osos, sistemul articulaţiilor, biomecanica mersului şi alergării la persoanele neamputate, biomecanica mersului şi sprintului la amputaţii cu proteze sportive ce conţin lamele protetice *„J”* ; elaborarea de metode teoretice de analiză a stratificatului compozit alcătuit din lamele epoxi armate cu ţesături din carbon, unidirecţionale şi în diagonală. Cercetarea se finalizează cu elaborarea de proceduri de determinare experimentală a caracteristicilor mecanice şi termice ale compozitului stratificat din lamele epoxi armate cu ţesături din carbon, unidirecţionale şi în diagonală. Procedurile de cercetare experimentală cuprind încercări de compresiune, încovoiere, analiza cu metoda DMA- Dynamical Mechanical Analyser şi încercări de determinare termică. Epruvetele testate sunt formate din stratificate din 3,5 şi 7 lamele avînd ţesături de carbon unidirecţionale şi în diagonală. Rezultatele experimentale permit determinarea valorilor reale ale legii de elasticitate a laminei şi respectiv a compozitului cât şi a analizei privind comportamentul termic real al compozitului. Teza de doctorat imbină cunoştinţe din diverse domenii: anatomi, biomecanică, biomateriale, materiale compozite stratificate, fizică. etc. Lucrarea de cercetare este de mare actualitate, cu ridicat potenţial în domeniul sportiv cît şi în îmbunătăţirea confortului şi pshicului amputaţiilor transtibial.

CONTENT

TERMS, SYMBOLS AND NOTATIONS

TERMS

Adduction. The adduction is the motion of a human body segment inside as against the longitudinal axis.

Amfiarthrosis or cartilaginous articulations. In these joints, the bones are connected by a hyaline cartilage (synchondrosis) or by a fibrocartilage (symphysis).

Anode. This represents the electrode where it is produced the oxidation reaction

Articulations with one free degree. These are represented by: a) plane joints which assure only a slide motion; b) cylindrical joints which are the same functions with the hinges.

Articulations with two free degrees. These joints can execute motions only in two senses (the rotation motion is not possible). These are represented by: a) ellipsoidal joints; b) joints of saddle shape.

Articulations with three free degrees called spheroidal joints (diarthrosis or enarthrosis). These joints can perform, reported on the three main spatial planes, the following motions: flexion and extension, abduction and adduction, rotation and circumduction.

Articulations, synarthrosis or fibrous joints. These are fixed or fine joints; bones are connected tight one with other by compact tissue represented by membranes or ligaments. When the mobility of synathrosis decreases till the disappearance, such a joint can be assimilated, by mechanical aspect, as a fitting. By mobility point of view these are semi mobile articulations.

Femoral – tibial articulation. Joint resulting from contact between the inferior extremity of the femur and upper end of the tibia.

Arthrodesis. Plane synovial joints with one free degree.

Biocompatibility. The property of a material of being compatible with the living organisms.

Biodegradation. The degradation of the characteristics of a biomaterial from the biological environment where it functions.

Bio functionality. It is the property of the material mass to satisfy the condition required as a implant quality, prosthesis, the substitution of the defective organ.

Biomaterial. This is referred at a product used at the restoration or the replacement of some living tissues which are not functional.

Biosecurity. An ensemble of precautionary actions for protecting the use of biological resources and/or the preventing of the risk of the contamination with infectious diseases, the environment pollution or by the loss of this biodiversity.

Stock serous. A pocket limited by a membrane of the same nature with a synovial joint membrane that is allocated to facilitate the sliding of the skin, a muscle or a tendon on the bone.
Capsule. The conjunctive formation which alongside of the ligaments constitutes a mode of connection of two bone segments.
Cathode. The electrode where it is produced the reduction reaction.
Diarthrosis or synovial articulations. These are complex joints at its level, by mobility point of view, it realize multiple and different motions, being considered as mobile joints. Diarthrosis is characterized by the presence of some articular cavities with the surfaces of spherical, elliptical, cylindrical and plane shape. These categories of surfaces can be assimilated, by geometrical point of view, at two basis shapes. [Pap.74]: 1- plane joints where the motions are reduced; 2- spheroidal joints.
The center of gravity of human body. The reference point of the body mass on which it is acted the force of gravitational attraction.
Pelvic belt. A bone belt consisted in two coxal bones (iliac bones) which connect the backbone with the legs.
Poisson coefficient. A coefficient of lateral contraction in the elastic domain.
Enarthrosis. Mobile joints.
Endosteal. The fine, conjunctive membrane which covers the medullar cavity of the long bones and the spans of the spongy bones tissue.
Extension (retroflexion). The stretch motion (bend back) in the sagittal plan of a body segment.
Flexion. The motion of tilting forward (bending) in sagittal plan of a human body segment.
Dorsal flexion. Lifting on heels.
Plantar flexion. Lifting on peaks.
Glens. Anatomic represents the joint cavity, a shallow bone interlock with another bone.
*Hydroxyapatite(HA).*Calcium phosphate based ceramic.
Synthetic Hydroxyapatite($Ca_{10}(PO_4)_6(OH)_2$). Inorganic biomaterial with chemical characteristics similar to the mineral hard tissues of mammals such as the bone and teeth.
Acetabulum labrum. Ring of cartilage that surrounds acetabulum.
Kinematic chain of the body. A chain of kinematic couples articulated each other, which is capable to execute different motions: own for each couple, for many constituents couples.
Open kinematic chain. A chain of kinematic couples articulated each other, with a free extremity.
Close kinematic chain. A chain of kinematic couples articulated each other where the extremities are not free (the hand or the leg is supported on the ground or a device).
Motion of nutation. The motion of the sacroiliac joint by that the basis of the sacred bone swings down and forward, while its peak is moved up and back. This motion is limited by the sacroischial ligaments.

Motion of inverse nutation. The motion of the sacroiliac joint by that the basis of the sacred bone swings up and back while its peak is moved down and forward.

Soleus muscle. The shank muscle which puns down the foot.

Sartarius muscle. The body muscle: controls movements during gait, stand stin and the balance maintainmg.

Agonist muscles. The muscles those are responsible of the main effort for the fulfillment of the specific tasks.

Antagonistic muscles. These are opposed of the action of the agonist muscles. These muscles are relaxed while the agonists contraction. The agonist and the antagonist muscles are located in the opposite sides of the joint.

Osteogenesis. The process by which it is produced the born and the forming of the bones in the characteristic forms, dimensions and structures.

Fibrous osteogenesis (endoconjunctive). The process of osteogenesis by which it is developed the calvaria bones and the most of the face bones.

Osteogenesis from cartilaginous model. The process of osteogenesis by which it is developed the long, short and plane bones.

Electrochemical reaction. A reaction of oxidation - reduction with electrons transfer.

Oxidation reaction. The reaction by which it is produced the dissolution of the metal.

Reduction reaction. The reaction by which it is produced the metal filling on the surface.

Rotation. The motion of a human body segment around his own longitudinal axis.

Scanning electron microscope ***(SEM)***. A type of electronic microscope which produces images of a sample by scanning with a fascicle focused of electrons.

Scanning probe microscopy ***(SPM)***. A branch of electronic microscopy which permits the forming of the sample surface images using a probe (with very sharpening peak) which scans without contact the surface. Ex. The microscopy with atomic force.

Syndesmo. A type of joint with reduced mobility where the bone surfaces are connected by a bon ligament. This joint can serve the inferior tibio – fibular joint.

Articular surface. Anatomic joint surfaces of bone ends. Usually covered with articular cartilage (can be spherical, ellipsis, cylindrical and planar).

Tribo - corrosion. This is the result obtained from the chemical corrosion with the relative cyclic motion of the surfaces.

Prepreg. Composite material obtained by impregnating continuous bands of fabric with resin.

SYMBOLS AND NOTATIONS

Symbol	Signification
	Human body anatomy
Art. (art)	Leg articulation.
BCOM	Mass center of human body.
COG	Gravity center.
COM	Mass center.
COP	Pressure center.
DM	Medical device.
DMI	Implantable medical device.
E_{cor}	Potential of corrosion.
Ed.	Editor.
Eds.	Publishing.
ESB	European Society for Biomaterials
F_{SA}	Leg joint.
GC	Going cycle
GRF	Ground reaction force.
$Rp_{0,2}$	Flows limit (02- value of disproportional deformation).
TCP	Tricalcium phosphate.
Lig	Ligament.
$\varepsilon_{ductibilitate}$	Coefficient of ductility.
Z	Coefficient de constriction.
	Bio polymer, Bio composite
DMA	Dynamic mechanical analyzer.
CFRP	Carbon fiber reinforced polymer.
CTE	Coefficient of thermal expansion.
E	Elasticity modulus or Young modulus.
E_{fL}	Elasticity modulus of carbon fiber on the longitudinal direction.
E_{fT}	Elasticity modulus of carbon fiber on the transverse direction.
E_M	Elasticity modulus of epoxy matrix.
F_{CA}	Milling against feed.
F_{SA}	Milling in the sense of feed.
FEM	Finite element method
HA	Hydroxyapatite.
PMMA	Polymetylmetacrylate
T_g	Temperature of glass transition
φ	Volume fraction of carbon fiber.
υ_F	Coefficient of transverse contraction of carbon fiber
υ_M	Coefficient of transverse contraction of epoxy matrix
ρ_M	Density of epoxy matrix.
UD	Unidirectional
α_{fL}	Coefficient of linear thermal expansion of carbon fiber on longitudinal direction.
α_{fL}	Coefficient of linear thermal expansion of carbon fiber on radial direction.

α_M	Coefficient of thermal expansion of the matrix
E_{fL}	Elasticity modulus of the fiber on the longitudinal direction
E_{fT}	Elasticity modulus of the fiber on the radial direction
E_M	Elasticity modulus of the matrix.
υ_M	Coefficient of transverse contraction of the matrix

FIGURES AND TABLES

FIGURES

TABLES

CHAPTER **1**

INTRODUCTION

The human health presents multiple and complex expression forms ranging in a multitude of plans of human, social, politics and economics nature. In essence, the human health quality is appreciated by the behavior and the real and durable function level of the organism bio system. In this context, the medical engineering is born, as a modern science that is based, by theoretical and experimental point of view, on the dynamic and systemic rectangle: the life science, the engineering science, the biomechanics and medical engineering. The main objective of the medical engineering is the realization of the health product, for the medical and rehabilitative clinics, these products being represented by biomaterials and medical devices.

The biomaterial represents, in a current and systemic approach, an inert substance, natural or artificial or obtained by the combination of these two categories, which interacts specific and relative with the living tissues or organism fluids for assuring and maintain its health. This interaction, synthetic characterized by biocompatibility and bio functionality, is realized with the help of some medical applications, general or personalized. These are materialized in the form of medical devices from biomechanics, clinic engineering, prosthetic devices, artificial organs, biomedical engineering domain.

The use of every type of medical device, as external prosthesis, urinary catheter, contact lens, bones prosthesis, neuromuscular sensors and stimulators, cardiac valves brings a lot of anatomic and behavioral human satisfactions, starting with the health and continuing with the possibilities of effectuation of different activities of professional, social, sports nature, etc.
With the evolution of the biomaterial science and technology, take place significant improvements of the prosthetic components. This trend is met in the area of the prosthetic components used by the amputated sportsmen. In this way, there are developed many types of prosthetic legs that are used both daily and for practicing of some collective sports, at the trainings and for the contests. An important step is the realization, by the Ossűr and Otto Back companies, of the prosthetic laminas in „J” shape. These allow the improvement of the performance conditions of the running (sprint) at the amputated sportsmen; this fact is highlighted by the South African runner, Pistorius, at the Olympics from London, in 2002.

Currently, are known a few data regarding the behavior of the material of the prosthetic laminas of „J” shape. There are presented commercial data regarding the shape, the dimensions and the material (carbon fiber reinforces epoxy). In this context, it is extremely required the expansion of the researches regarding the systematic analysis of the structure and the behavior of the prosthetics lamina biomaterial under the action of different loadings of mechanical and thermal nature that occur during their usage by the amputated sportsmen.

Starting from these considerations, the PhD thesis, entitled “ ***Methods and techniques for bio-system’s materials behaviour analysis***” proposes the development of an original study, with big potential in the improvement of the thermal and mechanic behavior of the prosthetic laminas from the construction of the prosthetic legs at the amputated sportsmen.

For the achieving of this goal, in the PhD thesis it systematically covers an experimental and theoretical research direction. This starts from the general with the study of the behavior of the materials from bio systems structure and continues with the identification of the anatomic and biomechanics characteristics of the leg, then it follows the identification of the methods of the analysis of the carbon fiber reinforced epoxy biomaterials and it finalizes with the methods of the experimental research of the thermal and mechanical properties of the carbon fiber reinforced epoxy layered bio composite.

The PhD thesis is structured on 7 chapters, where is gradually covered the scientific research subject. The research starts with an introduction and is finalized with the systemic presentation of the general conclusions, the description of the original contribution and the future research directions.

First chapter: *„Introduction”* presents in a systematic way the reasons of the effectuation of this scientific paper and its importance for the human factor, in the current case, for the sportsmen runners amputated with prosthetic laminas in „J” shape.

Chapter two: *„The currents stage in the thesis domain”* presents a synthesis of the current stage of the researches regarding the metallic, ceramics, polymeric and composite biomaterials behavior, in different applications in bio systems. It presents the methods of determination of the properties and the biomaterial behavior, and the composite biomaterials, particularly.

Chapter three: *„The objectives of the PhD thesis”* presents the objectives of this scientific research. These are reflected by theoretical studies, the simulation methods and the experimental researches regarding the behavior of the carbon fiber reinforced epoxy used in the construction of the prosthetic lamina of „J” shape.

Chapter four: *„Methodology of analysis of the biomechanical and anatomic characteristics of the leg”* is structured on seven subchapters. These describe, gradually and systematically, the functions of the leg: the bone and the articulation systems with the anatomic and biomechanical aspects which generate its structure and biomechanics, the walking and the running biomechanics at a normal person; the walking and the running biomechanics at the leg amputated persons with sports prosthesis. It is highlighted the information independency, the systematic approach of the characteristics and the functions of the bones and articulation systems with the kinematics and the kinetics of the leg components motions for the behavior on walking and running for a normal and amputated person.

Chapter five: „Methods of the analysis of the behavior of the carbon fiber reinforced epoxy composite biomaterials used in the construction of prosthetic laminas of J shape” is started from the fabrication process of the prosthetic laminas of „J” shape, used at the prosthetic leg of the amputated sportsmen. It is analyzed the following theoretical research stages:

- The simulation of the injection process of the „J" laminas by the RTM procedure with the Autodesk Moldflow Insight 2012® software;
- The theoretical thermal and mechanical behavior of the carbon fiber reinforced epoxy layered bio composite used in the construction of the „J" shape lamina;
- The simulation of the thermal and mechanical behavior of the carbon fiber reinforced epoxy layered bio composite;
- The methodology of the calculus of the carbon fiber reinforced epoxy layered bio composite mechanical strength.

The considerations and the characteristics of material presented in this chapter offer a global and theoretical founded representation of the behavior of the carbon fiber reinforced epoxy layered bio composite used in the construction of the „J" shape prosthetic lamina.

Chapter six: „Methods of experimental determination of the mechanical properties of the carbon fiber reinforced epoxy layered bio composite used in the construction of the „J" shape prosthetic lamina" is divided in two main parts. In the first part is presented the structure of the stages followed in the experimental tests for the determination of the mechanical characteristics of the carbon fiber reinforced epoxy layered bio composite under three testing categories: compression, bending and by DMA- Dynamic Mechanical Analysis method. The compression and bending mechanical testing were performed on the LS100 Plus and LR5K Plus testing machines from material testing laboratory, from the Mechanical Engineering Department of Transilvania University of Brasov, Romania. The DMA testing was performed on the ARES-G2 Rheometer experimental installation from the Mechanics and Materials Engineering Department from The Politechnical University of Valencia, Campus de Alcoy, Spain. In the second part is presented the structure of the followed stages for the determination of the linear thermal expansion coefficient for the carbon fiber reinforced epoxy layered bio composite. The testing were performed by the DIL 402 PC dilatometer from Material Science Department from Transilvania University of Brasov, Romania.

Chapter seven: *„Conclusions, original contributions and future research directions"* presents the conclusions obtained after the experimental and theoretical scientific researches, the elements of originality and the contributions of the author in the PhD thesis. It is highlighted the capitalizing of the research and the results dissemination by the participation at international conferences and the publishing of the articles in specialty journals. This chapter presents the future research directions.

The enclosed **References**, at the final of the PhD thesis presents the papers, the PhD thesis and the information sources consulted during the research. Due to the fact that the documentation sources have an interdisciplinary character, it was required, by the author side, the knowledge in different areas as mathematics, physics, chemistry, modeling and simulation and the anatomy and medical notions.

For the understanding and the capability of the processing of the theoretical and experimental research data, the beginning of the thesis was accompanied by an advanced preparation program consisting in courses as: The technology of research information, Creativity and Inventions, management and resources in research projects, Legislation and ethics in scientific research, Developing and elaboration of a report, etc. The PhD thesis includes, in the final a number of annexes required for the calculus, presented by tabular and graphical form.

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CHAPTER **2**

PRESENT STATE OF RESEARCH IN THE FIELD OF THESIS

2.1. INTRODUCTION

Knowledge in the bio-systems materials behavior has as theoretical and/or experimental research *platform* the triad composed of *life science (nature) - engineering - biomedical engineering.* Inside of it, the medical engineering is engineering science applied to human health [Sal.09] integrating the principles of physics, mathematics, chemistry etc. Multifaceted, health is determined, in essence, by the behavior of living body's bio-systems [Ola.98], [Teo.78] in specific environment, mechanical, thermal, psychic etc. conditions. In this context, medical engineering, treats all questions related to health and either those of related areas [Pop.08] as foodstuffs, pharmaceuticals, medical devices for diagnostic and treatment, health services provision systems etc. By structure, after Popa and al. [Pop.08], Grøndahl [Gro.04], the biomedical engineering is an interdisciplinary field in its own right between engineering and the health sciences (Fig. 2.1), field being in a continuous development. At present, the great variety of different types of issues related to human health give rise to a wide range of sub-discipline or branches of biomedical engineering. They are presented in different classifications, after EEE – EMBS (Society for Engineering in Medicine and Biology), [Sal.09], [Pop.08], [Bro.06], as:

- biomechanics;
- biomaterials;
- prosthetic devices and artificial organs;
- biological and bio-informatics systems;
- medical and biological analyze;
- clinic engineering;
- biomedical instrumentation and sensors;
- physiological modeling;
- bio-molecular engineering and biotechnology;
- bio-nanotechnology;
- medical imaging etc.

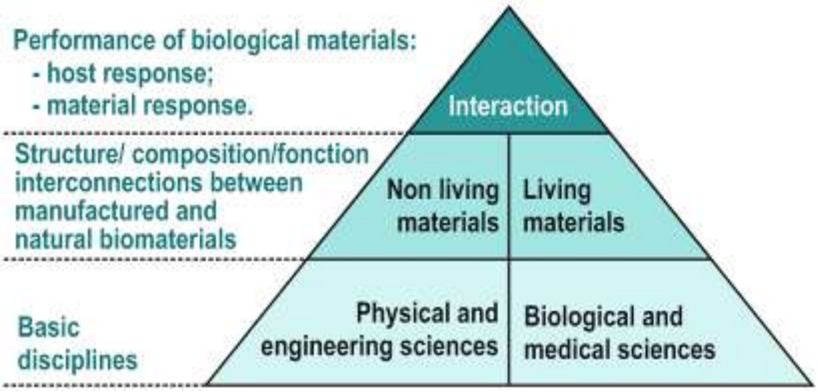


Fig. 2.1. Synergistic interactions of engineering and biological sciences disciplines involved in the manufacture of biomaterials, reproduction after Grøndahl. [Gro.04]

Biomedical engineering studies and realizes a complex and important health product intended for medical and rehabilitation clinic, represented by [His.11] *biomaterials and medical devices*.

Popa and al. [Pop.08] defines the medical device as: *it can be an instrument, apparatus, implant or mechanism including certain components, parts or accessories and, which is intended to be used for diagnosis, cure, treatment, or prevention of disease in humans or in animals.* In the *(French) Code of public health* through articles L52-11 and R5211-1 [Cyn.11], the medical device is defined being *any instrument, apparatus, equipment, material, product, excepting the products of human origin, used separately or in combination, including the software and accessories required for its proper function, intended by the manufacturer to be used for medical purposes and whose main action is not achieved by pharmacological, immunological or metabolic means, but any whose functioning can be assisted by such means. A computer software is also a medical device, intended by the manufacturer to be used specifically for diagnostic or therapeutic purposes*.

Medical devices present a wide functional and constructive variety, and have life duration dependent mainly on the performance and behavior of component materials, generically named, ***biomaterials***.

The main purposes of medical devices are the following:

- diagnosis, prevention, monitoring, treatment and mitigation of a disease;
- diagnosis, monitoring, treatment, mitigation or compensation for an injury or handicap;
- study, replacement or modification of the anatomy or a physiological process etc.

In medical practice, devices are classified according to several criteria [Cla.10], [Lem.07]:

- after the duration of use (Tab.2.1): temporary, short term, long term;
- after the effect on living body: non-invasive, invasive and measuring devices;
- after the main function (Tab. 2.1): superficial; with external communication; implant (with inner communication);
- by operating type of energy: active and passive devices;
- after the type of surgical act: reusable and disposable surgical instruments etc.

Table 2.1. Devices categories, reproduction after Park. [Par.12]

Type of medical device/functional characteristic		**Contact duration**	**Constructive exemples**
Superficial	Skin	limited temporary permanent	electrodes, external prostheses, fastening strip, compression bandages, monitors
	Mucous membranes	limited temporary permanent	contact lenses, urinary catheters, intra intestinal devices, endotracheal tubes, bronchoscope, dental prosthesis, orthodontic devices
	Injured surfaces/ compromised	limited temporary permanent	ulcers, burns, healing or bandaging devices, occlusive stains
With external communication	Indirectly, blood flow	limited temporary permanent	transfer or extension seals used in blood management, solutions, etc
	Communication bone tissue, dentine	limited temporary permanent	laparoscopes, drainage systems, dental cements, dental filling materials, skin staples
	Blood flow	limited temporary permanent	intravasculare catheters, temporary pacemaker electrodes, tubes and accessories for oxigenatoare and dialysis
Implant (with inner communication)	Device implant tissue/bone	limited temporary permanent	nails and orthopedic plates, sub-periostal and breast implants, replacement of joints and tendons, bone cements and intrabone devices and for drugs release, sensors and neuro muscular stimulators, artificial larynx, binding clamps
	Blood	limited temporary permanent	pacemaker electrodes, arteriovenous fistulae, artificial heart valves, vascular grafts, internal catheters for drugs release, ventricular assistance devices
Functional basic time	Limited < 24 ore	temporary : 24 hours - 30 days	permanent > 30 days

In European Union, any medical device is sold according to the regulations ,,EU Medical Devices Directive 93/42/EEC'' elaborated in 1995 and updated in 1998. In present, the medical devices must comply with the rules ISO 10993, Annex 1 [ISO.93], ISO/TC 194 [ISO.94], [Lem.07].

2.2. MATERIALS USED IN BIOSYSTEMS STRUCTURE

2.2.1. Definitions and brief history

A wide range of medical devices is used in the structure of biosystems - implants, osteo-synthesis plates, screws, medical instrumentation, etc. constructed from materials globally named, biomaterials. These materials are found in a wide range of functional requirements, processing technologies, the costs of use etc. [Lah.10].

The first definition of biomaterial is proposed, in 1982, by Williams [Wil.86] at Consensus Conference in Chester, United Kingdom, organized under the aegis of the European society for biomaterials – "*any substance (other than a drug) or a combination of natural or synthetic substances that can be used at any time as a whole system independently or as a part of a system that treats, enhances or replaces a tissue, an organ or a function of the body*". Later during the same Conference, in 1986 this definition was reformulated: biomaterial is "a lifeless material used in a medical device designed to interact with biological systems". [Wil.92] It is to highlights the definition formulated by the Department of Biomaterials of Clemson University, USA, as biomaterial is [Bul.12] "*an inert substance in terms of systematic and pharmacologically, created to be implanted in/or to cohabit with living systems*". There are also, natural biomaterials. Mayers and al. [Mey. 08] presents in a systemic and comprehensive study the structure and mechanical properties of these types of materials.

Regardless of the type biomaterial, natural or synthetic, the definitions given in the literature, the keystone is the understanding and ensuring the fundamental requirement to biomaterial to interact with specific and selective in direct contact with tissues or fluids of the body during a medical applications. Sedel and Janot [Sed 11], and Biltresse [Bil. 03] highlights two fundamental specific requirements which must be taken into consideration when developing or using a biomaterial in a medical application: bio-functionality, which is owned by the mass of the material to perform the role required in quality of implant prosthesis, substitution of a defective organ and, respectively, the bio-compatibility.

The use of materials in the structure of the human body, composed [Ola. 98] of biosystems such as musculoskeletal, dento-maxillary, cardiovascular etc., is not a new. Yet now 3500-4000 years Chinese, Phoenicians, Assyrians, Babylonians, Egyptians and later Greeks and Romans processed and used a variety of materials, gold, silver, wood, fabrics, etc., for medical purposes: dentures, gold and inside wire for immobilizing bone fractures, sheets of gold for filling cavities etc. [Man.10], [Bul.12] The techniques and technologies used by the early 19^{th} century to restore the damaged parts of the body such as hands, feet, teeth etc. or even lost due to disease, accidents, armed confrontations, etc. did not allow the notable achievements, being generally simple and rugged. To illustrate plastically this point, Narayan [Nar. 12] choose the picture titled "Beggars", painted by Pieter Brueghel the elder (1568), where the parts of the leg prosthesis (fig. 2.2) used in the middle ages you can be seen. From the late 1800^s autologous vein grafts are used (synthetic) and autologous saphenous grafts (the patient's own vein) for closure pressure. [Sny.09] Although the long-term results were not satisfactory, due to the development of aneurysms, this new medical technique was an important step in vascular surgery.

Fig. 2.2. "Beggars", painted by Pieter Brueghel the elder (1568), reproduced after Narayan [Nar.12] or http://www.ibiblio.org/wm/paint/auth/bruegel.

Once, however, with the discovery and development of surgical aseptic technique (Dr. J. Lister after the 1860^s) and with the discovery of new materials, first of all the metals, polymers, etc. a significant leap in the study and use of materials in medicine stands up. [Bul.12] Medical devices and advanced therapeutic methods begin to be invented. In this regard, it is to be mentioned the artificial heart, described by the scientist Étienne-Jules Marey, in 1881 (fig. 2.3), device that Ratner and al. [Rat.04] considered that "*perhaps was never built*" and, during the same period; the first attempts to remove toxins from the blood.

In 1895 [Her 11], a. w. Lane introduces the first metal plates for fixation of bone fractures. W. D. Sherman uses for first time (1912) steel alloyed with vanadium, *Sherman Vanadium Steel*, in the form of screws for bone fractures fixation. [Bla.03] This steel was characterized by resistance and improved ductility as well as having a low resistance to corrosion in body fluids.

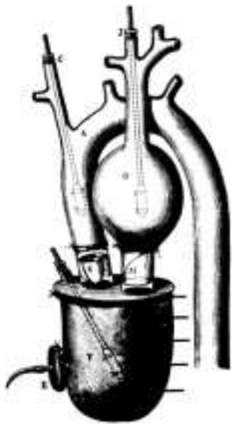


Fig. 2.3. Artificial heart, described by Étienne-Jules Marey (1881), reproduced after Ratner and al. [Rat.04]

Appearance on the market in 1920 of the 18-8 stainless steel (18% Cr-8% Ni), type 302 in modern classification [Won. 00], having increased resistance to corrosion (body fluids) cease using steel alloyed with vanadium in medical applications. A little later, with the addition of molybdenum in the steel 18-8, at the rate of about 2% the stainless steel 18-8 Mo ise elaborated, characterized by an improved resistance to corrosion in salted water. This steel is subsequently known as stainless steel 316 [Haï.05], [Pop.01].

The study of materials used for medical purposes has a significant leap after 1900 by the advent of new materials as well as works that have as their central research object the nature of the materials and their interaction with biological systems. Thus, metal alloys begin to be used in medical applications, assessments on issues related to their use from the mechanical point of view, the processes of corrosion, biocompatibility are done etc. [Bul.12] In 1932 the cobalt based alloy called Vitallium, is the first metallic biomaterial used successfully to solve corrosion problems [Bre.13] for the implant [Eli.08]. It cites also the work developed in 1917 by D'Arcy W. Thompson, titled, “On growth and form”, considered by Meyers and al. [Mey. 08] of major importance in the systemic study of biological systems approached as engineering structures.

During World War II, with disastrous effects for health, life and human life duration, spurred of exclusive military reasons the emergence of new durable and inert materials as well as with high performance metals, stainless steel and titanium, ceramics and polymeric, especially nylon, teflon, silicone etc. After the war, these new materials were quickly taken for medical purposes [Rat.04]. In the late 60^{s} Brånemark and al. discover the excellent biocompatibility of titanium properties describing that it may come into direct contact with the bone. It is the time of commencement of classification of different materials as biomaterials. [May.07] In 1976 the

European Society for Biomaterials (The European Society for Biomaterials ESB) is created. In 2001, Scott [Gor. 01] make an anniversary presentation of the society they belong to 27 countries in Europe and beyond: Australia; Austria; Belgium; Canada; Denmark; Egypt; Finland; France; Germany; Greece; Israel; Italy; Japan; South Korea; Norway; Poland; Portugal; Russia; Singapor; Slovakia; Spain; Sweden; Switzerland; Netherlands; Turkey; United Kingdom; USA.

At present, , multiple monographs, papers, guidance, doctoral theses, etc. are drawn in the field of biomaterials, that describe elements of structure, properties, and fields of use, etc. of biomaterials. In this regard, it is to cite the work developed by Bush [Bus.99], Bronzino [Bro. 06], Ratner and al, [Rat. 04], Park and Bronzino [Par. 03], Wong and Bronzino [Won.07], Bulancea [Bul.12], Popa and al. [Pop. 08], Pop [Pop.01] etc. At the present time international and national bodies which provide advice and develop standards for the production, testing and use of biomaterials: ISO, ASTM, FDA (Food and Drug Administration of USA) etc.

Researchers in the field of life sciences, such as Gh. Chiriţă, and M. Chiriţă [Chi. 09] believes that the future of medicine and quality of life is intrinsically linked to the present and the future use of biomaterials in the medical field. This assessment can be supported by the three main considerations: [Bio.11], [Psc.13], [Tex.05], [Rat.04]

1. social importance of biomaterials by improving the quality of daily life of human through the particularly broad range of devices, implants, artificial organs, etc. which are used;
2. the strategic importance of improving the life expectancy of the human being and in a global approach to support the existence of life on Earth;
3. the overwhelming economic role of considerable amounts, on the world market and the high number of concerned persons, as a result of production activities, marketing, etc., arising from the use of biomaterials.

Under these particularly complex circumstances, where a biomaterials is to be reviewed, developed and used, from the structural point of view, macro-micro and nanodimensional, biomaterials science is that part of the materials science that analyzes, processes, experience, tests, etc. the biological interaction of different biomaterials, natural or synthetic, with living systems. Depending on the requirements of medical, functional, body protectors, etc. imposed to biomaterial, or to medical device where it is integrated in a final processed form, optimizing the reaction is carried out in "real conditions, of biomaterial using" [Pop.08] with regard to the nature of triad nature/composition-structure-biomaterial properties, in conditions of maximum efficiency, achieved at minimal cost.

In the relevant literature [Wil. 95], [Ryh. 99], an "official" definition of biomaterials science is done "study and knowledge of the interaction between living materials and non-living materials". For Ratner and al. [Rat.04], biomaterials science consists in "physical and biological studies of the materials and their interaction with the surrounding biological environment". In the present time it is accepted, under the systemic aspect, the interaction between biomaterials science and its medical applications, in the form shown in Figure 2.4.

It should be noted that inter-correlations are established between the life science, materials science and engineering.

2.2.2 Biomaterials classification

In biomaterials science, are used, after Konttinen [Kon. 13], Bulancea [Bul.12], Park and Bronzino [Par.07], Grøndahl [Gro.04], Guillemot [Gui.00], Mehrotra [Meh.12], [Ass.07] various criteria for the classification of biomaterials with regard to:

1. nature and chemical composition;
2. biomaterial behavior with respect to host tissue and the environment;
3. the nature of the restored tissue in which is involved the biomaterial;
4. presentation form of biomaterial;
5. structure etc.

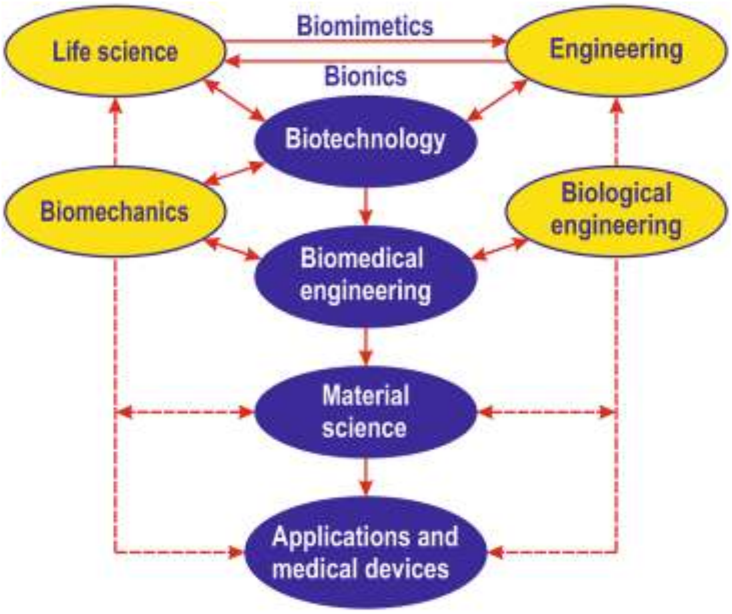


Fig. 2.4. Correlations between life science, engineering, and biomaterials science, adapted from [Chi.09]

At the moment, in the field of biomaterials are most used, two basic criteria that allow for a high degree of generalization of the types of these materials (Konttinen et al. [Kon.13], Bulancea [BUL.12], Park and Bronzino [Par.07], Wong and Bronzino [Won.07], Domşa [Dom. 05]):

6. chemical nature, which is the most used classification criterion;
7. origin, [Rod.09], [Ami.09], [Ams.06].

Based on these two criteria, the biomaterials are divided into the following five main categories (Table 2.2): metal; ceramic; polymeric; composites; and other biomaterials.

Table 2.2. Principles of biomaterials classification, processing after [Kon.13], [Bul.12], [Zhu.12] .

<table>
<tr><th>Classification criterion</th><th colspan="6">Classes of biomaterials</th></tr>
<tr><td>Origin</td><td colspan="6">Natural biomaterials or Biological materials:
1. vegetal;
2. animal
Synthesis biomaterials
Semi-synthetic or bio-hybrid</td></tr>
<tr><td rowspan="12">Chemical nature</td><td colspan="6">1. Metals – metallic biomaterials</td></tr>
<tr><td colspan="2">Pure metals</td><td colspan="2">Metallic alloys</td><td colspan="2">Inter-metallic compounds</td></tr>
<tr><td colspan="2">- precious metals: gold, silver, platinum;
- non-precious metals: titanium, tantalum; niobium; zirconium</td><td colspan="2">- traditional stainless steel: 316L..and advanced:350, 22-13-5…
- titanium alloys; TiAl6V4, TiAl5Fe2.5…
- chromium-cobalt with or without W, Mo, Ni…</td><td colspan="2">- dental amalgams Ag-Sn-Hg;
- shape memory alloys: nitinol...</td></tr>
<tr><td colspan="6">2. Ceramics – Ceramic biomaterials</td></tr>
<tr><td colspan="3">Bio-inert</td><td colspan="3">Bio-active</td></tr>
<tr><td colspan="3">-based on oxides Al_2O_3; Z_rO_2;
-based on carbides and nitrides Si,Ti;
- carbon: vitreous, pyrolytic, quasi-diamond.</td><td colspan="3">- based on calcium phosphate: hydroxyapatite - HA, tricalcic phosphate -TCP;
- based on other salts of calcium carbonates, sulfates, aluminum compounds ;
- bio-glass and vitro ceramice.</td></tr>
<tr><td colspan="6">3 Organics – Polimeric biomaterials</td></tr>
<tr><td colspan="3">Elastomers: polyurethane silicons</td><td colspan="3">Plastic materials:
- thermohardening;
- thermoplastic;
- thermoplastic with high resistance;
- bioabsorbable.</td></tr>
<tr><td colspan="6">4 Composed materials – Composite materials</td></tr>
<tr><td colspan="2">Organic-organic type</td><td colspan="2">Mineral-mineral type</td><td colspan="2">Organic-mineral type</td></tr>
</table>

In medical applications, and especially in orthopedics, a major importance has the tissular response of the body in contact with the biomaterial. This governs the division of biomaterials in various functional categories. Thus, Hennesand Nissan-Ben [Hen.04], Konttinen and al. [Kon.13], group biomaterials in three main categories:

- bio-inert (almost)materials with a smooth or porous surface. These biomaterials have little chemical interaction with the adjacent tissues of the body;

- bioactive (chemically reactive) materials with the tissue surface. They favors the formation of chemical bonds (stickers) with bone tissue, or, in some cases with soft tissue;

- degradable or absorbable, which are easily absorbed by the body or are completely dissolved and replaced by the adjacent bone tissue or skin, after a certain period of time.

Chemically, the metals are typically inert, ceramics can be inert, active or absorbable and the polymers can be inert or absorbable [Rod.04].

2.2.3 Overview on the biomaterials types

2.2.3.1 Metallic biomaterials

Medical applications of metallic biomaterials include three main areas: 1 - orthopedics; 2- surgery; 3 - dentistry. Metallic biomaterials are encountered in the form of pure metals or alloys. For alloys, metals like iron Fe, chromium Cr, cobalt Co, Ni nickel, titanium Ti, niobium Nb, molybdenum Mo, tantalum Ta, tungsten W, are used, which, in their great majority, are tolerated by the human body but only in small quantities [Bal.07]. Generally, in the literature, the metallic biomaterials are divided in four principal groups [Bul.12], [*Aci.12], [Bal.07]: stainless steels; cobalt-based alloy-chromium; titanium based alloys; other metallic biomaterials. Currently, the materials are used for the manufacture of bio-metallic implants, hypodermic syringes, plates, sterilizers, workbenches etc.

Stainless steels

The term stainless steel is taken from French terminology and designate an iron-carbon alloy which contains at least 12 % chromium and it's got a wide variety of steel grades, characterized by various chemical compositions [Con.98]. According to microscopic structure, the stainless steels are divided into the following basic categories:

1. martensitic, having chromium as main alloying element;
2. ferrous - martensitic;

3. ferrous;
4. ferrous –austenitic;
5. austenitic, allied with chromium and nickel.

The presence of chromium gives to these steels, specific properties called stainless: resistance to corrosion caused by atmospheric air, erosion resistance in contact with acids, with various chemicals etc. This resistance is achieved by creating a thin, protective film invisible of metallic oxides and very dense, adherents to the surface of the alloy materials. It is worth noting that if this film is damaged or removed, for various reasons, it quickly restores in contact with oxygen or with another oxidized substance [Con.98]. Corrosion resistance is highly improved by adding nickel in the alloy, which creates easily the oxide film, and by the addition of molybdenum, and at the rate of 2-4%, the obtained stainless steel becoming usable in the medical applications of the body [Pop.01], [Pop. 08].

Table 2.3. 300 series austenitic stainless steel used in medical applications, (after [Pop.01])

AISI symbol	**Chemical composition %**				**Observations**
	C	**Cr**	Ni	Other elements	
Group III-austenitic Cr-Ni Steels					
301	max.0.15	16-18	6-8	max 2% Mn	become harder during loading
304	max.0.08	18-20	8-12	max 1% Sn	18-8 special steel
304L	max.0.03	18-20	8-12	max 1% Si	very low carbon content
310	max.0.25	24-26	19-22	max 1.5%Si	25-20 steel resistant to hot
310X	max.0.08	24-26	19-22	max 1.5% Si	very low carbon content
314	max.0.25	23-26	10-14	1.5-3% Si	Si hot resistant steel
316	max.0.10	6-18	10-14	2-3% Mo	steel 18-8 with Mo for surgical implants
316L	max.0.03	16-18	11-14	2-3% Mo	steel with very low carbon for implants
317	max.0.08	18-20	11-14	3-4% Mo	steel with high content of Mo
321	max.0.08	17-19	8-11	max 4% Ti	stabilized steel with Ti

Austenitic stainless steels are characterized by a high hardness, high toughness and a very good corrosion resistance, being non-magnetic also. 300 series austenitic stainless steel (Table 2.3) is used in medical applications. The marks 304, 316 si 316 L, (ASTM F138, F139), grade 2) are typical. [Bru.04] The letter "L ", from 316L steel designates a low carbon content, 0.03% compared to 0.08% content in steels: 304 or 316 [Bru.04], [Des.08], [Haï.05]. Although 316L steel is resistant to corrosion, medical device components made of this steel can however corrode inside the body, under certain circumstances, such as powerful strain, oxygen-depleted zones etc.

[Ail.03] Under these circumstances, stainless steels are suitable to be used only in implants that have limited contact with the surrounding tissue [Rat. 04].

At the moment, the mechanical and chemical properties of austenitic stainless steels can improve by alloying elements and by controlling heating/cooling processes in material [Con.98].

Cobalt - chromium based alloys

Cobalt based alloys contain chromium and, almost always, molybdenum. (Table 2.4) [Pop.08] They are used in a wide range of applications [Soe.92]: aeronautics, buildings, special magnetic properties applications, orthopedic and dentistry medical applications. Their use in medical applications is determined by the following considerations [Pop.08], [Dis. 99]:

Table 2.4. Chemical compositions of cobalt based alloys used as biomaterials (after [Bru.04]).

Material	ASTM symbol	Commercial name	Composition %	Observations
Co-Cr-Mo	F75	Vitallium; Haynes Stellite 21; Protasul 2; Micrograin-Zimaloy;	58,9-69,5 Co 27,0-30,0 Cr; 5,0-7,0 Mo; max 1,0 Mn; max 1,0 Si; max 1,0 Ni; max 0,7 Fe; max 0,5 C	-Vitalium is the registered trademark of the company Howmedica; - Haynes Stellite 21 (HS 21) is the trademark of CabotCorp.; - Protasul is the trademark of Sulzer AG, Switzerland; - Zimaloy is the trademark of Zimmer, SUA.
Co-Cr-Mo	F799	Co-Cr-Mo forjat; Co-Cr-Mo thermo-mechanical FHS;	58,0-59,0 Co 26,0-30,0 Cr; 5,0-7,0 Mo; max: (1,0 Mn; 1,0 Si; 1,0 Ni; 1,5 Fe; 0,35 C; 0,5 N)	- FHS = high resistance by forging
Co-Cr-W-Ni	F90	Haynes Stellite 25	45,5-56,2 Co; 19,0-21,0 Cr; 14-16 W; 9,0-11,0 Ni; 1,00-2,00Mn; 0,05-0,15 C; max: (3,0 Fe; 0,04P; 0,40 Si; 0,03 S)	- Haynes Stellite 25 (HS25) is the trademark of Cabot Corp.
Co-Ni-Cr-Mo-Ti	F562	MP 35 N Biophase Protasul-10	29-38,8 Co; 33,0-37 Ni; 19,0-21,0 Cr; 9,0-10,5 Mo; max: (1,0 Ti; 0,15 Si; 0,010 S; 1,0 Fe; 0, 15 Mn)	-MP35 N is the trademark of SPS Technologies. - Biophase is the trademark of Richards Medical - Protasul 10 is the trademark of Sulzer, AG Switzerland

- cobalt has a particular behavior in biologic environment: he does not cause inflammation, ulcers, congestion, has a very good corrosion resistance, is not carcinogenic or allergenic;
- chromium , in proportion of 25-30% gives to Co-Cr alloy a high chemical stability and a good resistance to corrosion due to the spontaneous formation on its surface of the stable oxide film protectors $Cr_2 O_3$;
- molybdenum increases chemical and fatigue resistance and make it more ductile.

ASTM American standards recommends [Par.07], [Bul.12] four types of alloys (table 2.5) cobalt-based for prosthetic applications: CoCrMo cast alloy F76, CoNiCrMo forged alloy F562, CoCrWNi forged alloy F90, and CoNiCrMoWFe forged alloy F563. In the case of orthopedic implants that supports very large loadings (hip and knee implants) it is recommended to use the CoCrMo cast alloy F76, and CoNiCrMo forged alloy F562.

Table 2.5. Types of cobalt-based alloys. (after [Bul.12], [Par.07])

Element	**Co-Cr-Mo** (cast F75)		**Co-Cr-W-Ni** (forget F90)		**Co-Ni-Cr-Mo** (forged F562)	
	min. %	max. %	min. %	max. %	min. %	max. %
Cr	27,0	30,0	19,0	21,5	19,0	21,0
Mo	5,0	7,0	—	—	—	10,5
Ni	—	2,5	9,0	11,0	9,0	37,5
Fe	—	0,75	—	3,0	33,0	1,0
C	—	0,35	0,05	0,15	—	0,025
Si	—	1,00	—	1,00	—	0,15
Mn	—	1,00	—	2,00	—	0,15
W	—	—	14,0	16,0	—	—
P	—	—	—	—	—	0,015
S	—	—	—	—	—	0,010
Ti	—	—	—	—	—	1,0
Co	equilibrium	equilibrium	equilibrium	equilibrium	equilibrium	equilibrium

Nickel based alloys

Nickel is a grey-white metal and has as main alloying elements the chromium, titanium and the aluminum. It has a high atmospheric corrosion resistance but is corroded by saliva, perspiration or other fluids secreted by the body, and has the next technological properties: malleable, ductile, tenacious and easily deformable. By aligning themselves with the chromium corrosion, oxidation and abrasion resistant alloys are obtained. Ni-Cr alloys are used primarily in dentistry for dental prostheses due to the ductile nickel. [Gui.00] At the moment, by aligning Ni-Cr alloy under certain small percentages, and with other alloying elements as: Mo, Al, Mn, Be, Cu, Si, C, Co, Ga etc., complex biomaterials are obtained. They have a large range of mechanical characteristics and are suitable, especially, for dentistry, as: Verasoft (Ni-Cr cast alloy for Crowns, - restoration) Vera Bond (as support for porcelain, metal, total crowns superstructures for implants) etc., mentioned in the literature [Bra.94], [Pop. 08], [Veb.12], [*Ver.12].

Titanium and titanium alloys

Titanium can be included into the category of semi light metals with remarkable properties, among which stand out [Ger.81]: relative low density ρ = 4500 Kg/m^3 (Tab. 2.6), high mechanical resistance and high specific resistance R_m/ρ (where: R_m is breaking strength and ρ, the density). At the beginning it was employed for automobile and aviation but, recently, it is successfully used in medical applications.

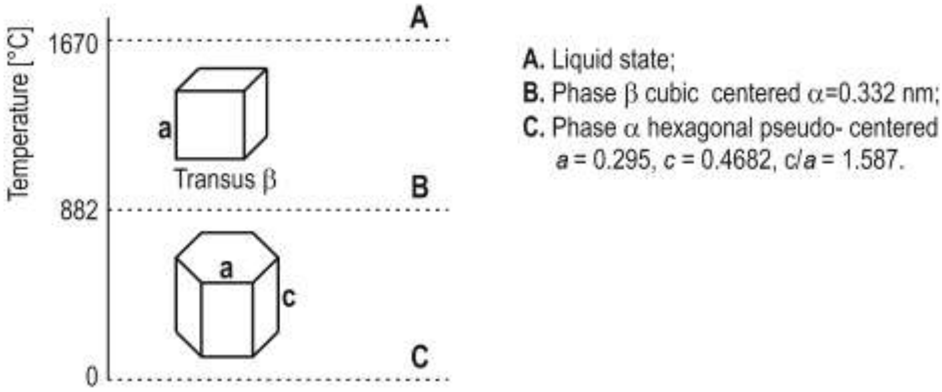


Fig. 2.5. Crystallization stages of pure titanium depending on temperature, after Froes [Fro.04].

Depending on the temperature T=882 °C, called polymorphic transformation point [Ger.81] or “beta transus” [Fro.04], titan has (Fig. 2.5) two different stable crystalline structures [Del.06]:

- state β or titanium β (high temperature stable state). In this state, the titanium crystallizes at high temperature T = 1668 °C in cubic system with centered volume;
- state α or titanium α (low temperature stable, ambient). Under 882 °C, the titanium from state β in state α, crystallizing in hexagonal system pseudo-compact [Let.01].

Pure commercial titanium (99% minimum content) are classified into four grades of purity according to the quantities of impurities present in the composition such as oxygen, nitrogen, iron, etc. [Fro.04], [Pop.01]. By alloying with Al, Mo, V, Mn, Cr, Sn, Fe, Sr, Nb, Si (sometimes in small proportions), titanium forms alloys by various properties. [Ger. 81] Alloying elements have the ability to raise or lower the position of the polymorphic transformation point α←—→β or "beta transus" [Fro.04], [Ger. 81], [Pop. 01], [* Pre.11].

Table 2.6. Mechanical characteristics of titanium, after [*Tit.12], [*Tit.11], [*Tit.11.a]

Mechanical characteristics	Symbol	Units of measure	Pure titanium		Technical titanium	
			From TiI_4 treated in vacuum at 750°C	Melted in vacuum and cast	Melted in vacuum, cast and heat treated	Synthesized in vacuum
Elasticity modulus	E	daN/cm^2	7840	10900-11200	10500	11760
Tensile strength	R_m	daN/cm^2	22,4	25,8	56-82	56
Yield strength	Rp_{02}	daN/cm^2	12,2	13,7	50-77	45
Elongation	A	%	55	62-70	12-25	5,5-25
Constriction		%	60	85-88	35-60	26-30
Resilience	K_{CU}	daN/cm^2	20	25-105	5-7	5
Hardness	HB	daN/cm^2	95		115-185	185

The first category of alloying elements are called alpha-gens or stabilizing elements of phase α. These elements are totally or partially soluble in α phase. The most common alpha-gen item is aluminum. The second category of alloying elements (descending point "beta transus") are called beta-gens or stabilizing elements of phase *β*. In this category are mentioned V, Mo, Nb, and Ta (isomorphic elements) and Fe, Cr, M, şi Si (eutectoid elements). There is, however, a third category of alloying elements which do not intervene on "beta transus" point. According to their structure at ambient temperature, titanium alloys are classified into three main categories [Pop. 01], [*Pre 11]: *α* alloy, *α–β* alloy, and *β* alloy. Niinomi [Nii.04] presents the main titanium alloys categories *α*, *α–β*, *β*, used in medical applications as follows:

1. pure Ti (ASTM F67–89), Degrees 1, 2, 3, and 4; purity-decreases (by adding N, Fe, and O), resistence – increases; less and less ductile;

2. Ti-6Al-4V ELI (ASTM F136-84, F620-87): type *α + β*;

3. Ti-6Al-4V (ASTM F1108-88): type *α + β*;

* 4. Ti-6A1-7Nb (ASTM F1295-92, ISO 5832-11): type Switzerland;

* 5. Ti-5Al-2.5Fe (ISO5832-10): type Germany;

* 6. Ti-5Al-3Mo-4Zr: type Japan;

* 7. Ti-15Sn-4Nb-2Ta-0.2Pd: type Japan;

* 8. Ti-15Zr-4Nb-2Ta-0.2Pd: type Japan;

* 9. Ti-13Nb-13Zr (ASTM F1713-96): type USA, low modulus;

* 10. Ti-12Mo-6Zr-2Fe (ASTM F1813-97): type USA, low modulus;

* 11. Ti-15Mo (ASTM2066-01): type USA, low modulus;

12. Ti-16Nb-10Hf: type USA, low modulus;

13. Ti-15Mo-5Zr-3Al: type Japan, low modulus;

14. Ti-15Mo-2.8Nb-0.2Si-0.26O: type USA, low modulus;

* 15. Ti-35Nb-7Zr-5Ta: type USA, low modulus;

* 16. Ti-29Nb-13Ta-4.6Zr: type Japan, low modulus;

* 17. Ti-40Ta, Ti-50Ta: tip USA, High corrosion resistance.

Observation: * - new developments for medical applications.

The using manner of titanium and titanium alloys for medical applications are determined by the characteristics of their bio-functionality [Pop.08] to the hard tissue replacement, cardiac and cardiovascular applications and others [Liu. 04]. To be used as implants, titanium alloys are subjected to heat treatment in order to improve their bio-compatibility [Pop. 08].

Nickel-Titanium (Nitinol) alloys

Smart materials group, belongs to and with shape memory alloys SME (Shape Memory Effect). These alloys have a remarkable thermomechanical property consisting of that they can save the cold form, and after cold deformation, by simple heating they return to the previously saved form [Bul.12], [Pop.08], [Par.07], [Par.07.a], [Jor.10], [Pil.09]. Thermo-mechanic behavior of shape memory material can be examined macroscopically, in two aspects [Bal. 07], [Jor. 10], [Bul.12], [Tho.00]: 1 - shape memory which is related to the transformation of solid phase called martensitic reversible thermo-elastic transformation; 2 – pseudo-elastic or super-elastic behavior characterized by the fact that after a very intense deformation, the shape is recovered after cycles of loading and unloading of material performed at constant temperature.

Shape memory alloys are clasified into three main families [Peu.05]:

- Ni-Ti alloys (~ 50-60%) with additional elements Cu and Fe, generic called „nitinols'';
- Cu based alloys;
- Fe based alloys.

Among the shape memory alloys more often used in medicine, mostly dedicated to dentistry, it is to mention Ni-Ti alloys. They are favored for their two particular properties: super-plasticity, shape memory [Jor.10] and good bio-compatibility.

Noble metals and alloys

In this family belong [Bra. 94], [Pop. 01], [Pop.08], [Gre.09] noble metals, gold, silver, platinum, palladium, rhodium, iridium, ruthenium, and osmium and their alloys. They are characterized by their particular physical, chemical and high anti-corrosive properties, being used especially in dentistry, in the form of fillings, dentures, fixed inlay (gold, silver and alloys) suture threads (tantalum), bone implants (zirconium) etc. In general, the use of these materials in medical applications remains marginal, primarily due to the high cost but also due to low values of mechanical properties [Gui.00], [*Deg.13], [Bra.94].

2.2.3.2 Ceramic biomaterials

At present, the term *ceramics* designates, [Des.08], [Tha.04], a wide range of materials, natural and synthetic pure oxides, carbides, nitrides, glasses, carbonates, etc., with ionic and/or covalent bonds. Ceramic biomaterials are in a wide range of medical applications as [Koh.09]:

- replacement of mineralized living tissue (bone or teeth);
- joints replacement;
- implant fixation in bone.

They can be classified considering the following mean criterions [Aza.06], [Sáe.99], [Mud.03]:

A. ***Bio-activity with biological tissue environment*** (Fig. 2.6):

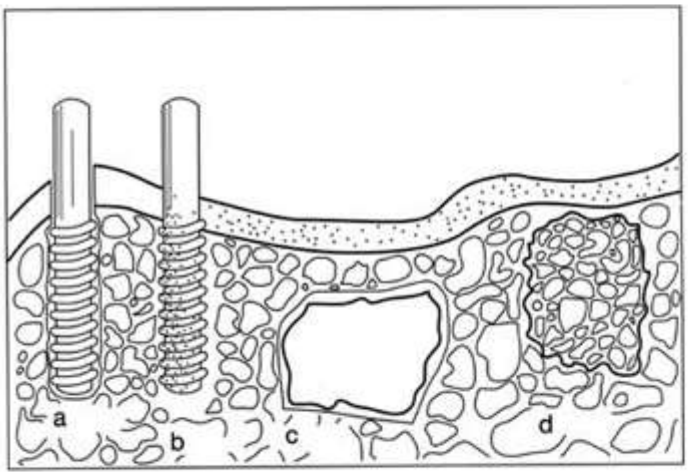


Fig. 2.6. Bio-ceramics classification according their bio-activity: inert ceramic, alumina dental implant (a); bio-active ceramic, hydroxyl-apatite layer on a metallic dental implant (b); active surface in bio-glass, absorbable ceramic (c), after Hennes and Nissan-Ben [Hen.04].

- bio-inert ceramics - interact weakly with biological environment, are not toxic, carcinogenic, inflammatory and allergenic, have good corrosion behavior. In this family belong alumina Al_2O_3, zirconium ZrOn, silicon nitride and carbon. Alumina and zirconium are the mean bio-ceramics used in medical applications, generally having high purity and density; [Hen.04]

- bio-active or bio-reactive ceramics - generally designed to promote the formation of bone tissue. They are characterized by surface activities at the level of the surrounding tissue to promote adherence to the surface of the bone tissue prosthesis, being biodegradable and being slowly replaced by the living tissue. In this family belong the hydroxyl-apatite ($Ca_{10}(PO_4)_2(OH)_2$), and the bio-glass.

- bio-degradable or bio-absorbable – bio-ceramics that dissolve over time and are replaced gradually by natural tissue.

B. ***Density/porosity***

Porous structure of the ceramics favors the bone regeneration. A distinction could be done between three categories: ceramic with micro-porosity; ceramic with macro-porosity (pore size over 100-150 μm); the particular porosity ceramics.

C. ***Material characteristics***

1. dense and inert bio-ceramics;
2. porous and inert bio-ceramics;
3. bio-active dense or porous bio-ceramics;
4. dense and absorbable bio-ceramics.

D. ***Medical application***

1. structural ceramics characterized by a high mechanical resistance (high performance ceramic) – the classic types are alumina (α-Al2O3) and zirconium (ZrO2);

2. non-structural ceramics - generally biodegradable bio-reactive ceramics, having a dense or porous structure and low mechanical strength, as hydroxyl-apatite (HA) and tri-calcium phosphate TCP ($Ca_3(PO_4)_2$).

2.2.3.3 Synthetic polymers

By definition [Wei.10], [Pol*.11], is called polymer an organic or inorganic macromolecule formed by repeated removing of basic unit(s) called monomer(s) attached by covalent bonds. The total number of monomers incorporated into a macromolecule defines its polymerization degree. Molecular mass of a polymer material is calculated with the help of two parameters: the numeric average molecular mass M_m and majority molecular mass M_j.

Depending on the spatial structure disposition of macromolecular bending agents, distinction is made between two states of the polymer: amorphous and crystalline. Molecular chains can be linear, branched or cross-linked. Polymers can be classified according to several criteria (Table 2.7): origin, thermo-mechanical properties [Sob.08] etc.

Table 2.7. Polymers classification elements. (processing after Batich and Leamz [Bat.09], [*Bom.11], Davis [Dav.03], Guidoum [Gui.13], Harrison [Har.07], Haudin [Hau.12])

Classification criterion	Type of polymer
Origin	- natural polymers (animal or vegetal), - artificial polymers; - synthetic polymers.
Type of covalent bond	- organics: carbon-carbon; carbon-hetero-atom; - inorganic.
Molecular mass (polymerization degree)	- oligomers (unique molecular mass or polymerization degree <30); - polymers (high molecular mass or polymerization degree >30).
The number of repetitive units	- homo-polymers (a single type of repetitive units); - co-polymers (at least two types of repetitive units).
Mechanic behavior	- fragile behavior (temperature T_g is highly superior to ambiental temperature) – high modulus; - high resistance to traction; - less ductile and tenacious, ex. PMMA); - ductile (semi-crystalline polymers, ex. polyethylene and PTFE; - temperature T_g is close to ambient temperature; - tensile modulus and strength are less and tenacity is higher than fragile polymers; - elastomeric behavior (temperature T_g is lower than the ambient temperature) - low modulus; - may return to their original shape.
Structure	- amorphous polymers; - semi- crystalline polymers.
Thermo-mechanic properties (reaction to heat) (Tab. 2.8)	- thermo-plastic (polyvinyl chloride, acrylic resins, Plexiglas, PMMA-polyethylene, polycarbonates, polyamides); - thermo-rigid (polyurethane, unsaturated polyesters).

Table 2.8. Thermo-mechanic characteristics of polymers. (processing after[*Car.11], [Cio.05])

Thermo-plastic polymers	Thermo-rigid polymers	Elastomers
Linear simple or branched chains, bonded to cold by cohesion forces. Have melting points. Independent at heat. Amorphous (PS, ABS, PMMA, PC, PSU, PVC..) or crystallline (PE, PET, PBT, PA, POM, PTFE...).	Rigid bonded chains even et heat. Macro-molecules oriented in 3D space. Do not have melting points. Families of polyesters, epoxy, phenolic resins, aminoplastic	Occasionally bonded chains, deformable nets.
Hot plastic forming. It is possible to	Single hot forming, more rigid	Elastic properties closed

repeat the forming	than Thermo-plastic polymers.	to those of rubber
Can be solder and plasticized, cold rigid	Cannot be solder and not fused	Partially fuse and cannot be solder

In medical applications, polymers have to fulfill the physical, mechanical, chemical properties, biocompatibility etc. requirements. Particularly, biocompatibility and mechanical behavior severely restrict the types of polymers, represented by [Rus. 03]: silicones; copolymers, acrylonitrile-butadiene-butadine; Poly(methyl metacril); polyethylene; polyurethane; poly-tetrafluoretina; Poly(alcohol vinyl); Poly(vinyl-pyrrolidone); polyamides; polycarbonates; polietilentereftalat; polyether; hydrogels, absorbable polymers; used in medical applications [Bol.12], [Sea.01], [Sny.09].

2.2.3.4 Biocomposite materials

The biocomposite materials are formed of a matrix – usually a polymeric matrix – and a reinforcement component made of fibres or particles (Table 2.9).

Currently, the next biocomposite materials classification criteria are being used [Par.07]: 1. the nature of the matrix; 2. the reinforcement component dimensional characteristic; 3. the biodegradation mode; 4. the nature of the composite (natural or synthetic).

1. According to the first criterion there are three categories of reinforcement components: - short fibres components; - long fibres components; - components with material particles (powder).

2. According to the second criterion the next main materials are being found: - polymeric materials (thermo-resistant polymer or thermo-plastic polymer); - metallic materials; - ceramic materials [Coh.09].

Further, according to this second criterion three main types of reinforcement materials are being used: - short fibres reinforcement materials; - long fibres reinforcement materials; - reinforcement materials with material particles (powder).

3. According to the third criterion the composite materials are divided into three categories: - fully absorbable; - partially absorbable; - non-absorbable.

As a general remark, the properties of the composite materials depend on: - the intrinsic characteristics of the matrix and of the reinforcement material; - the spatial arrangement of the fibres/particles into the interior of the matrix; the matrix-fibres adhesion degree. Thus: the long fibres composite materials present particles anisotropy; the short fibres composite materials and the composite materials with dispersed reinforcement materials randomly oriented into the matrix present isotopic properties.

In accordance to the Voigt model, the composite biomaterials' elasticity module may be expressed as [Ber.12], [Cut.09]:

Table 2.9 Biomedical composite**s** constituens, after [Ift.03]

Matrix	Fibers	Particles
Thermosets	***Polymers***	***Inorganic***
Epoxy	Aromatic polyamides (aramids)	Glass
Polyacrylates	UHMWPE	Alumina
Polymethacrylates	Polyesters	***Organic***
Polyesters	Polyolefina	Polyacrylate
Silicones	PTFE	Polymethacrylate
Thermoplastics	***Resorbable polymers***	
Polyolefins (PP,PE)	Polylactide, and its copolymers with polyglyocolide	
UHMWPE		
Polycarbonate	Collagen	
Polysulfones	Silk	
Poly(ether ketones)	***Inorganic***	
Polyesters	**Carbon**	
Inorganic	Glass	
Hydroxypatite	Hydroxypatite	
Glass ceramics	Tricalcium phosphate	
Calcium carbonate ceramics		
Calcium phosphate ceramics		
Carbon		
Steel		
Titanium		
Resorbable polymers		
Polylactide, polyglycolide and their copolymers		
Polydioxanone		
Poly(hydroxyl butyrate)		
Alginate		
Chitosan		
Collagen		

$$Ec=Ef\cdot Vf+Em\cdot Vm, \qquad (2.1)$$

in which,

$$Ec=Ec'+i\cdot Ec'',$$
$$Ef=Ef'+i\cdot Ef'', \qquad (2.2)$$
$$Em=Em+i\cdot Em'',$$

where E_f and E_m represent the elasticity modules of fibre *f* and matrix *m* expressed in GPa.

As far as *the fourth criterion* is concerned, it is noticed the biomedical composites' components classification offered by Iftekhar [Ift.03]. In this sense, currently, the biomedical composites use is oriented towards the next main domains: [Rat.04]

- General clinical use;

- Slight substitutions [Mar.08], [Li.97];
- Prostheses, especially of the lower limb. Thus, it is noticed the increasing interest on the use of polymeric matrix composites and reinforced with carbon fibres and Kevlar.

For the first two domains the fundamental condition is represented by biocompatibility under the two main requests [Pop.08], [Lam.92]: functionality; bio-host protection.

Concerning the third domain, the main request consists in simulating, modelling and assuring the movement's biodynamic. In this sense, in the speciality literature, the development of theoretical models to predict the real elastic (dynamic) coefficients of the composite biomaterials (e.g. carbon fibres reinforced polymeric composites) represents a priority. These coefficients are correlated to the experimental data mainly obtained from the performed measures using the DMA (Dynamic Mecanical Analyze) modern method.

2.2.4 Using biomaterials in bio-systems

In terms of the systemic characterization of biomaterials use in bio-sistems structure, the criteria used will be those of Park and Bronzino [Par.02], Wong and Bronzino [Won.07], and Bulancea [Bul.12], Mitu et.al [Mit.12.a], [Par.12], [Str.08], [Spe.06], represented by: level of the area to be cured (Table 2.10), level of tissues or organs (Table 2.11), and level of body's biosystems (Table 2.12), and different polymers used in medical applications (Table 2.13).

Table 2.10. Medical applications of biomaterilas. (after [Bul.12], [Par.07], [Mit.12.a])

Function	**Example**
Replacement of a diseased or affected part	- artificial hip joint, apparatus for kidney dialysis
Functions improvement	- sutures, prostheses and dental bone screws
Treatment of anomalies	- Harrington prosthesis for the backbone
Correction of cosmetic problems	- aesthetic surgery of the breast, chin correction
Aid in the diagnosis	- probes and catheters
Aid in the treatment	- apparatus for kidney dialysis, drainage tubes

Table 2.11. Medical applications of biomaterials in human body organs. (after [Bul.12], [Par.07.])

Organ	**Example**
Heart	- cardiac pacemaker, artificial heart valve
Lungs	- oxygenator
Eyes	-contact lens, crystalline transplant
Ear	- hearing aids, external ear cosmetic restoration

Bones	-bone prosthesis
Kidneys	- apparatus for kidney dialysis
Urinary vesicle	- catheters

Table 2.12. Medical applications of biomaterials in human body bio-systems. (after [Bul.12], [Par.07])

Bio-system	Example
skeletal system	Bone prosthesis, joints total replacement
Muscle system	Sutures
Digestive system	Sutures
Circulatory system	Artificial cardiac valve, artificial blood vessels
Respiratory system	Device for artificial respiration
Skin	Sutures, dressing, artificial skin
Urinary system	Catheters, apparatus for kidney dialysis
Nervous system	Cardiac pacemaker, hydrocephalic drainage
Endocrine system	Groups of encapsulated pancreatic cells
Reproductive system	surgery of the breast and other cosmetic improvements

Table 2.13. Different uses of polymers in medical applications, after Rusu [Rus.03], [Mid.00].

Polymers	Different uses in medical applications
ABS (Copolymers acrylonitril - butadiene – stirenic)	- are used for different purposes: in biomedical dialysis, for clamps and needles for infusions because of high resistance to breakage; parts of the auditory apparatus; connecting devices for syringes and catheters
HDPE (polyetylene)	- applications in the field of cardio-vascular prosthetic surgery, orthopedics, dentistry, and as suture threads, medical instruments.
HIPS (polystyrene)	- for various devices used in medicine, artificial kidneys, for development of the auditory apparatus of artificial components, dental prostheses.
PA (polyamide)	- applications in the cardio-vascular surgery, orthopedics, kidney dialysis, artificial casings, wearers of medicines, surgical sutures
PC (polycarbonate)	- as absorbable surgical suture threads, transport and release of drugs, dentistry, medical equipment, sterile packaging.
PET (Polyethylene terephthalate)	- applications in the field of cardio-vascular, in surgery of the abdominal anterior-lateral wall as restoration prosthesis and as surgical suture threads.
PP (polypropylene)	- used in cardio-vascular surgery, reconstructive surgery of the abdominal wall, dentistry, as the threads of suture material, medical instruments.

But in addition to this approach in the literature is also punctual exemplified, the using of different biomaterial type in medical devices, medical technique etc. In terms of the share of materials use in medical applications, metallic biomaterials and polymers are the most commonly used [Sal.09].

2.2.5 Future development of biomaterials

In the mid 1990^s significant changes taking place in the field of knowledge and handling of biomaterials with interconnectivity with information technology, micro and nano medical technology, technology transfer, etc. [Rig.07], [Fat.99], [Pop.11], [Pop.11.a], [Bej.08]. This has opened up unsuspected perspectives in the field of minimally-invasive therapy by improving existing instruments, tele-microsurgery, design of medical micro-robots and biosensors, developing of implantable systems for medicines transport etc.

Future development of biomaterials, is directed, after Lange and al. [Lan.90], Tathe et al. [Tat.10], on cell-polymer interaction, drugs transport systems and the development of new biomaterials in orthopedics, within are cited especially the bio-composites.

2.3. CURRENT STATE OF KNOWLEDGE AND RESEARCH IN THE BEHAVIOR OF BIOMATERIALS

2.3.1 General features of the biomaterials properties

Knowledge of the biomaterial use within a medical applications or pathology is based on the behavior and requirements imposed in the functional specification of the medical device, implant, etc. as well as the requirements of the methodology for the treatment of specific medical pathology. To this end, to biomaterial should be thorough analyses of the mechanical, chemical, biological, etc. behavior.

Knowledge of the biomaterial use within a medical applications or pathology is based on the behavior and requirements imposed in the functional specification of the medical device, implant, etc. as well as the requirements of the methodology for the treatment of specific medical pathology. To this end, to biomaterial should be thorough analyses of the mechanical, chemical, biological, etc.

Each category of behavior analysis requires detailed characterizations of intrinsic properties and surface of biomaterial and dimensional characteristics. Intrinsic properties of biomaterials can be divided into the following main groups: 1. mechanical, 2. physical, 3. chemical, and 4. biological.

The properties of a material means, after [Ash. 05], [Amz. 02], the specific combinations of the attributes of the material determined by its chemical composition, and the totality of phenomena in the environment in which the material is found. In the case of a biomaterial, the environment is represented by appropriate biological medium of the body fluids.

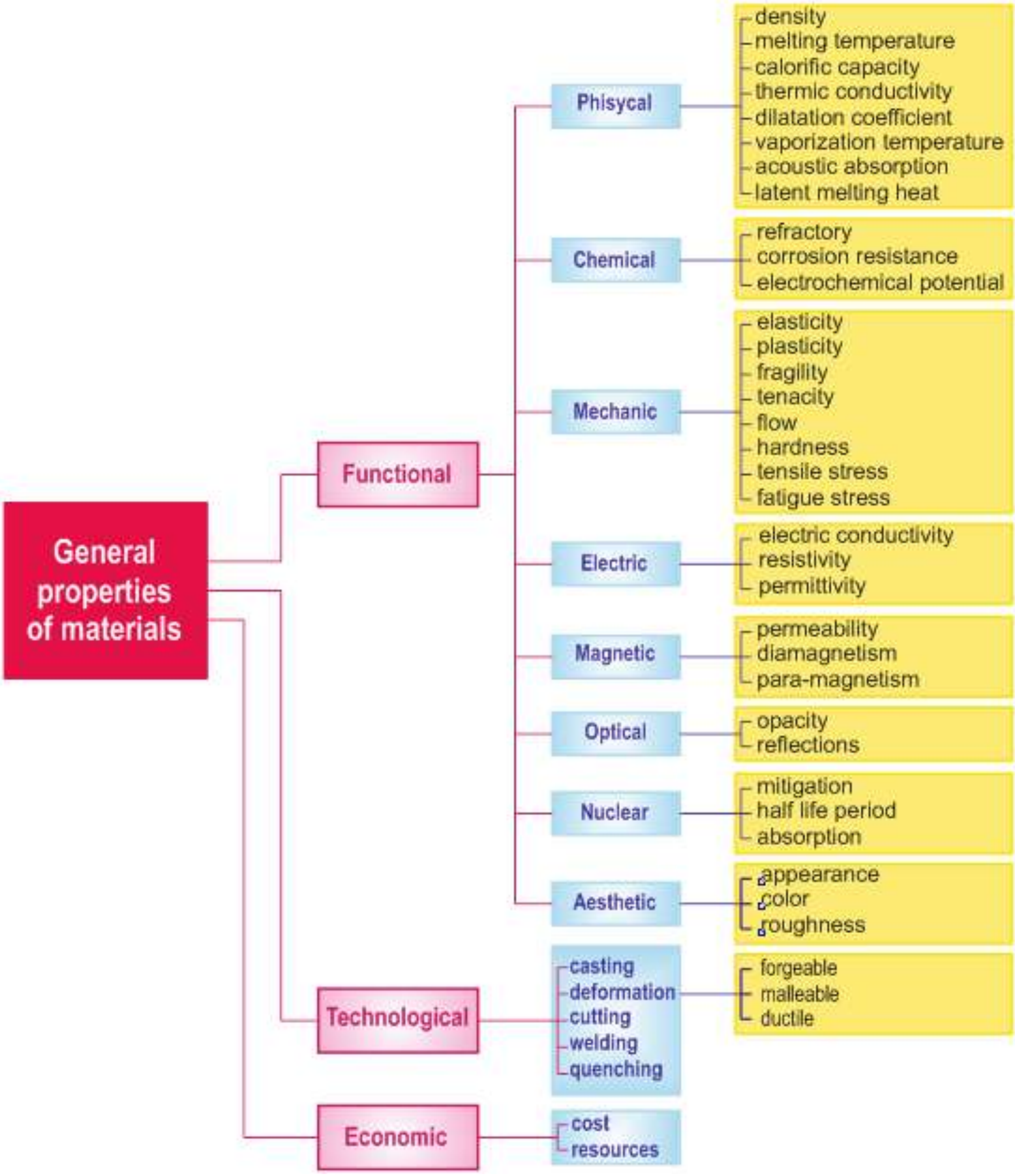


Fig. 2.7. Systemic representation of general materials properties reproduced from [Amz.02].

Intrinsic properties of the (bio)material are determined, after [Amz. 02], by its chemical/biological, mechanical, and physical properties, that may or may not be sensitive to the structure and its temperature. Currently it is accepted that the type of structural bond corresponding to states has a vital role on biomaterial intrinsic properties: crystalline, amorphous, and combined. Thus, each class of biomaterial (metals and alloys, ceramics and glass, polymers, and intermetalics composites) has different properties depending on the predominant type of connections between atoms or metal molecules, ionic covalent bonds, etc.

that characterize his condition. The stronger bond between the atoms or molecules, the higher melting temperature, density, modulus of elasticity, the material has a tendency to crystallize, and coefficient of thermal expansion is weaker. Systemic representation, after Amza and al. [Amz. 02], of materials highlights the three main categories of properties (fig. 2.7): 1. functional properties; 2. technological; 3. economic.

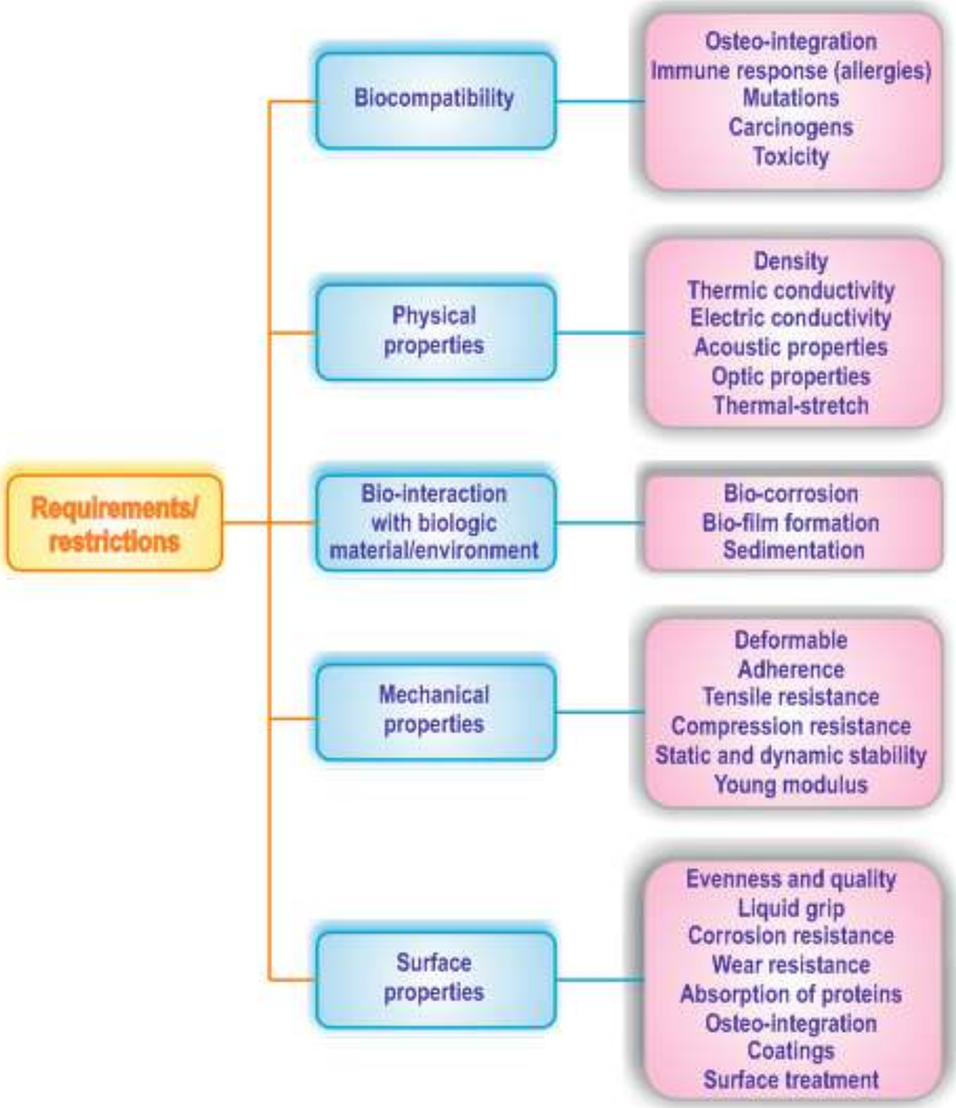


Fig. 2.8. General properties of materials systemic representation. (processing after [Amz.02], [Dom.06])

For a material to be approved as a biomaterial, it must meet some requirements summarized in Figure 2.8. At the same time, these requirements must comply, unconditionally, a number of restrictions, including a significant role in the commercial and technological barriers (fig. 2.9).

If a biomaterial is used in a device or in a biological environment, Domşa [Dom.06] considers that its properties are represented by the following main categories of properties (Table 2.13): 1 – intrinsic, 2 – behavior (functionql properties), 3 – surface properties, 4 – processing/treatment conditions.

These properties are determined by the mechanical, biological, and physical characteristics of the biomaterial. These properties categories interact to each other through a systemic action.

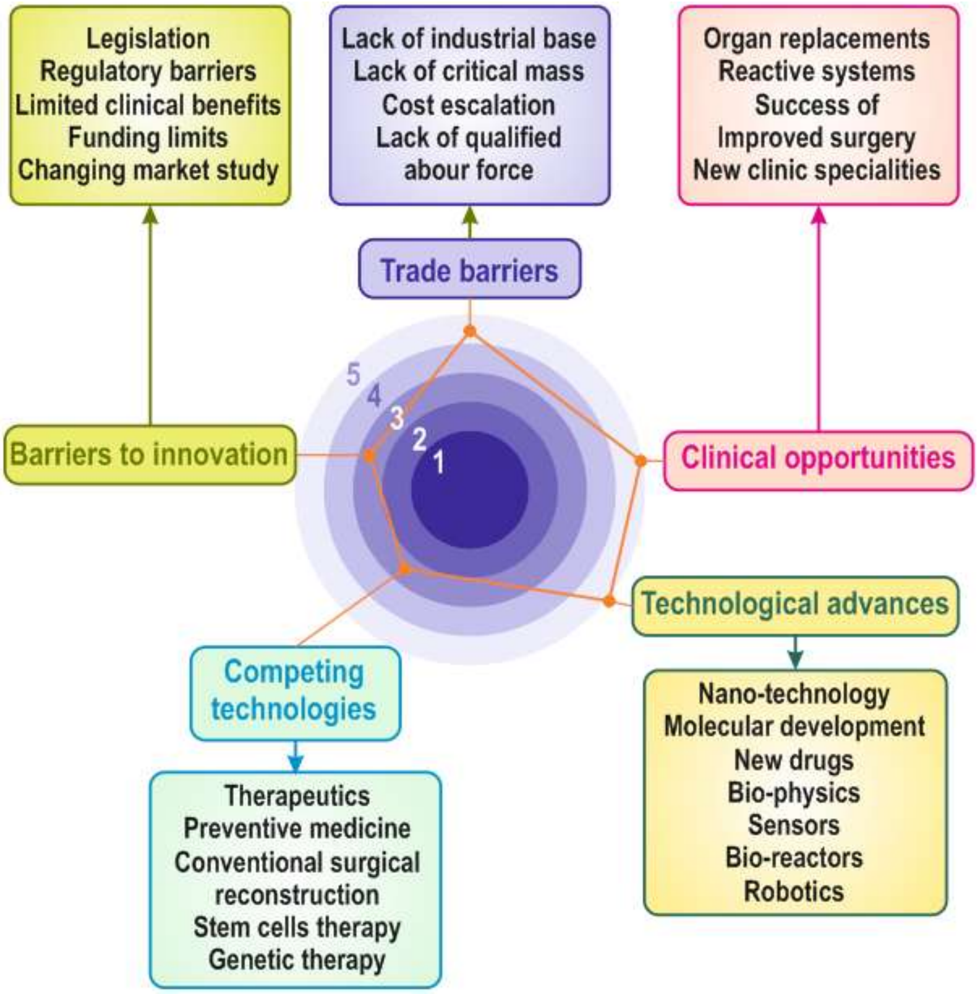


Fig. 2.9. Restrictions and requirements concerning the use of biomaterials in medical devices, processing after [*Deg.13], [Cyn.11].

2.3.2. Mechanical behavior

Mechanical behavior of materials is characterized by the way and limits to which vary the values of their mechanical properties under the action of external influences arising of the terms of the use in a medical application. These properties consist mainly of (Table 2.14): tensile strength, stiffness and fatigue resistance.

These properties are presented and analyzed in the basic works in the field of materials and biomaterials Ashby [Ash.05], Martin [Mar.06], Ratner and al. [Rat.04], [Pop.01], [Pop.08], Park and La Kes [Pas.07]. In table 2.15-2.17 are comparatively and selectively presented some values of mechanical properties of certain categories of biomaterials used in medical applications.

Table 2.14. Biomaterials properties different categories. (after [Dom.06, Amz.02])

Property	**Characteristics**		
	Mechanical	*Physical*	*Chemical/Biological*
Intrinsic properties (mainly determined by the chemical composition)	- elasticity modulus; - Poisson ratio; - flow limit; - tensile/compression resistance	Intrinsic properties (mainly determined by the chemical composition)	- elasticity modulus; - Poisson ratio; - flow limit; - tensile/compression resistance
Behavior	- rigidity; - breaking strength; - Fatigue resistance; - shock resistance; - wear resistance; - crack resistance	Behavior	- rigidity; - breaking strength; - Fatigue resistance; - shock resistance; - wear resistance; - crack resistance
Surface properties	- hardness; - shearing modulus; - shearing resistance; - bending modulus; - bending resistance	Surface properties	- hardness; - shearing modulus; - shearing resistance; - bending modulus; - bending resistance
Processing	- reproducibility; - can be sterilized; - packaging features		

Table 2.15. Features of certain bio-metals, after [*Ort.11]

Characteristics	**Alloy 316 L**	**Vitallium**	**Titanium alloy Ti-6Al-4V**
Rigidity	High	Medium	Reduced
Mechanical resistance	Medium	Medium	High
Corrosion resistance	Low	Medium	High
Biocompatibility	Reduced	Medium	High

Table 2.16. Mechanical behavior characteristics of some metallic biomaterials, after [Deg.13], [Cyn.11].

Mechanical properties	**Biomedical metals and metallic alloys**					
	stainless steel 316L	***alloy CoCrMo***	***alloy CoNiCrMo***	***Titan***	***alloy Ti6Al4V***	***Tantalum***
Resistance to tensile breaking *MPa*	485-860	655	793-1793	240-550	860	207-517

Flow limit (0,2% offset)	*MPa*	172-690	450	240-1585	170-485	795	138-345
Elongation	%	12-40	8	8-50	15-24	10	2-30
Surface reduction	%	-	8	35-65	25-30	25	-
Densitaty	10^3 Kg/m^3	7,9	8,3	9,2	4,5	4,5	16,6
Corrosion resistance		Very low	Very good	Very good	Very good	Very good	Good

Table 2.17. Characteristics of titanium alloys, processing after [Fro.04], [Mud.03], [*Tit.11,a,12].

Type of titanium alloy	Characteristics
α alloys	- small to medium mechanical resistance; - good toughness; - good to reasonable ductility; - excellent mechanical properties at cryogenic temperatures; - excellent corrosion resistance; - can be heat-treated and easy welded;
α–β alloys	- medium to high mechanical resistance; - good behavior in the thermo-forming (cold limited, normally good to warm); - at high temperature the creep resistance is lower than for α alloys; - can be heat-treated; - most of them can be welded;
β alloys	- good mechanical resistance at intermediate temperatures; - good creep behavior at intermediate temperatures; - can be heat-treated and, generally, can be welded; - easily processed by forming.

2.3.3 Chemical behavior

Formally, according to the relevant literature [Pop.01,08], chemical properties of biomaterial characterize the mechanism by which it interacts chemically with living tissues from the contact surface or chemical changes. In this approach, the process of corrosion (shortly, corrosion), is defined as Bahije [Bah.11], as the process of interaction between biomaterial in contact with biological environment where takes place a substances loss, a change in the characteristics or a loss of structural integrity. In this context it is evident the uniqueness of the human body to be a very aggressive chemical environment due to tissue fluid which contains water, dissolved oxygen, protein, and different ions, hydroxide and, chloride [Pop.01].

