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WYDZIAL MECHANICZNY

CONCEPTUAL DESIGN OF A FATIGUE TESTING MACHINE FOR COMPOSITE MATERIALS

Mechanical Engineering

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Honesty, hard work and humility are values that have been instilled in me from home and that I can proudly say that my father Antonio Mora Herranz and my mother Milagros Chisvert Badia possess.

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1.Background and purpose

Machine fatigue devices are machines that are designed to simulate real work conditions that a material experiment over some period of time and under some range of specific parameters such as loads, time and few others, giving information that how the material would react and predicting its behavior under some working conditions.

Composite materials include a wild range of different materials which has very different and unique properties and different impact on how fatigue affects in each type of composite materials.

Therefore, in order to realize a correct analysis of such elements, and due to the high variety of different properties that those materials present, the testing fatigue machine should be able to provide few technical and specifical characteristics that provides the user the capacity of changing the parameters in order to match the necessities of each of those specific materials.

Some of the typical fatigue methods applied to composite materials depending on the properties of the composite materials are: variable amplitude fatigue test, resonance fatigue test, variable amplitude fatigue test and high frequency fatigue testing, each one more accurate depending on the properties and the circumstances of the real word that want to be simulated on the specimen.

In all of those testing methods the main parameters that changes and need to be adjusted are the frequency and load applied and that's why, the fatigue machine for composite materials has to be versatile and has to be able to adjust the frequency and the load to specific values depending on what condition works would the user like to simulate.

That said, designing a fatigue machine using a hydraulic system provides the possibility of implementing high loads, but low frequency levels while conversely, electronic systems provide high frequency levels but low load levels.

That is why in order to meet the working conditions imposed by the user for any type of proposed scenario and for any type of composite material, both systems will be implemented in the design of the machine, working in parallel controlled by a PLC that provides the possibility to adjust both parameters according to the needs.

2. Literature review

2.1 Composite materials

2.1.1 Definition of composite materials

A composite material is a combination of two or more distinct constituents with different physical or chemical properties, which are usually categorized into matrix and reinforcement phases.

The combination of the matrix and reinforcement allows composite materials to exhibit enhanced properties compared to traditional materials. Composite materials can be engineered to have high strength-to-weight ratios, exceptional stiffness, excellent corrosion resistance, thermal stability, and tailorable electrical or thermal conductivity. These properties can be adjusted by varying the type, orientation, and volume fraction of the reinforcement and the choice of matrix material.

Composite materials find applications in various industries, including aerospace, automotive, construction, sports equipment, marine, and renewable energy. They are utilized where a combination of properties, such as strength, lightweight, durability, and specific functional requirements, are crucial for achieving optimal performance and efficiency in a wide range of products and structures.

They are popular on the nature, and in terms of history composite materials has been used and implemented by humans due their special properties since long time ago in order to create and achieve better weapons as for example, the Mongolian horn bow arcs that were made by mixing different materials. The compressed parts were made of corn and the stressed parts were made of corn and the stressed parts were made of wood and cow tendons glued together to obtain extraordinary strength.

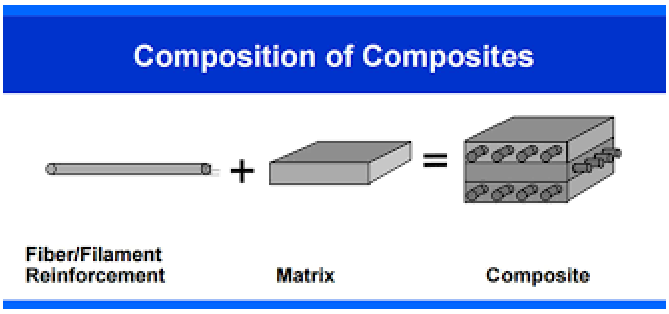


Figure 1: Phases of composite materials

Matrix face:

The matrix face refers to the material that surrounds and bins the reinforcement component together. It might be metallic, ceramic or a polymeric and this phase, provides stability, protects the composite material from external factors such as moisture, heat, and chemicals.

The matrix has several functions, being responsible for load transmission, stress distribution and protection of the reinforced phase.

It is also responsible for the adhesion of the material and the overall integrity of the structure, affecting mechanical parameters such as the elastic modulus tensile strength and elongation.

Matrix selection depends on the specific intended use of the material, taking into account mechanical properties as well as cost, manufacturing process, environmental conditions and other aspects.

Reinforcement phase:

Reinforcements are materials which are incorporated to the matrix in order to upgrade and improve the mechanical and physical properties, which are enchanted to the composite. It can be fiber, particles or sheets. Most common ones are fibers, like glass, carbon, ceramics, metal, natural or aramid fibers. Those types of fibers provide high strength and stiffness to the composite, and the choose of the reinforcement can be adjusted depending on the finality of the composite.

2.1.2 Types of composite materials

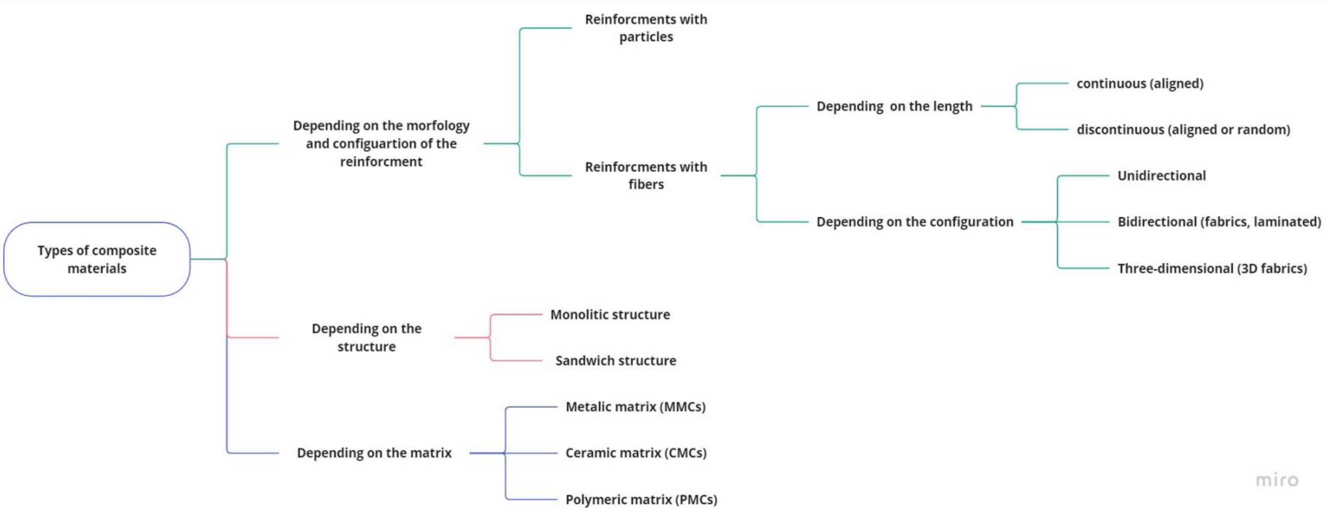


Figure 2: Types of composite materials

Reinforcement with particles:

Small particles of various other materials are dispersed within a matrix material to improve specific characteristics, for example, metal particles enhance properties like strength, stiffness and thermal performance to the composite. On the other hand, ceramic particles offer excellent hardness, wear resistance and high-temperature stability.

Meanwhile, polymer particles can improve properties like impact resistance, damping capacity and thermal insulation, whether other particles like carbon monotubes (graphene) offers exceptional mechanical strength, electrical conductivity and thermal conductivity.

Therefore, a mix of particles can be used in order to obtain the final properties that the user want adjusting to the properties of the particles like size, shape, volume fraction and the interaction with the matrix material and correct selection of particles materials.

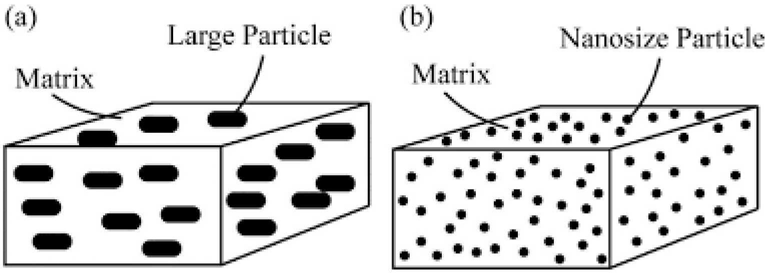


Figure 3: Composite material reinforced with particles

Reinforcement with fiber:

Fibers are incorporated into a matrix material to provide strength., stiffness and other desired properties. As the particles, depending on the material chosen, it provides a certain specific property to the overall composite.

Fibers generally provides higher strength and stiffness, possesses better impact resistance, toughness and offers high strength-to-weight radios than particles but the process of manufacturing are more complex and the costs tends to be higher in comparison to particles.

