



PROCEEDINGS BOOK

CEM2016

MECHANICAL ENGINEERING CONFERENCE

June 1-3 2016

INEGI - Porto, Portugal

Introduction

This book contains the abstracts and full papers presented at the MECHANICAL ENGINEERING CONFERENCE 2016 (CEM2016) promoted by LAETA and organized by INEGI that was held at FEUP, Porto, between 1st and 3rd, June of 2016.

LAETA is a research association recognized by the Foundation of Science and Technology of the Ministry of Education and Science. Its mission is to conduct basic and applied research in selected areas of Energy, Transport Technologies and Aeronautics and to contribute to advanced education and research in Mechanical Engineering. With more than 500 researchers drawn from several Universities and Research Institutes is the biggest organized group in Mechanical Engineering in Portugal. LAETA wants to play a significant role in stimulating innovation from basic discovery to translational application in Mechanical Engineering and related fields. The organization of CEM 2016 and future editions aims to create an international forum to engage stakeholders and partners not only from academia, but also from laboratories, industry, research settings, and funding bodies

The CEM 2016 has a broad and multidisciplinary nature, thus the call for Papers was based on the following Tracks: Key Enable Technologies (Biomechanics and Engineering Design), Energy, Aeronautics and Aerospace Technology.

We would like to thank all members of the Scientific Committee, Invited Lecturers and Authors for sharing their work and Participants for contributing to the effective discussion forum established during the meeting.

Porto, June 1st, 2016

The Organizing Committee:

António Augusto Fernandes

Jorge Seabra

Renato M. Natal Jorge

Proceedings of the
CEM2016 MECHANICAL ENGINEERING CONFERENCE
Porto, Portugal, 1-2 June 2016

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Conference Program

CEM2016

MECHANICAL ENGINEERING CONFERENCE

June 1-3 2016
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CONFERENCE PROGRAM



ORDEN
DOS
ENGENHEIROS



Organizing Committee

António Augusto Fernandes

Jorge Seabra

Renato Natal Jorge

Wednesday (Room: B032)	
08:00	Registration
09:00	Open session
09:30	Invited Lecture "No longer the tube-and-wing configuration: future manned and unmanned aircraft designs" Professor Luís Braga Campos Instituto Superior Técnico, Universidade de Lisboa
10:30	Coffee break

Wednesday (Room: B032)	
	<p>Oral presentations: Key Enable Technologies – Biomechanics I Chairpersons: Marco Parente / Jorge Belinha</p>
11:00	<p>THE INFLUENCE OF THE EXTERNAL AUDITORY MEATUS IN THE NUMERICAL MODEL OF THE HUMAN EAR Areias, Bruno; Parente, Marco; Gentil, Fernanda; Santos, Carla; Natal, Renato</p> <p>A BONE TISSUE REMODELLING ALGORITHM COMBINED WITH ADVANCED DISCRETIZATION MESHLESS TECHNIQUES Peyroteo, M.; Belinha, J.; Vinga, S.; Dinis, L.M.J.S.; Natal Jorge, R.M.</p> <p>THE MECHANICAL ANALYSIS OF TRABECULAR PATCHES USING ADVANCED DISCRETIZATION TECHNIQUES Maia dos Santos, C.I.R.A.; Marques, M.C.; Belinha, J.; Vinga, S.; Manzanares-Céspedes, M.C.; Chaussain, C.; Natal Jorge, R.M.</p> <p>ULTRASOUND IMAGING AND CAROTID BIFURCATION BLOOD FLOW Henriques, Helena A:M.; Castro, Catarina F.; Sousa, Luisa C.; António, Carlos C.; Santos, Rosa; Castro, Pedro; Azevedo, Elsa</p> <p>MECHANICAL DESIGN OF A LOW-PROFILE ASSISTIVE EXOSKELETON Pina, Daniel; Jorge, Renato N.; Mendes, Joaquim G.; Fernandes, António A.</p> <p>BIOMECHANICAL SIMULATION OF THE CUPULA IN THE INNER EAR Santos, Carla F.; Belinha, Jorge; Gentil, Fernanda; Parente, Marco; Areias, Bruno; Jorge, Renato Natal</p>
13:00	Lunch

Wednesday (Room: Sala de Atos)	
	<p>Oral presentations: Key Enable Technologies – Engineering Design Chairpersons: Paulo Tavares de Castro / Jorge Belinha</p>
11:00	<p>PARAMETER ESTIMATION OF VISCO-PIEZOELECTRIC MECHANICAL PROPERTIES IN SANDWICH STRUCTURES Carvalho, Vitor S.; Araújo, Aurélio L.; Belinha, Jorge A.O.P.</p> <p>STRUCTURAL INTEGRITY OF MORPHING STRUCTURES IN MAGNESIUM ALLOYS Aguiar, E.; Pereira, J.; Reis, L.; Tavares, S.M.O.; Moreira, S.J.; Gamboa, P.; de Castro, P.M.S.T.</p> <p>STRESS INTENSITY FACTOR CALCULATION USING CONVENTIONAL AND EXTENDED FINITE ELEMENT METHOD Hermosilla, Maria; Tavares, S.M.O.; de Castro, P.M.S.T.</p> <p>DAMAGE TOLERANT STRUCTURES UNDER MIXED MODE LOADING Tavares, S.M.O.; Moreira, S.J.; Gamboa, P.; Reis, L.; Aguiar, E.; Pereira, J.; de Castro, P.M.S.T.</p> <p>ANALYSIS OF COMPOSITE LAMINATED PLATES USING A HIGH-ORDER SHEAR DEFORMATION THEORY: A MESHLESS APPROACH Rodrigues, D.E.S. ; Belinha, J.; Araújo, A. L.; Ferreira, A.J.M.; Dinis, L.M.J.S.; Natal Jorge, R.M.</p> <p>COMPUTATIONAL STUDY OF THE FLOW INSIDE AN INVERTER'S COMPARTMENT Salvador, Hélder ; Ferreira, J. P. G; V. Farahani, Behzad; Palma, J.M.L.M</p>
13:00	Lunch