Depending on the interaction type, we distinguish the following types of corrosion [Pop. 08], [Bah.11], [Gro.09]: chemical, electrochemical, the most frequent in the field of biomedical (bio-metallic materials) and microbial corrosion that occurs in dental applications.

Bio-metals capability (used as implants) to resist to electrolytic corrosion can be estimated [Pop.01], [Pop.08] using Pourbaix diagrams called "thermodynamic stability charts" or "corrosion potential diagrams Ecor-PH". In essence, the corrosion analysis of a biomaterial offer the possibility to establish the existence of passive immunity and its corrosion limits [*Dia.12].

In the appropriate biological medium corrosion can be of two kinds, namely uniform or generalized, and localized corrosion in points, respectively. In the case of the defects presence in the passive adherent protective layer covering bio-metallic alloys: stainless steel, titanium and titanium alloys, etc.:

- corrosion through cracking - occurs as a result of a local deficiency in oxygen;
- inter-granular corrosion - appears, in particular, through the accumulation of oxidizing compounds (contaminants, carbides, etc.);
- corrosion under load - manifests as a result of combining the effects of localized biological corrosive environment tasks;
- galvanic corrosion - it appears between two metals with different electrode potentials if they are in contact. The metal with the lower potential (metal less "noble") will be heavily corroded. ;

In practice corrosion factors are evident: biological medium; biomaterial; product design and exposure time in the corrosive biological medium. Research on the of metallic biomaterials behavior reveal that all the components made of these materials are subject to corrosion reaction. [Pop.08] For this reason, stable alloys must be used, the choice of noble metals and alloys in the limits: cost price and mechanical characteristics. Descriptions of the behavior to corrosion of biomaterials can be obtained from the literature of which stated [Pop. 01], [Pop.08].

2.3.4 Biomaterials degradation

Degradation process of a biomaterial in the biological environment in which they operate, is complex and is determined by different origin factors such as: 1. Mechanical – static and/or dynamic stresses; 2. Contact process between synthetic and/or biologic surfaces; 3. Corrosion. 4. Bio-absorption; 5. Wear processes, friction corrosion process; 6. Degradation processus by swelling and/or exploding etc.

In essence, the degradation affects two important sides of the biomaterial functioning in the human body: 1. changes of the projected material properties; 2. modification of the characteristics of functional biocompatibility. Biomaterials degradation has as main component, the biodegradation, defined by Mayer [May 10], as "the biomaterial characteristics degradation given by the technological environment in which it operates".

This process of degradation is conditioned and accompanied by the presence of complex interactions that take place between biomaterial, physiological environment, solicitation, etc. Teoh [Teh.00] presents, in this example a metallic biomaterial surface surrounded by physiological environment where can be distinguished three types of layers: molecular layer absorbed the physiological environment; the existing passive oxide layer on the surface of biomaterials; and deformed surface layer of metallic biomaterial. During the operation of the medical device, after [Teo.00], the three layers intervening in the process of degradation of biomaterial through the mechanism of the fatigue-wear.

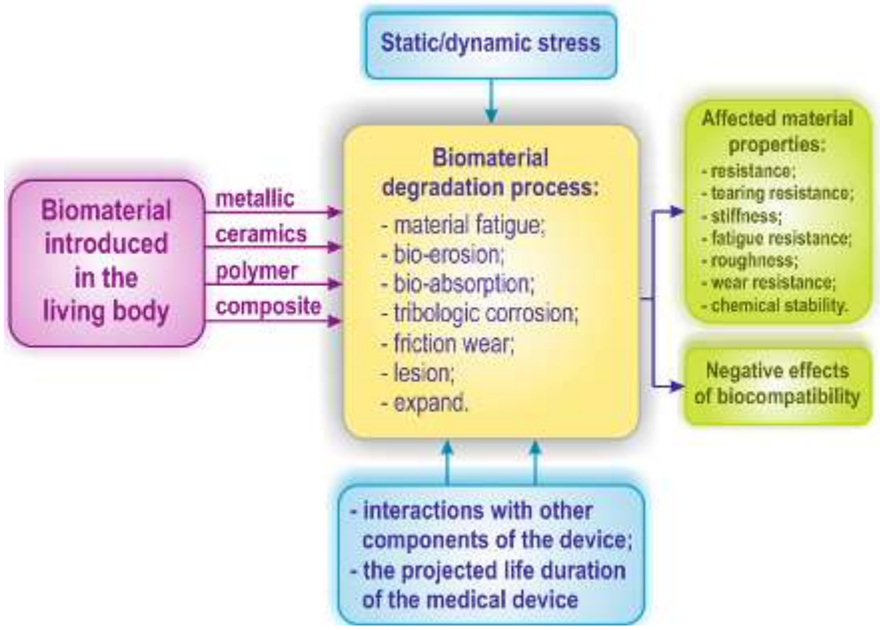


Fig. 2.10. Model of systemic approach of biomaterial degradation process, adapted [Cha.05], [*Deg.13]

At the moment, the researchers pay attention to friction corrosion phenomenon which results in the transformation or degradation characteristics of biomaterial through the combined action of corrosion and wear. This phenomenon is researched by Muroz and Mischler [Mis.13] in the case of hip prostheses for to metal-to-metal contact (CoCrMo Alloy). They illustrates schematically the friction corrosion and also shows that this mechanism depends on the use cycle (locomotion and the rest) and on location (the mounting surface, structural, parts).

From the literature in the field, Chaouki and al. [Cha.05], [*Deg.13] the process of degradation of biomaterial is systematically represented the in figure 2.10.

In conclusion, the degradation of biomaterials is analyzed by various mechanisms that are based on the interaction between chemical and mechanical factors. At the moment the attention is focused on the effort between tissue and biomaterial in terms of absorption of bone. [Nii.4].

2.3.5 Thermal behavior

Thermal behavior of biomaterials has to be analyzed from two directions: 1 - thermal properties of biomaterials characterizing thermal behavior in the medical applications; 2 - thermal properties of materials during heat treatment processes required by the medical component manufacture for a medical application.

In the first case are important after Popa and al. [Pop.08] two properties:

1. The thermal conductivity which designates the ability (physical property) of the biomaterial to transfer heat from a hot to a colder source (e.g. heat transfer in the oral cavity from hot food to the teeth and jaw), expressed by the thermal conduction coefficient λ.

2. Thermal dilation interests primarily the bio functionality of biomaterial within the application. This property is particularly important in the case of multi-materials. [Pop. 08]

2.3.6 Biocompatibility

The biocompatibility is inherently linked to contact between a technical system and a biological one. It is considered that a biomaterial is compatible to the extent that it is able to replace a function within a biological system without harmful effects on biological environment in which it works. A current example is the presence and operation of implants in the biological systems.

Given the great variety of biomaterials are different approaches, as well as formulations of biocompatibility phenomenon. There is a widely accepted formulation in the literature that the biocompatibility is (Williams, 1987) *the ability of a material to work under a specific medical device, producing a corresponding reaction in the host body*. Many researches carried out on biomaterials have singled out the main influence factors (Figure 2.11).

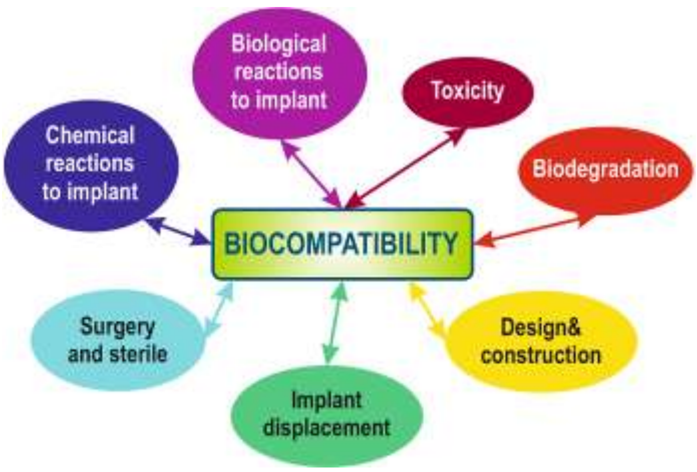


Fig. 2.11. Factors influencing the biocompatibility, after Spencer şi Textor [Spe.98].

In medical practice there are two main types of biocompatibility [Pop.08], [Lib.12]:

- structural biocompatibility;
- surface biocompatibility.

Structural biocompatibility is defined by the interactions between biomaterial structure and the properties of the biological system. In report to these interactions, results in a particular ability of biomaterial to accomplish a particular function within a medical device.

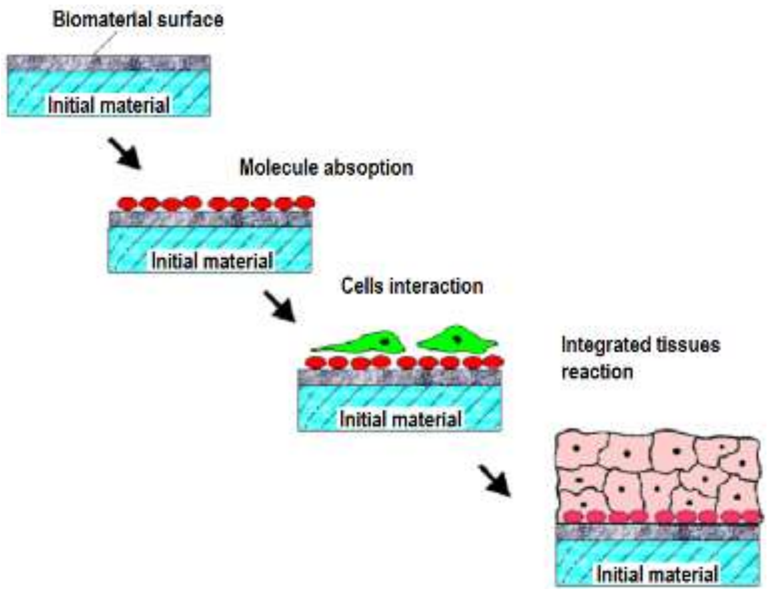


Figure 2.12. Schematization of body response (body cells) on the surface of biomaterial, reproduced after Spencer and Textor [Spe. 98].

In the literature in the field of biomaterials [Kor. 04], [Nii.08], [Nii.04] the surface biocompatibility means all those interactions between biomaterial structure and the properties of the biological system (body) at the level of chemistry and biomaterial topography and its neighboring cells (Figure 2.12). Thus, the composition of the biomaterial surface must not content ions likely to provoke an immune response [Rat.04], [Pop.08]. Also, the resistance to wear of biomaterial must be high in order to avoid the formation of micro particles in the friction process between biomaterial component active surface and the biological entity. The profile of biomaterial surface must be adapted to the development of neighboring cells.

In essence, the biocompatibility must respond to two main requirements: 1 functional requirements, and 2 host bio-protection (fig. 2.13).

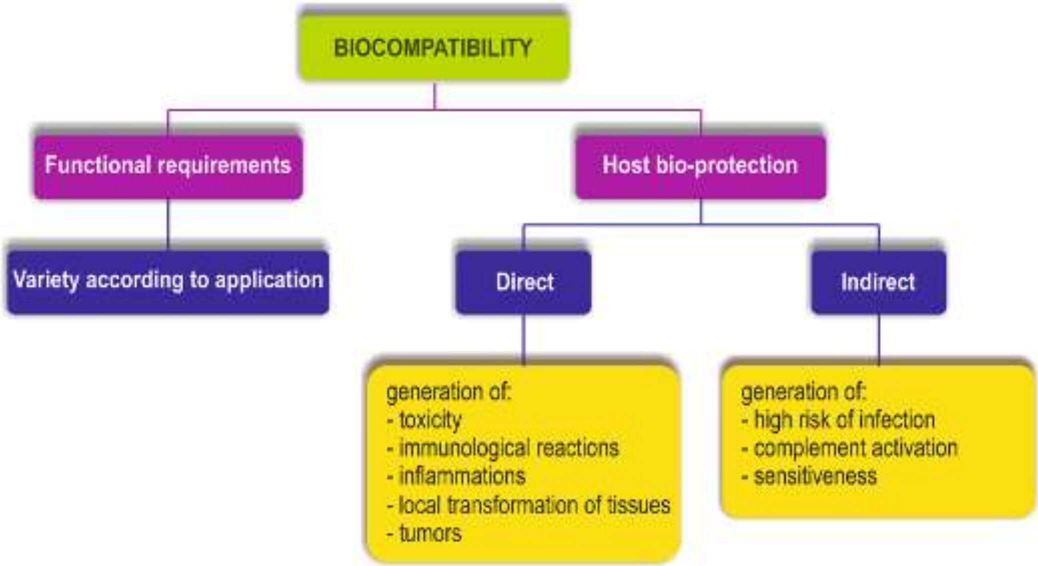


Fig. 2.13. Requirements imposed to biocompatibility of materials, after [Lam.92].

2.4. METHODES FOR DETERMINATION, STUDY AND CONTROL OF BIO-COMPOSITE MECHANIC AND THERMAL BEHAVIOR

Materials are very diverse in terms of chemical composition, behavior, surface properties, processing etc. Under these circumstances, numerous methods have been developed for the determination, the study and control of their properties. In this sense, Amza and al. [Amz.02] presents, in a systemic approach, a classification of methods used in technique for determining material properties (Fig. 2.14).

According to it, the methods used for determining material properties can be classified based on the following main criteria:

- according to the goal pursued in research and technological practice;
- according to the used measuring principle;
- according to provided information;
- according to the stress intensity;
- according to the studied feature;
- according to the stress type.

This classification is also applicable in the case of biomaterials, specific methods and tests to assess the biocompatibility of biomaterials in the field, described in the literature: Cynober

[Cyn.11], Grosgogeat and Colon [Gro.09], Lam [Lam.92], Li [Li.12], Brendel [Bre.09], [Pop.08].

The current assessment of the mechanical behavior of polymeric bio-composite materials, research are directed upon the following factors: reinforcing fibers properties, material properties used as matrix, fiber content, fiber orientation, etc. Theoretical and experimental research pursues the following main types of applications covered by the rules and standards:

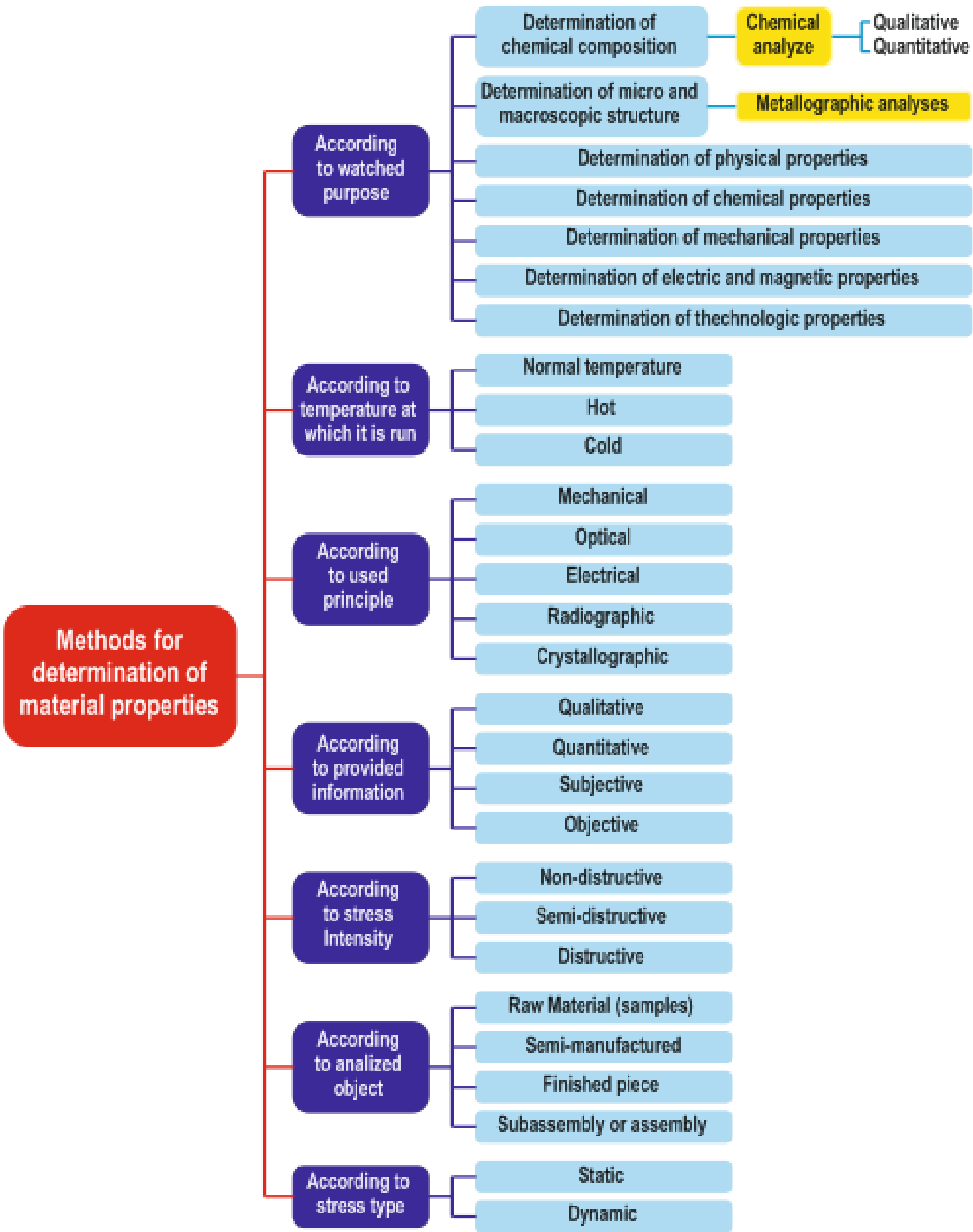


Fig. 2.14. Systemic approach to methods for the determination of material properties, spawning after Amza and al. [Amz. 02].

- traction (SR EN ISO 527-1, ISO527-4/5, ISO 4899, ISO 14129, ASTM 3039, ASTM D3916, ASTM D 5083 etc.);
- compression (ISO 14126, DIN 65375, ASTM D 3410 etc.);
- bending (ISO 14125, ASTM D 4476, DIN 53390);
- shearing (ASTM D 3846, ASTM D 3914, DIN 53399-2);
- inter-laminar shearing resistance (ISO 14130, EN 2377, EN 2563, JIS K 7078, DIN 65148, ASTM D 4475);
- breaking strength, tenacity, resilience, Kc, Gc (LEFM), J-R (ISO 13586, NASA R.P. 1092, ISO 17281, ASTM D 5045, ASTM D 6068, ASTM D 6671, ASTM D 5528);
- fatigue resistance (ISO/DIS 13003, ASTM D 3479);
- processing properties by drilling through the analysis of delaminating phenomenon (DIN 65562, ASTM D 5961).

In respect of these categories of requests of bio-composite materials, it is necessary to mention some particularities on the main types of mechanical stresses:

- traction (stretching) - behavior under tensile load is strongly dependent on the fibers strength and rigidity, because they are far higher than those of its own filling material;
- compression - the adhesive and the stiffness properties of binder are crucial to keep the fibers and prevent loss of stability (buckling);
- shearing means an attempt to slip the adjacent fiber layers over each other. Here the glue transfers the tensions through composite, cross direction.

For composite material to fulfill effectively the task, the matrix (the glue) must have good longitudinal mechanical properties, with strong adhesion to reinforcement fibers. In the case of composite biomaterials there are two main types of shear:

- plain shearing – indicates the extent of the bond fiber-array in each layer;
- inter-laminar shearing – indicates the extent of the bond between layers (lamine);
- bending - combines traction, compression and shear;
- fatigue in traction.

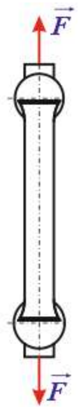
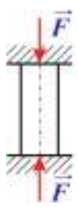
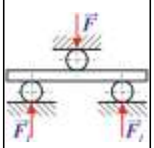
Residual resistance module, and the number of cycles till breakages are measured as functions of frequency and amplitudes. Frequency is a significant variable for the polymeric bio-composite, because polymers absorb energy in each cycle, which results in self-heating of tested piece, finally affecting strongly the fatigue behavior of the material;

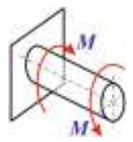
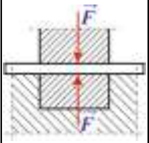
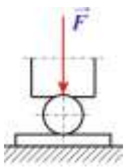
- impact test is intended to simulate the conditions of impact to which material or structure is expected to face during exploitation. For measuring the energy required to break a sample, first it is necessary to determine the proper use conditions parameters (like the impact velocity, energy, geometry, temperature variations) of the material.

To make possible the comparison between the behavior of different materials in various actions, tests must be made in the same conditions and with the same shapes and sizes of samples, i.e., standardized terms. In general, the standards provide the conditions which must be considered for materials test and control, relating to the samples fabrication, form, size, processing, and also test conditions, interpretation and presentation of results.

The methods and conditions for carrying out mechanical resistance tests are governed by standards (table 2.17).

Table 2.17. Classification of mechanical resistance tests, after Amza and al. [Amz.02].

Schema	**Stress**		**Number of loadings**	**Temporal action**			**Test**	**Stability characteristics**
	Type	Mode		STAS*	Duration	Name	STAS	
	Traction	Static	Unique	Progressive Constant Regressive	Short Long Long	Traction Flow Relaxation	200-75, 6834-75, 6638-79, 6605-78, 2649-76 6596-73 7209-73	Yield strength,tensile strength, elongation, breaking thinning. Flow limit, elongation and thinning at breaking. The technical limit of creep, long technical resistance,. Boundary relaxation technique
		Dynamic	Unique Repeated	Progressive -	Short Long	Dynamic traction Traction fatigue	- 8027-78	Energy breaks Fatigue limit, Fatigue resistance for *N* cycles
	Compres-sion	Static	Unique	Progressive	Short	Compres-sion Buckling	1552-78 -	Yield strenght, compression resistance, specific shortening, Buckling resistance
	Bending	Static Dynamic	Unique Unique	Progressive Progressive	Short Short	Bending Bending by shock	1660-80 7511-81, 1400-75, 6833-79	Bending resistance, bending deformation
			Repeated	-	Short or long	Fatigue by bending	7400-77, 6774-79 5878-77	Breaking energy, resilience. Fatigue limit, limited durability resistance

	Torsion	Static	Unique	Progressive	Short	Torsion	-	Torsion resistance
		Dynamic	Unique	-	Short	Dynamic torsion	-	Breaking energy
	Shearing	Static	Unique	Progressive	Short	Shearing	7926-67, 7927-67	Shearing resistance
	Contact pressure	Static	Unique	Progressive Constant	Short Short Long	Crushing Static hardness Long term hardness	- 165-66, 492-78, 493-67, 7057-78, 8251-68, 8525-70	Crushing resistance Brinell, Vickers, Rockwell hardness
		Dynamic	Unique	Progressive	Short	Dynamic hardness	8315-69	Dynamic hardness

2.5. CONCLUSIONS

In bio-systems structure are used five main categories of biomaterials: 1. Metallic biomaterials; 2. Ceramic biomaterials; 3. Polymeric biomaterials; 4. Composite biomaterials; 5. Other biomaterials. They are characterized by following basic properties: 1. Intrinsic; 2. Behavior (functional properties); 3. Surface properties; 4. Processing and fabrication conditions.

Table 2.19 shows, in comparison, certain properties of biomaterials. Biomaterials properties are different, depending on their chemical composition and the terms of use, conditions that include categories of requirements and restrictions. Mechanical behavior of materials mainly consists of: tensile strength, stiffness and fatigue resistance.

Table 2.19. Comparisons of biomaterials properties, after [*Cri.12].

Biomaterial characteristics	Metals	Ceramics	Polymers	Composites
Density	Medium High	Medium	Little Very little	Medium Little
Elasticity	High	Very high	Medium Low	High
Mechanical resistance	High	Very high (compression)	Medium Weak	High
Behaviour with defaults and shocks	Very tenacious	Very fragile	Few tenacious Great absorbed energy	Very tenacious
Chemical aggression behavior	Defective medium	Good Very good	Medium	Medium

Work temperature	High mean	High Very high	Low mean	Medium
Heat conduction	Good Very good	Medium Weak	Weak Very weak	Weak
Electric current conduction	Good Very good	Weak Very weak	-	-
Processing	Facile	Difficult	Very facile	Medium. According to constructive form

Related to the biomaterials' processing, the cutting processes, the injection processes, etc. are of high interest Mitu et. al [Mit.12], Mitu et. a. [Mit.13.a], Mitu et.al. [Mit.13], [Bej.10], [Bej.11], [Zha.01], [Ruj.78].

CHAPTER **3**

THESIS OBJECTIVES

3.1. MOTIVATION OF THE THEME

Design of composite structures and therefore those in biomedical field, regardless of the type of materials used, of their constituents and of the distribution of the proportion in which they are found in combination, involves special attention to knowledge of their behaviour in terms of functional operation, identification and quantification of the main influential factors, in addition to specific environmental problems related to the design, all in order to ensure a rapid transition towards manufacturing processes and/or correlation with manufacturing technologies and obtaining an incresing flexibility aimed at manufacturing costs, at properties or for meeting certain imposed conditions of exploitation.

Thesis theme is integrating in current trends in terms of ensuring all the issues mentioned above, seeking thus to develop *a coupled analysis*, as a synergy, between information arising from the processes of manufacture of polymer composite materials, the specific properties of the material in conjunction with the design/structure, behavior, and analyzed in terms of the functional or operational requirements in order to estimate its behavior. In order to ensure the best deals of the concept to be discussed and developed in this thesis, in Figure 3.1 has been synthesized the method of interconnecting the individual phases that constitute general guidelines, and in figure 3.2, the mode of ensuring the specificity for the external prosthesis selected as the representative for the biomechanical structures class.

Fig. 3.1. General concept associated to coupled analysis which underlies the choice of theme.

As an additional explanation for choosing this prosthetic configurations, it must be noted that in addition to special geometric form that strikes at the first contact with it, there are few technical details regarding used materials, their functional characteristics, their properties, functional characteristics, which poses a challenge for the engineers of various specializations (mechanics, material sicence etc.)

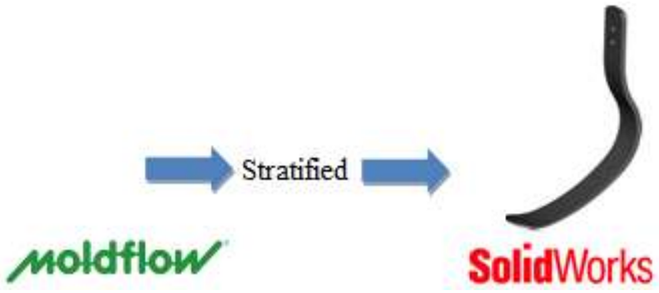


Fig. 3.2. Synergetic concept of coupled analysis that underlie the choice of theme.

As can be seen from figure 3.2 or 3.3, coupled analysis to be initiate and developed throughout this doctoral theses is aimed at the inclusion of the effects of technological processes of manufacture of polymer composite materials (e.g. forming by resin infusion – constituents distribution, orientation, border effects, flow, etc.) and material properties resulting from the *multi-scale* analysis in the simulation/modeling process of mechanical/biomechanical structures reaction in real operating conditions.

The challenge lies in highlighting all aspects that contribute to the functional behavior of proposed exterior prosthesis or are specific to the manufacturing technology, given that this is a *multi-layered* structural element on different sections of it.

In general, these issues have started to be implemented relatively recently and constitutes a new paradigm for healthcare professionals in design, analysis and simulation/modelling structures. In addition, the results of coupled analysis will be integrated and compared with those obtained from the proposed materials characterization, developed and elaborated in the elaboration process of experimental support of thesis.

The above mentioned aspects have allowed delimitation of theoretical and experimental research development direction, constituting the pillars of this thesis but also identifying, defining and relevance of its objectives, in close correlation with the progress of the investigations in the field both nationally and internationally, as well as trends and prospects associated with this fascinating field of biomechanics.

It is necessary to mention the fact that the theme and its dealing mode is a border area, it cannot be limited strictly to the biomechanical field, but includes particular aspects of science and engineering of materials, product design, mechanical engineering, etc.

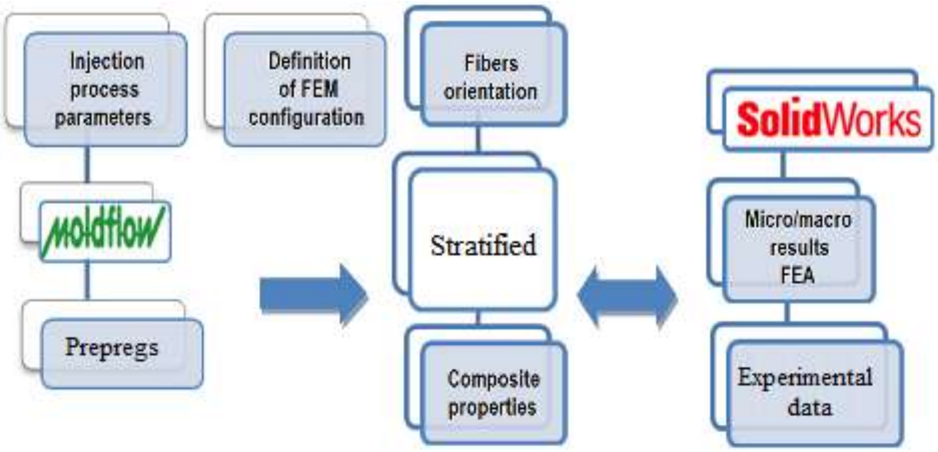


Fig. 3.3. Interconnection mode of the coupled analysis stages which underlies the development of the thesis.

The main goal of this PhD thesis is aimed at developing an integrated analysis concept of the of an ortothic element made of a polymer composite material reinforced with carbon fibres of various architectures and/or in conjunction with other metallic materials for additional stiffening, to include in a perfect symbiosis, particular scenting of process/manufacturing technologies, material properties and structural behavior, with the possibility of rapid implementation and practical translation in the development and elaboration of the biomechanical performance structures.

3.2 THESIS OBJECTIVES

The starting of the current thesis is due to a deep human requirement: the renderind of the possibilities of the motion and running for the leg amputated persons.

The realization of some prosthetic components regarding of the prosthetic laminas of „J" shape must offer to the amputated person a comfortable, durable usage with the functional performances similar with the natural leg, etc. In this context, the knowing of the structure and the mechanical and thermal behavior of the prosthetic lamina material is an extremely inportant and current duty of human, professional, sports and economic nature etc.

For achieving of this goal it were established four main objectives.

The first objective has to be focused on the realization of a systemic and current study of the structure and the behavior of the biomaterials from the bio systems. It is proposed that the development of this study to follow three research directions:

- The syatematic of the biomatrials used in the bio systems structure: types, structure, properties, the using domain;
- The study of the thermal, chemical, mechanical behavior of the biomaterials and the systemic approach of the process of the biomaterial degradation ;
- The determination of the thermal and mechanical behavior of the composite biomaterials.

The second objective consists in the elaboration of an analysis method, by anatomic and biomechanical aspect, of the leg. For the realization of this objective it has to accomplish the main underlying objectives:

- The syatematic and systemic study of the bones and articular systems for the leg, by anatomic and biomechanical point of view;
- The walking and running biomechanics for the case of a normal anatomic person;
- The walking and running biomechanics for the case of the leg amputated person with sports prosthesis.

The third objective is the elaboration of theoretical methods of analysis of the behavior of the carbon fiber reinforced epoxy composite from the construction of the prosthetic laminas of „J" shape. For the accomplishing of this objective it has to define the following stages:

- The realization of a simulation of the injection process of the J lamina by RTM procedure. The aim of this study is to obtain information regarding the conditions and the restrictions of technological nature referred to the fabrication of the prosthetic lamina of „J" shape by RTM injection;
- The theoretical study regarding the thermal and mechanical behavior of the carbon fiber reinforced epoxy layered composite used for the fabrication of the prosthetic laminas of „J" shape;
- The realization of the simulation of the mechanical behavior of the carbon fiber reinforced epoxy layered composite from the construction of the prosthetic lamina.

The fourth objective consists in the elaboration of the new method and performances of experimental determination of the mechanical behavior at compression, bending and DMA - Dynamical Mechanical Analysis and of the thermal behavior of carbon fiber reinforced epoxy layered composite.

CHAPTER **4**

ANALYSIS METHOLOGY OF THE LOWER LIMB ANATOMICAL AND BIOMECHANICAL CHARACTERISTICS

4.1 INTRODUCTION

Human body is considered as an open biologic system [Ola.98] consisting of various sub-systems represented by anatomic structures, organs, tissues, cells etc. mean parts of the human body are: head, neck, trunk, and limbs – superior and inferior.

Human body movements and, also, of its parts are ensured by an anatomic apparatus, specialized in this respect, called ***locomotors***. It consists on bones, articulations, muscles and tendons. The locomotors can be divided at the components levels, so et the level of lower limb. In this respect, (sub)system locomotors of the lower limb S_{mi} can be systemically described by the relationship:

$$S_{mi}\{\{O_i\},\{A_{rj}\},\{M_k\},\{T_e\},\{C_m\},\{R_{intn}\},\{R_{exto}\},\{S_{cp}\}\}, \quad (4.1)$$

where: $\{O_i\}$ represents the bone units set (finite) of lower limb, $\{A_{rj}\}$ is the articulation set, $\{M_k\}$, the muscles set, $\{T_e\}$ is the tendos set, $\{C_m\}$ other anatomic components, $\{R_{intn}\}$ represents the assembly of internal relations established between the S_{mi} component components, $\{R_{exto}\}$, the assembly of external relations established between the S_{mi} component components, and $\{S_{cp}\}$ is the set of all aims pursuit inside the (sub)system locomotors.

The bones are considered as geometric bodies defined by length, width and thickness. In this representation, the bones of the limb are encountered under the following forms [Pap.74], [Ola.98], [Baï.04]: long bones in which predominates the length (the femur, tibia and fibula), flat bones, the length is almost equal to the width, but exceed the thickness (hip bone), irregular bone (pelvic belt) and short bones from which the three dimensions are approximately equal (patella, astragals, phalanges of the foot). Skeletal system of the lower limb (and in general of the locomotors system) may be analyzed by studying the anatomy of a long bone. [Baï.04] It is formed [04 Baï] (fig. 4.1) by body or diaphysis and two extremities (heads), called epiphyses, the joint cartilage, the Medullar Canal (spinal cord cavity) containing the marrow, periosteum (space inside the fiber-membrane plastic shaft inside the bone) and endosteum.

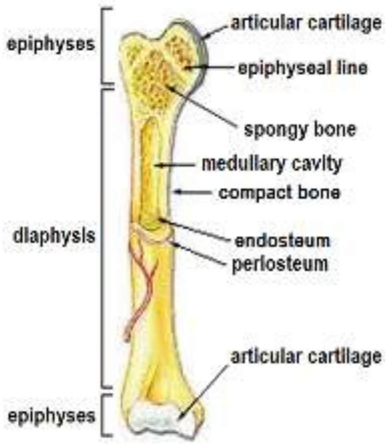


Fig. 4.1. Long bone structure, after [https://www.google.ro/#psj=1&q=endosteum].

In terms of composition, bone is a natural composite material that consists of a rigid phase represented by HA hydroxyl-apatite, and a flexible matrix, the collagen.

Both bone and its components are characterized by specific mechanical properties such as density, resistance to breakage (at slow and fast breaks), Young's modulus, fatigue resistance, hardness, etc., properties whose values are presented in the literature [Par.07], [Bro.06], [Rat.04], **[**Baï.04], [*Mec.12], [*Ana.12].

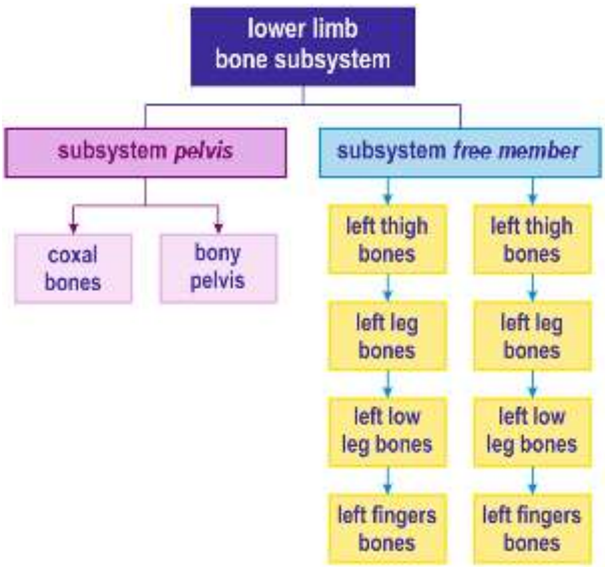


Fig. 4.2. Systemic representation of the lower limb.

In a systemic presentation, (under)skeletal system of the lower limb skeleton is composed of two main bone subsystems [Lep.07], [Pap.74], [Art.03], [Alb.98]: the subsystem „pelvis or the bony pelvis", and the subsystem „free member" (fig. 4.2), consisting, in its turn, in (fig. 4.3) thigh bones (left and right) represented by femur and patella, the bones of the lower leg (left/right) - tibia and fibula, bones of the leg (left/right), and the bones of the fingers (left/right).

Joints (juncturae or articulationes ossium) constitute the totality of the anatomical elements through which bones are connected to each other by means of anatomical items and have the opportunity to achieve functional movements between them. Characteristics and anatomical structure of joints is determined by its basic function expressed through movements enabled to the bones of their structure. [Pap.74] A joint is characterized by [* Cin. 07]: orientation, shape, and anatomical positioning. Joints can be categorized [Ola. 98], [Bac. 81] according to three criteria: 1-degree of mobility, i.e. the specific motions that that it allows to the bones of its structure; 2-degree of freedom of movement or the number of axes of movement which is achieved in the articulation; 3 - after driving mode of motion in the joint.

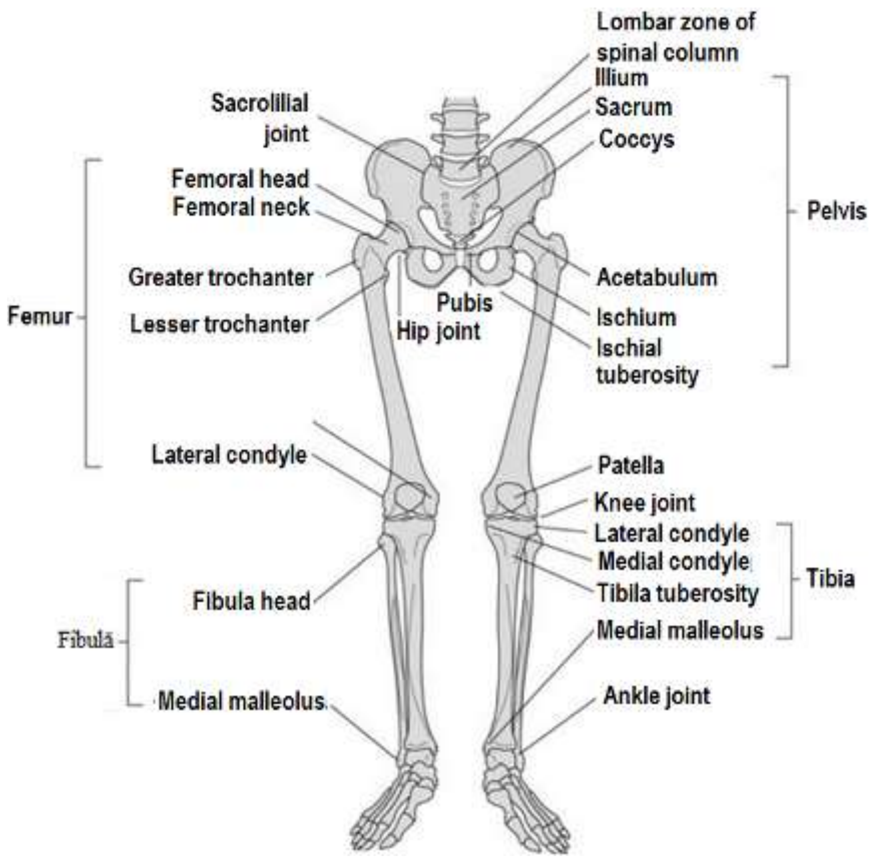


Fig. 4.3. Lower limb skeleton, after [Lev.12].

After the first criterion, in Romanian literature Papilian [Pap.74], Olariu and al. [Ola. 98], [Baz.13] as well as the foreign one [*Art.03], joints are divided into three main categories: 1-fixed joints - synarthrosis (fibrous joints). Do not allow movements or allow very small movements; 2. amphiarthrosis-semi-mobile joints (cartilaginous joints); 3 – mobile joints -diarthrosis. They are made up of two components: 1 - joint faces; 2 - the liaison agencies represented in the joint capsule, muscles and ligaments. Bone surfaces of the joint are lubrifiate with synovial fluid. Depending on the shape of the joint surface, diarthrosis can be [*Baz. 13]: planar joints; ginglymus (hinge joint); Trochoid (pivot) joints; condylian joints; saddle joints; the ellipsoidal joints or enarthrosis. These joints allow performing various movements with high amplitude: flexion, extension, abduction, adduction, rotation (spin).

In terms of the number of axes of movement, joints are classified into three categories:

1. The uniaxial joints that allow the motion in one plane performs the movements of flexion and extension. In this group include ginglymus (hinge joint); trochoid (pivot) joints; condylian joints.

2. The biaxiale joints provide movement after two perpendicular axes. In this group are included the ellipsoidal and the saddle joints;

3. Joints which ensures the tri-axial movements in all planes of space - sferoidal joints or enarthrosis.

According the third criterion, there are the next joint types:

1. joints with muscular driving, ex. wrist joint, knee joint;

2. joints with bone driving, ex. elbow joint;

3. joints with tendons driving, ex. hip joint.

Within the lower limb, exist the following main joints (fig. 4.3): pelvic joints, hip joint or the coxo-femural, the knee and the ankle joints.

At present, the joints study in terms of functions geometry, mobility and stability, is approached with by non-deformable body mechanics. Thus, bony segments as rigid structures and joints as bridges between two mechanical components are considered allowing degrees of freedom. [Lea.13] In this case, the human body can be modeled as made of articulated rigid bars. [Lea.13]

Muscular system of the lower limb (musculoskeletal system) comprises the skeletal striated muscles that are attached to the bones of the lower limb skeleton and their annexes - tendons and synovial bursae. The muscular system is the active component of the lower limb (musculoskeletal). [Pap.74], [Bac.81] Depending on their topographic position, the inferior limb have four major muscle groups [Bac.81], [Dro.12], [Dja.07]: muscles of the pelvis, thigh muscles, calf muscles and the muscles of the leg.

4.2. LOWER LIMB MOVEMENTS,

AXES AND SPATIAL PLANS OF THE MOVEMENT

In terms of classical mechanics, the human body is considered a three-dimensional body in space. To define the position, movements and spatial directions, axes and principal planes of reference and specific terms of direction and position are used, having as its starting point the normal anatomical position PAN of human body, respectively, the orthostatic position, (Fig. 4.4). [Ola.98] Thus, through the human body, three axes and three space plans that crosses at right angles are imaginated. Each plane is determined by two of these axes (fig. 4.5). The three-imaginary axis and plans are represented below. [Ola.98], [*Baz.13]

Sagittal axis ***X-X***, or **anterior-posterior**, called *ventro-dorsale*, corresponds to the thickness of the body. It has a ventral/anterior and another posterior/dorsal pole and forms with the vertical axis (axis y-y), an angle of 90°.

Transverse axis ***Y-Y*** or **lateral** corresponds to the width of the body that crosses through from left to right. It is perpendicular on the longitudinal axis (*x-x*), having two poles: left and right and defining the senses left-right

Vertical ***Z-Z*** **axis** or **longitudinal** cross the human body in orthostatic position, in its entire length and is perpendicular to the ground. It is defined by two poles or extremities: one higher/cranial and the other lower/caudal. In this context, a vertical ax is also called the cranial-caudal axes. This is the main vertical axe *Z-Z* when starts from the middle of the highest surface of the crane or vertex and passes through the body centre of gravity and, through the support polygon of the body.

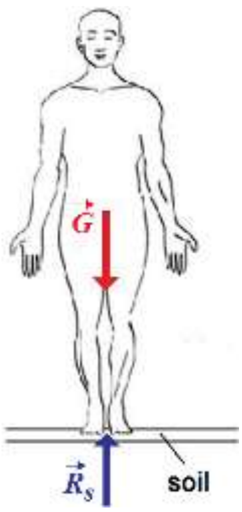


Fig. 4.4. Orthostatic human body position and the vertical forces in balance when horizontal air resistance and other horizontal forces are minimal, after [Knu.07].

The three imaginary planes are surfaces that section the human body and are the frontal, sagittal, and transversal plane.

The frontal plane contains transverse axis *Y-Y* and longitudinal *Z -Z* and divides the body into two parts non-similar: ventral/anterior and the other dorsal/posterior. This plane is parallel to the forefront and with cranial suture of the skull, the reason which is also called the coronal plane.

Median, sagittal or **medio-sagital plane** passes through the longitudinal axis *Z-Z* and sagittal axis *X-X* and by the body's crossing on midline splits it in two symmetrical halves, right and left, respectively called *antimeres*. It is also called the plane of bilateral symmetry. All planes that are parallel to the sagittal plane are called *para-sagittale plans*.

The transverse or **horizontal plane** passes through the sagittal axis *Y-Y* and transverse axis *Y-Y* being perpendicular to the sagittal and frontal planes. It divides the body into two parts: superior and inferior.

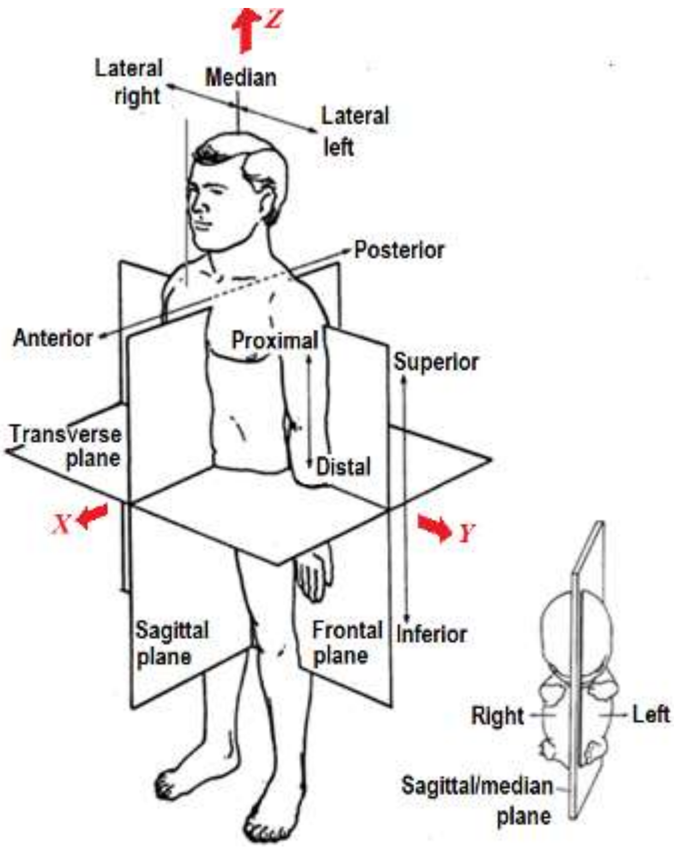


Fig. 4.5. Main space planes and axes of the body in standard anatomical position, after [Ola.98], [Avr.13].

To indicate position or location, one to another, in relation to the three basic plans, of some formations and/or anatomical elements specific anatomic terms for direction and position are employed. For example [Ola.98]: medial; proximal lateral; terminal or distal; the dorsal or the posterior; the frontal/anterior (ventral), etc. (see Definitions).

From the biomechanical point of view, the limbs and segments of human body can perform various moves in which, the plane of motion is always perpendicular to the motion axis that may be a biomechanical or a joint axis. [Avr.13], [Dja.07] Around the same axis and in the same plane, are always two opposite motions (Fig.4.6), which have the following depictions [Ola.98], [Avr.13]: flexion and extension (movements in the sagittal plane, around a transverse axis); adduction and abduction (movements performed in the frontal plane around a sagittal axis); movements of internal or external rotation (movements performed in the transverse plane around a longitudinal axis). Particular rotation movements taking place in the forearm and leg are named pronation and supination; circumduction (motion axis intersects more than one plane).

Movements performed in a joint by a body segment are characterized by the rank or the amplitude of the movement that expresses the maximum angular displacement (fig. 4.6).

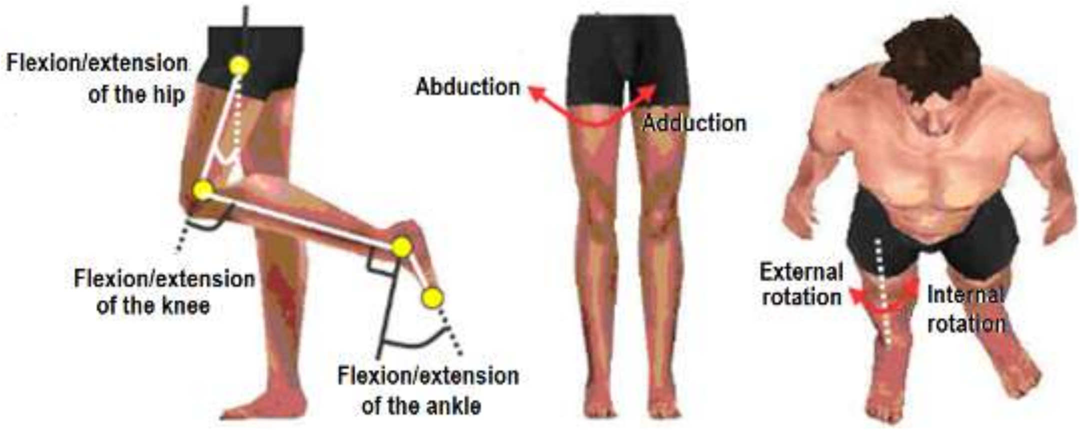


Fig. 4.6. Movements and angles at the lower limb during walking, after [Nik.07]

4.3 LOWER LIMB BONES

4.3.1 Bony pelvis

The bony pelvis represents an bony complex structure, located in the bottom of the abdomen, which makes the connection between the vertebral column (supports the vertebral column) and the lower limbs in the vertical plane, being positioned between pelvic limbs and vertebral column. The shape and proportions of the basin ranges from one person to another. [Avr.13], [Pap.77] Pelvis bone is made up of great basin (abdominal) and in the small pelvis (pelvic canal). The basin has the general configuration in the form of a truncated cone, with large base positioned up and the small, down. It consists of three bone formations [Bac.81], [Pap.74], [Ant.86], [*Ana.12] (Fig.4.7): 1. two lateral and symmetrical bone called coxal or iliac bones (left iliac bone and right iliac bone); 2. the sacrum; 3. the coccyx.

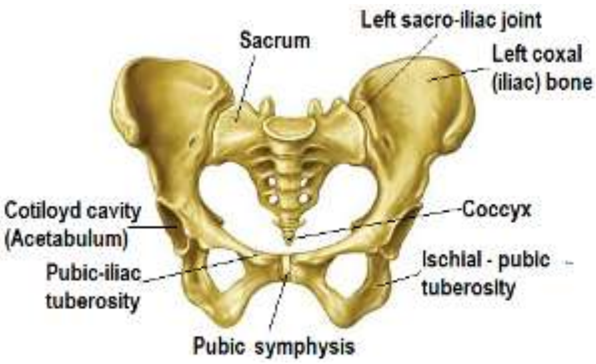


Fig. 4.7. Pelvis anatomy, after [Pap. 74], [*Mem.13].

The coxal bone is anatomically, a flat bone, of quadrangular shape and is made up of three bony formations that converge to its center: ilion, ischium and pubis (Fig.4.8). It has two sides, one external (lateral) one internal(medial) and, respectively, four edges - the upper part called the iliac crest, anterior, inferior and, posterior. On the external side, in the middle, is cotyloid or acetabular cavity (fig. 4.8) playing the role of articulation with the femur, and an inner (medial) one showing an arched line that constitutes the boundary between the great and the small pelvis.

Acetabulum has different shapes and sizes that are dependent on age and gender. In the adult, acetabulum has a depth average of 22-30 mm and can be defined by the acetabular index that is expressed by the ratio of the depth and diameter of the cavity. The inner surface of the acetabulum presents two sides [Art.13*], [*Mem.13]: a semilunar area at the peripheral, covered with hyaline cartilage and the acetabulum fossa, the central part of the acetabulum which is not covered by the cartilage.

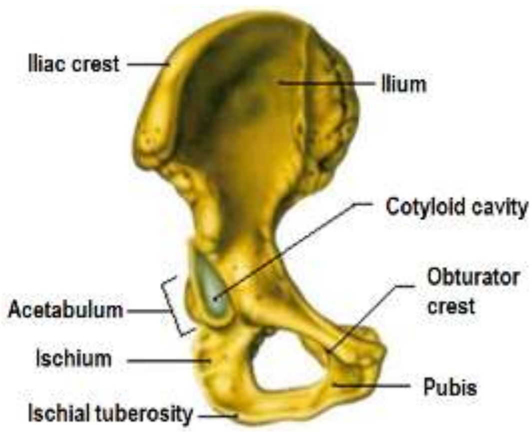


Fig. 4.8. Right coxal (iliac) bone: frontal view, after [*Atl. 08].

Coxal bones are articulated at the bottom by the pubic symphysis and, in the posterior by sacrococcygeal joint to the spine (fig. 4.7).

The sacrum is a median and posterior bone, with roughly triangular shape, and the base facing superior. It is formed by the five sacral vertebrae welding and is situated in a continuation of the spine between the two hip bones, like a feather. [Bac.81], [Avr.13] It is directed obliquely from up to down and from before to back and forms with the last lumbar vertebra an angle called promontory. Sacrum presents: four faces, from which an anterior front (concave and oriented forward and down towards the pelvis), a posterior face (convex and directed backwards and upwards) and two lateral sides; a base articulated with the last lumbar vertebra; a peak that has an elliptic facets that articulates with the base of the coccyx. Coccyx, a small triangular bone, presents two faces, two edges, a base and a peak. [*Avr.13]

4.3.2 Thigh bones

According to the description of the lower limb components, starting from the pelvis to the foot (fig. 4.1), that is the first important lever thigh of the lower limb. Its skeleton is formed from a single bone, the femur (Fig. 4.9). It is a long, pair, and unsymmetrical bone pointing obliquely downwards and latero-medial. [Art.03], [Pop.74]

The femur is the most voluminous bone of the human body, the longest (from 40 cm to 50 cm), the most heavy and resistant, anatomical features that indicate high levels of static and dynamic stresses acting upon him. Femur articulates on skeleton [Bac. 81], [Pap.74], in the upper region with the coxal bone (at the hip), and in the lower region at the knee, with the tibia and patella (Fig.4.3). From the anatomic point of view, it has a body (diaphysis) and two extremities: superior and inferior.

Femoral body (corpus femoris) or diaphysis is a prismatic-shaped cylinder with triangular, hollow on the inside (the medullar cavity), with one wall consisting of resistant bone tissue, with thickness range (4-6 mm up to 9-10 mm). It features three sides: internal and external, and three edges: rear, internal and external. Posterior edge is highly developed and is thick, rough, and prominent and has the name of rough line (fig. 4.9). This line runs through the femur from top to bottom and serves at his orientation. In long of the femur, upper and lower, rough line forms the following anatomical representations [Pap.74], [Bac.81]: a. in the upper portion of the rough line is separating in three branches: lateral branch, called the gluteal tuberosity; medial branch and the middle branch; b. in the lower zone, the rough line bifurcating bordering the popliteal facet. Femur presents two axes, namely: the long axis of the femur, named anatomical axis and the biomechanic axis of the femur that pass from the center of the hip (femoral head) to the central part of the lower extremity of the femur (the knee center). The two axes are meeting in the central part of the lower extremity of the femur (the knee center) forming an angle α (anatomic angle of the femur) of 6°-9°, open upward (Fig. 4.9, a).

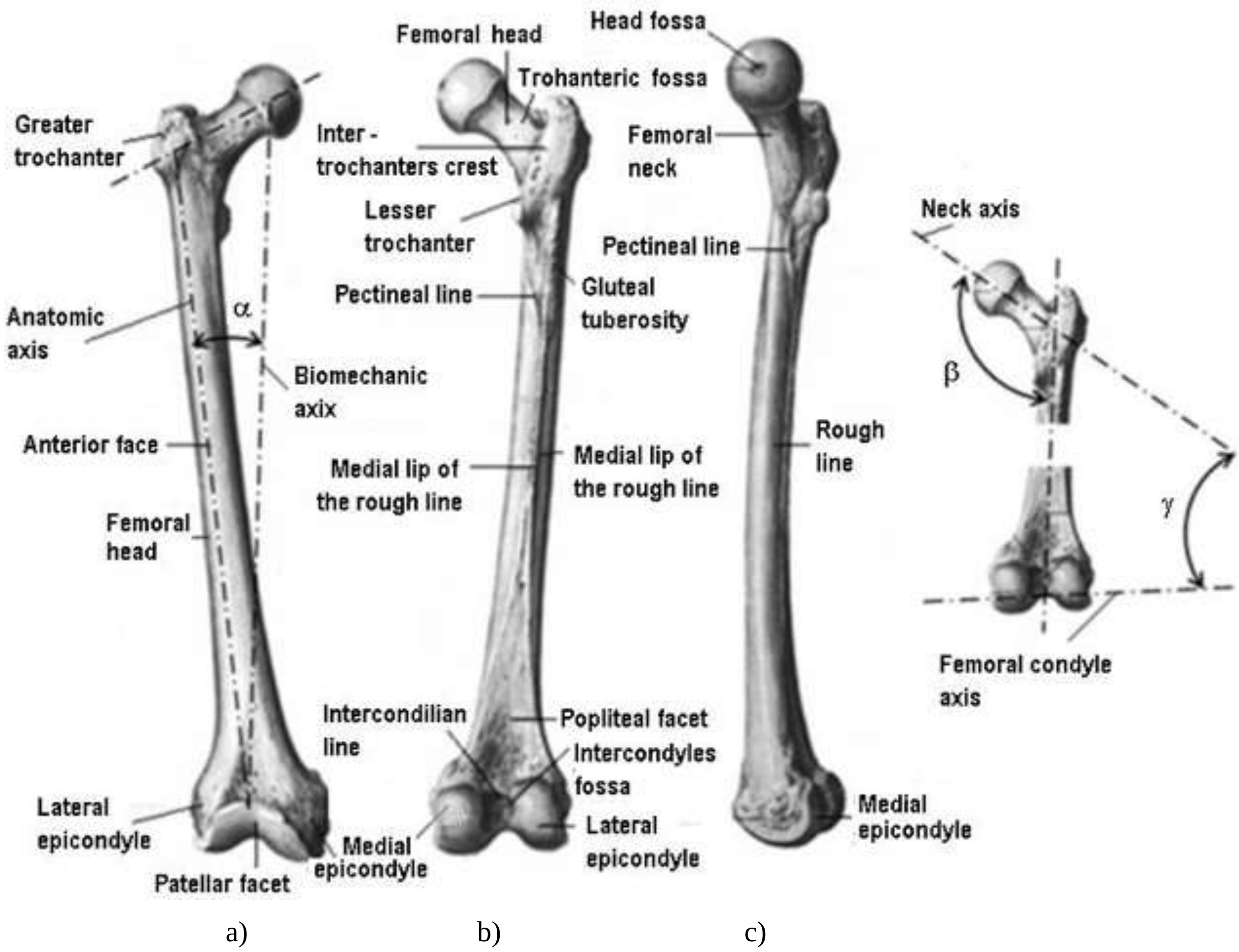


Fig. 4.9. Femur, view: a- anterior; b- posterior; c- medial, where α is the femur anatomic angle, β is the inclination angle, and α is the declination angle, after [Lep.07], [*Fem.12].

Upper extremity (epiphysis) present: a femoral head (caput femoris), a neck (collum femoris), a large tuberosity (great trochanter) and a lesser tuberosity (small trochanter). Femoral head has a nearly spherical shape being 2/3 of a sphere with a diameter of about 40-50 mm. It is rounded upwards, forwards and inside of diaphysis.

The femoral head has a small central depression known as head fossa (fovea capitis femoris) that is linked to the acetabula through the femoral head ligament. It is covered entirely with a hyaline cartilage, excepting the head fossa. It articulates with the cotiloyd cavity as to form the coxo-femural or hip joint.

The neck joins the head with femoral diaphysis. It is oblique in relation to the diaphysis (pointing obliquely downwards and medio-lateral). The long axis of the neck is tilted towards the anatomical axis angle β of diaphysis, called the angle of inclination. The value of this angle varies according to age, sex and individual. Thus, in adults has the value of 125°, till 140° for newborn babies and, for elderly people, till 115°. [Dru.11] Because the femur is eccentric loaded by the body weight and, thus, is subject to composed compression and bending, the neck requires a high strength, anatomical feature which is confirmed by his particularly complex configuration (the longest bone neck in the body and of the vaults of trabecular architecture).

The greater trochanter (trochanter major) and lesser trochanter (trochanter minor) are two very bulky tuberosity muscle insertion [Pap.74], [Bac. 81], [*Oas.13] and they are connected by the inter-trochanters line and by the inter-trochanters crest. [*Sch.13]

The greater trochanter is a large quadrangular prominence that continues up the body of the femur, and presents two sides (lateral and median) and four edges (front, back, top and bottom). It provides insertions to the following twins muscles: medial gluteal muscle, least gluteal muscle, pyramidal, external obturator superior, internal obturator, and twins muscles. The muscle psoas-iliaque is inserted on the lesser trochanter.

Inferior extremity or epiphysis extended down the femoral body. It consists of two strong articulation prominences called condyles (fig. 4.9, b, c.) represented by medial condyle (condylus medialis) and lateral condyle (condylus lateralis), separated by the intercondyliar fossa. The two occipital femur condyles have the shape of sphere segments and, they are oriented obliquely, having the rotating axis pointing obliquely downwards. [Pap.74] It has three sides - joint face, intercondyliar face and, and cutaneous face. The two condyles have a form of volute (fig. 4.10), and their radii of curvature have centers arranged on a spiral. [Ant.86] Medial condyle descended lower than the lateral one, which is why, anatomically, the thigh forms with the leg an obtuse angle, laterally open, which is more pronounced in women than in men.

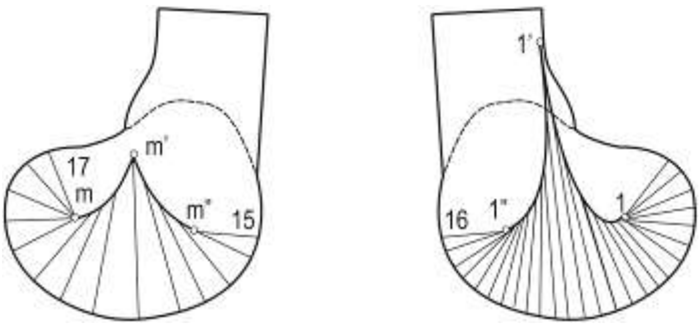


Fig. 4.10. Femural condyles curvature, after [Ant.86].

The long axis of the neck forms with the femoral condyles (with the frontal plane) another angle γ named declination with values between 15°-20°. The changes of the inclination and declination angles have repercussions on anatomical attitude of limb. Thus, after [Pap.74] increase and conversely decrease, of inclination angle drives to the abduction of lower limb and respectively, to adduction. Vice versa, increase and conversely decrease or zeroing of declination angle drives the lower limb in medial rotation and, respectively, in lateral rotation.

4.3.3. Shank bone

The anatomical formation, „ shank " constitutes the segment that connects the thigh of the low leg. It is, after thigh, the second significant lever of limb. It has the skeleton consisting of two tubular long bones [Bac.77], [Bac.81], [Pap.74] tibia and fibula (fibula) that are joined along their bodies by an inter-osseous tibio-fibular membrane (Fig.4.11). [Bac.81]

Tibia is a voluminous, pair long bone, with vertical direction, placed in anterior internal of the leg. In orthostatic position, through the tibia will be transmitted the pressure stress from the femur in the shank. Tibia presents a body and two extremities (epiphyses): upper and lower.

The tibia body (corpus tibiae) is prismatic triangular in shape and has three sides and three edges. The three sides are [Bac.77], [Bac.81]: 1 – medial side (facies medialis), smooth, located directly under the skin; 2 – lateral side (facies lateralis); 3- posterior side (facies posterior) having in the posterior portion, the solearului line (white line facing downward and medially) on which is inserted the solear muscle. The edges are represented by: 1 – anterior edge (margo anterior); 2 – medial edge (margo medialis); 3- interosseus edge (margo interossea).

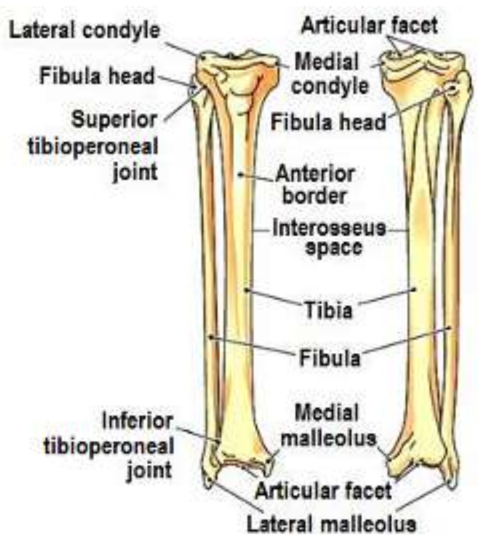


Fig. 4.11. Tibia and fibula: anterior view (a); posterior view (b), after [*Atl.08], [*App.13].

Superior extremity (epiphysis) is a voluminous body, approximately quadrangular in shape and elongated in the traversal, that has two condyles: one medial (condylus medialis) and another lateral (condylus lateralis). The two condyles have in common a circumference and a face or upper tibia plateau.

Tibia's *inferior extremity* is irregularly shaped cuboids, with six sides: superior, inferior, anterior, posterior, lateral, and the medial side that extended by medial malleolus visible and palpable under the skin. Anatomic axis of tibia is the same with the mechanical one (Fig.4.12). Thus, tibia has a proximal and distal anatomical axis or an mechanical proximal and distal one.

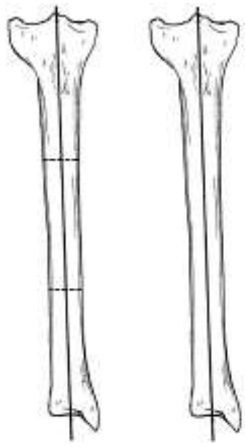


Fig. 4.12. Tibia axis: anatomical (a); biomechanic (b), after [Ala.09].

Fibula is a long, pair bone, thinner than the tibia located postero-external in report with tibia [Bac.81], [Pap.74], [*Oas.13]. It is composed of a body and two extremities (epiphyses): superior and inferior.

Fibula's body is triangular and square, with three sides (internal, external and posterior) and three edges (anterior, internal and external). *Superior extremity* is constituted by the fibula's head extended by its tip. *Inferior extremity* is represented by the lateral malleolus, a prominent flattened from outside to inside. [Bac.81], [*App.13]

Tibia and fibula are articulated at the two ends - upper and, through two joints of type arthrodia [Bac.81]: tibioperoneal superior and, respectively inferior joints.Fibula has an important role in strengthening the stability of the leg.

4.3.4 Foot bones

The leg is, after thigh and shank, of the third main lever of lower limb [Ola.98], [Bac.81]. It forms the anatomical link between the body and the ground, so it ensures the contact with the ground, participating in a complex ensemble of biomechanical body actions corresponding to biped position. Thus, the foot has a complex anatomical structure, functionally very well adapted to biped position, performing in this respect two main functions: supportive of the body, and body locomotion. Leg consists in 26 bones, classified in three main groups [Pap.74], [Bac.81], [*Atl.08] (Fig.4.13): tarsus and metatarsus, and fingers bones – phalanges.

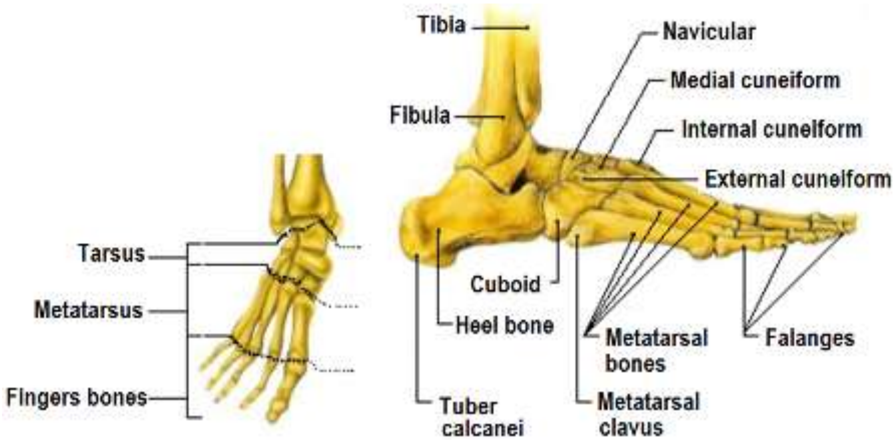


Fig. 4.13. Right leg bones, frontal view: frontal (a); lateral (b), after [*Atl.08].

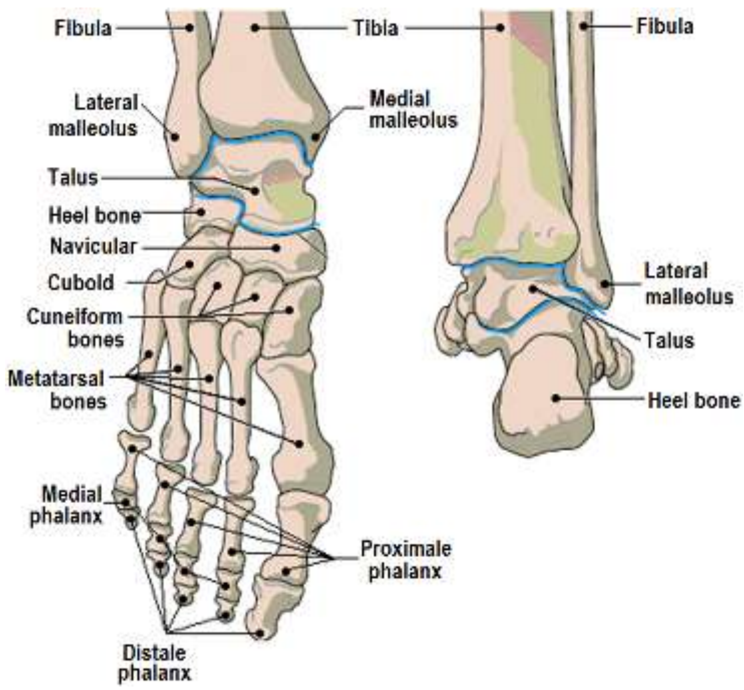


Fig. 4.14. Bony skeleton of the anatomic system ankle-leg: anterior view (a); posterior view (b), after [Dru.11].

Tarsus is placed in the upper zone of the leg, being composed from the following bones (Fig.4.13, Fig.4.14): talus or astragal; navicular bone (located on the medial side of the foot); cuneiform bones (prismatic triangular shape and participate in the building of the cross vault of the foot); heel bone (elongated prismatic-shaped anterior-posterior and transverse slightly flattened and located under the talus); cuboid bone (sitting on the side of the foot and the heel bone).

Metatarsus, corresponds to the foot and includes five metatarsal bones (fig. 4.14) which are long pairs bones. Phalanges (fig. 4.14) are in number of 14; each finger (from the five of the foot) consists of three phalanges, except from the thumb which has only two. Depending on their position, phalanges are grouped into three categories: the proximal phalanx, medial phalanx and the distal phalanx.

4.4. LOWER LIMB JOINTS

4.4.1. Pelvis joints

Bones of bony pelvis, represented by the two hip bones, the sacrum and coccyx are joined by means of the following joints (fig. 4.15): 1. sacro-iliac joints, right and left, located in the posterior and median zones of the pelvis; 2. The joint of sacral with vertebral column, without functional importance; 3. the joint of pubic symphysis.

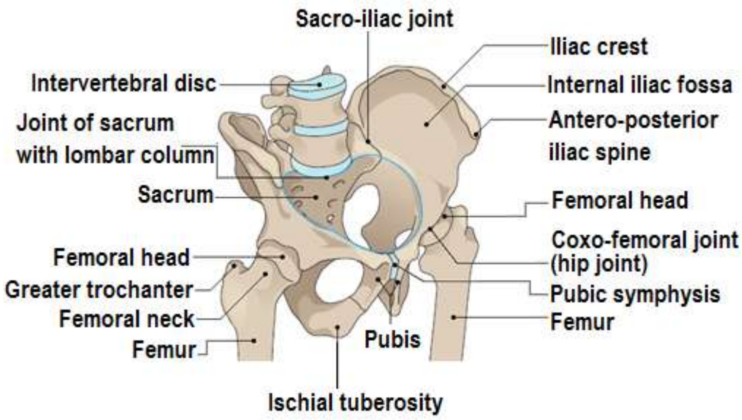


Fig. 4.15. Pelvic girdle's joint, after [Rad. 09], [Dru. 11].

Sacro-iliac joints ensure the contact between the joint surfaces of iliac bones and sacrum (Fig.4.15). The coxal bones are fixed [Pap.74] on vertebral column by iliolumbar ligaments and on lateral sides of sacrum and coccyx by sacroischial ligaments (sacro-tuberal and sacro-spinal) (Fig.4.16). Joint surfaces are represented by auricular sides of sacrum (few concave) and of iliac bones (few convex) and, by a joint capsule having the form of a sleeve that is inserted on the peripherals of the two joint surfaces and, in particularly, by strong ligaments: [Avr.13], [Pap.74], [Bac.81] (Fig.4.16): ventral sacro-iliac ligament (ligg. sacroiliaca ventralia), dorsal sacro-iliac ligament (liig. sacroiliaca dorsalia), interosseus sacroiliac ligament (ligg. sacroiliaca interossea) and, ilio-lombar ligament (ligg. iliolumbale).

In sacro-iliac joints are produced two tipping movements of sacrum around a transverse axis, passing through the dorsal sacroiliac and interosseous ligaments or the joint, called nutation movements (limited by sacro-ischial ligaments) and contra-nutation mevements. These two movements can be performed also "by the displacement of the two coxal bones on immobile sacrum". [Pap.74]

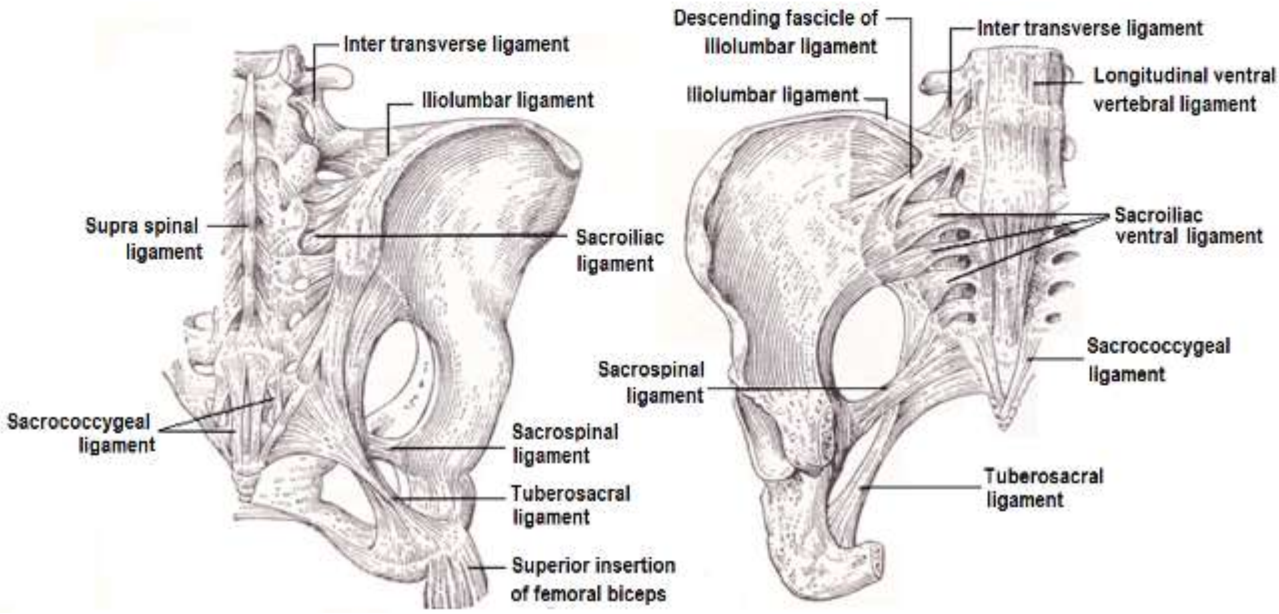


Fig. 4.16. Ligaments in pelvis joints, after [Pap.74]

Sacrum do not to collapse in the small pelvis when applying weight forces because sacro-iliac joints are semi-mobile and stops that, through the following mechanism: the weight ***G*** is directly transmitted from the vertebral column [Ant.86], [Bac.81], [Gor.91], [Ver.13] to sacrum after it is decomposed to two sacroiliac joints. Further it is transmitted through the chain - coxal bones - coxo-femural joints - superior extremities of femurs and is balanced by the reactions ***R*** of the ground, also transmitted through femurs to vertebral columns.

Pubic symphysis is a semi-arthritis joint positioned in the anterior part of coxal bones and, is formed by union of the pubic bones. This union is done by fibro-cartilaginous inter-pubic disk (discus interpubicus) and two strong peripheral ligaments: pubic superior and pubic arched ones. Although the joint has a very low mobility, it allows small landslides only in the position on a single leg, the action being cancelled immediately by ligaments actions and discrete vertical sliding while walking [Ver.13], [*Ana.12]. In certain situations, namely in pregnancy and childbirth the pubic symphysis has a certain elasticity in the sense that through relaxation allows the pelvic diameter increase. [Ava.13], [Pap.74]

The pubis fulfills anatomical-biomechanical features such as [Ola.90], [Ant.86], [Bac.81], [Mem.13], [Ana.12]:

- support of superior segments of the human body, transmission of its weight to lower limbs, and reception of counter pressures of ground, during human biped locomotion. These important functions determines very little movements of the pubis and, for this reason, it is considered as static single rigid. [Bac.11], [Ant.86];

- protection for pelvic organs;

- specific function in childbirth mechanism.

4.4.2. Hip joint (coxofemoral joint)

Hip joint is composed of [Ver.12], [Pap.74]: coxofemoral joint, motor and stabilizer muscles, and a complex nervous-vascular system. Coxofemoral joint ensures the liaison between the trunk and lower limb, which is oriented in all directions in the space, playing a capital role in human static and locomotion. [Pap.74], [Ola.98], [Ver.12] It is a typical spherical joint – a ball-and-socket joint with three degrees of freedom (rotations), very important in locomotion and ensuring the maximum stability and mobility. The joint is situated on the external side of iliac bone, outside and downside oriented, with an approximate diameter of 60 mm. The coxofemoral joint is composed from the following parts [Bac.77], [Pan.07], [Pap.77], [Şte.07] (Fig.4.17): 1 - joint surfaces – semilunar side of acetabulum and the femoral head. Both of these surface are covered by a layer of hyaline cartilage; 2 - means for keeping in contact of the two joint's surfaces: the very strong joint capsule and the labrum that is not a bearing surface, but improves the joint matching, the synovial, and femoral head modeling. [Boi.02]

In addition to these, the periarticular muscles and barometric pressure are involved. [Pap.74] Stability and solidity of the hip joint are ensured by: the anatomy of the joint surfaces, the presence of labrum, a series of strong joint ligaments - iliofemural, pubic-femoral, ischiofemoral femoral head ligament (fig. 4.17), and abductor muscles [*Lea.13], [Bac.77], [Pan.07].

The coxofemoral joint allows the movements of: flexion and extension (in flexion the thigh approaches to the anterior wall of the abdomen and, in extention it is removing from it), abduction and adduction, internal and external rotation.

Due to the femoral neck length and to the inclination angle (fig. 4.5), flexion-extension and abduction-adduction movements are associated with rotational movements . Thus, the flexion is accompanied by an internal rotation motion while, in extension, by an internal rotation.

Flexion-extension movements (Figure 4.18) runs around the central bio-mechanic axis which corresponds to the central axis of cotyloid cavity [Bac,81], [Bac.77], [Nen.05], while pure flexion-extension movements would run around a transversal axis passing through the tip of greater trochanter. [Pap.74, [Nen.05], [Şte.07]

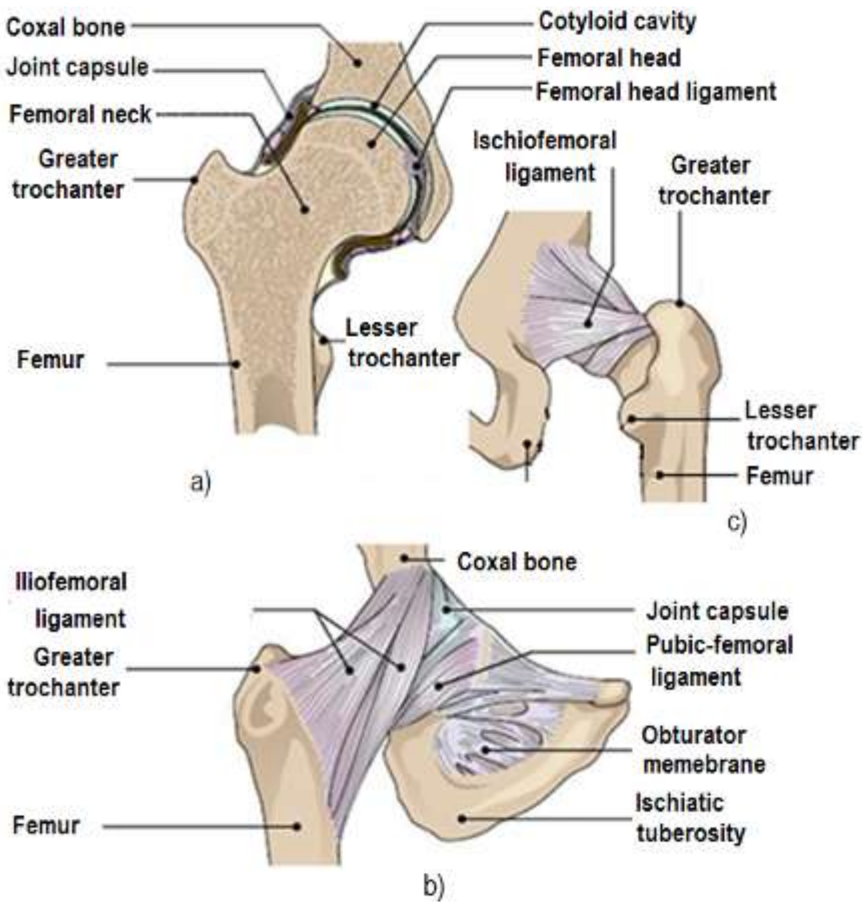
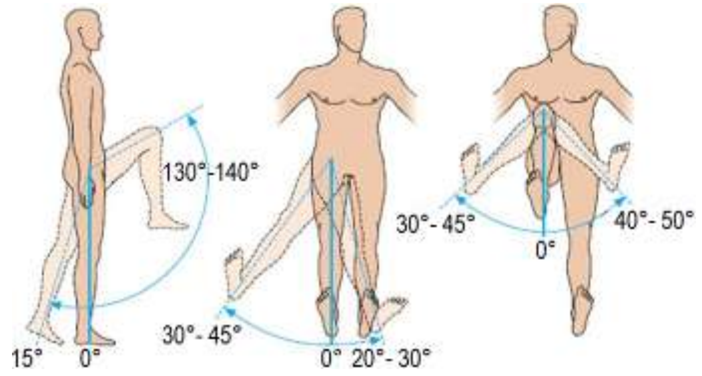


Fig. 4.17. Hip joint anatomy: coronary section (a); anterior view (b); posterior view (c), after [Rad. 09], [Dru. 11].

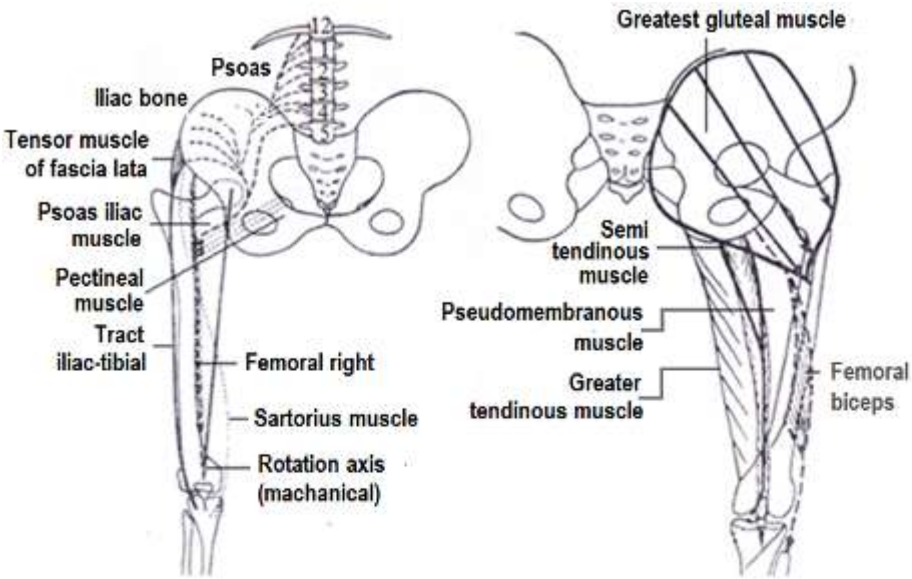
The total amplitude of the movement of flexion-extension depends on the knee position [Pan.97], [Bac,81], [Bac.77]: thus, if it is flexed (fig. 4.18, a), flexion of the thigh reaches approximately 130°-140° (limited by the ischial muscles of the thigh and by the contact between thigh and pelvis) and, if the knee is extended (fig. 4.18, b), flexion of the thigh will be limited to about 90° (limited by the stress of ischial muscles).



a) b) c)

Fig. 4.18. Different movements run by the lower limbs in hip joint: flexion-extension with flexed knee (a); abduction-adduction with extended knee (b); rotation with flexed knee (c), after [Dru. 11].

The movement of flexion is achieved mechanically by strong muscles (Figure 4.19) which link the femur, with different application points of force. In its turn, the movement of the extension is well mechanically ensured by an ensemble of muscles (fig. 4.19) with various application points of force. [Ifr.78]



a) b)

Fig. 4.19. Mechanical schema of thigh on pelvis: flexion (a); extension (b), after [Ifr.78].