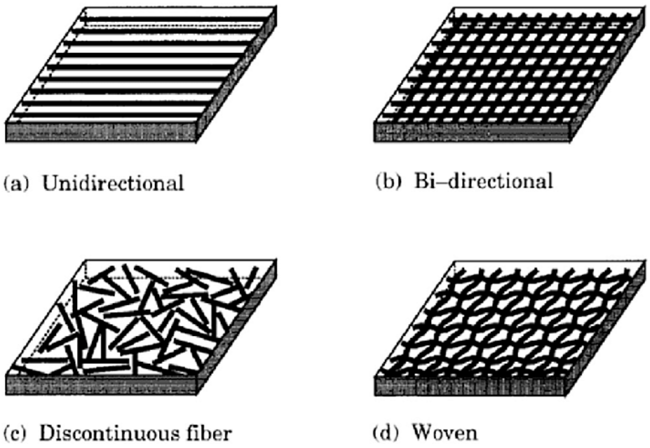


Figure 4 Reinforcement with fibers

	PROS	CONS
Reinforcement with particles	- Cost -effective - Improved stiffness - Enhanced wear resistance - Easier manufacturing	-Limited strength -Limited aspect radio -Increased weight -Limited impact resistance
Reinforcement with fibers	- High strength and stiffness - Light weight - Directional reinforcement -Improved fatigue resistance	- High cost - Labor / intensive manufacturing - Susceptible to impact damage - Environmental sensibility

Figure 5: Pros and cons depending on the types of reinforcement

Monolithic structure:

These structures are composite materials whit geometrical complexity with very particular orientations of the materials and fibers which allows to obtain very specific properties.

Monolithic structures generally are designed to carry heavy structures.

Sandwich structure:

Generally, consist of two outer layers of composite material and a core made of a low-density material made of some low-density material. The reason for including this core is to increase the resistance of the panel to loads perpendicular to the faces.

It is common to use both techniques in composite structures. Each face of the core is covered with a stack of several fabrics.

The structural components are usually of the monolithic stiffened laminate type, or of the sandwich panel type.

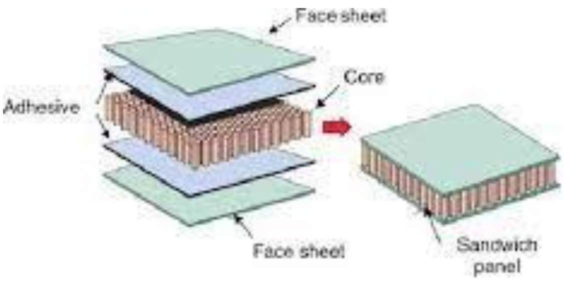


Figure 6: Sandwich structure

	PROS	CONS
Monolithic structure	- Simplified design - High strength and stiffness - Improved durability - Cost/effective manufacturing	- Weight -Limited design flexibility - Limited damping properties
Sandwich structure	- High strength-to-weight ratio - Enhanced stiffness and rigidity - Improved impact resistance -Enhanced thermal and acoustic insulation	- Complex design and manufacturing - Potential delamination - Higher manufacturing costs

Figure7: Pros and cons depending on the type of structure

Metallic matrix (MMCs):

Metal matrices involve the use of metals, such as aluminum, magnesium or titanium.

MMCs cam have much higher strength-to-weight ratios, stiffness and ductility but also have lower thermal and electrical conductivity and poor resistance to radiation compared to traditional materials. Also, because of their properties, MMCs are limited in very harshest environments.

Ceramic matrix (CMCs):

Ceramic matrices are composed of ceramics, such as oxides, carbides or nitrides.

They present a high-temperature stability, hardness and wear resistance, but generally presents a low crack resistance.

Polymeric matrix (PMCs):

Polymeric matrices present a wild range of variability and are the most used type in composite materials. They can be classified in thermosetting polymerics and thermoplastic polymers and offer advantages as low weight, ease of processing and good resistance to corrosion.

	PROS	CONS
CMCs	- High temperature resistance - Excellent hardness and wear resistance - Chemical resistance - Low thermal expansion	- Brittle behavior - Limited toughness - Fabrication challenge - Design limitations
MMCs	- High strength and stiffness - Temperature resistance - Electrical conductivity	- High density - Susceptible to corrosion - Limited design flexibility
PMCs	- Light weight - Design flexibility - Corrosion resistance - Damping properties	- Limited temperature resistance - Lower mechanical properties - Environmental stability

Figure 8: Pros and cons depending on the type of matrix

2.1.3 Properties of the composite materials

Composite materials are widely sought-after for a variety of applications because they have numerous distinguishing qualities. The following are some of the crucial qualities of composite materials:

High Strength-to-Weight Ratio: Composite materials are incredibly strong compared to how little weight they have. They may be designed to be lightweight while having strong tensile, compressive, and flexural strengths. This quality is especially helpful in fields like aerospace and automotive, where weight reduction is essential for performance and fuel efficiency.

Adjusting the composition, orientation, and volume fraction of the component materials allows for the tailoring and optimization of the mechanical characteristics of composites. This makes it possible to create materials that meet certain stiffness, strength, and toughness specifications for various purposes.

Corrosion Resistance: Many composite materials, especially those reinforced with fibers like carbon or glass, offer good corrosion resistance. This makes them excellent for use in harsh environments, such as marine or chemical industries, where typical materials like metals may decay or corrode.

Flexibility in Design: Composites provide engineers and designers more freedom to shape and create complicated structures. They may be formed into a variety of forms and sizes, making it possible to produce complicated and unique components that are challenging to make with conventional materials.

Fatigue Resistance: Composite materials can exhibit superior fatigue resistance, with the ability to withstand cyclic loading over extended periods. However, fatigue behavior can vary depending on factors such as fiber orientation, matrix material, and manufacturing process. Proper design and testing are necessary to ensure long-term structural integrity under cyclic loading conditions.

Exceptional thermal stability allows some composite materials to maintain their characteristics even at high temperatures. This quality qualifies them for uses in the energy, automotive, and aerospace industries, among others, where exposure to high temperatures is a concern.

Electrical and Thermal Conductivity: Composite materials may be designed to have certain electrical and thermal conductivities, making them appropriate for applications where insulation or conductivity is required. Consider the low electrical conductivity of carbon fiber-reinforced composites, which makes them suitable for applications needing electromagnetic shielding.

2.1.4 Basic calculations of composite materials

Density of composite:

The density of composite materials can be evaluated using the law of mixtures, under the condition that the matrix and the reinforcement phase both have to be independent form each other.

Notice that Vm and Vr refers to the Volumetric fraction of matrix and reinforcement respectively.

$$\rho_c = V_m \cdot \rho_m + V_r \cdot \rho_r$$

This property also can be used in oder to calculate the volumetric fraction of the reinforcment in composite materials appliying Arquimedes method.

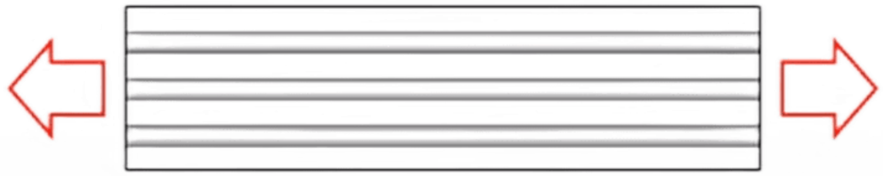
This is important because sometimes it is hard to calculate the volumetric fraction of reinforcment.

Elastic modulus:

Elastic modulus of the composite will depend not only on the volumetric fraction but also on the morfology and configuration of the composite.

Depending on the direction of the fiber:

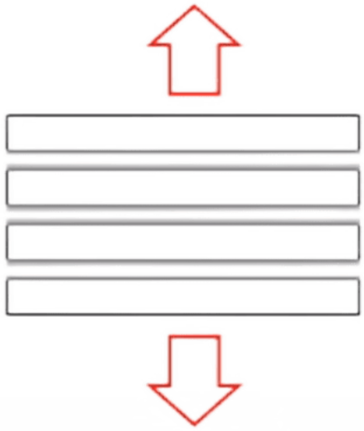
Tension applied in the fiber orientation:



$$E_c = E_m V_m + E_f V_f = E_m (1 - V_f) + E_f V_f$$

This formula is valid when matrix and reinforcement are under the condition of isodeformation, meaning that both phases suffer the same deformation.

Tension applied in the perpendicular direction to the fiber:



$$E_c = \frac{E_m \cdot E_f}{E_f \cdot V_m + E_m \cdot V_f}$$

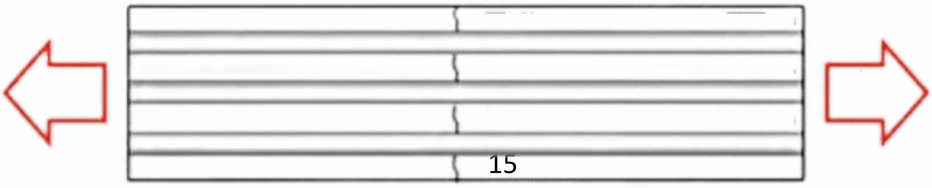
This case present low values of the elastic modulus and it also due to the condition of isosteres.

Resistance:

The resistance of a composite material generally depends on the reinforcement, being that said, if the fibers do not break, the part of stress that the matrix suffers has to be taken on account.

$$\sigma_{\max,c} = \sigma_{\max,f} \cdot V_f + \sigma^*_{\max,m} \cdot V_m$$

$$\sigma^*_{\max,m} = \varepsilon_{\max,f} \cdot E_m = \frac{\sigma_{\max,f}}{E_f} \cdot E_m$$



$$\sigma^*_{\max,m} = 0$$

2.2 Fatigue

When materials are subjected to repetitive or cyclic loading over time, a condition called fatigue develops. Even though the applied load is less than the component's maximum strength, a component may fail due to a localized, gradual damage process. In engineering and structural design, fatigue failure is a major worry since it may happen to a variety of materials and structures, including metals, composites, and even biological tissues.