Wednesday (Room: B032)	
	<p>Oral presentations – Energy I Chairpersons: Mário Costa / João Ribau</p>
14:30	<p>ON THE MODELLING OF TRANSCRITICAL NITROGEN JETS Antunes, Eduardo L. S. F.; Silva, André R. R.; Barata, Jorge M. M.</p> <p>FOREST PRODUCTS VALORIZATION AS A TOOL TO REDUCE FIRE RISK: FOREST BIOMASS MANAGEMENT AND CHARACTERIZATION TO DEVELOP ENERGY PRODUCTION SYSTEMS AND BIOCOMPOSITES Pais, Diana; Novais, Catherine; Marques, António; Viegas, Domingos; Baptista, António; Nóvoa, Paulo</p> <p>FOREST PRODUCTS VALORISATION AS A TOOL TO REDUCE FIRE RISK: FOREST BIOMASS MANAGEMENT AND CHARACTERIZATION FOR BIOENERGY PRODUCTION Ribeiro, Jorge S.; Viegas, Domingos X.; Marques, António T.</p> <p>NUMERICAL SIMULATION OF SPRAY-WALL INTERACTIONS Rodrigues, Christian; Barata, Jorge; Silva, André</p> <p>BIODIESEL PRODUCTION AND USE IN THE URBAN TRANSPORT SECTOR IN PORTUGAL Ribau, J.P.; Silva, C.M.; Bastos, J.; Castanheira,E.G.; Freire,F.</p> <p>LARGE EDDY SIMULATIONS OF COAL AND BIOMASS COMBUSTION IN LARGE- SCALE LABORATORY FURNACES Miriam Rabaçal; Mário Costa; Andreas Kempf</p>
16:30	<p>Coffee break</p>

Wednesday (Room: Sala de Atos)	
14:30	<p>Oral presentations – Aeronautics and Aerospace Technology I Chairpersons: Jorge Barata / André Silva</p> <p>THE EFFECT OF THE IMPINGEMENT HEIGHT OF TWIN JETS IN TANDEM THROUGH A CROSSFLOW Vieira, Diana F.C.; Barata, Jorge M.M; Silva, André R.R</p> <p>EXPERIMENTAL RESEARCH OF SYMMETRY BREAKING IN A FLAPPING WING Neves, Fernando M. S. P.; Barata, Jorge M. M.; Manquinho, Pedro A. R.</p> <p>QUANTITATIVE ANALYSIS OF NEAR VERTICAL TAKE-OFF FORCES IN BIRDS Silva, Telmo; Neves, Fernando; Silva, André; Barata, Jorge</p> <p>PARAMETRIC STUDY OF INTAKE GROUND VORTEX FORMATION UNDER CROSSWIND CONDITIONS Manquinho, Pedro; Barata, Jorge; Silva, André</p> <p>OVERVIEW OF DIFFERENT STRENGTH PREDICTION TECHNIQUES FOR SINGLE-LAP BONDED JOINTS de Sousa, C.C.R.G.; Campilho, R.D.S.G.; Marques, E.A.S.; da Silva, L.F.M.</p> <p>EVALUATION OF DIFFERENT DAMAGE INITIATION AND GROWTH CRITERIA IN THE COHESIVE ZONE MODELLING ANALYSIS OF SINGLE-LAP BONDED JOINTS Rocha, R.J.B.; Campilho, R.D.S.G.</p>
16:30	<p><i>Coffee break</i></p>

Wednesday (Room: B032)	
	<p>Oral presentations: Key Enable Technologies – Biomechanics II Chairpersons: Pedro Martins / Luisa Costa</p>
17:00	<p>INFLUENCE OF DRILL SPEED AND FEED RATE ON BONE DAMAGE Fernandes, Maria G.; Fonseca, Elza M.M.; Jorge, Renato N.</p> <p>MODELS OF BONE METASTASES USING FRACTIONAL DERIVATIVES Christ, Luiz Filipe; Valério, Duarte; Coelho, Rui; Vinga, Susana</p> <p>DETERMINATION OF THE BIOMECHANICAL PROPERTIES OF THE PELVIC FLOOR MUSCLES USING AN INVERSE FINITE ELEMENT ANALYSIS Silva, Maria Elisabete; Parente, Marco; Mascarenhas, Teresa; Natal Jorge, Renato</p> <p>ELASTO-PLASTIC ANALYSIS OF FEMUR STEM IN TOTAL HIP ARTHROPLASTY Marques, Marco; Belinha, Jorge; Dinis, Lúcia; Vinga, Susana; Jorge, Renato</p> <p>DIAGNOSTIC TECHNIQUES AVAILABLE FOR THE ANALYSIS OF PIP RUPTURED IMPLANTS Ramião, Nilza; Martins, Pedro; Fernandes, Antonio A; Barroso, Maria L; Costa Santos, Diana</p> <p>MECHANISM OF MATERNAL VAGINAL BIRTH RELATED INJURY Oliveira, Dulce; Parente, Marco P. L.; Calvo, Begõna; Mascarenhas, Teresa; Natal Jorge, R. M.</p> <p>THE EFFECT OF IMPAIRED PELVIC LIGAMENTS IN UTERINE POSITION: COMPUTATIONAL MODEL OF VAGINAL MESH Brandão, Sofia; Parente, Marco; Da Roza, Thuane; Mascarenhas, Teresa; Natal Jorge, Renato</p>

Wednesday (Room: Sala de Atos)	
17:00	<p>Oral presentations – Aeronautics and Aerospace Technology II Chairpersons: Raúl Campilho / Sérgio Tavares</p>
	<p>DRAG AND DOWN FORCE OPTIMIZATION OF A LE MANS LMP1 PROTOTYPE USING SPECIAL SURFACE MATERIALS Varandas, Eduardo E.; Barata, Jorge M.; Silva, André. R.</p>
	<p>NUMERICAL STUDY OF FREEZING DROPLETS Magalhães, Leandro; Barata, Jorge; Silva, André</p>
	<p>PRESSURE DISTRIBUTION ON A VECTORED-THRUST F35-B FIGHTER IN GROUND EFFECT Cerqueira, Ana T. S.; Vieira, Diana F. C.; Neves, Fernando M. S. P.; Barata, Jorge M. M.; Silva, André R. R.</p>
	<p>EXPERIMENTAL AND NUMERICAL INVESTIGATION ON WAKE DYNAMICS OF A PLUNGING AIRFOIL Sousa, J.M.M.; Khorasanizade, Sh.; Barata, J.M.M.; Silva, A.R.R.; Neves, F.M.S.P.</p>
	<p>USE OF THE DIRECT METHOD FOR ADHESIVES CHARACTERIZATION APPLIED TO THE STRENGTH PREDICTION OF DOUBLE-LAP JOINTS Carvalho, U.T.F.; Campilho, R.D.S.G.</p>

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Thursday (Room: B032)	
09:30	Invited Lecture "Towards micro-structural design of composite materials: numerical methods and experiments" Professor Silvestre Pinho Imperial College London, UK
10:30	Coffee break

