

Contents

Abstract	I
Resumen	II
Resum	IV
Acknowledgments	IX
Index	XIII
1 Introduction	1
1.1 Introduction and aim	1
1.2 Organization of the Thesis	2
2 Introduction to hierarchical levels of bone	5
2.1 Macrostructural level	6
2.2 Microstructural level (10-500 μm)	7
2.3 Sub-microstructural level (1-10 μm)	7
2.4 Nanostructural and sub-nanostructural levels (less than 1 μm)	8
3 Elastic properties of cortical bone	13
3.1 Introduction	13
3.1.1 Lekhnitskii transformation	17
3.1.2 Unitary cell of a composite material	19
3.2 Elastic properties at nanostructural and sub-nanostructural levels . . .	22
3.2.1 Unitary cell of a mineralized collagen fibril	22
3.2.2 Numerical homogenization model of a mineralized collagen fibril	26
3.2.3 Effect of longitudinal and lateral overlap	28

3.3	Elastic properties at lamellar level	29
3.3.1	Elastic properties of secondary osteons	42
3.3.2	Homogenized properties for thick and thin lamellae	45
3.3.3	Elastic properties of interstitial tissue	46
3.3.4	Elastic properties of cement line	47
3.4	Fulfilment of thermodynamic restrictions	49
4	Strength properties of cortical bone	53
4.1	Introduction	53
4.2	Strength properties of an osteon	57
4.2.1	Strength properties of thick and thin lamellae	58
4.3	Strength properties of cement line and interstitial tissue	61
5	Introduction to FEM in bone analysis	65
5.1	Bone failure and damage background	67
5.1.1	Stiffness degradation method (MPDM)	74
5.1.2	Element failure method (EFM)	76
5.2	Failure criteria	81
6	2D cortical bone models	85
6.1	Single osteon model	85
6.1.1	Including lacunae to the model	87
6.2	Material model	90
6.3	Coordinate systems	91
6.4	Failure initiation	92
6.5	Interlaminar failure propagation using the node release technique	93
6.6	Progressive damage model	100
6.6.1	Failure propagation using the progressive damage approach	100
7	Three point bending simulation of an ovine bone sample	107
7.1	Mechanical tests	112
7.2	Finite element model	115
7.2.1	Failure initiation strains	118
7.3	Damage model	119
8	Numerical 3D model	123
8.1	Realistic geometry based on micrographs	123
8.1.1	Radial compression	125
8.1.2	Axial compression	127
8.1.3	Damage model	127

8.1.4 Detailed geometry	130
9 Conclusions	139
Bibliography	143