Fatigue failure can have serious implications, including structural collapse, equipment malfunction, and accidents. In order to ensure the dependability, safety, and lifespan of components and structures, fatigue must be understood and managed.

Fatigue failure typically begins with the initiation of small cracks or defects within the material, often at stress concentration points or areas of high stress. Under the cyclic stress, these cracks slowly spread and deepen, finally resulting in catastrophic failure. The degree and kind of stress, material characteristics, geometrical features, surface conditions, and environmental elements including temperature and corrosive chemicals are some of the factors that affect fatigue behavior.

When a material is subjected to cyclic loading, such as alternating stress or strain, cracks may initiate and propagate within the material. These cracks typically form at stress concentrations, such as notches, sharp corners, or material defects. Over time, as the cyclic loading continues, these cracks grow and eventually result in failure.

It is different from sudden or catastrophic failure, which occurs when a material is subjected to a single high-load event that exceeds its ultimate strength. Fatigue failure, on the other hand, occurs after a significant number of load cycles, even if each cycle is below the material's ultimate strength. This makes fatigue particularly insidious because it can occur without any obvious signs of damage or deformation.

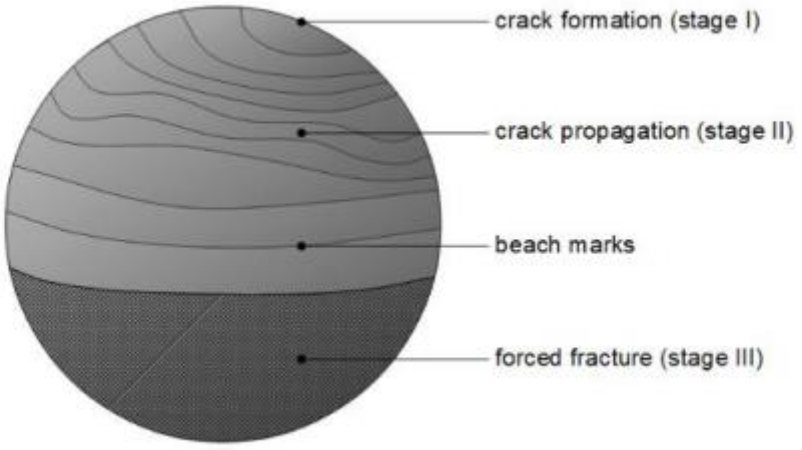
Several factors contribute to the occurrence of cyclic amplitude fatigue, including the stress level, the number of cycles, the material's properties, and the presence of stress concentrations or defects. Higher stress levels or larger cyclic amplitudes generally lead to faster crack growth and reduced fatigue life. Materials with high strength and good resistance to crack propagation tend to have better fatigue performance.

To address or mitigate cyclic amplitude fatigue, there are several techniques that can be employed. These include improving the design to reduce stress concentrations, utilizing materials with higher fatigue strength, introducing surface treatments to enhance fatigue resistance, and employing fatigue analysis and testing to estimate the component's fatigue life. Additionally, monitoring and regular inspection of components subjected to cyclic loading can help detect early signs of fatigue damage, allowing for preventive maintenance or replacement before catastrophic failure occurs.

Overall, understanding cyclic amplitude fatigue is crucial for designing and maintaining reliable and durable structures, machinery, and components, particularly those subjected to repeated loading and unloading over their operational lifetimes.

Engineers conduct fatigue tests to evaluate a material's or component's fatigue resistance. In these tests, the specimen is put through cyclic loading patterns designed to simulate actual-world scenarios. The test findings offer important information on the material's fatigue life, endurance limit, stress-life relationship, and other fatigue attributes.

Stress-life (S-N), strain-life (ε-N), and fracture mechanics-based methods are among the methods used to study and forecast fatigue behavior. These techniques assist in determining the component's safe working limits, estimating its remaining life, and designing for robustness and dependability.



2.2.1. Fatigue basic nomenclature under loading cycling

Cyclic amplitude fatigue, also known as cyclic loading fatigue or simply fatigue, is a phenomenon that occurs when a material undergoes repeated cycles of loading and unloading, leading to its failure under relatively low stress levels. It is a common cause of failure in various engineering structures and components.

In some practical applications and some fatigue test experiments, the stress alternate between a maximum and minimum values that are constant.

Therefore, the maximum value can be defined as the maximum stress (σ_{max}) meanwhile the minimum value can be defined as the minimum stress (σ_{min}) and the range can be defined as the difference between the maximum and minimum value of those ($\Delta\sigma$).

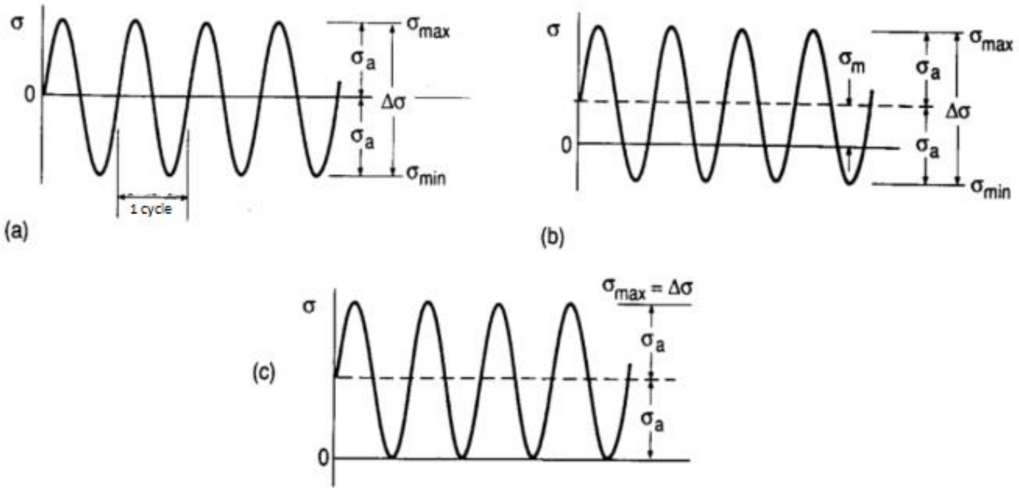


Figure 5 Cycling loading diagrams

It can be defined the average stress (σ_m) as the average of the sum of the maximum and minimum stress.

The alternate stress(σ_a) is going to be the average of the range ($\Delta\sigma/2$) and it is also possible to define R as the ratio of the min and maximum stress and A as the ratio between the average stress and the medium stress.

The following equations shown the relations between each component.

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \quad , \quad \sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad , \quad \sigma_a = \frac{\Delta\sigma}{2}$$

$$\sigma_{max} = \sigma_m + \sigma_a \quad , \quad \sigma_{min} = \sigma_m - \sigma_a$$

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad , \quad A = \frac{\sigma_a}{\sigma_m}$$

2.2.2. S-N curve

Agust Wohler developed the S-N curve, which shows the relation between the stress applied against the number of cycles to failure (N) of a specific specimen.

Generally, ordinates correspond to the stress applied and use to follow a linear progression, meanwhile the axis contains the number of cycles presented in a logarithmic scale in order to simplify the longitude of the axis.

If a component or material specimen is subjected to a sufficiently severe stress cycle, fatigue cracking or other damage will develop, leading to complete failure of the component. If the test is repeated at a higher level of stresses, the number of cycles required will be less. The result of such tests, for different stress levels, can be plotted to obtain the stress-life curve, called the stress-life curve, also called S-N curve.

It is possible to realize the tests taking in account the average stress, (σ_m), null or not null. It is also usual to define S-N curves for a specific value of the stress ratio, R. Although amplitudes are normally used, it is also possible to use.

The number of cycles required to produce the failure varies rapidly with the level of stresses. For this reason, the number of cycles is considered on a logarithmic scale. The difficulty associated with linear scaling is illustrated in the following figure in which the S-N curve is plotted on both linear and logarithmic scales.

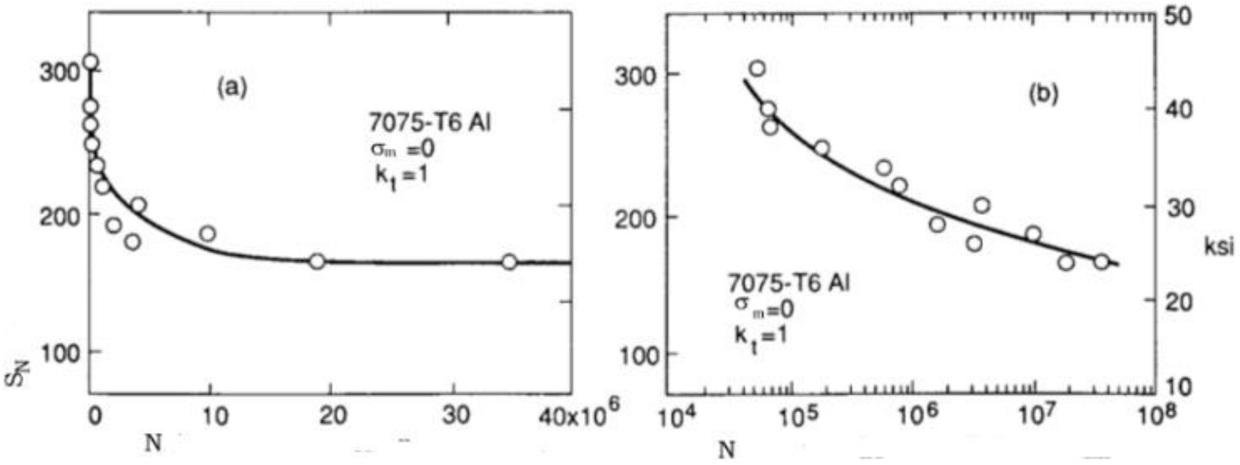


Figure 6 S-N curve with linear scales (a) and linear-logarithmic scales (b)

In some materials, especially steels, there is a level of alternating stresses below which fatigue does not occur under normal conditions. This it is illustrated in the figure 6, in which the S-N curve asymptotically approaches the stress amplitude called Se. This value is called the fatigue limit. For test specimens without any microdamage and with good surface finishes, these can be considered to be local actual stresses (since at low stress levels there is no creep, the nominal and actual stresses are similar), and can be considered as a material property.