Thursday (Room: B032)	
11:00	<p>Oral presentations – Energy II Chairpersons: Mário Costa / Inês Ribeiro</p> <p>IGNITION BEHAVIOUR OF SOLID FUELS IN A DROP TUBE FURNACE Carvalho, André; Rabaçal, M; Costa, M</p> <p>IMPACT OF THE BIOFUEL SPRAY QUALITY ON THE PERFORMANCE OF AERO-ENGINES Silva, André R. R.; Panão, Miguel R. O.; Costa, Mário M. G.; Barata, Jorge M. M.; Rodrigues, Sérgio; Pizziol, Bruno; Rodrigues, Christian M. G.</p> <p>COMPARATIVE WELL-TO-WHEELS ASSESSMENT OF BIODIESEL AND FOSSIL DIESEL FOR HEAVY DUTY TRANSPORT IN LATIN AMERICA Malça, J.; Marques, P.; Serrano, L.; Castanheira, E.; Freire, F.</p> <p>TEMPORAL VARIABILITY IN THE ENVIRONMENTAL LIFE-CYCLE ASSESSMENT OF ELECTRICITY IN PORTUGAL Garcia, Rita; Marques, Pedro; Freire, Fausto</p> <p>DIELECTRIC AND TG ANALYSES OF A LEAF OF VEGETATION FOR THE MODELING OF FOREST FIRES Khelloufi Khadidja; Baara Yamina; Zekri Nourdine; Pinto Claudya; Domingo Xavier Viegas</p> <p>DEVELOP A MODEL TO ESTIMATE THE ENERGY CONSUMPTION IN THE INJECTION MOULDING PROCESS Cardeal, Gonçalo; Ribeiro, Inês; Peças, Paulo; Baptista, A.J.; Pereira, J.P.; Henriques, Elsa</p>
13:00	Lunch

Thursday (Room: Sala de Atos)	
	Oral presentations – Aeronautics and Aerospace Technology III Chairpersons: Jorge Barata / Eduardo Marques
11:00	<p>PHILOSOPHY AND ETHICS OF AERONAUTICAL ENGINEERING Mendes, Antonio L. M.; Barata, Jorge M. M.</p> <p>GEOMETRICAL STUDY OF MIXED ADHESIVE JOINTS FOR HIGH TEMPERATURE AEROSPACE APPLICATIONS Marques, Eduardo; Campilho, Raul; da Silva, Lucas</p> <p>NONLINEAR ESTIMATION OF ORBITAL TRAJECTORIES FROM RADAR MEASUREMENTS Bousson, K.; Coelho, Milca F.</p> <p>A 3D DIMENSIONAL STRESS ANALYSIS OF AIRPLANE WINDSHIELDS CAUSED BY BIRD IMPACT Noronha, J.P.M.C.; Belinha, J.; Araújo, A.L.; Dinis, L.M.J.S.; Natal Jorge, R.M.</p>
13:00	Lunch

Thursday (Room: B032)	
14:30	<p>Oral presentations: Key Enable Technologies I Chairpersons: António Ferreira / Eduardo Varandas</p> <p>DAMAGE ASSESSMENT OF DRILLED COMPOSITES PLATES Silva, Jorge; Ferreira, Filipe; Abreu, Stella M. ; Matos, João E.; Durão, Luís M.</p> <p>BRITTLE STRUCTURAL ADHESIVES REINFORCED WITH MICROPARTICLES OF CORK Barbosa, A.Q.</p> <p>FORMABILITY LIMITS BY FRACTURE IN COPPER SHEET METAL FORMING Jawale, Kishore; Duarte, J. Ferreira; Reis, Ana; Silva, M. B.</p> <p>MODELLING RESIN FLOW PHENOMENA IN A VACUUM INFUSION PROCESS SUBJECT TO VARIABLE INLET PRESSURE Silva, Fernando; Pina, Luis; Almeida, Fernando G.; Bodaghi, Masoud</p> <p>MODELLING OF INJECTION MOULDING PROCESS TO FOSTER RESOURCES EFFICIENCY? A CASE STUDY Ribeiro, Maria; Ribeiro, Inês; Peças, Paulo; Henriques, Elsa</p> <p>OPTIMIZATION OF FOREST CLEANING Novais, Catherine; Pais, Diana; Ribeiro, Jorge; Viegas, Domingos; Marques, António; Baptista, António</p>
16:30	<p><i>Coffee break</i></p>

Thursday (Room: Sala de Atos)	
14:30	<p>Oral presentations – Aeronautics and Aerospace Technology IV Chairpersons: Braga Campos / Luís Santos</p> <p>DRONES SAFE FLIGHT: ON ADDRESSING OPERATIONAL SAFETY FOR LOW COST SMALL DRONES Marta, A. C.; Moutinho, A.; Gamboa, P.</p> <p>ACQUISITION AND PROCESSING OF CRITICAL PSYCHOPHYSIOLOGICAL AND FLIGHT PARAMETERS IN LIGHT-SPORT AVIATION Silva, Jorge; Zorro, Sara; Patrão, Luís; Moutinho, Alexandra; Vieira, Susana; Fonseca, Agostinho; Gabriel, Joaquim</p> <p>GYROSTAT SATELLITE? GENERAL CASE OF BIFURCATION OF EQUILIBRIA AND ANALYTICAL EXPRESSIONS Santos, Luis; Sarychev, Vasili; Silva, André; Gutnik, Sergey</p>
16:30	<p><i>Coffee break</i></p>

Thursday (Room: B032)	
17:00	<p>Oral presentations: Key Enable Technologies – Biomechanics III Chairpersons: João Folgado / Marco Parente</p> <p>AN EXPERIMENTAL PROTOCOL TO INVESTIGATE ARTERIAL MECHANICS Martins, Pedro; Natal Jorge, Renato; Sousa, Luísa; Castro, Catarina; Chaves Pereira, José; Folgado, João; Fernandes, Paulo; Fernandes Pereira, José</p> <p>THE NONLINEAR NUMERICAL ANALYSIS OF ATHEROSCLEROTIC PLAQUE TISSUE Lopes, P.F.O.; Belinha, J.; Dinis, L.M.J.S.; Natal Jorge, R.M.</p> <p>APPLICATION OF IN SILICO MODELS INSTEAD OF IN VIVO MODELS IN A PELVIC ORGAN PROLAPSE STUDIES Rynkevich, Rita ; Martins, Pedro ; Parente, Marco ; Fernandes, Antonio</p> <p>A BIOMECHANOCHEMICAL BONE REMODELING MODEL FOR DISEASE AND THERAPY DYNAMICS Capacete, Joana; Folgado, João; Fernandes, Paulo; Coelho, Rui; Vinga, Susana; Natal Jorge, Renato; Belinha, Jorge</p> <p>STRONGLY-OBJECTIVE MODELLING OF FIBER-REINFORCED HYPERELASTIC MATERIALS Ferreira, João P; Parente, Marco P; Natal Jorge, Renato</p> <p>CAN NONLINEAR MIXED EFFECTS (NLME) MODELS BE APPLIED TO THE MECHANICAL TESTING OF BIOMATERIALS? Martins, Pedro S.; Renato, Natal Jorge; Veríssimo, André; Vinga, Susana</p>
19:00	<p><i>Departure for conference dinner</i></p>