Abduction – adduction movements are achieved around an antero – posterior axis passing by the femoral head and, being accompanied by thigh rotations. [Pap.74] *Abduction* has the maximum amplitude of 30^0 45^0 60^0 , when the thigh is in extension. [Pap.74] When thighs are in maximal flexion, the abduction growth to 70° and, both thighs form an angle of 140° [Pap.74]. Abductor muscles are: greater and medial gluteal and internal obturator. The abduction is limited by the strain of iliac-ante-trochanterian ligament (when the thigh is in extention) and by pubic-femoral one (when the thigh is in flexion). *Adduction* has an amplitude of approximately 30° and is achieved by the adductor muscles presented in figure 4.20. the movement is limited by the connection of thighs and by the ante-trochanterian ligament and by the round one, when the thighs are crossed. [Pap.81, [Pap.74], [Dru.11]

Total rotation, composed from the internal and external rotation (Fig.4.18), runs around a vertical axis passing through the femoral head. Maximal amplitude of external rotation is of about 40° - 50°, while those of the internal rotation is of 30° – 45°. When the thigh is in position of flexion and abduction, i.e. with the ligament relaxed, the rotation has a total amplitude that can rich the value of 100°. [Bac.81], [Pap.74] For external rotation achievement participle the medial and greater gluteal muscles and, for internal rotation participate the medial and greater gluteal muscles and, the semi membranous.

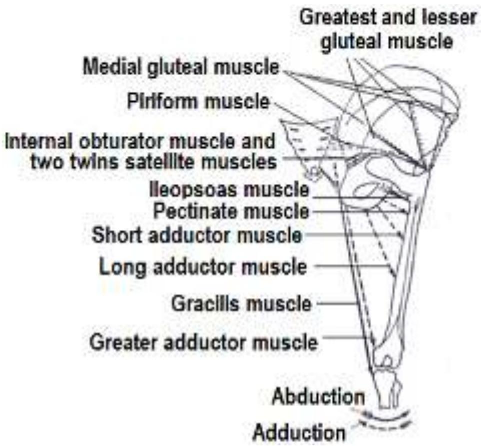


Fig. 4.20. Abduction and adduction thigh movements schema, after [Ifr.78].

Circumduction movement is defined as the combination of elementary previous movements, run simultaneously around the three reference axis [Pap.74], [Şte.07], [Bac.77] and for what participate all muscular groups of the hip. During this movement, run the following components: femoral head turns around in acetabulum, the femur inferior extremity describes a circle and, the femur body, a cone.

In biomechanical aspect, the coxo-femoral joint presents, in terms of gait, the following characteristic [Kha.12]: joint functional stability is a priority in report with its mobility. Stability factors are represented by [Kha.12]: 1. depth of cotyloid cavity; 2. Functional characteristic of labrum and of joint capsule; 3. the state of ligaments and of periarticular muscles. 4. dynamic characteristics of loadings on femoral head by the body's weight; 5. balance dynamic characteristics of medial gluteal muscles.

Coxo-femural joints fulfill the next principal functional characteristics [Ant.86]: 1. represent the area in which the pelvis transmits the body weight to lower limbs, on the trajectory sacrum – iliac bone body – cotyloid cavity (fig. 4.12); 2. represent the center around which the pelvis can move, modifying its position and interfere in locomotion stability and gait.

4.4.3. Leg joints

The two bones of the leg – tibia and fibula (fig. 4.11) are articulated at superior and, respectively, inferior epiphysis level forming two articulation: upper tibio-fibular joint and, respectively, lower tibio-fibular joint. At the same time, tibia and fibula are linked all along their body by a membrane called the tibio-fibular interosseous membrane. As a result of this union, an oblong oval space called the interosseous space is formed. [Bac.11]

Upper tibio-fibular joint is an arthrodia characterized by joint surfaces (posterior side of external tuberosity of tibia's superior tuberosity and internal side of fibula head) plate and covered by a hyaline cartilage and a fibrous capsule, reinforced by two ligaments, having the role to keep the contact between the two joint surfaces. The two ligaments are the anterior and the posterior of fibula's head, the interior side of the sleeve is covered by a synovial.

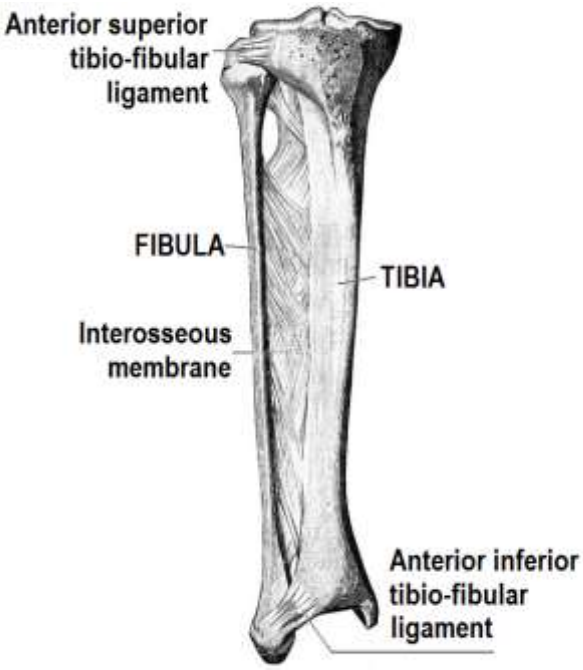


Fig. 4.21. Tibio-femoral joint ligaments. [Pap.74]

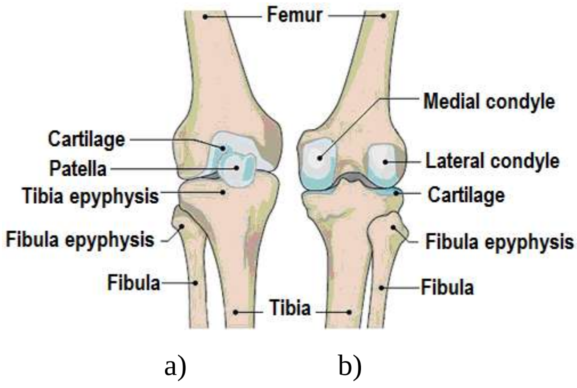


Fig. 4.22. Knee joint skeleton: anterior view (a); posterior view (b). [Dru. 11]

4.4.4. Knee joint

The knee is the mobile segment of limb skeleton (fig. 4.3), which connects the thigh and leg (shank). [Bac.77], [Pil.03] The of the knee skeleton is composed (fig. 4.22) from lower epiphysis of femur (4.3.2), epiphysis of the tibia and of the fibula (Chapter 4.3.3) and by patella, which is a short bone, located toward the front of the knee. The knee presents a number of special features such as [Pap.74], [Lav.07], [Ant. 86], [*Ana.13], [*Les.13] 1 - it is the largest joint in the body, also ensuring that changing of the distance between the body and the low foot or with the ground [Lav. 07]; 2 - it is fragile and unstable due to its anatomical conformation (less covered and protected by the soft parts) and, thus it is frequently exposed to the actions of noxious external factors; 3 - it is a joint with single degree of freedom: flexion-extension. Supplementary it has a second degree of freedom: axial rotation; 4 - stability in rest and gait is ensured through a complex muscular ligamentar system; 5 - is intensely stressed in static and locomotion, doing over a million cycles of extension and flexion during a year [Dru.11]. In principle, the knee is working in compression; 5 – it is a joint with discordant surfaces, e.g. radii of femoral condyles curvatures, which have the centers arranged on a spiral (fig. 4.10), are not equal with curvature radii of tibial surfaces leading to a discrepancy between the joint surfaces [Ant.86]; 6 - under the functional aspect, it presents four types of structures: bearing (are the lower part of the femur, i.e. lower epiphysis of the femur upper epiphysis of tibia and, patella), fixation (keep in contact the bone extremities and allow movements between the joint surfaces), sliding (improve in contact joint surfaces movement and has the role to of damper of movements carried out under static and dynamic loading), and the knee movements (extensor, flexor, and totating muscle groups).

Knee joint is formed by two others : a tibiofemoral joint which is imperfect through the contact between lower femur epyphysis and upper tibia epyphysis, the contact having a relatively low congruence, is improved by the presence of two meniscus, and femoral-patellar joint.

The joint surfaces of the knee joint are : lower femur epyphysys that has two surfaces of condyles and of femoral trochlea and, upper tibia epyphysis by superior surfaces of tibial condyles, inter-joints meniscus (an external meniscus, in the form of letter O and an internal one, in the form of letter). Inter-joints meniscus are placed on the outskirts of every joint tibial fossa, being formed by two fibrous cartilages.

In the knee joint, the means of connection are represented by a joint capsule which is highly resistant and, also, a complex series of ligaments located inside, outside, in front and behind (rear side) of the knee[*Les.13]: patella ligament, collateral fibular and, respectively tibial ligaments, crossed ligaments and other aponevrotic joint strengthening structures.

Joint capsule has the form of a sleeve perfectly inserted on the femur, tibia, peripheral sides of meniscus and, on patella. [*Les.13] The knee is described as a single degree joint, respectively a single simple movement - flexion-extension of leg (shank) in report to the thigh. [Bac. 81], [Sed.08], [Ant.86], [*Les.13] Besides these movements, the knee can also describe, secondarily, other movements: internal – external rotation and in front and back sliding movements (Fig. 4.23). [Dru.11], [Rad.09], [Sed.08], [Ant.86]

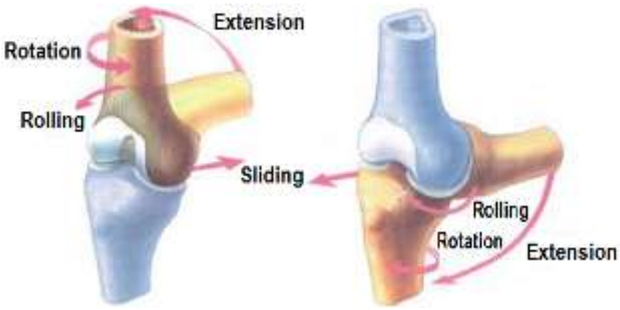


Fig. 4.23. Knee joint movements, after [Dru.11].

Flexion – extension is the knee mean movement and it runs around an axis that is not fixe, due to the volute form of femoral condyles (Fig.4.10). From the biomechanic point of view, this movement is described as : when the lower limb is an open cinematic chain, the knee joint plays the role of a third degree lever and, when it is a close cinematic chain, joint is a first degree lever. The flexion begins with a rolling and finishes by a rotation, while the extension begins with femoral extremity rotation and finishes with rolling on the femoral plateau.

Table 4.1. Muscles complex for knee movement, after [Sed.08]

Muscle	Knee movements			
	Flexion	Extension	Internal rotation	External rotation
Ilio-psoas				
Cvadriceps	#	*		
Tensor fascia lata	#	*		
Right	*	#	*	#
Semi-membranous	*	#	*	#
Semi - tendinous	*	#	*	#
Femoral biceps	*	#	#	*
Sartorius	*	#	*	#
Popliteal muscle	*	#	*	#
Gastrocnemius	*	#		

* Agonist muscles; # Antagonist muscles

The flexion – extension and internal – external rotation movements in knee joint are acquired by different complex muscular groups, presented in table 4.1. In the present, it is considered that the knee joint movement can be described by three rotation axis. [Sed.08]

The amplitude of flexion-extension movements of the knee (Fig. 4.25) reaches 120 ° when the hip is extended and 140 ° when the hip is flexed. Flexion movement amplitude can reach 160°

when the subject is grouped on coming, while the internal – external rotations has maximal amplitudes of 30° and, respectively, 40°.

4.4.5. Ankle articulation

The ankle articulates the leg on foot segment (Fig.4.3). It supports all the weight of the body, being also the meeting point of the vertical axis of the body and the horizontal axis of the foot and, respectively, the ground. [Pap.74], [Bac.77], [Lav.07], [Lab.12] From the biomechanic point of view, the talocrural joint is described together with the joint between talus and calcaneum. This approach takes into account the complex ankle - foot joint that moves in the three reference planes (Fig. 4.5). It plays an important role in the good lower limb locomotion because different anomalies of the ankle has negative influences on knee, hip etc. joints. It is represented by [Pap.74], [Bac.81], [Şte.07] the talocrural joint of tibia, talus and fibula (Fig. 4.14, Fig 4.24). It is a hinge joint (ginglymus). The joint surfaces of ankle joint (Fig. 4.24) are formed by [Pap.74], [Bac.81], [*Les.13]: (up) by the tibial -fibular staple at lower extremities of tibia and fibula (down) by the astragal bolt.

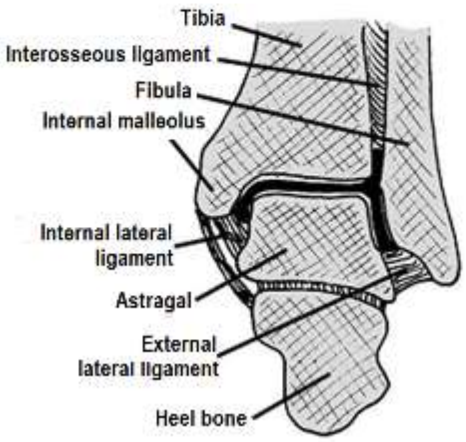


Fig. 4.24 Frontal section, after [*Les.13]

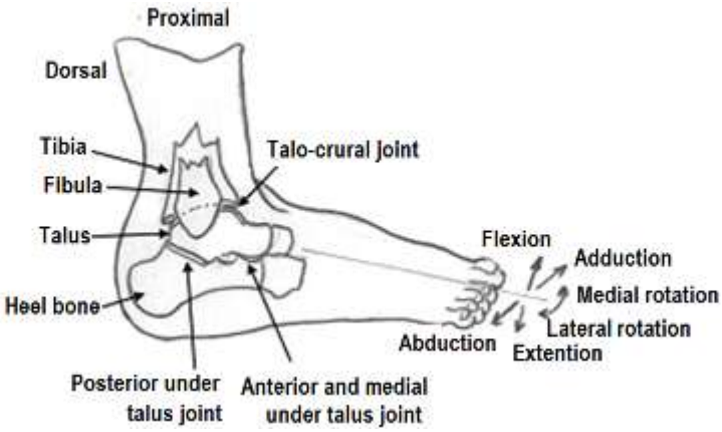


Fig. 4.25 Ankle – foot assembly, after [Che.13]

To the two sides formation of joint, the two joint sides of medial and lateral malleolus take part. The joint surfaces are covered by a thin layer of hyaline cartilage. The bony component are joined by the joint capsule, strengthened by strong ligaments (Fig. 4.25): inter-osseous ligament, and lateral extern and intern ligament. Together with the foot joints can be performed the movements: dorsal flexion, plantar flexion, abduction, adduction, internal rotation, supination and, pronation (Fig.4.26). [Dru.11], [Sed.08], [Pap.74]

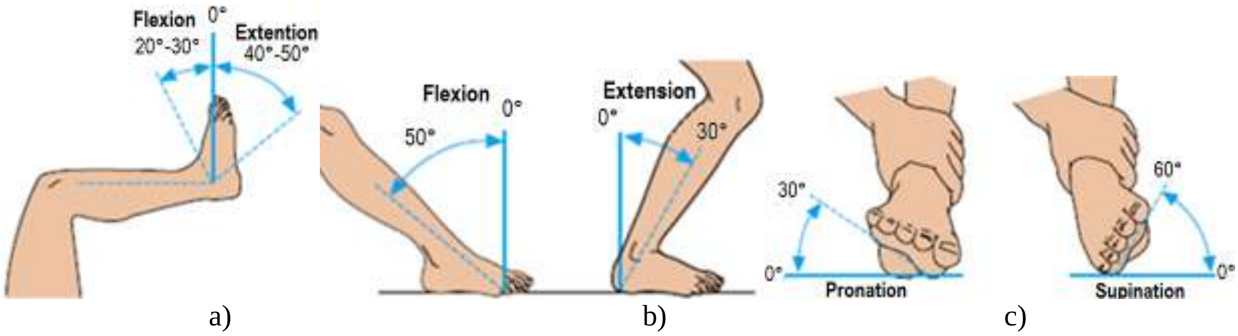


Fig. 4.26. Ankle-foot assembly, after [Dru.11].

The dorsal flexion (dorso-flexion) and plantar flexion movements run around an axis in frontal plane that passes through the two malleolus, while the abduction and adduction run around the longitudinal axix of the leg. The pronation-supination movements run aroung the longitudinal axis of the foot. [Sed.08], [Dru.11], [*Les.13] Their amplitudes are presented in figure 4.26.

4.4.6. Levers categories in cinematic chain of lower limb

During different movements and positions of lower limb components, the pelvis, the hip, the thigh, the knee, the leg, the ankle and, the foot act as an open cinematic chain (without support on ground) or a closed one (in support on ground). [Nen.05] The closed cinematic chain corresponds to following positions and movements Nen.05], [Ola.98]: the distancing and approaching the legs, twisting outside and inside, hitting, pushing, etc. The lower leg is a closed cinematic chain in the next positions and movements: static, walking, running, beating in the jump, etc. The nature of the cinematic chain determines the lever-type under operates the lower limb component (Tab. 4.2).

Table 4.2. Lever-type in cinematic chain of lower limb, after [Ola.98], [Bac.81]

Lower limb component	The nature of the cinematic chain	
	Open	Closed
	Lever-type under operates the lower limb component	
Femur	IIIrd degree	Ist degree
Tibia (thigh)	IIIrd degree	Ist degree

The lever-type stability is important for the prosthetic adaptation. Thus, if the segment is a first degree lever, the force ***F*** necessary for the balance, is given by the relation:

$$F = 2\frac{Rxr}{l}, \tag{4.2}$$

Where: F [N] is the action of foot extensors on the thigh, R [N] is the body weight, r [m] is the resistance arm and, l [m] is force arm.

The tibia loading force *F* value increases during the propulsion movement (over 5000 N), and during the falling on the ground (over 20 000 N)

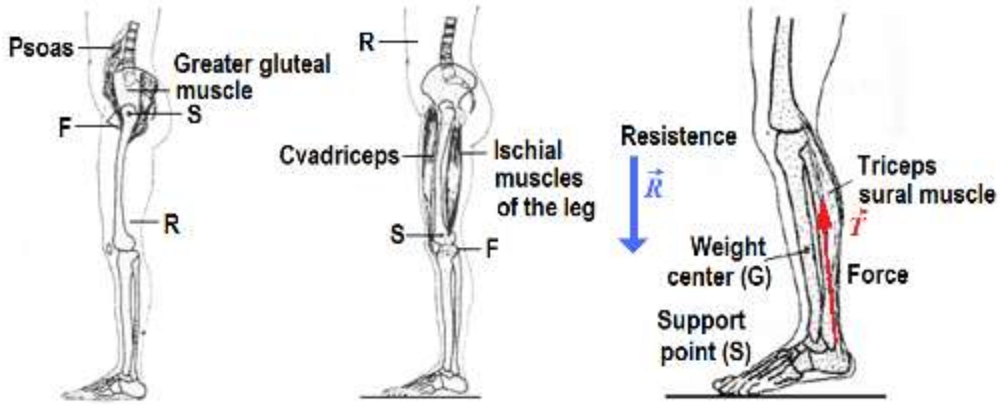


Fig. 4.27. Femur functioning in the lower limb cinematic chain: *F*- application point of muscular forces; *S* – support point; *R*- application point of resistant forces, after [Ola.98]

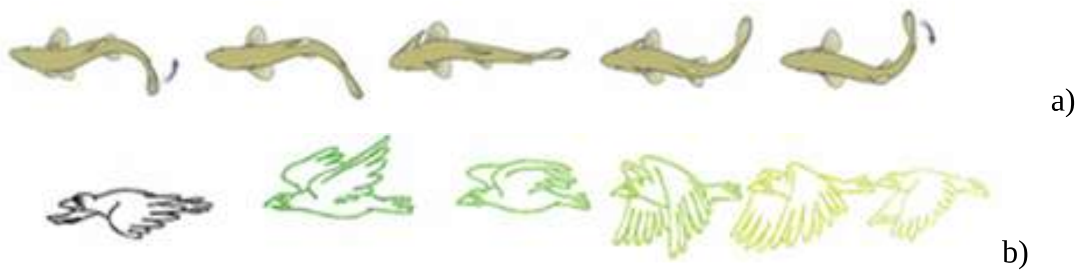
4.5. BIOMECHANICS OF GAIT

4.5.1. Human locomotion

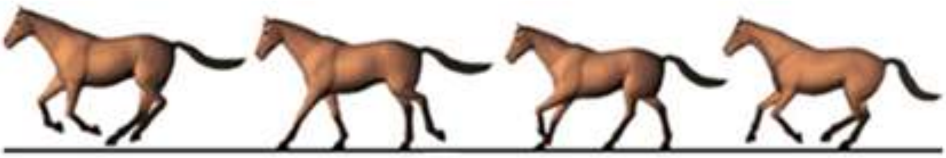
Locomotion is mainly defined as an in time changing of movement coordinates of a body or of a vertebrate. One of essential attributes of any living vertebrate is locomotion, which is ensured by an internal skeleton and strong muscles acting on it.

Depending on vertebrate type, different types of locomotion are possible (fig. 4.28): swimming, flying, gait etc. for locomotion, several tasks have to be accomplished:

- locomotion must follow a stereotype plan;
- the balance must be maintained during locomotion;
- the movement must be adapted to external conditions.



c)



d)

e)

Fig. 4.28. Locomotion for different vertebrates : fish (a); bird (b); salamander (c); horse (d); human (e), after [Tru.10]

The human body can perform simple or composed (complex) movements, in its integrality or only by some of its parts.

The whole body movements are the complex ones, performed under three principal forms: locomotion, rotation, and combined movements, which are defined by a series of characteristics: spatial (direction and sense of the movement, trajectory length etc.), temporal (longer or shorter duration), locomotion etc. The movements are performed by body's muscles, disposed around joint and, they can be classified in two groups: agonistic and antagonistic muscles. Locomotion is influenced by many types of forces as [Șer.11], [Ifr.78]: motor forces that produce the speed growing by a positive acceleration, braking forces that produce the speed diminution by a negative acceleration, neutral forces that modify only the movement direction, human body balance and stability disturbance forces, which act especially in sagittal and frontal planes. In connection with this, the following can be noted: [Șer.11]

- bipodal contact ensures a higher stability in frontal plane and less in the sagittal one;
- monopodal contact ensures a higher stability in sagittal plane and less in the frontal one.

Locomotion is the displacement in space and time of the entire human body or of some of its parts in report with a previous support point. [Ola.98] It is one of human vital functions, made by lower limbs as propulsion elements. [Sam.09] According the elements participating to the cycling locomotion, it can be systematically defined (Vacherat [Vac.10]) as an assembly of joint, muscular and biomechanic events produced between two successive positions of the movements: initial and the following, identical with the first.

The movement and movement variation causes can be studied by the three Newton's laws: [Ola.98], [Sam.09]

1. **First law** – inertial law that postulated that the movement can be modified only by an external force action;
2. **Second law** – fundamental law of dynamics – the human body movement variation is proportional to external acting force, the proportionality factor being the body mass;
3. **Third law** – the interaction law, defining the reciprocal action principle – the environment force acting on human body is the consequence of the force exerted by the human on it, both forces having the same intensity, support and opposite acting senses (fig. 4.29).

Locomotion supposes two main movements categories: cyclic and non-cyclic. [Bac.81] In the case of cyclic locomotion, the whole body or each of its parts is moving from an initial position, considered as start position, to the next one, which is identical. [Ifr.78] therefore, the cyclic locomotion is defined by repetition of uniform alike, movement cycles named, after, [Ifr.78], „movement units".

From biomechanic point of view, locomotion is a complex process constituted by the coordination of many mechanisms coupled with the neuro-muscular system. [Ifr.78] Human locomotion is conditioned by a series of different variable factors [Bac.77]: locomotion speed, variation level and sense (up, down), the bone of movement subject, subject gender – masculine or feminine, subject size –height and weight, ground nature, different subjective factors – gravitation, climatic conditions, etc. [Ser.11]

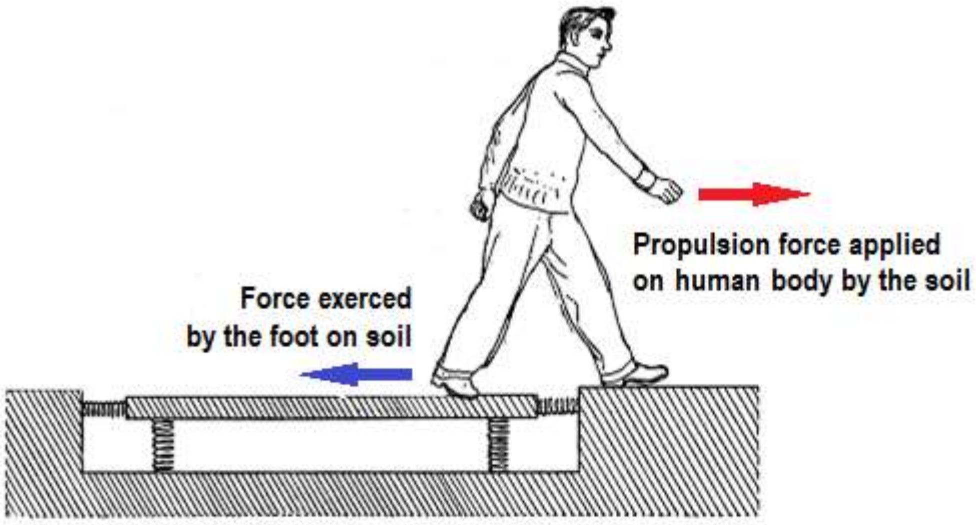


Fig.4.29. Reciprocal action principle in the case of human locomotion, after [Ifr.78].

If locomotion is understood as the result of internal body forces in interaction with displacement external forces acting on human, the analysis and description of locomotion mechanisms have a particular significance. [Bac.81] In this order, Dedieu [Ded.81] proposes three human movement describing levels:

1. Space-temporal level describing the movement in length and duration;
2. Cinematic level, which quantifies locomotion in terms of displacement, speed or acceleration;
3. Kinetic level that analyzes all forces generating movement, grouped in internal and external forces categories.

Internal forces interfering in movement generation are, in order of succession, the following [Bac.81], [Ser.11], [Ola.98]: nervous impulse, muscular contraction force, intra-abdominal force and, osteo-joint levers generating the joint reaction to nervous impulsion.

External forces are represented by [Bac.81], [Ifr.78]: gravitational forces, body and its segments weight, atmospheric pressure, environment resistance, inertia, reaction of the ground or of the support surface, friction force, forces producing accelerations, and diverse external resistances.

Gravitational force (fig. 4.30) always acts vertically up to down. To compensate it, the cumulated internal forces act in inverse sense, down to up. If the movement surface is not horizontal, the gravitation force can be decomposed in two components: a perpendicular component *N* on the support surface (pressure force) and a parallel one, named, of slipping.

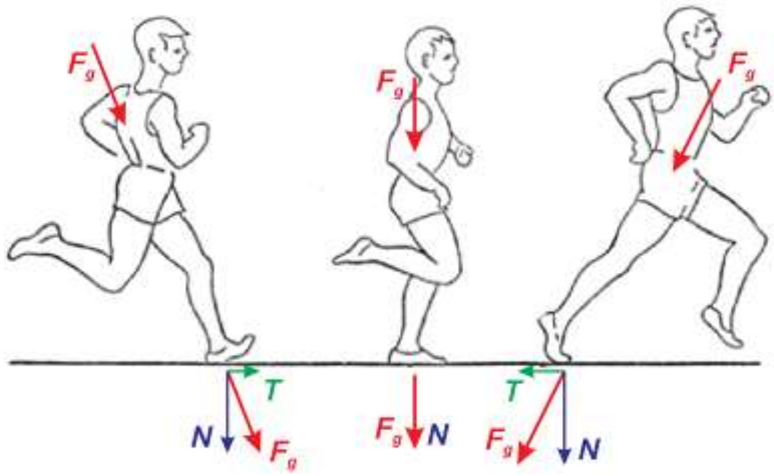


Fig. 4.30. Gravitation force (F_g) : ***N*** – normal component ; ***T*** – tangential component, after [Ifr.78].

Body's and its segments weights always act vertically, up to down on their mass centers, in any position of them in space. The value of this force is determined by the mass of moving respective bodies. The reaction of the hip or of support surface occurs when the body acts on the ground or on the support surface with forces related to the weight and its displacement speed. In this case, according to the third law of Newton, the ground exercises on the moving body a reaction having the same value and direction, but inversely oriented. The hip reaction acts on bony levers and generates external joint moments. [Ded.11] The reaction can be represented in two ways : a – by the static reaction when the body is in repose, having the same value as the body static weight and being directed in opposite sense; b – by the dynamic reaction in the case when the body is moving. Its value is equal to the body weight composed with the inertial force (due to the acceleration of the movement). When the gravitational force is not perpendicular on support (sol), the reaction is formed by two components (fig. 4.30): a normal component (perpendicular) on support and a tangential component. If the body is moving on an horizontal surface, the normal component balance the body weight while the tangential one represents the friction force, which is opponent to its displacement.

The external forces are considered, by Gillet [Gil.04], as the result of accelerated bony segments mass composing the body and, analytically represented as below:

$$\sum \vec{F}_{ext/R} = M \cdot \vec{a}_G = \sum m_k \cdot \vec{a}_{G_K} \; ; \qquad (4.3)$$

$$\vec{G} + \vec{R}_{sol} = \sum m_K \cdot \vec{a}_{G_K} \; ; \qquad (4.4)$$

$$\vec{R}_{sol} = \sum m_K \cdot (\vec{a}_{G_K} \cdot \vec{g}) \; , \qquad (4.5)$$

where: $\sum \vec{F}_{ext/R}$ represents the external forces applied to the body, *M* is the body mass, $\vec{a}_G$ is the acceleration of body's mass center, m_k is the mass of the *k* order bony segment, $\vec{a}_{Gk}$ is the acceleration of the *k* order bony segment, $\vec{G}$ is body's weight, $\vec{R}_{sol}$, the body reaction, $\vec{g}$ is the gravitational acceleration and, *K* the order of bony segment.

4.5.2. Gait. Definitions

The gait is a locomotors allowing to human to displace from a point to another. [Ola.98] It is a complex activity difficult to learn, once acquired, it is automatic, unconsciously performed [Win.91], [Vil.11]. Perry [Per.92], considered by Villalobos [Vil.11] as an authority in the domain of biomechanic analyze of the gait, considers the gait as a repetitive sequence of body's limbs (at each sequence, a synergic displacement of upper and lower limb is realized) with the aim of forward displacement of the whole body. The gait complexity is expressed in the multitude of theoretical and experimental researches related to it and, also in the multitude of its definitions. Gillet [Gil.04] defines the human gait as being the combination in time and space of different body segments movements, which allows the body displacement in horizontal plane. Ifrim and Iliescu [Ifr.78] define the human gait as a cyclic locomotion performed by forward displacement of a leg before the other. Baciu [Bac.77] defines it as the locomotion human body movement that uses as main mechanism the alternate constant movement of two lower limbs. During displacement, those play successively the support and propulsion functions. Radu [Rad.09] defines the gait as a displacement process of human body that, being in movement, is supported cyclic and alternately on one and on the two feet. Viel [Vie.00] appreciates the human gait as being a motor fundamental activity, which needs a difficult learning process. Lepoutre [Lep.07] considers that, from the biomechanical perspective, the gait is constituted by an assembly of lower limb segmental rotations, ensuring the body's locomotion (translation). As to perform the gait, after Oliver [Oli.98] and Gillet [Gil.04], the next conditions must be fulfilled:

- during the contact with the ground, the leg is almost longed;
- the limb contact with the ground is done by the heel;
- during the different phases of the gait the dynamic balance must be ensured;
- instant coordination of body propulsion conditions with the environment conditions. In this sense, Baciu [Bac.77] shows that the internal forces F_{int} must defeat the resultant *R* of external forces (gravity *G* and air resistance F_{air} oposed to gait), acting on the body mass center, for gait (fig. 4.31). besides the resultant *R* the ground adherence is acting;
- biped posture is standing.

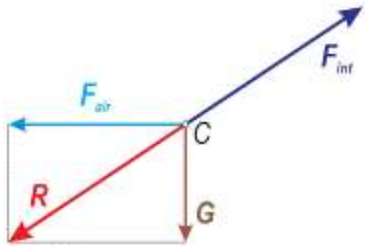


Fig. 4.31. Forces acting on body mass center during gait: F_{int} - internal forces resultant; R – external forces resultant; C – body mass center; F_{air} – air resistance, and G – body weight, after [Bac.77].

The gait can be performed in two ways [Hel.05], [Bac.77]: static, during which the static balanced is permanently ensured and, dynamic, during which the environments produces unbalance, i.e. non-plane support surface. Heliot and Pissord-Gibollet [Hel.05], Dao [Dao.09] show that gait associated movement can be decomposed in the three reference planes: sagittal, frontal and, transversal. Main movement is in the sagittal plane, while particular movements, i.e. pelvis movement or foot position are in the others planes.

4.5.3. Gait phases

The functional unit of the gait is the double step. This is composed of all movements performed between two successive support states of the same foot. [Ifr.78] Physically it is represented by the distance between the heel contact point of a foot with the ground and its next contact [Rad.09], measured along the antero-posterior axis [Oli.08]. The right lower limb gait cycle is conventionally considered as reference element. [Lep.07] The double step consists of two successive simple steps. A simple step is represented by the distance between the contact point with the ground of a foot and the contact point of the other, during bilateral support. Gait cycle is described by successive, repetitive movement phases. [Lap.07], [Bac.77] In the literature (Perry [Per.91], Radu [Rad.09], Faivre [Fai.03], Lepoutre [Lep.07], Olivier [Oli.08], Gasq et al. [Gas.12], Ayyappa [Ayy.97], Ayyappa [Ayy.97.a], Gillet [Gil.04], Dugan and Bhat [Dug.05], Novacheck [Nov.98], Rodgers [Rod.88], Armand [Arm.05], Soutas-Little [Sou.12], Õunpuu [Õun.94], Hayot [Hay.06]) it is decomposed in two principal phases (periods) (Fig.4.32 and Fig.4.33):

1. Stance phase – approximately 60 % of the cycle;
2. Swing (oscillation) phase – approximately 40 % of the cycle.

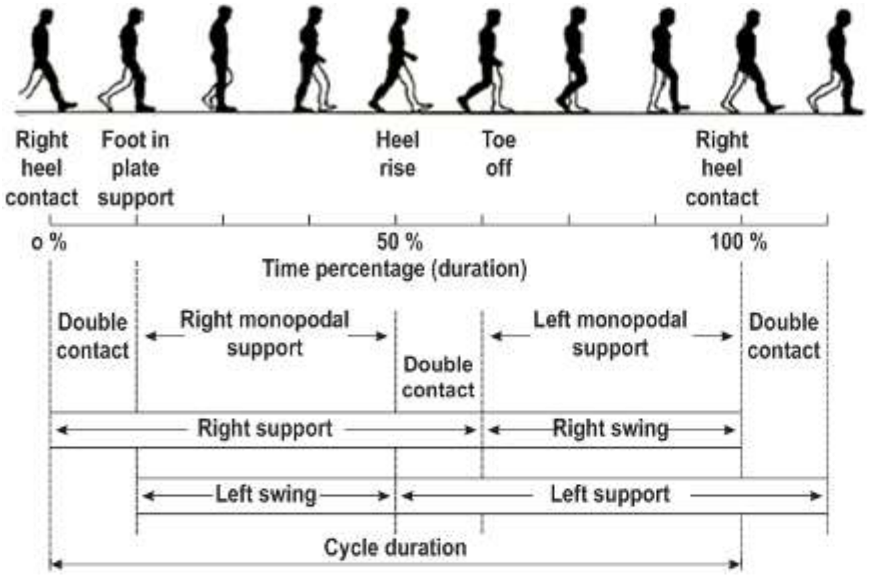


Fig. 4.32. Gait cycle, after [Vie.00].

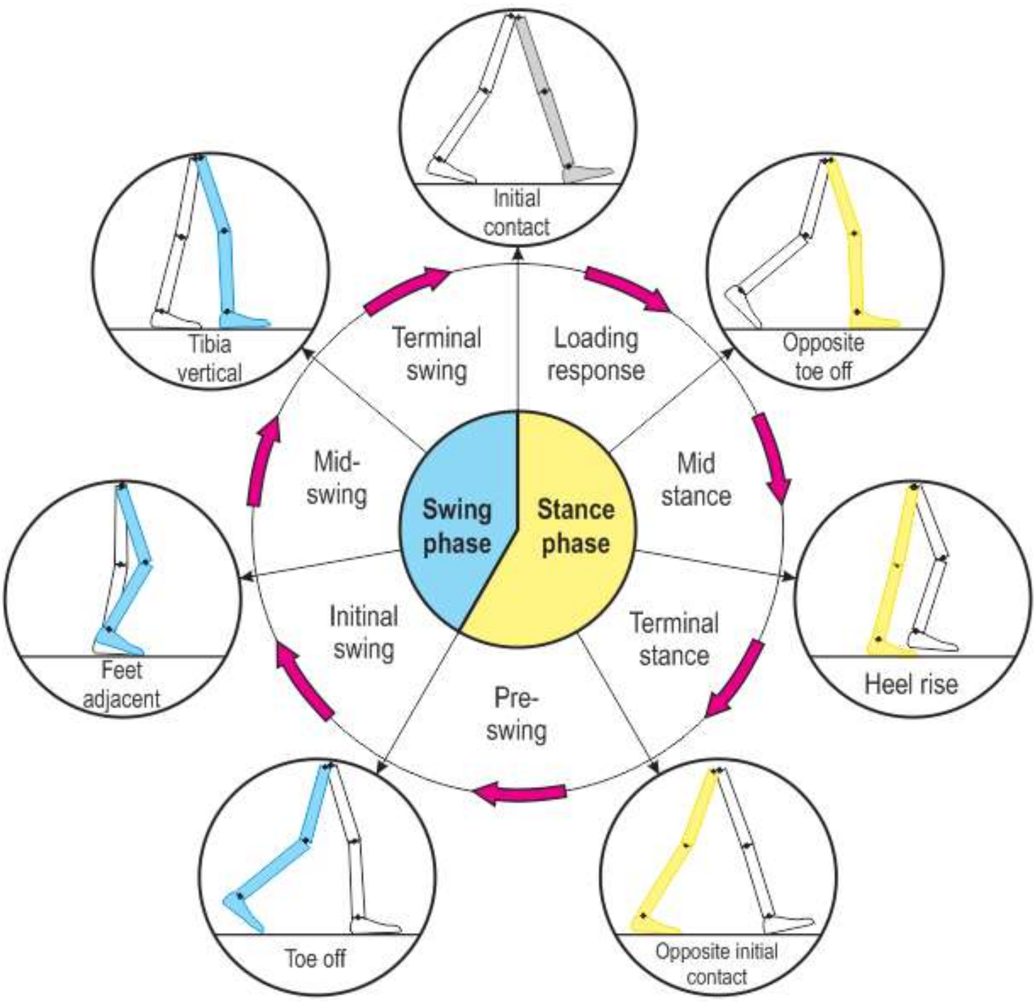


Fig. 4.33. Gait cycle, after [Whi.02].

During gait, these two phases alternate for a single limb and superpose for the two limbs. [Gil.04], [Sou.12] Thus, while the two feet (right and left) are in stance state, the bipodal support or double contact is defined [Arm.05], and when one foot is in stance and the other in swing, the monopodal support is defined.

The stance phase is when the foot is in contact with the ground. It can be decomposed (fig. 4.32) in three parts: two phases of double contact at the beginning and at the end of stance phase and, between them, a monopodal stance phase. During the double support, both feet are in contact with the ground: a finger contact when the foot leaves the ground and, respectively an approach of the ground by a little part of the heel.

Swing phase is the laps of time when the foot is no more in contact with the ground and it oscillates as to initiate the next contact. That means [Gil.04] that the swing phase begins in the very moment when the supporting foot leaves the ground and becomes an oscillating one.

In literature, the gait cycle is divided in many sub-phases (table 4.3) according their characteristics. Is very interesting the presentation of double step done by Ifrim and Iliescu [Ifr.78], formed by six phases (fig. 4.34): I – damping, II – the moment of vertical support leg, III – impulsion, IV – posterior step, V – the moment of vertical swimming leg and, VI – anterior step of swimming leg.

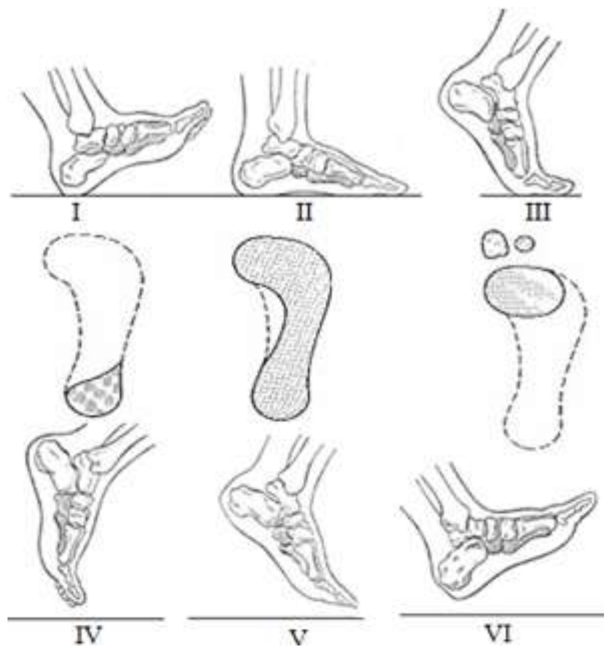


Fig.4.34 Representation of the foot during gait, after [Ifr.78], [Lep.07].

Table 4.3. Phases of gait cycle.

Author	**Gait cycle**		
	Stance phase	Swing phase	Total number of sub-phases
	Number of sub-phases		
Radu [Rad.09]	5	3	8
Faivre [Fai.03]	5	3	8
Gillet [Gil.04]	3	1	4
Lepoutre [Lep.07]	4	3	7
Ayyappa [Ayy.97]	5	3	8
[*Lam.12]	4	4	8
Dugan si Bhat [Dug.05]	4	3	7
Novacheck [Nov.98]	4	3	7
Õunpuu [Õun.94]	4	3	7
Perry [Per.91]	5	3	8

4.5.4. Gait parameters

Gait evaluation must ensure the next three phases [Fai.04]:

1. Direct observation by experimental observers – global, relative or directioned;
2. Description where the data obtained by measurement, video vision etc. are presented;
3. Biomechanical analyze concerning different parameters: temporal, spatial, cinematic, cinetic, energetic etc.

4.5.4.1. Spatial – temporal parameters

The gait cycle is described with respect to space and duration. [Ded.11] For biped locomotion, the spatial – temporal parameters are frequently analyzed because they are globally characteristic for the gait. The principal parameters are [Rad.09], [Oli.08], [Fai.03]: step length, step frequency and plantar mark on ground.

The step length is dependent on the lower limb dimensions and on impulsion, having the mean values of 0,63 m for men and of o,5 m for women. Step description must be reported either to the strait displacement (fig. 4.35) and either for the curved trajectories (fig. 4.36).

The step width is defined as medio–lateral distance between a point of the left foot and the homolog point of the right foot measured at heel level for a medium speed (fig. 4.35 and 4.36).

The cadence or the frequency represents the number of steps performed during a minute. The subject height, sex and age influence the frequency, which is accelerated for the persons with a height less than the normal mean.

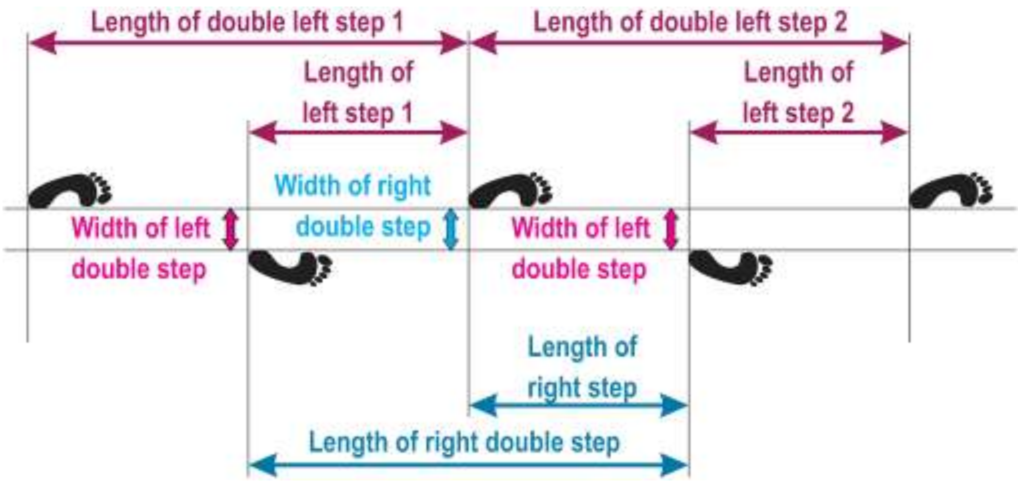


Fig. 4.35 Spatial parameters of the gait, after [Oli.08].

The gait speed express the subject's length of displacement during a unit of time. It can be defined as the product of step length and the cadence. Between the displacement speed and the steps frequency is a curved relationship and, thus, it is not possible to obtain speeds by multiple combinations of step length and its frequency. Plantar marks on ground (fig. 4.35 and 4.36) make evident two gait characteristics [Rad.09], [Oli.08]: the marks are not placed on a straight line and, the feet tips are outside oriented.

The double stance duration, expressed in seconds or in percentage of gait cycle is defined from the mean gait double stance duration and analogous for the simple stance duration. [Gas.12]

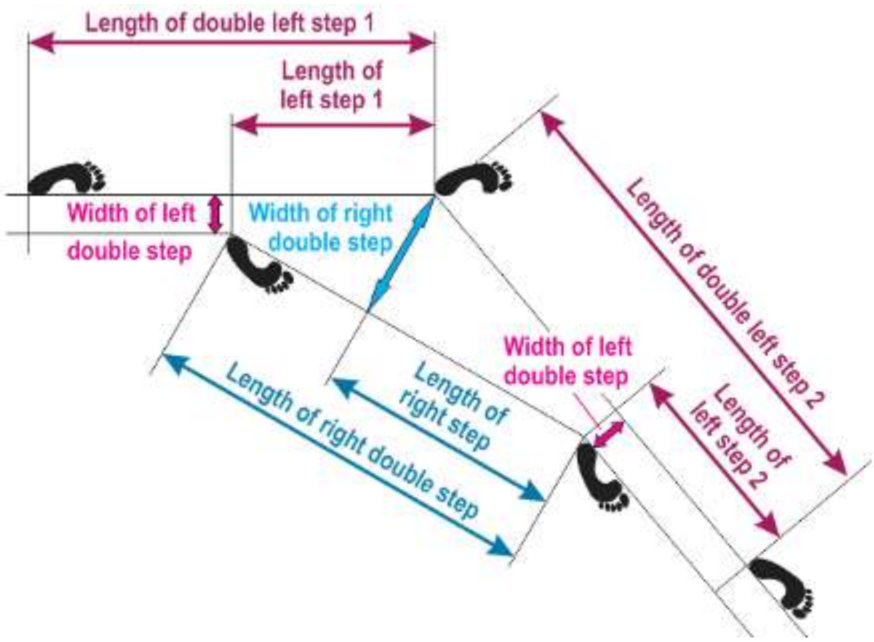


Fig. 4.36. Spatial parameters of curved locomotion, after [Oli.08].

4.5.4.1. Cinematic parameters

Basically, the movement cinematic describes or quantifies the movement in respect with oscillations (little displacements}, speeds, accelerations, as well as angular evolutions of different lower limbs moving joints. [Ded.11]

The biomechanic analyze shown that the gait is a continuous movement associated with multiple oscillations. During gait, the mass center of a body displacement is not linear but, it performs a series of vertical, lateral, forward and backward oscillations. As a consequence, the mass center describes a sinusoidal trajectory in the plan of the movement.

Vertical oscillations are justified by the difference between the height in single stance, when the legs are straight and the double stance, when both legs are oblique. In these conditions, in the first phase the mass center is in the highest position and in the next one it is lowered at the lowest level. Lateral oscillations are the consequence of movements designated to maintain the body's equilibrium during simple stance, phase in which the support base is represented only by the foot surface (fig. 4.34 I, II and, III). For equilibrium, the mass center vertical must be inside the support base and this condition is satisfied by a lateral displacement of the pelvis through the supporting limb. [Ifr.78] Thus, the mass center oscillates to right and left on the supporting limb, in the same time with pelvis and trunk. The two displacements of pelvis and trunk give an oscillating aspect to gait. Lateral oscillation is equal to zero during the double stance.

The gait corresponds to a cyclic, coordinated and autonomous muscular activity [Gas.12] guided by nervous cortical centers. The most important contribution to this movement is brought by the lower limb muscles (Table 4.4) that act on limb joints: coxo-femoral joint, knee joint and ankle joint. During the gait cycle, these joints have particular cinematic characteristics (Table 4.4, fig. 4.37 and 4.38).

Table 4.4. Lower limb muscular activities during gait cycle, after [Bac.77], [Ifr.78].

Muscular group	Stance phase	Oscillating phase
Pelvis stabilizator muscles, Mean gluteal muscle	+	-
Hip flexors	-	+
Knee extensors, Quadriceps	+	-
Knee flexors, Ischial muscles	-	+
Tibial anterior muscle	-	+
Foot extensors, Triceps surreal	+	-

In the present, linear and angular displacements of joint bony segments are calculated by the cinematic. The cinematic calculus needs, after Lepoutre [Lep.07], the modeling of lower limb anatomy as to describe the joint movements. In this aim, to each segment mass center is attached an orthogonal reference $R_K = (O_K, \vec{X}_K, \vec{Y}_{K,} \vec{Z}_K)$, with $\vec{X}_K, \vec{Y}_{K,} \vec{Z}_K$ axis (fig. 4.37). Each system is reported to a fixe reference $R_0 = (O_0 \ , \vec{X}_0 \ , \vec{Y}_{0,} \vec{Z}_0)$ placed on ground. The lower limb movements are modeled with respect of these references.

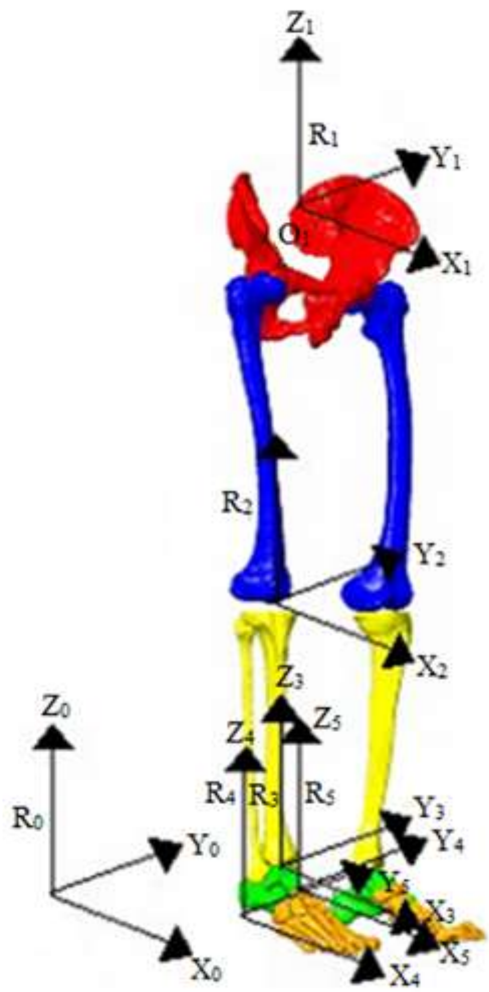


Fig.4.37. Orthogonal references used for lower limb anatomic modeling: R_0 - fixe reference, R_1 - the pelvis, R_2 – femur, R_3 is tibia, R_4 is the system astragal – heel, R_5 are the metatarsus and anterior tarsus, after [Lep.07].

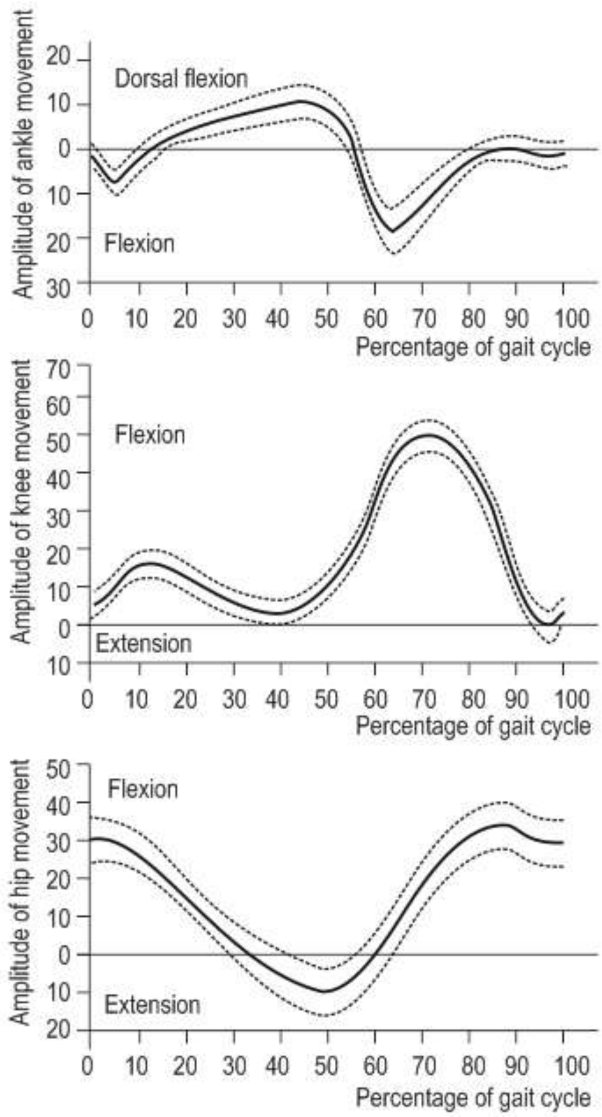


Fig.4.38. Joint trajectories of ankle, knee and, hip: continuous line – the mean value for the population; dotted line – deviation, after [Hel.05].

Table 4.5. Principal cinematic parameters of lower limb in sagittal plane during gait, after [Gas.12]

	Initial contact and transition to double stance	**Single stance phase**	**Propulsion double stance**	**Oscillating phase**
Hip	Flexion 30°	Transition to 10°extension	Recovery of neutral position	30° flexion
Knee	0° extension followed by 20° flexion (damping)	Recovery of complete extension	0° ÷ 30° flexion	0° ÷ 30° flexion and transition to extension
Ankle	Neutral position at 0°	Dorsal flexion	0° ÷ 20° extension°	Return to 0°
Foot	Heel contact	Support on sole	Support on fingers	
Functions	Charging and damping	Supporting charging and progress of tibia	Propulsion Limb preparing for progress	Flexion of limb for step

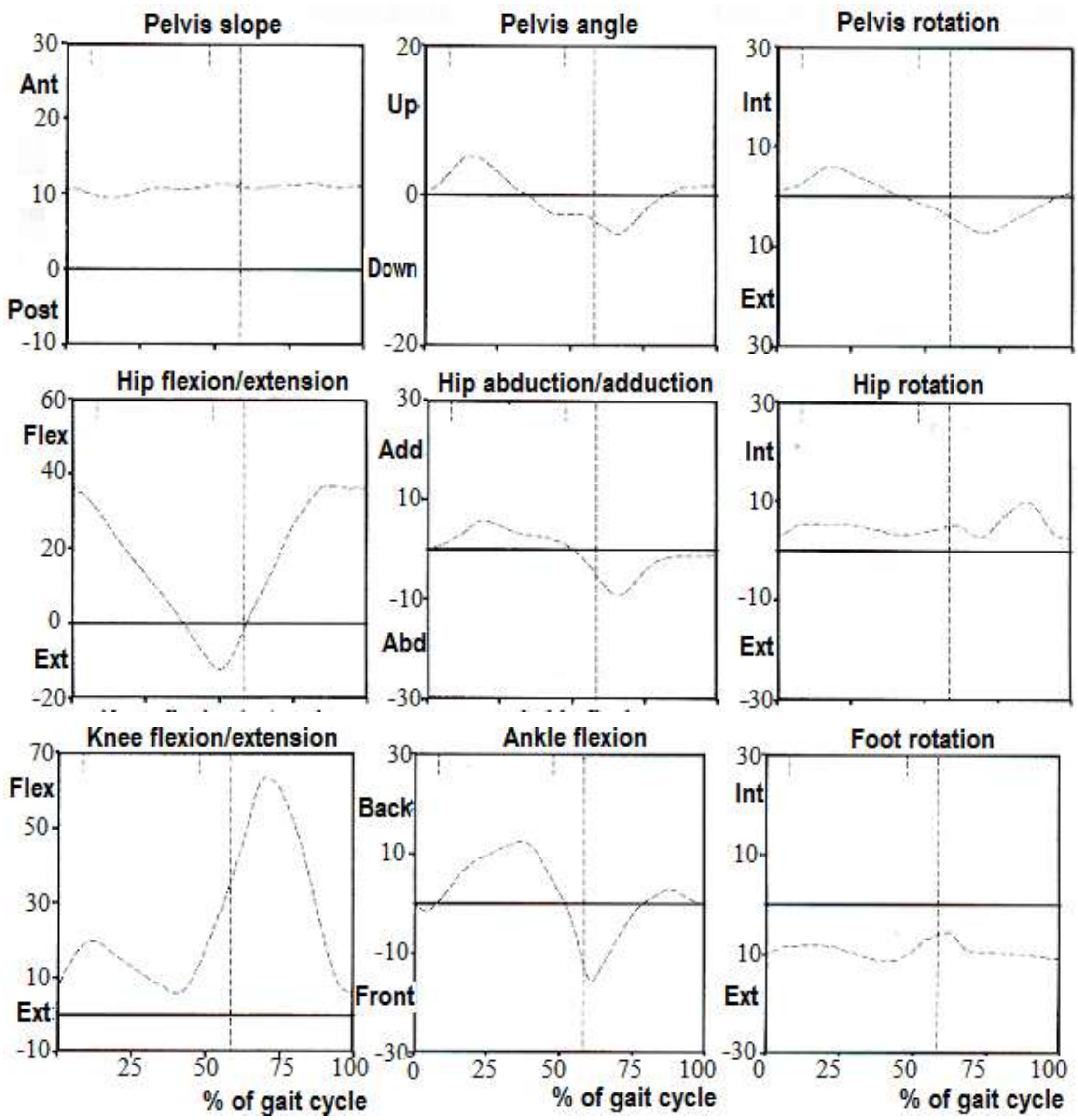


Fig.4.39. Normal gait cinematic parameters, after [Lep.07],[Vie.00].

4.5.7. Kinetic parameters

By definition, the kinetics represents the study of external and internal forces generating the locomotion. [Ded.11], [Fai.03] Joint function analyze (hip, knee, ankle and, foot) is based on fundamental equation of dynamics, which express the proportionality established between forces and moments that interfere in gait process and, linear and angular accelerations. [Oli.98]

Sensitive anatomic and functional characteristics of joint expressed by the necessity to maintain the contact of mobile parts through the ligaments, by movements generating through muscles action etc. lately contributed to the development of non-invasive investigation methods. They allow to measure many secondary categories as: lower limb segment in-space displacement, ground reaction force to the contact with the foot and, electric activity levels of lower limb muscles.

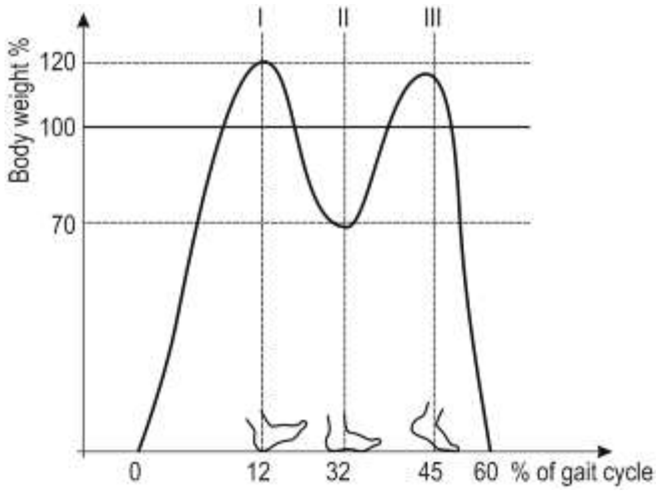


Fig. 4.40. Ground reaction force normal component on foot in stance phases: I, II and; III, after [Lep.07].

Ground reaction force acting on the foot, has an important role in lower limb modeling by inverse dynamic method. [Rad.09] It is specifically represented in gait stance phases (fig. 4.40). It is to note that, during initial contact and during charging, the magnitude of ground reaction force normal component increases rapidly till 1,1÷1,3 of body weight, whose value depends on body's speed. [Rod.88]

4.6. Biomechanics of the Race

4.6.1. Running phases

Besides walking, the race is a natural means of human body locomotion in space. It presents the next mean characteristics [Ifr.78], [Lab.06], [Sas.06], [Ton.12]:

1. is a form of cyclic movement that allows a faster displacement of the human body;
2. as for walking, running is determined by the interaction of internal and external forces;
3. in terms of the biomechanical, it occurs through an aerial body launch (Fig.4.41) during translation, by alternately (successive) pass of a lower limb in front of the other. Thus the runner has a periodic contact with the ground, with one foot only that produces the mono-contact phase. Consequently, during the race, the human body goes forward in translation by a succession of jumping called flight phases (that replace the bilateral support) alternated by mono-contact support. [Lou.12], [Lab.06], [Buc.11], [Ifr.78]

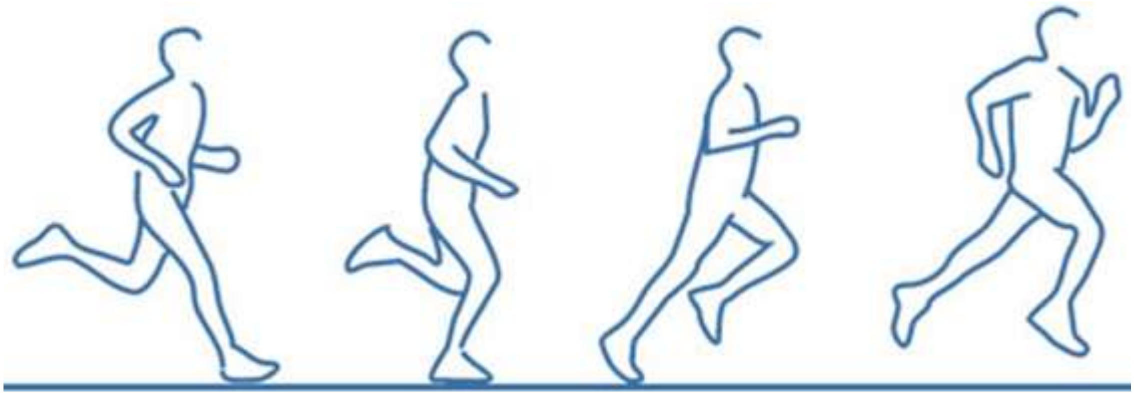


Fig. 4.41. Race and its components: dumping (a); verticality (b); impulsion (c); flying (d), after [*Bie.12]

The two lower limb, left and respectively right, fulfill successively two basic functions: unilateral support, and flight or oscillation function.

In these conditions the race is divided in two basic periods [Dug.05], [Ifr.78], [Bac.11] (Fig.4.42):

1. the support period when the runner foot is in contact with the ground (fig. 4.41) by: heel (generally, the support starts with its external side), sole of the foot, fingertips etc.;
2. the flying period, following the support one, when the runner has not any contact with the ground. In terms of biomechanics, during this phase, the runner cannot perform any motor action, while its mass center describes a trajectory in gravitational field and, thus it is impossible to interfere on trajectory.

The support period is composed of three phases (sub phases) [Õun.98], [*Bie.12], [*Teh.12], [Bac.77]:

- dumping or absorption phase in which the foot exerts on ground a pressure force motor, skewed, oriented forward and downward (Figure 4.43, a) in the form of an impact action. During dumping, the ground in its turn, exercises on runner body a reaction force (impact) inverse to the displacement. It was shown (Louis [*Lou.12]) that the runner's body balance during dumping is dependent on specific sensitivity of the bones, muscles and tendons of lower limb;

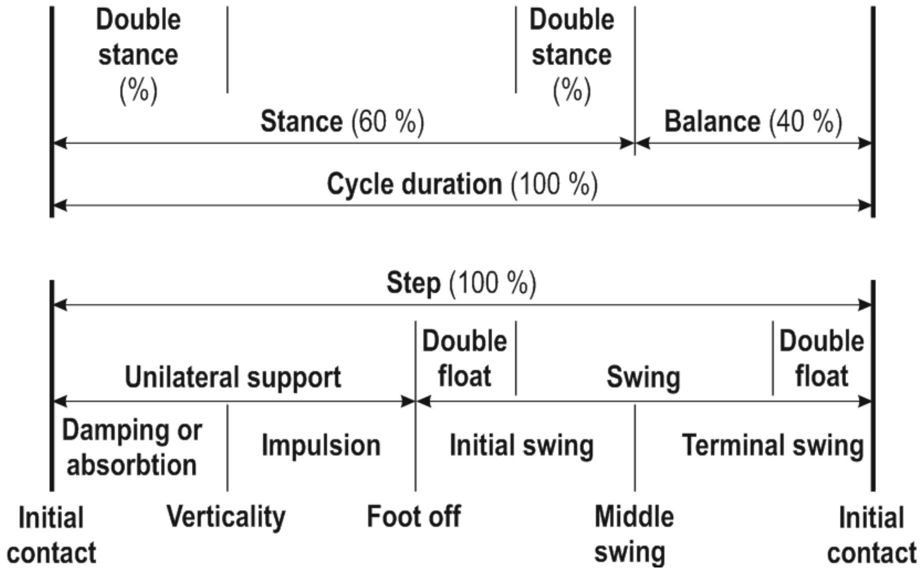


Fig. 4.42. Comparison between cycle phases: gait (a); running (b), after [Õun.94].

- the verticality corresponds to the moment when the body's mass center is placed on the vertical of the of contact point with the ground (Figure 4.43, b). In this phase it is possible the evaluation of the race altitude value;

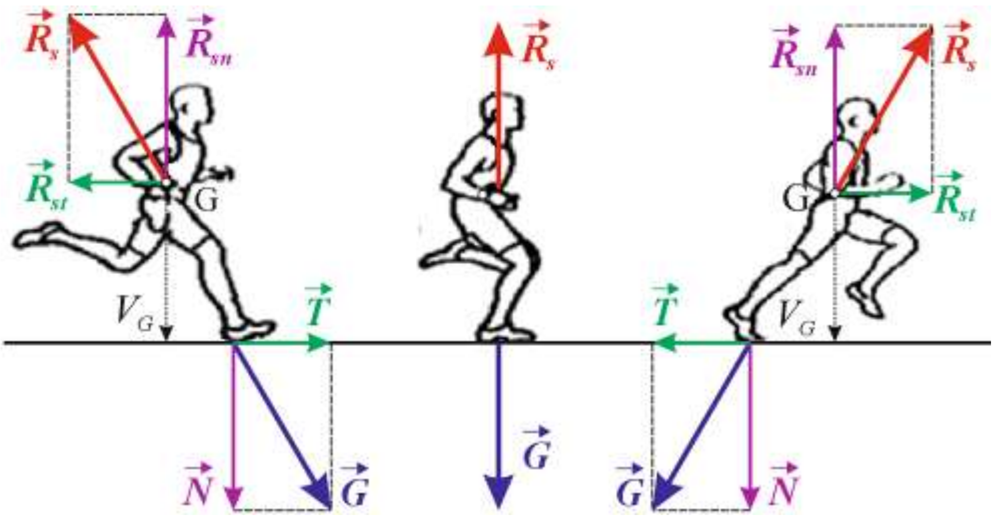


Fig. 4.43. The forces acting during support phase: *G* – runner weight; *N* – normal component of the weight; *T* – tangential component of the weight; R_s – ground reaction; R_{sn} – normal component of ground reaction; R_{st} – tangential component of ground reaction, after [Ifr.78], [Luc.12]

- the propulsion phase, defined as the horizontal acceleration of the body's mass center [Sas.06], when the runner press the ground on a skewed direction, backward and downward (Figure 4.43, c). It is the most important in running mechanism because it is the principal motor factor in running [Ifr.78], [Bac.77]. During this phase, the ground reaction is oriented in the sense of displacement, downward and forward. The sum of the body motor force with the of the reaction of the ground generates a motor couple that allows the body displacement.

From the biomechanic perspective, the impulsion is a dynamic phase in which any increase in the horizontal ground reaction force component leads directly to increasing the body's impulse. This characteristics is very important in efficiency evaluation. It is also mentioned that impulsion is highly dependent on surface hardness and on contact type of the foot with the ground – heel, sole or fingertips. [Lou.12.a] According to runner support position in report with its mass center position, two categories of running cycles can be defined [*Ful.12], [*Bie.12]: the *forward cycle*, when the support is located before the runner center of gravity, and *backward cycle*, when the support is almost located behind the runner center of gravity.

The flying phase is divided in three parts [*Bie.12], [Õun.98], [Bac.77]:

- initial, when the body is projected forward and upward due to the impulsion motor force;
- middle, which corresponds to the maximum high of body trajectory;
- terminal, when the body returns to the ground due to gravitational forces, acting on it.

4.6.2. Race parameters

As in the case of walking, the race can be analyzed with the help of the following types of parameters: 1 - space-temporal; 2 - cinematic; 3 – kinetic parameters.

4.6.2.1. Space-temporal parameters

The main parameters of space-temporal are represented by Louis [Lou.12], Dugan si Bhat [Dug.05], Ifrim si Iliescu [Ifr.78]: runner step; double runner step; race speed; amplitude, cadence, flight time (t_f) [Maz.12], support duration (t_s), the ratio between the time of flying and support duration. These parameters can influence, together with the runner morphological aspects characteristics, the cycle length.

The runner step (*simple*) constitute the cyclical race unit. It is formed of the two-legged phases during race, between two successive contacts from one foot to the other. These actions corresponds to a certain length of the running step. In comparison with the gait step, it is [Ifr.78] longer and has a shorter duration. The running step is directly dependent on race speed. [Bie.07]

The double runner step consists of successive phases carried out by the two feet during the laps of time between two identical moments of the same foot. Therefore it comprises two support periods and two flies, so includes two simple running steps.

The race speed (*horizontal speed*) is defined as the product of amplitude and the frequency (cadence) of running simple step. Thus, any increase of running speed is obtained by the increase of simple running step, followed by the increasing frequency. [*Lou.12.a], [Dug.05], [Ōun.94] It is known however, that the running frequency remains, in general, about the same. [*Bie.12] Assessment of space-temporal parameters can be done with temporal measurement systems, i.e. photoelectric cells and sensors fastened on the soles of runner.

4.6.2.2. Cinematic parameters

Race kinematics is influenced by two main parameters [Bie.07]: 1. characteristics and the number of running cycles (Fig. 4.41); 2. race speed. Works presented in the kinematics and dynamics of gait and race - Farley şi Ferris [Far.88], Sasaki and Neptune [Sas.06], Ifrim and Iliescu [Ifr.78], Novacheck [Nov.98], Rodgers [Rod.88], Chai [Cha.03], Õunpuu [Õun.94], present aspects that differentiates, in terms of kinematics and kinetic, the two locomotion movements: walking and running.

Table 4.6. Comparisons of kinematic and kinetic parameters of running and walking after [Bac.77], [Õun.94].

	Running	**Walking**
Entire cycle	swing phase longer	stance phase longer
Duration of stance phase	shorter	longer
Double support period	absent	present
Duration of swing phase	longer	shorter
Floating period	present	absent
Stride length	longer	shorter
Stride frequency	higher	lower
Position of body COM	lower	higher
Vertical oscillation of body COM	less	more
Linear and angular velocity of lower limb	faster	slower
Required ROM	greater	less
Muscle activities	greater	less
Leg drive during swing phase	muscular	momentum (pendulum)

Foot progression line	1 line along midline of body	2 parallel lines
Ground reaction force	2.5~3 times body weight	~90% of body weight

In terms of the kinematics and the running efficiency, the study of mass center behavior as well as of the movements performed by the lower limb components during support and flying, have great theoretical and practical importance.

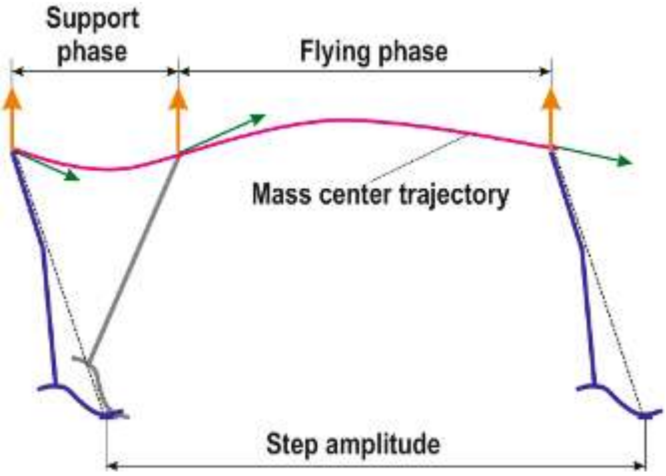


Fig. 4.44. Mass center trajectory in support and flying phases, after [Lou.12.a].

Thus, can be mentioned (Baciu [Bac.77], Blanchi et al. [Bla.12], Louis [Lou.12.a], Dugan si Bhat [Dug.05]) that during race the body mass center is moving on a sine curve within the support and flying phases (Fig. 4.44).

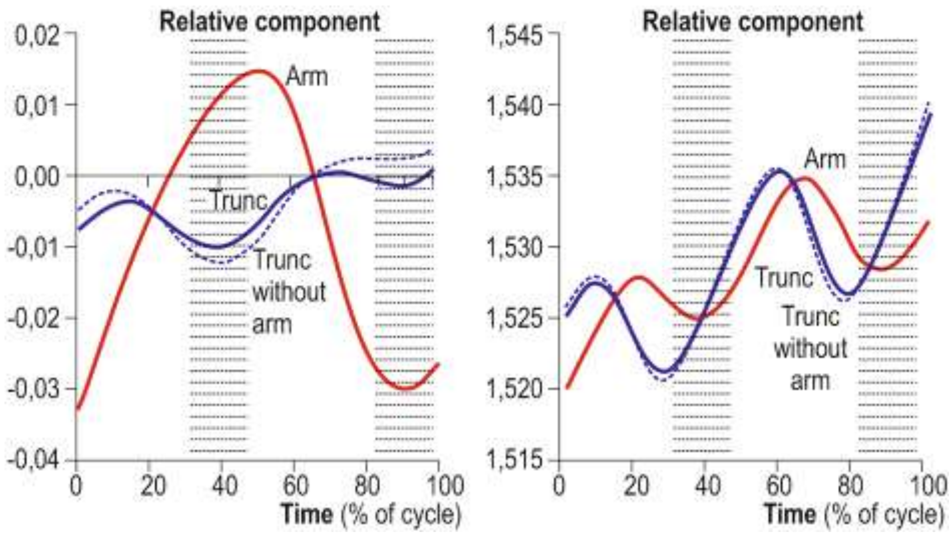


Fig. 4.45. Upper limb contribution to the global body's mass center at: transverse displacement (a); longitudinal displacement (b), after [Leb.06].

It is observed that during the period of the concave mass center trajectory – when it tends to fall forward, which ends with the transformation of the lower limb in motor (fig. 4.41, c) and for the convex flying period, the altitude is maximum in the mid of the phase. In mass center displacement, several movements of superior limbs and of the trunk interfere (fig. 4.45). Their characteristics are described in, Leboeuf et al [Leb.06], Ifrim and Iliescu [Ifr.78], Baciu [Bac.77].

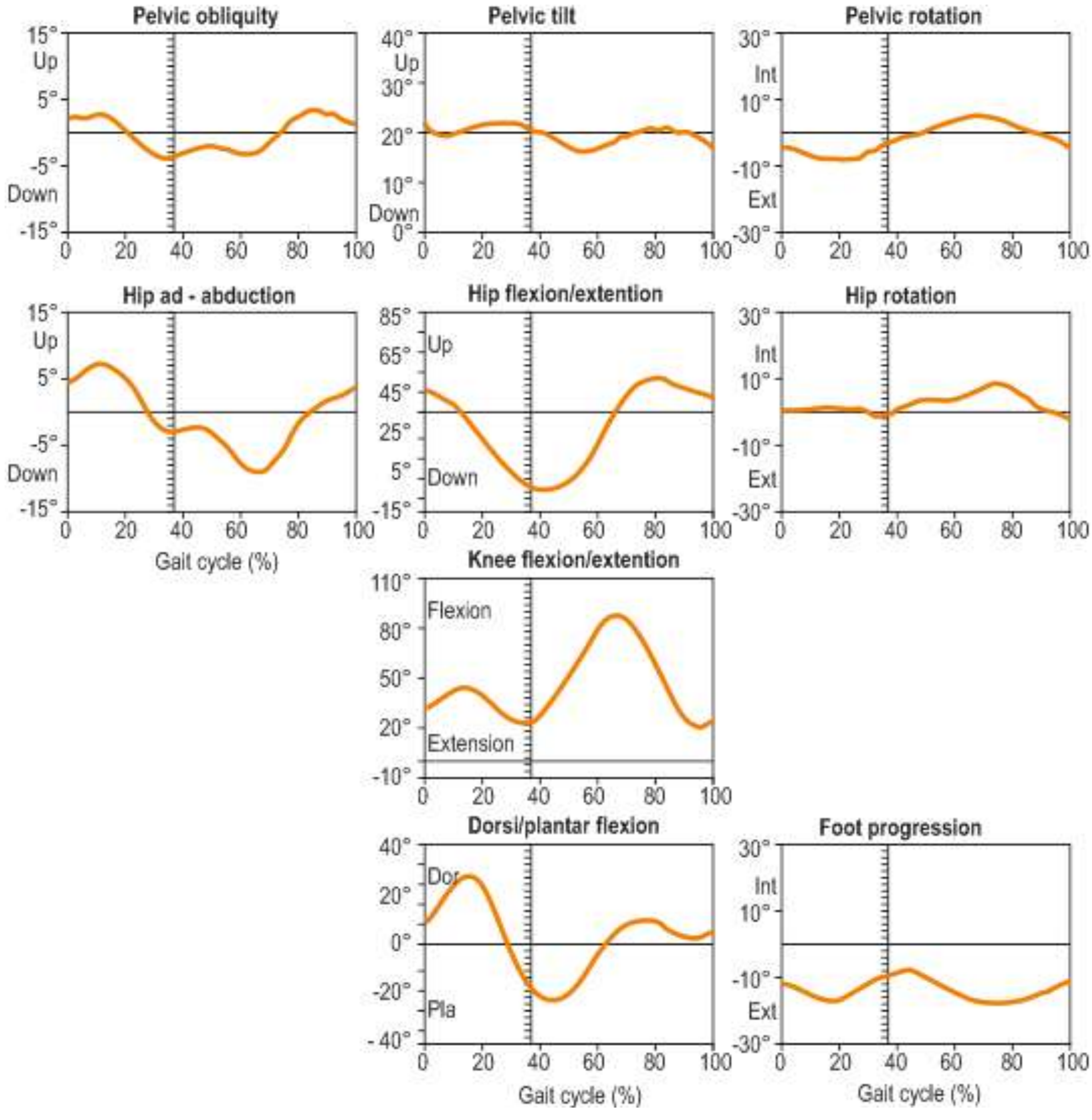


Fig. 4.46. Kinematic parameters of the race in three reference planes, after [Nov.98].

During race, the mass center performs vertical, lateral and transverse displacements determined by the following main categories of forces Baciu [Bac.77], Blanchi et al [Bla.12]: muscular motor force F_{int}, ground reaction force, body weight, friction forces in joints and muscles of lower limb, air resistance (relatively low) and, friction forces due to ground adhesion.

Because the balance of these forces action depends on the runner displacement speed, the mass center conditions of movement change.

Kinematics analysis of running aims to describe the spatial movements of pelvis, hip, knee, and ankle during the race. The projections of these movements are described in frontal, transverse and, sagittal planes. From this perspective, in figure 4.46 are presented, after Novcheck [Nov.98] (a similar one is in the works of Õunpuu [Õun.94]), the pelvis and hip (in the three planes of movement) performed during race. It is to note that in frontal plane the hip movement is significant.

4.6.2.3 Kinetic parameters

As in the case of gait, the study of race kinetic parameters is directed on following the main research directions:

- ground reaction force and its components – horizontal and vertical;
- vertical displacement of body mass center;
- lower limb stiffness.

Ground reaction force during race, after Farley and Ferris [Far.88], has the following characteristics (fig. 4.47):

1. graphic representation has a single peak, unlike the gait, where two peaks are present. This peculiarity is due to the presence of a single support phase, in which case the sub-phase of double support (like in gait) no longer appears;
2. at the beginning of support phase, the leg contacts the ground by an impact action, which results in a much higher magnitude of the normal component in comparison with the gait.

Biomechanical analysis of the mass center displacement and limb stiffness, during the race, in the specific literature (Mazet [Maz.12], Megoman et al [Meg.12], Farley and Ferris [Far.88], Ferris et al [Fer.98], McMaon and Cheng [Mcm.90], Divert [Div.05], Morin et al [Mor.05]) the *model spring – mass* is used (fig. 4.48). According to these works, the model is built with the following assumptions:

- the human body, having a fixe mass, is regarded as a deformable structure, with a linear dependency between the forces acting on it and its deformations;
- lower limb is equated to a resort, theoretical without mass;
- during the contact, the system oscillates vertically and horizontally in repport with contact point vertical direction;

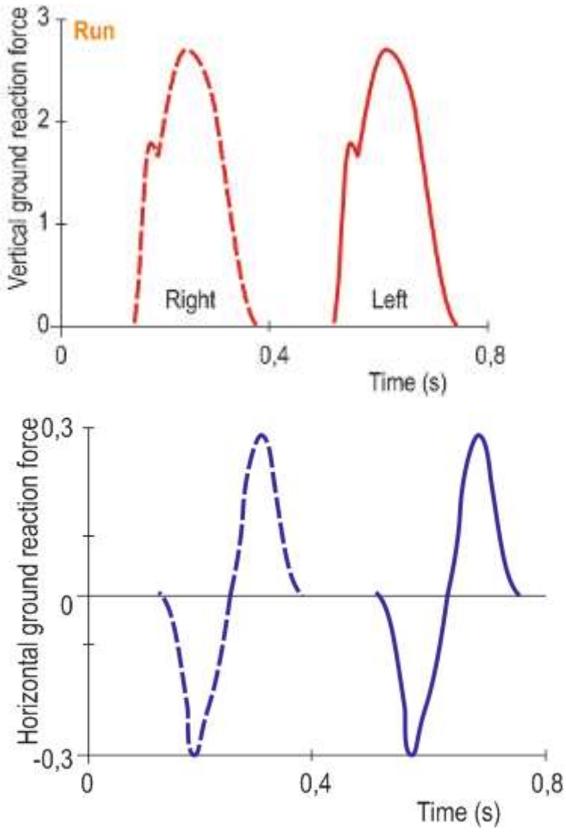


Fig. 4.47. The ground reaction force as a function of time for running in a human, after [Far.88].

- the compression maximal spring force is reached when the point mass lies on the vertical point of contact;
- oscillating period of spring-mass system is equal to the sum of support and fly times;
- vertical displacement of body mass center is determined by the maximum vertical component of ground reaction F_{sZ};
- the lower limb stiffness k_p is given by the ratio between maximal value of ground reaction vertical component and the variation Δ_L of its length during the support phase;
- it is necessary to consider the differences between the vertical oscillation of the body mass center, the vertical stiffness k_v and, the foot stiffness k_p.

Basically, stiffness calculus k_v and k_p, based on the spring-mass model, uses the following relationships [Maz.12], [Div.05], [Far.96], [Mem.90]:

$$k_v = \frac{F_{s,n,max}}{\Delta_z}\left[\frac{N}{m}\right]; \tag{4.6}$$

$$\Delta_z = \frac{F_{s,n,max} \times t^2{}_c}{m\pi} + g\frac{t^2{}_c}{8}[m]; \tag{4.7}$$

$$F_{s,n,max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_s}+1\right)[N]; \qquad (4.8)$$

$$K_p = \frac{F_{s,n,max}}{\Delta_L}\left[\frac{N}{m}\right]; \qquad (4.9)$$

$$\Delta_L = L - \sqrt{L^2 - \left(\frac{v \times t_s}{2}\right)^2} + \Delta_z\,[m]; \qquad (4.10)$$

$$\Theta = sin^{-1}\left(\frac{v \times t_s}{2L}\right)[arc], \qquad (4.11)$$

where: L is the length of lower limb; Δ_z is the vertical displacement of body mass center; Δ_L represents the variation of lower limb length, m is the body mass; t_s, the contact duration in support phase; t_f is the duration of the fly and, v, the race speed.

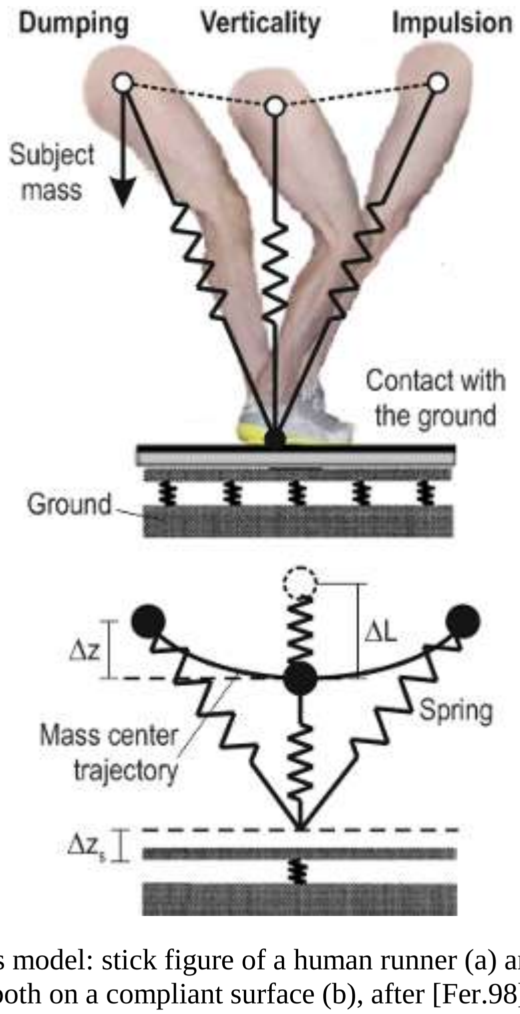


Fig. 4.48. The spring-mass model: stick figure of a human runner (a) and, the spring-mass model, both on a compliant surface (b), after [Fer.98].