For those materials whose S-N curve does not tend to approach an asymptote, such as aluminum or copper alloys, a fatigue limit is usually defined for a sufficiently large life, as for example a sufficiently large life, such as 10^7o 10^8cycles. The term fatigue strength is used to specify the stress amplitude of an S- N curve for a given life. Thus, the fatigue strength for 10^5 cycles is simply the stress amplitude corresponding to that life. Other terms used with S-N curves are high and low cycle fatigue. The former identifies situations of large fatigue lives, in which the stresses are sufficiently small that the behavior is not dominated by creep. The life for which high cycle fatigue begins depends on the material, although it is often between the range of 10^2 and 10^4 cycles. In the low-cycle fatigue range, the more general approach of strain analysis is particularly useful, as it specifically since it deals specifically with creep phenomena.

If the S-N data approximates a straight line on a linear-logarithmic scale, the following equation can be used to approximate them:

$$SN = C + D \log(N)$$

Where C and D are constants that allows the adjustment. If the data taken from the results result in a straight line in a linear-logarithmic, it is possible to use the following equation in order to define the curve:

$$SN = A\ NB$$

Where A and B are the constants of adjustment. It corresponds to the equation of the slope of the straight line where N is the slope.

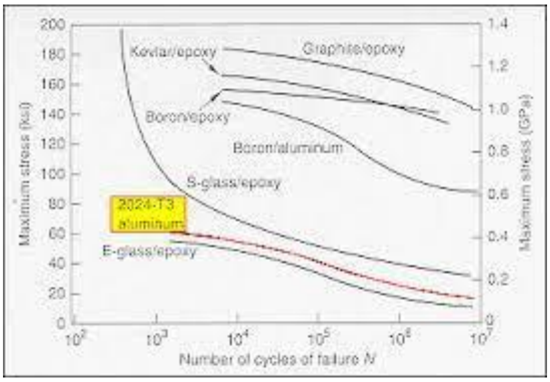


Figure 7 S-N curve for some composite materials

2.2.3. Variable load amplitude.

Until know, it is been considerate the existence of stress of constant amplitude. Meaning that it is been supposed the existence of a temporal evolution of the stress defined exclusively by their average and alternant stress value. Due to different conditions of working of a machine, in practice, it is usual that the temporal history of stress evolve in a more irregular way.

Therefore, it has to be considerate few new approaches in order to be able of analyze those cases, as for example the rule of Palmgren-Miner.

Assuming that a test sample has been subjected to a variable load amplitude test. It is been applied a range of stress of σ_{a1} for a delimitated number of cycles (n1), and assuming that it is possible to extract the numbers of cycles that the specimen has managed to pass until the failure N_1. The fraction of life for this particular case can be defined as the ratio between n_1 and N_1 $(\frac{n1}{N_1})$.

Now, suppose that is going to be applied another range of amplitudes known as σ_{a2} to the other specimen with the same characteristics and same material as the previous one, being n_2 the number of cycles that it has been applied, with the correspondent $N_{2,}$ extracted from the S-N curve, meaning that the fraction of life for this case can be defined as $(\frac{n2}{N_2})$.

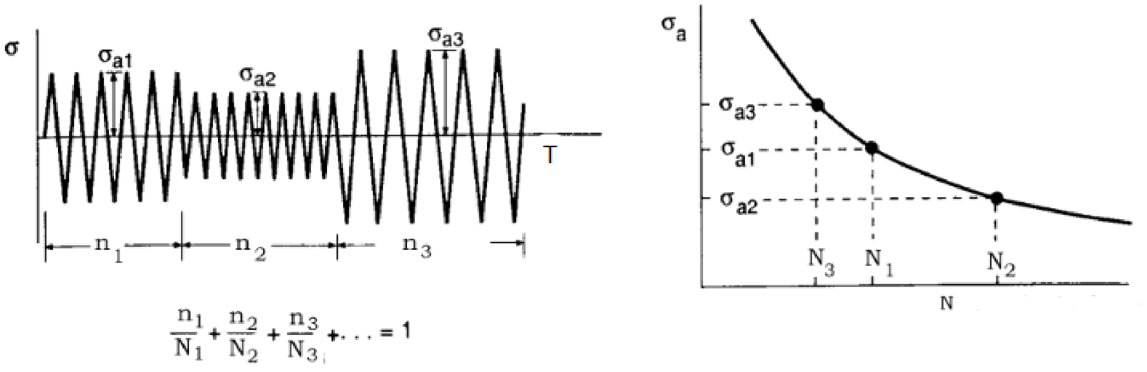


Figure 8 Variable load amplitude applied to a specimen

This process can be repeated as far as it is being applied different range of amplitudes to the specimen.

The rule of Palmgren-Miner establish that failure of fatigue will be expected when the sum of the life fractions equal to the value of the unit.

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \dots = \sum \frac{n_j}{N_j} = 1$$

Equation 2: Palmgren-Miner rule

This method was proposed by A.Palmgren in 1924 but it was not applied until 1945 when A.Miner used this method in order to calculate the axial fatigue of a aluminum fuselage skin in aircraft for Douglas Aircraft Company.

On the other hand, this rule is the most accurate now at days for variable load calculations but it presents few limitations, meaning that the damage done for one level of stress depends on the level apply previously, so it is possible that the failure happens on values which differs the unit, sometimes a little bit higher or sometimes lower, as 0,6 or 2,3 for example.

It is important to consider that the same cycles of the load amplitude may have average component.

2.2.4. Fatigue phenomena on composite materials

Composite materials, consisting of reinforcing fibers embedded in a matrix material, exhibit complex failure behavior due to the interplay of multiple damage mechanisms. Fatigue loading introduces cyclic stresses, causing the initiation and propagation of various types of damage, such as matrix cracking, fiber/matrix debonding, fiber breakage, and delamination between layers. These damage mechanisms interact and influence each other, leading to a cumulative deterioration of the material's mechanical properties.

Matrix cracking is one of the initial stages of damage in composites subjected to fatigue loading. As cyclic stresses exceed the matrix's fatigue strength, microcracks form within the matrix material. These cracks can propagate perpendicular or parallel to the fiber direction, compromising the load transfer efficiency between the matrix and fibers.

Fiber/matrix debonding occurs when the cyclic loading causes cracks to propagate along the fiber/matrix interface, weakening or breaking the bond between the fibers and the matrix. Debonding reduces the load-carrying capacity and can lead to stress concentrations at the deboned regions.

Under fatigue loading, brittle fibers may experience breakage due to cyclic stresses exceeding their fracture strength. Fiber breakage introduces additional stress concentrations and contributes to the progressive degradation of the composite material.

Delamination is a significant concern in laminated composites, where cracks propagate at the interfaces between adjacent layers, resulting in separation or debonding between the layers. Delamination reduces the structural integrity of the composite by promoting crack growth in a direction parallel to the layers.

All of this kind of microstructural damage can be related and can coexist with the others, sometimes leading one to each other depending on the conditions.