Thursday (Room: Sala de Atos)	
17:00	<p>Oral presentations: Key Enable Technologies II Chairpersons: Miguel Almeida / Carla Roque</p> <p>ANALYSIS OF HETEROGENEOUS PLATES BY MESHLESS METHODS Ferreira, António J. M.</p> <p>RBF-FD MESHLESS OPTIMIZATION USING DIRECT SEARCH (GLODS) Roque, Carla M.C.; Madeira, J.F.A.</p> <p>METHODOLOGIES FOR ENGINEERING LEARNING AND TEACHING (MELT) Gabriel, Bárbara F. C. C.; Valente, Robertt A. F.; Dias-de-Oliveira, João A.; Neto, Victor F. S.; de Andrade-Campos, António G. O.</p> <p>ON THE GLOBALIZATION OF THE PORTUGUESE MECHANICAL ENGINEERING EDUCATION Barata, Jorge M. M.</p> <p>FIRE SAFETY IN AREAS DEDICATED TO CAMPING AND CARAVANING ACTIVITIES Almeida, Miguel; Raposo, Jorge; Neves, Fernando; Moutinho, Alexandra; Ervilha, Rita; Martins, Marta</p> <p>LIFE-CYCLE ASSESSMENT OF URBAN TRANSPORTATION MODES Bastos, J.; Marques, P.; Batterman, S.; Freire, F.</p> <p>THE ANALYSIS OF LAMINATED PLATES USING DISTINCT MESHLESS TECHNIQUES Belinha, J.; Araújo, A.L.; Ferreira, A.J.M.; Dinis, L.M.J.S.; Natal Jorge, R.M.</p>
19:00	<p><i>Departure for conference dinner</i></p>

Wednesday & Thursday

All day	Poster
	<p>“Contribution to state of the art review on wing morphing and damage” Sérgio M.O. Tavares¹, Sérgio J. Moreira¹, Maria Hermosilla^{1,2}, Paulo M. S. T. de Castro¹</p> <p>1 - University of Porto, FEUP, Portugal; 2 - Universidad Politécnica de Cartagena, Spain, and ERASMUS student at FEUP</p>

CONFERENCE DINNER

Conference dinner		
19:00	Departure from FEUP	
20:00	Casa da Música	

INFLUENCE OF DRILL SPEED AND FEED RATE ON BONE DAMAGE

Fernandes, Maria G.¹; Fonseca, Elza M.M.²; Jorge, Renato N.³

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KEYWORDS: *Bone Drilling, Damage, Dynamic Finite Element Model*

ABSTRACT: Implant failures and postoperative complications are often associated to the bone drilling. Estimation and control of drilling parameters are critical to prevent mechanical damage to the bone tissues. For better performance of the drilling procedures, it is essential to understand the mechanical behaviour of bones that leads to their failures and consequently to improve the cutting conditions. This paper investigates the effect of drill speed and feed-rate on mechanical damage during drilling of solid rigid foam materials, with similar mechanical properties to the human bone. Experimental tests were conducted on biomechanical blocks instrumented with strain gauges to assess the drill speed and feed-rate influence. A three-dimensional dynamic finite element model to predict the bone stresses, as a function of drilling conditions, drill geometry and bone model, was developed. These simulations incorporate the dynamic characteristics involved in the drilling process. The element removal scheme is taken into account and allows advanced simulations of tool penetration and material removal. Experimental and numerical results show that generated stresses in the material tend to increase with tool penetration. Higher drill speed leads to an increase of von-Mises stresses and strains in the solid rigid foams. However, when the feed-rate is higher, the stresses and strains are lower. The numerical normal stresses and strains are found to be in good agreement with experimental results. The models could be an accurate analysis tool to simulate the stresses distribution in the bone during the drilling process.

1 INTRODUCTION

Bone drilling as a part of surgical procedure has become progressively crucial in many fields of surgery including orthopaedics, dentistry, neurosurgery, plastics and reconstructive and craniomaxillofacial (Staroveski et al. 2015). Only in the dentistry, each year there are millions of dental implants that are placed worldwide (Soriano et al. 2013). Also, knee and hip implant surgeries are performed around the world and

considered to be amongst the most commonly performed operations in clinical practice (Lughmani et al. 2015). According to public data, between 250000 and 300000 total knee arthroplasties are performed each year in the United States alone, with the number increasing every year (Harrysson et al. 2007). All these clinical interventions require the creation of cylindrical holes in the bone and the postoperative success is largely dependent on the degree of damage induced by drilling

process. The reduction of damage during drilling has a positive impact on the reduction of rejected implants, bone regeneration time and patient recovery time (Soriano et al., 2015; Bertollo et al., 2011). Also, the recovery time clearly affects the quality of life of thousands of citizens. Reducing this interval would help to reduce the hospital stay and period of disability, which has a direct impact on public health costs.

Indeed, the importance of this clinical procedure has awakened the interest of the scientific community. Recently, several researches on bone drilling have been published. The vast majority of them focus on the influence of parameters (e.g. drill diameter, drill speed, feed-rate and cutting force) on bone drilling temperature (Soriano et al. 2015; Lee et al., 2012; Sezek et al., 2012; Hou et al., 2015; Fonseca et al., 2014; Fernandes et al., 2015). However, there is still a lack information with regard to the mechanical damage, especially on the analysis of strain and stress distribution during bone drilling. The mechanical damage that occurs around the drilled hole is a major concern during bone drilling, as greater the damage greater will be the postoperative healing time (Fernandes et al. 2015; Pandey et al. 2015). Furthermore, Harris and Kohles (2001) claimed that the heat generation during drilling have a positive correlation with the developed stress at the surgical site. These claims have encouraged research to address the measurement of peak stress generation as a relative indicator of the peak elevation of temperature.

In traditional bone drilling process, the surgeon requires considerable amount of force to penetrate the rotating drill into bone. This cut effort with high drill speed and tool vibrations can induce the formation of microcracks and fracture of bone tissue, which are the prime source of reducing the strength of the bone postoperatively (O'Brien et al. 2005). It is knowing that the microcracks occur when the bone strain exceeds the threshold. The process of microcracks accumulation in the bone, eventually leads to a reduction of bone stiffness, resulting in

damage by cracks of the material (O'Brien et al. 2005; Wang et al. 2013; Taylor et al., 2001). Despite all relevant experimental investigations on bone drilling and the conclusions adopted, none of them provided a functional relationship that represent the effects of drilling conditions, drill bit geometry and material behaviour on bone drilling. The large number of significant drilling parameters, including the difficult regulation of experimental methods, temperature measuring equipment and bone materials, makes the experimental study of bone drilling impracticable.