The above presented calculi, allow to analyze the variables quantities Δ_z and Δ_L in comparison with their measured values. In the same time, they allow to analyze the vertical component of ground reaction force in respect to vertical displacements of body mass center during support phase.

From the diagram in figure 4.47 it is possible to observe that the value of ground reaction normal component in race is considerably greater than in gait (fig. 4.40).

4.7 THE BIOMECHANICS OF THE RUNNING AND THE SPRINT AT THE LEG AMPUTATED PERSONS WITH SPORTS PROSTHESIS

4.7.1 Characteristics

Tibia leg amputation is a surgical intervention by the removing, under the knee, a portion of leg at one or both legs. In the case of standard leg amputation, the level of choice of the amputation is of 12-19 cm (Fig. 4.49).

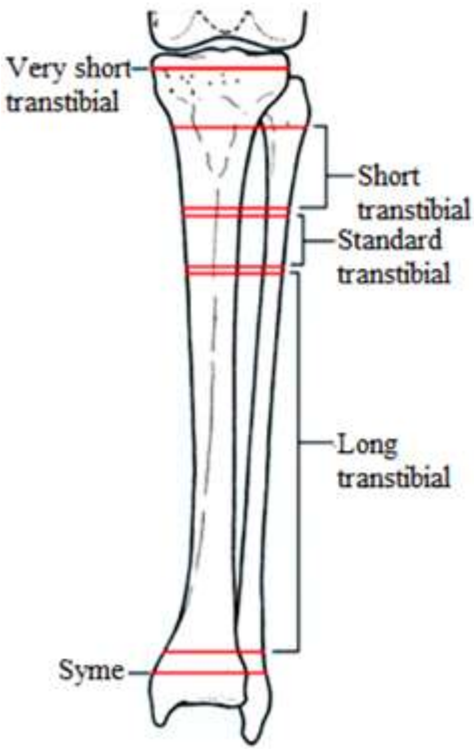


Fig.4.49. Tibia leg amputation, after [Leb.13].

The leg portion remained after the amputation is named amputation blunt. By amputation, the patient hasn't a part of tibia and fibula, the leg and the ankle and the leg muscles grouped around the tibia and the fibula are sectioned in the right of amputation section. In the same way it is happened with the ligaments. The sectioned muscles are constituted by the extensor group, the flexor group and the group represented by the long and short fibula. The tibia leg amputated person is able to continue different activities, from the work place, home, the sports domain, etc. if he will wear prosthesis. It is obvious that this has not the same functions as a real leg.

Fig. 4.50. The sports contests – running: normal sportsmen (a), and the sportsman with prosthesis on the both lower legs (b), after [*Lep.13].

In the leg prosthetics area, tibia leg amputated, it can use [Voi.12]: prosthesis with simple construction (Sach prosthesis, All Terrain Foot prosthesis etc.), prosthesis with energy storage and release, prosthesis with the adjustment of the angle between the sole and the rod, the bionic prosthesis. The technological innovation from biomechanics and biomaterials area has as the effect the construction of the sports prosthesis for the tibia leg amputated sportsmen from the athletics area: running and sprint [Pri.12], [Bid.09], (Fig.4.50): sport prosthesis feet, Springlite sprinter [*Pro.08], Flex-Foot Cheetah (With Lamination connector and with pylon connector), Flex-Sprint^{TM} [Oss.13] Flex-Run^{TM}. The world market is dominated by the Flex- Sprint, Flex-Foot Cheetah and C- Sprint prosthesis.

Such prosthesis is composed by the following components (Fig.4.51): the socket or the fitting sleeve, the intermediate sleeve and the prosthetic leg. This is represented by an elastic lamina with the shape, as the constructive solutions presented by the companies of this area. (Fig.4.52) [*Den.13]. The laminas or the prosthetic leg or dynamic [Pai.04] are fabricated by carbon, carbon fiber with aramid and glass fibers [Pai.04], [Öss.13]. These have a thickness of approximate 7 mm. The presence of the fitting sleeve and the intermediate sleeve offers much comfort for the runner. In this way, is obtained an increase of the training duration for the sportsmen. These prosthesis have a lot of characteristics [Not.13], [*Cmm.13] as: not produce energy and these only transmit the energy; against to the biological foot, the prosthesis doesn't fatigue; this allows the participation of the sportsmen at the running contests in the same conditions with the normal sportsmen; comparative with the biological legs, the prosthesis are, generally, lighter; at the start stage the prosthesis doesn't assure the performance that is met at the valid runners.

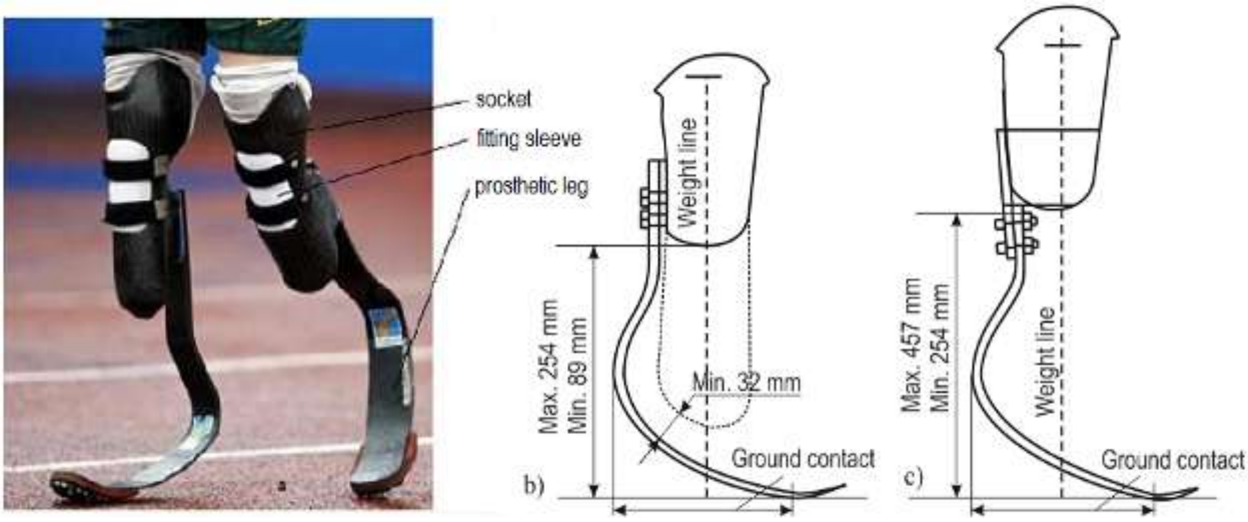


Fig. 4.51 Flex-foot Cheetah prosthesis, a. the prosthesis caught on the leg; b. prosthesis with laminated connector; prosthesis with pylon connector, after [*Lep.13].

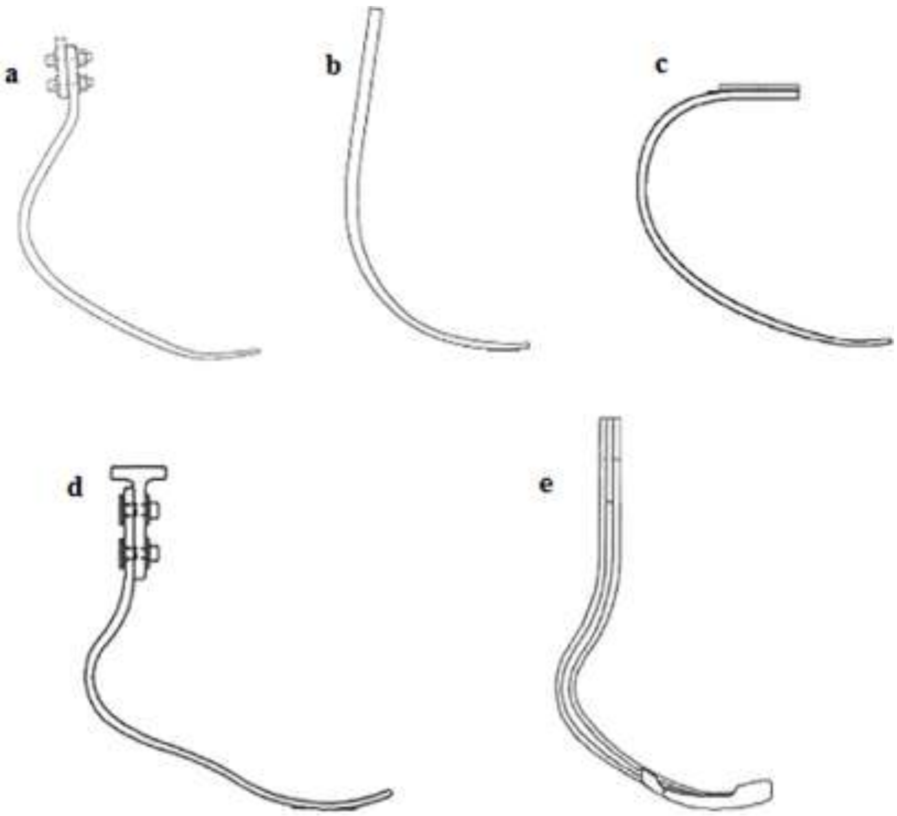


Fig. 4.52 The different sprint foot designs: cheetah (Össur) (a); flex-sprint (Össur) (b); flex-run (Össur) (c); sprinter (Otto Back) (d); sprint (Otto Back) (e), after [Nol.98]

4.7.2 The behavior of the sports prosthesis

In the case of tibia leg amputated sportsman, the running has the same stages (Fig.4.53) as the running of the normal persons (Fig.4.42): the support stage and the stride or the flight stage (Fig.4.53). The prosthetic leg or the dynamic leg [Pai.04], [Man.13], [Man 12], [Mcp.12] replaces the "tibia – fibula" segment and the foot. So, it has to take the locomotion function of these anatomic elements removed by the leg amputation.In the support stage of the running, the elastic lamina behaves in the following way (Fig.4.54):

a. in the damping stage it is contracted with a value determined by the elastic characteristics of the prosthetic leg in function of the body weight (Fig.4.54.a);
b. from the verticality stage, a process of the displacements of the energy stored to the elastic lamina peaks, starts (Fig.4.54.b);
c. the animus stage when the energy is stored at the lamina peaks. In this stage the energy generated at the not valid runner is the one produced by the gluteal muscles at the hip level. These muscles have to produce an energy twice as high than the valid runner. The stage is finalized by the forward propulsion of the runner body.

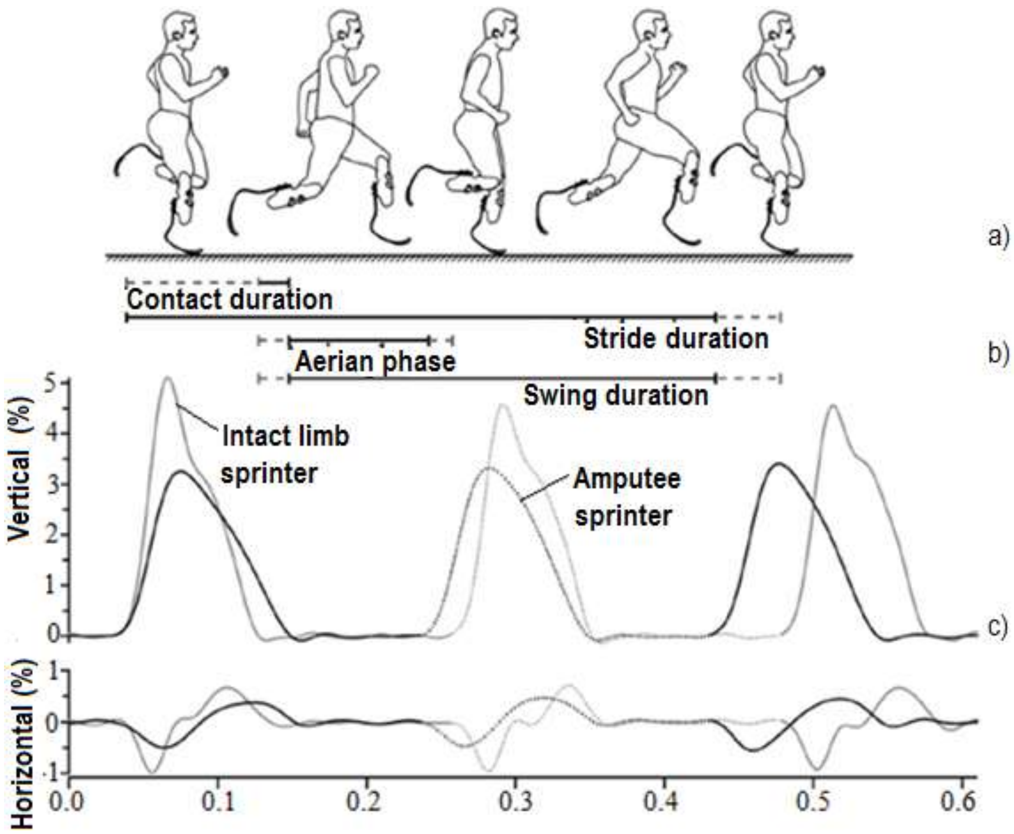


Fig. 4.53. The representation of the running (sprint) cycle at the tibia leg prosthesis runners, Flex-Foot-Cheetah:a- the running stages; b- vertical ground reaction; c- horizontal ground reaction, after [Wey.09,10]

4.7.3. The kinematics parameters

In the case of the leg prosthesis design (tibia leg prosthesis) it follows a set of characteristics corresponding to the walking or running executed by a valid person [Das.09], [Dru.11]:

- the return of the energy generated in the support stage;
- the motion of dorsal flexion (dorsiflexion);
- the ankle torsion;
- the energy and the inversion of the leg, executed [*Ari.13] around an axis with triple obliquity: up – down, foregoing – posterior, medial-lateral;
- the adsorption at the contact with the ground.

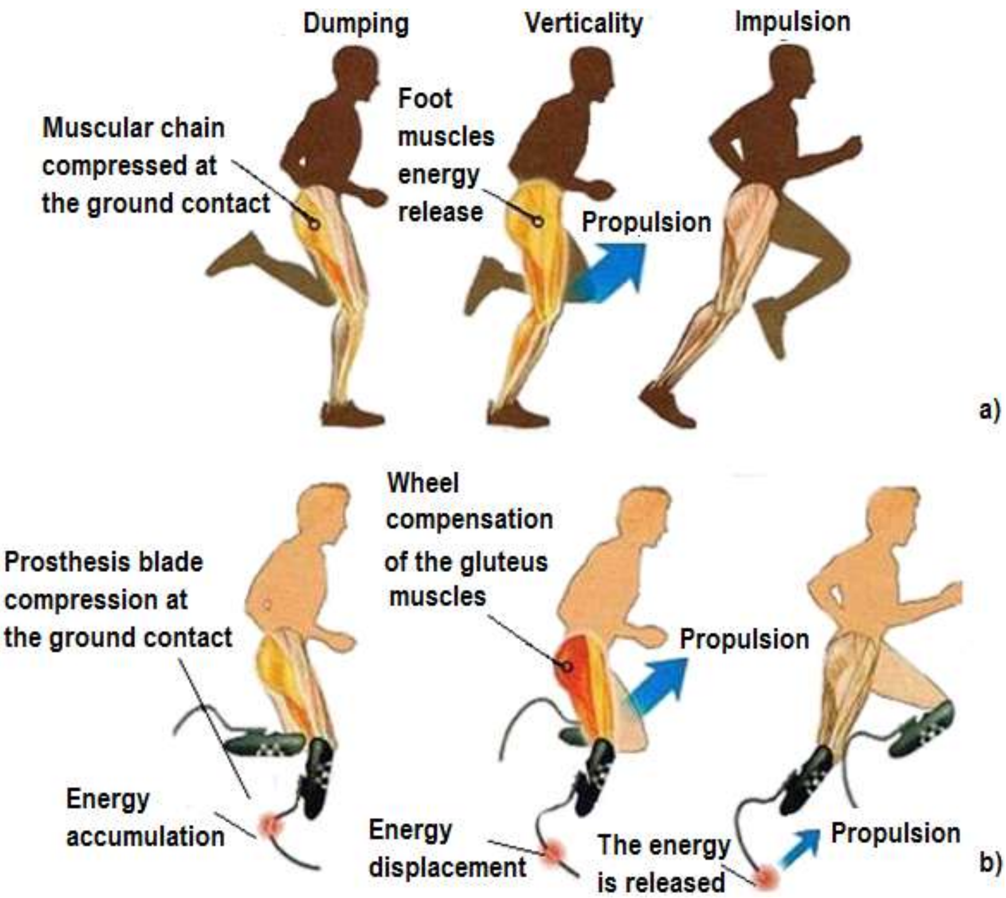


Fig. 4.54. The mechanism of the energy storage and release during the support stage at the running, after [*Com.13].

For the case of Flex-Foot Cheetah prosthesis type it takes into account the following particularities [*Com.13], [Wey.10], [*Oss.13].:

- the prosthesis has not heel;
- the prosthetic leg reproduces, during the running the support and the stride stages that are met in the case of the valid leg;

- at the final of the support stage, the elastic lamina takes back the original shape releasing the stored energy, by the propulsion of the body forward.

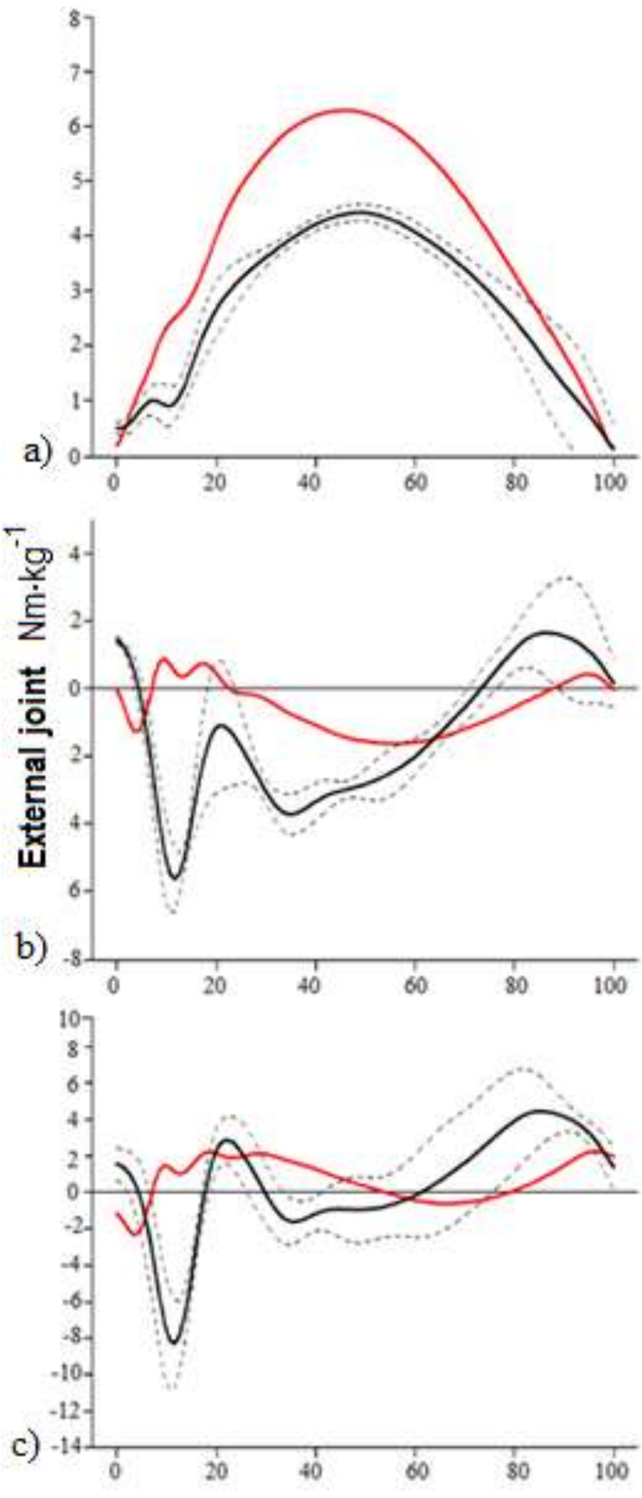


Fig. 4.55 The external moments in at the ankle, knee and hip during the support stage at the running , for the both tibia leg amputated runners: a- external dorsiflexion-plantar flexion ankle joint moment; ,b- extension-flexion knee joint moments;c- extension flexion hip joint moments, after [Brü.08].

These characteristics influence the kinematics and the kinetics of the running in the case of the valid and the prosthetic persons. So, the biomechanical researches elaborated, Brüggemann

[Brü.08], [Brü.07] Buckley [Buc.00], highlighted different aspects in the motion kinematics during the support stage of the running, at the ankle level (external dorsiflexion, external plantar flexion), of the knee (extension – flexion) and of the hip (extension – flexion). These differences are presented in the figure 4.55. Some researches regarding the tibia reaction force of the hip (at the running) Brüggemann [Brü.08], Buckley [Buc.00] highlighted that its value is lower in the case of the tibia leg prosthesis runner comparative with the valid runner.

CHAPTER **5**

METHODS FOR ANALYZING THE BEHAVIOR OF CARBON FIBER REINFORCED EPOXY COMPOSITES BIOMATERIALS USED IN THE CONSTRUCTION OF J PROSTHETIC BLADES

5.1. J BLADES MANUFACTURING PROCESS FEATURES

J blades are manufactured from epoxy composites reinforced with carbon fibers. Their form is a technological novelty in the field of sports prostheses for transtibial amputations, wherefrom the few published information concerning the manufacturing process and material characteristics testing methods used for their conception and use. In the literature of prosthetic prostheses for transtibial amputations is mentioned that the prosthetics blades J have personalized construction to amputee. Thus, constructive-functional characteristics of the blade, as i.e. the flexibility, are determined in function of mechanic carbon fiber properties (Annex 2), by runner weight, developed muscular force, if he needs one leg or two legs prosthesis. [Pai.04], [Man.12] For this thesis research the model of blade presented in figure 5.1 was designed. It can be used for transtibial amputees with the maximum weight of 50 kg. This variant is manufactured in 4-8 mm thickness range of multilayered material.

The J blades can be executed in two constructive variants:

1. one piece;
2. multilayered.

Design and technological process of carbon fiber/epoxy composite aims the following objectives: [Pet.98], [Pai.04], [Rou.05], [*Gui.12].

- carbon fiber contribution: fiber mechanical properties, fiber volume, fiber orientation inside the composite;
- internal stresses reduction correlated to the fiber – resin interface;
- the smallest weight;
- minimal cost.

These objectives are correlated with blade configuration and dimensions, with manufacturing tools and, with technological process.

Taking into account all these conditions, two technological process are recommended for the J blades manufacturing [*Glo.06], [Lec.99], [*Fab.13], [Şer,96], [Man.86], [Nis.80], [Das.09]:

- injection casting by RTM (Resin Transfer Molding) processing;
- fabrication of multilayered material of pre-impregnated blades subjected to polymerization process.

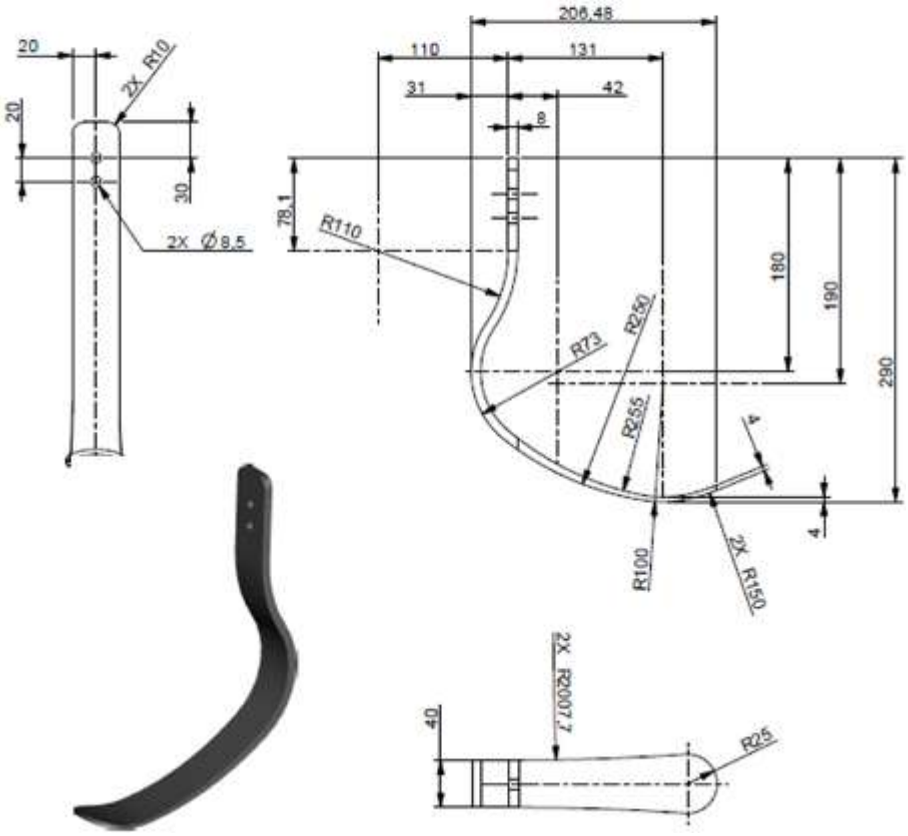


Fig.5.1. Design of prosthetic J blade.

The choice of RTM manufacturing method and of "*prepreg*" technological process is justified, in comparison to other manufacturing processes, by performance-production volume ratio (Fig. 5.2).

The use of pre-impregnated composite material for prosthetic leg fabrication and, generarily, for transtibial prosthesis is justified, in our days, by a series of advantages in report with classical procedure for composite manufacturing process, including RTM [Kla.95].

The technique to obtain the pre-impregnated material consists in impregnating a carbon fiber fabric with epoxy resin, followed by a partial polymerization. [Nis.80], [*Hex.13] The final form is usually obtained in autoclave or vacuum bag. The pre-impregnated material polymerization can rapid for thin parts and slow for large and thick ones [Hex.13], [Das.08].

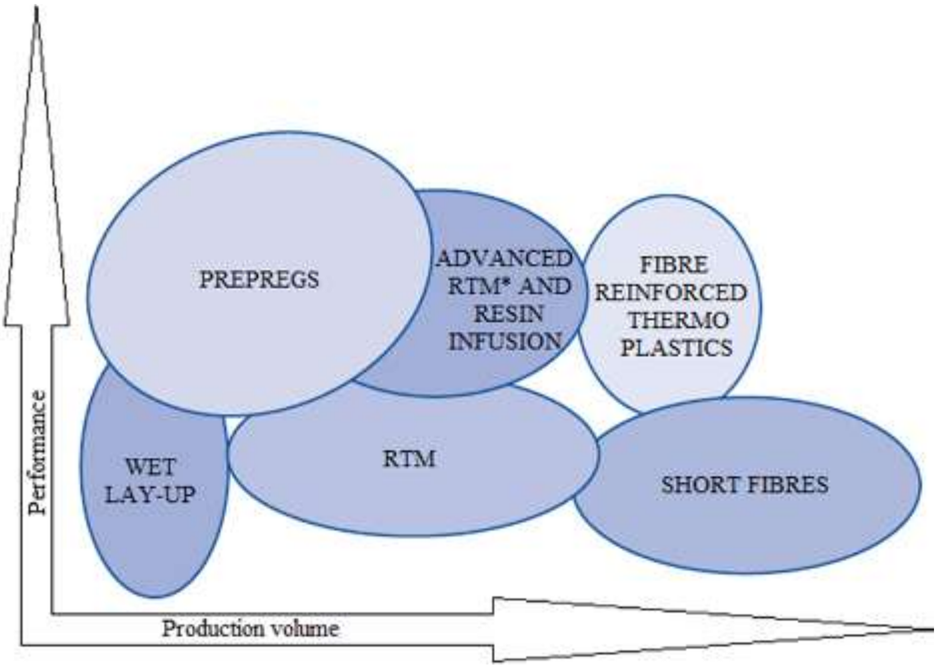


Fig.5.2 The "*prepreg*" technology among other manufacturing processes, after [*Hex.13].

In multilayered composite materials, two types of fabrics are used:

a. an unidirectional fabric (Fig.5.3.a);

b. a fabric with such named *diagonal connection* in which the threads of the warp and weft are programmed woven in respect with the order and frequency as a diagonal aspect to be obtained (Fig.5.3.b).

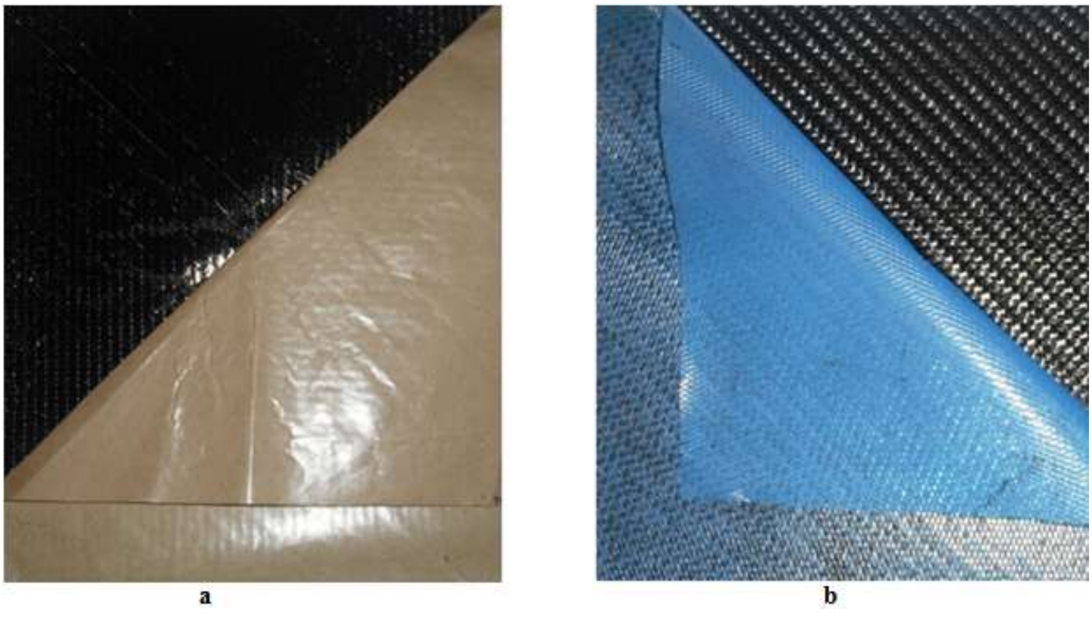


Fig.5.3: Blade of epoxy resin prepreg composite reinforced with carbon fibres fabric: unidirectional fabric (a); biaxial fabric (b).

Thus one side of fabric appears in warp and, the opposite one as it would be done, mainly, from weft yarn. [Teo.07], [Roş.10]

In the case when is aimed the calculus of multilayered composite formed of lamia with diagonal fabric, the following equivalence can be done: the diagonal fabric layer with *h* thickness is aquated with two layers of *h/2* thickness, unidirectional armed on the warp and, respectively, on the weft directions (Fig.5.4). [Vla.08], [Teo.07], [Roş.10]

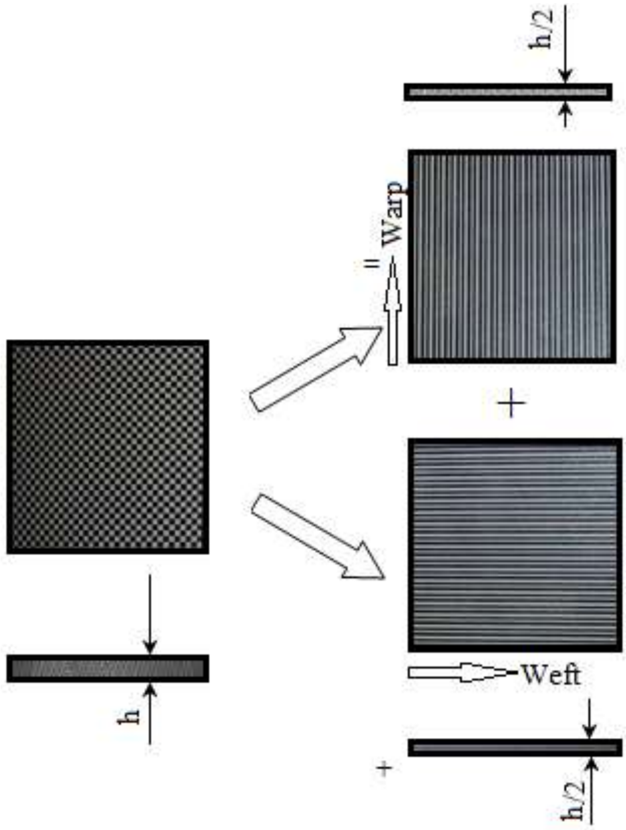


Fig.5.4 Equivalence model of the diagonal type carbon fiber with two layers of unidirectional fabrics layers on the warp direction and respectively, on the weft direction, after [Teo.07].

In production it is possible to determine the theoretical thickness of the pre-impregnated polymerized carbon fiber layer, through relationships [*Gui.03] based on carbon fibers weight, fibers density, volumic fraction of fibers; resin density and, the weight percentage of the resin. But, usually, the laminated composite is manufactued at the imposed thickness, further its thickness is measured and, the obtained value is divided to the component number of lamina. A normed variation of laminate composite thickness corresponding to specific consomptions in fabrication is admitted.

In this research, the manufacturing of the prosthetic blade composed of 3, 5 and, 7 layers was aimed. Thus, the next constructive variants were manufactured:

a. laminated formed of 3 layers, in which the central one is an unidirectional preimpregnated, covered on the two sides by a preimpregnated with diagonal fabric;

b. laminated formed of 5 layers, in which three layers are unidirectional preimpregnated, covered on the two sides by a preimpregnated with diagonal fabric;

c. laminated formed of 7 layers, in which five layers are unidirectional preimpregnated, covered on the two sides by a preimpregnated with diagonal fabric. The preimpregnated layer presents the characteristics described in Annex 2.

The quality of pre-impregnated material is verified by a series of physical, mechanical; and chemical tests according to its state: partially or completely polymerized. Thus can be mentioned [Nis.80] jellying time test, viscosity, volatility, resin content (partially polymerized pre-impregnated) or the amount of fiber, the composite density, of heat treatment level etc. (completely polymerized pre-impregnated material).

5.2. Injection process simulation by RTM procedure with Autodesk Moldflow Insight 2012® software

5.2.1. General assumptions for simulation

Injection process by resin transfer, RTM - Resin Transfer Molding (Fig. 5.5) is usually employed or is "the most popular process" for carbon continuous fiber reinforced composite manufacturing. [Ipe.05]

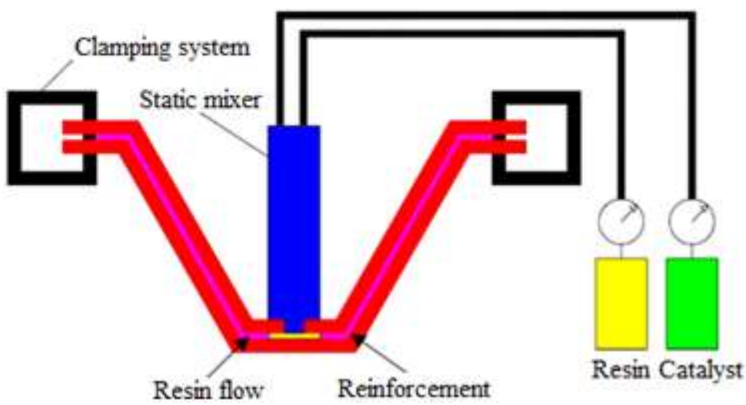
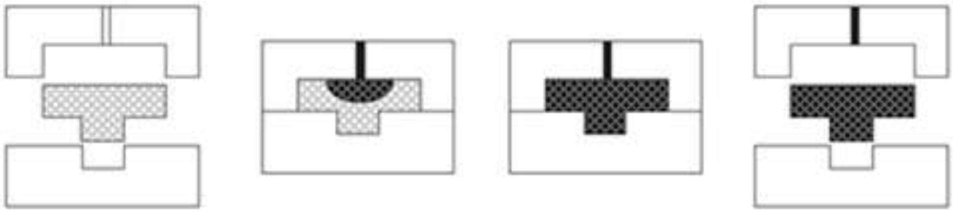


Fig. 5.5. Injection molding process RTM, after [Ipe.05].

In essence, the RTM process consists in the injection at low pressure of a resin, in a mould, where was place in advance a reinforcing material of compacted fibers in form of a fabric.

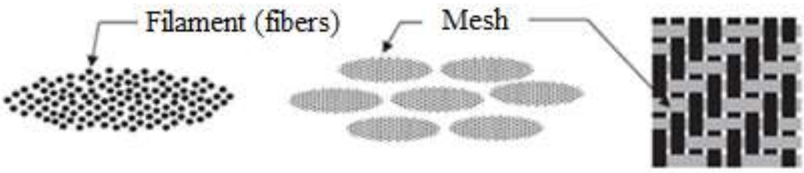
RTM process supposes the following working phases (Fig.5.6): [Fab.13], [Lec.99]

- placing the reinforcing material into the heated mold (Fig.5.6, a) at the established temperature.



a) b) c) d)

Fig. 5.6. The stages of the injection molding RTM process: placing the reinforcing material into the mold (a); resin injection (b); polymerization (c); de-molding (d), after [Lec.99].



a) b) c)

Fig. 5.7. Description of carbon fibers reinforcing fabric at the level: microscopic (a); meso-scopic (b); and maso-scopic (c), after [Lec.99].

- impregnation of reinforcing material with resin, at low pressure and with low speed (fig. 5.6, b);
- complete polymerization of composite material matrix, at the same injection pressure (fig. 5.6, c);
- mould opening and de-molding of composite part (fig. 5.6, d).

The reinforcing material has a complex geometrical structure with three dimensional levels (fig. 5.7): microscopic, meso-scopic, and maso-scopic;

Reinforcing material fiber impregnation is a complex and difficult model process, in which the reinforcing material is assimilated to a porous environment. Lecointe [Lec.03], [Lij.03] Through this approach, the resin speed, V_{rs} is calculated by Darcy's law that establishes a relationship between the injecting speed and resin flow pressure Prs:

$$V_{rs} = -\frac{K}{\mu_{rs}} \cdot P_{rs}, \quad (5.1)$$

where: μ_{rs} is resin viscosity and K is the tensor characterizing the permeability of reinforcing fabric.

$$K = \begin{vmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{vmatrix}, \qquad (5.2)$$

where: *x* and *y* define the plane of composite lamina and *h* characterizes the lamina thickness.

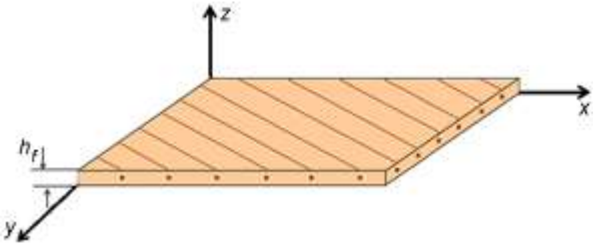


Fig. 5.8. Reference axis on directions *x*, *y* and *z* of composite lamina, after [Ber.12].

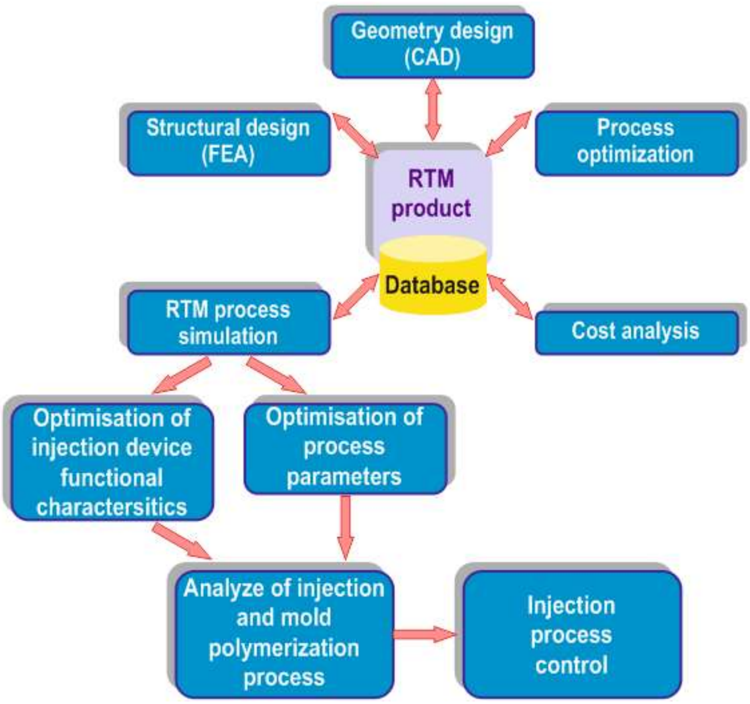


Fig. 5.9. Injection process simulation impact on RTM for a J blade fabrication. [Lec.99], [Lij.03].

Considering the directions *x*, *y*, and *z* as principal axis of composite lamina (fig. 5.8), the permeability tensor can be written as:

$$K = \begin{vmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{vmatrix}, \qquad (5.3)$$

In these conditions, injected resin flow simulation represents, besides injection process optimization, the design of composite part geometry etc. (fig. 5.9)

Based on these consideration, in sections 5.2.2 and 5.2.3 a key component of prosthetic J blade design and manufacturing is developed – the simulation of fabrication process by injection for J blades and for samples used in tests for determining their mechanical characteristics.

5.2.2 Simulation of the RTM manufacturing by injection of J prosthetic element

The simulation by finite elements method of the manufacturing process of the prosthesis element type was performed using specific software Autodesk Moldflow Insight 2012® in some conditions:

- the injection process was selected of type RTM;
- it was imposed 1 and/or 2 injection locations for the material injection of the prosthesis element. It is known its nominal dimensions and its adaptability of different configurations of forming machines by injection;
- firstly, the material was selected as a composite polymer reinforced with carbon fibers in 50% volume percent, provided by Acadia Polymers, technically named Krynac, with the material properties specified in Table , Annex ;
- the settings for the finite elements meshing of the component were as follows as: dual domain type, triangle type elements – being generated 1048 elements and 522 nodes;
- the specific values for the injection process: the temperature of the matrix surface – 170° C, the melting temperature of the polymer resin - 135° C, the nominal time of injection – 4 s, the maximum pressure of the injection of the working machine - 180 MPa.

The process optimization by DOE (DOE - design of experiments) was performed, using Taguchi method, to identify the process variables (the nominal time of injection, the required time of polymerization, etc.) and of design of the injection process based of the quality criteria (the final temperature of the injection process, the clamping force, the injection pressure, etc.).

After the simulations realized by finite elements method for the injection process of the prosthesis element resulted some information regarded to:

- the time required for the finalization of the injection process;
- the medium speed of the material flow;
- the presence and the distribution of the air gaps;
- the clamping force;
- the orientation of the constitutive elements at the surface and inside the element;
- the distribution of the deformations field inside the element;

- the variation of the pressure field during and after the finalization of the injection process.

In the figures 5.10 - 5.14 some results of the simulations done by finite elements method of the injection process for the prosthesis element are presented. For the simulations it used one or two injection locations.

Fig. 5.10. The configuration meshed by FEM for the two cases.

In figure 5.11 it notices that the times required for performing and the finalization of the injection process in the both cases, one or two injection locations, respectively, are the same. It results that the process can be performed in optimum conditions unconcerned of the number of injection locations.

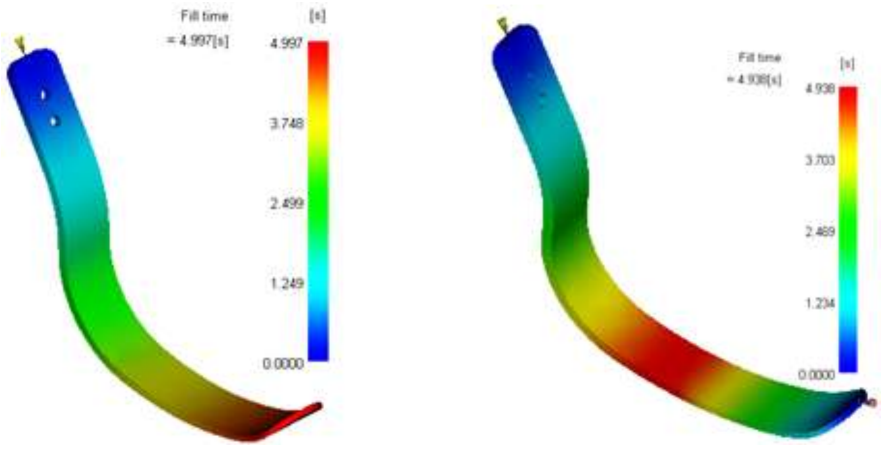


Fig. 5.11. The variation of the times required for the finalization of the injection process in the two cases**.**

The size of the prosthesis element doesn't influence the times required for the composite material injection. In the case when it uses two locations for the material injection it can observe that the curvature area of the prosthesis element represents a sensitive area that needs a special attention due to the influence under other process parameters.

Regarding of the temperature distribution at the final of the injection process (see Fig. 5.12), it can identify some similarities with these previously mentioned, the maximum temperatures of the process reaching at the values close to 154,6 °C and 152,7 °C respectively, for one or two injection locations. In this case, the area closed to the curvature of the element provides the same sensitivity for the injection process.

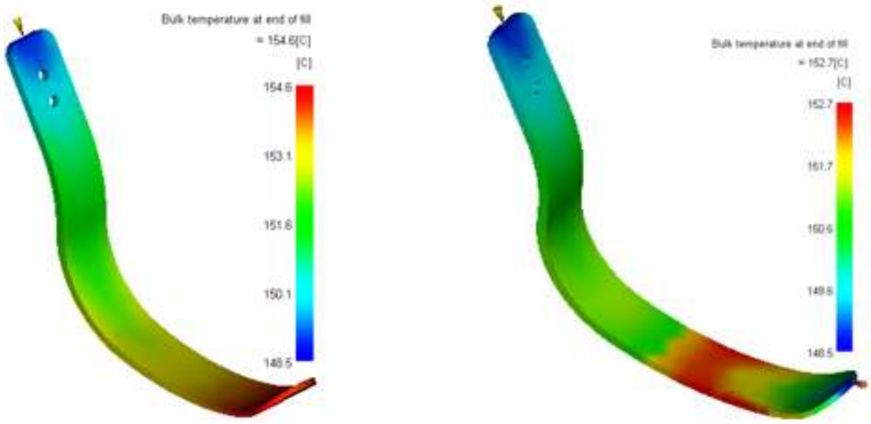


Fig. 5.12. The variation of the temperatures field at the final of the injection process

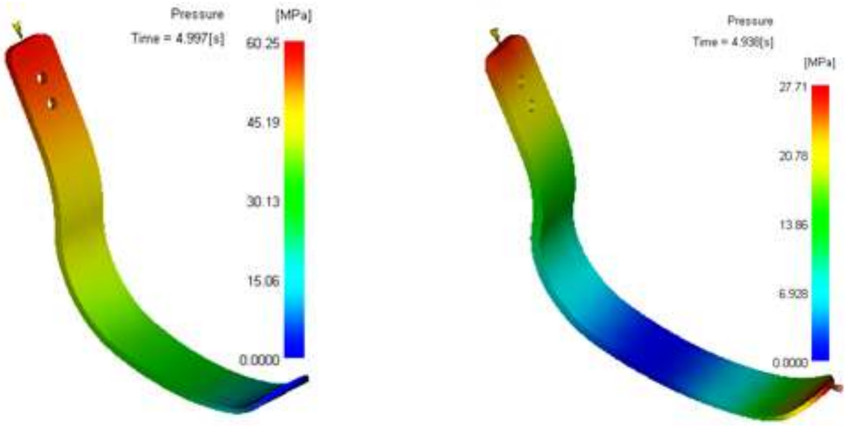


Fig. 5.13. The variation of the pressure at the final of the injection process.

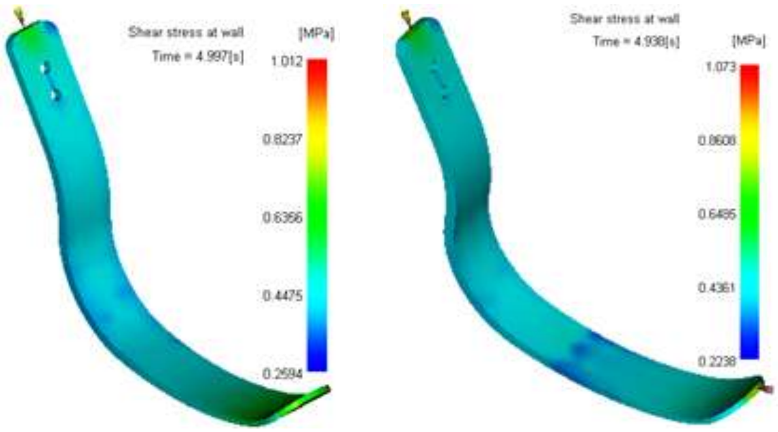


Fig. 5.14. The variation of the shear stresses field at the surface of the elements.

Related to the pressure distribution at the final of the injection process it observes the appearance of some values with a size order multiplied with two for the injection process which involves one location, comparatively with the other case. So, the maximum value of the pressure at the final of the process is of 60.25 MPa, for one injection location case, comparatively with the value of 27,71 MPa obtained in the second case (Fig.5.13). Regarded to the prediction of the process parameters in the previous cases, the curvature area doesn't generate the extreme values of the pressure; this is relative small in the case that uses two injection locations.

In the figure 5.14 it can observe that it was obtained approximately the same variations of the shear stresses field for the both cases, the maximum values obtained being of 1.012 MPa, and 1.073 MPa respectively for one or two injection locations..

After the DOE analysis by Taguchi method for the two selected variables – the melting temperature of the composite material, and the time required the polymerization of the matrix material, it notices that these variables present some similarities related to the process parameters selected as the quality criteria for the analysis – the distribution of the temperature during and at the final of the injection process, the clamping force of the matrix, and the injection pressure respectively. It observes that the melting temperature is the only one which can influence the quality parameters selected.

In this context it can perform a DOE analysis which to facilitate the identification of the variables that influence the most the product quality by injection, followed of the use of the variable response for the determination of the sensitivity variables on the quality of the prosthesis element obtained by injection.

5.2.3 Simulation of specimen injection

Using the specialized software Autodesk Moldflow Insight 2012®, the simulation by finite elements method of the manufacturing process, through injection of the standard specimens type Iosipescu (bone shape) was done. The conditions of the working flow were as follows as:

- the injection process was selected of type RTM;
- it was imposed 1 and/or 2 location for the material injection;
- the selected material is a commercial one, from Acadia Polymers, technically named Krynac, with the properties specified in the Annex 3;

- the settings for meshing with finite elements of the component were: dual domain type, the triangle type elements – being generated 636 elements and 320 nodes, without a further correction of a meshed volume;
- the specific values for the injection process: the temperature of the matrix surface – 170° C, the melting temperature of polymeric resin - 135° C, the nominal time of the injection – 4 s, the maximum pressure of the injection of the machine - 180 MPa;
- the process optimization by DOE (design of experiments) was performed using Taguchi method, for the identifying of the process variable (the nominal time of injection, the required time for the polymerization, the length of the reinforcement element, etc.) and of design about the injection process based on the quality criteria (the final temperature of the injection process, the clamping force, the injection pressure, etc.).

After the simulations using finite elements method of the injection process of the standard specimens, type Iosipescu, were done it was obtained some results related to:

- the required time for the finalization of the injection process;
- the medium speed of the material flow;
- the presence and the distribution of the air gaps;
- the clamping force;
- the orientation of the constitutive elements of the surface and inside of the element;
- the distribution of the deformations field inside the element;
- the variation of the pressure fields during and after the finalization of the injection process.

In the figures 5.15 – 5.19, some results obtained after simulations by finite elements method of the injection process for the analyzed standard specimen, using one or two injection locations, were presented.

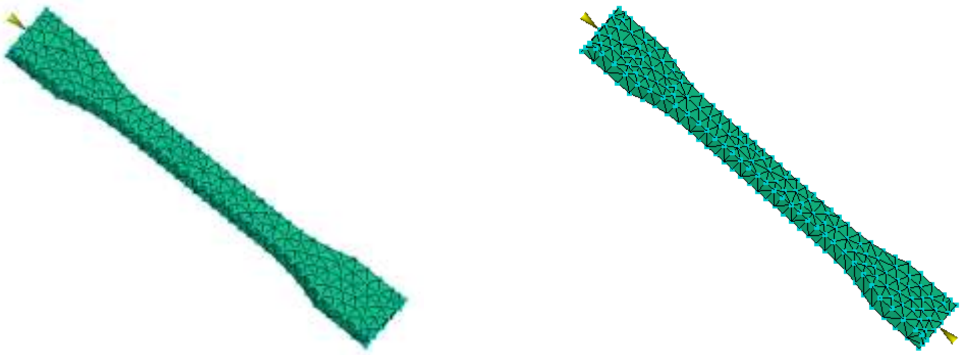


Fig. 5.15. The meshed configuration using FEM for the two cases.

It is noticed, in figure 5.16 that the required times for performing and the finalization of the injection process for the two cases – one, respectively two injection locations – are approximately the same and it is highlighted that the process may be performed in optimum conditions, unconcerned of the number of the injection locations. It is known that the central area (functional or between landmarks area) of the standard specimen constitutes the sensitive area of the element and requires a special attention.

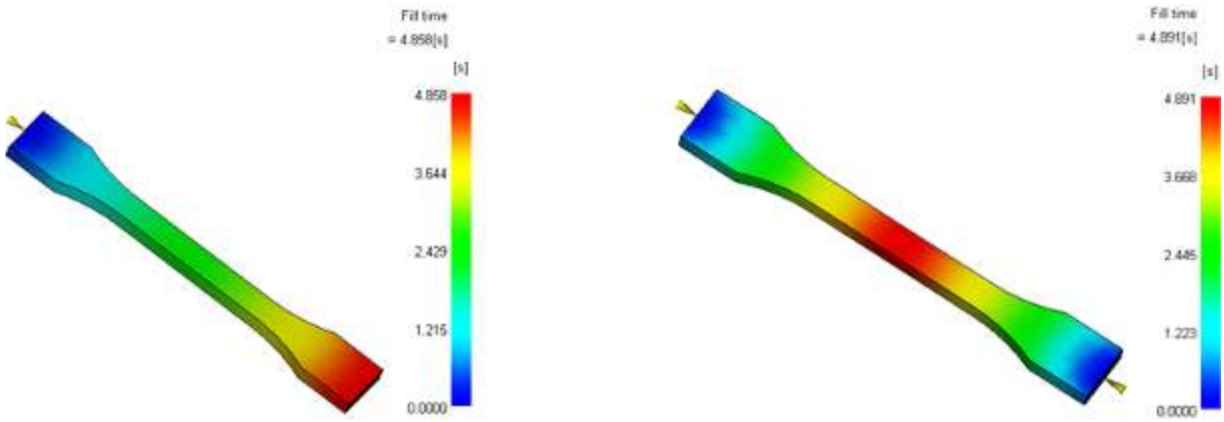


Fig. 5.16. The variation of the times for the finalization of the injection process for the two cases.

In the figure 5.17 it can observe that the maximum temperature developed in the two analyzed cases is approximately the same, of 156.7 °C for one injection location, respectively of 156.2 °C for two injection locations. It observes that the distribution of the temperatures field from the volume of the specimen material is different in these two studied cases.

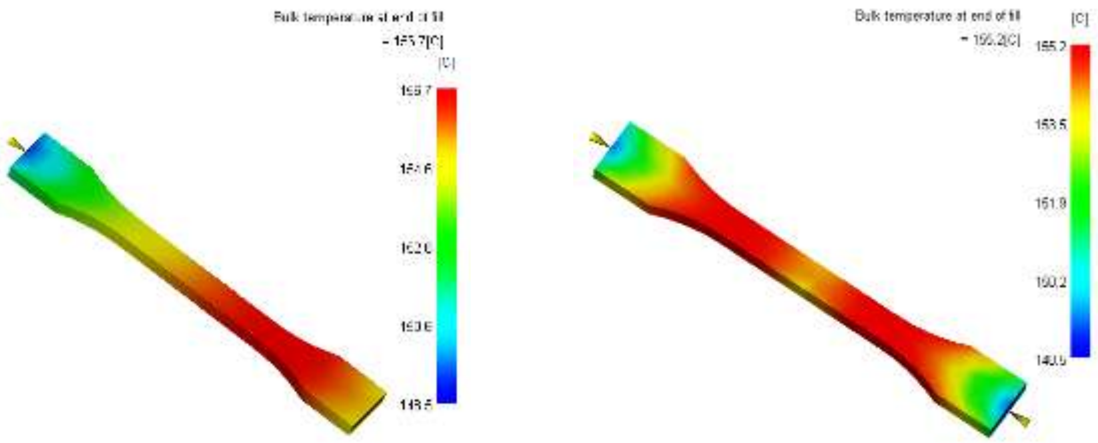


Fig. 5.17. The variation of the temperatures field at the final of the injection process.

Regarding of the pressure developed inside the specimens, it can consider a difference of the size order for the two studied cases. So that, for one injection location this value of 18.07

MPa is approximately double of the value recorded for the second case (7.409 MPa). For this process parameter it identifies some discrepancies resulted due to the number of injection locations used (Fig.5.18). It results a different distribution in the specimen model.

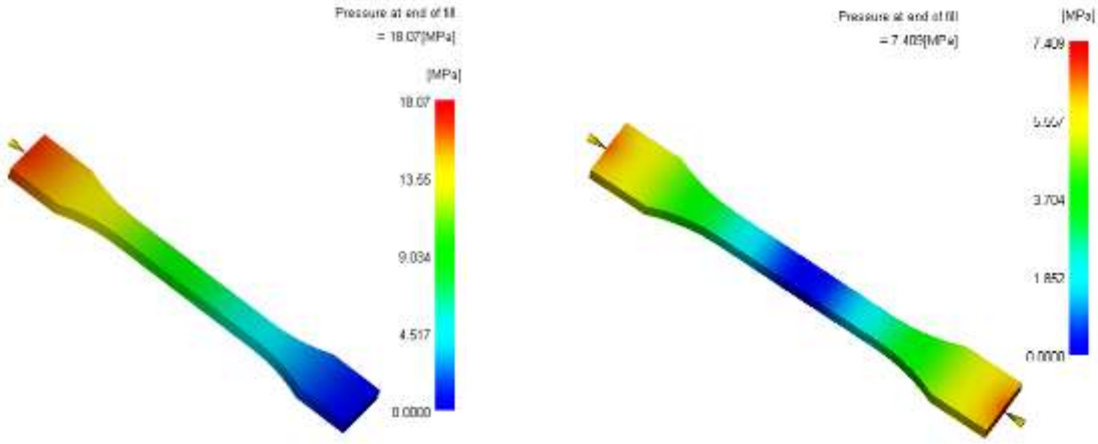


Fig. 5.18. The variation of the pressure at the final of the injection process.

The shear stresses field at the surface of the specimens presents similarities regarding their distribution; the obtained maximum values were approximately the same. In this case it can observe in the central area a small discrepancy related to the variation of this process parameter (Fig.5.19).

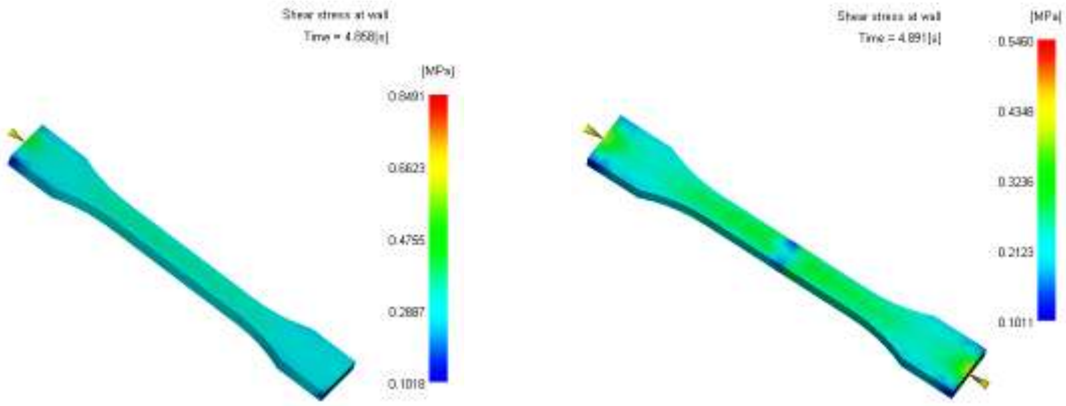


Fig. 5.19. The variation of the shear stresses field at the surface of the specimens.

After the DOE analysis by Taguchi method for the three selected variables – the melting temperature of the composite material, the required time for the polymerization of the injected material and the length of the reinforcement element, respectively, it identified some differences between their influence way under the process parameters selected as quality criteria for the analysis – the temperature distribution during and after the injection process, the clamping force of the matrix and the injection pressure, respectively.

In the Table 5.1 are provided the values obtained after the DOE analysis for the both simulations. The obtained values indicate that the number of the injection locations constitutes an additional source of variation for the process sizes which are influenced of the selected process parameters. The differences recorded are not significant but contribute at the identifying of all the factors of influence under the injection process and under the material quality for the obtained specimen.

Table 5.1. The results of DOE analysis for standard specimens.

Variable	**Process parameters**			
	Temperature of the injection process performing	Temperature of the injection process finalization	Clamping force of the matrix	Injection pressure
1 injection location				
Melting temperature °C	90.23 %	94.02 %	99.45 %	99.45 %
Time of polymerization s	5.54 %	1.71 %	0.12 %	0.12 %
Length of reinforcement element mm	4.23 %	4.27 %	0.43 %	0.43 %
2 injection location				
Melting temperature °C	90.23 %	94.29 %	97.45 %	99.37 %
Time of polymerization s	5.54 %	1.48 %	1.57 %	0.38 %
Length of reinforcement element mm	4.23 %	4.22 %	0.98 %	0.25 %

5.3. THEORETICAL STUDY OF CARBON FIBER EPOXY REINFORCED MULTILAYERED BEHAVIOR

5.3.1. General assumptions on carbon fiber reinforced multilayered composites

By definition, Berthelat [Ber.12], Alămareanu and Chiriță [Ală.97], Vlase et al [Vla.08], the composite material is a combination of adjoining, no miscible materials. In practice, a series of criteria is used to classify the composite materials.

From the constructive perspective, of constitutive elements as well as of their disposition, the following categories are possible:

- composite with long, short or hybrid fibers, placed in another material, named matrix, which can be polymeric, ceramic or metallic;

- multilayered composite materials;
- composite materials with dispersed particles etc.

Composite materials with polymeric matrix are known as fiber reinforced polymeric (or plastic) composite. The composite materials with expoxy matrix and reinforced with carbon fiber enter in this category.

The fiber reinforced composite materials are formed (Alămoreanu and Chiriță [Ală.97], [Ber.12], [Mor.97]) of two or more layers, named lamina, stick together (fig. 5.20). A group of lamina is formed of several successive lamina having the same fibers orientation. A multilayered composite material is defined by layers number – lamina- in its composition and, by fiber inclination angle, α. This indicates the fibers orientation in lamina reported to *Ox* axis of reference systems *Oxyz*, solider with the composite (fig. 5.20). The *Ox* and *Oy* axis of *Oxyz* reference system are positioned in medium plane of the multilayered composite, while the *Oz* axis is perpendicular on the composite.

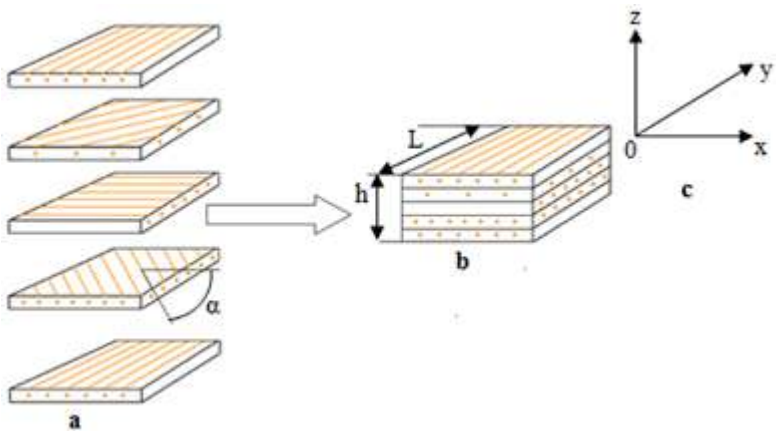


Fig. 5.20. Structure of multilayered material: lamina (a); multilayered material (b); reference system solider with the composite (c); α is the inclination angle of lamina; *L* is the multilayered composite length and, *h* is the multilayered composite thickness, after [Ber.12].

In order to define the multilayered composite structure in the perspective of the lamina number and of angle α, the following codification is used (Fig.5.21): [Ală.97], [Ber.12], [Nic.11]

- the order of lamina is described beginning from the face of material located at the level $z=-h/2$ and finishing at the level $z=h/2$;
- the number of the lamina in the successive lamina group, having the same orientation is indicated by an index;
- the separation of different lamina or groups is codified by a coma or an inclined bar;
- jointing lamina, having equal angles α but opposite are codified by ± notation;

- the above mentioned codifications are put in brackets [……]. The index *s* is used if the multilayered composite has a symmetrical structure, in mirror in report with the plane *Ox*, i.e. the identical lamina as type and orientation are located on the two sides of the *xOy* plane.

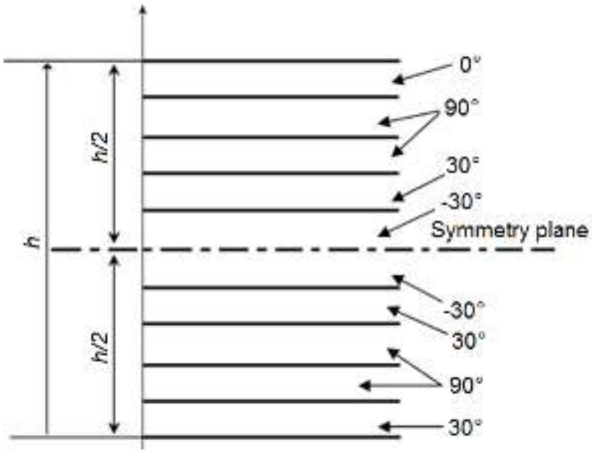


Fig. 5.21. Example of multilayered composite material codification, after [Ber.12].

5.3.2. Elastic behavior of lamina and of multilayered composite

A lamina has the following characteristics [Ber.12], [Vla.08], [Mor.07]: it is homogenous and orthotropic, linear elastic and does not have initial stresses. In order to describe the stress state of the carbon fibers reinforced lamina inserted in an epoxy polymeric matrix (Vlase et al [Vla.08], Teodorescu [Teo.07], Berthelot [Ber.12], Mortensen [Mor.07]), two reference systems are defined (Fig.5.22):

1. the reference (*LTT'*) or (*1,2,3*), i.e. (*1,2,3*) ≡ (*LTT'*), named local reference coordinates system of lamina. It has the characteristics:

- axis *L* (*1*) is directed parallel with the fibers and is called *longitudinal direction of lamina*;
- axis *T* (*2*) is perpendicular on fibers and is called *transverse direction of lamina*;
- axis *T'* (*3*) is perpendicular on the plane (*LT*) ≡ (*12*) and is *the vertical direction of lamina*.

The positive value is considered when, measured in trigonometric sense, the positive direction of the *L* (*1*) axis is superposed on the positive direction of *Ox* axis, as in figure 5.22.

2. the reference coordinates system of solider with the composite.

The mechanical behavior of epoxy resin with carbon fiber lamina can be completely characterized by the next parameters, measured in a simple state of stress and strains: [Vla.07], [Teo.07], [Ber.12]

1. Young modulus E_L or E_1 and Poisson ratio ν_{LT} or ν_{12} , measured in longitudinal traction tests (on parallel direction with the fibers);
2. Young modulus E_L or E_1 and Poisson ratio ν_{LT} or ν_{12} , measured in transversal traction tests (on transverse direction in report with the fibers);
3. Shearing moduli G_{LT} or G_{12} and $G_{TT'}$ or G_{13} measured in longitudinal and, respective, transversal shearing tests;
4. Hydrostatic compression modulus K_L measured in a hydrostatic lateral compression or longitudinal deformation test.

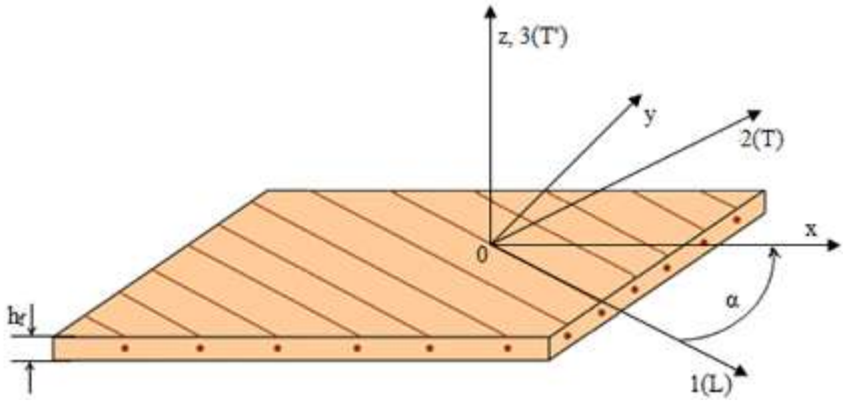


Fig. 5.22. Coordinate systems of lamina: *OLTT'* (*O123*) **-** local reference coordinates system of lamina ; *Oxyz* **-** reference coordinates system of solider with the composite; h_f – lamina thickness, after [Ber.12].

In the case when the exterior charges act on the local reference system of coordinates and, from the plane stress state (fig. 5.23), the elastic deformation law of lamina results from the superposition of charges actions , σ_T and τ_{LT}. it can be written as [Teo.07]:

$$\begin{bmatrix} \varepsilon_L \\ \varepsilon_T \\ \gamma_{LT} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{LT}}{E_T} & 0 \\ -\frac{\nu_{LT}}{E_L} & \frac{1}{E_T} & 0 \\ 0 & 0 & \frac{1}{G_T} \end{bmatrix} \cdot \begin{bmatrix} \sigma_L \\ \sigma_T \\ \tau_{LT} \end{bmatrix}. \qquad (5.4)$$

The above relationship (5.4) can be expressed in matrix form through compliance matrix [Vla.08], while the stresses σ_L, σ_T , and respectively, t_{LT} can be described in report with the elongations and slipping. [Teo.07]

A situation currently encountered in practice occurs when external loads are acting on the directions of the global coordinates system axes of lamina *Oxyz*: σ_{xx}, σ_{yy} and, τ_{xy} (fig. 5.24).

It is possible to observe that the solicitation directions are not in coincidence with local reference system directions of lamina (*123*). In this situation, the elongations of composite lamina in plane stress state can be analytically described in function of stresses σ_{xx}, σ_{yy} and, τ_{xy} and of transformed components of compliance matrix c_{ij}, using the formula [Vla.08], [Teo.07]:

$$\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \gamma_{xy}\end{bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{13}\\ C_{21} & C_{22} & C_{23}\\ C_{31} & C_{32} & C_{33}\end{bmatrix}\cdot\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \gamma_{xy}\end{bmatrix}. \qquad (5.5)$$

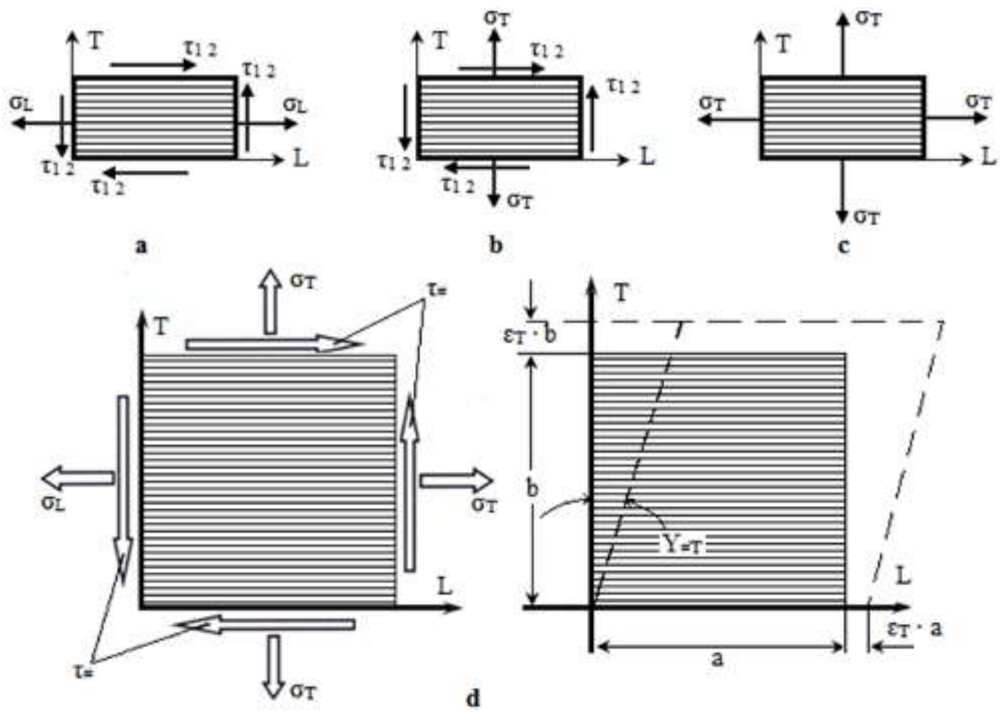


Fig. 5.23. Plane stress state of lamina *UD*: longitudinal and tangential combined stress (a); transversal and tangential combined stress (b); longitudinal and transversal combined stress (c); elongation and slipping of lamina in longitudinal, transversal and, tangential combined stress (d),after [Sed.98], [Teo.07].

In order to find the c_{ij} components, the next formulas are used [Vla.08], [Teo.07], [Roş.10]:

$$c_{11}=\frac{cos^4\alpha}{E_L}+\frac{sin^4\alpha}{E_T}+\frac{1}{4}\left(\frac{1}{G_{pa}}-\frac{2\cdot\nu_T\cdot L}{E_{pa}}\right)\cdot sin^2 2\alpha, \qquad (5.6)$$

$$c_{22}=\frac{sin^4\alpha}{E_L}+\frac{cos^4\alpha}{E_T}+\frac{1}{4}\left(\frac{1}{G_{LT}}-\frac{2\cdot\nu_T\cdot L}{E_{pa}}\right)\cdot sin^2 2\alpha, \qquad (5.7)$$

$$c_{33} = \frac{cos^2 2\alpha}{G_{LT}} + \left(\frac{1}{E_L} + \frac{1}{E_T} \frac{2 \cdot \nu_T \cdot L}{E_L} \right) \cdot sin^2 2\alpha , \tag{5.8}$$

$$c_{12} = \frac{1}{4} \cdot \left(\frac{1}{E_L} + \frac{1}{E_T} - \frac{1}{G_{LT}} \right) \cdot sin^2 2\alpha - \frac{\nu_{TL}}{E_L} \cdot \left(sin^4 \alpha + \boldsymbol{cos}^4 \alpha \right), \tag{5.9}$$

$$c_{13} = \left(\frac{2}{E_T} - \frac{2 \cdot \nu_T \cdot L}{E_L} - \frac{1}{G_{LT}} \right) \cdot sin^3 \alpha \cdot cos\alpha - \left(\frac{2}{E_T} - \frac{2 \cdot \nu_T \cdot L}{E_L} - \frac{1}{G_{LT}} \right) \cdot cos^3 \alpha \cdot sin\alpha , \tag{5.10}$$

$$c_{23} = \left(\frac{2}{E_T} - \frac{2 \cdot \nu_T \cdot L}{E_L} - \frac{1}{G_{LT}} \right) \cdot cos^3 \alpha \cdot sin\alpha - \left(\frac{2}{E_T} - \frac{2 \cdot \nu_T \cdot L}{E_L} - \frac{1}{G_{LT}} \right) \cdot sin^3 \alpha \cdot cos\alpha . \tag{5.11}$$

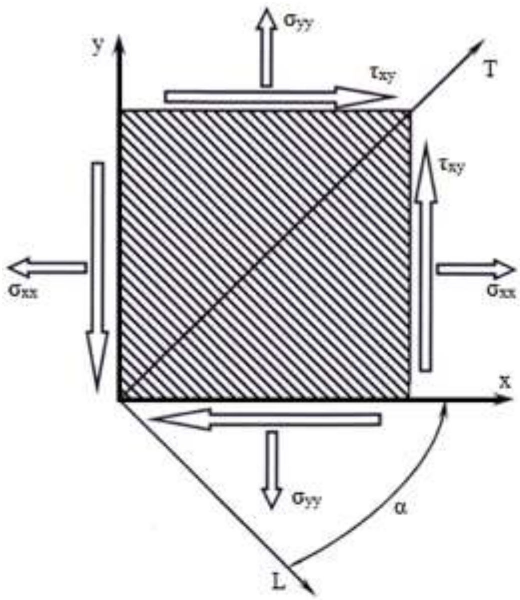


Fig. 5.24. Plane stress state of composite lamina when the local reference system *O123* is not in coincidence with the global reference system *Oxyz,* after [Vla.08], [Teo.07].

The composite lamina stresses can be expressed in function of elongations ε_{xx}, ε_{yy} and, γ_{xy} [Vla.08]:

$$\begin{aligned} \sigma_{xx} &= r_{11} \cdot \varepsilon_{xx} + r_{12} \cdot \varepsilon_{yy} + r_{13} \cdot \gamma_{xy} ; \\ \sigma_{yy} &= r_{12} \cdot \varepsilon_{xx} + r_{22} \cdot \varepsilon_{yy} + r_{23} \cdot \gamma_{xy} ; \\ \tau_{xy} &= r_{13} \cdot \varepsilon_{xx} + r_{23} \cdot \varepsilon_{yy} + r_{33} \cdot \gamma_{xy} , \end{aligned} \tag{5.12}$$

where: r_{ij} represent the transformed components of stiffness matrix, expressed in function of parameters E_L, E_T, ν_{TL}, G_{LT} and, the angle of inclination α of fibers.

The components r_{ij} can be determined by the relationships [Vla.08]:

$$r_{11} = \frac{E_L \cdot cos^4 \alpha}{1 - \nu_{TL} \cdot \nu_{LT}} + \frac{E_T \cdot sin^4 \alpha}{1 - \nu_{TL} \cdot \nu_{LT}} + \frac{1}{2} \left(\frac{\nu_{LT} \cdot E_T}{1 - \nu_{TL} \cdot \nu_{LT}} + G_{LT} \right) \cdot sin^2 2\alpha , \tag{5.13}$$

$$r_{22} = \frac{E_L \cdot cos^4\alpha}{1-\nu_{TL}\cdot\nu_{LT}} + \frac{E_T \cdot sin^4\alpha}{1-\nu_{TL}\cdot\nu_{LT}} + \frac{1}{2}\left(\frac{\nu_{TL}\cdot E_T}{1-\nu_{TL}\cdot\nu_{LT}} + G_{LT}\right)\cdot sin^2 2\alpha\,, \tag{5.14}$$

$$r_{33} = G_{LT} + \frac{1}{4}\left(\frac{E_L}{1-\nu_{TL}\cdot\nu_{LT}} + \frac{E_T}{1-\nu_{TL}\cdot\nu_{LT}} - \frac{2\nu_{TL}\cdot E_T}{1-\nu_{TL}\cdot\nu_{LT}} - 4G_{LT}\right)\cdot sin^2 2\alpha\,, \tag{5.15}$$

$$r_{33} = \frac{\nu_{TL}\cdot E_T}{1-\nu_{TL}\cdot\nu_{LT}} + \frac{1}{4}\left(\frac{E_L}{1-\nu_{TL}\cdot\nu_{LT}} + \frac{E_T}{1-\nu_{TL}\cdot\nu_{LT}} - \frac{2\nu_{TL}\cdot E_T}{1-\nu_{TL}\cdot\nu_{LT}} - 4G_{LT}\right)\cdot sin^2 2\alpha\,, \tag{5.16}$$

$$\begin{aligned} r_{13} = \Bigg[&\left(\frac{E_L}{1-\nu_{TL}\cdot\nu_{LT}} + \frac{E_T}{1-\nu_{TL}\cdot\nu_{LT}}\cdot\frac{2\nu_{TL}\cdot E_T}{1-\nu_{TL}\cdot\nu_{LT}} - 4G_{LT}\right)\cdot sin^2 2\alpha - \\ &-\left(\frac{E_L}{1-\nu_{TL}\cdot\nu_{LT}} - \frac{\nu_{TL}\cdot E_T}{1-\nu_{TL}\cdot\nu_{LT}} - 2G_{LT}\right)\Bigg]\cdot sin^2 2\alpha \end{aligned}\,, \tag{5.17}$$

$$\begin{aligned} r_{23} = \Bigg[&\left(\frac{E_T}{1-\nu_{TL}\cdot\nu_{LT}} + \frac{E_T}{1-\nu_{TL}\cdot\nu_{LT}}\cdot\frac{\nu_{TL}\cdot E_T}{1-\nu_{TL}\cdot\nu_{LT}} - 2G_{LT}\right) - \\ &-\left(\frac{E_L}{1-\nu_{TL}\cdot\nu_{LT}} + \frac{E_T}{1-\nu_{TL}\cdot\nu_{LT}} - \frac{2\nu_{TL}\cdot E_T}{1-\nu_{TL}\cdot\nu_{LT}} - 4G_{LT}\right)\cdot sin^2 2\alpha\Bigg]\cdot sin2\alpha \end{aligned}\,, \tag{5.18}$$

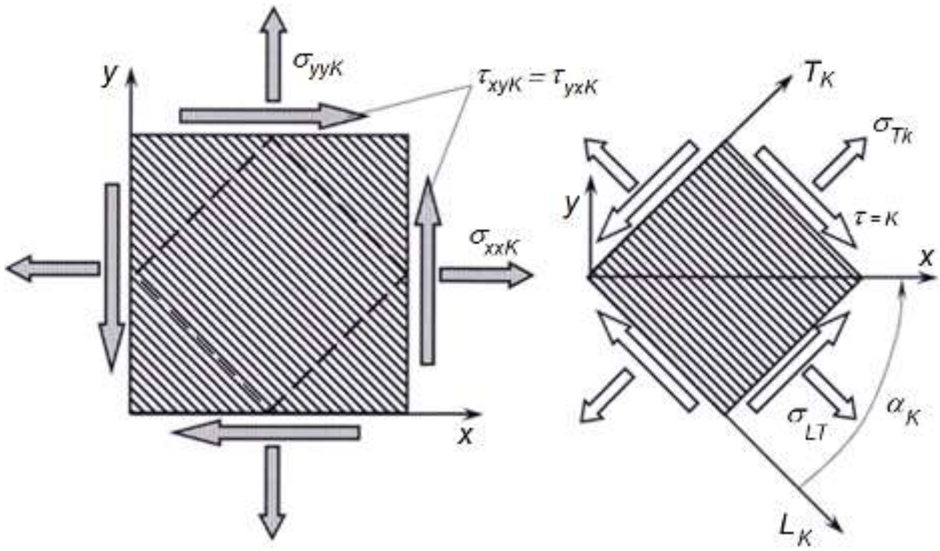


Fig. 5.25. Plane stress state diagram of carbon fibers reinforced epoxy composite, after [Vla.08], [Teo.07].

In the solicitation diagram (fig. 5.25) of multilayered composite, consisting of K (K=1-N) lamina having the inclination angles $\alpha_1, \alpha_2,...,\alpha_\nu$, its elastic behavior relationship can be determined, using the equation:

$$\underline{\sigma}_{xx} = \underline{r}_{11} \cdot \varepsilon_{xx} + \underline{r}_{12} \cdot \varepsilon_{yy} + \underline{r}_{13} \cdot \gamma_{xy};$$
$$\underline{\sigma}_{yy} = \underline{r}_{12} \cdot \varepsilon_{xx} + \underline{r}_{22} \cdot \varepsilon_{yy} + \underline{r}_{23} \cdot \gamma_{xy}; \quad (5.19)$$
$$\underline{\tau}_{xy} = \underline{r}_{13} \cdot \varepsilon_{xx} + \underline{r}_{23} \cdot \varepsilon_{yy} + \underline{r}_{33} \cdot \gamma_{xy},$$

Berthelot [Ber. 12] presents diagrams of the parameters E_x, G_{xy} and $\eta_{xy,x}$ (that is analogous to Poisson ratio, connecting the shearing strain to ε_{xx} strain on x direction) (fig. 5.26).

In calculus of stresses defining the elastic behavior of carbon fiber reinforced epoxy multilayered material, two main requirements must be considered: composite lamina are adherent to each other and, the entire composite as well as the component lamina support the same strains in a given point.

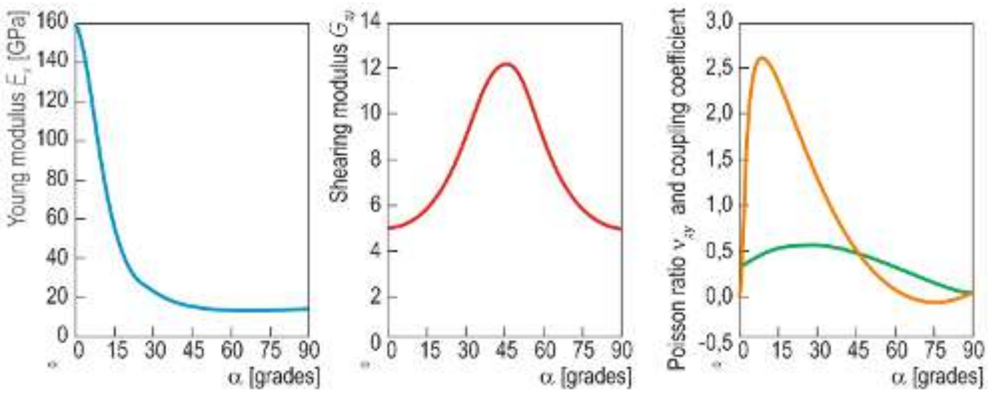


Fig. 5.26. Modules of elasticity variation of epoxy/carbon fibers composite in function of inclination angle α, after [Ber.12].

5.3.3 Thermal behavior of multilayered composite epoxy/carbon fiber

Thermal behavior of composite material can be decribed by the next parameters: thermal conductivity, thermal dilatation coefficient and, respectively, thermal capacity. Karadeniz [Kar.05] Curtu and Motoc Luca [Cut.09], present teoretical models for prediction of thermal dilatation coefficients of composite materials armed reinforced with unidirectional fibers.