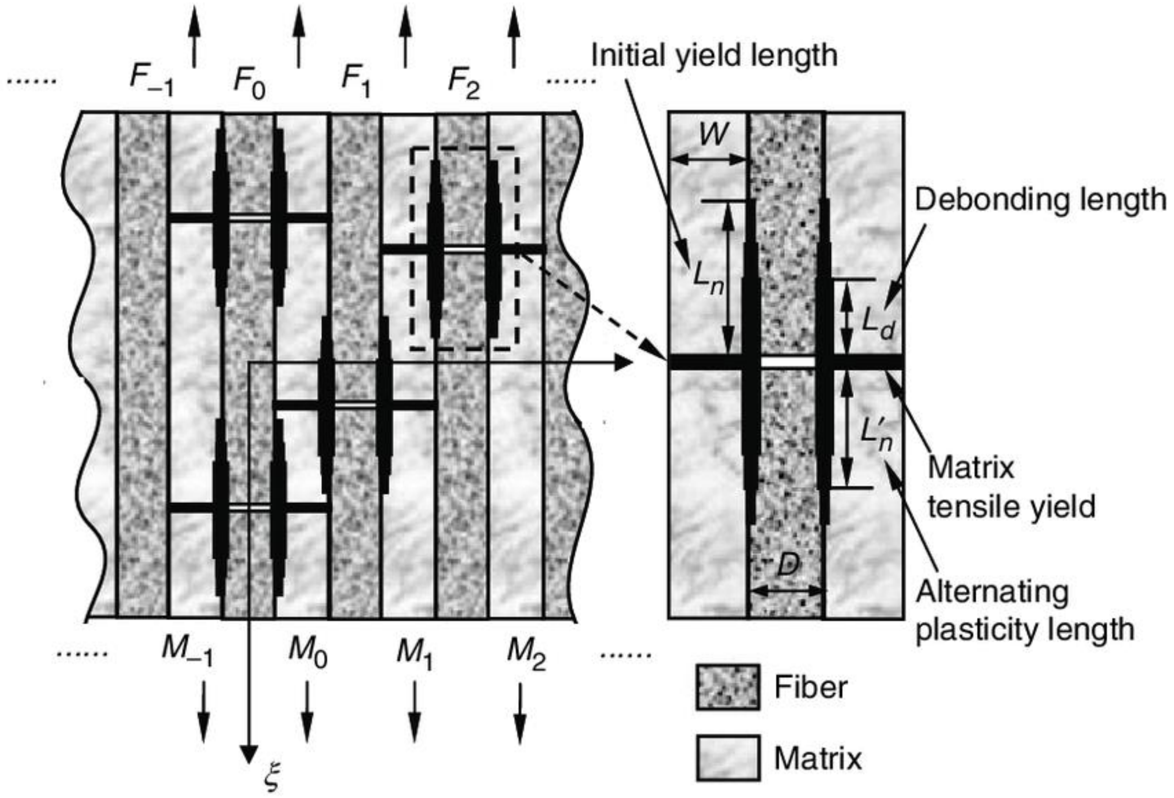


Figure 9 Fatigue on composite materials

2.2.5. Damage mechanisms on composite materials

It is going to be assumed that flexion, tensile and compressive load excursions are going to be considerate, and also, it is going to be considerate that the laminates include piles which have various orientations to a principal load direction, called the 0° direction.

Taking this in consideration, it is probable that few of the damaging methods before named will occur simultaneously. The development of each stage would depend upon the stacking sequence, ply thickens, material types, in a specific laminate.

For laminates that have off-axis piles, as the common [0,90+/-45] °, quasi-isotropic staking sequence, despite the toughness and ductility of the matrix material, typically the first micro-damage that take place is the matrix cracking.

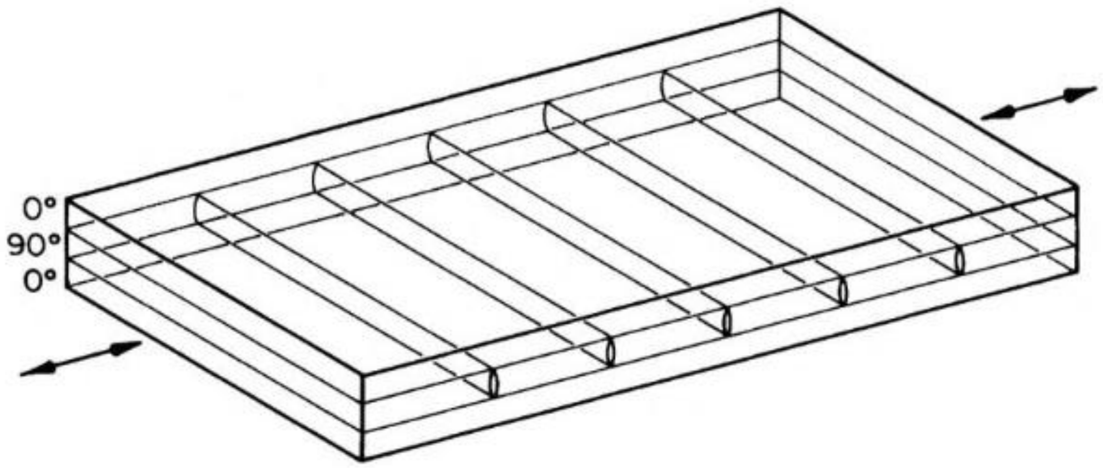


Figure 10: Schematic diagram of matrix crack formation in a cross-ply laminate

Matrix cracking usually is form through the thickness of the piles in the parallel direction to the fibers and perpendicular to the dominant load axis (named before as the “0º” direction).

Therefore, this process of cracking follows the typical crack process named before and can be summarized and classified into commons failure theories such as the maximum-stress, Tsai – Wu or Tsai – Hill concepts for quasi – static loading. Instead, for cycling loading, quasi-static models seem to work quite well and seems to be the best approximation.

For cycling load, it can be said that that the matrix cracks will always form at cycling load amplitudes which exceeds the levels of load known for quasi-static, causing the first-ply failure, but is possible that the cracks will occur on lower levels calculated for the quasi-static case.

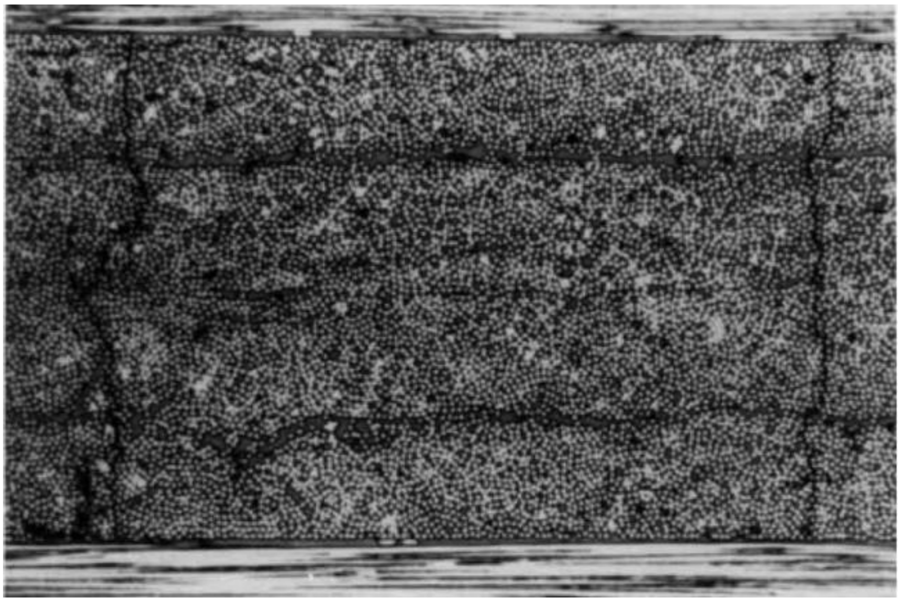
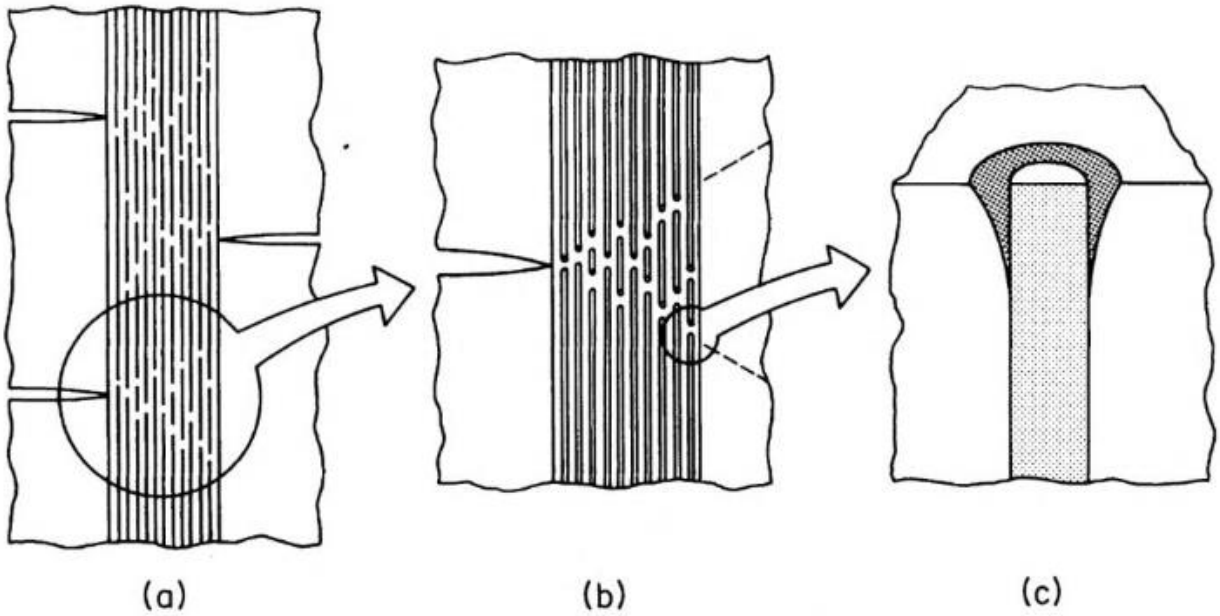


Figure 11 Specimen of graphite epoxies coupon showing crack matrix

It will be considerate this kind of cracks as the initial ones, shown in the last figure, as primary cracks, which would have sub consequent damage micro events leading into secondary cracks which will lead into fiber fracture and partial reduction of the strength of the composite.



In the figure **"7"** it can be seen how the matrix cracking (a) lead to a fracture of the fibers (b) causing local debonding near the tips of the broken fibers end (c).

Delamination will come with the secondary cracks, which will appear in the later part of the life composite, initiated due to the tensile normal stress field created parallel to the crack front of the primary matrix cracks.