The use of validated tools, such as numerical models with the finite element method could help the analysis and the definition of optimal drilling parameters. Only a few numerical models in the literature have attempted to simulate the bone drilling. However, most of them were executed with limited parameters and using two-dimensional (2D) simulations, furthermore were not validated with experiments (Sezek et al. 2012). Recently, Marcos et al. (2015) have made a bibliographic review of the main contributions on the field of numerical modelling of bone cutting, including bone drilling. They found that the numerical models are still far from clinical application and there is a clear requirement of improvement of the available models for drilling simulation.

The current study is focused on the evaluation of mechanical damage generated during bone drilling, as function of different drill speeds and feed-rates. In effort to improve the bone drilling process, a new experimental approach of strain and stress profile in bone drilling is present in this study, which includes biomechanical test blocks from Sawbones with mechanical properties similar to the human bone. The blocks were instrumented with strain gauges in different surface positions during the drilling process. A set of experiments were performed to assess the uncertainty and repeatability of the results. Subsequently, a three-dimensional (3D) dynamic finite element (FE) model was built to simulate the drilling process. With an

explicit dynamic simulation, it is possible to obtain fast solution, large structural deformation and applying high intensity loading in a short time frame. This model allows to predict the strain and stress as a function of drilled conditions, bit geometry and material bone model. The contact friction between the drill bit and the bone material, with the element removal scheme, are taken into account and allow advanced simulations of tool penetration and material removal. Remarkable conclusions were obtained, finding a strong influence of the drilling parameters on the stress distribution during drilling.

2 MATERIALS AND METHODS

2.1 Experimental analysis

To assess the bone damage, it is important to take into account the variation in mechanical and thermal properties of samples taken from different bones in the animal, and from different animals of the same species, leads to the variations in the measured results subject to virtually identical drilling conditions in repeated measurements (Lee et al. 2012). In addition, the tests with biological materials often require a larger frequency of repetitions in comparison with testing on engineering materials due to their high variance in properties, caused by age, weight, gender and physical characteristics. In order to conduct the experimental work in a cost-effective manner, a set of polyurethane foam blocks (from Sawbones; Pacific Research Laboratories Inc., Vashon Island, WA, USA) were used as an alternative to the cadaveric human bone because of its consistent and homogeneous structural properties (Kim et al., 2012; Liu et al., 2016). The samples were supplied in rectangular shape with the dimension of 130x180x40 mm and the material has a closed cell with density of 0.80g/cm³.

Nine combinations of feed-rates (25, 50, 75 mm/min) and drill speeds (600, 800, 1200 rpm) have been analysed (Table 1). This combinations of drilling parameters have been

chosen with regard to existing clinical practice based on hand-held drilling machines, as well as helping in the development of completely robotised drilling systems.

Drillings were performed in Mechanical Laboratory at Polytechnic Institute of Bragança using a computer numerically controlled (CNC) machine system with total control of the involved parameters. A conventional HSS twist drill bit was chosen to produce the holes, as described in Table 1. All holes were made with 30 mm of depth and the measurements for each combination of drilling parameters were randomly repeated six times.

Table 1. Drilling parameters used in experimental tests

Drilling Parameters	
Drill bit	Ø4mm, point angle 118°
Feed rate (V)	25, 50, 75 mm/min
Drill speed (ω)	600, 800, 1200 rpm
Hole depth	30 mm

For the strain measurements, a set of flexible linear strain gauges (1-LY18-6/120, 120 Ω \pm 0.35% from HBM) were installed on the blocks surface. In order to promote the uniformity of results, the locations of the holes were properly marked to maintain the same distance of 3.5 mm between the hole and the strain gauge, as illustrated in Figure 1. The block surfaces were cleaned and prepared to receive the strain gauges, which were bonded following the instructions of the manufacturer. Finally, the strain gauges were connected to the data acquisition system (Vishay Micro Measurements P3 Strain Indicator and Recorder). This installation allows to read the strains along the drilling time and to obtain the corresponding profiles of stress in block surface versus drilling depth.

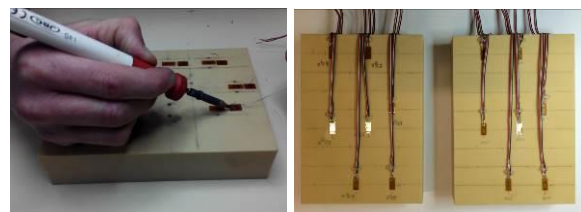


Figure 1. Installation of the linear strain gauges.

The complete experimental setup is shown in

Figure 2. In this setup the position of the drill is fixed and perpendicular to the block axis. All tests were performed at room temperature (approximately 20 °C) with no interference in the strain measurements. Detailed results of the temperature in the surface and inside of the block, could be obtained in previous publications from numerical and experimental tests (Fernandes et al. 2015; Fernandes et al. 2016). The control of the temperature conditions in all holes was monitored by a thermal camera (ThermaCAM 365, FLIR Systems) which measured the temperature in the block surface and in the drill bit. Between successive holes, sufficient time was provided to ensure the same initial temperature conditions in all holes.

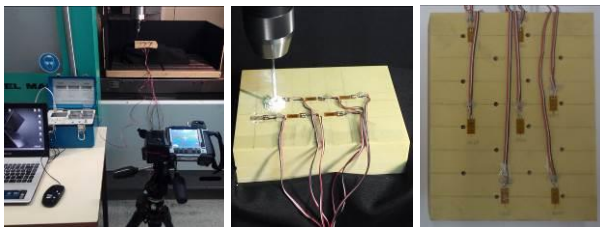


Figure 2. Experimental setup.

2.2 FE dynamic model approach

Considering the experimental methodology adopted in this study, a 3D FE model has been developed to simulate the drilling process. The numerical analysis was performed using an explicit finite element code, ANSYS LS-DYNA (LSTC, Livermore, CA, United State). The FE model consists of a set made up of a HSS twist drill bit and the bone block. The drill bit geometry was designed through the CAD software SolidWorks® (Dassault Systems S.A., France) with a similar geometry to the drill used in the experimental procedure (Ø4 mm and point angle of 118°). The bone was modelled as rectangular shape considering a little part of the block with the dimensions 14x10x4 mm. The block region of particular interest is around the cutting zone. The geometric domain in this part is chosen as a circular disc with 6 mm of diameter and 4 mm of height, as shown in Figure 3.

The element contact interaction usually require extremely fine mesh resulting in huge

computational efforts. Reasonable selection of mesh size allows reduction of required CPU time without compromising solution accuracy. The finite element used for the 3D model was *Solid 164* (8 nodes with three degrees of freedom at each node in X, Y, Z directions). A mesh sensibility analysis was carried out to obtain a more suitable model for this kind of simulation. As the most important part is located in the vicinity of the drilled zone, element size of 0.5 mm was chosen, and 1.0 mm for the external part of the structure. This mesh has been proven to be adequate to produce consistent results through the mesh sensitivity analysis. The final model of the block and the drill bit comprises a total of 20477 elements (Figure 3).