For the presentation of these models, Shapery, Strife-Premo, Chamis, Hopkins-Chamis, Chamberlain, Dong, Geier, Christensen, Hashin, Schneider, Van Fo Fy, Wakashimo and Takahaschi, Thomas, Rosen and Hashin use four research hypothesis:

1. reinforcing fibers have circular transverse setion and are infinitely long;
2. the condition of displacements continuity at fibre-matrix interface is satisfied;
3. temperature is uniform distributed along the structure;
4. to store the material properties of composite phases in repport with temperature changes is preserved.

In Schneider model is considered that the longitudinal reinforcing fibers have hexagonal distribution and are surrounded by a mantle consisting of matrix composite. Schneider [Sch.71] proposes the calculus of thermal dilatation coefficients along and in perpendicular direction to fibers (Fig. 5.23) by the relationships:

$$\alpha_L = \alpha_{fL} + \frac{\alpha_M - \alpha_{fL}}{\frac{\varphi}{1-\varphi} \cdot \frac{E_{fL}}{E_M} + 1}, \tag{5.20}$$

$$\alpha_T = \alpha_M - (\alpha_M - \alpha_{fT}) \left[\frac{2(\nu_M^3 + \nu_M^2 - \nu_M - 1) X 1{,}1\varphi}{1{,}1\varphi x (2\nu_M^2 + \nu_M - 1) - (1 + \nu_M)} - \frac{\nu_M x \frac{E_{fT}}{E_M}}{\frac{E_{fT}}{E_M} + \frac{1 - 1{,}1\varphi}{1{,}1\varphi}} \right]. \tag{5.21}$$

If the fibers are inclined with the angle α (fig. 5.20), the dilatation coefficient on *x* and *y* directions can be calculated with respect of coefficients α_L and α_T , using the formula: [Ros.10]

$$\begin{aligned} \alpha_{xx} &= \alpha_L \cdot \boldsymbol{cos}^2 \alpha + \alpha_T \cdot \boldsymbol{sin}^2 \alpha, \\ \alpha_{yy} &= \alpha_L \cdot \boldsymbol{sin}^2 \alpha + \alpha_T \cdot \boldsymbol{cos}^2 \alpha,, \\ \alpha_{xy} &= 2 \boldsymbol{sin} \alpha \cdot \boldsymbol{cos} \alpha (\alpha_L - \alpha_T), \end{aligned} \tag{5.22}$$

where: α_{xx} is the tangential thermal dilatation coefficient.

Expansion coefficient *CTE* describes the variation of the material's volume when temperature modifies with one degree. It is supposed that this variation of expansion coefficient is linear in the little temperature ranges. This coefficient is found in three representations [Mat.10]: linear, superficial and, respective volume.

The linear expansion coefficient describes the relative variation of linear dimension of the material for each one-degree temperature modification [*Lin.13], [Mil.09]:

$$\alpha_{et,1} = \frac{\Delta L}{l_c \cdot \Delta T}, \tag{5.23}$$

where: l_c represents the length of composite and, ΔT the temperature variation.

For long fiber-reinforced composite, the thermal expansion coefficient can be found from the relationships [*Est.13]:

1. in longitudinal direction, along the fiber:

$$\alpha_{et,cl} = \frac{\alpha_M \cdot E_M \cdot \nu_M + \alpha_f \cdot E_f \cdot \nu_f}{E_M \cdot \nu_M + E_f \cdot \nu_f}, \tag{5.24}$$

where: $\alpha_{et,cl}$ represents the thermal expansion coefficient in longitudinal direction along the fibers, αf is the fiber thermal expansion coefficient and, E_f is the elastic modulus of the fiber.

2. in transversal direction of the fiber:

$$\alpha_{et,ct} = (1 + \mu m) \cdot \alpha_m \cdot V_m + \alpha_f \cdot V_f , \qquad (5.25)$$

where: $\alpha_{et,ct}$ represents the thermal expansion coefficient in transversal direction of the fiber, μm is matrix Poisson ratio.

Thermal expansion coefficient of a composite material (reinforced with fibers), generally has a form corresponding to the diagram in the figures 5.27 and 5.28.

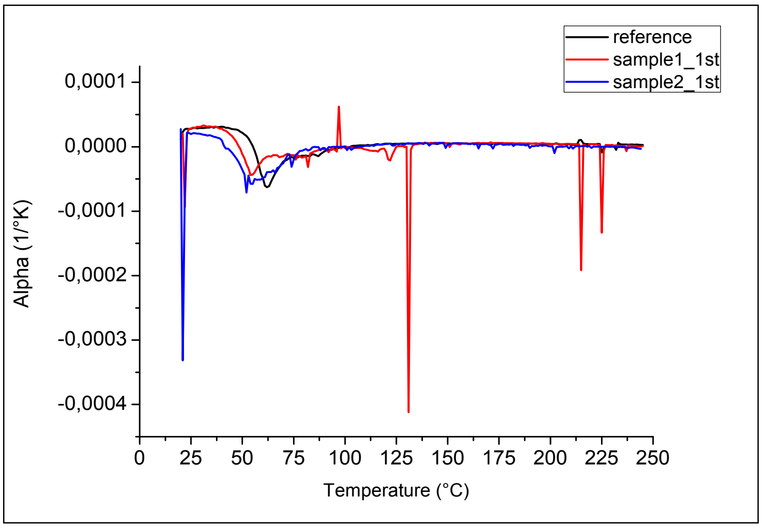


Fig. 5.27 Instantaneous CTE variation for different multiphase unidirectional carbon fibers and random E-glass fibers , after [Mit.12], [Mot.11].

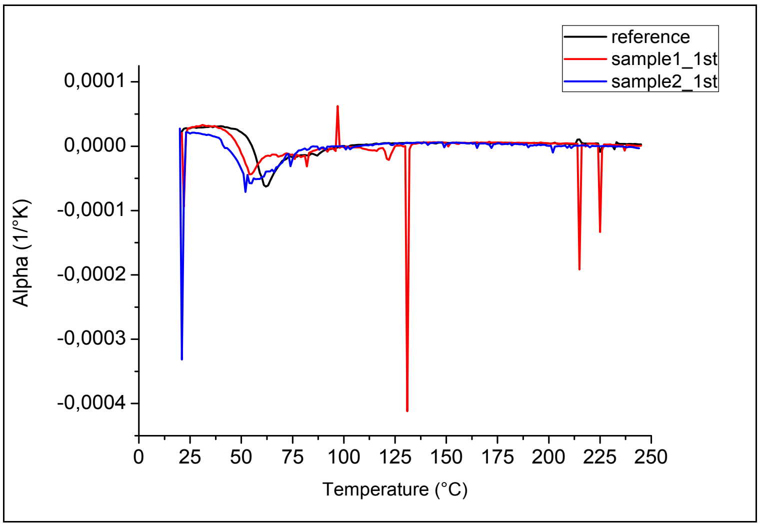


Fig. 5.28. Instantaneous CTE variation for different multiphase unidirectional carbon fibers and random E-glass fibers, after [Mit.12], [Mot.11].

5.4. SIMULATION OF LAYERED COMPOSITE BEHAVIOR OF EPOXY RESIN AND CARBON FIBER-REINFORCED OF J PROSTHETIC BLADE

5.4.1. Calculus hypothesis

Let consider the prosthetic J blade in layered composite formed of pre-impregnated lamina of epoxy resin, reinforced with carbon fibers. The composite is formed of six layers. The configuration orientation for each layer (lamia) is presented in figure 5.29. The simulation of mechanical behavior of composite material under static loading of prosthetic blade is aimed in the theoretical research. The finite element method by SolidWorks software is used.

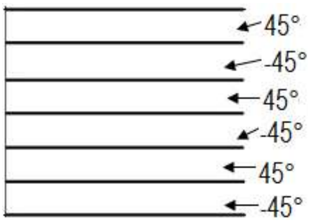


Fig. 5.29. Composite configuration.

5.4.2. Geometrical definition of the model

The simulation fist stage consists in defining geometrically the prosthetic blade model, described in figure 5.30.

The blade has the next dimensions:

- length: 290 mm;
- variable width on length, between 40 and 50 mm;
- thickness: 6 mm.

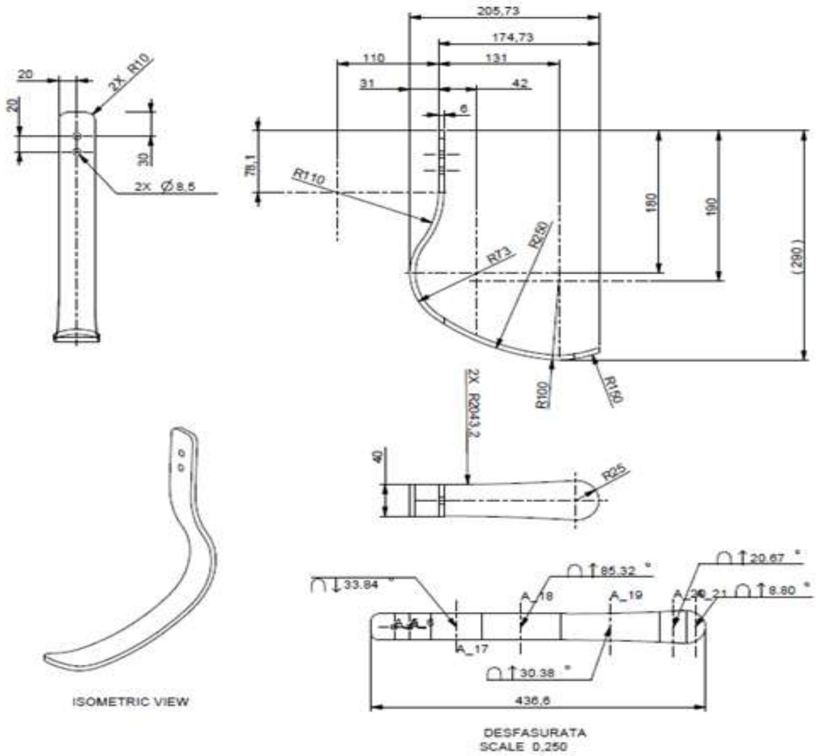


Fig.5.30 Geometric structure of prosthetic J blade used for simulation.

5.4.3. Prosthetic J blade meshing

The geometrical model was meshed by quadrilateral finite elements type SHELL (QUAD); in figure 5.31 is represented the meshed model of the analyzed blade (Table 5.2).

Table 5.2. The number of elements and of nodes resulted from meshing.

Meshed structure on prosthetic system	
Numberof elements	1462
Numberof nodes	3133
NumberGDL	15912

Simulation is done in SolidWorks software.

In order to solve the model it is necessary to specify the limit conditions and the loading of prosthetic J blade:

- loading conditions of prosthetic blade;
- the static and dynamic loading values of prosthetic blade;
- the zones of the blade where the breaking conditions are satisfied;
- the layered composite number of lamina from which is done the blade;
- thickness variation along the blade;
- material characteristics of layered epoxy composite reinforced with carbon fibers.

Fig.5.31 Prosthetic J blade meshing.

5.4.4. Definition of limit load conditions

5.4.5. Loading cases definition

- the prosthetic blade loading was by a force *F* evaluated in biodynamic: *F*=400 daN;
- the loading force acts along the blade. Thus, the real conditions of blades use in running are satisfied;
- the force application points are situated in fixation holes for mounting the blade on the prosthesis.

5.4.6. Materials definition

Usually the material has been defined as isotropic with the following properties:

- Young modulus [MPa]= 17331 MPa;
- Density=1800 Kg/m^3;
- ɣ=0,32 (Coef. Poisson);
- G=11439 MPa;
- Force : dynamic 400 daN;
- Number of layers: (6 layers);
- Layer thickness: (1 mm/layer);
- Fiber orientation: (+45°;-45°);

- Yield stress 1600 Mpa (generic).

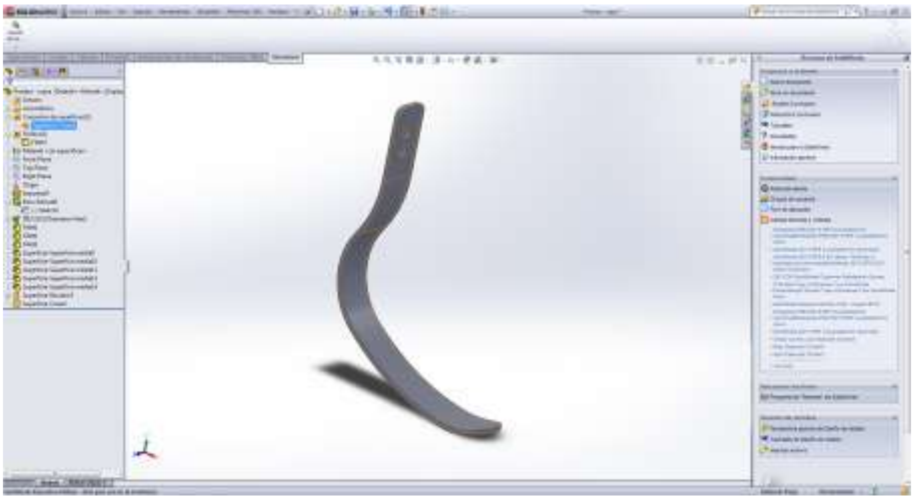
5.4.7. Simulation of blade behavior

5.4.7.1. Static analyze

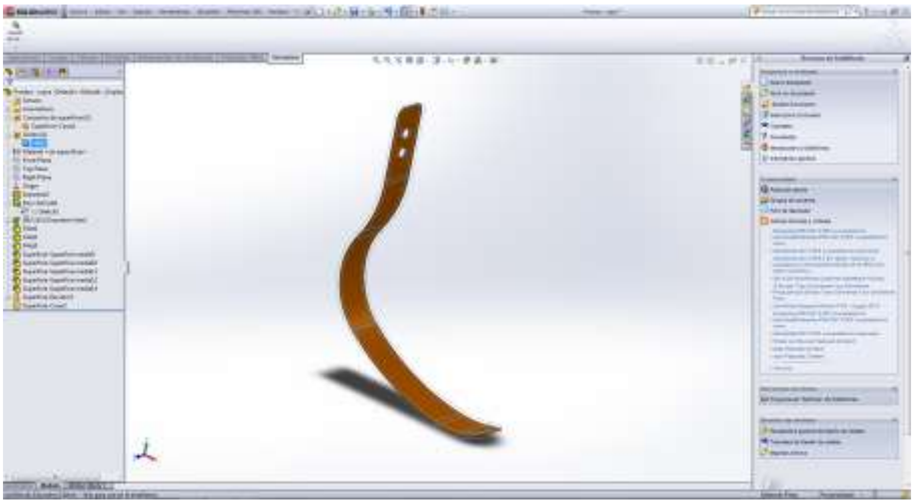
A. Loading force *F*=400 daN, **blade constant thickness** of 6 mm.

Simulation is done inside a working cycle with many steps.

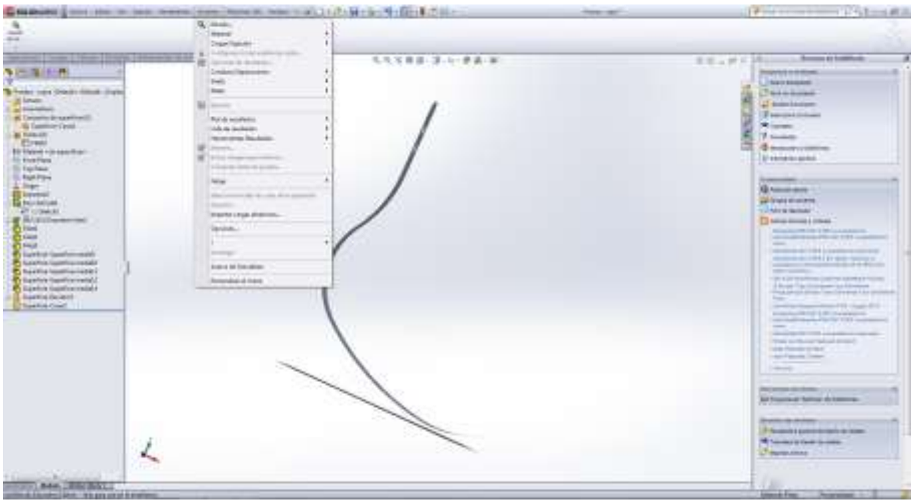
- **First step** - mid-plane creation. It's based on solid part drawn. After that we will define the thickness of carbon fiber layer and the total layer.



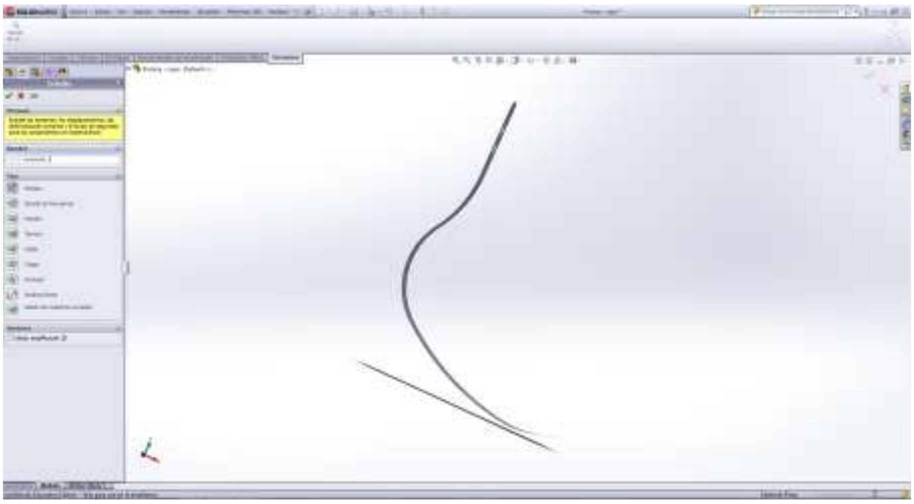
- **Second step .** The solid part was hidden. We will work only with the mid-plane.



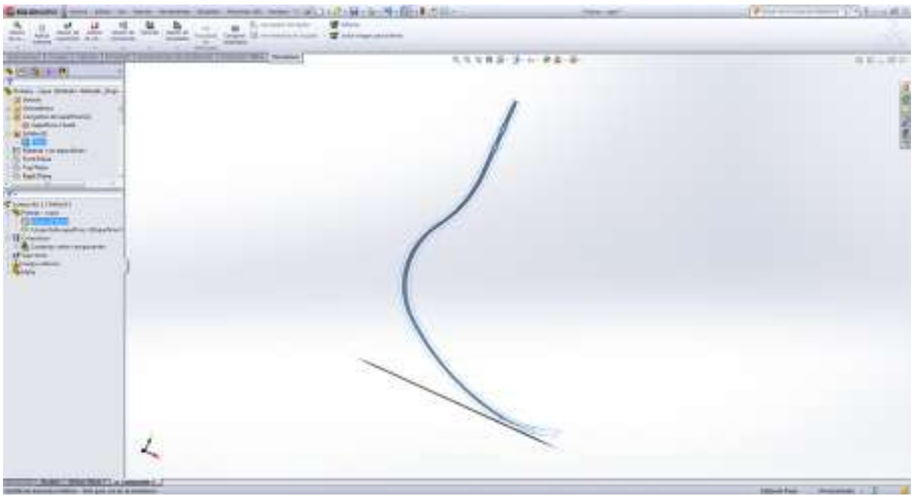
- **Third step.** Preparing the simulation work



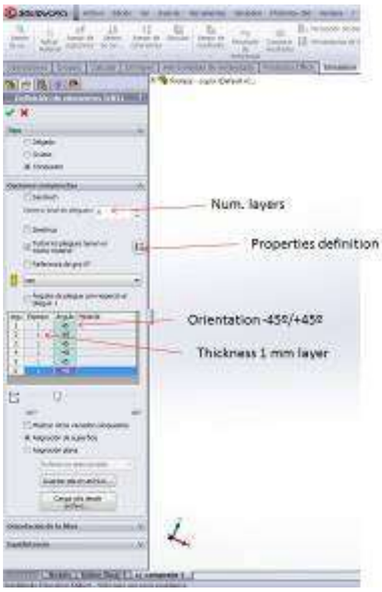
- **Fourth step**, we will specify the type of analysis:
- Static analysis



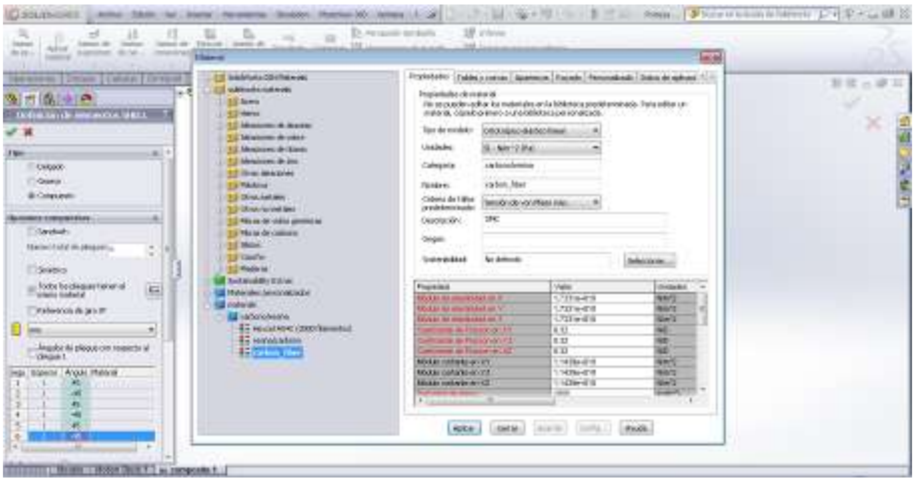
- Solid part excluded from analysis. We will work only with the mid-plane part.

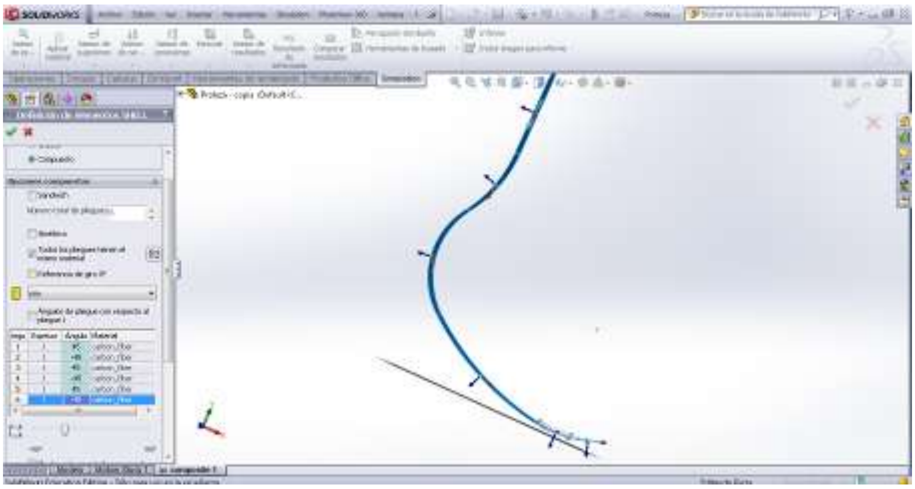


- **Five step:** Materials properties definition-carbon fiber composite, 6 layers/1 mm, -45º/45º.

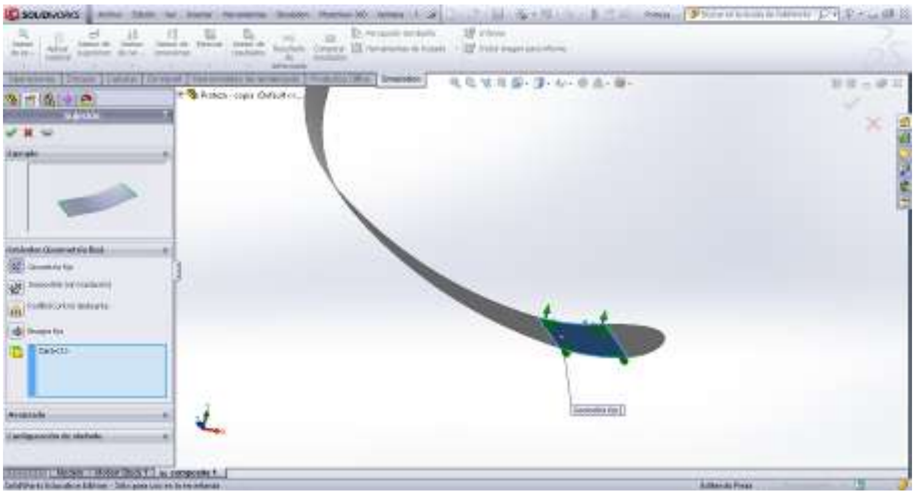


- **Six step**, it's click on properties definition.

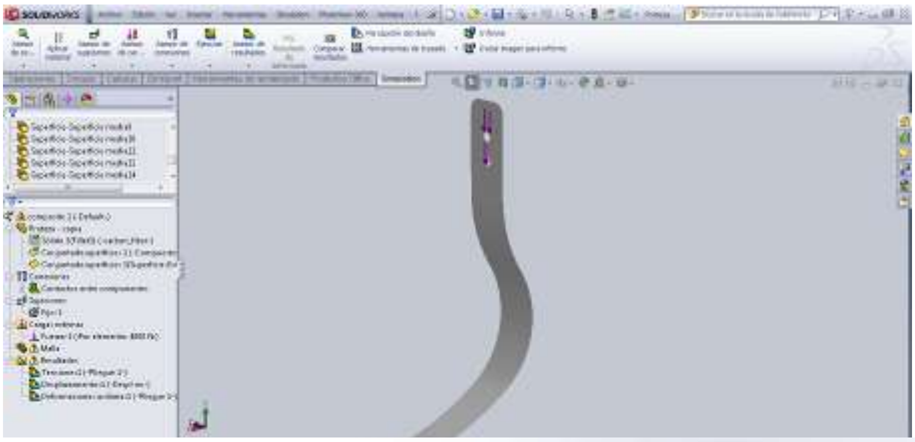


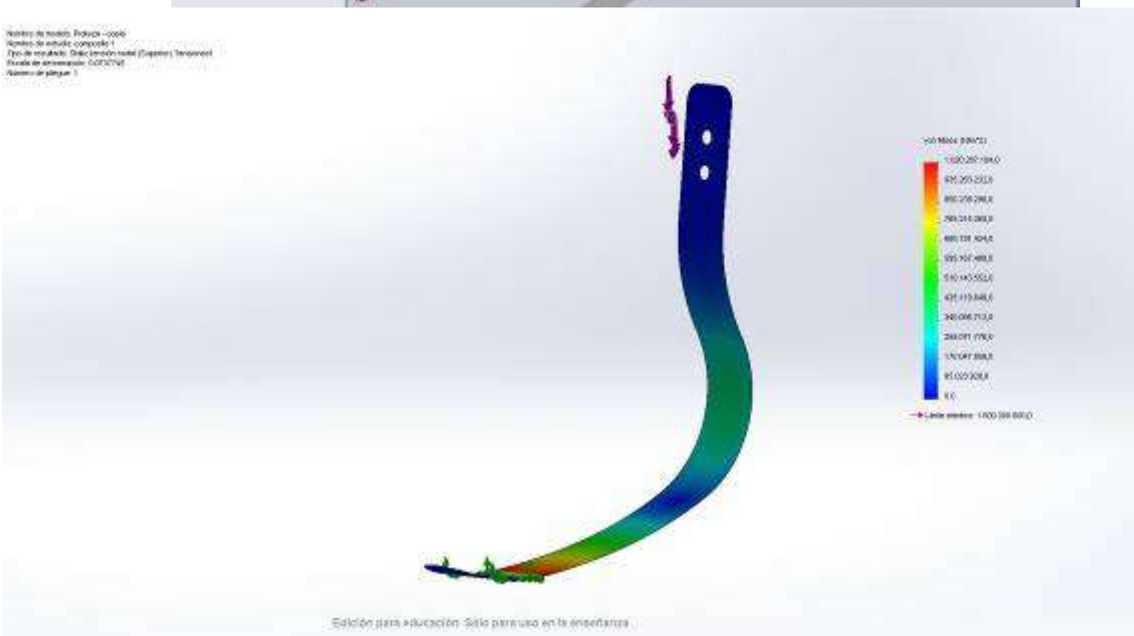


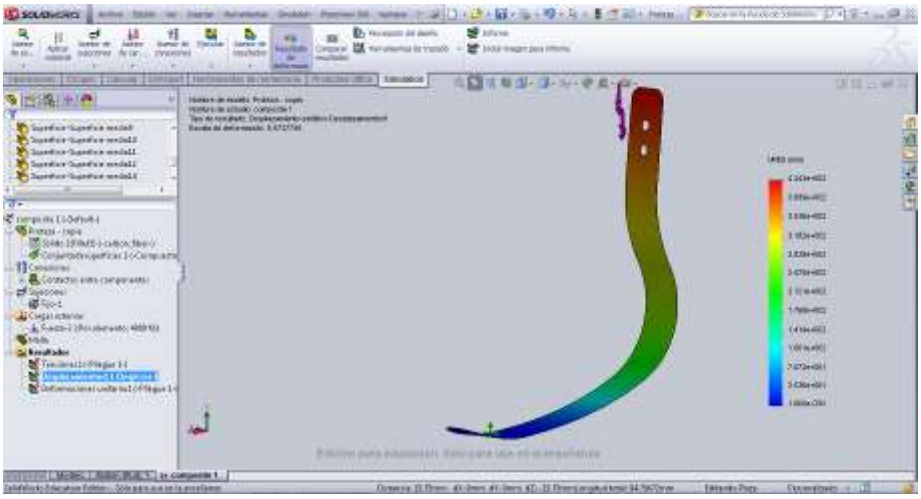
- The materials properties have been assigned to each layer, including fiber orientation.
- **The next step** only we add the constraints on the bottom side of the part.

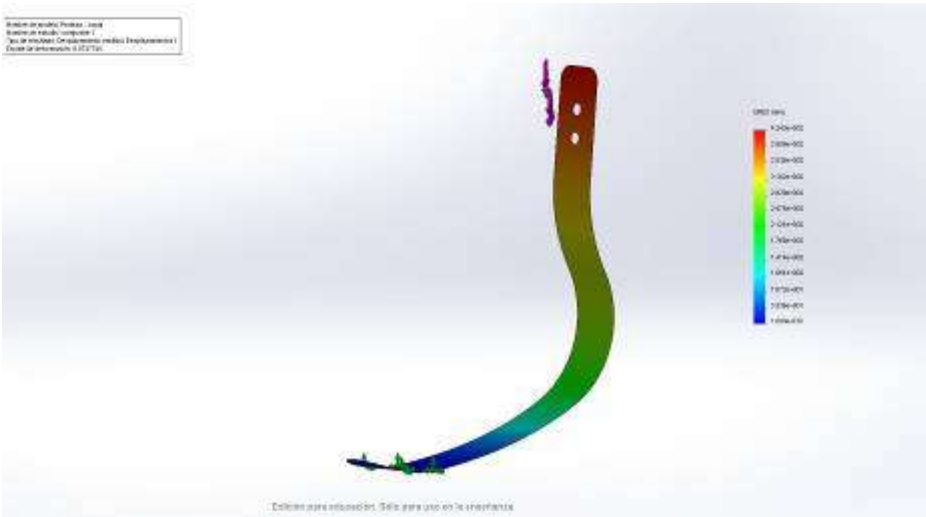


- Now we must to apply the loads on the top of the part: 400 daN applied



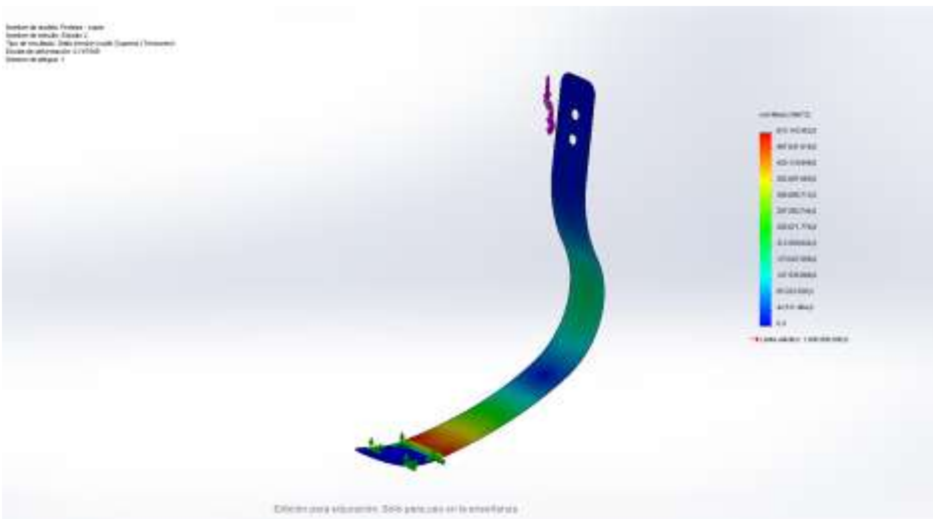




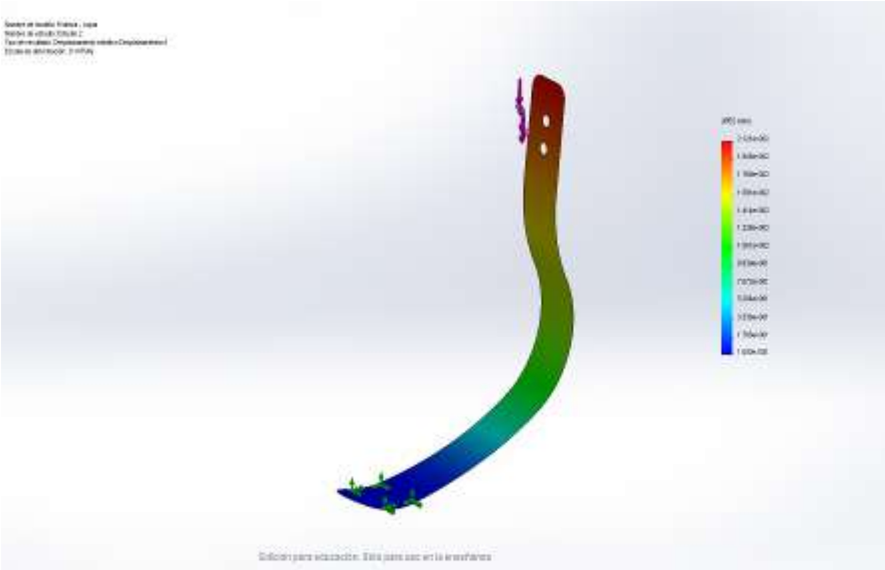


B. Loading force *F*=200 DaN**. Blade constant thickness of** 6 mm.

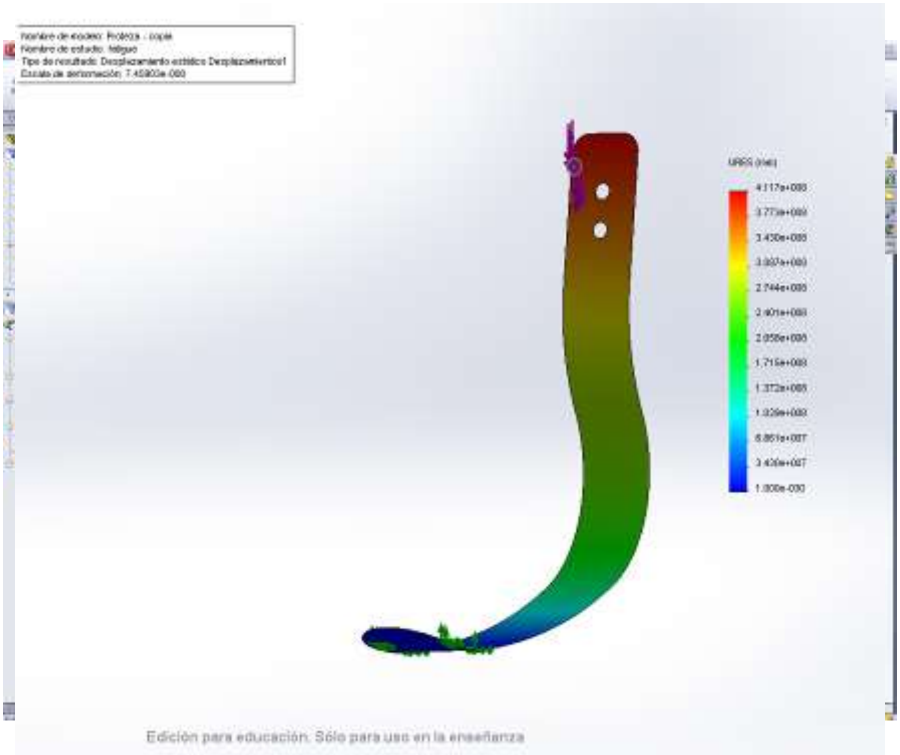
Load 200 DaN, similar situation with the last problem.

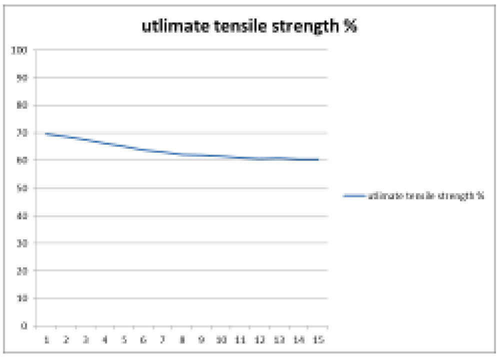


- Less than limits. 510 Mpa.
- Displacements.



- Displacement 212 mm



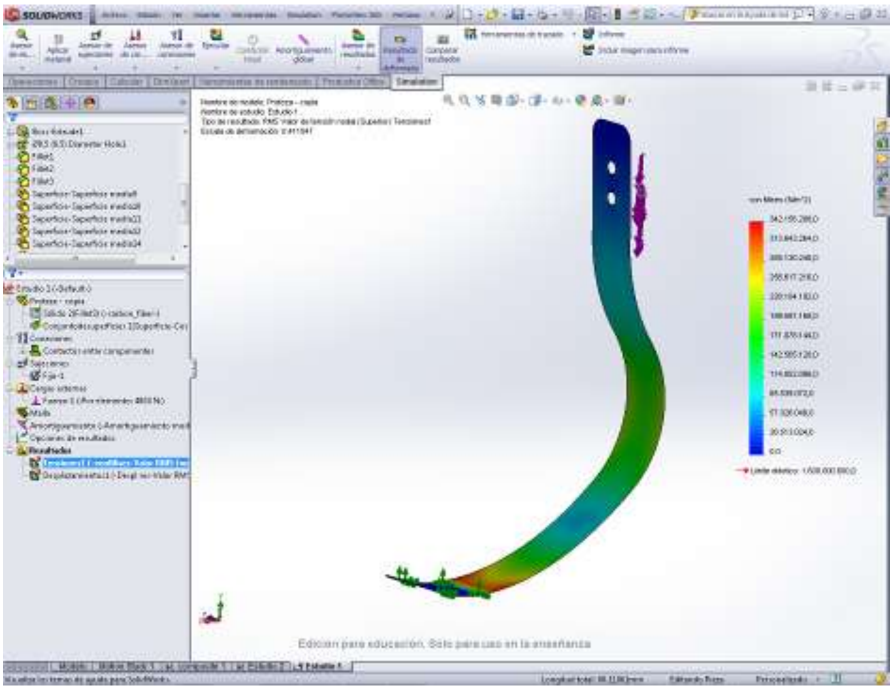


- Generic S-N curve for carbon fiber/resin prepegs.

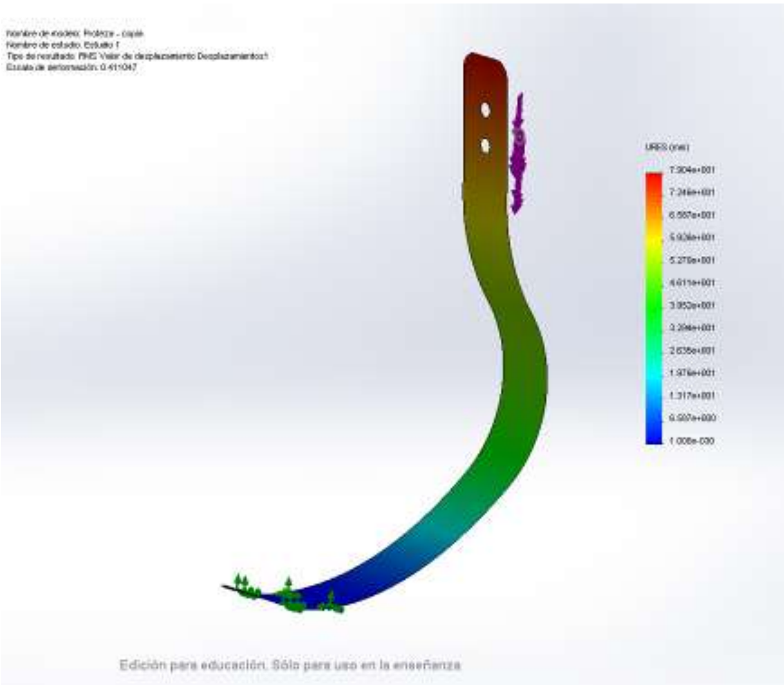
5.4.6.2. Dynamic linear analysis.

A. Loading force *F*=400 daN**. Blade constant thickness of** 6 mm.

We use the same procedure of last analysis. We assigned the carbon fiber material used last time. Thickness assignation 6 mm

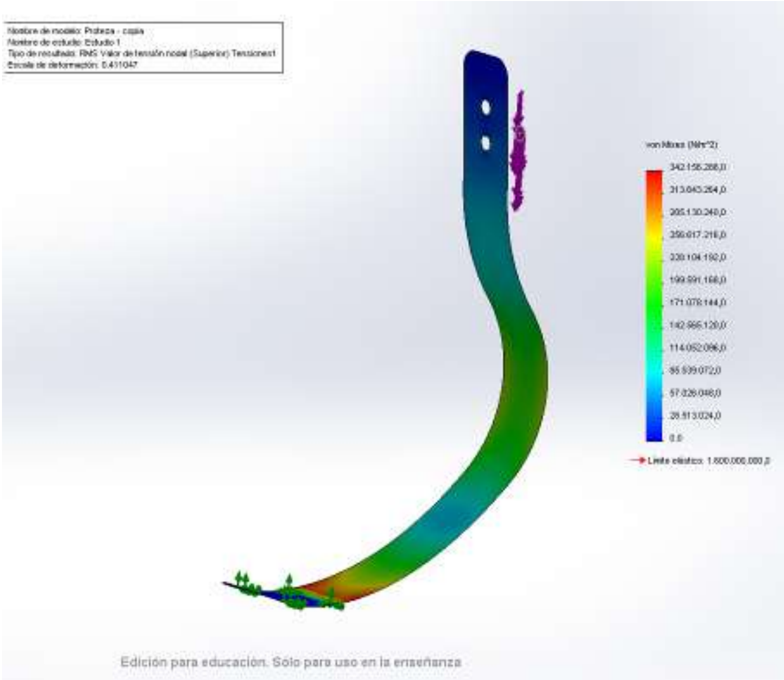


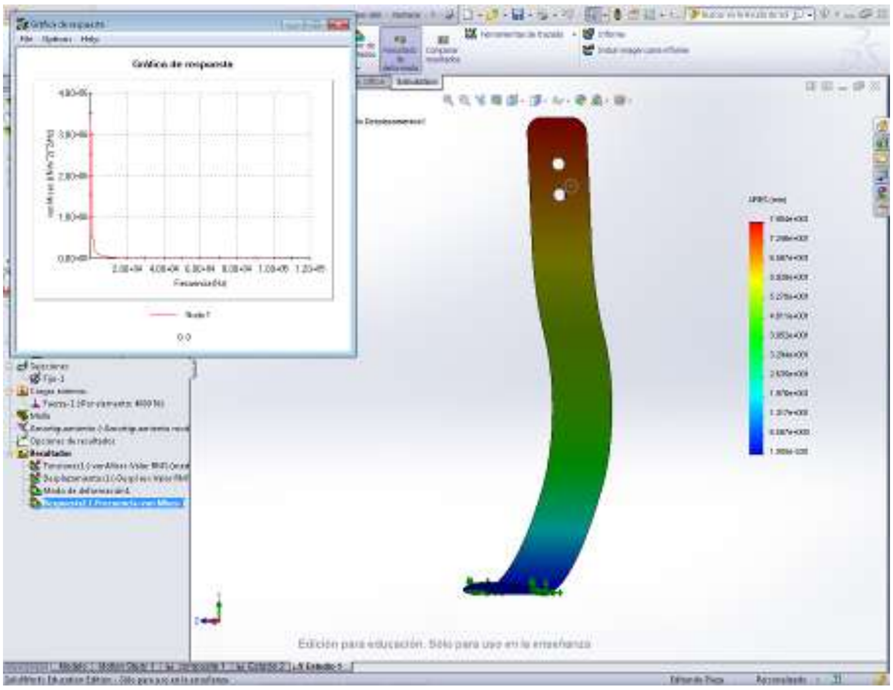
Dynamic load 400 daN/Hz; dumping mode 0,8



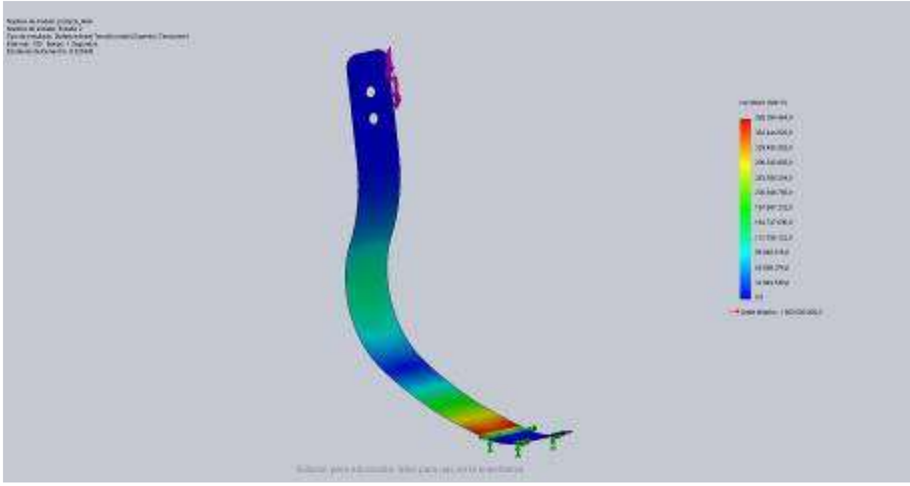
Displacements 79 mm on the top of the part.

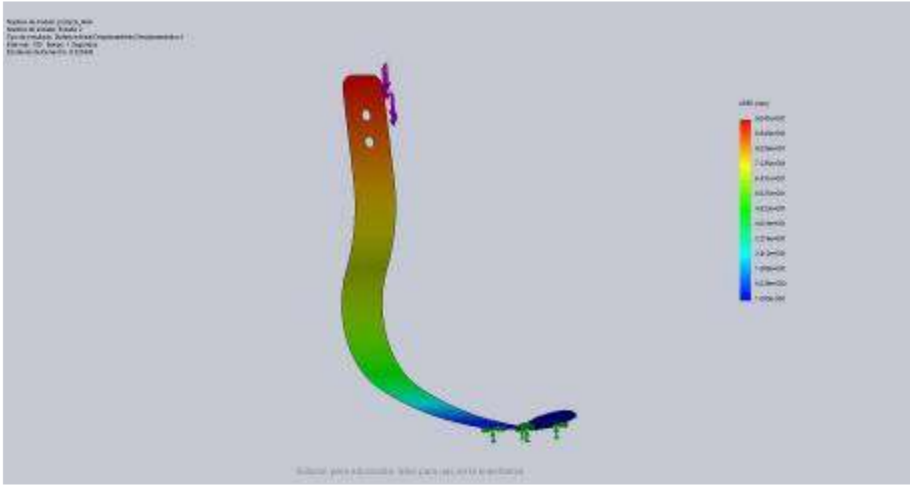
Von Misses stress





B. Loading force *F*=400 daN**. Blade variable thickness of** 4÷6 mm.





Displacement 9.4 mm

The simulating process generates the following conclusions:

- blade displacements decrease with the loading force decreasing;
- dynamic simulations make evident the real conditions of blade behavior, illustrated by displacements values;
- if the blade has a variable thickness of 4÷8 mm (at the peak), the mechanic behavior of layered composite is improved: 9.6 +001 mm.

5.5. METHOD FOR DETERMINING THE EPOXY/CARBON FIBER REINFORCED COMPOSITE BEHAVIOR IN PROSTHESIS NORMAL FUNCTIONAL CONDITIONS

Through this calculus is aimed to find information for dimensioning the prosthesis and its testing in similar conditions with real exploitation conditions. For this, the calculus pattern was done in programming environment LabView (Fig. 5.32), as rapid and continuous observations could be obtained for different inputs (loads, prosthesis's dimensions, admissible stresses and strains etc.). Concretely, it is aimed to find out if the prosthesis would resist in exploitation at similar loads as those developed during race of adults or children. In addition, the application allows simultaneous checking for various sizes of prosthesis (width, the thickness given by the number of carbon fiber lamina and the length determined by the support point).

LabView application has a graphic interface (fig. 5.32), in which the dialog box for input values are in red and, the results boxes are green.

The input data are related to:

- admissible maximal strains in the critical point (F_a - admissible arrow);
- admissible maximal stresses for different thickness of material (number of layers);
- applied load on the prosthesis (determined by the weight in support on it during the contact with the ground);
- length of the prosthesis arm in report to support point on the ground (distance between the support point and the load application point);
- material elastic modulus (variable with the number of layers);
- prosthesis width;
- prosthesis thickness;
- the height of contact point with the ground (the height wherefrom the prosthesis descend on ground during race).

The values of admissible maximal strains of material used for prosthesis manufacturing (pre-impregnated carbon fiber), of admissible bending maximal stress, respectively the Young modulus (elastic modulus) are the values obtained by the experimental research on three points bending of prosthesis material samples. The other values are measured values on different manufactured prototypes or indicated in specific literature.

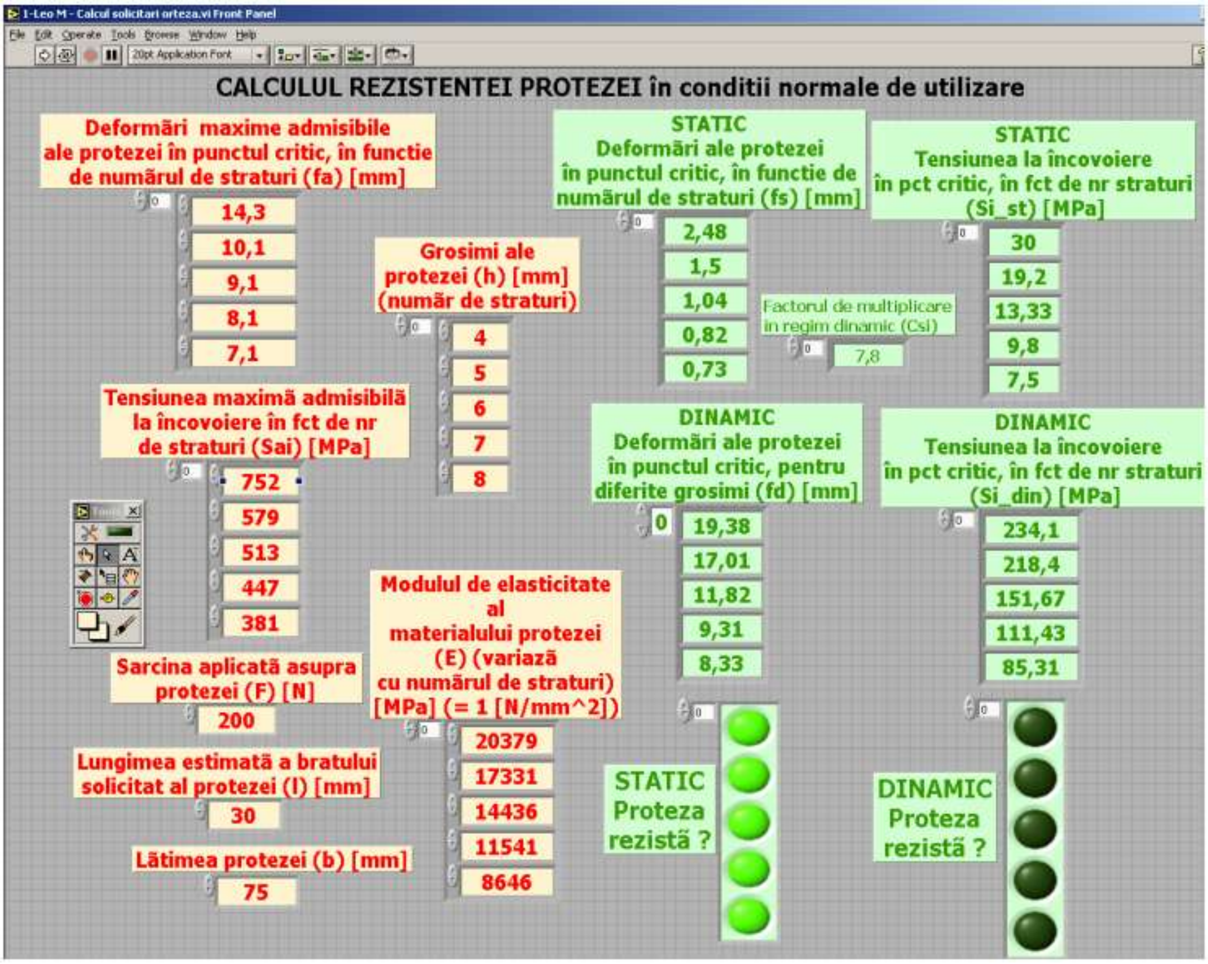


Fig.5.32. Interface for displaying the results of prosthesis behavior simulation.

The simulation results are related to two categories of values: numerical values and Boolean values concerning the degree of non-resistance of the prosthesis to the simulated loading values:

- numerical values concern the static and dynamic prosthesis strains, where the static regime implies the subject support on the prosthesis with its whole weight, without shock (orthostatic position with the whole weight in support on contact area of the prosthesis);
- dynamic regime concerns the real gait and/or race conditions, when the subject steps and place all its weight on the prosthesis contact point with the ground, with a shock coefficient determined by the fact that the gait supposes the descent of the foot (of the prosthesis) on the ground from a certain height.

The Boolean results give information on the response if the prosthesis resists to static and dynamic loads with respect of two aspects:

1. the prosthesis strains must comply with the maximum permissible limit up the plastic flow material.

2. Bending stress must be less or not more than the maximal stress (experimentally determined).

The application supposes the development of a program routine that contains a sequential structure with four distinct sequences. In the first, the prosthesis static deformation calculus sub routine is realized: (Fig. 5.33)

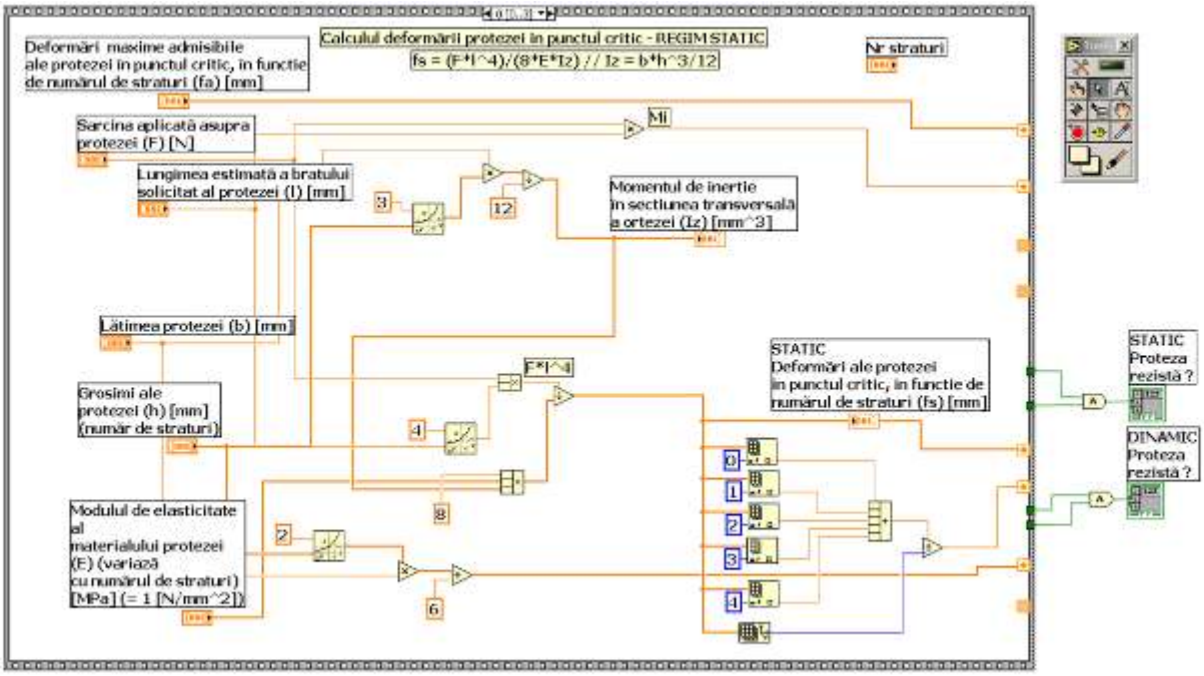


Fig. 5.33. First sequence.

In this subroutine, the mathematical operators specific to arrow calculus are defined:

$$f_s = \frac{3E \cdot I_z}{F \cdot l^4}, \tag{5.26}$$

where: f_s is the static deformation (static prosthesis arrow in report with the support point on the ground), F is the longitudinal elastic modulus (Young modulus), $I_z = \left(b \cdot h^3\right)/12$ is inertial moment in the transverse section of the prosthesis, where b is the prosthesis width and h is its thickness, determined by the layers number.

The second sequence concerns to the program subroutine for determining the dynamic prosthesis arrow (Fig. 5.34). It contains the structures specific to the relationships for dynamic deformation (arrow) calculus:

$$f_d = \psi \cdot f_s(2), \tag{5.27}$$

where: f_d is the dynamic deformation (arrow), $\psi = \sqrt{\frac{2H}{F \cdot s}}$ is the multiplying factor caused by specific dynamic shock regime, where H is the height of prosthesis descendence on the ground.

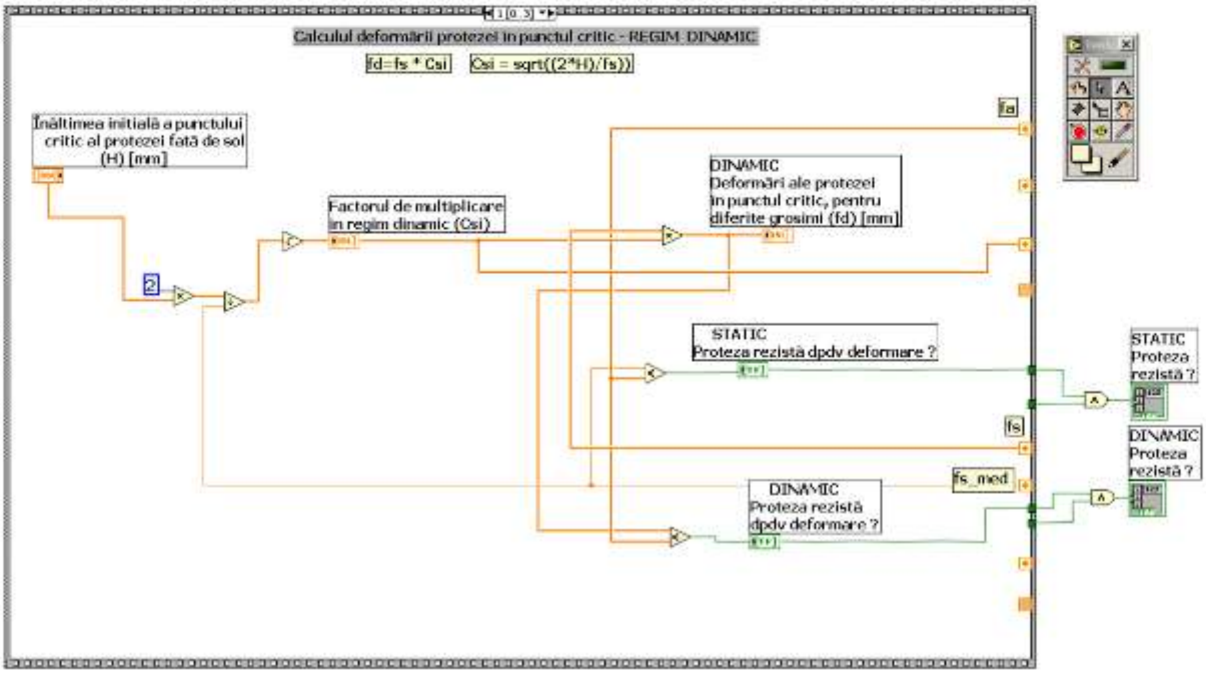


Fig. 5.34. Second sequence.

In the third sequence, the program subroutine structures for static stresses, where the bending stress is done by:

$$\sigma_{i\_s} = \sqrt{\frac{M_i}{W_z}}, \tag{5.28}$$

where: M_i is the prosthesis bending moment in the fixation zone, $W_z = (b \cdot h^2)/6$ is the resistance modulus of transverse section.

The last sequence concerns the subroutine for determining the dynamic bending stress, according to relationship:

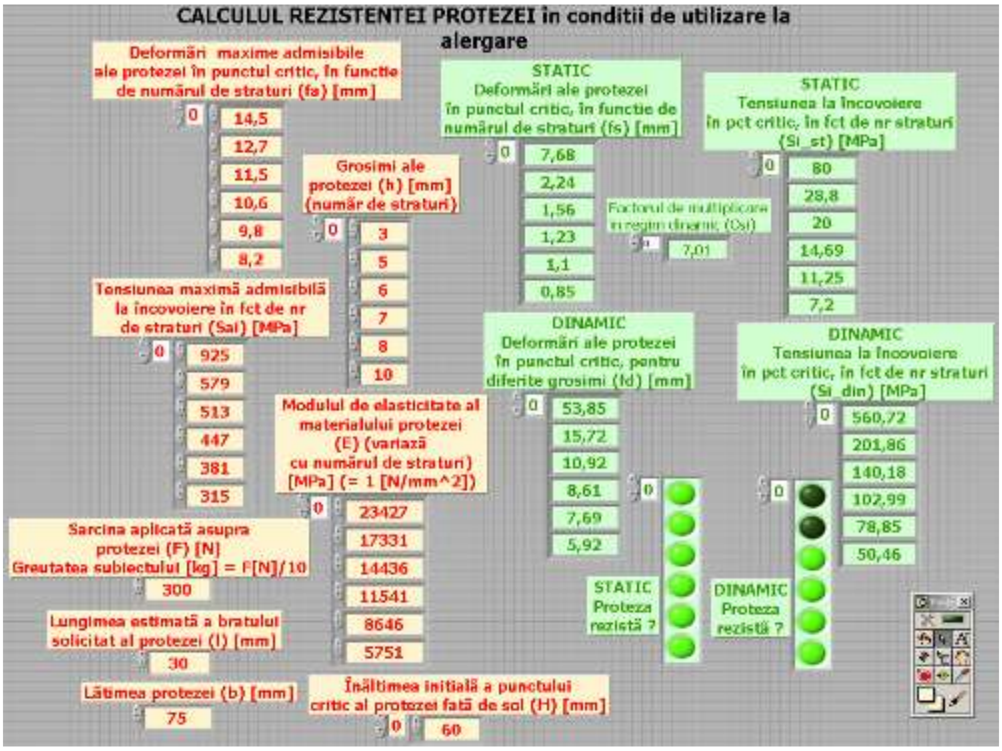
$$\sigma_{i\_s} = \Psi \cdot \sigma_{i\_s}, \tag{5.29}$$

where Ψ is calculated with (5.27)

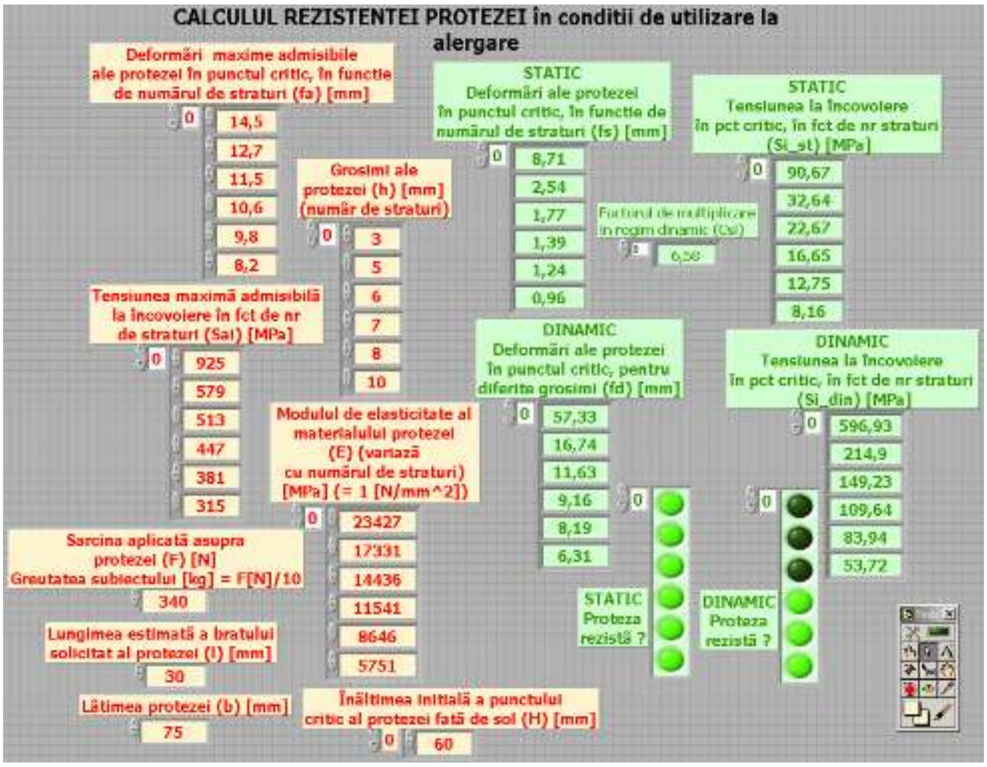
5.7. DISPLAY PROSTHESIS BEHAVIOR SIMULATION INTERFACE

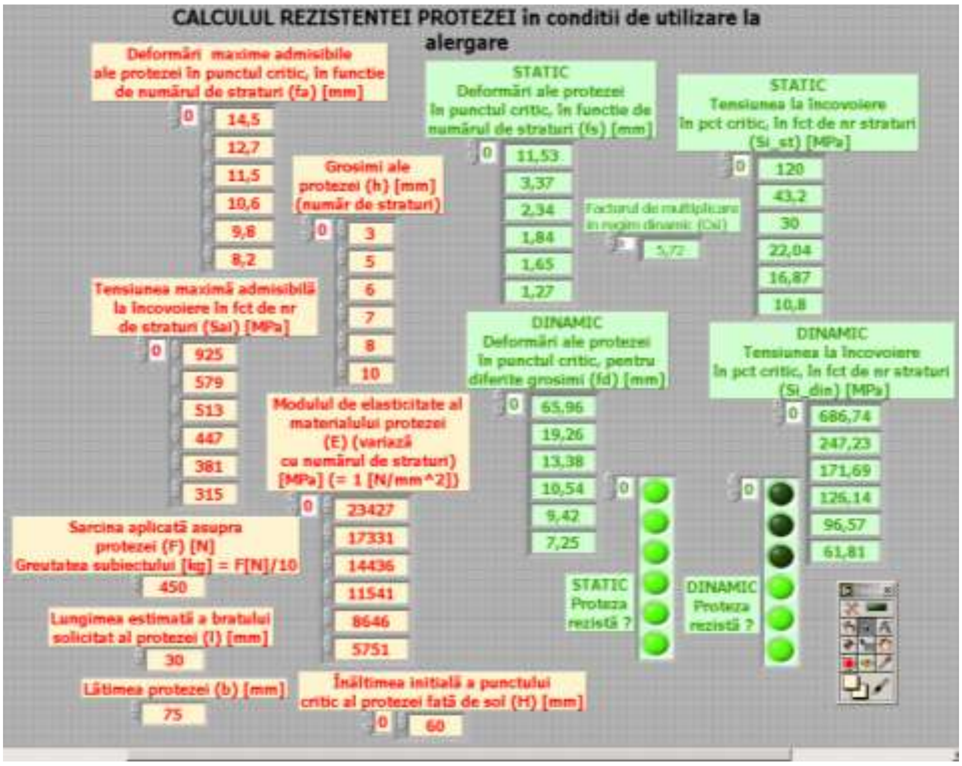
A. Conversational window for user

A_1 for a ***subject with the weight up to 33 kg****, a prosthesis with* ***minimum 6 layers*** *can be used.*

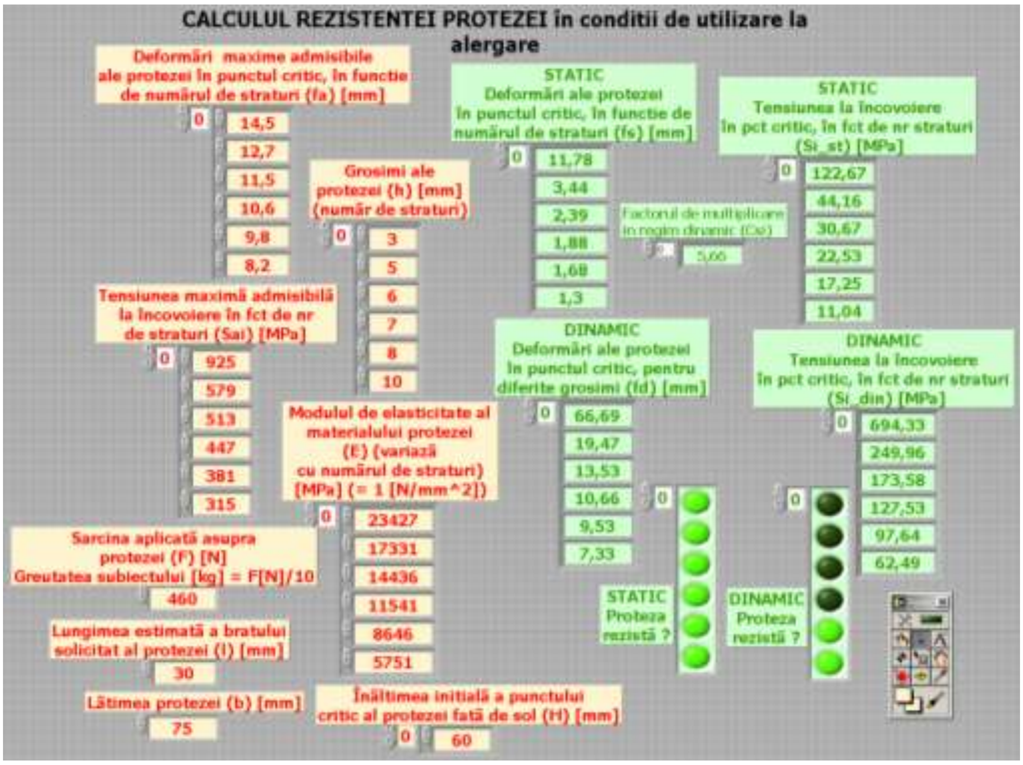


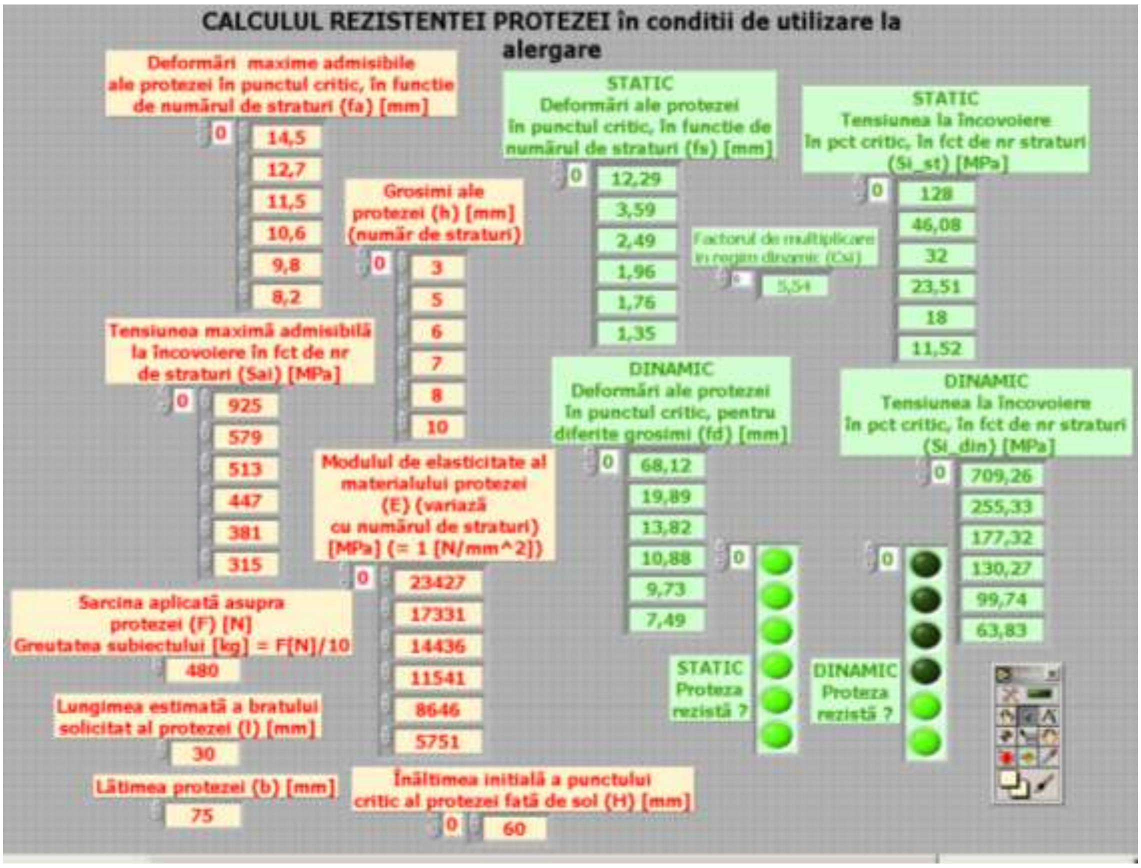
A_2 for a ***subject with the weight of 34 ÷ 45 kg****, a prosthesis with* ***minimum 7 layers*** *can be used.*



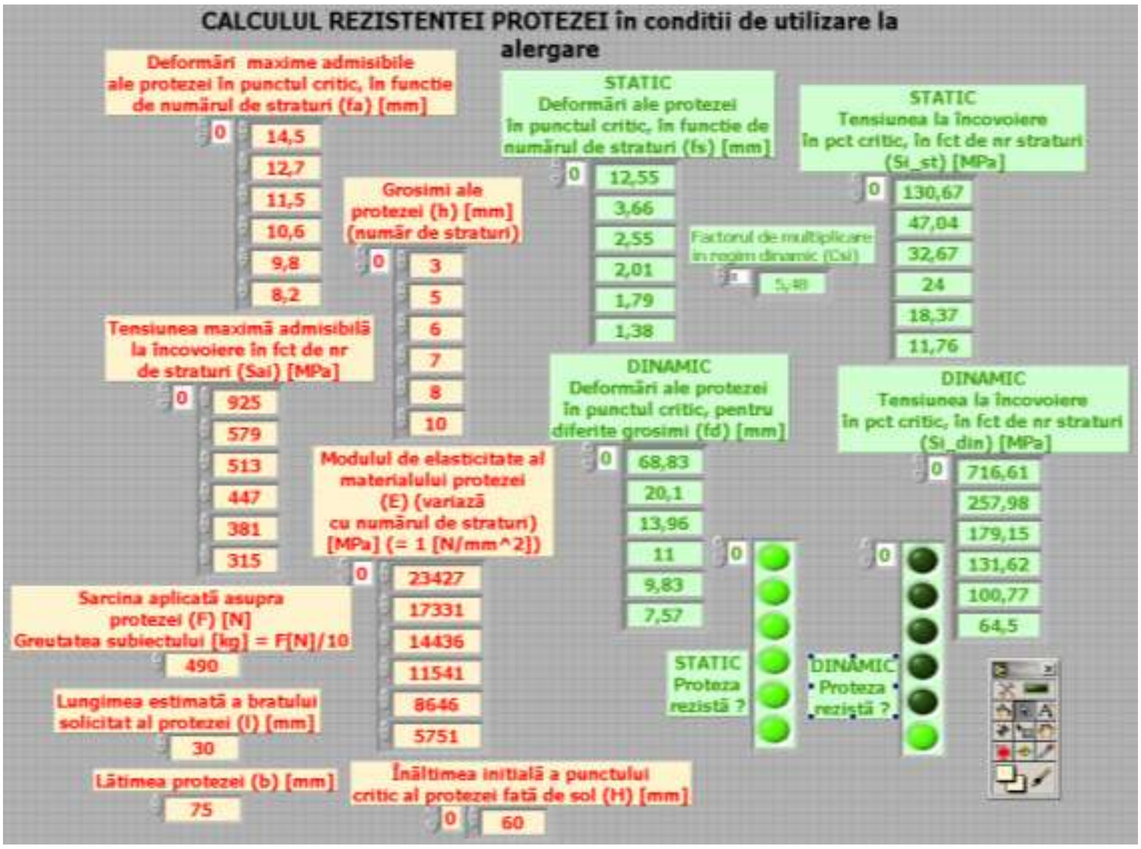


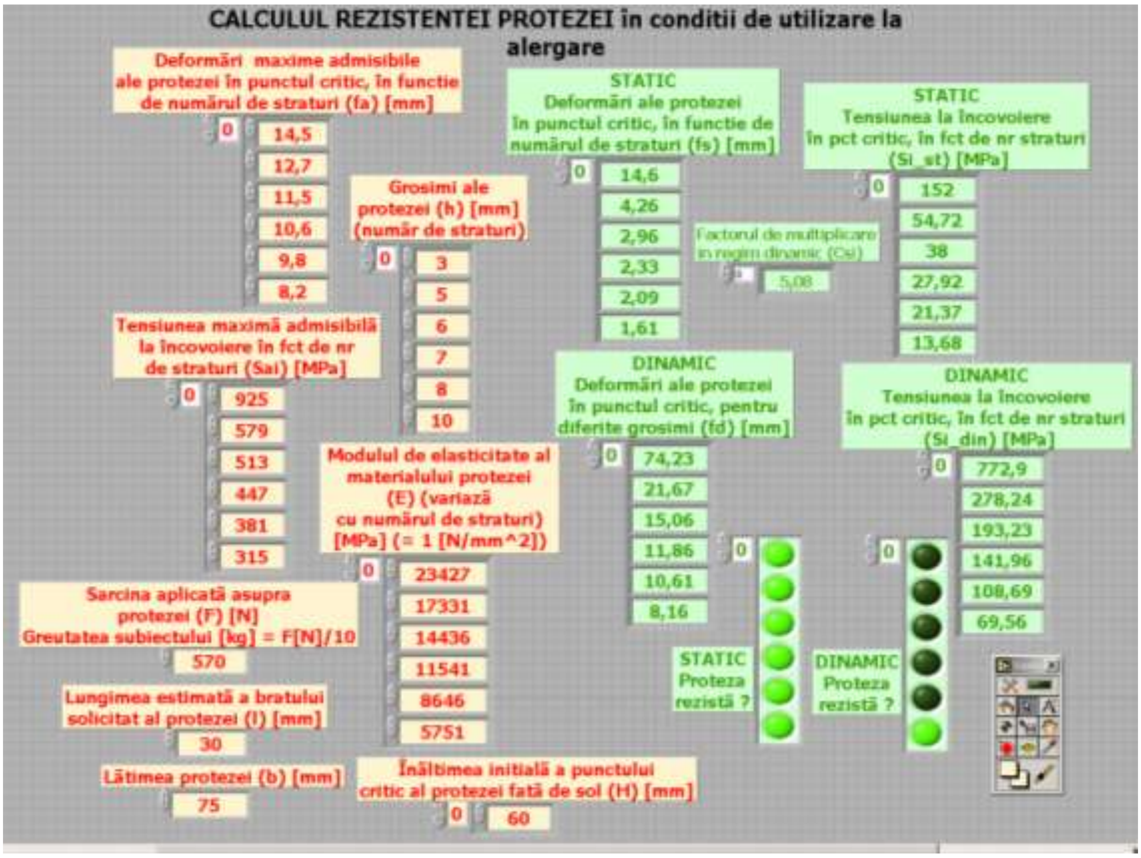
*A_3 for a **subject with the weight of 46 ÷ 48 kg**, a prosthesis with **minimum 8 layers** can be used.*



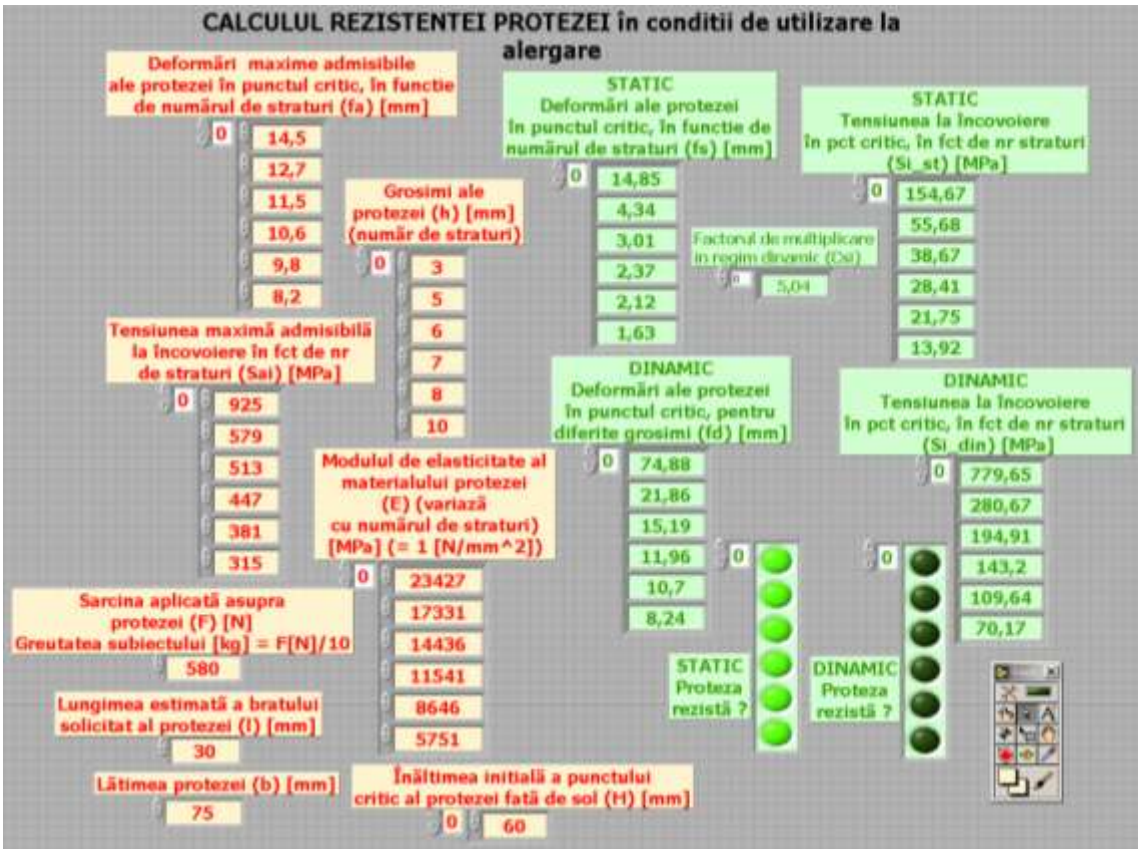


*A_4 for a **subject with the weight of 49 ÷ 57 kg**, the prosthesis has with **minimum 10 layers**.*

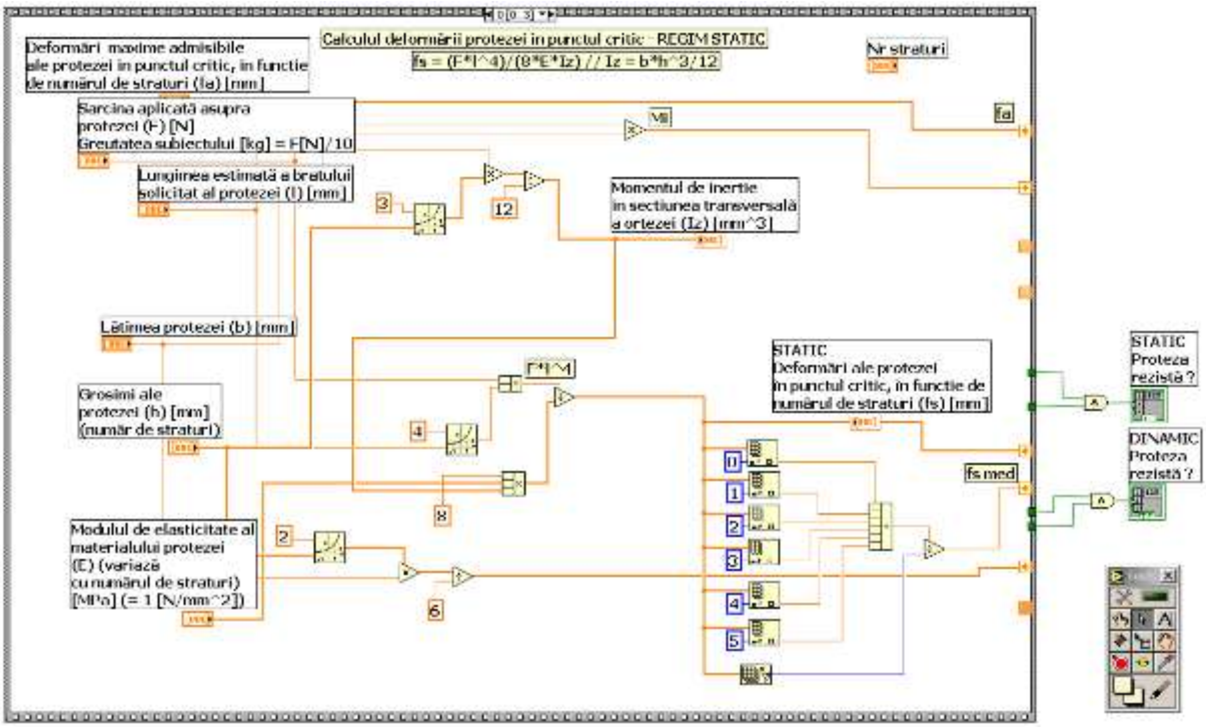




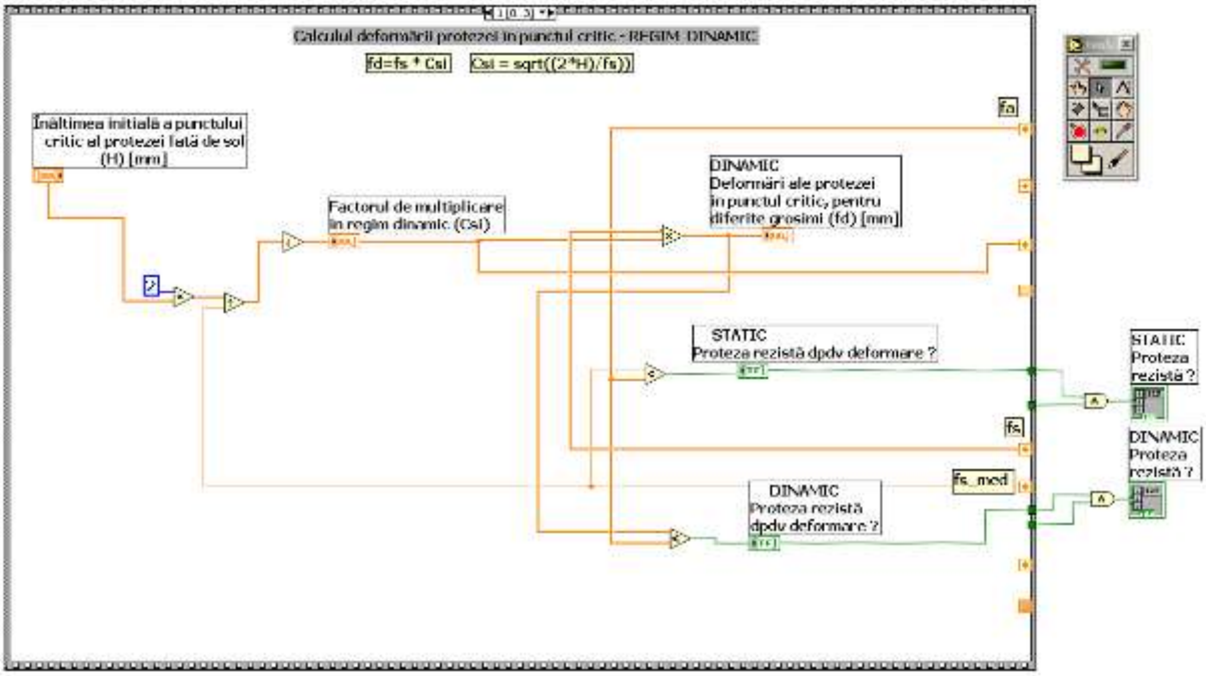
*A_5 for a **subject with the weight greater than 57 kg**, the prosthesis must have **bigger dimensions**.*



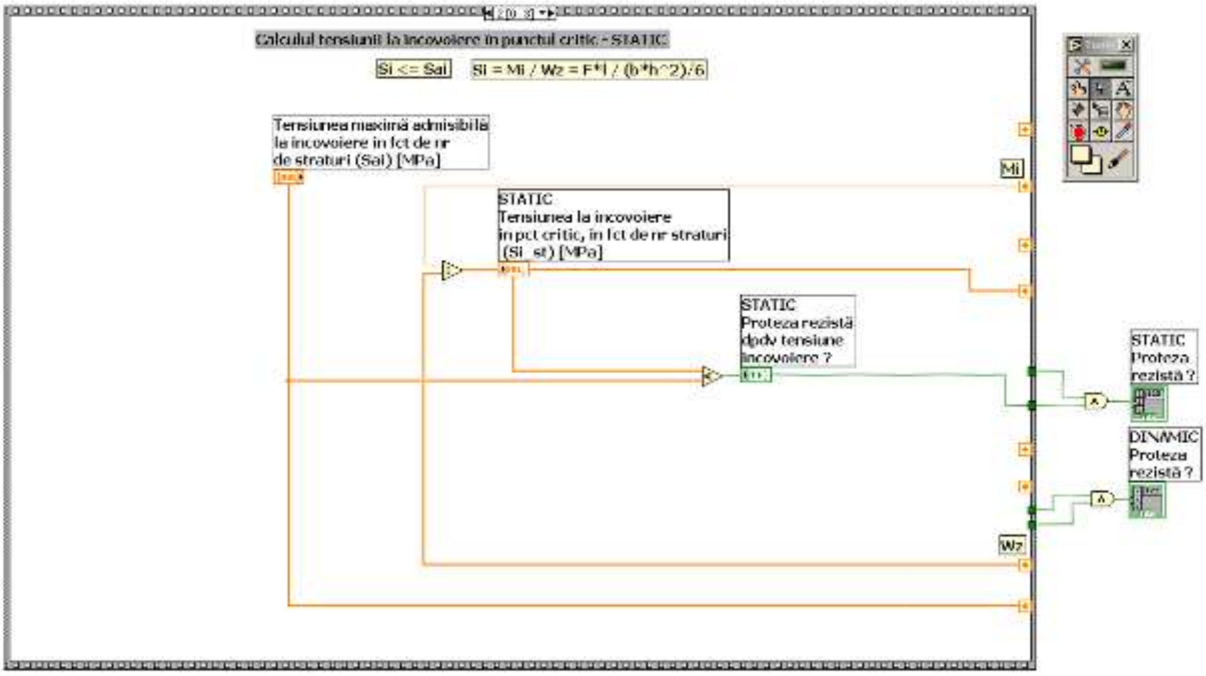
B. Conversational window for application programation



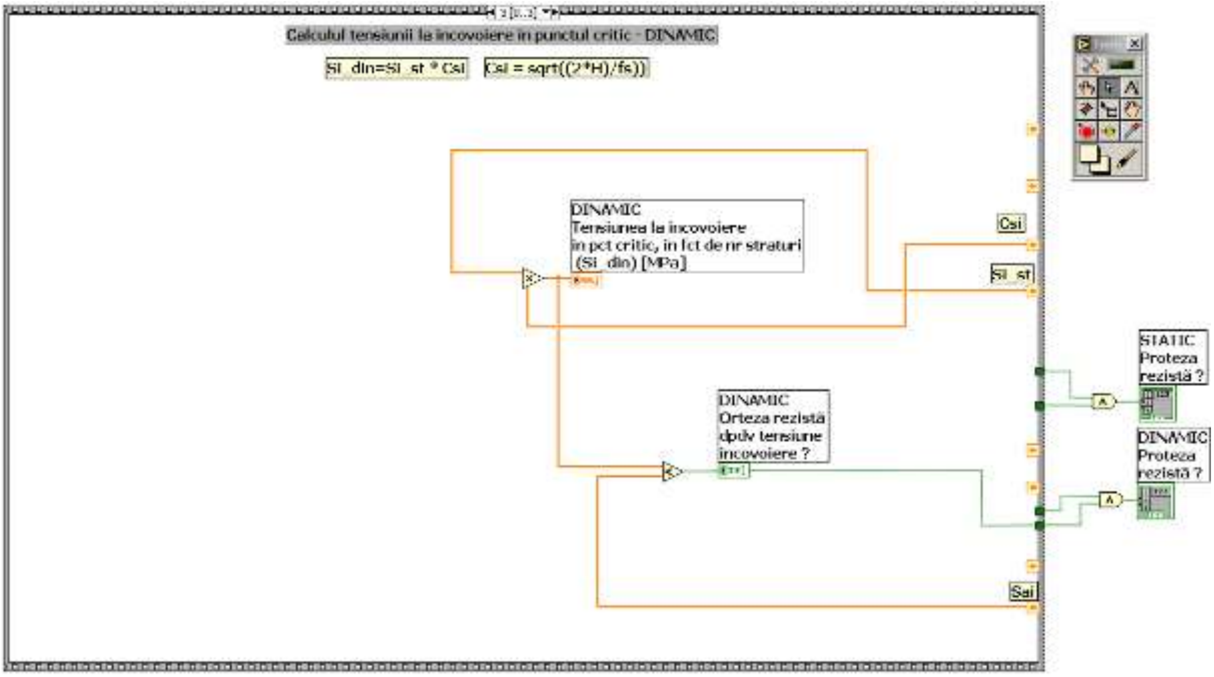
Sequence 1



Sequence 2



Sequence 3


Calculul tensiunii la incovoiere in punctul critic - DINAMIC
Si_din=Si_st * Csi
Csi = sqrt((2*H)/fs))
DINAMIC
Tensiunea la incovoiere
in pct critic, in fct de nr straturi
(Si_din) [MPa]
Csi
Si_st
STATIC
Proteza
rezistă ?
DINAMIC
Orteza rezistă
dpdv tensiune
incovoiere ?
DINAMIC
Proteza
rezistă ?
Sai

Sequence 4

CHAPTER **6**

EXPERIMENTAL DETERMINATION OF CARBON FIBER REINFORCED MULTILAYERED COMPOSITE MECHANICAL PROPERTIES

6.1. SUCCESSION OF STAGES FOLLOWED IN EXPERIMENTAL RESEARCH

The experimental research aimed to test experimentally the samples as those presented in figure 6.1. In the experimental study carried out to determine the mechanical properties of the multilayered composite, the tests for determining the tensile characteristics were dropped, and compressive and bending tests were preferred. In this research approach, the constructive, functional characteristics of J prosthetic blade were took into account. [*Des.13], [*Oss.13], [*Gur.12], [*Gui.12] In the same time, the bending and compression tests have been completed with dynamic type DMA tests.