It can be concluded that the damage mechanisms of fatigue in composite materials are caused due the phenomenon's named before which can happen independently or as it has been shown one before other, leading into the degradation of the properties of the components under the applications of cycles resulting in the final breakage of the composite,

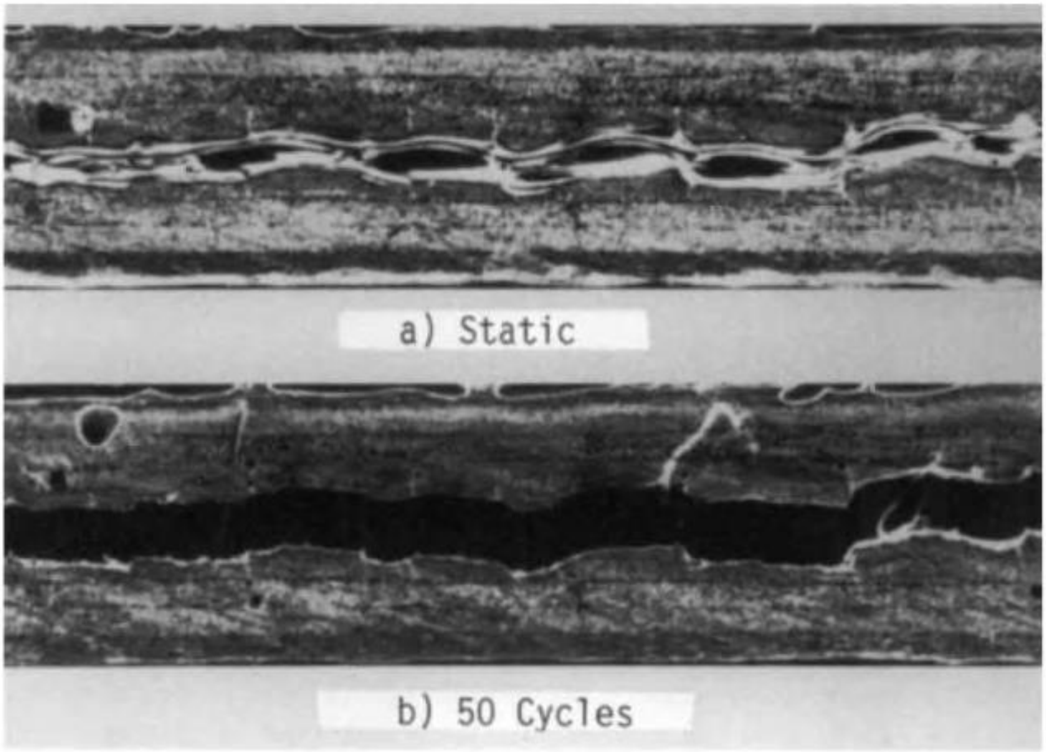


Figure 12: Microdamage caused to a composite under 50 cycles

2.2.6. Fatigue testing methods for composite materials

There are few methods that are used in order to make fatigue tests, which differ one from each other depending on few important parameters, as the way that the load is applied, the quantity of load that it is applied, the frequency applied and the environmental factors.

Constant Amplitude Fatigue Testing:

In constant amplitude fatigue testing, a cyclic load with a constant amplitude is applied to the composite specimen. The load can be applied in tension-tension or tension-compression mode, depending on the material and the application. The test involves applying a specified stress or strain level to the specimen and cycling it until failure take place, plotting the number of cycles and the stress on a S-N or strain curve to assess the fatigue behavior of the material.

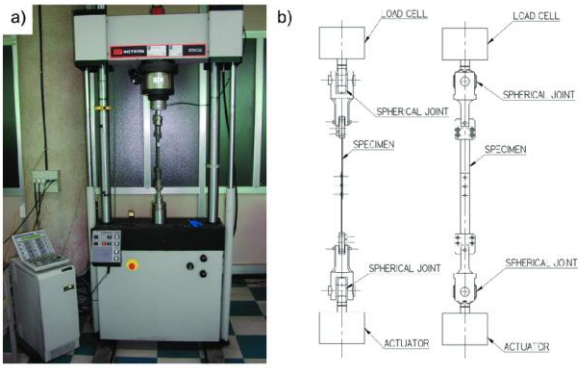


Figure 13 Constant amplitude testing fatigue machine

Variable Amplitude Fatigue Testing:

Variable amplitude fatigue testing aims to simulate real-world loading conditions where the load and frequency changes. The composite specimen goes under varying loads, and the number of cycles to failure or the accumulated damage is recorded.

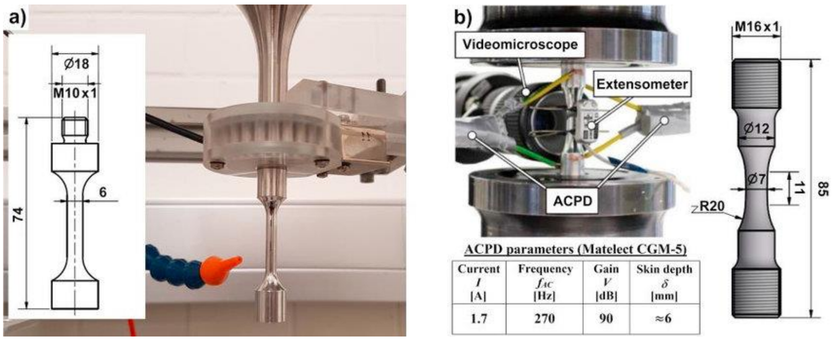
The test uses load spectra that can be derived from historical data or simulated based on the application. This load spectra that represent the varying loads experienced by the composite structure.

This method provides insights into how the composite material withstands complex loading scenarios that can take place in service.

Resonance Fatigue Testing:

Resonance fatigue testing is performed by applying a sinusoidal or harmonic load at the resonant frequency of the specimen. The load amplitude is gradually increased until failure or a specific number of cycles is reached.

Resonance testing helps to identify potential vulnerabilities and asses the durability of composite structures.



ACPD parameters (Matelect CGM-5)

Current I [A]	Frequency f_{AC} [Hz]	Gain V [dB]	Skin depth δ [mm]
1.7	270	90	≈6

Figure 14 Resonance fatigue testing machine with a defined specimen

Multi-axial fatigue testing:

Multi-axial fatigue involves applying cycling loads in more than one direction simultaneously. It can be performed by mixing different loading models such as tension-tension, tension-compression, compression-compression or torsion

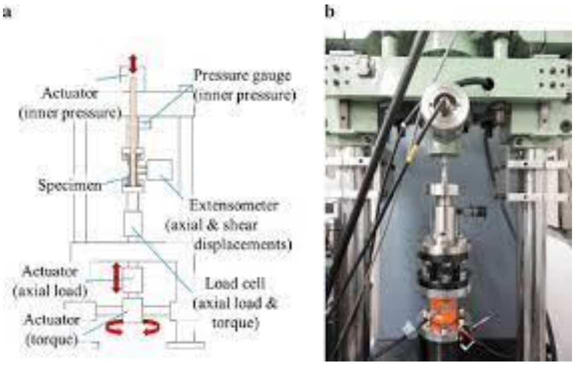


Figure 15 multi-axial fatigue testing machine

High-Frequency Fatigue Testing:

High-frequency fatigue testing involves subjecting the composite specimen to cyclic loading at relatively high frequencies.

This method is used to evaluate the material's fatigue behavior at frequencies beyond what can be achieved with conventional fatigue testing machines. High-frequency testing is particularly relevant for applications where the material experiences high-frequency vibrations or rapid loading cycles. It helps assess the fatigue strength and durability of composite materials under dynamic and high-frequency loading conditions.

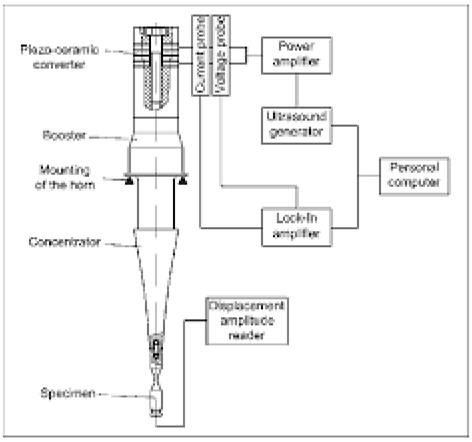


Figure 16 A schematic diagram of the design of the KAUP-ZU fatigue testing machine

Each fatigue testing method offers unique advantages and is suitable for different aspects of evaluating composite materials' fatigue behavior. The choice of method depends on the specific research objectives, intended application, and the desired understanding of how the composite material responds to different loading conditions.

When it comes to standards for composite material specimens, there are specific guidelines and requirements that dictate the preparation, dimensions, and testing procedures. These standards ensure consistency and comparability of test results across different laboratories and applications. Here are some examples of standards related to composite material specimens:

ASTM D638 - Standard Test Method for Tensile Properties of Plastics: This standard provides guidelines for preparing and testing tensile specimens made from plastic materials, including composite materials. It specifies the specimen dimensions, testing procedure, and calculation methods for determining tensile properties.

ASTM D790 - Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials: This standard outlines the specimen preparation, testing procedure, and calculation methods for determining flexural properties of composite materials. It includes specifications for specimen dimensions and supports.

ASTM D3039 / D3039M - Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials: This standard focuses on determining the tensile properties of polymer matrix composite materials. It provides details on specimen preparation, gripping methods, testing conditions, and calculation methods.

ASTM D2344 / D2344M - Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates: This standard specifies the preparation and testing of short-beam specimens for determining the strength properties of composite materials. It includes guidelines for specimen dimensions and testing conditions.

ISO 14125 - Fiber-reinforced plastic composites - Determination of flexural properties: This ISO standard defines the preparation and testing procedures for determining the flexural properties of fiber-reinforced plastic composites. It includes requirements for specimen dimensions and testing conditions.