In order to carry out calculations it was necessary to establish initial boundary conditions which represent the real system with appropriate accuracy. Following the experimental tests, the bottom surface of the block was fully constrained while the drill bit movement was explicitly simulated through a dynamic FE approach to rotate and move only about its own longitudinal axis (Y axis) with a specific drill speed (ω) and feed-rate (V) vertically downwards into the block, as shown in Figure 3. The magnitudes for drilling speed and feed rate were varied over ranges used in the experimental tests (Table 1).

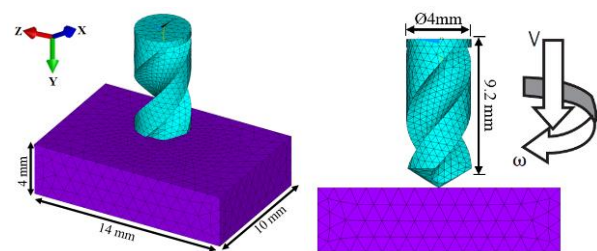


Figure 3. Numerical model of the bone drilling.

2.2.1 Material models

There are many material models to describe the behaviour of the bone tissue. However, it is well known that the FE simulation results are very sensitive to the material properties, and thus it is the most important issues to choose the most suitable material model. Materials

subject to drilling are highly affected by large strains and high strain rates, which finally leads to failure. To define the block in high impact deformation, an elastic-plastic material with kinematic isotropic hardening was chosen (*MAT_PLASTIC_KINEMATIC). The strain rate effect is considered using the Cowper-Symonds model, and the yield stress is defined with the following equation (Cowper and Symonds, 1957; ANSYS/LS-DYNA User's Guide, 2009):

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}} \right] \left(\sigma_0 + \beta E_p \varepsilon_p^{eff} \right) \quad (1)$$

where σ_y is the yield stress, σ_0 the initial yield stress, $\dot{\varepsilon}$ is the strain rate, β is the strain hardening parameter, which adjust the contribution of isotropic and kinematic hardening (between 0 for kinematic hardening and 1 for isotropic hardening), C and P are the Cowper-Symonds strain rate parameters, ε_p^{eff} is the effective plastic strain, and E_p the plastic hardening modulus which is given in terms of the elastic modulus E and the tangent elastic modulus E_{tan} as shown in the following equation:

$$E_p = \left(\frac{E_{tan} E}{E - E_{tan}} \right) \quad (2)$$

The Cowper–Symonds model was adopted in this work because it is one of the typical material models used in the material formulation of human bones and has the ability to represent the mechanical behaviour of materials at high strain rates (Asgharpour et al. 2014; Li et al. 2010). It shows the usual configuration of strain rate dependant phenomenological models in which the yield stress is modified by constant parameters. Then, the Cowper–Symonds model is a good example to show the performance of the proposed dynamic material characterization and the ability to determine the material

parameters of a given material model (Hernandez et al. 2013).

The mechanical properties of the polyurethane foam material were obtained from the uniaxial tensile tests and have been comprehensively defined in our previous studies (Fernandes et al. 2015). Mean values of Young's modulus, initial yield stress, tangent modulus and failure strain were calculated and incorporated into the finite element model. The remaining material properties were taken from literature (Li et al. 2010; Fernandes et al. 2015).

The drill bit was modelled as a rigid body (*MAT_RIGID), since its stiffness is much higher than the bone. This is a practice way to reduce computational cost and resources involved in the drilling simulation. All the material properties used in the numerical analysis are listed in Table 2.

Table 2. Material properties used in FE analysis.

Properties	Bone Block	Drill bit
Density (kg/m ³)	800	7850
Young's Modulus (GPa)	0.987	200
Poisson's ratio	0.3	0.3
Initial Yield Stress (MPa)	22.59	
Tangent Modulus (MPa)	0.91	
Hardening Parameter	0.1	
Cowper-Symonds model		
<i>C</i>	2.7	
<i>P</i>	7	
Failure Strain	0.05	

2.1.2 Contact algorithm and failure criteria

Numerical simulations with the penetration tool it is important to take into account the type of contact between the different components.

The interaction between block and cutting tool was modelled using the contact algorithm *CONTACT_ERODING_SURFACE_TO_SURFACE, available in LS-DYNA code (ANSYS/LS-DYNA User's Guide, 2009). This type of contact is used when a surface of one body penetrates the surface of another body. In this case, simulation of the hole generation process in bone block needs the element removal. The eroding option is the most appropriate choice when solid elements involved in the contact are subject to erosion (element deletion). Here, the surface of the

drill bit was classified as the contact surface. The target surfaces include all the block surfaces that will be contacted with drill bit. The frictional contact between the drill bit and the block is assumed to be governed by Coulomb's friction law. In accordance with results presented in the literature, the friction coefficient is assumed equal to 0.3 (Tu et al. 2013).

To control the element removal and the hole generation during the drilling operation, a failure criteria was applied. Through the LS-DYNA code, an approach of element erosion can be used to simulate the perforation when any element exceeds a specified plastic strain. Based on the bone properties, a critical failure strain of 0.05 is defined as the criterion in the erosion algorithm implementation, above which the solid elements are eroded and excluded from the calculation.

Dynamic analysis was used with the simulation range subdivided into 15000 time increments of 8.0×10^{-4} seconds. The simulation time was chosen on the basis of minimum cost and time of simulation as well as better assessment of the pattern of stress and deformation at each second of the simulation.

All FE analyses were executed by a workstation with a quad-core Intel I7-4790k with 16 GB RAM. The average CPU time of our simulations lasted for 68-82 hours.

3 RESULTS AND DISCUSSION

Nine different combinations of parameters were performed in order to analyse the influence of drill speed and the feed-rate on the bone mechanical damage during drilling. The study includes an experimental method which measures the strains during the drilling and a numerical model which incorporates all dynamic parameters involved in the experimental method. Experimental results and FE results were compared and discussed.

Three feed rates (24, 50, 75 mm/min) were chosen for three drill speeds (600, 800, 1200 rpm). For each feed-rate was considered three drill speeds and a drilling time that ensures the complete perforation of the block. The

dynamic analysis is treated using an explicit time integration scheme with an appropriate time step for each increment.

In order to allow a better comparison of the experimental and numerical results, the average of normal stresses was calculated experimentally and compared with the numerical results at different times instant of drilling. The distance between the edge of the drilled hole and the strain gauge, as well as the direction of the linear strain gauge were considered on the selection of the nodal points in the numerical model. Figure 6 (a), (b) and (c) show the mean and standard deviation of normal stresses in one direction (σ_{zz}) obtained in both methods, at different times of drilling and for each parameter combination.