The experimental research also aimed the determination of the thermal expansion coefficient of multilayered composite, being well known its importance in describing its behavior. [Kar.05]

6.2. PREPARATION OF TEST SPECIMENS

For test specimens, multilayered plates armed with carbon fibers and epoxy resin were manufactured. The talons, necessary for compression test were also manufactured. Laminated plates, wherefrom the test pieces have been taken, has been fabricated according to a well known technology. [Roş.10], [Gur.12], [*Gui.12] Test specimens were executed in multilayered composite configurations: with 3, 5, and 7 layers.

There, plates with 3, 5 and 7 layers were been laminated from which pieces have been cut for the test. The drafting process has the following steps:

1. Layers of unidirectional, diagonal connected carbon fiber fabrics were impregnated with epoxy resin, with respect of norms for pre-impregnated blades [*Ast.99], [*Ast.99.a], [*Gui.03]:

- fabric with diagonal type connection has a specific gravity of $3 \cdot 10^{-4}$ kg/m^2;
- the layers of fabric were impregnated with epoxy resin;

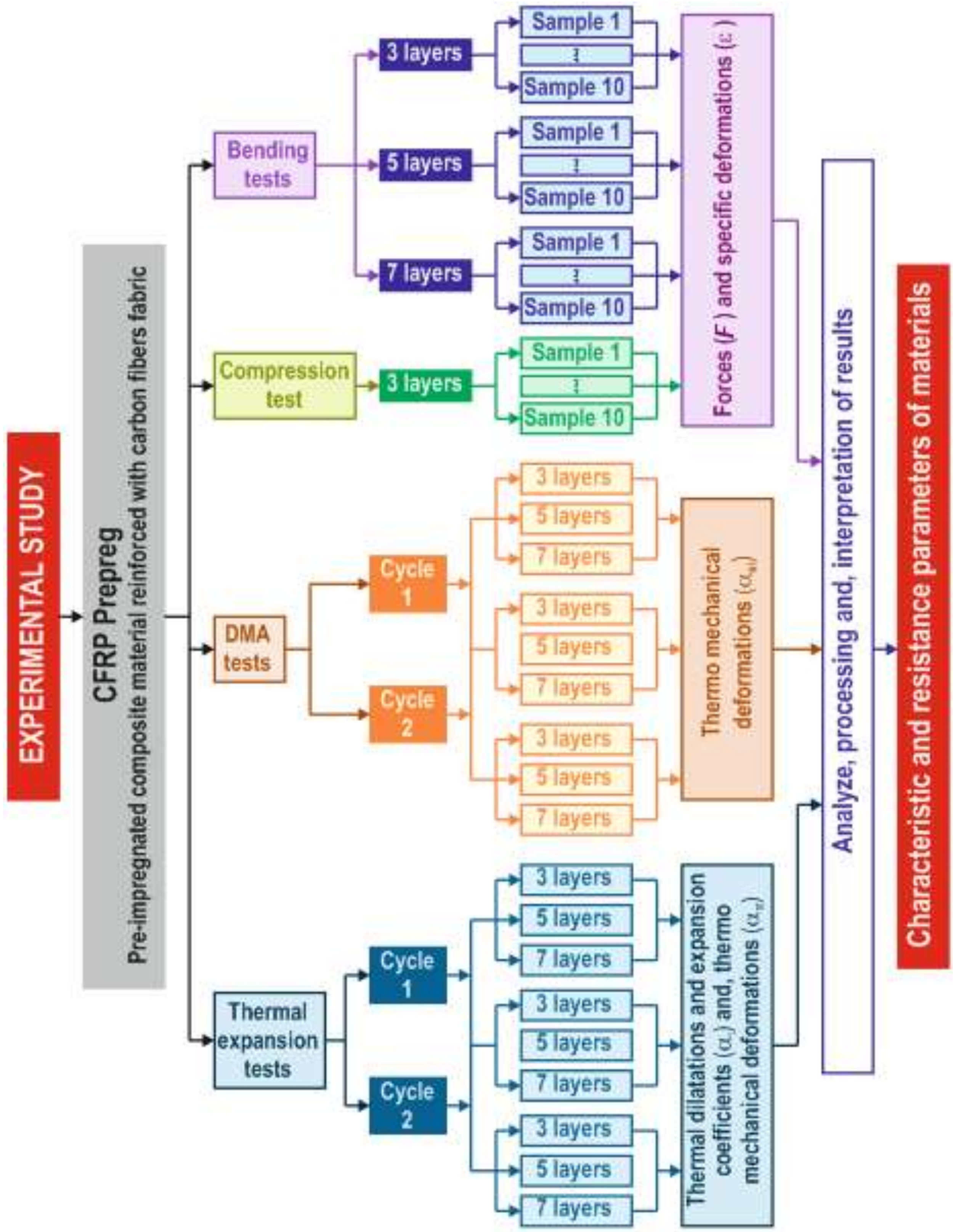


Fig. 6.1. Experimental study stages.

2. Pre-impregnated lamina were covered with foil and kept at low temperature until the multilayered material was manufactured;

3. Final form of layered plates was achieved through a process of polymerization: controlled pressure and temperature.

Test pieces for mechanical tests at compression and bending were debited using a cutting device Proxxon 27070 (D) with diamond blade size of 80 mm and, width 2 mm, at the appropriate forms and dimensions of each type of stress.

6.3. DETERMINATION OF MULTILAYERED COMPOSITE MATERIAL MECHANICAL PROPERTIES IN COMPRESSION

6.3.1. Form and dimensions of samples

The form and the dimensions of multilayered composite material [*Sre.03] are presented in figure 6.2 and in the table 6.1.

Compression tests have been performed on a composite with three layers and it was considered that its thickness *b* provides basic information concerning the behavior of prosthetic blade. A number of 10 pieces, numbered in the configuration shown in Figure 6.3 were manufactured. Thus, is ensured the minimum number of measurements required to obtain information on the statistical values for necessary data processing.

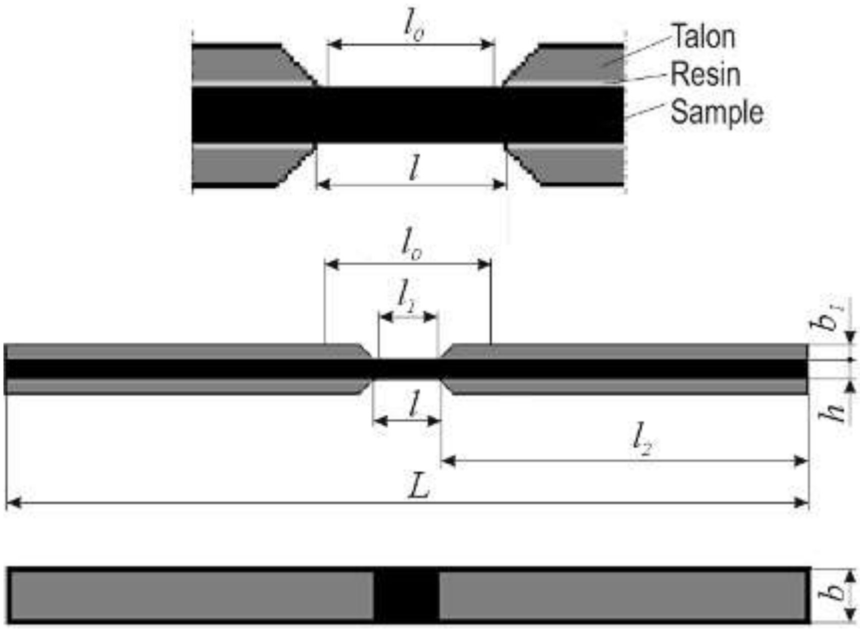


Fig.6.2. Standardized dimensions of specimens for compressive tests.

Table 6.1. Geometrical parameters of epoxy pre-impregnated carbon fiber multilayered composite samples.

Samples of epoxy pre-impregnated carbon fiber multilayered composite							
Total length L *mm*	Distance between talons l *mm*	Reference length l_0 *mm*	Distance between clamps l_1 *mm*	Talon length l_2 *mm*	Sample width b *mm*	Talon thickness b_1 *mm*	Composite thickness h *mm*
110	12	10	20	50	8	2	2.3

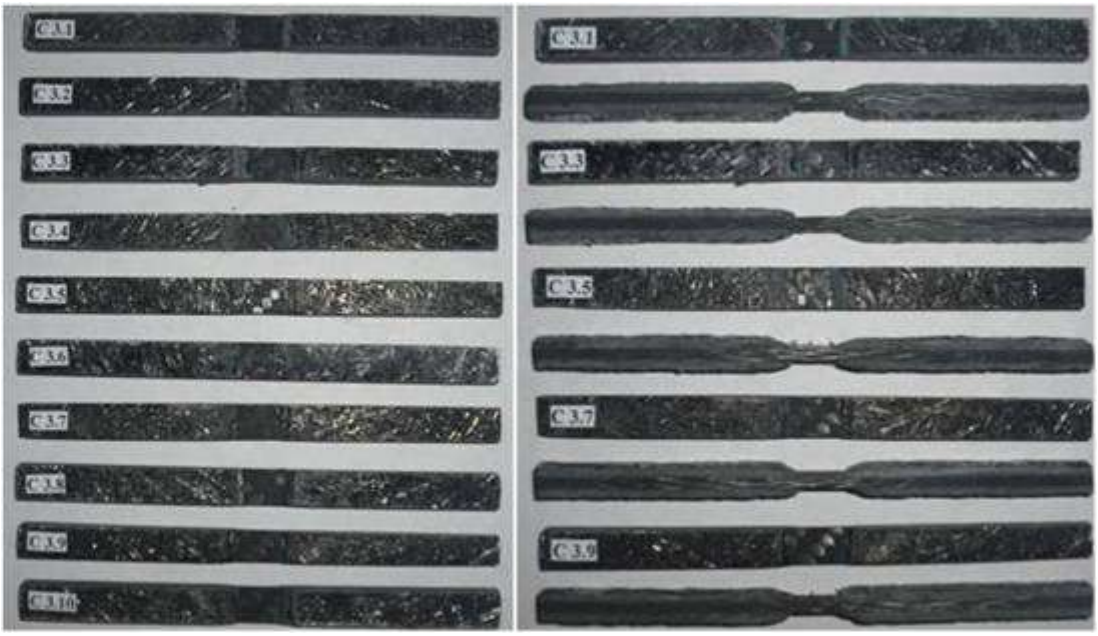


Fig.6.3 Samples used for compression tests – general view.

6.3.2. Working method

6.3.2.1. Experimental device description

Experimental compression tests were performed by sample loading on testing machine LS100 Plus from Lloyd Instruments (UK) shown in figure 6.4, charging cell type XLC-5K-A1, till a maximum force of 100kN. The testing machine has the following characteristics and technical data:

Characteristics:

- Easy to set up, use and maintain;
- Allows the force measurement with high precision;
- Maintains a constant load;
- The data sampling rate of 8 kHz;
- Coefficient of compression resolution < 0.01%;

- Load rate control;
- Save up to 600 results;
- Settings for 10 different tests;
- Samples can be preloaded;
- Performs tests composed from many different steps;
- Wide range of accessories.

Technical data:

- Maximal force – 100 kN;
- Hold-down speed: 0.001 ÷ 254 mm/min under 50 kN and, 101.6 mm/min up to 100 kN;
- Compression load force of samples (3 mm thickness) – 5 kN;
- Speed precision: < 0.2%;
- Maximum hold-down displacement: 840 mm;
- Maximum width between columns: 4 mm;
- Specific stress resolution: < 0.01%;

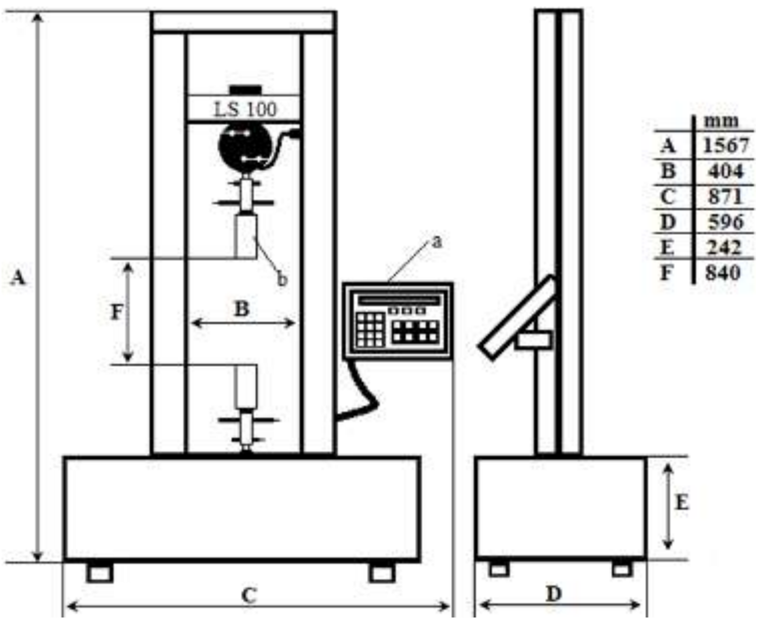


Fig.6.4. Universal testing machine (LS100 Plus) - scheme and sizes: a - control panel with electronic display; b - hold-down for samples gripping.

- Strain resolution: < 0.03 μ;
- Acquisition data rate: 8 hHz;
- Displays up to: 40 characters × 4 lines LCD;
- Type of output signal: digital RS323, analog 10V DC;
- Optimum temperature operation range: 5°-35°C;

- Experimental data analyze software: NEXYGEN data analysis softer;
- Device weight: 200 kg;
- Experimental data collected for a number of samples (10 in this case) by the software NEXYGEN Plus

Collected data are statistically processed for identification of minimum, average and maximum values of compression elasticity modulus, of stiffness, of stress and strains in conditions of a maximum load etc.

6.3.2.2. Sample fixing on testing device

Each sample shall be placed in the clamps so that its longitudinal axis to be aligned with the axis of installation. The machine has the possibility to ensure a correct alignment between clamps. Fixation mode is presented in figure 6.5.

6.3.2.3. Testing speed

During compression testing, the clamps move with the speed specified in the technical note of installation, according to the applied load. In the specific done tests, a speed of 1 m/s was chosen and it was maintained constant.

a) b)

Fig. 6.5. Sample fixation on testing machine LS100 Plus: a - view of the machine; b - clamping system.

6.3.3. Experimental data processing

As a result of the experimental research, values of compressed composite properties were obtained: longitudinal elasticity modulus, admissible stress and stiffness corresponding to the obtained forces at sample breaking. In figure 6.6 are represented the variations recorded for five samples representative according with their structure and associated strain. In table 6.2, the experimental values for three layers composite material architecture can be seen.

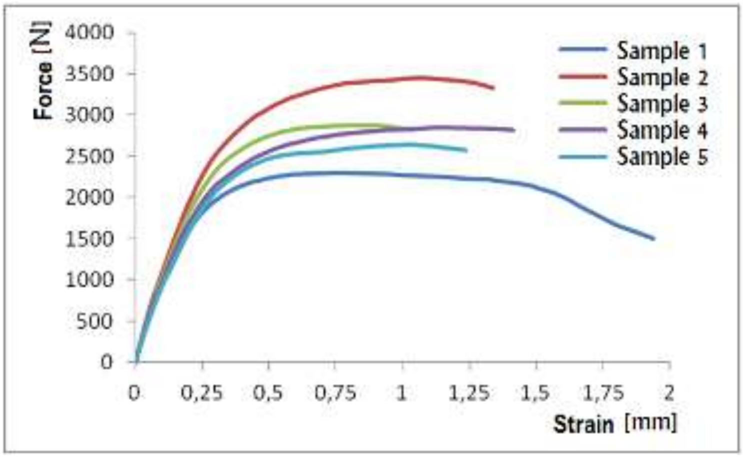


Fig.6.6. Force-elongation dependence curve for three-layer composite of carbon fiber.

Table 6.2. Experimental values associated to individually compression tested specimens.

Sample	Stiffness *K* *N/m*	Longitudinal elasticity modulus *E* *MPa*	Permissible stress *σ* *MPa*	Breaking forcce *F* *N*
Sample 1	11369473,82	6179,061858	124,897262	2,29810962
Sample 2	13441712,81	7305,2787	187,901373	3,45738526
Sample 3	12172904,55	6615,708994	156,404292	2,87783898
Sample 4	12192988,49	6626,624178	154,799217	2,8483056
Sample 5	10887213,08	5916,963631	143,603901	2,64231179
Sample 6	12112851,27	6583,07134	162,849887	2,99643792
Sample 7	12583706,48	6838,970911	199,995056	3,67990904
Sample 8	13444450,53	7306,766592	198,964576	3,6609482
Sample 9	12700112,38	6902,234988	214,369298	3,94439509
Sample 10	13617046,8	7400,568914	193,844534	3,56673942

Based on these data, σ-ε experimental curves were traced out for the five representative samples of 10 pieces lot tested (Fig. 6.6).

In the figure 6.7, the recorded variations stress-specific deformation *σ(ε)* are represented for five representative samples in carbon fiber reinforced composite composed of three layers. It is possible to observe that for values greater than 125 MPa, the curves have a linear variation that is not associated to composite structure behavior as response to the external loading but, to some specific clamping conditions in machine. Due to the very fine exterior surfaces of composite structure resulting from their manufacturing process, basically there is a slip of them in clamps, with direct consequences shown in the variation of these curves.

It is necessary to mention the fact that any attempt by conditioning of samples external surfaces lead to the possibility of additional surface tension effects that are found in their rapid deterioration. Statistical treatment of experimental data allows obtaining the average, maximal/minimal values, the standard deviation of longitudinal elasticity modulus, stiffness, stress and deformations, recorded for the maximal loading force and/or, maximal deformation, admissible stress etc.

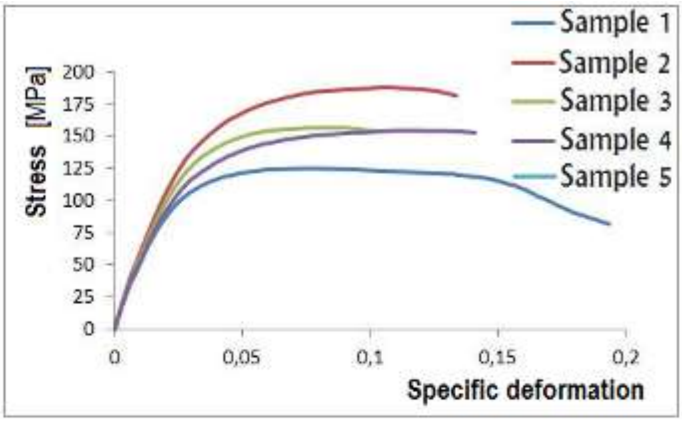


Fig.6.7. *σ-ε* experimental curves for the five representative samples of 10 pieces lot tested.

Table 6.3. Statistical values obtained for compression tested multilayered composites.

Property/Value		Maximum value	Minimum value	Average value	Median value	Standard deviation
Stiffness	*N/m*	13617000	10887000	12452000	12388000	853300
Young modulus of elasticity	*MPa*	7400,6	5917,0	6767,5	6732,8	463,75
Admissible stress	*MPa*	214,37	124,90	173,76	175,38	27,664
Stress for maximum load	*MPa*	214,37	124,90	173,76	175,38	27,664
Specific deformation for maximum load		0,11391	0,076347	0,10068	0,10433	0,011913
Stress for maximum deformation	*MPa*	209,28	81,587	165,59	168,90	35,598
Specific deformation for maximum deformation		0,19378	0,10372	0,1351	0,12955	0,023203

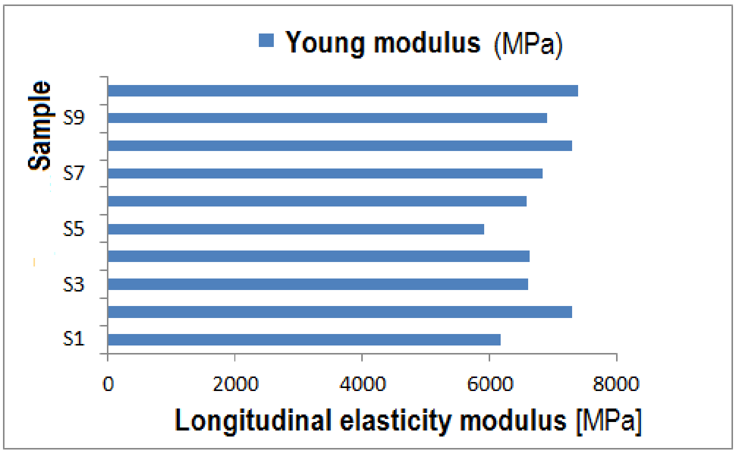


Fig.6.8. Longitudinal elasticity modulus variation for three layers composite samples.

Based on these data, in figure 6.8 is represented the variation of longitudinal elasticity modulus for all samples of carbon fibers reinforced composites with three layers, which make evident the fact that there are not major discrepancies between values Annex 4. This is also emphasized by the little value of standard deviation – of 463.75 MPa, mentioned in previous table 6.3.

6.4. DETERMINATION OF MULTILAYERED COMPOSITE MATERIAL MECHANICAL PROPERTIES IN BENDING

6.4.1. Experimental research hypotheses

Bending test characterizes the composite behavior under an external loading applied perpendicularly on its longitudinal axis. Bending tests were performed in according with EN ISO 14125 [*Sre.00.a], ASTM D 790 [*Ast.93]. the method is defined by the following characteristics [*SRE.00.a]:

- *testing speed* – v_{in} – [mm/min] defines the speed of relative movement between the supports and loading elements of installation. This speed has a constant value, at ambient temperature, and is obtained by a suitable device, component of bending test system.
- *bending effect* – σ_f [MPa] is the nominal effort on the sample's outer surface applied midway between the supports. It is calculated by the formula [Pai.09], [Nic.11]:

$$\sigma_f = \frac{3FL}{2bh^2};\qquad(6.1)$$

where: σ_f is the bending effort, *F* is the measured force [N], *L* is the distance between the supports [mm], *h,* the sample thickness [mm] and, *b* is the width of sample [mm].

- *bending effect at breaking* - σ_{fB} [MPa] represents the bending effort in the moment of sample breaking (Fig.6.9);
- *bending resistance* - σ_{fB} [MPa] represents the bending effort that sample supports at the maximum load (Fig.6.9);
- *arrow – s* [mm] is the displacement of a point from the superior side of sample in report with its initial position. It is measured at the middle of distance between supports.
- *arrow* – s_B [mm] corresponds to the moment of sample breaking;
- *arrow of bending resistance* – s_M [mm] corresponds to the maximum bending force recorded during testing;

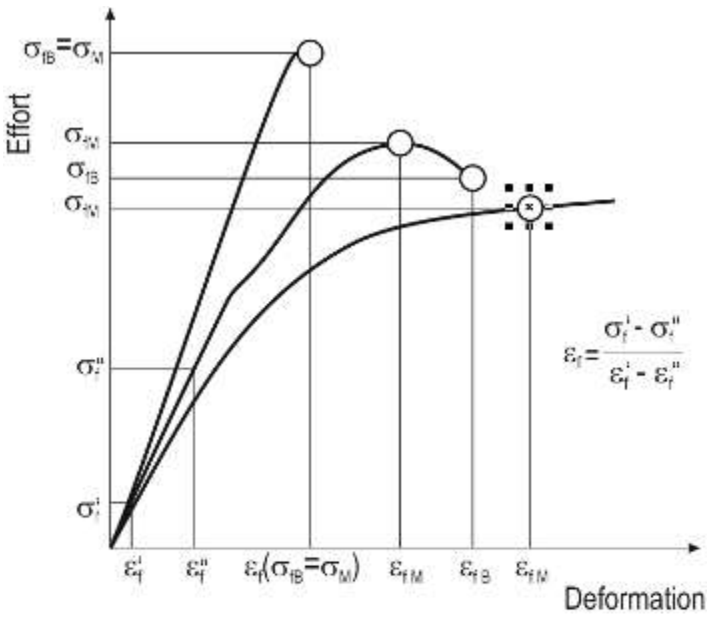


Fig. 6.9. Typical effort-deformation curve, after [*Sre.00].

- *bending deformation* - ε_f [%] represents is the dimensional variation of an elementary length situated on the external surface of sample, at the middle of distance between supports;
- *bending elasticity modulus* - E_f [MPa].

Bending testing was done by the method of three touch or three-point method (Fig. 6.10). The method involves the sample positioning on two points and the application of force midway between those two support points. Testing speed is 5 mm/min.

6.4.2. Apparatus

Experimental tests were carried out at bending by samples charging in 3 points on the test machine LR5K Plus from Lloyd Instruments (UK), with loading cell type XLC-5K-A1 and forces up to 5 kN. Installation schema and dimensions are represented in figure 6.11.

The test machine LR5K Plus from Lloyd Instruments (UK) has the following characteristics and technical data:

Characteristics:

- Easy to use and maintain;
- Easy to set up;
- Allows the force measurement with high precision;
- The data sampling rate of 1000 Hz;
- Save up to 600 results;
- Great displacement between clamps (1000 mm);
- Complete integration with the computer through the NEXYGEN™ software;
- Wide range of accessories.

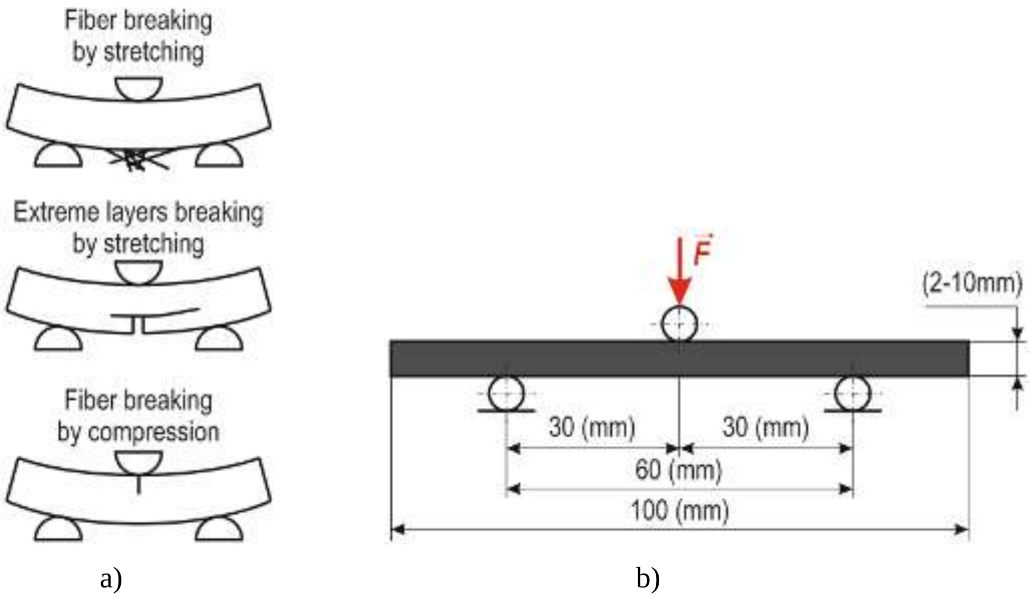


Fig. 6.10. Bending testing schema by the method of three touch or three-point: testing in three points (a); sample charging and support (b).

Technical data:

- Maximal force – 5 kN;
- Hold-down speed: 0.01 la 1020 mm/min;
- Compression load force of samples (3 mm thickness) – 5 kN;
- Compression force exerted on samples (3 mm thickness) – 5 KN;

- Speed precision: better than 0.2% in static state;
- Maximum hold-down displacement: 1000 mm, 1500 mm (with the frame expansion);
- Maximum width between columns: 404 mm;
- Specific stress resolution: < 0.005%;
- Strain resolution: better than 0.001 mm;
- Data acquisition rate: 1000 Hz;
- Display up to: 40 characters × 4 lined LCD;
- Type of output signal: digital RS323, analogous 10 V DC;
- Analyze/post treatment software: NEXYGEN MT data analysis softer;
- Working optimal temperature: 5°-35°C;
- Installation weight: 105 kg;
- Testing speed 5 mm/min.

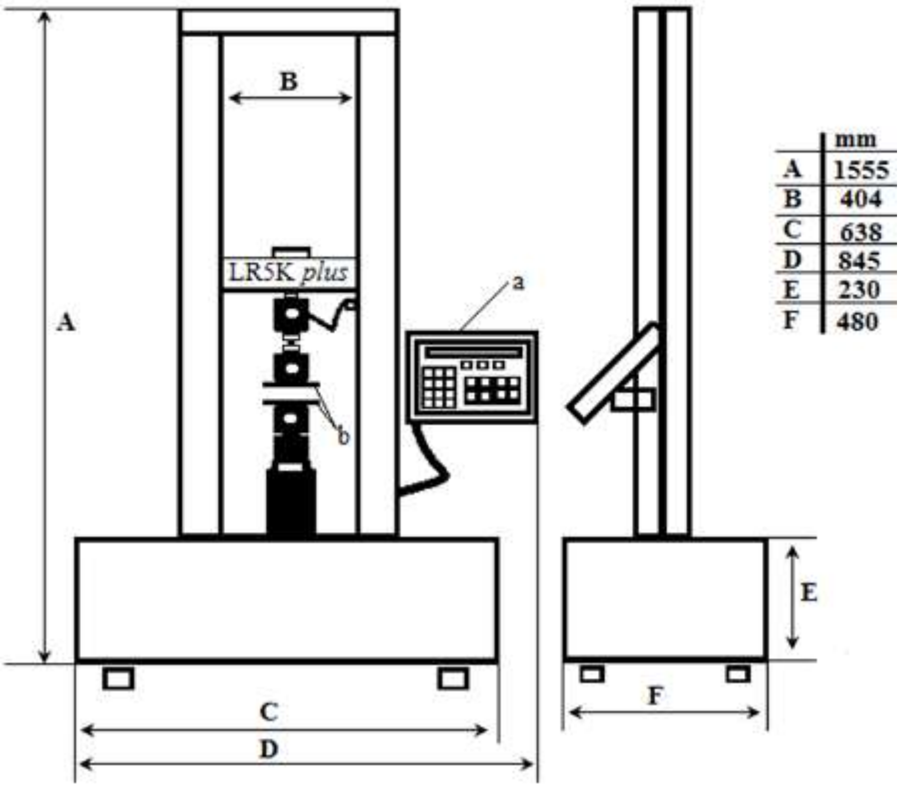


Fig. 6.11. Universal material testing machine (LS100 Plus) - scheme and sizes: a - control panel with electronic display; b - hold-down for samples gripping.

Machine's adjusting ensured the alignment of supports and spherical piercer as to be parallel with an accuracy of 0.02 mm, while the spherical piercer and supports diameters were chosen for samples bigger than 3 mm. The test machine LR5K Plus from Lloyd Instruments (UK) can treat the experimental data through the software NEXYGEN MT.

6.4.3. Samples form and dimensions

Test specimens for static bending mechanical tests were manufactured at standardized form and dimensions, presented in figure 6.12, corresponding to IV[th] class for composite materials (Table 6.4).

Table 6.4. The type of samples for three-point bending testing.

Class IV Unidirectional composite (0°) and multi-directional (systems with carbon fibers)	**Sample length** *l*	**Distance between supports** *L*	**Width** *b*	**Thickness** *h*
	mm	*mm*	*mm*	*mm*
	100	80	15	2-10
Tolerances	-0…+10	±1	±0.5	±0.2

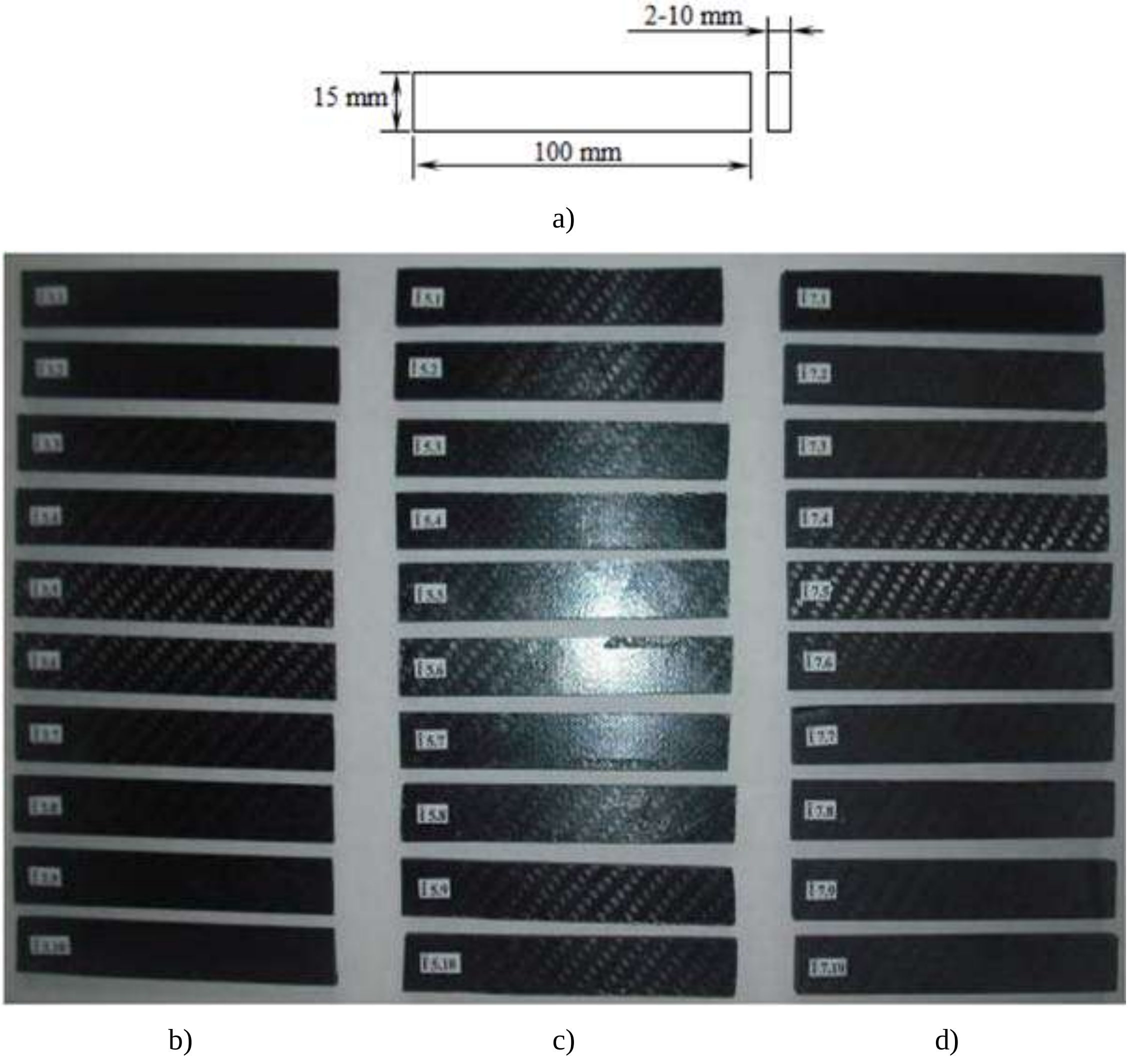


Fig. 6.12. The test-pieces from the three-point bending: geometric configuration of the specimens; b-layered with three layers; c-layered with five layers; d-layered with seven layers.

Table 6.5. Values of geometrical parameters of multilayered composite samples impregnated with resin.

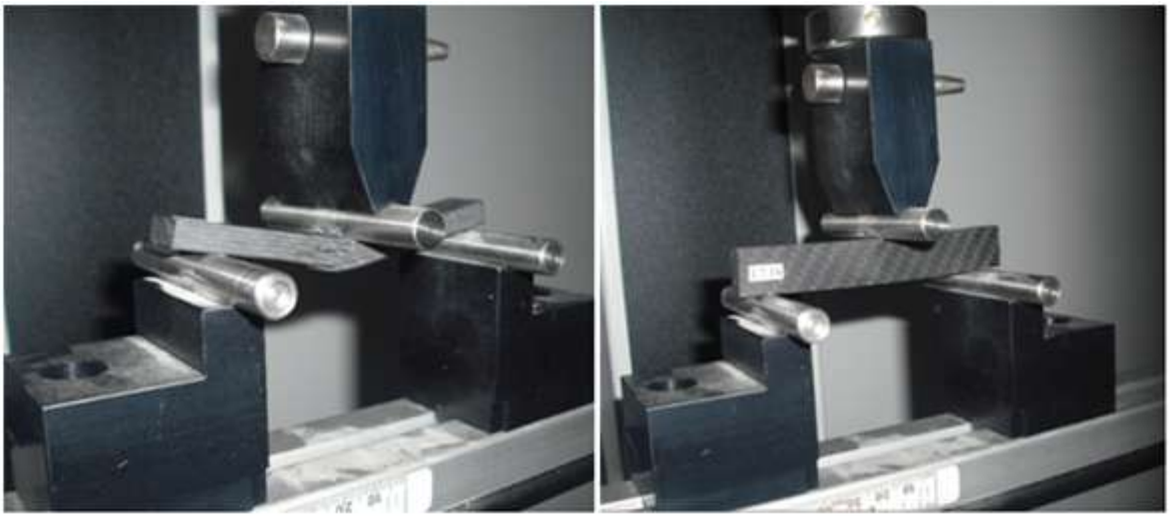
Number of layers	Multilayered composite samples pre-impregnated with resin				
	Distance between supports *L*	Sample length *l*	Sample width *b*	Sample thickness *h*	Surface area *A*
	mm	*mm*	*mm*	*mm*	*mm*
3	80	100	10	2.3	36.80
5	80	100	10	4.5	67.50
7	80	100	10	7	105.00

In table 6.5 the values of geometrical parameters for each of the three samples classes (3, 5 and, 7 layers), submitted to bending are presented.

6.4.4. Working method

Bending stress tests were conducted in the following conditions:

- tests were carried out at the temperature and humidity in which were made at the compression tests;
- the bending tests were carried out on longitudinal and transversal directions of sample (Fig. 6.13);
- for each charging class, five samples of multilayered composite material (3, 5 and, 7 layers) were used;
- bending test was performed at a constant speed of v=5 mm/min.



a) b)

Fig. 6.13. Bending test: longitudinal (a), and; transversal (b).

6.4.5. Data acquisition

The experimental data collected for the representative number of samples subjected to the investigation were acquired with the help of the NEXYGEN Plus software. They were acquired in the form of text files for each representative sample of composite material with architecture made up of 3 layers carbon fiber impregnated and contain information on: applied force (F [N]), arrow or displacement to the central area of the sample (f [mm]), stresses values (σ [MPa]) and, strains developed as a consequence of applied solicitations. The results favor the estimation of the following values:

- bending elasticity modulus E_f of multilayered composite material (E_{f1}, E_{f2});
- bending effort σ_f,

calculated by the NEXYGEN MT software.

6.4.6. Experimental data analysis

The acquired data were statistically processed by the NEXYGEN MT software. The parameters that define the mechanical behavior at bending of all three categories of multilayered composite material were pointed out - 3, 5 and, 7 layers: elasticity modulus for the two principal directions, bending stiffness, maximal stresses and strains etc Annex 4. After acquired experimental data statistical processing, statistical values presented in tables 6.6 ÷ 6.11 were obtained.

Table 6.6. Statistic values resulted for composite tested at longitudinal bending: 3 layers – 5 samples.

Property/Value		Maximum value	Minimum value	Average value	Median value	Standard deviation
Stiffness	*N/m*	32663,0	29667,0	30994,0	30775,0	1237,5
Young modulus of elasticity	*MPa*	21476,0	19506,0	20379,0	20235,0	813,67
Bending stiffness	Nm^2	0,34840	0,31645	0,33060	0,32827	0,013200
Force at structure breaking	*kN*	0,56326	0,50144	0,53098	0,53227	0,020362
Bending stress for maximum load	*MPa*	798,75	744,08	769,98	771,74	22,009
Specific deformation at maximum load		0,041824	0,037897	0,040136	0,040388	0,0012727

Table 6.7. Statistic values resulted for composite tested at longitudinal bending: 5 layers – 5 samples.

Property/Value		Maximum value	Minimum value	Average value	Median value	Standard deviation
Stiffness	*N/m*	194280	166940	185080	189230	9565,0
Young modulus of elasticity	*MPa*	18193,0	15633,0	17331,0	17720,0	18193,0
Bending stiffness	Nm^2	2,0723	1,7807	1,9742	2,0184	0,10203
Force at structure breaking	*kN*	1,6720	1,1694	1,4658	1,4330	0,17843

Bending stress for maximum load	*MPa*	687,47	660,52	676,74	683,53	10,482
Specific deformation at maximum load		0,040524	0,039581	0,040137	0,040342	0,0003881

Table 6.8. Statistic values resulted for composite tested at longitudinal bending: 7 layers – 5 samples.

Property/Value		**Maximum value**	**Minimum value**	**Average value**	**Median value**	**Standard deviation**
Stiffness	*N/m*	507650	437270	463900	461130	23698,0
Young modulus of elasticity	*MPa*	12630,0	10879,0	11541,0	11472,0	589,58
Bending stiffness	*Nm²*	5,4150	4,6643	4,9482	4,9188	0,25278
Force at structure breaking	*kN*	3,4744	2,0156	2,7386	2,7321	0,51703
Bending stress for maximum load	*MPa*	350,89	175,25	258,48	232,21	63,565
Specific deformation at maximum load		0,058808	0,046701	0,053225	0,053696	0,004597

Table 6.9. Statistic values resulted for composite tested at transversal bending: 3 layers – 5 samples.

Property/Value		**Maximum value**	**Minimum value**	**Average value**	**Median value**	**Standard deviation**
Stiffness	*N/m*	654640	581710	604390	590460	27668,0
Young modulus of elasticity	*MPa*	8894.,5	7903,7	8211,8	8022,5	375,92
Bending stiffness	*Nm²*	6,9828	6,2049	6,4468	6,2982	0,29512
Force at structure breaking	*kN*	1,3322	0,64006	1,0088	0,93779	0,27115
Bending stress for maximum load	*MPa*	271,51	130,45	205,60	191,13	22,009
Specific deformation at maximum load		0.037364	0.020169	0.028641	0.027759	0.0064064

Table 6.10. Statistic values resulted for composite tested at transversal bending: 5 layers – 5 samples.

Property/Value		**Maximum value**	**Minimum value**	**Average value**	**Median value**	**Standard deviation**
Stiffness	*N/m*	1015000	726900	909940	932010	100990
Young modulus of elasticity	*MPa*	8554,2	6126,3	7669,0	7854,9	851,14
Bending stiffness	*Nm²*	10,826	7,7535	9,7060	9,9414	1,0772
Force at structure breaking	*kN*	3,4918	2,7934	3,1080	3,0535	0,22586
Bending stress for maximum load	*MPa*	458,27	382,91	427,97	437,98	27,569
Specific deformation at maximum load		0.072129	0.053706	0.035114	0.063328	0.0061848

Table 6.11. Statistic values resulted for composite tested at transversal bending: 7 layers – 5 samples.

Property/Value		**Maximum value**	**Minimum value**	**Average value**	**Median value**	**Standard deviation**
Stiffness	*N/m*	1157300	973910	1081400	1087300	64521,0
Young modulus of elasticity	*MPa*	6270,1	5276,6	5859,1	5890,7	349,57
Bending stiffness	*Nm²*	12,344	10,388	11,535	11,597	0,68822
Force at structure breaking	*kN*	4,9500	4,9000	4,9125	4,9000	0,021651

Bending stress for maximum load *MPa*	377,78	373,07	374,51	373,85	1,6667
Specific deformation at maximum load	0.058362	0.055369	0.045373	0.056281	0.0010717

Based on the statistic data in tables 6.6 ÷ 6.11, the figures 6.14 ÷ 6.19 vere represented.

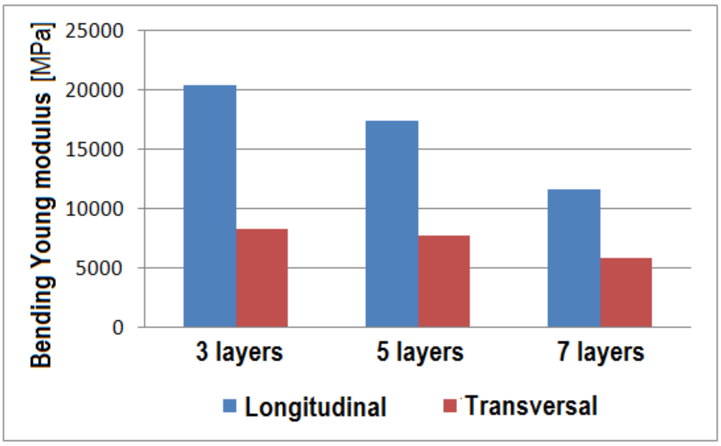


Fig. 6.14. Bending Young modulus variation in function of layers number and charging direction.

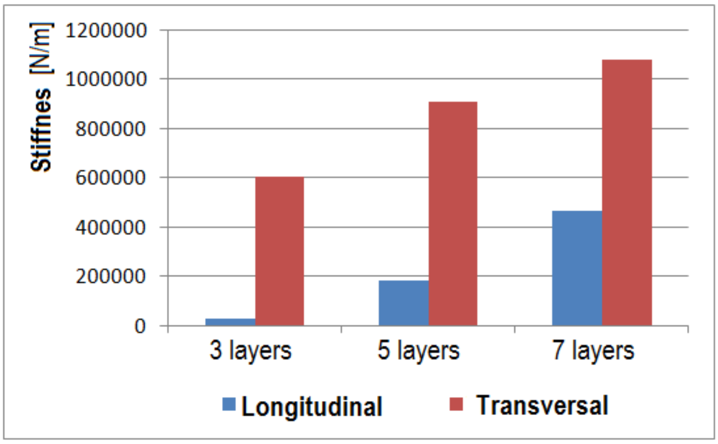


Fig. 6.15. Average stiffness variation of composite samples in function of layers number and charging direction.

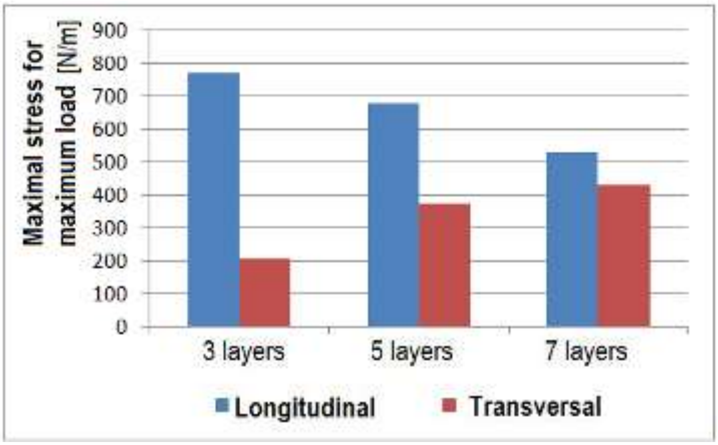


Fig. 6.16. Maximal stress for maximum load variation in function of layers number and charging direction.

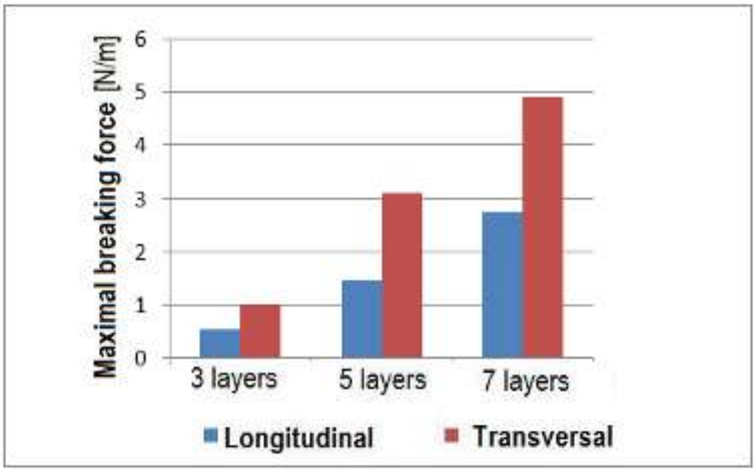


Fig. 6.17. Maximal breaking force variation in function of layers number and charging direction.

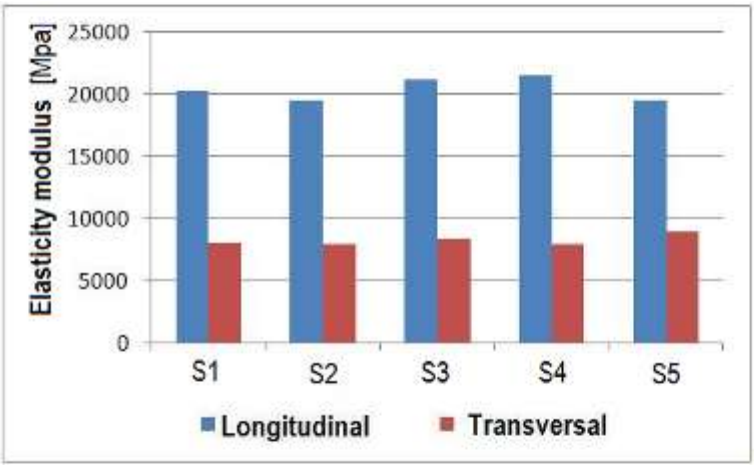


Fig. 6.18. Elasticity modulus variation in function of layers number for three layers samples.

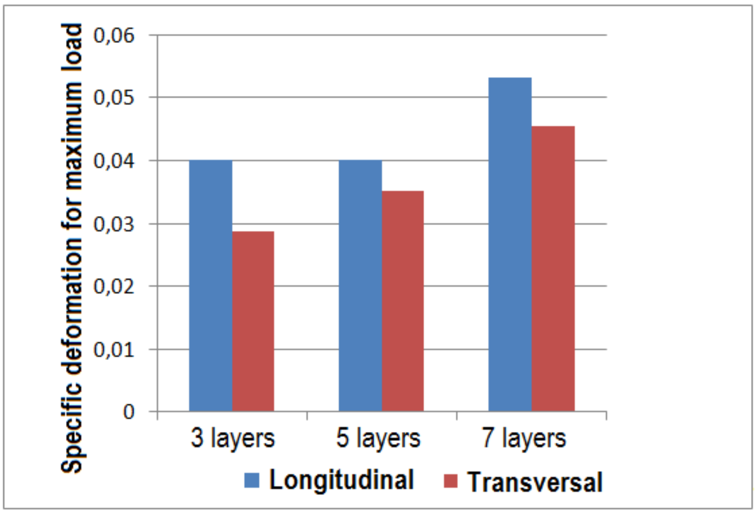


Fig. 6.19. Specific deformation for maximum load for 3, 5 and, 7 layers samples.

As shown in the figure 6.14, the elasticity module (Young) resulting from bending test decreases with increasing the number of layers of composite structure and, it retains the same decreasing trend according to the sample solicitation directions – longitudinal and, respectively, transversal.

Thus, *in longitudinal direction*, if the 3 carbon fabric layers sample is selected as a reference, the elasticity modulus decreases with approximately 15 % if two supplementary layers are added, respectively, with 43.36 % for five additional layers.

In transversal direction, the recorded differences are approximately of 6 %, respectively, of 258.65 % for the samples with 5 and 7 carbon fabric samples. As is natural, the rigidity of the samples shows an opposite trend to the elasticity module variation, and its maximum values are attempt for configuration with 7 layers of carbon fabric, regardless of the direction of their solicitation.

An interesting trend presents the maximum developed tension variation at the maximum load of samples. Thus, in the case of the longitudinal direction, the variation tendency of maximum stress is increasing with the increased layers number, which is not also found when they are transversely to the direction of loading. Due to the individual properties of reinforcement elements, consisting of the two categories of carbon fiber fabrics (unidirectional and diagonal) the increase in maximum breaking force at the transversal loading according to the three categories of layered composite is observed. It reflected the stiffness behavior of layered composite during bending load: with the increasing number of layers of composite the stiffness increases, in longitudinal and transverse direction (fig. 6.15).

6.5 DETERMINATION OF LAYERED COMPOSITE MECHANICAL PROPERTIES FOR MECHANICAL SOLICITATION DMA

6.5.1. Principle of experimental DMA analyze method

Dynamic analyze, Dynamic Mecanical Analyze (DMA) – is a modern experimental method for researches on polymeric composite material visco-elastic behavior. [*Dma.13], [For.13] The method is also known by the name: Dynamic Mechanical Spectroscopy or Dynamic Mechanical Thermal Analyis – DMTA. [*Dma.12]

The working principle of DMA method [*Dma.13] consists in charging the sample with a sinusoidal loading and in measuring the material elongation (Fig. 6.20) concretized in a viscosity modulus or in the viscosity expressed by a series of dynamic data.

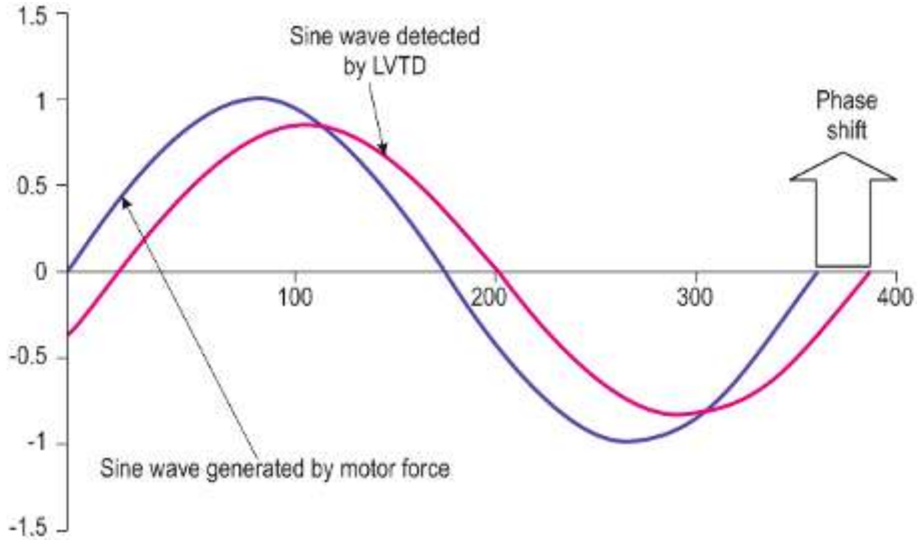


Fig. 6.20. Relation between sinusoidal applied sollicitation and resulted deformation.

This module defines the intrinsic property of the material that does not change in report with the sample shape or size, is expressed by the ratio solicitation/deformation and viscosity, in principle, the ratio between loading and deformation rate. The modulus is expressed through two components: as a component in phase – storage modulus and, as a phase output component – dumping modulus.

The expression corresponds to particular deformation ways of layered composite material. Storage mode defines the sample elastic behavior, the ratio between the dumping and storage is called dumping measuring energy dissipation for the analyzed material. [*Dma.12], [*Dma.13] During testing, the sample temperature or loading frequency can suffer variations – this characteristic leads to variations of determined modulus. Through it, the temperature of vitrous transition of polymeric composite can be made evident. In DMA method, the sample structure is deformed and, further, the mechanical properties of polymeric materials are measured with respect of sample temperature, loading frequency and, time. In testing device structure is also included a thermal analyze instrument, which allows testing the mechanical properties of different materials. [*Dma.12]

6.5.2. Experimental installation description

DMA experimental tests were performed on the installation ARES-G2 Rheometer, of TA Instruments US, which is described in figure 6.21. It is in C1DB8 Laboratory of Mechanics and Material Engineering Department of Valencia Polytechnic University of Alcoy.

The installation technical specifications are:

Fig. 6.21. DMA ARES-G2 testing installation,
http://www.tainstruments.com/pdf/brochure/AR_Brochure.pdf

Force/Torque Rebalance Transducer (Sample Stress):

- Transducer - Type Force/Torque Rebalance
- Transducer - Torque-Motor Brushless DC
- Transducer - Normal/Axial Motor Brushless DC
- Minimum Transducer Torque in Oscillation - 0.05 μN.m
- Minimum Transducer Torque in Steady Shear - 0.1 μN.m
- Maximum Transducer Torque - 200 mN.m
- Transducer Torque Resolution - 1 nN.m
- Transducer Normal/Axial Force Range - 0.001 to 20 N
- Transducer - Bearing Groove Compensated Air

Separate Motor (Sample Deformation):

- Maximum Motor Torque 800 mN.m
- Motor Design Brushless DC
- Motor Bearing Jeweled Air, Sapphire
- Displacement Control/Sensing Optical Encoder
- Strain Resolution 0.04 μrad
- Min. Angular Displacement in Oscillation 1 μrad
- Max. Angular Displacement in Steady Shear Unlimited
- Angular Velocity Range 1 x 10-6 rad/s to 300 rad/s
- Angular Frequency Range 1 x 10-7 rad/s to 628 rad/s
- Step Change in Velocity 5 ms
- Step Change in Strain 10 ms

Stepper Motor:

- Movement/Positioning Micro-stepping Motor/Precision lead Screw
- Position Measurement Linear Optical Encoder
- Positioning Accuracy 0.1 micron

Temperature Systems:

- Smart Swap Standard
- Forced Convection Oven, FCO -150 to 600°C
- FCO Camera Viewer Optional
- Advanced Peltier System, APS -10 to 150°C
- Peltier Plate -40 to 180°C
- Sealed Bath -10 to 150°C

ARES-G2 allows measurements in large ranges of loads, displacements and, frequency. The device is provided with electronic high speed components; signal digital processing for transducer and control of motor.

6.5.3. Samples forms and dimensions

The samples are manufactured from layered composite from epoxy resin reinforced with carbon fiber fabric, having the structure of blades tested at compression and bending from figure 6.12. The DMA tested samples geometrical characteristics are presented in table 6.12.

Table 6.12. Samples recommended for DMA tests.

Samples length *l*	**Width** *b*	**Thickness** *h*
mm	*mm*	*mm*
40	30	3-7

For the experimental research, two types of samples were used:

a. with 3 layers;
b. with 6 layers.

6.5.4. Working mode

DMA tests are conducted on experimental installation ARES-G2 Rheometer, presented in figure 6.21 and they suppose the following steps, according to user guide [*Are.13], [*Dma.13]:

- calibration;
- samples selection and preparing;

- loading type selection;
- solicitation type and form of obtained data selection;
- fixation of the sample in rectangular clamps for torsion of the device;
- closure and sealing the convection oven semi-chambers (fig. 6.22);
- experiment startup;
- results processing and displaying by Rheology Advantage software;
- experiment stopping;
- opening of the convection oven semi-chambers;
- sample removing.

During thermal charging phase, the temperature variation was in the range 35-100°C with a thermal gradient of 5 degrees/minute.

Samples torque solicitation was performed in the frequency range (0.35 – 1) Hz.

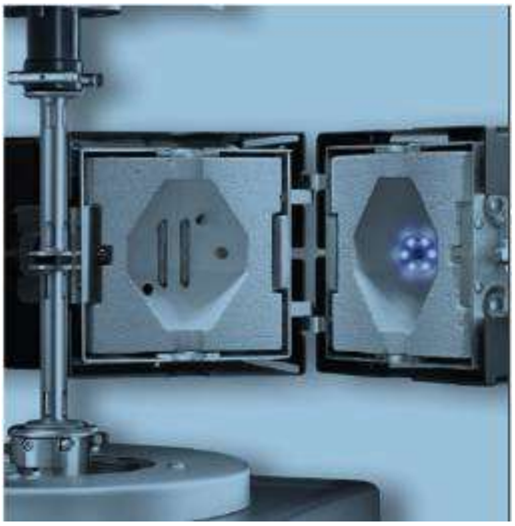


Fig.6.22. Forced *Convection Oven* , after [*Are.13].

6.5.5. Experimental data processing

After DMA loading of samples, were obtained experimental data on:

- viscous-elastic behavior of layered composite by *G'* (Fig. 6.23) and *G"* (Fig. 6.24) coefficients variation, in function of temperature variation for samples with 3 mm and, respectively, 6 mm thickness;

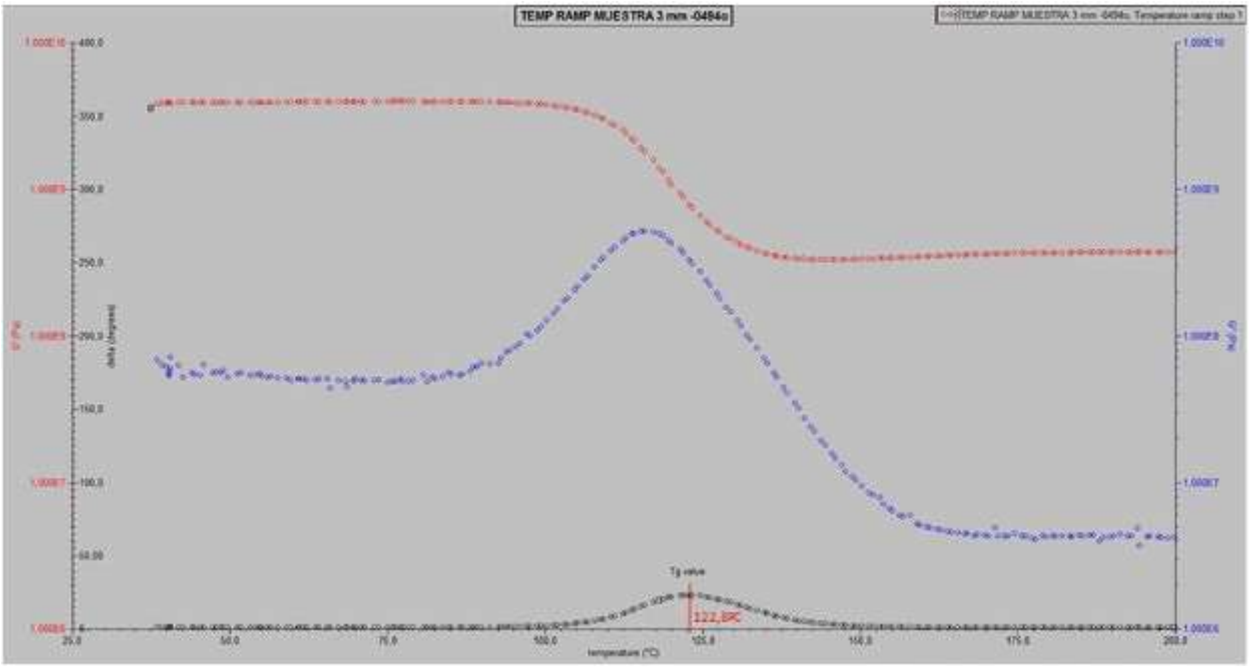


Fig.6.23. Viscous-elastic coefficients variation in report with the temperature for layered epoxy composite carbon fibers reinforced, with 3 layers.

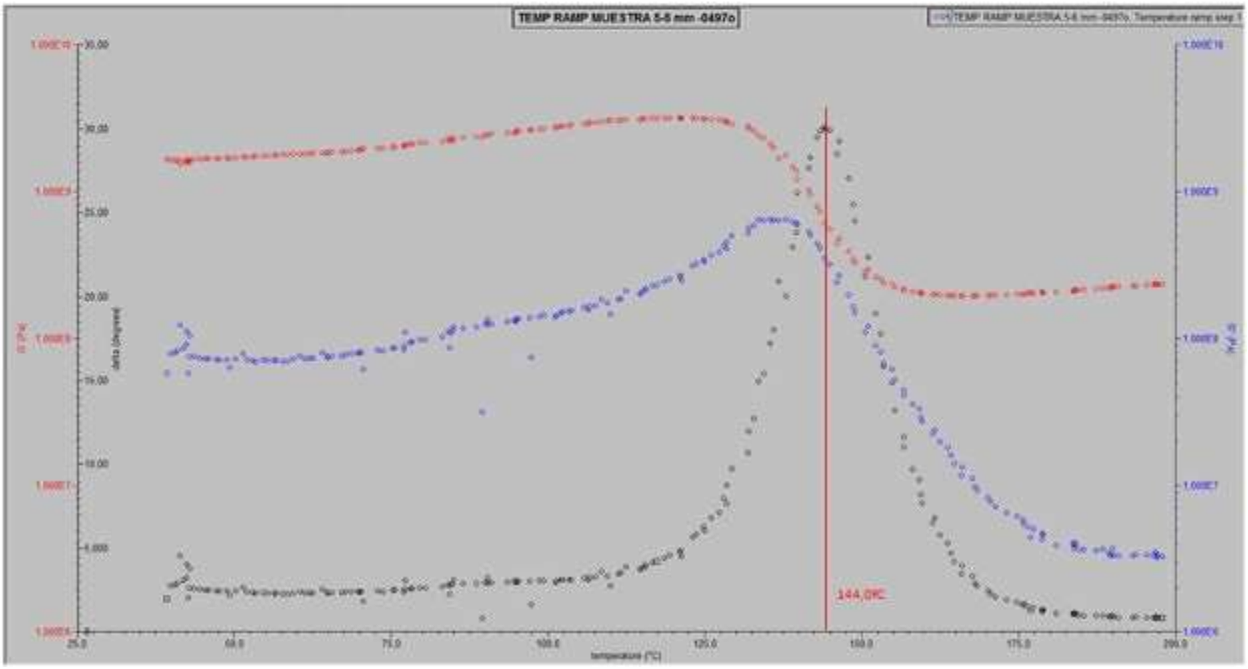


Fig.6.24. Viscous-elastic coefficients variation in report with the temperature for layered epoxy composite carbon fibers reinforced, with 5 layers.

- viscous-elastic behavior of layered composite by *G'* and *G"* coefficients and, respectively of vitreous transmission temperature of layered composite for samples with 3 mm thickness;

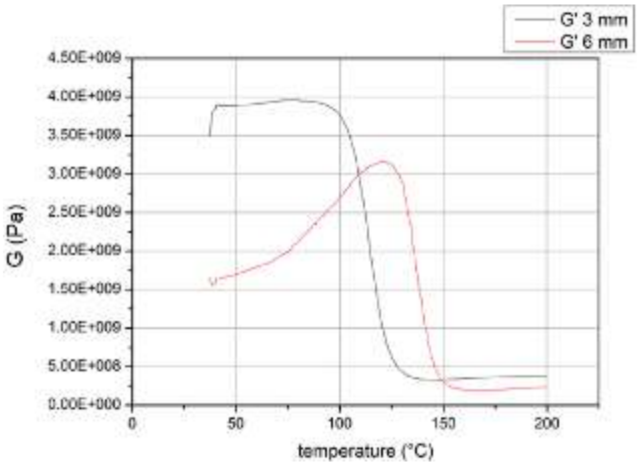


Fig.6.25. Layered epoxy composite carbon fibers reinforced *G'* coefficient variation, in function of elastic modulus and temperature variation for samples with 3 mm and, respectively, 6 mm thickness.

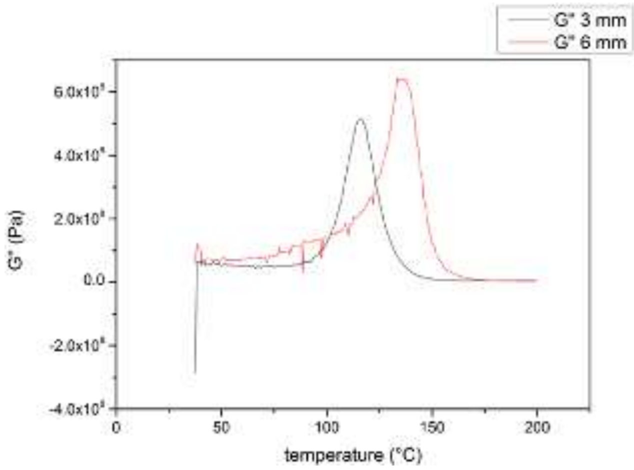


Fig.6.26. Layered epoxy composite carbon fibers reinforced *G"* coefficient variation, in function of elastic modulus and temperature variation for samples with 3 mm and, respectively, 6 mm thickness.

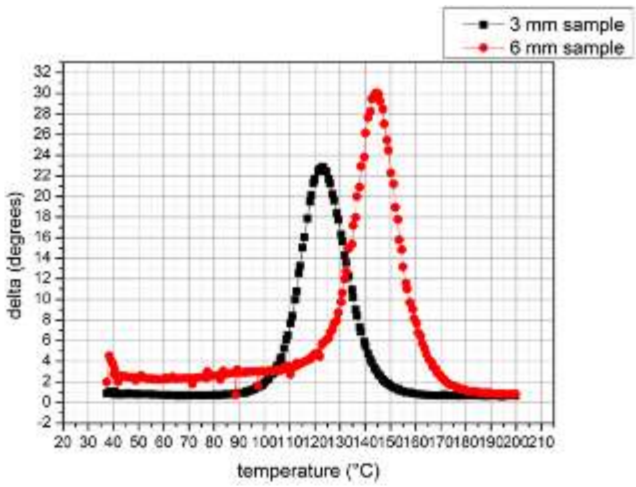


Fig.6.27. Tan delta parameter variation of layered epoxy composite carbon fibers reinforced, with 3 mm and, respectively, 6 mm thickness, in function of temperature variation for DMA testing.

- viscous-elastic behavior of layered composite by *G'* (Fig. 6.25) and *G"* (Fig. 6.26) coefficients and, respectively vitreous transmission temperature for samples with 3 mm and, respectively, 6 mm thickness;
- tan delta coefficient variation in function of temperature variation in the range 35-200°C (fig. 6.27).

6.6. EXPERIMENTAL RESEARCHES ON LINEAR THERMAL DILATATION COEFFICIENT OF LAYERED EPOXY COMPOSITE WITH CARBON FIBERS REINFORCED

6.6.1. Experimental device

Thermal dilatation coefficient of pre-impregnated carbon fiber values were estimated with the DIL 402 PC device, with horizontal disposition of samples and thermocouple (fig. 6.28) of Netzsck (Germany). It has the following technical specifications:

- function mode: static/dynamic;
- controlled working environment;
- adjustable parameters;
- testing temperature range: 25°-1200°C;
- calibration according to thermal schemes;
- data acquisition, storage and, processing through PROTEUS software;
- samples dimensions: maximal length 25 mm and 5 mm width;
- easy to use and maintain.

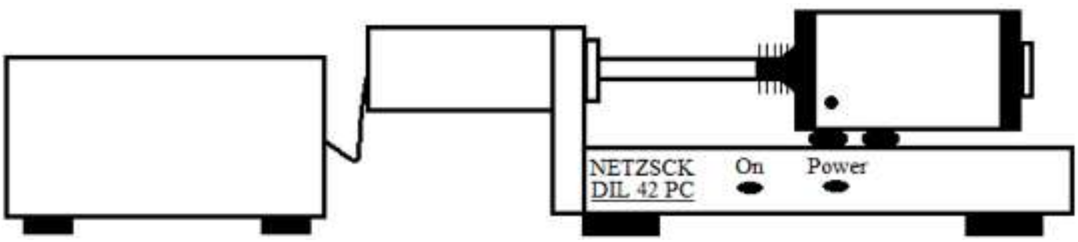


Fig. 6.28. Thermal analyze installation (NETZSCK DIL 42PC).

The measuring device is formed of the following components:

- S type thermocouple;
- temperature-controlled enclosure;
- oven control system;

- sample support enclosure;
- sample support ($SiO2$).

Accessories and auxiliary elements:

- support tubing;
- samples supports.

6.6.2. Samples-specifications, characteristics and particularities

Test specimens were debited from a layered composite plate fabricated under similar conditions to those used in mechanical solicitations.

Test specimens were cut with a cutting device Proxxon 27070 (D) of PROXXON (România) with the diamond cutting disk of 80 mm diameter and 2 mm width. The samples are paralelipipedic in form (fig. 6.29) and have the dimensions imposed by the dilatation measurement device DIL 402 PC (Table 6.13).

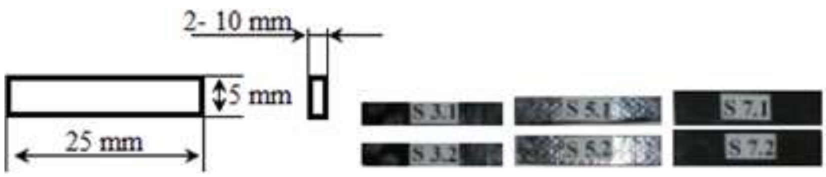


Fig. 6.29. Geometric form of samples.

Tabelul 6.13 Samples type recommended for DMA test.

Sample length *l*	**Width** *b*	**Thickness** *h*
mm	*mm*	*mm*
40	30	3-7

6.6.3. Working mode

Thermal dilatation coefficients of pre-impregnated carbon fiber measurement were done in the next working conditions:

- static controlled atmosphere;
- imposed range of temperature: 25° - 250°C;
- heating speed: 2.5 grades/min;
- imposed number of thermal cycles: 2;
- samples dimensions: 25×5×h ($L \times l \times h$) m^3;
- calibration done on a glass etalon with standard dimensions 25×5×h ($L \times l \times h$) m^3.

6.6.4. Experimental data processing

The experimental data were acquired through the PROTEUS software that allows the placement of curves associated to thermal deformations, linear thermal dilatation, phase transformations, polymerization transformations process for glass state transitions temperatures etc. with the possibility to be transferred to other statistical software (ex. Excel 2007/2010, Origin 8.0) for estimation of thermal dilatation coefficient and/or other important parameters.

In figures 6.30 and 6.31 the variations of thermal deformations fields recorded during the two imposed thermal cycles are compared. The comparison is done for carbon fibers reinforced composites formed of 3, 5 and 7 layers. Is visible from graphic representations, the increasing number of polymer composite layers drives to a progressive modification of associated values of thermal deformations but it keeps the same form of curve along the temperature working interval. For temperatures greater that 100°C, phase transitions and post-curing (relaxation) effects can be identified in the composite structure.

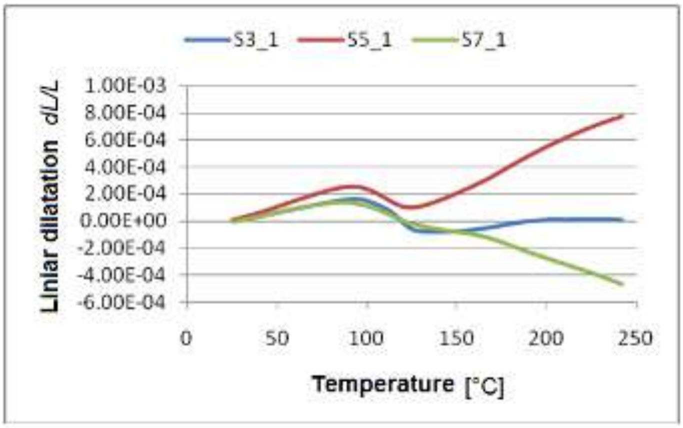


Fig. 6.30. Thermal dilatations fields variation during the first thermal cycle.

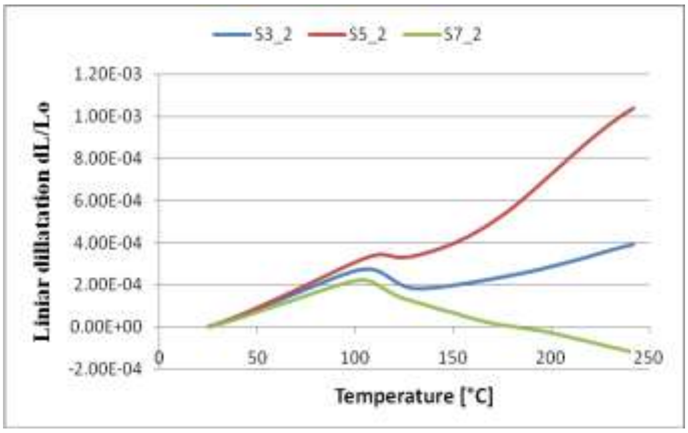


Fig. 6.31. Thermal dilatations fields variation during the second thermal cycle.

In figures 6.32 and 6.33 the variations of first degree derivative of linear dilatation field are compared and this allows the estimation of linear dilatation coefficient. The curves analyze make evident their non-linearity in temperatures interval where phase transformations occur. In table 6.14 are given, the associated temperature and linear dilatation coefficients connected to two thermal cycles associated to phase transformation in composites structure. As we can observe, both from graphic representation and also from obtained values, glass transition temperatures values (T_g) are very closed, around the 115°C value. Occurring differences can be associated with the composites manufacturing process, architectures configuration, experimental conditions, even the temperature value is *an indicator of composite matrix material quality.*

Table 6.14. Transition temperatures and linear dillatation coefficients values.

Composite architecture	Thermal cycle	Process parameters	
		Temperature [°C]	α [$^{-6}$ 1/K]
3 layers	1st cycle 2nd cycle	117.5 118.2	-10.241 -5.109
5 layers	1st cycle 2nd cycle	109.2 111.3	-7.915 -0.826
7 layers	1st cycle 2nd cycle	112.9 113	-5.753 -2.835

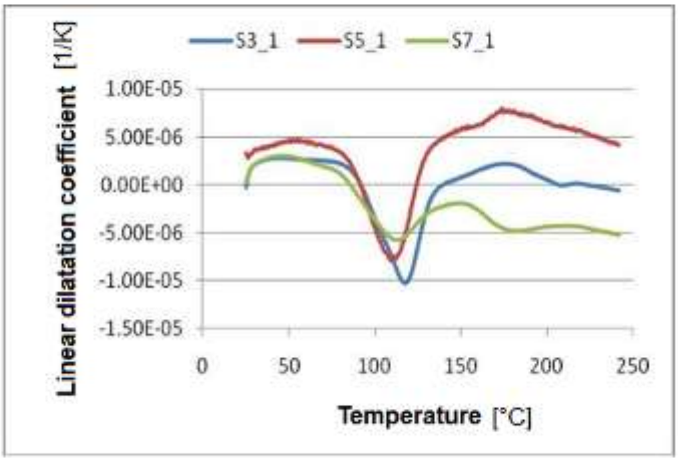


Fig. 6.32. Thermal dilatation coefficient variation with respect of temperature (first conditioning cycle).