These standards, among others, provide specific guidelines for specimen preparation, dimensions, testing equipment, and testing procedures to ensure accurate and reproducible results. It's important to refer to the relevant standards specific to your composite material and the properties you wish to evaluate.

3. Design Considerations

3.1 General Desing

The Fatigue Machine for composite materials is going to be composed of four main systems, one each other with their specific purposes and characteristics in order to accomplish the correct functionality of the device. These four systems are going to be the control system, the hydraulic system, the electric system and the mechanical system.

The main goal of this machine is to integrate a piezoelectric actuator in parallel with a hydraulic actuator working together.

The hydraulic actuator is primarily responsible for applying the main load to the specimen, such as tension, compression, or flexural load. It is connected to the specimen through a suitable grip or fixture that can transmit the load effectively.

The hydraulic actuator applies the primary cyclic load, generating the main stress or strain on the specimen.

The piezoelectric actuator is positioned in parallel with the hydraulic actuator, coupled or adjacent to the specimen, in a way that allows it to induce additional dynamic excitation.

Both actuators should be controlled and synchronized to work together during the fatigue test. The control system should have the capability to regulate the hydraulic actuator for the main load application and the piezoelectric actuator for high-frequency excitation.

The control system can be designed to allow independent control of the two actuators, adjusting the amplitude and frequency of the piezoelectric actuator's vibrations.

The hydraulic actuator can be controlled using a closed-loop control scheme, where feedback from sensors (such as load cells or displacement sensors) is used to maintain the desired load conditions.

To ensure proper synchronization, the control system should have precise timing capabilities.

The control system can be programmed to activate the piezoelectric actuator during specific phases of the hydraulic actuator's cyclic loading. The timing and frequency of the piezoelectric actuator can be adjusted to achieve the desired high-frequency excitation and fatigue behavior simulation.

By connecting the piezoelectric actuator in parallel with the hydraulic actuator, you can combine the advantages of both systems. The hydraulic actuator provides the main load, while the piezoelectric actuator adds dynamic excitation, allowing for high-frequency testing and more accurate simulation of real-world loading conditions.

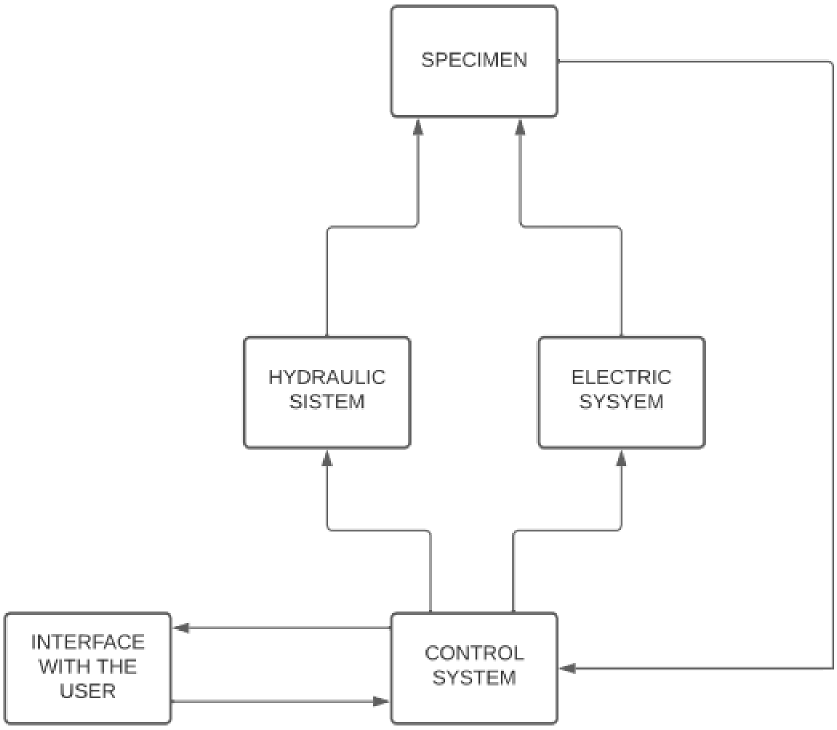


Figure 17: Block diagram of the overall device

As it can be seen, the control system is the mainly block of the diagram, allowing to the user to set certain parameters and then adjusting the hydraulic and the electric system in order to achieve the test that it wants to be applied from the user.

As it has been said before, the hydraulic system has the main goal to change the load that it wants to be applied to the specimen, but hydraulic systems present a general problem for this kind of machines and is that they can provide a huge range of loads to be applied to the specimen but they offer a low range of frequency. The opposite occurs with the electric systems, which are able to offer a wild range of frequency but a low range of loads.

That is why this device combine both advantages of both systems to provide a wild range of different possible tests and offers a possibility of simulate real working conditions for a huge range of different specific composite materials with their own particularities.

Meanwhile the electrical system adjusts the frequency that is going to be applied into the specimen, leading into a wild range of tests that can be performed by this specific machine because as it has been shown on the section test, the main parameters that differs one from another kind of test is the way in that the force is applied (tension, flexure, compression) and the load (high or low) applied and also the frequency applied (high or low frequency).

In order to adjust the way that the load want to be applied it is necessary to implement the mechanical system, and it would be presented on further points.

3.2 Design of the hydraulic system

The hydraulic system has the main function of applying the force to the specimen.

It has been selected as an actuator a double-cylinder in order to achieve the range of loads that it is necessary.

The overall system is going to be presented in the follow figure.

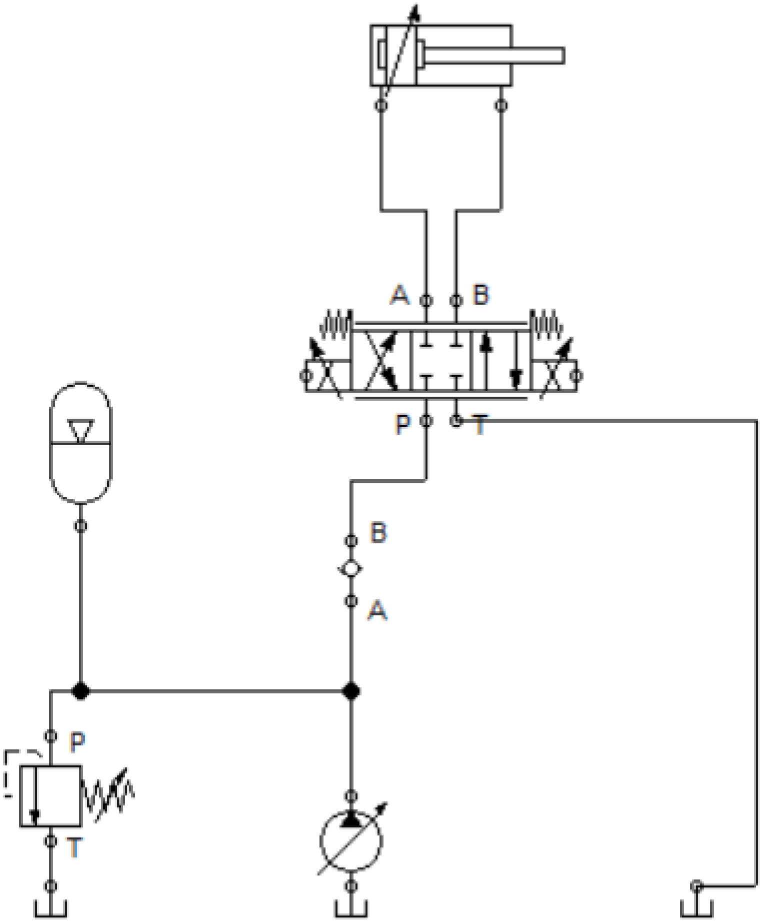


Figure 19 Schematics of the hydraulic system

The hydraulic system is composed by a variable displacement pump, which can adjust the quantity of flow rate that is going to be required, which is going to be regulated by the loading sensing 4 way- 3 positions directional control valve. The DCV will be controlled by the PLC via electromagnets, allowing the piston to extend in one direction and retract in the other direction

The flow rate will be adjusted by the PLC depending of the force that the user wants to apply regulated by the simple equation of F=P x A where the “F” corresponds to the force which relays the pressure applied by the piston and the cross section or the area of the specimen.

For terms of safety a pressure relief valve will be controlling the maximum pressure that the system is going to handle in order to prevent any possible damage on the components and maximizing the overall efficiency of the system by reducing the leakage.

A check valve will be incorporated for safety measures too, in order to prevent the flow to return to the pump in case of an error in the system, avoiding possible damage to the pump.

The accumulator would provide and easier return of the stroke of the piston smoothing the path and avoiding the possible dumping, providing a cleaner and smoother path.

For the actuator a double effect cylinder has been chosen.

The range of load that the hydraulic piston should be able to generate for fatigue testing of composite materials can vary depending on the specific material and application. Composite materials can have a wide range of mechanical properties, including different strength, stiffness, and failure characteristics. Therefore, it is challenging to provide an exact range that would cover all possible composite materials.

However, as a general guideline, it is recommended to have a hydraulic piston with a load capacity that can cover a broad range of composite materials typically encountered in engineering applications. This can range from a few kilonewtons (kN) up to several hundred kilonewtons (kN).

Some common load ranges for hydraulic pistons used in fatigue testing of composite materials are:

Low Load Range: 1 kN to 20 kN

Medium Load Range: 20 kN to 100 kN

High Load Range: 100 kN to 500 kN

These ranges can be adjusted based on the specific requirements of the application.