Experimental and numerical results indicated strong relationship between either drill speed, feed-rate, or drilling depth and the high stress levels. Overall, it was observed that the normal stress in drilling process increases with the increasing of feed-rate and drill speed, for the same time instant. For the nine combinations of parameters, numerical and experimental results showed a clear trend for an increase in level of stresses with tool penetration along the time. The maximum values were reached when the drill bit penetrated completely in the block. After reaching the total depth, normal stresses start to decrease. The greater of the drilled hole depth, the greater the normal stress in the bone block. However, this fact was more obvious for the drill speed of 600 rpm (Figure 4 (a)). A comparison between numerical and experimental data for relationship between the levels of normal stress and drilling parameters (drill speed, feed-rate and drill depth) demonstrates that the obtained numerical results are well within the range of experimental data.

Most important than analyse the bone tissue behaviour at different drilling times is analyse its behaviour at end of the process. The effect of drill speed and feed-rate for the complete penetration of the block was examined. The average of peak stress generated was calculated and compared for different feed-rates and drill speeds, as represented in Figure

5 (a), (b) and (c), respectively. The peak of stress generated was also observed to be unaffected by the range of drill speeds and feed-rates used in experiments.

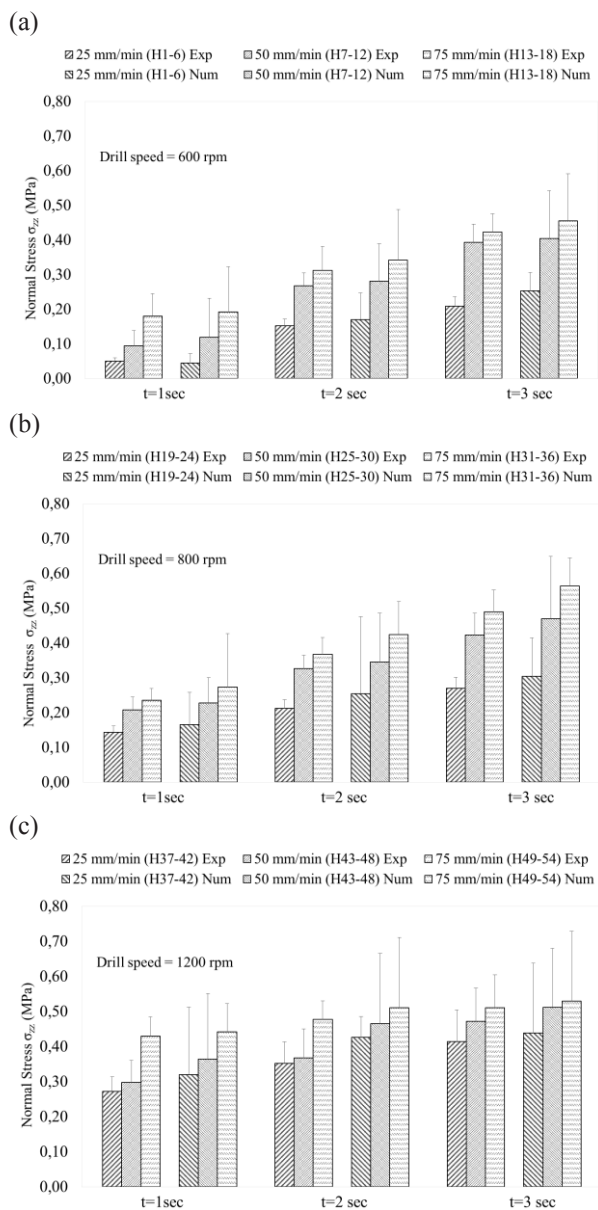


Figure 4. Comparison of normal stress σ_{zz} (MPa) in the numerical and experimental study: (a) 600 rpm, (b) 800 rpm and (c) 1200, at different times of drilling.

Analysing the results for the total time of drilling, it was observed that the peak of normal stress maintained the same behaviour with respect to the drill speed. Regarding to the feed-rate, the normal stress decreased with the increase of feed-rate. Although at the start of drilling, the generated normal stresses are

higher for higher feed-rates (75 mm/min), in the entire process are found higher stresses for lowest feed-rate (25 mm/min) because the drilling time also increases.

It was observed from the results that the peaks of normal stress are between 0.586 MPa and 0.837 MPa for the considered ranges of drill speed, feed-rate and 4 mm of drilling. In generally, the numerical results were validated and are in good agreement with the experimental results.

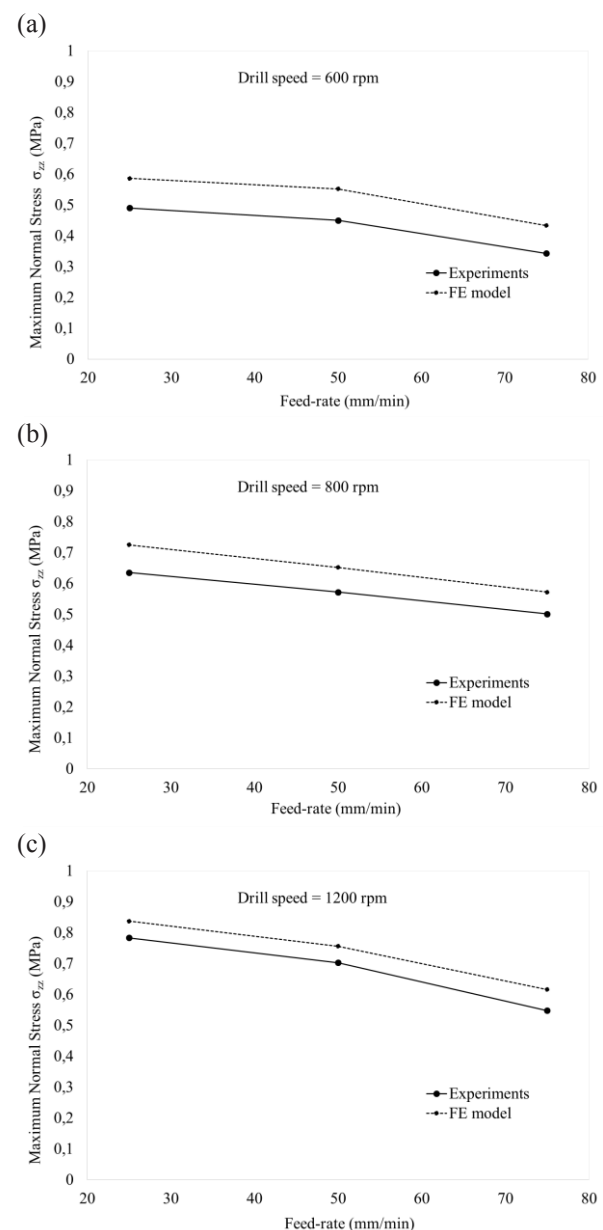


Figure 5. Comparison of maximum normal stress σ_{zz} (MPa) in the numerical and experimental study: (a) 600, (b) 800 and (c) 1200 rpm, at the end of drilling.