Supplementary, the thermal deformations filed variations in report with temperature make evident the relaxation phenomena that occur in composite structure for higher temperature than the specific glass transformation temperature, which leads to the conclusion that the composite matrix represents the predominant constituent in composite dilatation.

The reinforcing element number of lamina contributes to the difference in experimental data values because it is well known and proved in literature that the carbon fibers represent a class of materials that have negative dilatation coefficients, i.e. materials that are contracting the afferent structure if the temperature increases. Thus, it is possible to asses that a bigger number of layers (i.e. 7 layers) lead to important diminution of dilatation effect in polymer composite structures.

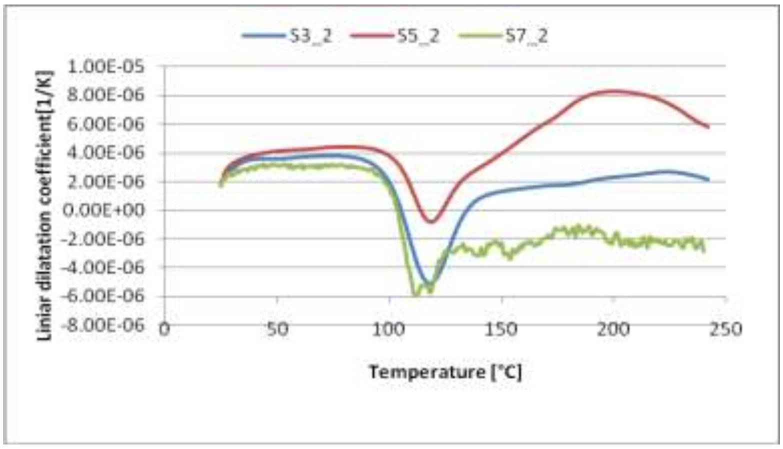


Fig. 6.33. Thermal dilatation coefficient variation with temperature (second conditioning cycle).

In figures 6.34÷6.36 the average values of linear thermal dilatation coefficients are comparatively presented and, in the selected temperature intervals they have not major phase transformations in polymers matrix material, in each thermal cycle and in sum in both of them. These representations have the role to make evident the phenomenon occurring in structures, due to environment modifications and to material architecture with accent on the dominant element of variation. Thus is possible to observe that polymer matrix of composite relaxation phenomena are much greater than those of glass transition, while the five layers pre-preg carbon fibers architecture does not show great differences between linear dilatation coefficients of the two thermal cycles, important less of analyze temperature interval. In this case, similarly to those mentioned in previous chapters, this architectural configuration constitutes an optimal one, which can ensure an optimal functionality of designed orthotic structure. This is the reason for what the five layers structure is refund in the biggest percentage in analyzed orthotic structure configuration.

Supplementary, the experimental research made evident that the increasing number of carbon fibers pre-preg layers in structure, leads to the increasing number of phase transitions in comparison with the other architecture types; excessive carbon fibers dominates the evolution of dilatation phenomenon in report with the temperature. In the table 6.15, the phase transformations temperatures values and associated dilatation coefficients are presented.

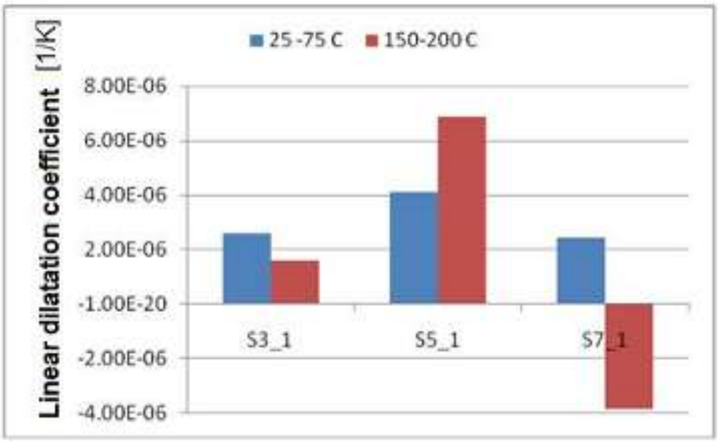


Fig. 6.34. Thermal dilatation coefficient average values with temperature (first conditioning cycle).

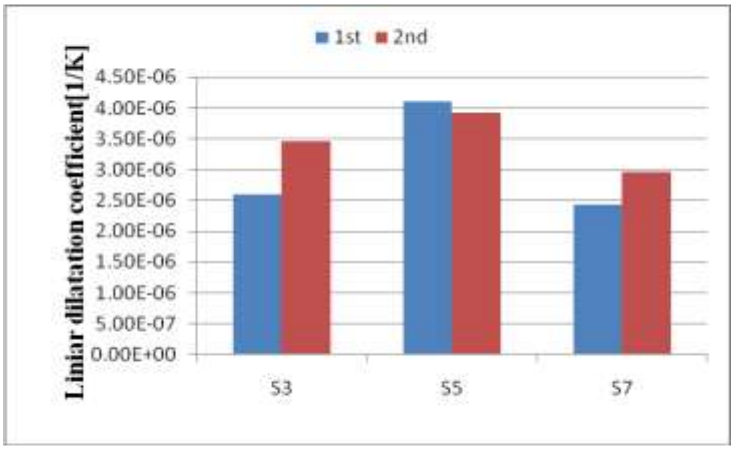


Fig. 6.35. Thermal dilatation coefficient comparative values in 25-75°C temperature interval, thermal conditioned samples in two cycles.

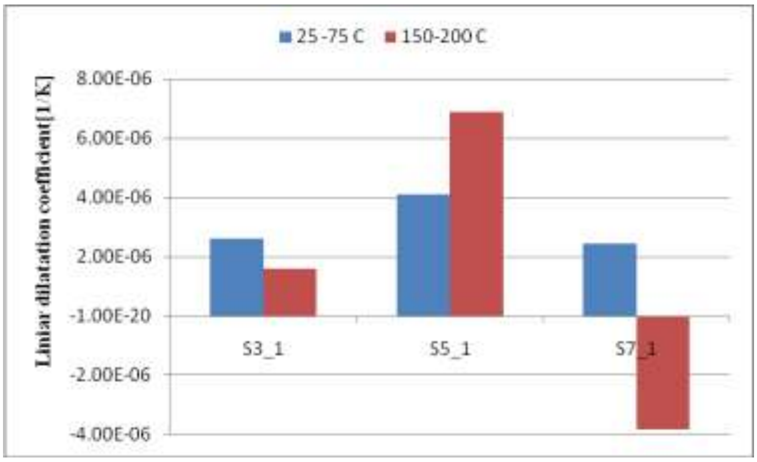


Fig. 6.36. Thermal dilatation coefficient comparative values in 150-200°C temperature interval, thermal conditioned samples in two cycles.

Table 6.15. Transformation temperature and linear dilatation coefficient values.

Composite architecture	**Process parameters**	
	Temperature *°C*	α *6 1/K*
7 layers	46.2	3.050
	112.9	-5.753
	149.0	-1.896
	182.7	-4.806

6.6.5. Conclusions

Experimental analyze of composite material samples designed for this PhD thesis, allowed the identification of principal material properties – i.e. mechanical, thermal, physical etc. – with respect of principal influence factors that contribute to their variations.

CHAPTER **7**

FINAL CONCLUSIONS. ORIGINAL CONTRIBUTIONS. THE MODE OF RESULTS CAPITALIZING AND FUTURE RESEARCH DIRECTIONS

7.1. FINAL CONCLUSIONS

The study on the behaviour of the biomaterials within the biosystems structure has on its' bases the importance of the biomaterials characteristics upon the human health, in general, and, namely, the importance of carbon fibres reinforced epoxy layered biocomposites on the improvement of life quality in the case of sportsmen suffering from transtibial amputees who wear **"J"** shaped prosthetic blades, in particular. The more new methods to analyse the mechanical and thermal characteristics of the **"J"** shaped blade's material are established, the smaller the distance – extremely sensitive – between the comfort and motion safety of the natural leg and the comfort and motion safety of the transtibial amputated **"J"** blade prosthetic limb, gets.

The final conclusions, regarding the approaching and the conducting of the theoretical and experimental research carried out the paper may be described as compared to the proposed objectives from the beginning of the paper. It must be taken into consideration that each objective gives the paper precision and scientific credibility.

The first objective consists in performing a systematic and current study on the structure and the behaviour of the biomaterials within biosystems. From the start, the presence of synergic interactions involved in the biomaterials manufacturing is noticed. Thus, the main importance of the mechanical engineering is reasserted: biomaterials and medical devices realization. At this moment, the medical device is still systemically defined by a wide range of constructive representations corresponding to the biosystems typology, being, at the same time, associated to different uses in treatments, cures, attenuation of clinical pathological phenomena, etc. The biomaterials range is structured in five main groups: natural biomaterials, metallic biomaterials, ceramic biomaterials, polymeric biomaterials and composite biomaterials. Each of these categories is characterized by specific behaviour (properties) that recommend them to different medical applications within the biosystems structure.

The determination of the biomaterials behaviour is performed using mechanical, thermal, chemical, etc, evaluation methods and proceedings. In these evaluation categories, the accomplishment of the biocompatibility and biofunctionality requests plays an essential role. In the end of the first objective, a special attention is paid to composite biomaterials, which is a natural fact considering the logic of the research work performed in the paper, namely the carbon fibres reinforced epoxy layered composite materials analysis. It is highlighted that the carbon fibres reinforced polymeric layered composites mechanical behaviour is oriented on types of experimental research where this behaviour is emphasized according to the material's functional characteristics and according to the standard testing to compression and bending. These tests are accompanied by thermal behaviour evaluations too.

The second objective consists in elaborating an analysis method in terms of the lower limb anatomy and biomechanics. In order to accomplish this objective within the PhD thesis, it was decided to conduct a systematic and synthetic study on the human body movements by means of the locomotive system. The research had in view the movements of the lower limb locomotive system. This system has the next configuration: - the bone formation set (finite) or the bone system; - the joints set or the joints system; - the muscles set; - the tendons set and the other anatomic component set; - the set of relations established by the lower limb and the environment; - the set of goals pursued within the lower limb locomotive system.

Thus, in the paper, the performed research regards:

- The lower limb bone system formed of the lower limb belt, the thigh bones, the shank bones, the foot bones and the fingers bones, from both the right and the left lower limb. In the paper, the lower limb bone system is systemically analysed from both anatomical and biomechanical points of view;
- The lower limb joints system formed of the pelvic joints, the hip joint (the coxo-femoral joint), the shank joint, the knee joint and the ankle joint. In the paper, the lower limb joints system is systemically analysed from both anatomical and biomechanical points of view;
- The gait biomechanics on anatomically normal persons;
- The running biomechanics on anatomically normal persons;

- The running and sprint biomechanics on sports prostheses shank amputations that have in their construction the **"J"** shaped prosthetic blade.

The lower limb locomotive system movements and, respectively, each joint category movements were analysed in relation to the reference system which includes the main spatial axes and planes of the human body in the standard anatomical position. Thus, there were analysed the conditions for achieving the next movements: flexion-extension; abduction-adduction, body total rotation (formed of the internal rotation and the external rotation) the movement of circumduction, pronation and supination. The paper has emphasized that during their movements and positions, the lower limb components, namely the pelvis, the hip, the thigh, the knee, the shank, the ankle and the foot, act as an open kinematic chain (without ground support), or as a closed one (with ground support). The nature of the lower limb kinematic chain determines the type of the lever according to which the lower limb component functions. The determining of the lever types under which the lower limb components function presents beside the clinical interest related to the lower limb pathology, also an interest related to the prosthesis of one or both lower limbs. An important aspect in achieving the second objective is the theoretical research work carried out in the paper on the gait and running biomechanics in the case of the anatomically normal persons, and, respectively, on the running and sprint biomechanics in the case of sports prostheses shank amputations that have in their construction the **"J"** shaped prosthetic blades.

This research has as a starting point the phases of gait (the phase of support – about 60 % of the cycle and phase of balance or oscillation – about 40% of the cycle) and those of the run (the phase of support and the phase of flight). Therefore, are defined, in detail, the parameters that characterise the gait and run: spatio-temporal parameters, kinematic parameters and kinetic parameters.

The analysis of these parameters allows the kinematico-kinetico determination of the characteristics that define gait and running biomechanics.

Thus, the gait corresponds to a muscular, cyclical, coordinate and autonomic activity led by the cortical nerve centres. Within this activity the main contribution belongs to the lower limbs muscularity which acts on the limbs joints, the coxo-femoral joint, the knee joint, the ankle joint and the foot joint.

In the case of running the kinetic parameters define the behaviour of the body weight centre and the movements of the lower limb components during the phase of support and the phase of stride As in the case of gait, the kinetic parameters define the action mode of the ground reaction force, the conditions of the vertical displacement of the body weight centre and, respectively, the lower limb rigidity evaluated according to the "spring-mass" model.

An important component for the research of the lower limb biomechanics is included in the running and sprint biomechanics on sports prostheses shank amputations that have in their construction the **"J"** shaped prosthetic blades. The kinematic parameters study reveals to main particularities of running: the **"J"** prosthetic blade reproduces in the phases of support and stride the accumulation of energy found in running with a valid lower limb; at the end of the phase of support the **"J"** prosthetic blade takes back its' initial form by releasing the stored energy accumulated during the phase of support, and, thereby, propels the body forward.

The third objective was to develop theoretical methods to analyse the behaviour of the carbon fibres reinforced epoxy composite biomaterials within the **"J"** prosthetic blades construction. This objective included, in the beginning, the production characteristics of the **"J"** prosthetic blades, in the sense that they may be manufactured in two versions: 1. as one piece by the RTM molding process – Resin Transfer Molding; 2. as a layered formed of carbon fibre reinforced epoxy composites prepreg blades.

Choosing the two "**J"** prosthetic blades manufacturing methods, over other manufacturing proceedings, is firstly conditioned by the performance-production volume ratio. In the third objective, were pursued the main aspects related to these two manufacturing methods, insisting, however, on the behaviour of the blade obtained from the layered composite. As a result of the **"J"** prosthetic blade injection process simulation by the RTM proceeding in the specialized software Autodesk Moldflow Insight, was obtained technological information on a number of key features of the injection process, which are important to optimize the real manufacturing process of the **"J"** prosthetic blade: the flow velocity of the material into the mold; the presence and the distribution of air gaps; the orientation of the injected component; the distribution of the deformations field into the interior of the component; the variation of the pressure fields during and after completion of the injection process; the necessary time to polymerize the material. These technological data, obtained from conducting the simulation process, allow running a DOE analysis to facilitate the highest quality of the **"J"** prosthetic blade obtained by the RTM injection process.

The **"J"** prosthetic blade judicious design, its' construction from carbon fibres reinforced epoxy layered and the analysis of its' operating characteristics, require performing a theoretical study on the material's thermal and mechanical behaviour. The study presented in the paper has as a starting point the general hypotheses that define the carbon fibres reinforced epoxy layered composites. In essence, the lamina is homogeneous and orthotropic, linearly elastic and has no initial stress. The study determines the elasticity law of lamina which is stressed by the external loads under the next conditions: - the stress is performed on a plane state; - the stress is performed in the directions of the local coordinates system attached to the lamina. The elasticity law of lamina is also determined for the currently met in practice situation when the external loads stress it in the directions of the axes of the global coordinates system attached to the layered. In this case, the stress directions of the lamina do not correspond to the directions of the layered's local coordinates system. Based on the stress scheme of the layered consisting of K (K=1-K) laminas that have the inclination angles α1,α2…….αN, the elasticity law of the composite was determined. On determining this law, two main conditions were taken into account: the layered's composite laminas are adherent one to each other; the component laminas suffer the same deformations at a given point of the layered.

In the paper was performed a study on the thermal behaviour of the composite material which is defined by thermal conductivity, thermal expansion coefficient and, respectively, thermal capacity. It is noticed the importance of the theoretical models for the unidirectional carbon fibres reinforced layered composite materials thermal expansion coefficients predicting.

As part of the third objective, in the paper was proposed and carried out a simulation of the mechanical behaviour of the carbon fibres reinforced epoxy layered within the **"J"** prosthetic blade construction. For the simulation the next gauge data and constructive characteristics of the **J"** prosthetic blade were used: length – 290 mm; width, variable along the blade's length, in the range of 40 mm at the mounting end on the prosthesis and 50 mm at the free end which comes into contact with the ground; thickness 6 mm, constant along the entire blade's length; the layered is formed of 6 prepreg composite blades reinforced with diagonal carbon fibres fabric. The simulation fallowed the next steps: the "J" prosthetic blade digitization; defying the limit loading conditions; defying the loading cases; defying the material and its' characteristics.

The simulation was performed in regime of both static and dynamical analysis. The results of the simulation allow the following conclusions: - the displacements into the blade decrease as the loading stress decreases. Thereby, the choosing of the lamina's gauge dimensions must be customized according to the anatomical characteristics of the athlete suffering from transtibial amputation wearing the **"J"** prosthetic blade; the simulation in a dynamic regime highlights the **"J"** prosthetic blade's real mechanical behaving conditions; if the blade has a variable thickness, smaller on the top, the **"J"** prosthetic blade's mechanical behaviour improves.

In the paper is also performed a simulation in the software Virtual Lab V9 on the strength of the carbon fibres reinforced epoxy layered composite within the **"J"** prosthetic blade construction for both normal use conditions of the blade and different loadings applied to the lamina, and, respectively, for different thickness of the lamina (constant thickness along the blade's length).

The simulation results highlight the strength conditions of the **"J"** prosthetic blade's material in terms of static and, respectively, dynamic stress.

The fourth objective was to develop new and efficient methods to experimentally determine the thermal and the mechanical behaviour of the epoxy layered composite formed of blades made of carbon fibres reinforced prepreg fabrics. The experimental research methodology aimed to elaborate a proceeding to determine the mechanical characteristics: the compression testing method, the bending testing method and the DMA analysis – Dynamical Mechanical Analyser – method. The including of the DMA method among the procedures for testing the mechanical properties of the layered offers additional data on its' mechanical behaviour.

7.2 ORIGINAL CONTRIBUTIONS

The doctoral thesis, ***"Methods and techniques for bio-system's materials behaviour analysis",*** essentially, combine research elements from various fields, such as: human anatomy, biomaterials, the movements biomechanics of the lower limb locomotive system, carbon fibres reinforced epoxy layered composite materials, mechanical testing of the materials, etc. It is noticed the multidisciplinary character of the research. At the same time, the originality of the paper is expressed by the personal, own, contributions brought by the author through the way of approaching the thesis objectives, through the presented synthesis and also through the way of conducting the experimental research. These contributions are listed above and structured on chapters:

The first chapter entitled ***"Introduction"*** presents, in a systemic approach, the facts that justify the research topic. The original contributions that mark this chapter may be summarized in the fallowing manner:

- The need to extend the systematic research on the prosthetic blade material – from the prosthesis construction – thermal and mechanical behaviour to athletes with transtibial amputees. This material is represented by the carbon fibres reinforced epoxy composite.

Chapter two entitled ***„Present state of research in the field of thesis"*** synthesizes the research current stage in the behaviour of the biomaterials within the biosystems structure domain. In this chapter the original contributions are the next:

- The performing of a complex bibliographical study on the concept of *"behaviour of the biomaterials within the biosystems structure"*;
- The systematic approach of the biomaterials structure within the biosystems in accordance to the specific aspects of the biomaterials behaviour and the methods of determining it;
- The systematic approach model of the biomaterial's degradation process that has on its' basis a current bibliographical research;
- The synthesis of the factors that determine the mechanical behaviour of the carbon fibres reinforced epoxy layered biocomposites (prepregs) and also of the methods to determine this behaviour.

Chapter four entitled "***Analysis methodology of the lower limb anatomical and biomechanical characteristics"*** may be characterized by the next original contributions:

- The methodology structure of the research concerning the lower limb anatomic and biomechanical characteristics. By this methodology, there are approached, in a systemic manner, the lower limb's movements on its' interactions with the bone system, the joint system and with the gait and running kinematics and kinetics;
- The systemic approach of the gait and running parameters: spatio-temporal parameters, kinematic parameters and kinetic parameters;
- The action mode of the ground reaction force on the human body study, established in the logic of the gait and running locomotive movement;
- The systematic presentation of the mechanisms that define running and sprint kinematics and kinetics in the case of athletes suffering from transtibial amputees.

Chapter five entitled ***"Methods to analyse the behaviour of carbon fibre reinforced epoxy composite biomaterials used in the construction of the "J" prosthetic blades"*** is a chapter that theoretically describes the mechanical and thermal behaviour of the carbon fibres reinforced epoxy composites. This chapter offers the necessary information in order to obtain the prosthetic blade. It is characterized by the next original contributions:

- The prosthetic **"J"** blade and the samples (necessary in the mechanical tests) injection process simulation using the RTM procedure;
- Customizing, for the prosthetic blade, the calculus of the thermal and mechanical behaviour of the carbon fibres reinforced epoxy layered;
- The mechanical behaviour simulation of the carbon fibres reinforced epoxy layered for different layers of the **"J"** blade's material. The simulation was performed both in a static and a dynamic regimes;
- The endurance simulation, in LabView software, of the carbon fibres reinforced epoxy layered composite on different testing of the prosthetic blade and on different thickness of the prosthetic blade.

Chapter six entitled ***"Experimental determination of carbon fiber reinforced multilayered composite mechanical properties"*** is characterized by the next original contributions:

- Developing the methodology to experimentally determine the mechanical and thermal properties of the carbon fibres reinforced epoxy layered composite;
- Defying the conditions in order to conduct the mechanical and thermal testing of the carbon fibres reinforced epoxy layered composite, in 3, 5 and 7 layers sequence;
- Defying the layered construction: 3 layers – 1 blade with unidirectional fibres fabric coated with 2 blades reinforced with diagonal fibres fabric; 5 layers – 3 blades with unidirectional fibres fabric coated with 2 blades reinforced with diagonal fibres fabric; 7 layers – 5 blades with unidirectional fibres fabric coated with 2 blades reinforced with diagonal fibres fabric;
- Including the DMA testing – Dynamical Mechanical Analysis, within the methodology to experimentally measure the mechanical characteristics of the carbon fibres reinforced layered;
- Determining the thermal characteristics of the layered with 3, 5 and 7 layers. Its' constructive configuration is: 3 layers – 1 blade with unidirectional fibres fabric coated with 2 blades reinforced with diagonal fibres fabric; 5 layers – 3 blades with unidirectional fibres fabric coated with 2 blades reinforced with diagonal fibres fabric; 7 layers – 5 blades with unidirectional fibres fabric coated with 2 blades reinforced with diagonal fibres fabric.

7.3 THE MODE OF THE CAPITALIZING OF THE RESULTS

The scientific research conducted on the PhD thesis topic and its' adjacent domains and carried on over a period of three years, has materialized in the fallowing outcomes capitalized by publications in specialty journals, by research contracts and an invention patent:

- **2** scientific papers in ISI Journal;
- **2** scientific papers in ISI proceedings;
- **7** scientific papers at international conferences with program committee;
- **1** research contract;
- **1** invention patent.

Of which, the author is: at **1 – single author**; at **6 – first author**; at **4 – co-author**;

Research contracts/project proposal PN-II-PT-PCCA-2013-4-0860/**member:** Developing, testing and manufacturing some hybrid composite structures based on natural constituents with advanced characteristics and low costs in order to improve the quality of human life.

Invention patent no. a 2013 00388/23.05.2013: *Device for the footwear cleaning and drying.*

7.4 FUTURE RESEARCH DIRECTIONS

The theoretical and experimental research developed in the current PhD thesis opens new research directions regarding the use conditions of the layered composites in the transtibial amputated lower limb prosthetics. Thus, the research may be continued in the fallowing directions:

- The mechanical behaviour of the carbon fibres reinforced epoxy layered composite study performed through RTM injection processes;
- The developing of stands for the experimental research of the assembly: sports prosthesis-"J" shaped and, respectively "C" shaped prosthetic blade;
- The performing of studies and research on running and sprint kinetic parameters optimization on shank amputees with sports prosthesis;
- The conception and the testing of the new design ideas for the sports transtibial prosthesis with prosthetic blades;
- Studies on the optimization of the experimental research of the epoxy layered formed of blades with diagonal fabrics, impregnated by DMA method.

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Annexes

Annex 1

Structure of ISO 10993, after [*Int.13]

Part	Title
1	Evaluation and testing within a risk management process
2	Animal welfare requirements
3	Tests for genotoxicity, carcinogenicity and reproductive toxicity
4	Selection of tests for medical devices that interact with blood
5	Tests for in vitro cytotoxicity
6	Tests for local effects after implantation
7	Ethylene oxide sterilization residuals
8	Selection and qualification of reference materials for biological tests
9	Framework for identification and quantification of potential degradation products
10	Tests for irritation and skin sensitization
11	Tests for systemic toxicity
12	Sample preparation and reference materials
13	Identification and quantification of degradation products from polymeric medical devices
14	Identification and quantification of degradation products from ceramics
15	Identification and quantification of degradation products from metals and alloys
16	Toxicokinetic study design for degradation products and leachables
17	Establishment of allowable limits for leachable substances
18	Chemical characterization of materials
19	Physico-chemical, morphological and topographical characterization of materials
20	Principles and methods for immunotoxicology testing of medical devices

Annex 2

Composite material constituents physical – chemical characteristics

Material Epoxy prepregs (carbon fiber)

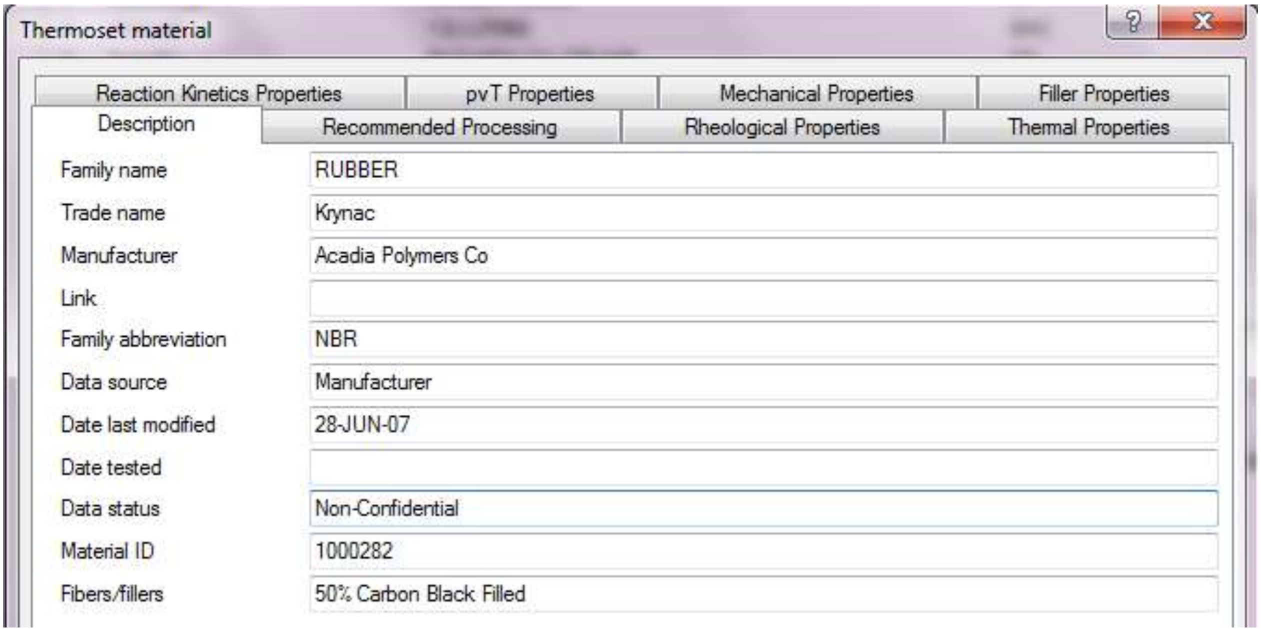
Modulul de elasticitate Young [MPa]= 21476,0 MPa;

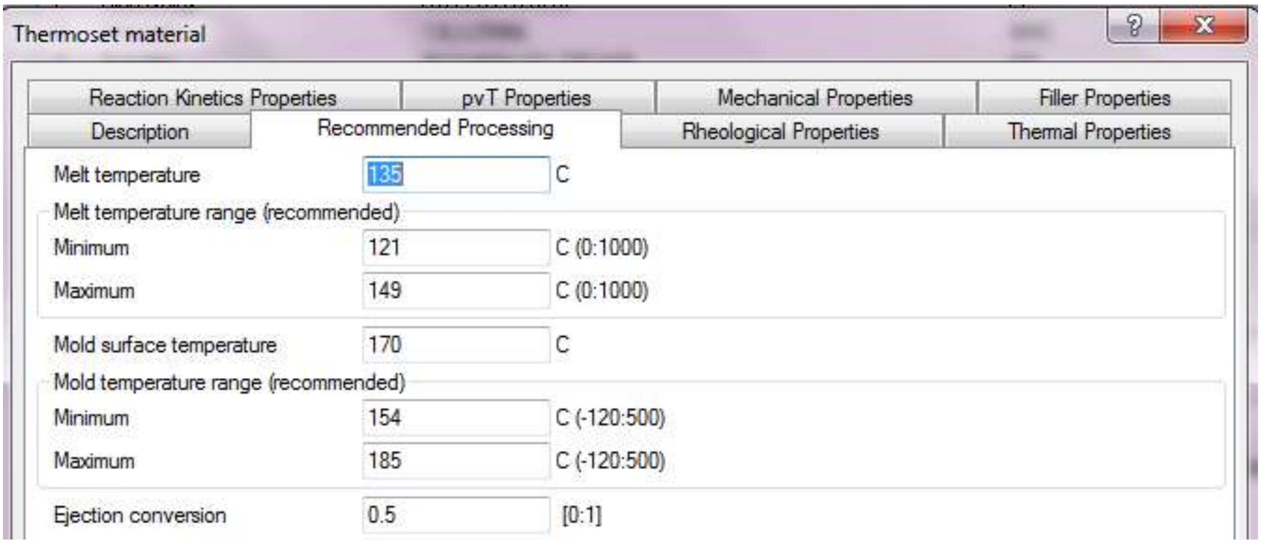
- Density=1800 Kg/m^3;
- ɣ=0,32 (Coef. Poisson);
- G=11439 MPa;
- Layer thickness: (1 mm/leyer);
- Fiber orientation: (+45°;-45°).

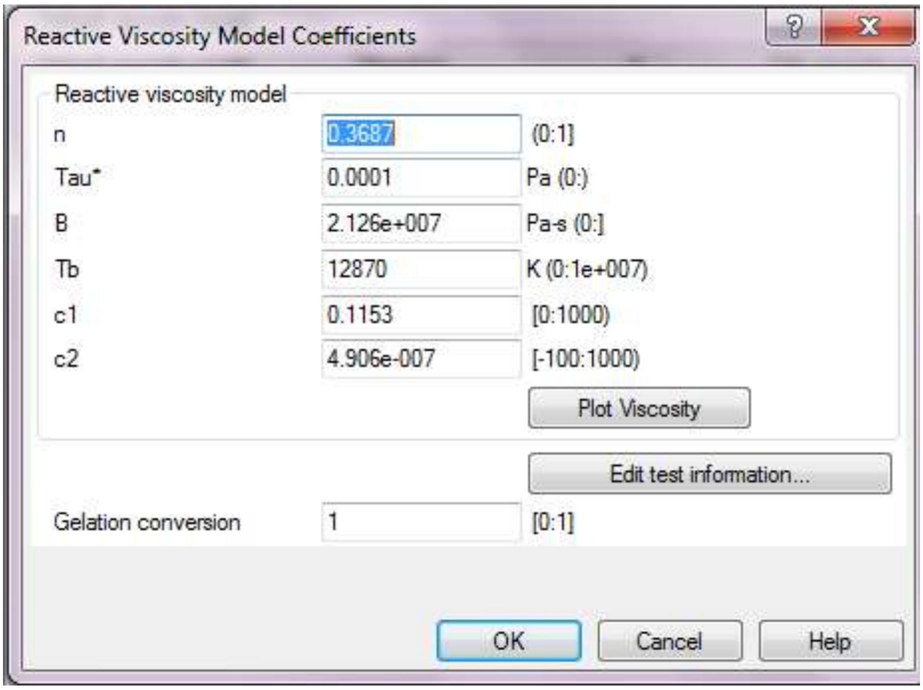
Resin epoxy FT 102

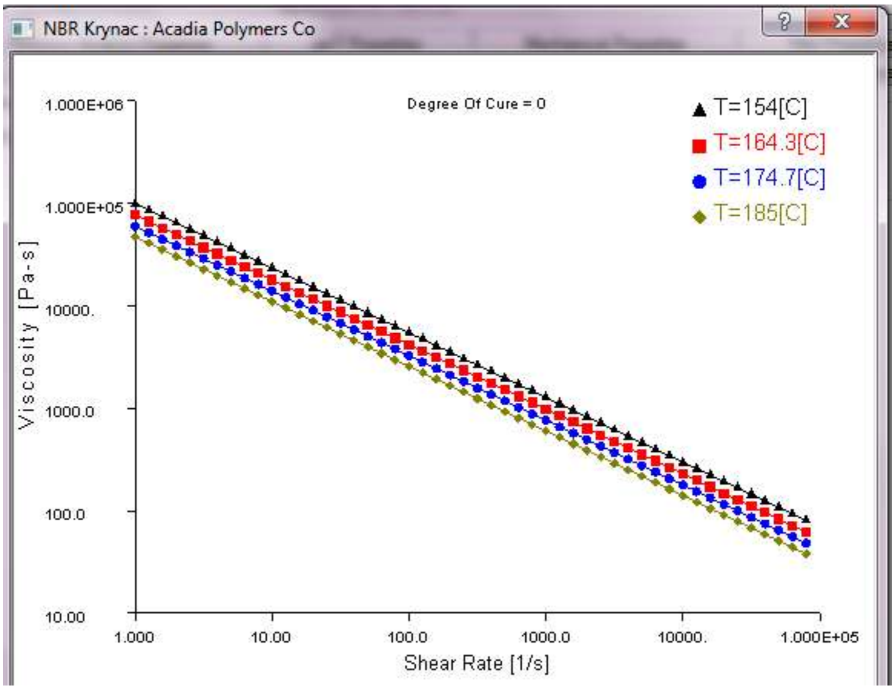
- Type – epoxy;
- Tg °C – 120;
- Curing temperature °C – 80-160;
- Durability at RT (20 °C) days – 14;
- Durability at RT (-18 °C) months – 6;

Moldflow material database used for simulation





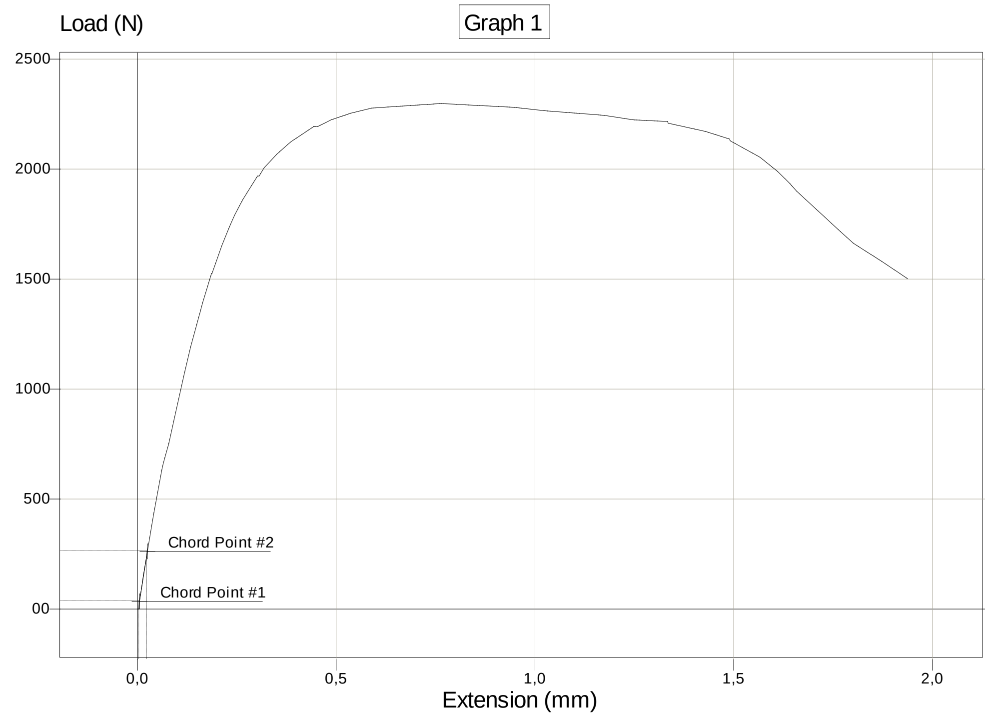

Reactive Viscosity Model Coefficients
Reactive viscosity model
n
0.3687
(0:1]
Tau*
0.0001
Pa (0:)
B
2.126e+007
Pa-s (0:]
Tb
12870
K (0:1e+007)
c1
0.1153
[0:1000)
c2
4.906e-007
[-100:1000)
Plot Viscosity
Edit test information...
Gelation conversion
1
[0:1]
OK
Cancel
Help

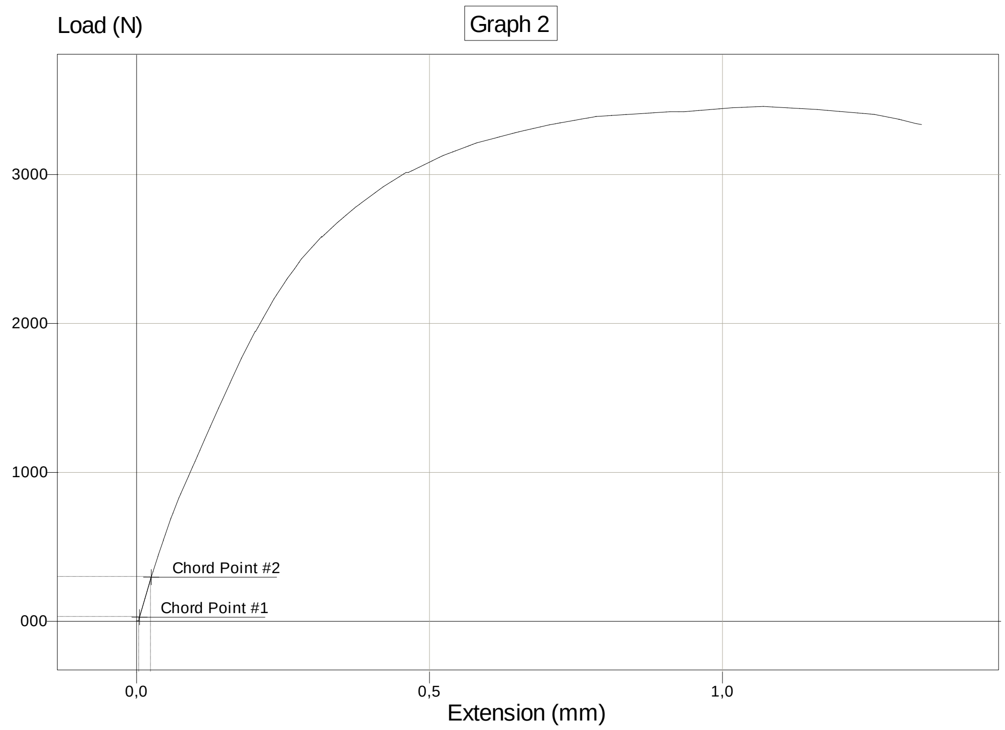

NBR Krynac : Acadia Polymers Co
Degree Of Cure = 0
T=154[C]
T=164.3[C]
T=174.7[C]
T=185[C]
Viscosity [Pa-s]
1.000E+06
1.000E+05
10000.
1000.0
100.0
10.00
1.000
10.00
100.0
1000.0
10000.
1.000E+05
Shear Rate [1/s]

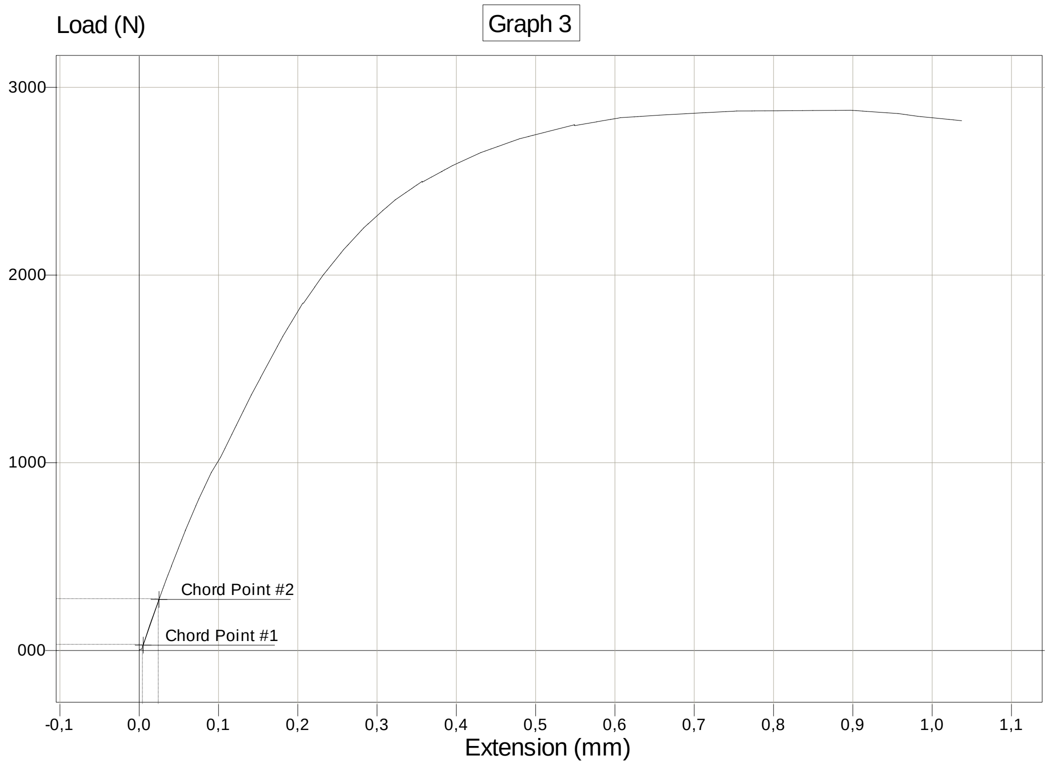
Annex 4

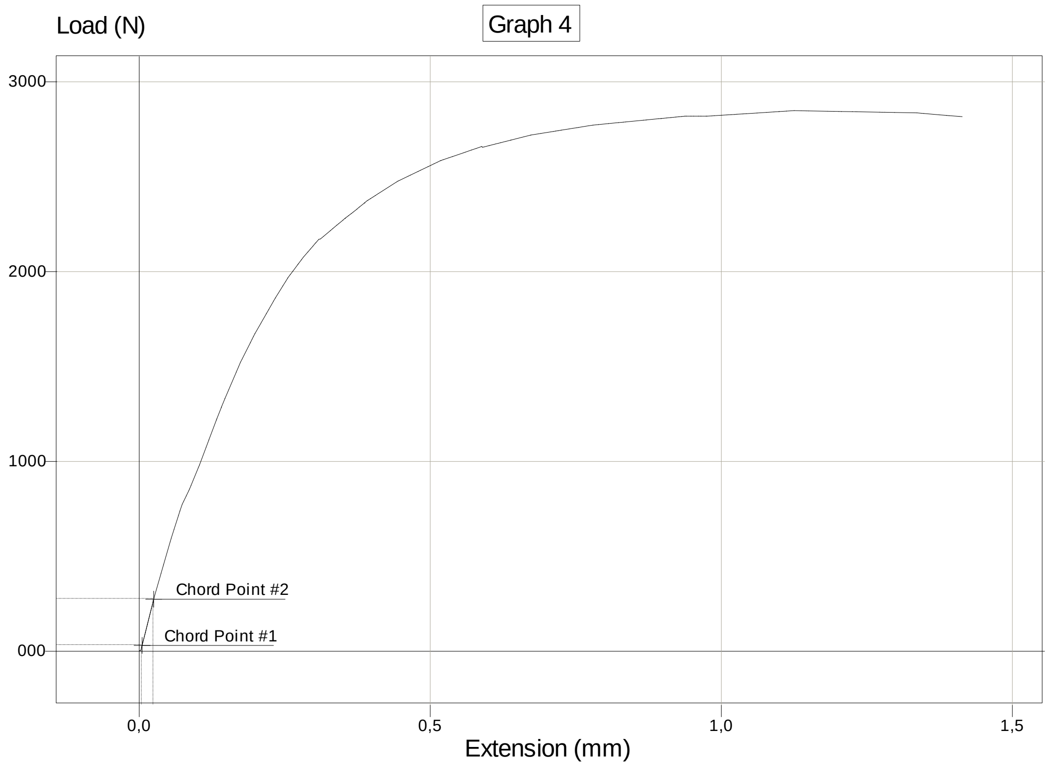
Results of static compression tests

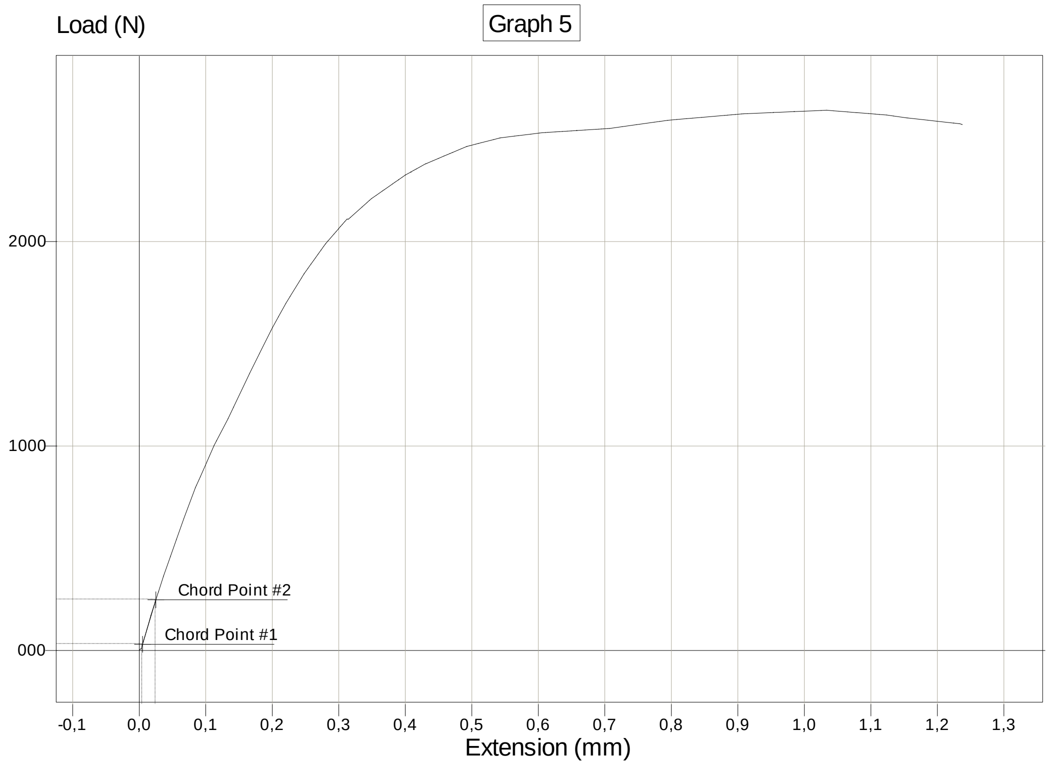
A.1. Compression of carbon fiber reinforced multilayered epoxy composite with 3 layers

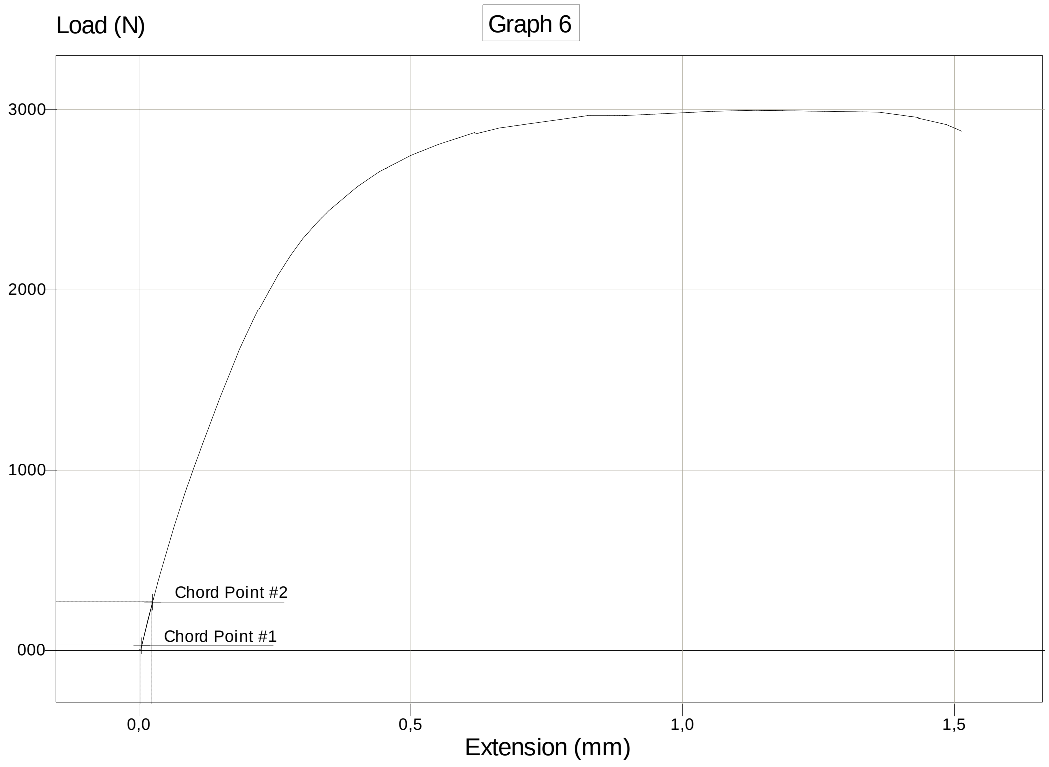


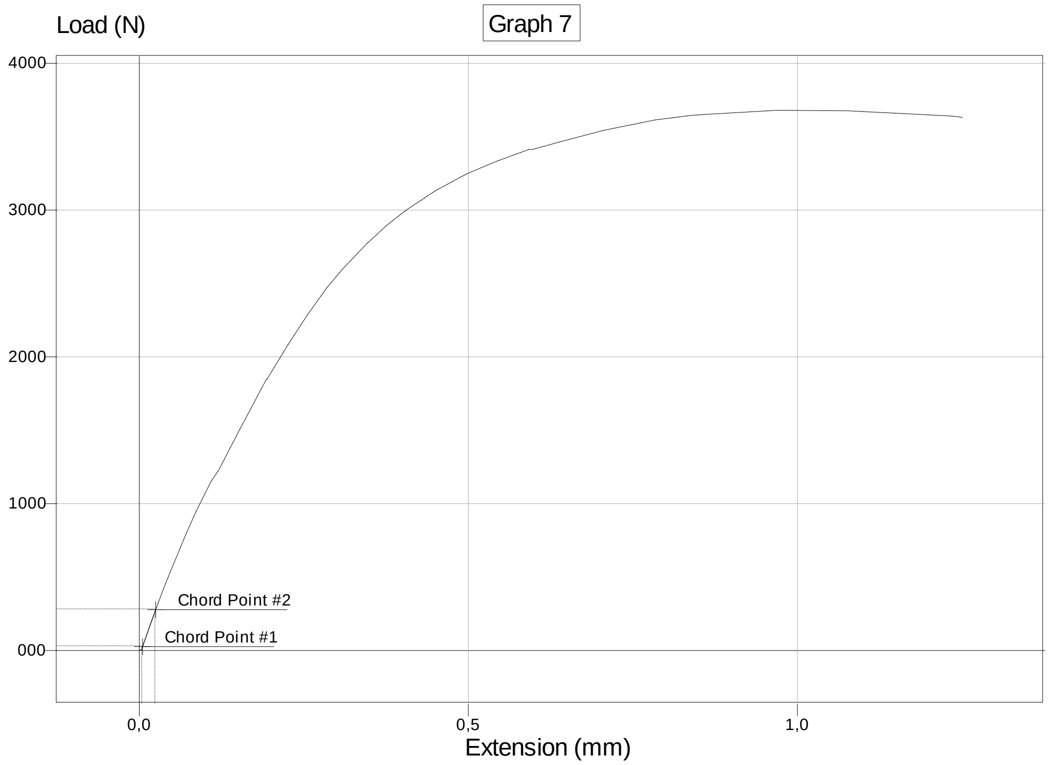


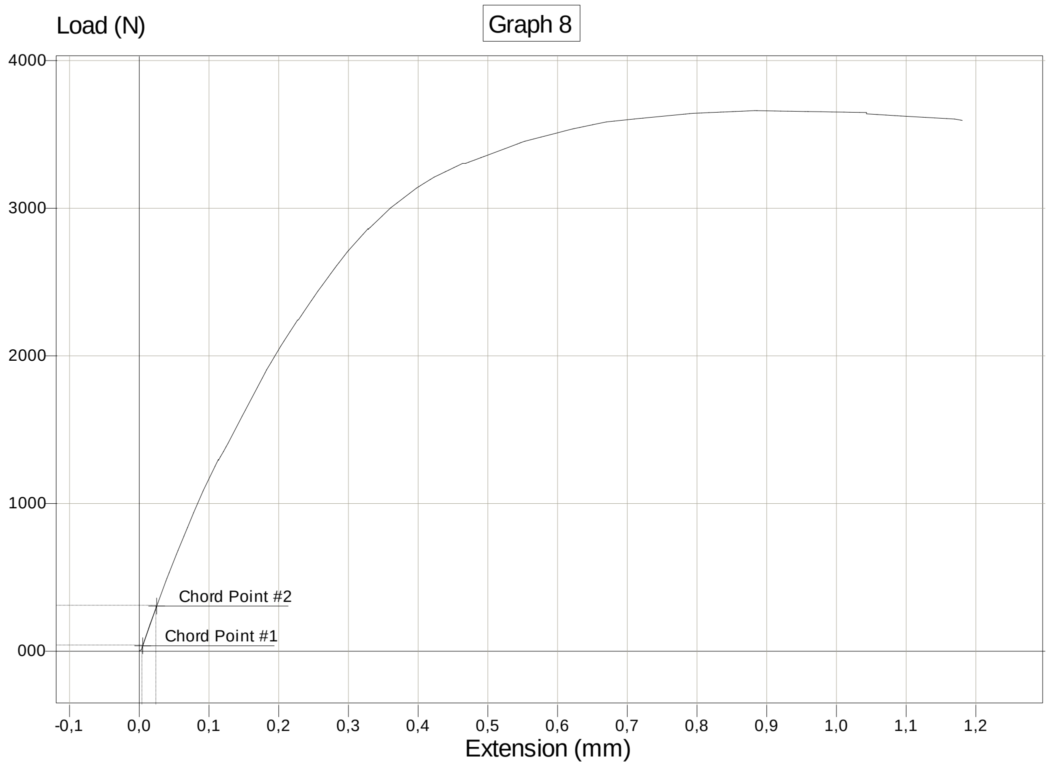

Load (N)
Graph 3
3000
2000
1000
000
Chord Point #2
Chord Point #1
-0,1
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
Extension (mm)

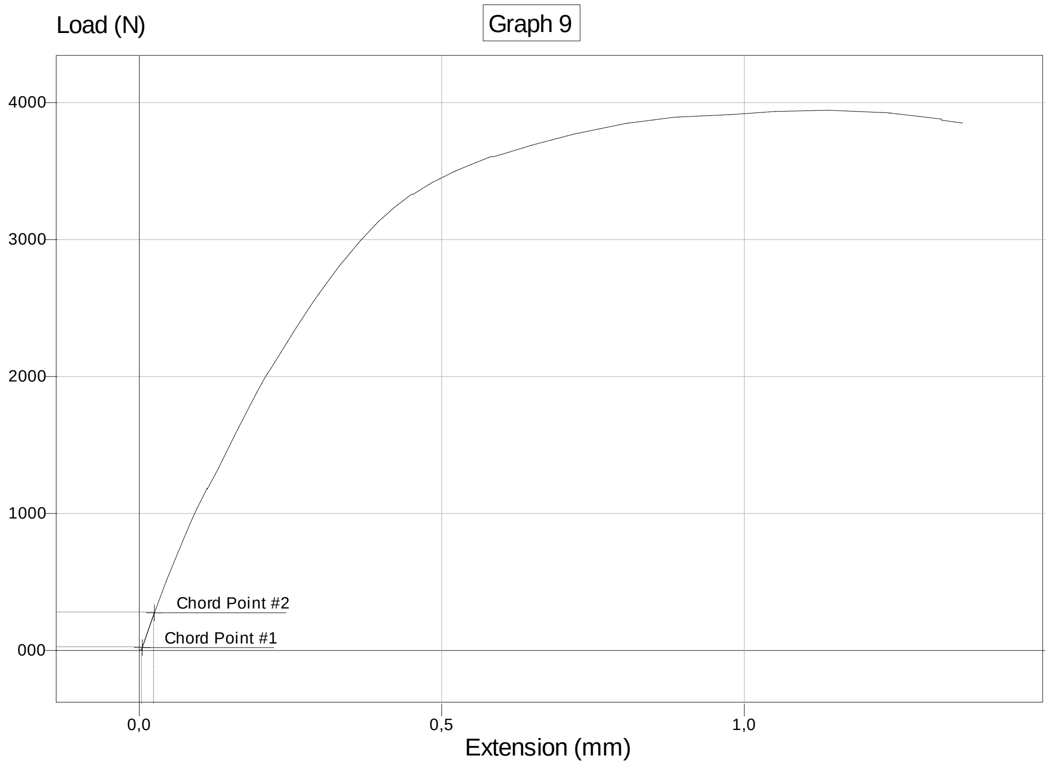

Load (N)
Graph 4
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
0,5
1,0
1,5
Extension (mm)

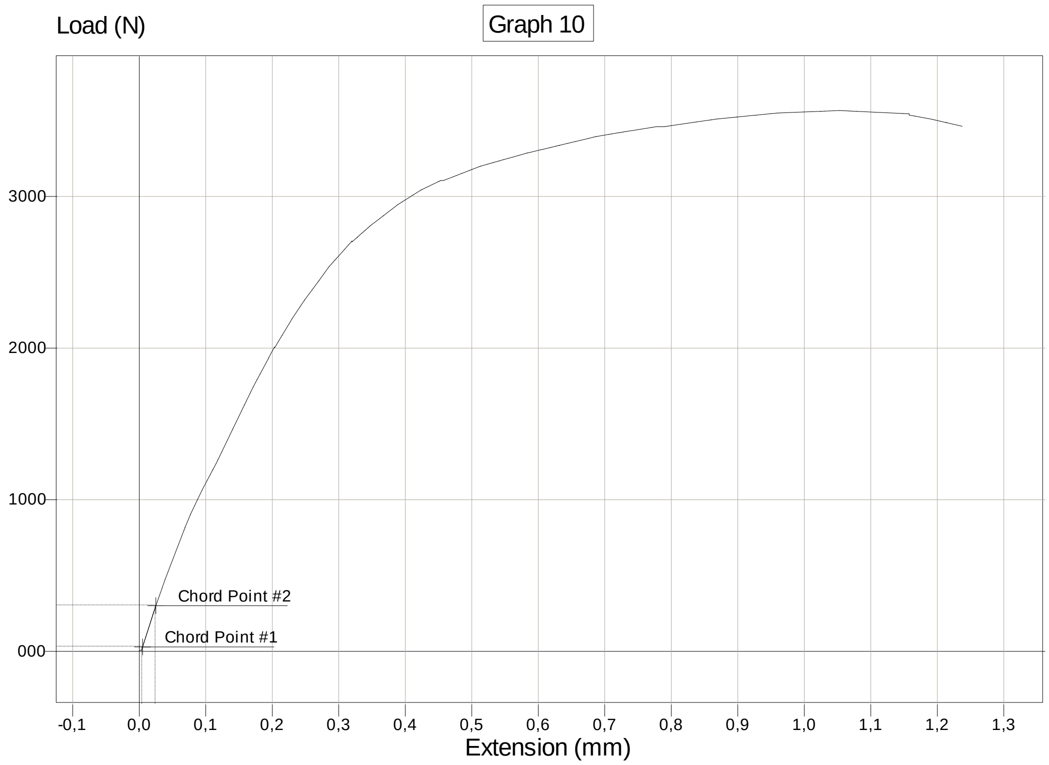

Load (N)
Graph 5
2000
1000
000
Chord Point #2
Chord Point #1
-0,1
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
1,3
Extension (mm)


Load (N)
Graph 6
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
0,5
1,0
1,5
Extension (mm)


Load (N)
Graph 7
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
0,5
1,0
Extension (mm)


Load (N)
Graph 8
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
-0,1
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
Extension (mm)

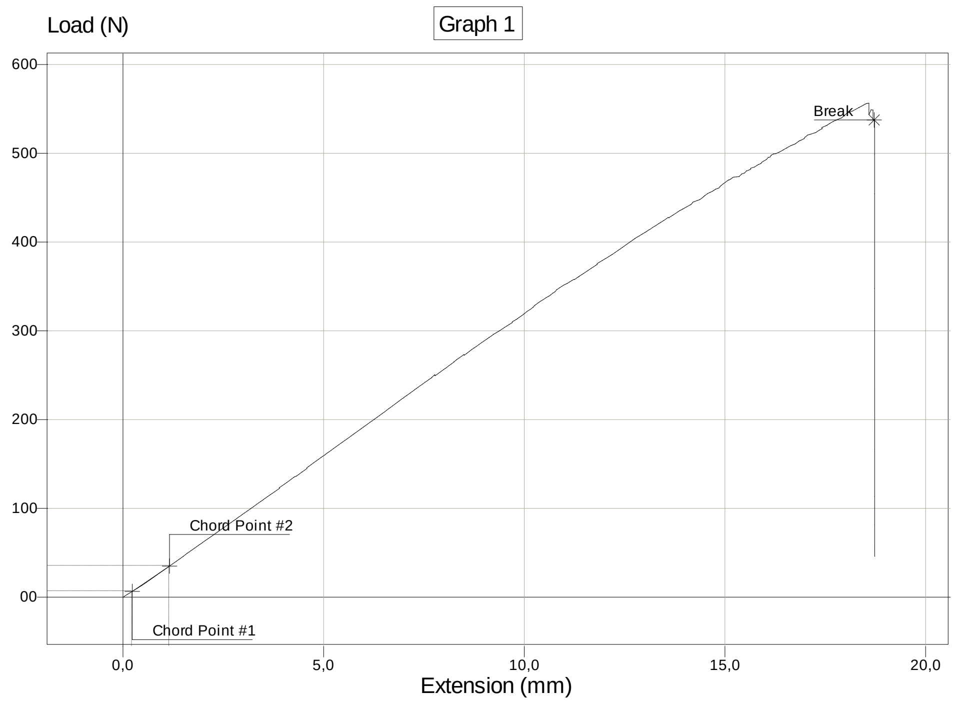

Load (N)
Graph 9
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
0,5
1,0
Extension (mm)

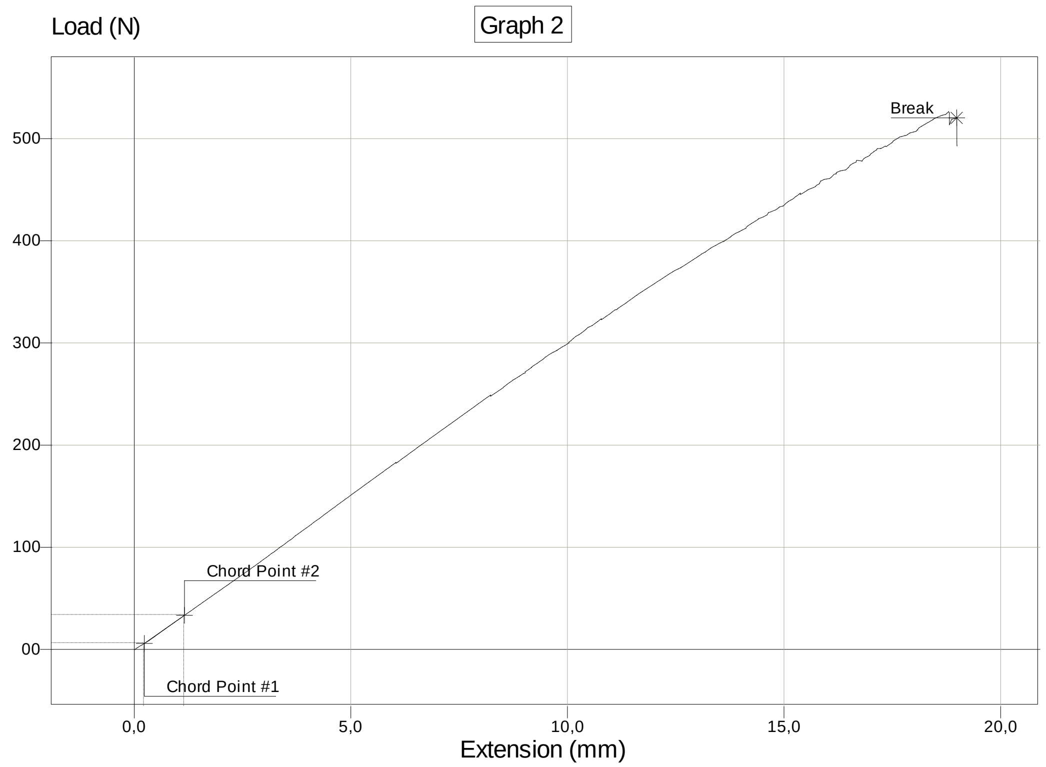

Load (N)
Graph 10
3000
2000
1000
000
Chord Point #2
Chord Point #1
-0,1
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
1,2
1,3
Extension (mm)

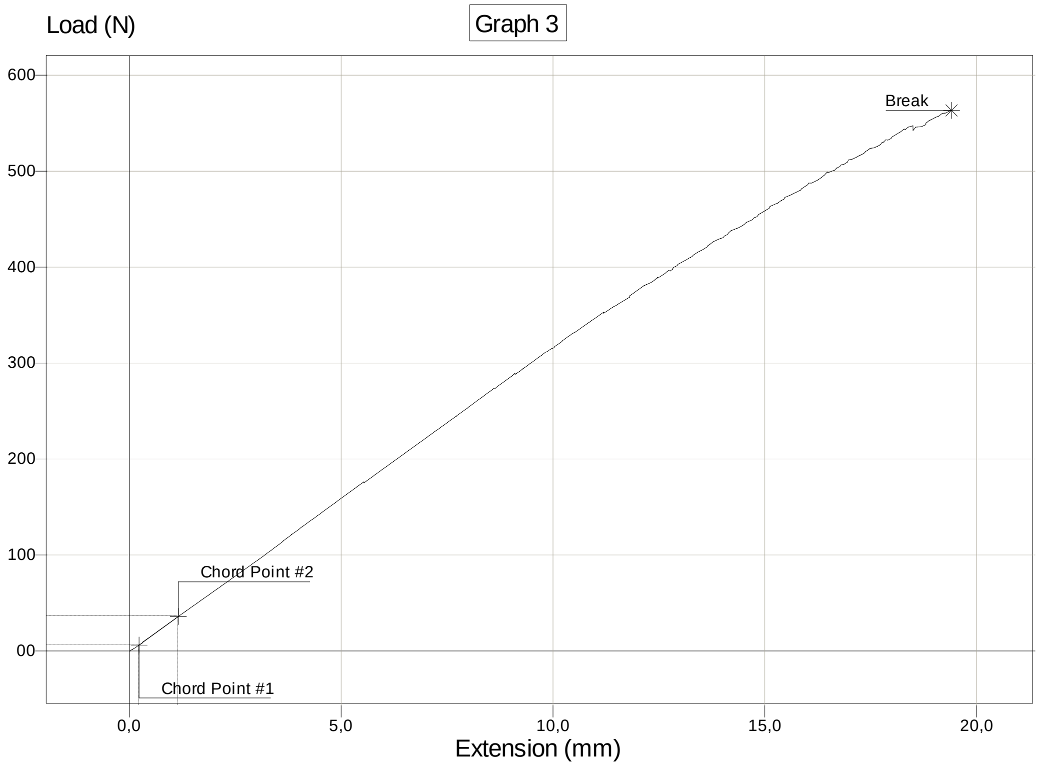
Annex 4

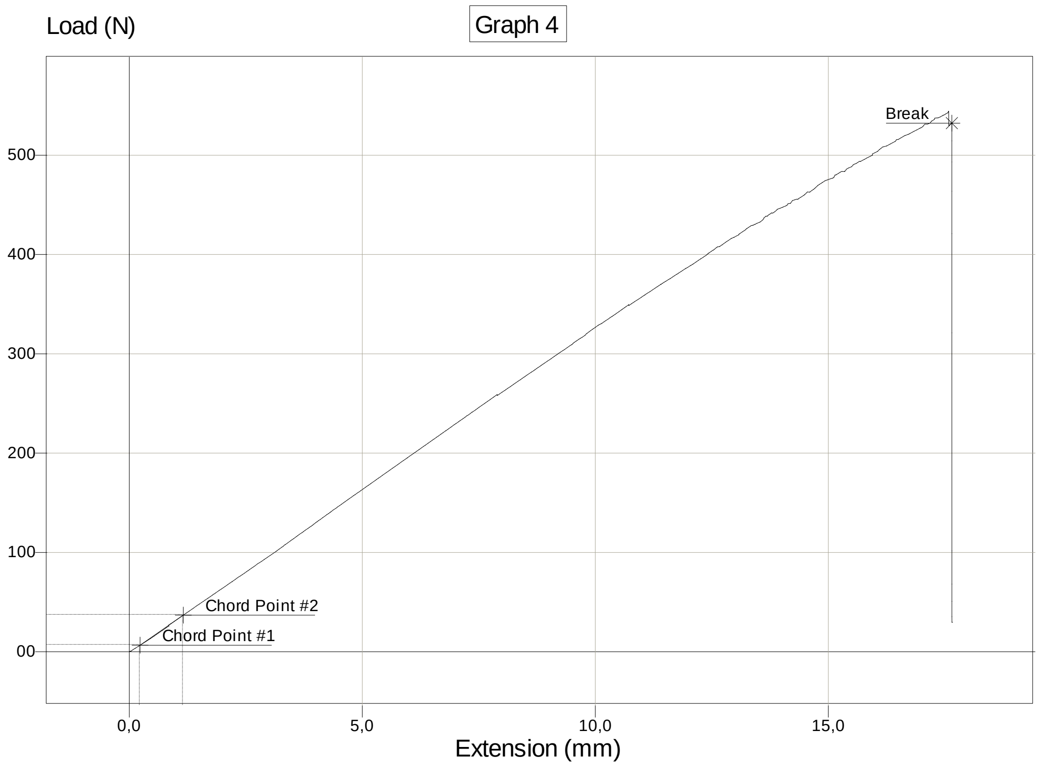
Results of static bending tests

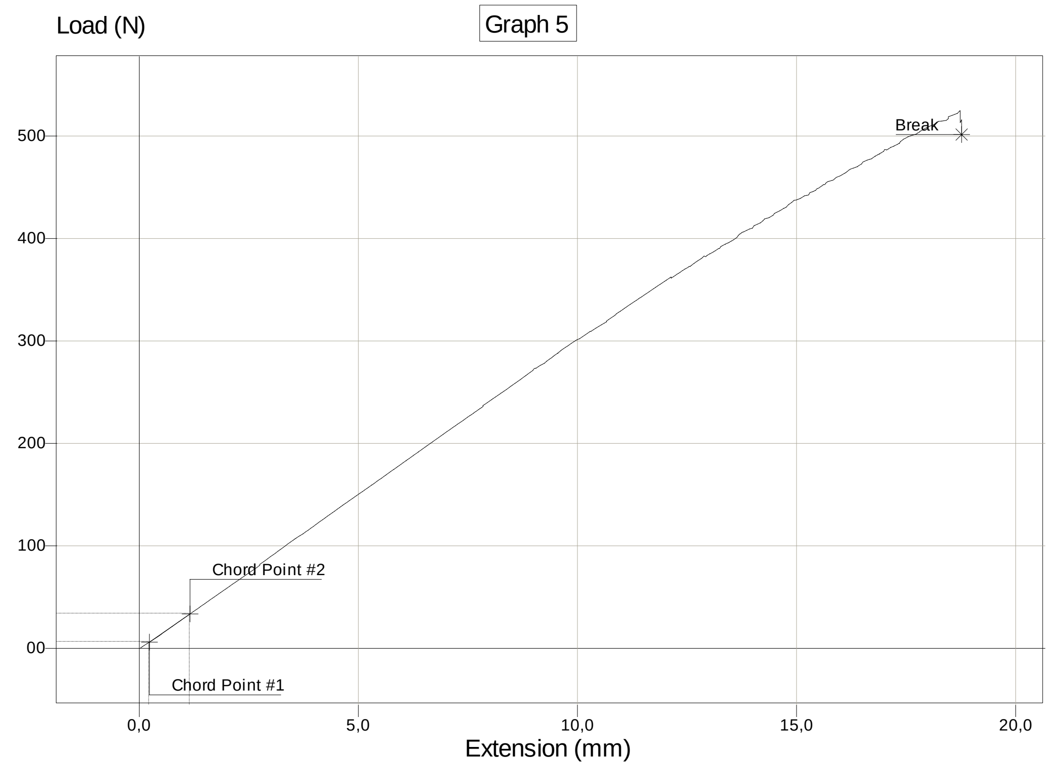
A.4.1. Bending of carbon fiber reinforced multilayered epoxy composite with 3 layers (E1)



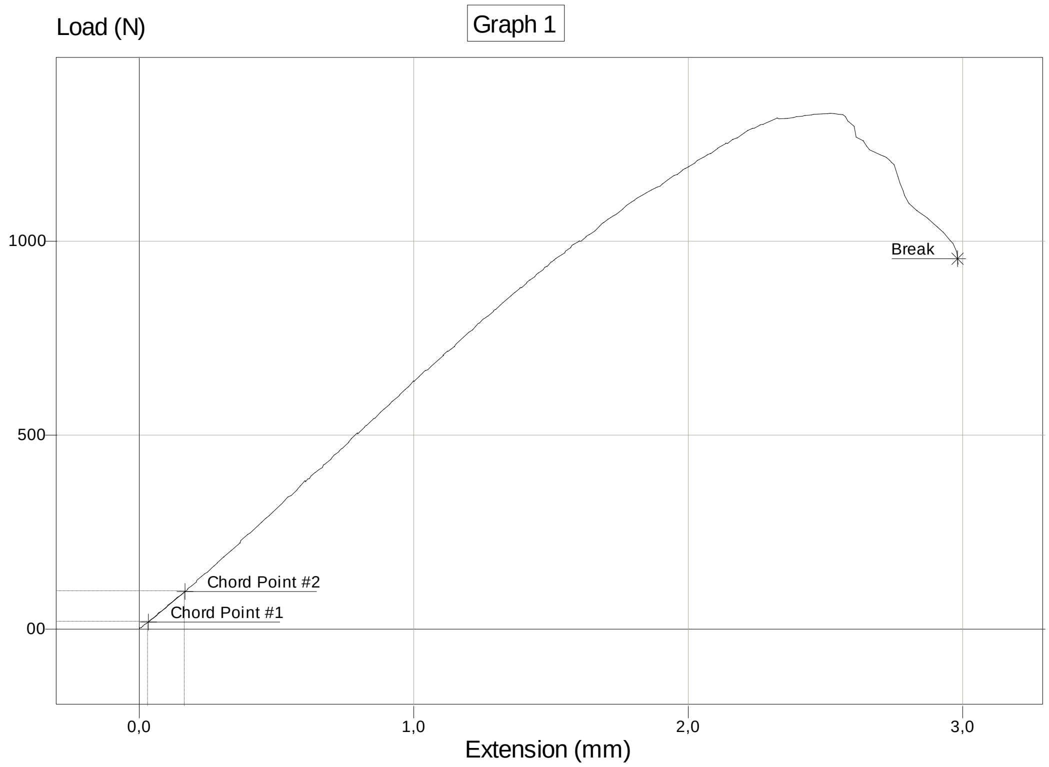


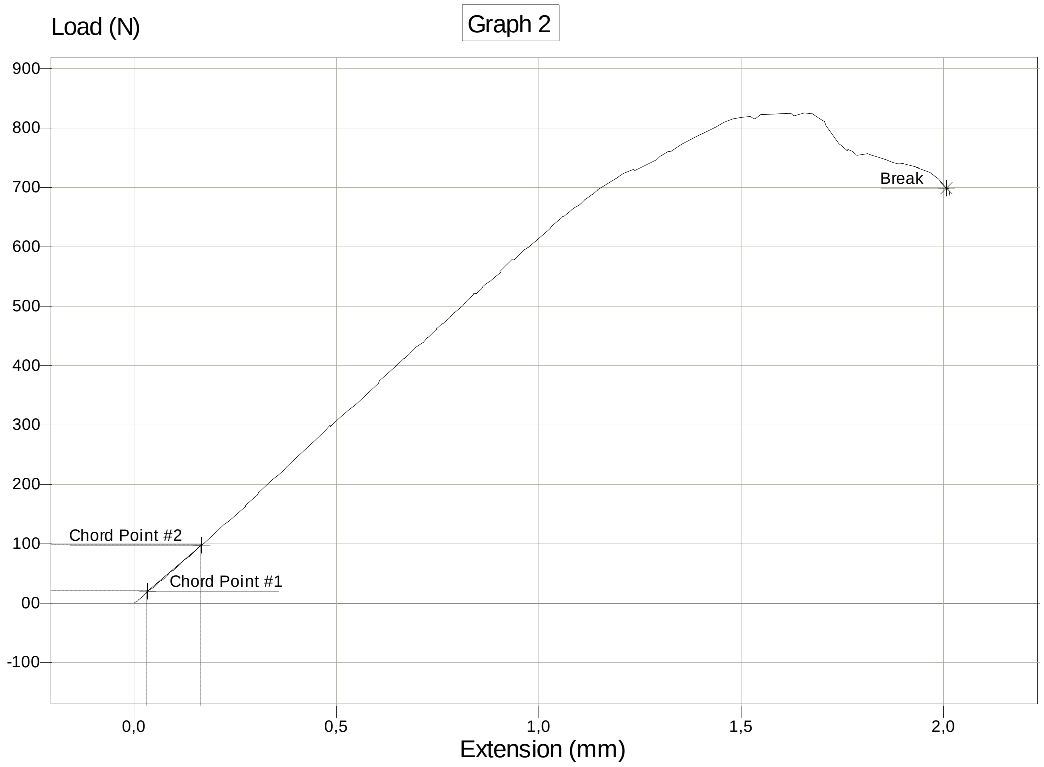

Load (N)
Graph 3
600
500
400
300
200
100
00
Break
Chord Point #2
Chord Point #1
0,0
5,0
10,0
15,0
20,0
Extension (mm)

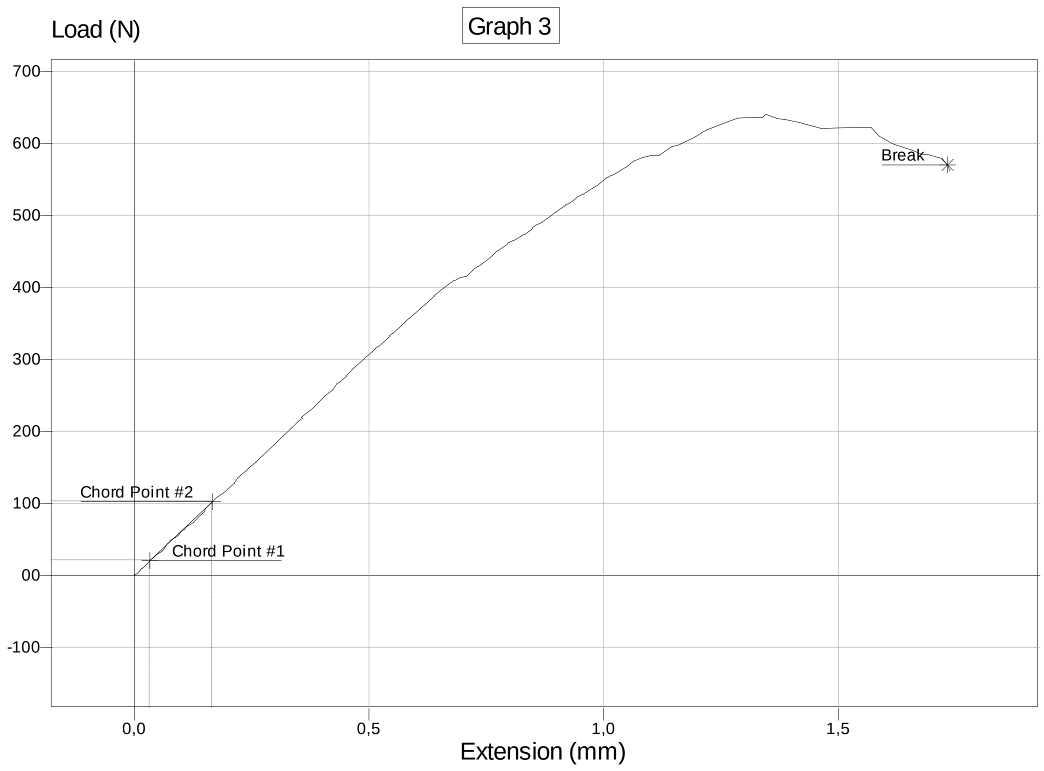

Load (N)
Graph 4
500
400
300
200
100
00
Break
Chord Point #2
Chord Point #1
0,0
5,0
10,0
15,0
Extension (mm)

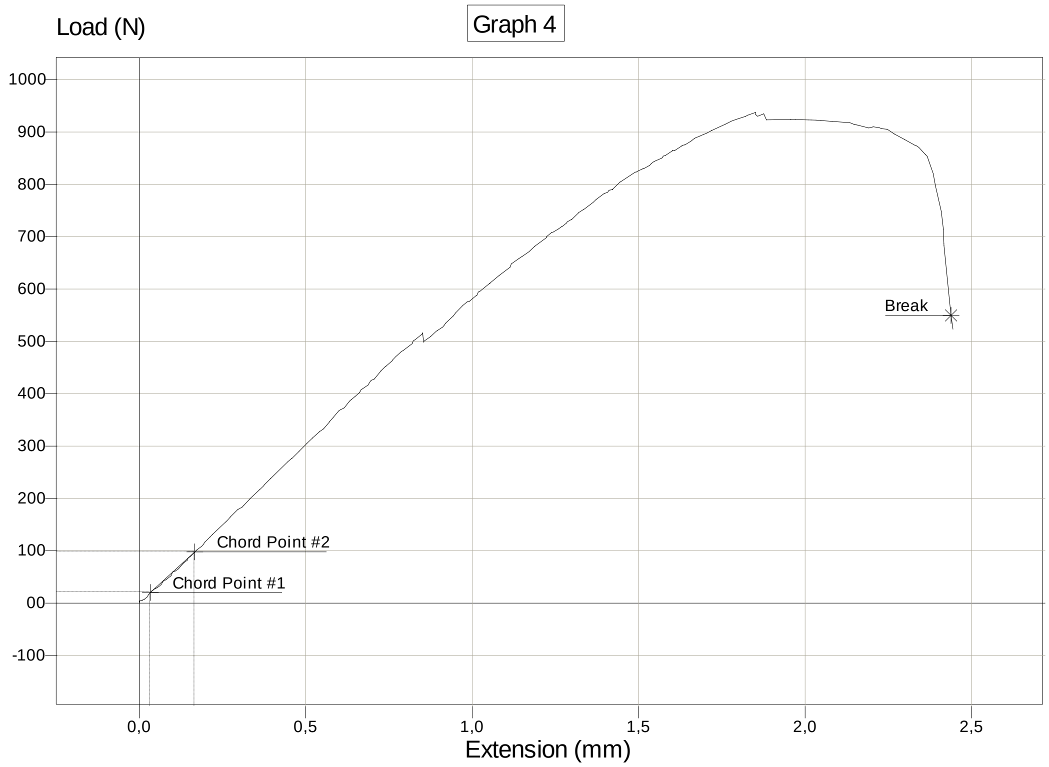


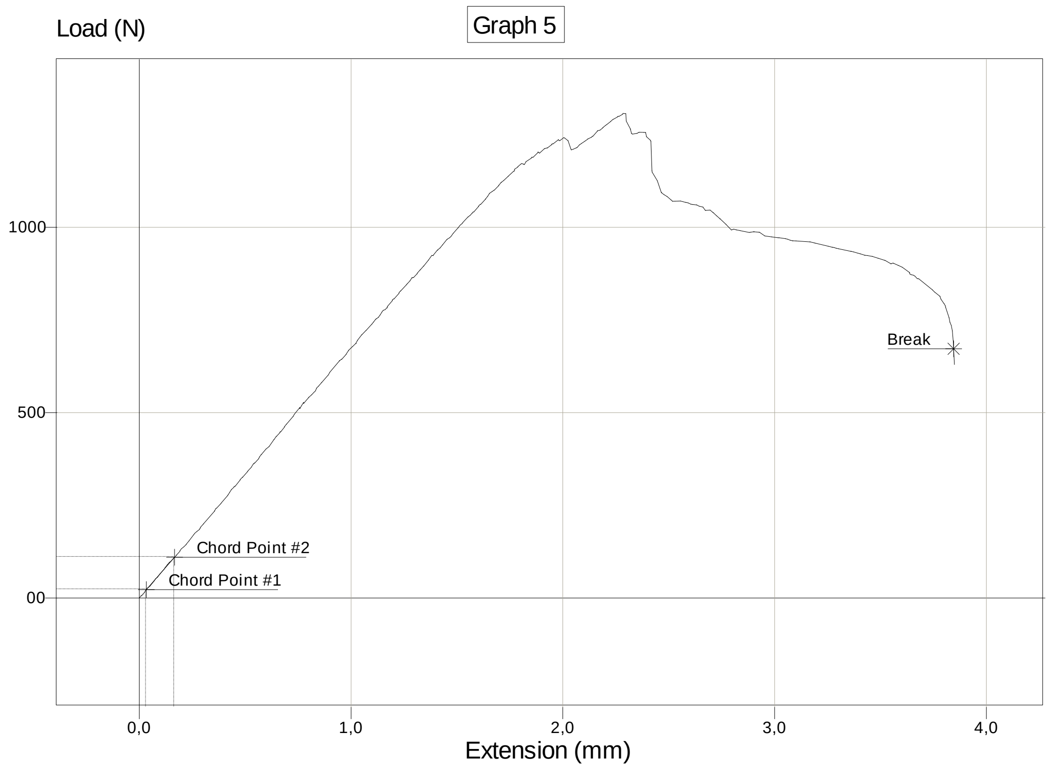
A.4.2. Bending of carbon fiber reinforced multilayered epoxy composite with 3 layers (E2)