3.2 Design of the electric system

The electric system has the function of regulating the frequency that is going to be applied to the specimen through an electric actuator.

In order to realize the different kind of tests depending the frequency, as for example some low frequency tests as constant amplitude test, the electric system should be able to oscillate between low frequency range (0.1 Hz- 20 Hz). For some higher frequencies which some tests require as for example resonance fatigue tests or variable amplitude tests, some higher frequencies generally are required (from for example 1 kHz to 20 kHz or higher) so since the hydraulic system can not provide those ranges of frequency, it is necessary to implement an electric system which takes care of the adjustment.

Other of the main functions of this system is to implement sensors in order to monitories the evolution that the specimen is suffering during the process, allowing the trackage of the specimen and the evolution that the composite is suffering during the time before failure.

In the next figure is going to be illustrated the schematics of the electric system

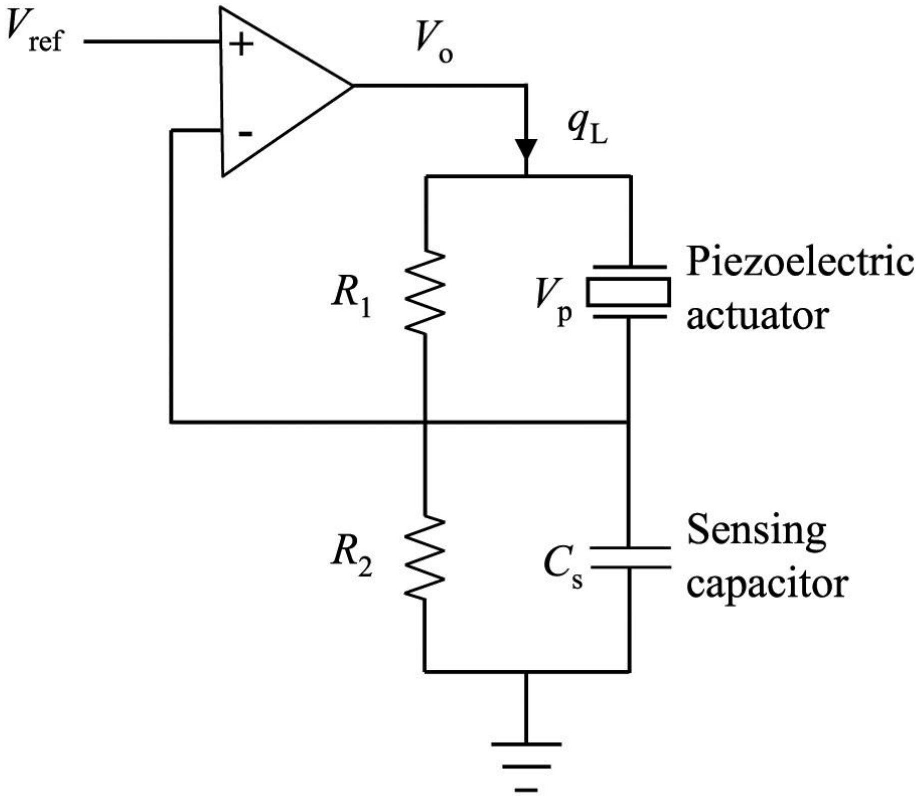


Figure 20 Schematics of the electric system

For the piezoelectric actuator an PZT Bimorph Actuator: PZT (Lead Zirconate Titanate) bimorph actuator is going to be chosen.

Consist of two layers of PZT ceramic bonded together with a passive layer in between. They can generate bending motion when an electrical voltage is applied. It will go coupled into the specimen providing the possibility of adjusting the frequency of the vibration for the PLC.

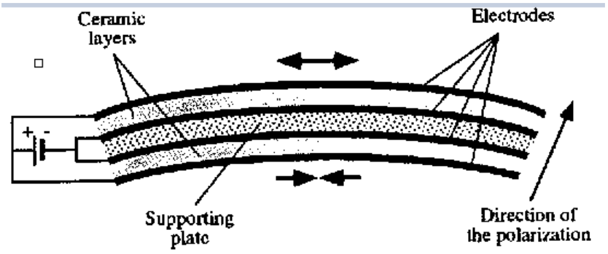


Fig. 1 PZT bimorph

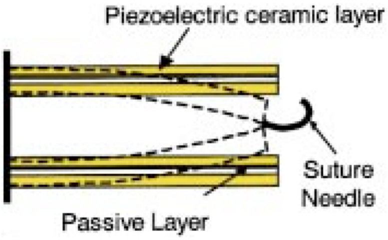


Fig. 2 Bimorph grasper

Figure 21 Electric acuator

The sensing capacitor that has been chosen in order to monitor the evolution of the fatigue damage occur on the specimen during the different cycle is going to be a load cell which will go near the specimen.

The load cell is going to be integrated into the hydraulic actuator (the cylinder) to directly sense the force being applied. The load cell converts the mechanical force into an electrical signal, which goes directly into the PLC of the control system, providing feedback of the process. So it is critical as it provides accurate measurements during the test, it enables data acquisition, feedback control and safety monitoring.

Figure 22 Load cell

3.3 Design of the control system

The control system is the main component in the testing fatigue machine. It has the main purpose of adjusting the variables as the force, the velocity and frequency that is going to be applied to the specimen. In order to realize those tasks, the core of the system is going to consist on a PLC (Programable logic control) which basically has a code that allows the user to put the input of a several parameters that has to be adjusted in order to perform a test, as the velocity, the flow rate, the range of frequency that is going to be needed and the load that it want to be applied to the specimen, and with that input, using some simple equations mentioned before of hydraulics and dynamics and with the feedback that recipes from the load cell , the PLC is going to be capable of giving the proper output to the machine.

In order to put the variables from the user, the PLC will have a digital interface.

Figure 23 Digital control Panel

Therefore, it will consist on a close-loop control system, because with the input given by the user and with the feedback from the load cell the control system is capable of running the machine.

Also, with the feedback given from the load cell, the PLC is going to be able to store all the information until the failure to make a S-N curve, giving the evolution of the specimen during the chosen fatigue test method until the breakage or until the user decision.

3.4 Design of the grip for the specimen

In order to be able to apply both bending, compression and tension in a fatigue testing machine, a suitable option would be to use a universal clamping device. This type of fixture is designed to allow for different loading modes and accommodates different specimen configurations.

The universal clamping device can consist of adjustable jaws that can be configured according to the geometry and needs of the specimen. These jaws can allow secure and reliable gripping of the specimen in different positions, whether for bending, compression or tension.

In addition, additional adaptations or accessories may be required on the clamping device to allow for the different loading configurations. For example, to apply flexure, support brackets or rollers may be added at the sample support points. To apply tension, a cradle-type gripping fixture may be used.

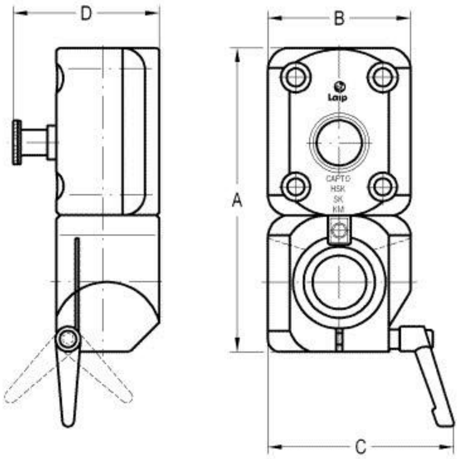


Figure 24 Universal clamping device

4. Conclusion

Fatigue of composite materials is a crucial area of research in the engineering field due to the need to understand and predict the behavior of these materials subjected to repetitive loads. In this thesis, the design and development of a fatigue testing machine for composite materials has been addressed, with the aim of providing a reliable and efficient tool to evaluate the strength and durability of these materials under realistic conditions.

First, a comprehensive review of the existing literature on fatigue of composite materials has been carried out, investigating the different methods and standards used to perform fatigue tests. The fundamental principles of fatigue, loading modes and failure mechanisms specific to composites have been explored. In addition, constant and variable loading methods, as well as resonance and high frequency tests have been analyzed, evaluating their advantages and limitations in terms of applicability and accuracy.

Based on this review, the design of a fatigue testing machine specifically adapted for composite materials has been proposed. The machine is composed of a hydraulic part and an electrical part, each playing a key role in the application and control of the test loads. The hydraulic part uses an actuating cylinder to apply bending, compression or tensile loads to the specimen, while the electrical part is composed of a control and monitoring system, including a PLC, sensors and actuators to adjust the frequency and amplitude of loading.

To provide greater versatility and frequency adjustability, a piezoelectric actuator has been incorporated into the machine design. This actuator allows the generation of higher and more accurate load frequencies, enabling high-frequency testing of composite materials. In addition, universal clamping devices have been included to allow the application of loads in different modes, such as bending, compression and tensile, providing greater flexibility in testing.

The proposed fatigue testing machine provides a robust and reliable platform for fatigue evaluation of composite materials. By integrating different loading methods, both static and dynamic, and offering the ability to adjust the loading frequency, greater accuracy and adaptability in the evaluation of composite performance is achieved. This allows researchers and engineering professionals to obtain more realistic and meaningful results on the durability and strength of composite materials under different loading conditions.

In summary, the thesis addresses the need for a specific fatigue testing machine for composite materials, presenting a detailed design and proposals for improvement. The multidisciplinary approach adopted, combining knowledge from mechanical, hydraulic and electrical engineering, provides a solid basis for the development of future research in the field of fatigue of composite materials.

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