Von-Mises stress distribution of the numerical results at drilling time of 3 seconds are shown in Figure 6. In these images, the scale for stress runs from the minimum stress value (blue) to the maximum stress value (red).

Figure 6 shows the contours of von-Mises stress in the bone drilling for the feed-rate 25, 50 and 75 mm/min and drill speeds of 600, 800 and 1200 rpm, respectively.

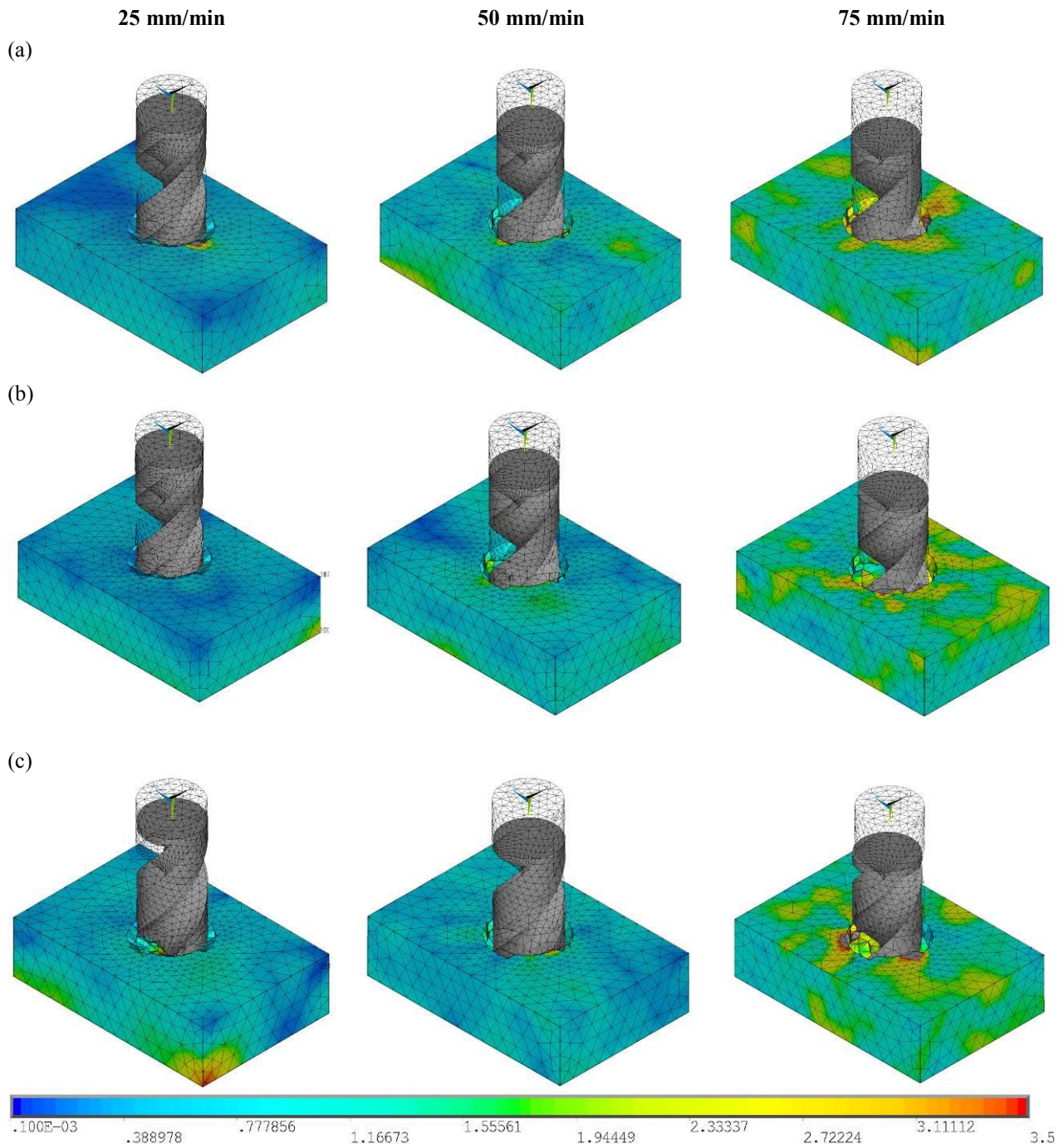


Figure 6. Von-Mises stress (MPa) distribution at drill speeds (a) 600, (b) 800 and (c) 1200 rpm and different feed-rates.

The maximum stresses were mainly located in the drilled zone and around the hole. In the drilled hole was verified that the elements have been removed when the yield stress and

the plastic strain failure in the material were reached. Also, for the same time instant was verified that the stresses increase with the increases of feed-rate. The results are

acceptable, since for the same drilling time the depth is greater when higher feed speeds were used. Regarding the drill speed, once again the numerical results indicated that the increase of drill speed leads to an increase in the values of von-Mises stress distribution in the bone block.

4 CONCLUSIONS

Bone damage under penetration of the cutting tool has been extensively studied in animal models, human cadavers and synthetic materials. However, the inherent variation in mechanical and thermal properties of specimens taken from different bones, and from different animals of the same species, results in variations in the results subject to identical drilling conditions in repeated tests. Furthermore, the guideline of medical ethics can be one reason for the limitation of using animals or human cadavers in such research. Thus, it is desirable to develop effective computational models for the research of bone drilling process. Recently, numerical models are proving to be a successful alternative to complicated and practically unfeasible or unethical (human or animal) experiments. FE analysis can provide a good simulation of the dynamic interaction processes between the cutting tool and bone tissues.

In this study, experimental and numerical approaches were used to study the effect of drill speed and feed-rate on bone mechanical damage during the drilling process. A 3D dynamic finite element model was developed to simulate the drilling process. The bone behaviour was defined as an elastic-plastic material with kinematic isotropic hardening. The failure criterion was used to replicate the hole making process. Specifically, once the effective plastic strain in an element reached a specified critical value, the element was removed or eroded from the simulation. The numerical models can simulate the drilling process with several parameters. In addition, can to promote the damage determination in the material without the use of real biologic tissue. Through the models it was possible to

obtain the stresses distribution during bone drilling for different cutting parameters.

The following conclusions were reached from this study:

- The generated stresses in the bone block increase with the tool penetration and, consequently with increasing of hole depth.
- A drill bit with a higher drill speed and lower feed-rate leads to an increase of stresses and strains in the bone block.
- It was observed several stress propagations with different magnitudes during simulation. Specifically, the maximum stressed zones were located at the hole and near to this region, with less intensity with the remoteness of that location.
- The validated numerical model may offer the possibility to precisely measure the stress and strain amount during bone drilling, which may correlate with the degree or patterns of biological tissue injury.

5 ACKNOWLEDGEMENTS

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