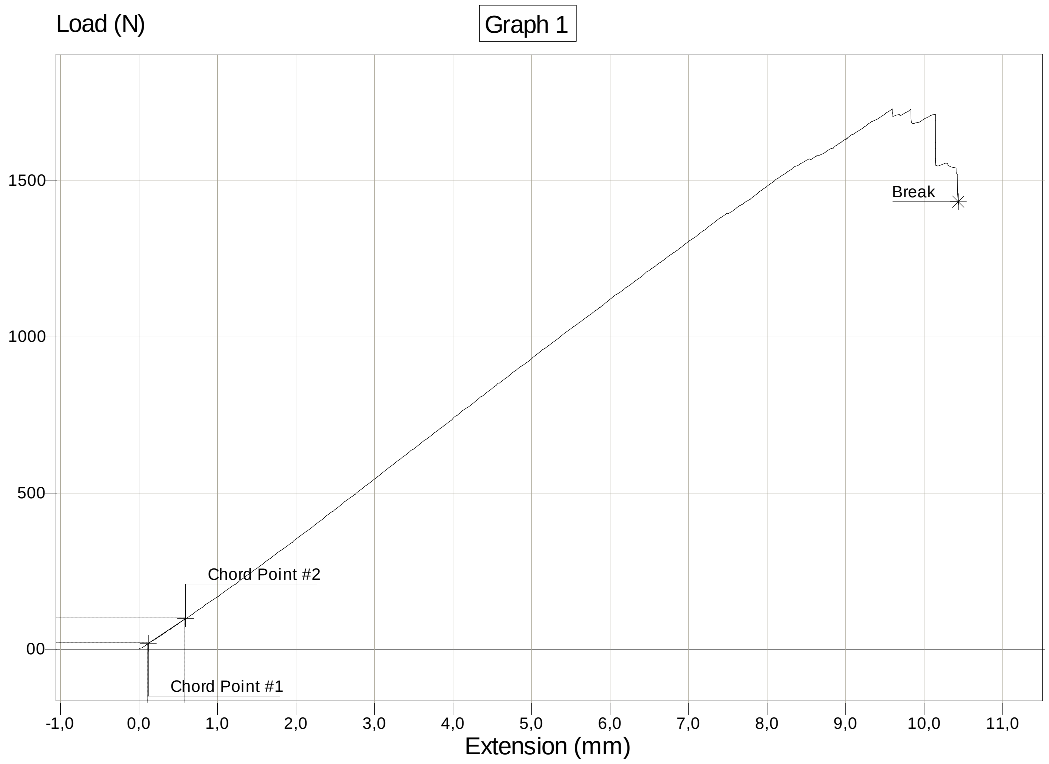

Load (N)
Graph 2
900
800
700
600
500
400
300
200
100
00
-100
Chord Point #2
Chord Point #1
Break
0,0
0,5
1,0
1,5
2,0
Extension (mm)

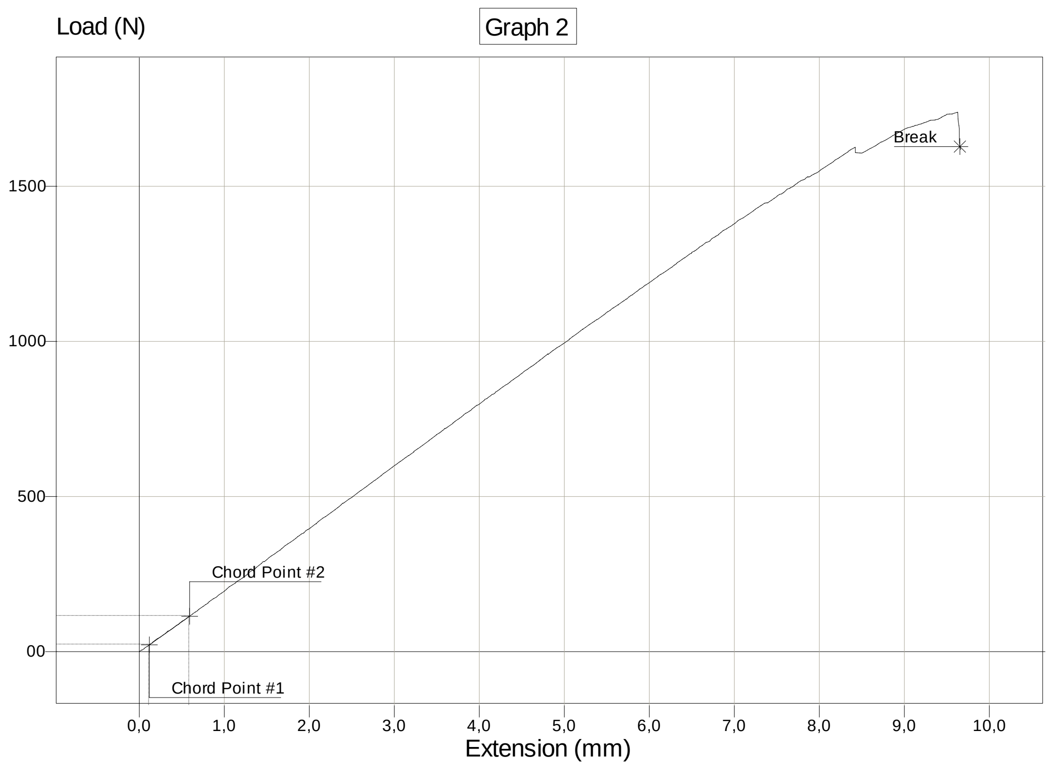

Load (N)
Graph 3
700
600
500
400
300
200
100
00
-100
Chord Point #2
Chord Point #1
Break
0,0
0,5
1,0
1,5
Extension (mm)

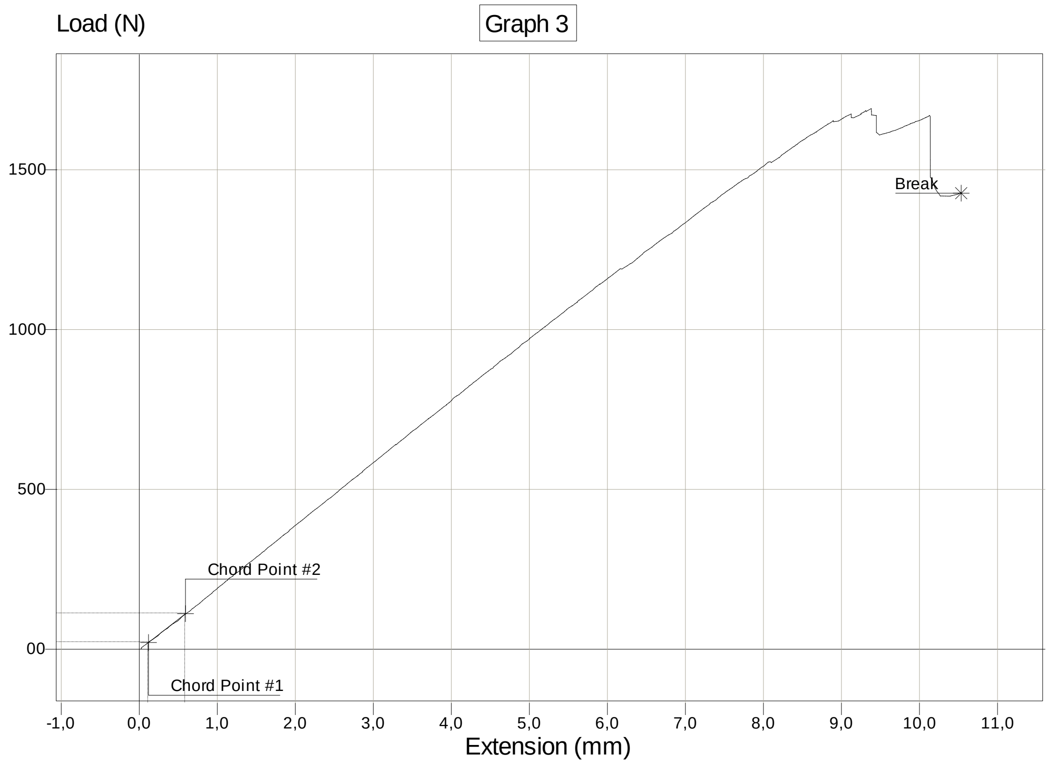

Load (N)
Graph 4
1000
900
800
700
600
500
400
300
200
100
00
-100
Break
Chord Point #2
Chord Point #1
0,0
0,5
1,0
1,5
2,0
2,5
Extension (mm)

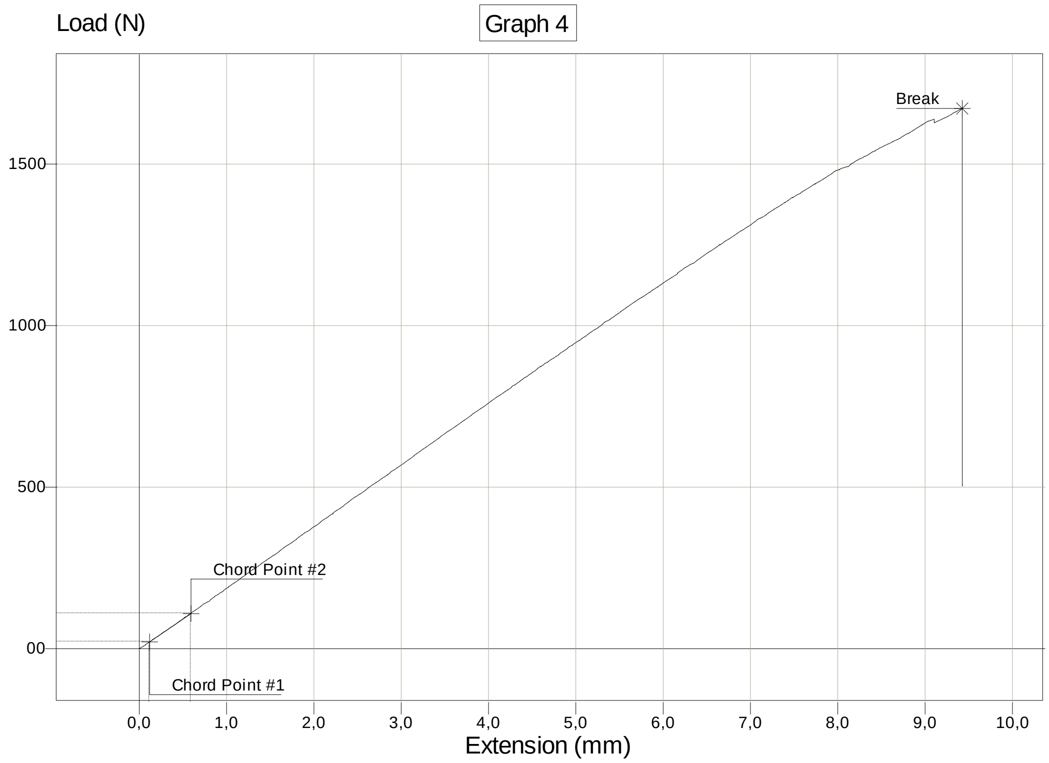

Load (N)
Graph 5
1000
500
00
Break
Chord Point #2
Chord Point #1
0,0
1,0
2,0
3,0
4,0
Extension (mm)

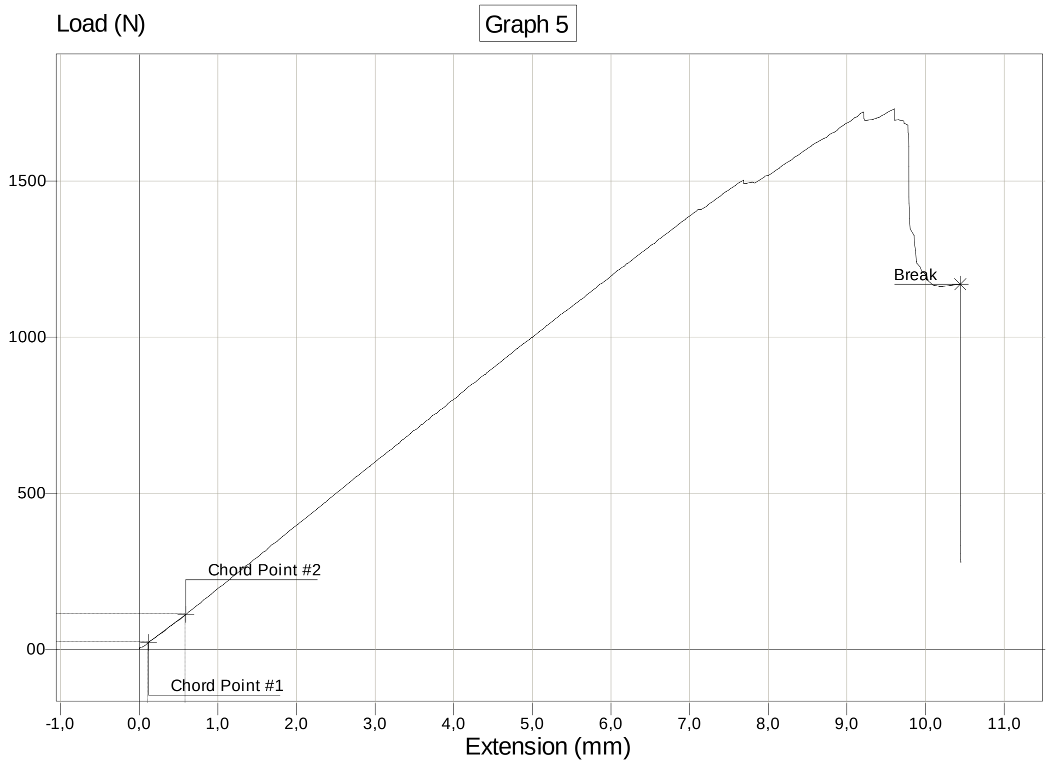
A.4.3. Bending of carbon fiber reinforced multilayered epoxy composite with 5 layers (E1)



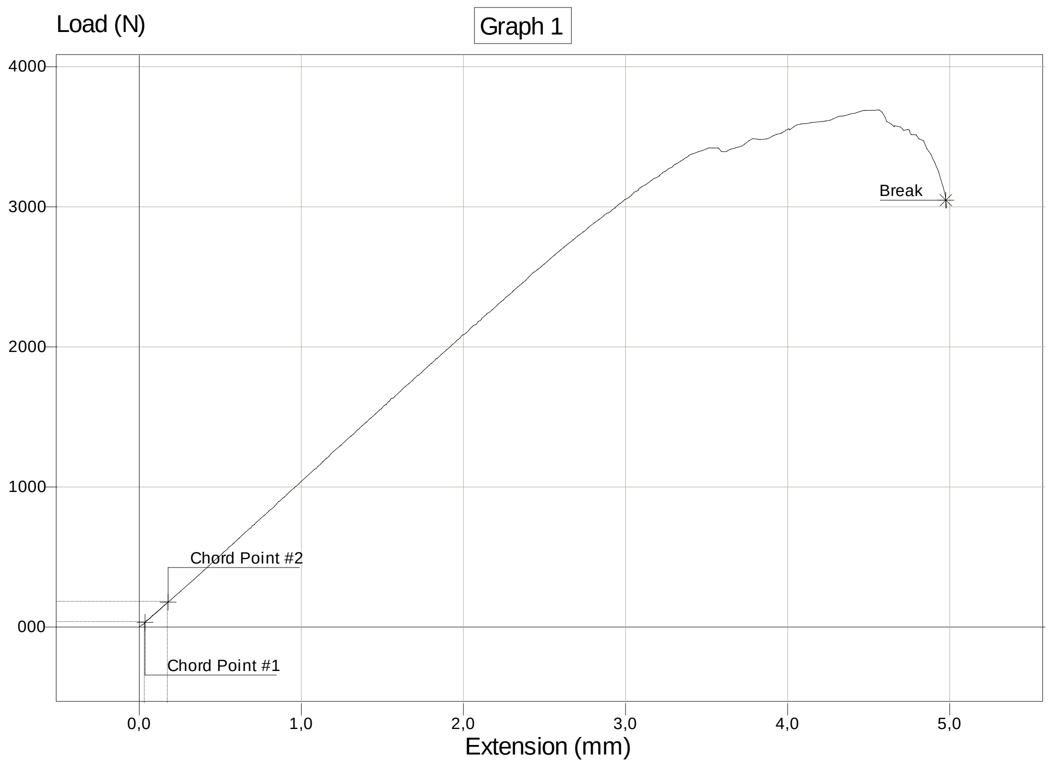


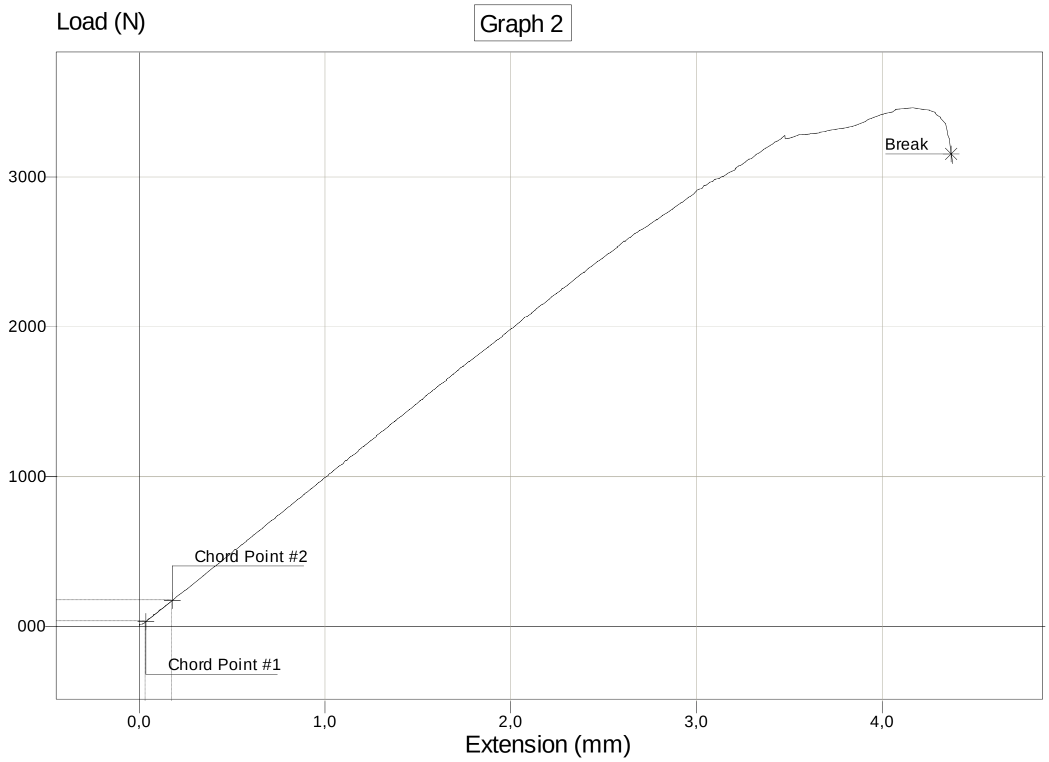

Load (N)
Graph 3
1500
1000
500
00
Chord Point #2
Chord Point #1
Break
-1,0
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
11,0
Extension (mm)

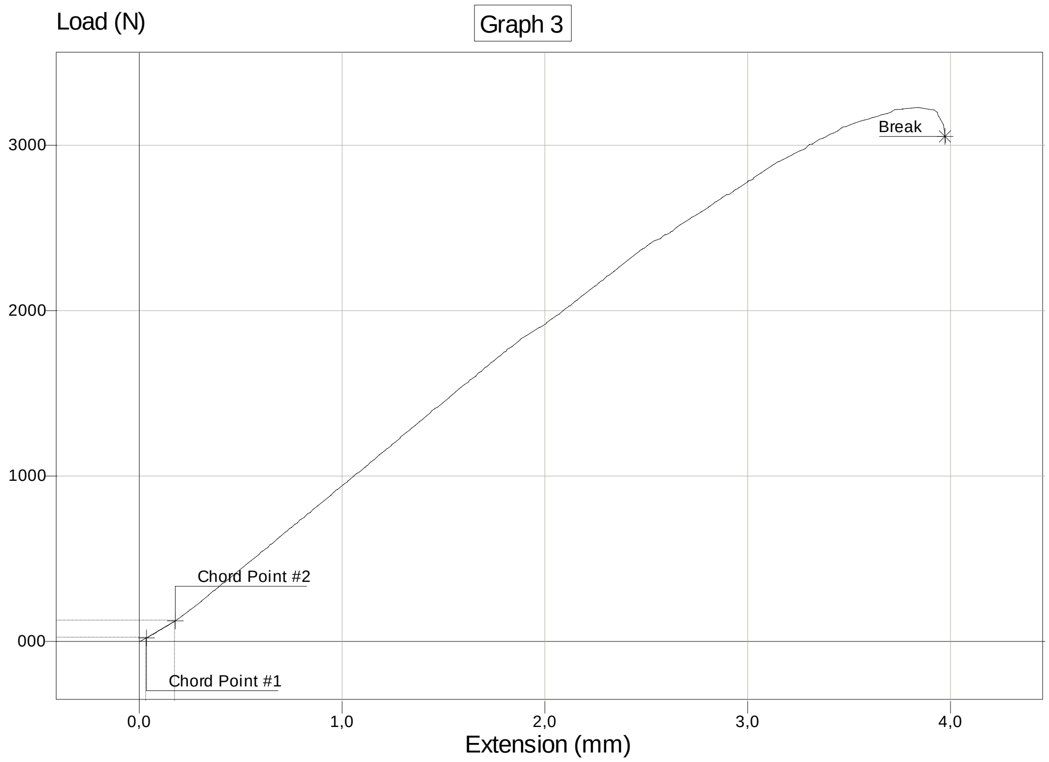

Load (N)
Graph 4
1500
1000
500
00
Chord Point #2
Chord Point #1
Break
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
Extension (mm)

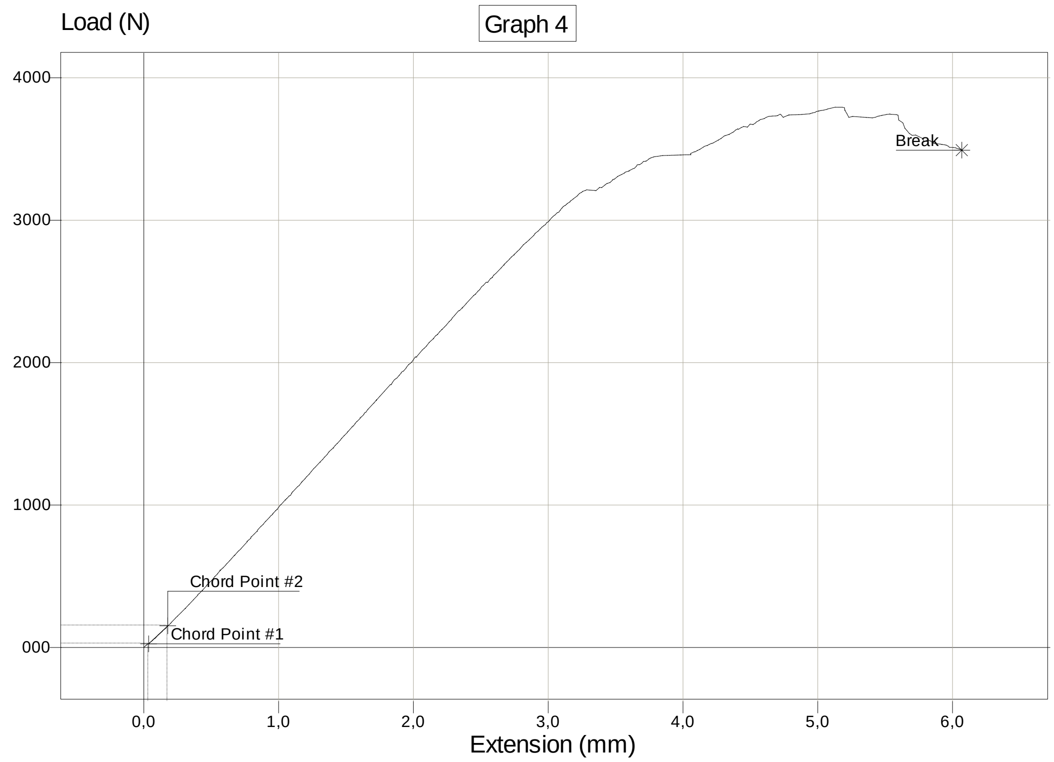


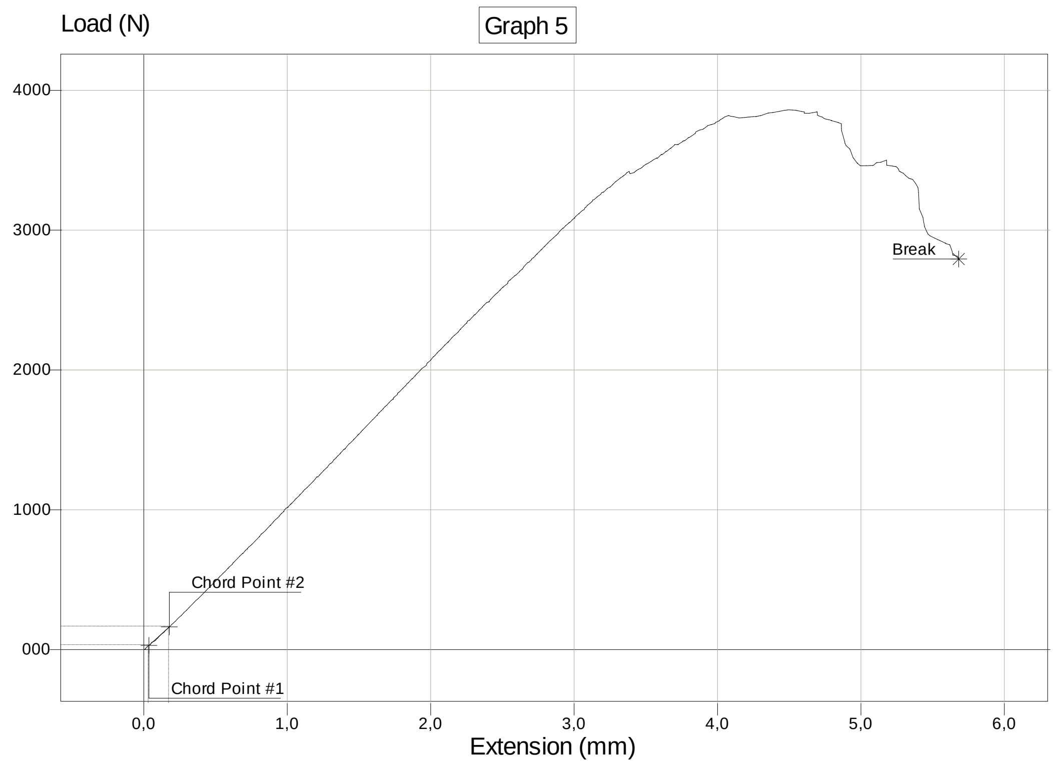
A.4.4. Bending of carbon fiber reinforced multilayered epoxy composite with 5 layers (E2)



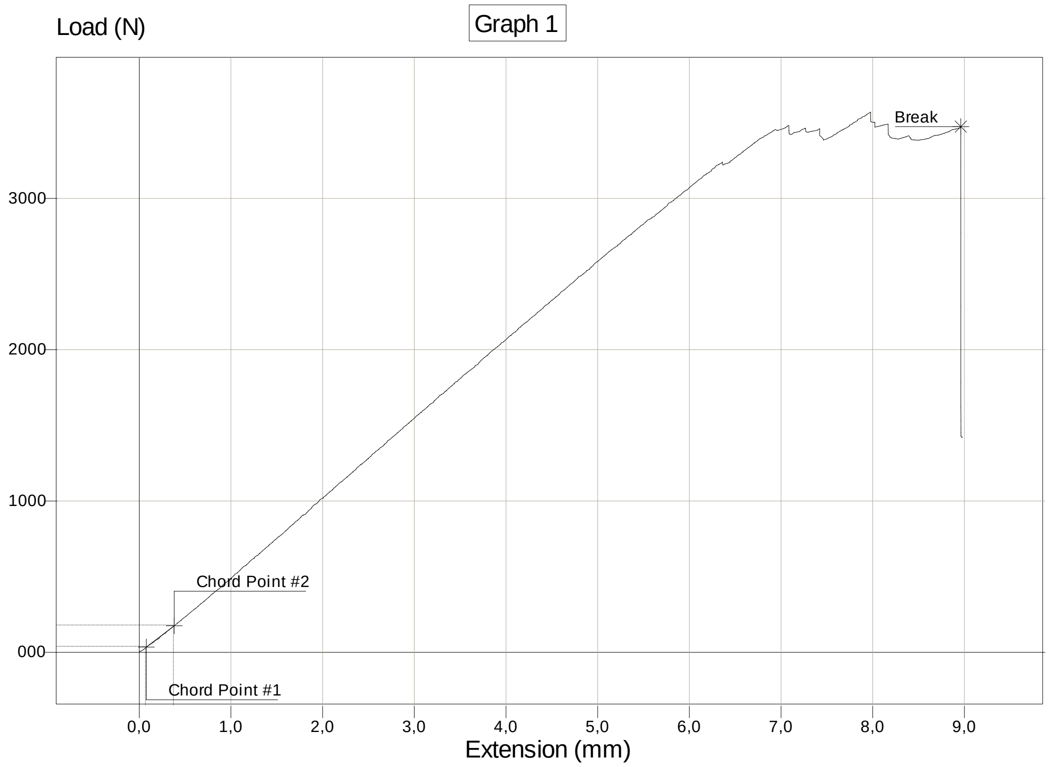

Load (N)
Graph 2
3000
2000
1000
000
Break
Chord Point #2
Chord Point #1
0,0
1,0
2,0
3,0
4,0
Extension (mm)

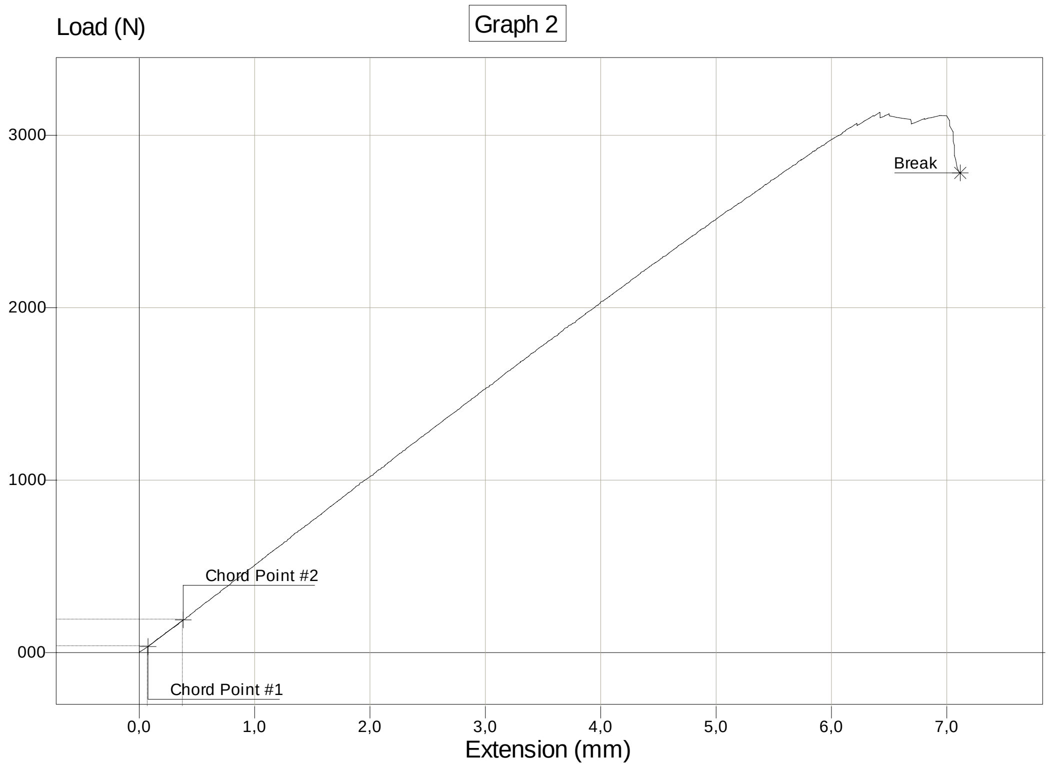

Load (N)
Graph 3
3000
2000
1000
000
Break
Chord Point #2
Chord Point #1
0,0
1,0
2,0
3,0
4,0
Extension (mm)

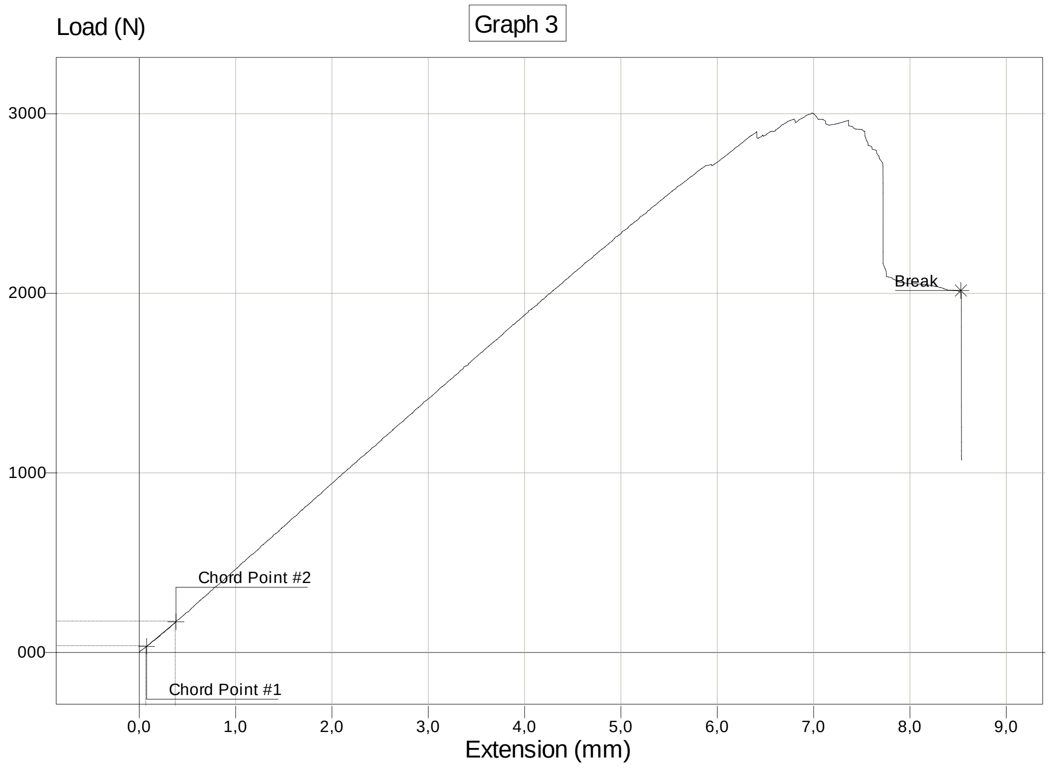

Load (N)
Graph 4
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
Break
0,0
1,0
2,0
3,0
4,0
5,0
6,0
Extension (mm)

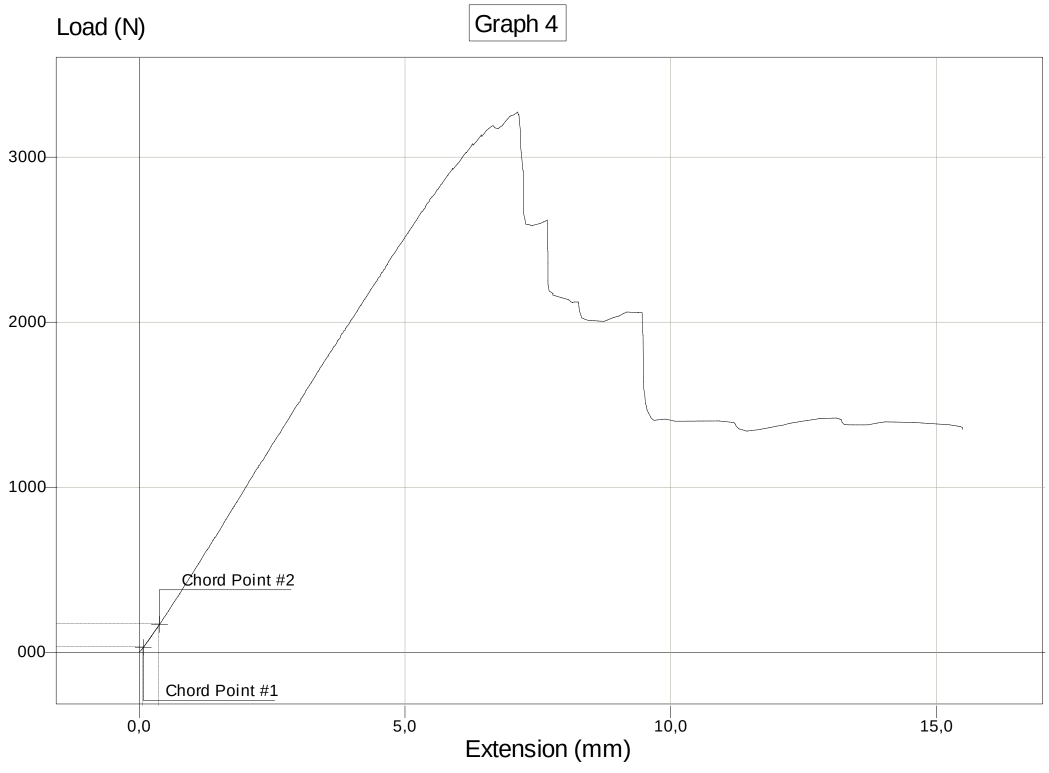

Load (N)
Graph 5
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
Break
0,0
1,0
2,0
3,0
4,0
5,0
6,0
Extension (mm)

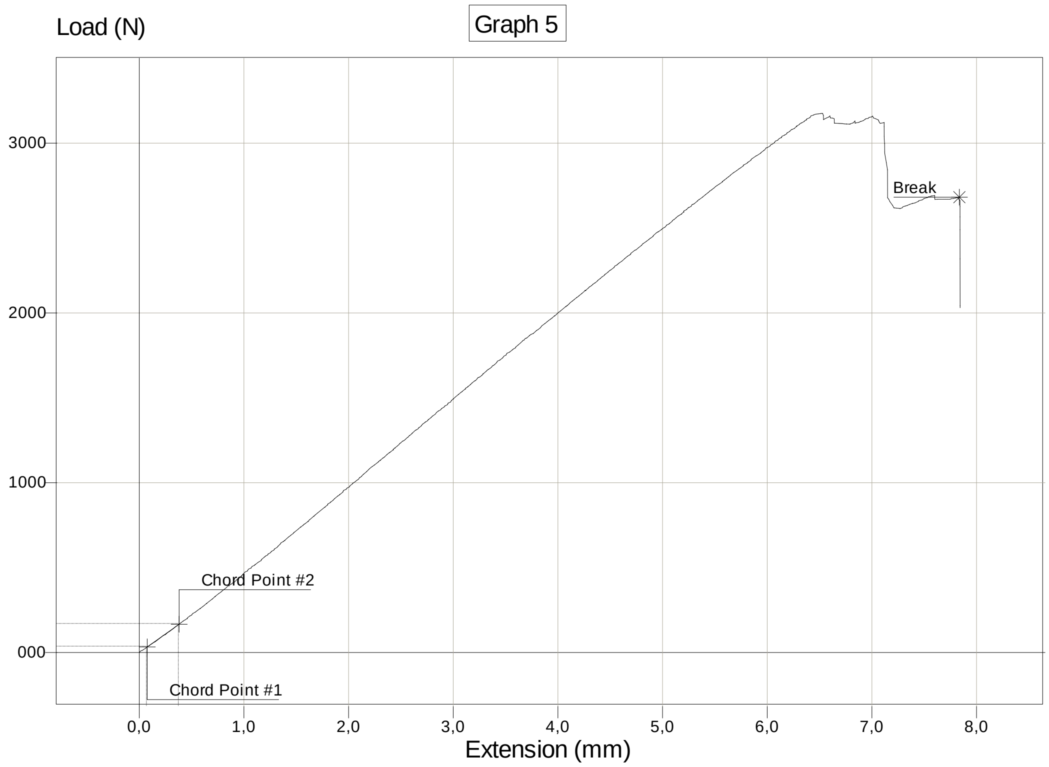
A.4.5. Bending of carbon fiber reinforced multilayered epoxy composite with 7 layers (E1)



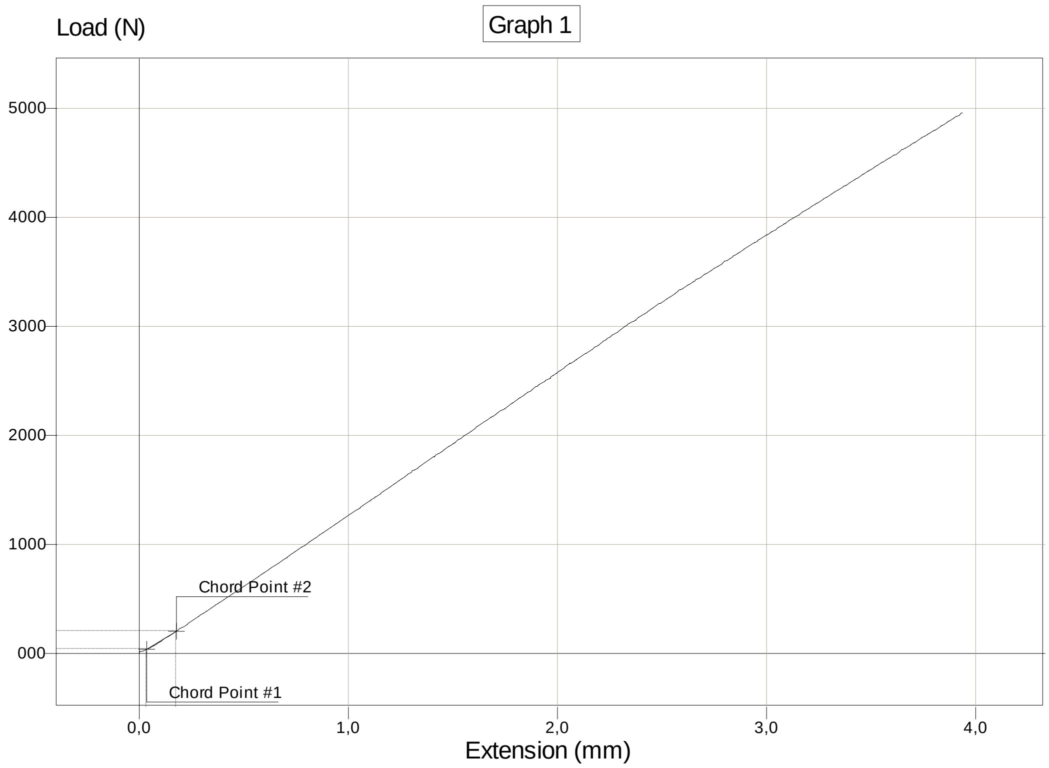


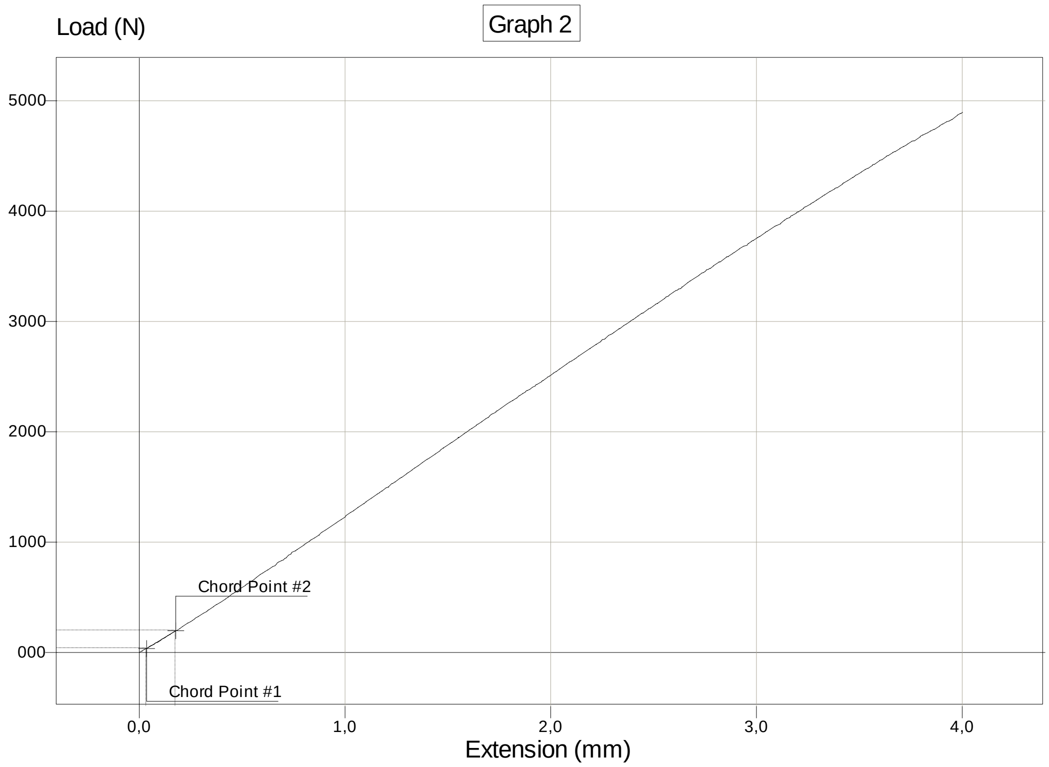

Graph 3
Load (N)
3000
2000
1000
000
Chord Point #2
Chord Point #1
Break
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
Extension (mm)

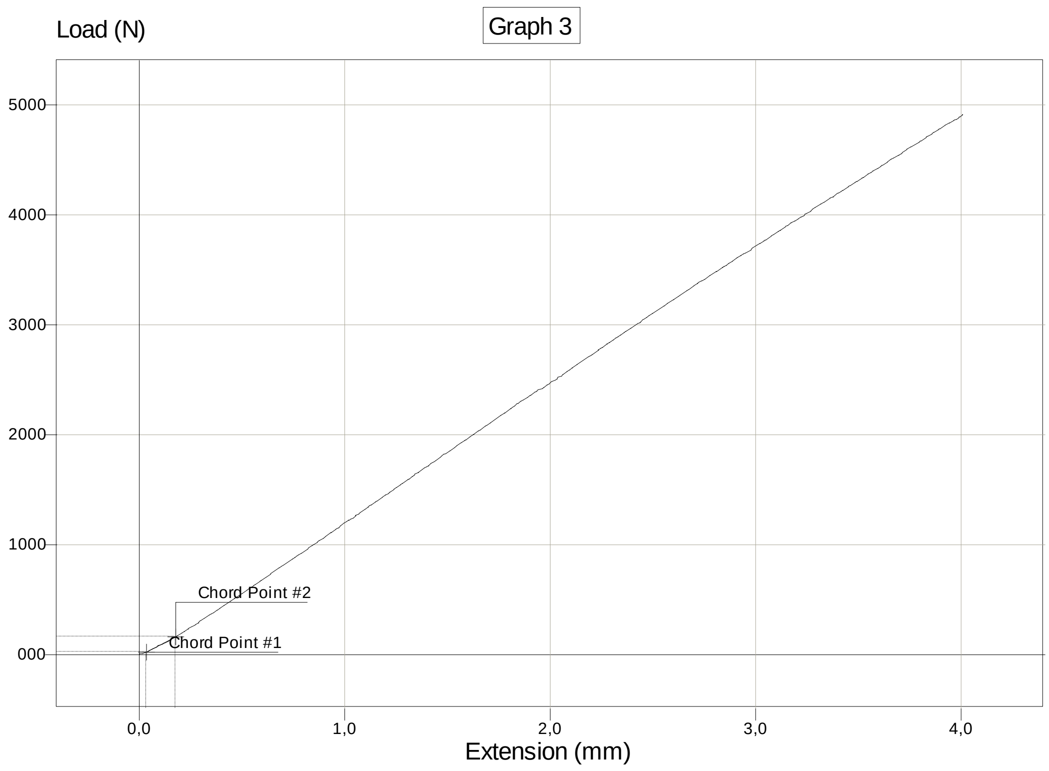

Graph 4
Load (N)
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
5,0
10,0
15,0
Extension (mm)

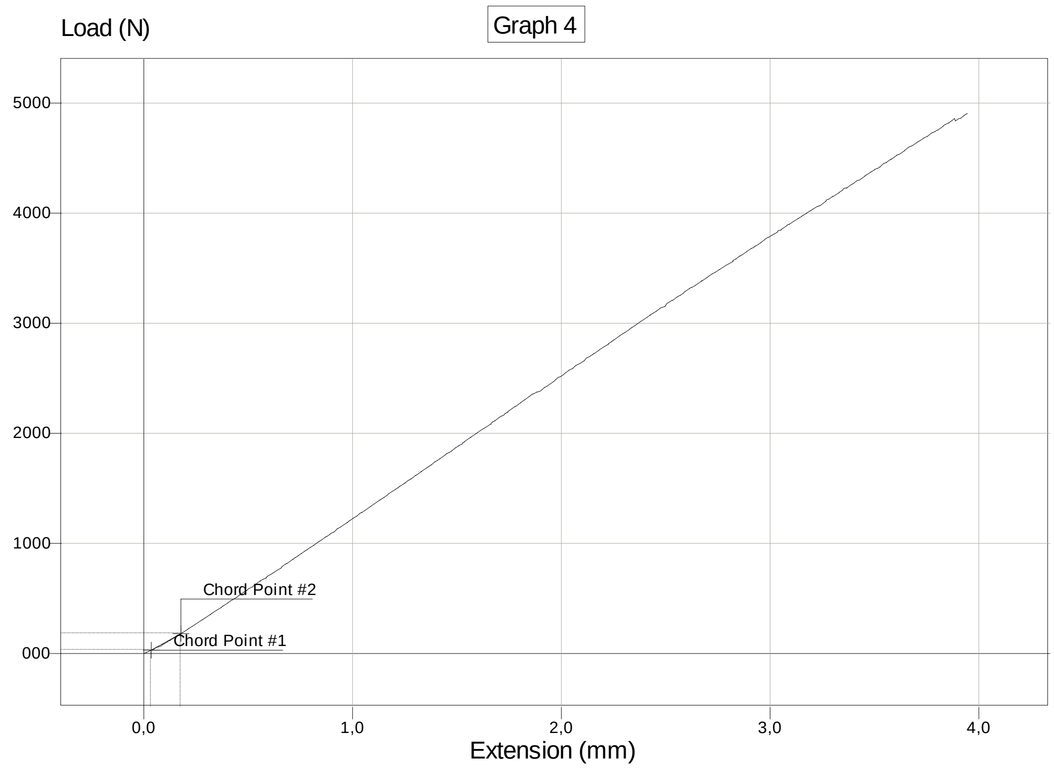


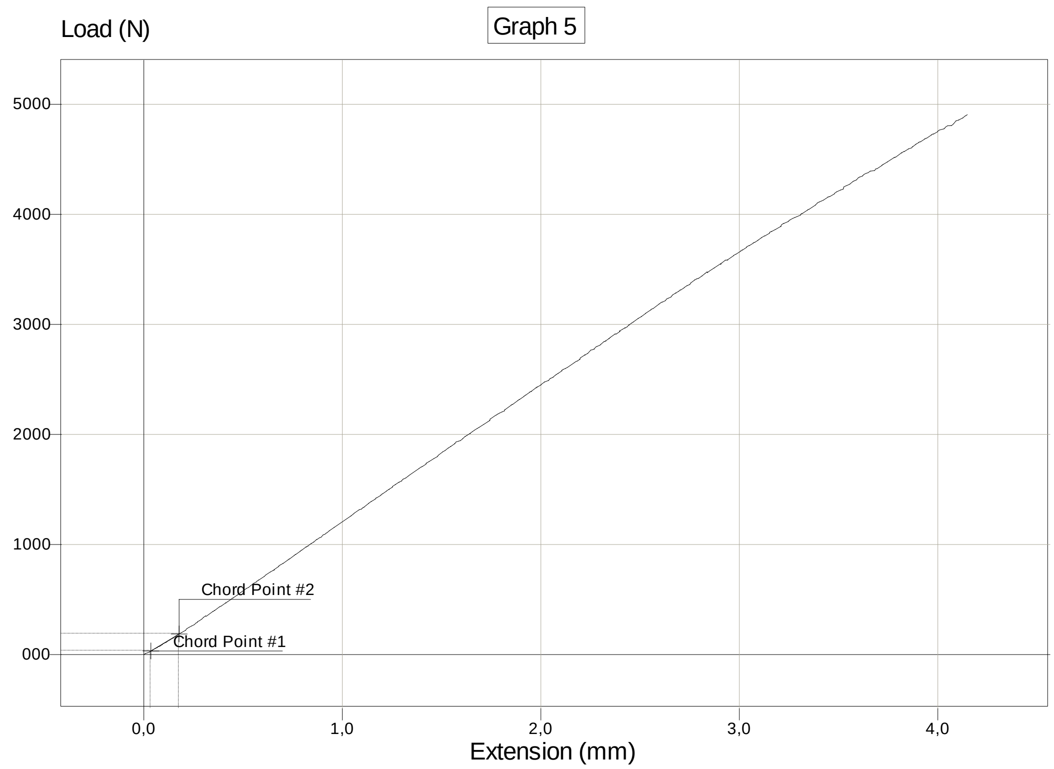
A.4.6. Bending of carbon fiber reinforced multilayered epoxy composite with 7 layers (E2)




Load (N)
Graph 2
5000
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
1,0
2,0
3,0
4,0
Extension (mm)


Load (N)
Graph 3
5000
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
1,0
2,0
3,0
4,0
Extension (mm)


Load (N)
Graph 4
5000
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
1,0
2,0
3,0
4,0
Extension (mm)


Load (N)
Graph 5
5000
4000
3000
2000
1000
000
Chord Point #2
Chord Point #1
0,0
1,0
2,0
3,0
4,0
Extension (mm)

Annex 5

Published papers connected to the PhD Thesis research

METALURGIA INTERNATIONAL vol.XVIII no. (2013)

These journals are included on ISI Web of knowledge-regional Journal Expansion European Union 2010, multidisciplinary fields http://isiwebofknowledge.com/products_tools/multidisciplinary/webofscience/contentexp/eu/

ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE – UHMWPE BEHAVIOUR IN INJECTION MOLDING PROCESSES

[1]Leonard Gabriel MITU, [2]Ileana Constanţa ROŞCA, [3]Santiago FERRANDIZ BOU

[1]Transilvania University of Brasov, [2]Transilvania University of Brasov, [3]Polytechnic University of Valencia

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Key words: polyethylene UHMWPE, injection moulding, acetabular cup.

Abstract: *Polyethylene UHMWPE is a semi-crystalline thermoplastic polymer. UHMWPE polyethylene structure consists of ordered regions (as sets of crystalline lamellae) embedded in a disordered amorphous phase. In production and research, five categories of polyethylene are found: very low density VLDPE, linear low density LLDPE, low density LDPE, high density HDPE and ultra high molecular weight UHMWPE. UHMWPE polyethylene has a relative molecular mass* M_r *(usually within 2-6* $x10^6$ *g/mol, with an average minimum 3.1 x106), superior to the HDPE polyethylene (values ranging from 50.000 to 300.000 g / mol). In the last 40 years, the polyethylene UHMWPE is widely used for the manufacture of implants, especially for load-bearing applications such as the acetabular cup of total hip and the tibial plateau. In this medical application, polyethylene UHMWPE has relative molecular mass of (4 to 6) x 106 Mr. In polyethylene processing through ram extrusion, compression moulding, injection moulding etc, the viscosity in the polymeric system gets considerably high once the molecular weight increases. In this situation, the polyethylene processing (in pure state)by moulding injection, raises major difficulties. Given this, the present paper analyses the UHMWPE polyethylene behaviour in the injection process using the Moldflow program. The modelling and the simulation of the injection process were effectuated for the acetabular cup manufacture.*

1. INTRODUCTION

Polyethylene PE is a semi-crystalline thermoplastic polymer [1], [2] which has the structure described by a set of crystalline blades (ordered regions) embedded in a disordered amorphous phase [2].

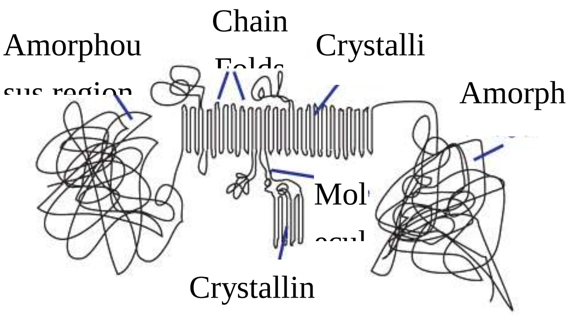

Fig.1. Morphological features of the polyethylene UHMWPE [ ]

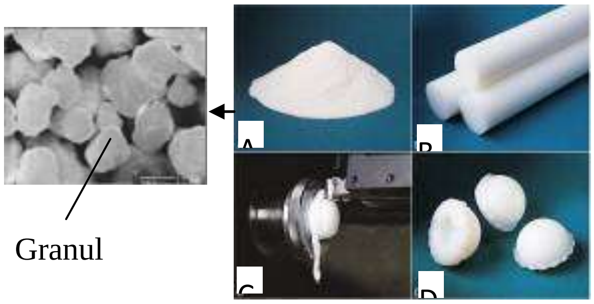

Fig. 2 Typical proccesing steps in the mnufacture of polyethylene UHMWPE implants: A.- the resin powder; B-semifinished rods; C- machining of the UHMWPE rods on a lathe; D- UHMWPE acetabular components after machining, after S. M. Kurtz, ref [4], [11]

Depending on the processes and mechanisms of polymerization, polyethylene is commercialized in five major grades [3], [4], [5]: very low density VLDPE, linear low density LLDPE, low density LDPE, high density HDPE and ultra high molecular weight UHMWPE. The polyethylene grades are used in the production of technical articles, household items, toys, medical devices, etc.

Usually polyethylene is processed using [4], [6], [5], [7]: film extrusion (LDPE, LLDPE, HDPE) ram extrusion (UHMWPE), blow moulding (HDPE, injection molding (HDPE) compression moulding (UHMWPE, PTFE). Based on the experience in production, the final product qualities are influenced by the processing techniques and the temperatures being used. Typically, the polyethylene processing temperatures are above their melting points. During processing, the viscosity of the polymeric system increases considerably with the increasing of the molecular weight [6], [7].

The polyethylene UHMWPE is obtained through a process in suspension with Ziegler-Natta catalysts and it has a relative molecular mass M_r (usually within 2-6 x10^6 g/mol, with an average minimum 3.1 x106), superior to the HDPE polyethylene (values ranging from 50.000 to 300.000 g / mol) [6], [7], [8], [9], [10].

In primary state, UHMWPE polyethylene is delivered in powder form (Fig.2.A) having particles with irregular shapes and sizes up to 500µm and an average size in the range 135-150 µm (Tacona grade) [9], [11] [12].

The viscosity increasing of UHMWPE polyethylene, just above the melting temperature, raises difficulties in its processing, in pure state, by injection moulding, blow moulding, or conventional screw extrusion [10], [8].

The UHMWPE polyethylene is characterized by a set of physical, mechanical, chemical, etc. [9], [13]-[14], [20]-[25]:

- Low coefficient of friction;
- High wear resistance, which is related to the molecular mass and to the polymer crystallization;
- Good chemical and impact resistance;
- Resistance to environmental stress cracking;
- Dimensional stability over a wide temperature range;
- High notched impact strength;
- High energy absorption at high stress rates;
- Low moisture absorption;
- Resistance to radiation.

Due to its physical, mechanical, chemical and so on, the polyethylene UHMWPE is widely used in the last 40 years in the medical field for the manufacture of orthopedic implants and, especially for load-bearing applications such as the acetabular cup (Fig. 1.D) of total hip and the tibial plateau [3], [1]. Currently, polyethylene UHMWPE used in the manufacture of implants has relative molecular mass of (4 to 6) x 106 Mr [15].

Fig. 2 Injection machine Mateo&Sole

The different trade names for UHMWPE, used in orthopedics can be classified into two categories: GUR resins produced by Ticona; the 1900 resins produced by Basell. The trade names for UHMWPE have the specifications mentioned in standard F648 [16] and ISO standard 5834-1 [17].

In the literature of the processing by injection are works that model the injection process using Moldflow simulation software [18]. Research does not seek polyethylene UHMWPE.

2. THE PROCESSING BY INJECTION SIMULATION ELEMENTS

In practice, the research of the injection process characteristics is made within the technological system formed of [19]: man/operator; machine; mold; method; material.
Each of these components affect directly and indirectly the behaviour of the polymer in the injection.

The polyethylene processing by injection is performed on specialized machines.

These machines operate in a working cycle which includes a sequence of operations such as [5], [18]: the material heating

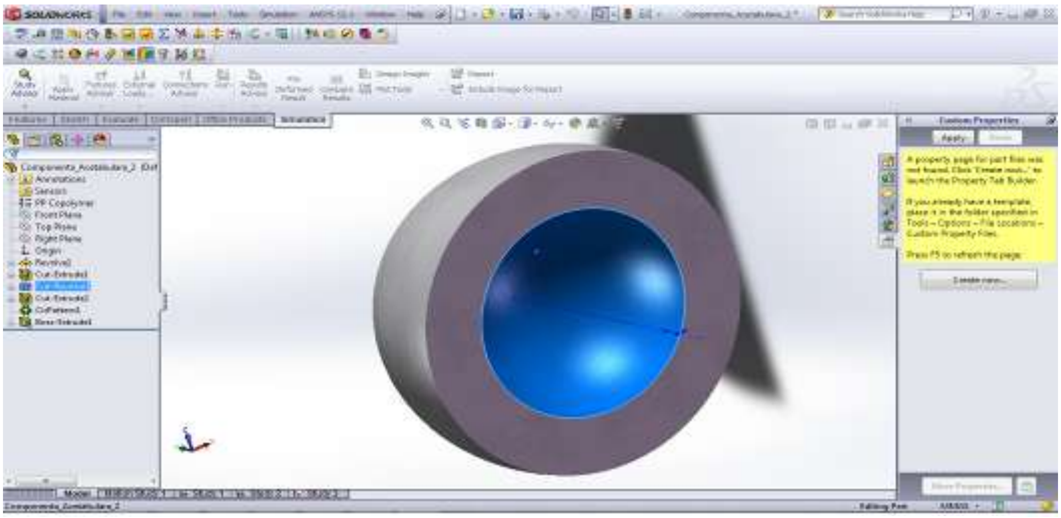

Fig. 4 The Acetabular cup 3D design representation in Solidworws program

and melting within the machine cylinder [20], [21], introducing the molten polymer in the pressurized matrix, the solidification and cooling of the polymer moulded in matrix. Diagrams of the injection cylinder temperatures and of the matrixes are done for each type of polymer.

According to PK Kennedy [18], the injection process simulation can be simplified by considering the following criteria:

- material properties ;
- geometric consideration;
- simplification by mathematical analysis

For the theoretical analyses of the UHMWPE polyethylene behaviour in the injection processing, the acetabulare component injection process modelling and simulation were made using Moldflow injection moulding program. Autodesk Moldfalow is a simulation program for the plastic materials injection moulding in which the injection process for plastic parts can be simulated and optimised.

In this paper we used injection machine Mateo & Sole (Fig. 3) and UHMWPE material with the following characteristics: elastic modulus 1100 MPa Coefficient
Poisson: 0.43, shear modulus: 384.6 MPa

In the first phase of the research, the drawing of the acetabular cup is done in Solidworks software as it is presented in Figure 4.

The modelling and simulation of the acetabular component injection process is performed during the following phases according to the Autodesk Moldflow simulation program:

- the model that characterises the polyethylene

UHMWPE injection process is imported from the Solidworks program;

- the 3D models are transformed in a network of nodes and triangular elements called MESH MODEL;
- the injection moulding process for thermoplastics is chosen;
- the next step is to choose as material the UHMWPE polyethylene having the mentioned characteristics;
- the cooling circuit is chosen depending on the acetabular cup model (Fig. 5);

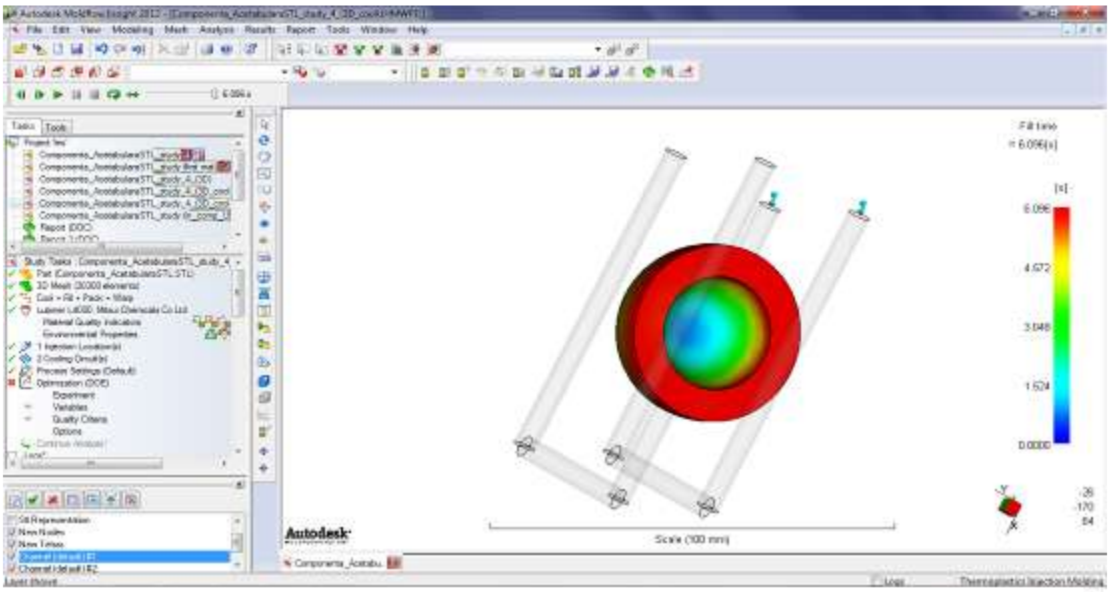

Fig. 5 Cooling circuit according to the acetabular cup model

- the moulding point is selected (Fig. 6);

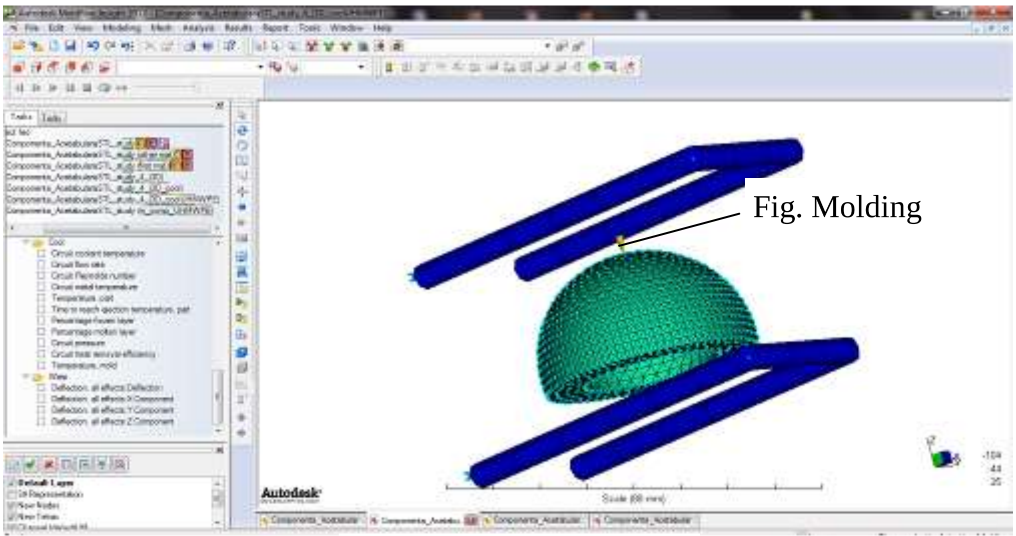

Fig. 6 Choosing the molding point;

- the simulation ends and Run is selected in order to execute the simulation process running.

Based on the results of the ongoing research, theoretic data that describe the UHMWPE polyethylene behaviour in the injection process are obtained. The variation of the injection pressure

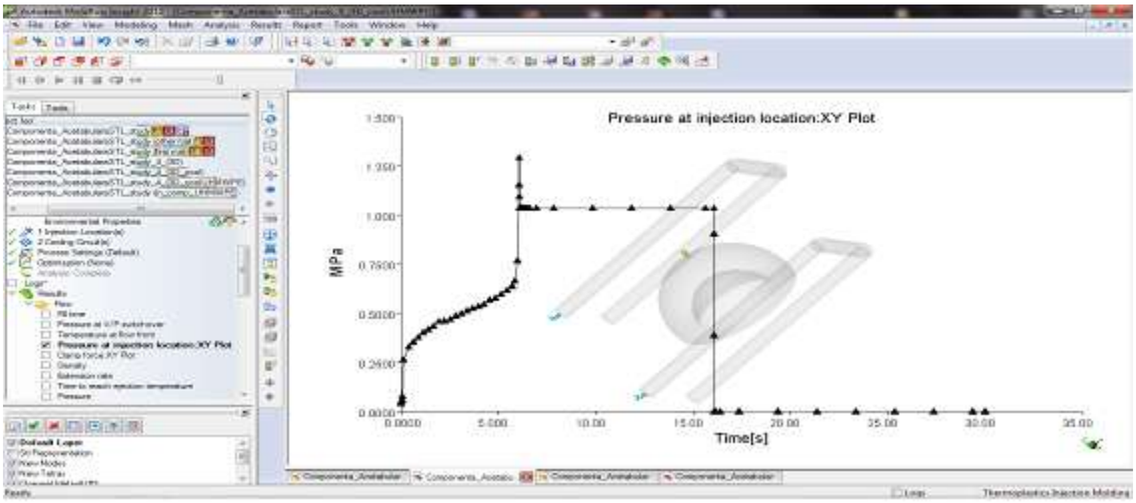

Fig. 7 Variation of injection pressure

is presented as an example (Fig.7).

3. CONCLUSION

Currently, polyethylene UHMWPE is a semi-crystalline thermoplastic polymer that is used to manufacture the medical component acetabular cup of total hip and the tibial plateau. The polyethylene behaviour in the injection process can be studied through the modelling and the simulation of the injection process. To this end three criteria are taken into account: material properties; geometric consideration; simplification by mathematical analysis. The Moldflow program is used in the research. Under this program a sequence of steps must be fallowed. These steps are presented in the paper.

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EXPERIMENTAL RESEARCH CONCERNING THE PLASTIC MATERIALS BEHAVIOUR IN MEDICAL ENGINEERING

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Key words: polymeric materials, mechanical properties, medical application, tensile testing

Abstract: *In literature, polymeric materials have a number of properties which are divided into three broad groups: 1. intrinsic properties arising from the chemical structure of the material, 2. technological properties resulting from processing methods and techniques used to obtain the piece or the finite product 3. properties arising from the use conditions of polymeric materials (products). In literature it is used the term of "polymers' property" that summarizes the polymeric materials systemic properties assembly from the planning stage, to the finite product. Within the polymeric materials properties, the mechanical properties are analyzed extensively, especially in the case of the polymers used in medical applications. The paper presents, in a systemic form, the study of the tensile behaviour for a number a polymers used in the medical applications: Acrylonitrile butadiene styrene (ABS), Polycarbonates(PC),Polyamide(PA6),Polypropylene(PP),etc.*

1. INTRODUCTION

By definition [1], [2], [3], [4], the polymer is a material consisting of macromolecules (large molecules) and it is obtained by repeating a constitutive unit (the repeating units or monomers) which comprises a group of atoms connected by covalent bonds. As a result, the behavior of polymers is the continued behavior “of smaller molecules at the limit of very high molecular weight" [5]. According to Vasiliu-Oprea., Al. Constantinescu and P. Barsanescu [1] and D.W. Van Krevelen and K. Nijenhuis [6], the properties of polymeric materials are divided into three main groups:

1. intrinsic properties arising from the chemical structure of the material. According to D.W. Van Krevelen and K. Nijenhuis [6], the chemical structure of the polymer is defined by four basic structural components: “a. the nature of the repeating units, b the nature of the end groups; c. the composition of possible branches and cross-links; d. the nature of defects in the structural sequence”;

2. technological properties that determine the possibility and efficiency of the polymeric materials processing. It is noted [1] the particularity of the processing operations to give polymers new properties such as the shape and the size;

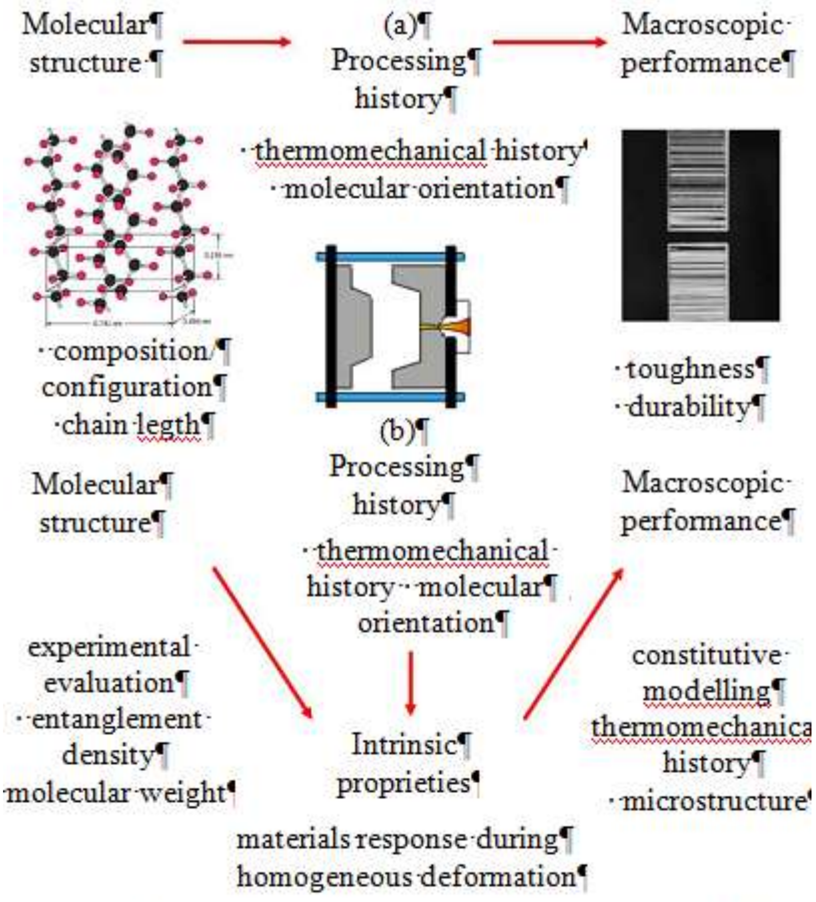


Fig.1. The representation of the notion “polymers quality” from the intrinsic properties, to the macroscopic properties of the polymer corresponding to the finite piece - from H. E. H. Meijer and L. E. Govaert, ref. [8]

3. property arising from the use characteristics of polymeric materials. Generally, these properties are the result of the biunique interaction between intrinsic properties and technological ones.

Currently, polymers' structure and properties are studied in many theoretical and experimental studies [5], [6] [7]. Regarding this, H. E.H. Meijer and L. E. Govaert [8] prezintă (Fig. 1) present a synthetic scheme of the polymer's properties described by the interactions among: the polymer's structure – the polymer's processing history – the polymer's macroscopic performances within the finite product. A quite similar scheme is also presented by C. Vasiliu-Oprea., Al. Constantinescu and P. Bârsănescu [1] and D**.**W**.** Van Krevelen and K. Nijenhuis [6**].**

The polymers' mechanical properties are determined by their two main characteristics, namely the chemical structure and the molecular weight distribution.

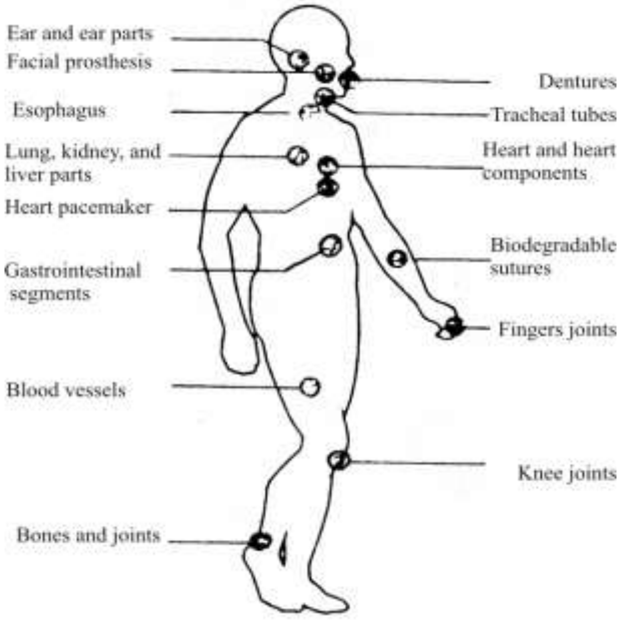
The polymers' mechanical properties are represented by the next main groups [7]:

- Viscoelastic behaviour at constant temperature;
- Viscoelastic behaviour in constant time;
- Tensile behaviour;
- Hardness behaviour;
- Tensile and shear behaviour;
- Aging behaviour.

2. Experimental Data

Polymeric materials are used in various fields, among which the medical applications can be listed (Fig. 2).

The polymeric materials and the polymeric composite materials must meet stringent requirements related to their behaviour in the biological environment. These requirements are analyzed and studied by a number of researchers such as



Ear & Ear Parts	Acrylic, PE, PVC, Silicone
Facial Prothesis	Acrylic, PE,PVC, Silicone
Dentures	Acrylic, UHMWPE, Epoxy
Esophagus & Tracheal Tube	Acrylic, PVC, PU
Upper body	PE, PP, PVC
Lung, Kidney&liver parts	Polyester, PVC, P-Aldehyde
Heart Pacemaker	PE, P-Acetal
Heart&Heart Components	Polyester, PVC, Silicones
Gastro-intestinal Segments	Silicone, PVC, Nylons
Biodegradable sutures	Poly-glycolides
Finger Joints	Silicones, UHMWPE
Blood Vessels	Polyester, PVC
Knee Joints	PE
Foot Bones and Joints	PE

Fig. 2. Polymer used as medical device from H. Sobhi., M. E. Matthews, B. Grandy., J. Masnovi., A. T. Riga ref. [ ]

B.D. Ratner., Al. S. Hoffman., Fr. J. Schoen and J. E. Lemons [9], J.Y. Wong and J.D. Bronzino [10], J.B. Park [11] J.M.

Hoffman [12], H. Sobhi., M. E. Matthews, B. Grandy., J. Masnovi and A. T. Riga [13].

Along with the mechanical properties, the thermal properties of the simple and reinforced polymeric materials [14], [15], [16], [17], [18] are of great importance in defining their behaviour in different medical applications.

The research was based on the experimental analyses of the tensile behaviour of the next simple and reinforced polymeric materials that are used in medical applications: Acrylonitrile butadiene styrene *(ABS*), Polycarbonates *(PC)*, Polyamide *(PA6)*, Polypropylene *(PP)*, High-density polyethylene (HDPE), High-Impact Polystyrene (HIPS), Polyethylene terephthalate (PET) and Fiber Glass Rreinforced Polypropylene (PPGF).

The experimental research consisted of the following steps:

- there were chosen the materials that were about to be subjected to the tensile test and their characteristics;

- there were established the testing conditions according to the guidelines from literature and the current standards (tab.1) for medical applications [20], [21], [22], [23],[24];
-there were executed by injection test samples at the required sizes and forms (Fig. 3);

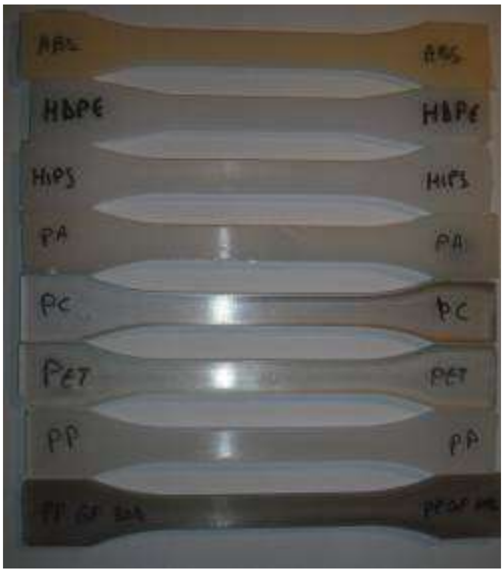


Fig. 3 Epruvete pentru încercări la tracţiune, executate prin injecţie

- experiments were performed on the tensile test machine (Fig. 4);

Fig. 4 Maşina de încercat la tracţiune folosită la experimentări

- the data obtained from the experiments are presented in Table 1;
- based on the experimental data, the diagram, from Figure 5, was drawn. The diagram shows how the selected polymeric materials behave at mechanical solicitations. It is noted that this behavior is different for each type of polymer used in the experimental research.

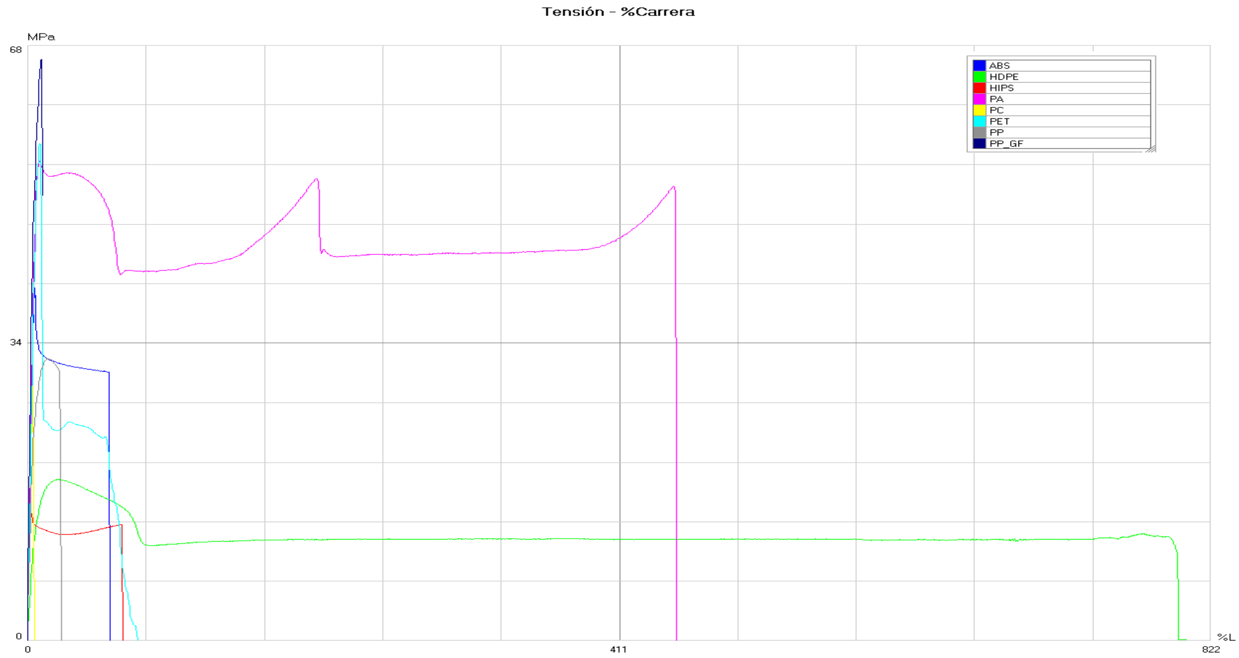


Fig.5. The polymeric materials behaviour in tensile testing

6. CONCLUSION

The polymeric materials used in medical applications have specific properties under restrictive conditions imposed by the medical devices functional role, endurance characteristics, etc.

Within these devices the next categories of polymers are used:

acrylonitrile butadiene styrene *(ABS*), polycarbonates *(PC)*, polyamide *(PA6)*, polypropylene *(PP)*, hHigh-density polyethylene (HDPE), high-Impact Polystyrene (HIPS), polyethylene terephthalate (PET) and fiber Glass Rreinforced Polypropylene (PPGF). For these materials tensile mechanical tests were performed. After testing on the behavior of these materials were obtained. These data can be used to design specific medical devices and to track their behaviour in use.

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Table 1 Theoretical and experimental data used for tensile testing of the polymers used in research

Application characteristics		**Experimental data**							
Type	**U/ M**	**ABS**	**HDPE**	**HIPS**	**PA**	**PC**	**PET**	**PP**	**PP_GF -30%**
Section	**Rectangular**								
Width	Mm	10	10	10	10	10	10	10	10
Thickness	Mm	4	4	4	4	4	4	4	4
Length	Mm	100	100	100	100	100	100	100	100
Area	mm 2	40	40	40	40	40	40	40	40
Length between rage marks	Mm	96	97	99	81	95	104,5	87	91
Final length between rage marks	Mm	124	500	132	307	97	145	99	96
Maximum stroke	Mm	29,14	402,76	33,63	225.95	2.88	42,39	12,13	5,02
Maximum force	kN	1,611	0,737	0,596	2.193	1,332	2,271	1,290	2,657
Yield (Rp)	MP a	34,8	11,6	11,9	41,2	0,0	42,8	21,1	43,4
Modulus of elasticity	MP a	906,5	207,2	1160,3	945,4	0,0	879,9	555,8	1127,3
Area breaking	mm 2	6,5	6,5	6,5	6,5	6,5	6,5	6,5	6,5
Elongation at break	%	29,167	415,46	33,333	279,01	21,053	38,756	13,79 3	54,945

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