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RESEARCH ON THE DESIGN AND MANUFACTURING OF A WRIST-HAND ORTHOSIS BY FUSED DEPOSITION MODELLING

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Abstract: *This article is focused on using the Finite Element Analysis (FEA) for assessing the mechanical strength of a wrist-hand orthosis manufactured by Fused Deposition Modelling (FDM) for a patient suffering from a fracture that needs stabilization. The finite element analysis has been performed by simulating a three-point bending test, which is the most relevant method for evaluating the strength of such medical devices. The numerical results have been used for examining the distribution of the von Mises equivalent stress for different bending loads, as well as for determining the critical load for which the maximum value of this stress reaches the yield strength of the base material. After validating its design by FEA, the wrist-hand orthosis has been manufactured by Fused Deposition Modelling.*
Key words: *Finite Element Analysis, three-point bending, wrist hand orthosis, Fused Deposition Modelling*

1. INTRODUCTION

The recent advances of 3D printing technologies and numerical simulation have brought important innovations in the field of orthopaedic rehabilitation [1]. The integrity and mechanical performances of wrist-hand orthoses made by Fused Deposition Modelling (FDM) have gained global recognition [2-3]. Due to the use of 3D printing (FDM in particular), medical devices have become more personalized, thus ensuring enhanced patient care and cost-effectiveness [4, 5]. 3D printing especially allows the creation of accurate and patient-specific orthoses at reduced costs, produced by using versatile, affordable thermoplastic materials. In this way, advanced medical care becomes accessible to more people [6-7]. The success of 3D printing in orthotics has emerged with structural and mechanical reliability.

Here, Finite Element Analysis (FEA) proves to be crucial in many cases. FEA allows the simulation of complex mechanical responses of models by simulating their behaviour when subjected to different types of loads [8]. By using FEA, critical aspects (e.g., stress distribution and deformation patterns) can be investigated. Such aspects play a key role in optimizing the orthosis design [9-10]. Moreover, FEA is helpful in developing lightweight yet robust designs ensuring patient’s comfort and orthotic use compliance, thereby enhancing the overall treatment effectiveness [11].

The orthosis shown in Fig. 1 has been customized based on a 3D scan of a patient’s hand who suffered an injury needing stabilization. The 3D model of the orthosis has been generated by the AutoMedPrint system developed at Poznan University of Technology. The AutoMedPrint system has been described in some previous studies [12,13].

For customizing the orthotic device to the patient's hand and forearm geometry, non-contact measurements have been performed using an optical 3D scanning system. In the next stage, the data resulted from measurements has been subjected to a series of transformations ensuring the transition from raw scans to a refined, seamless model of the limb. Finally, specific sets of points have been extracted from this model and passed as input to the CAD system.

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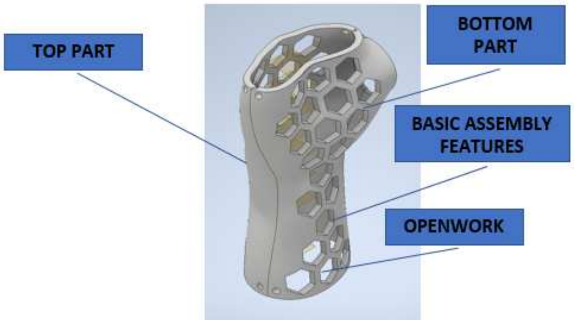

Fig. 1. 3D model of the wrist hand orthosis.

2. FINITE ELEMENT ANALYSIS PERFORMED FOR ASSESSING THE MECHANICAL STRENGTH OF THE WRIST-HAND ORTHOSIS

The FEA program SolidWorks Simulation has been used to assess the strength characteristics of the wrist-hand orthosis by simulating a three-point bending test. The principle of this test is shown in Figure 2. As one may notice, the lower and upper parts of the orthotic device are assembled and placed on a support block. A downward vertical force is then applied to the upper part of the orthosis. The area where this load is applied is marked as a red surface patch in Figure 2. The numerical simulation of the three-point bending test has been performed by gradually increasing the force from 0 to 125 N.

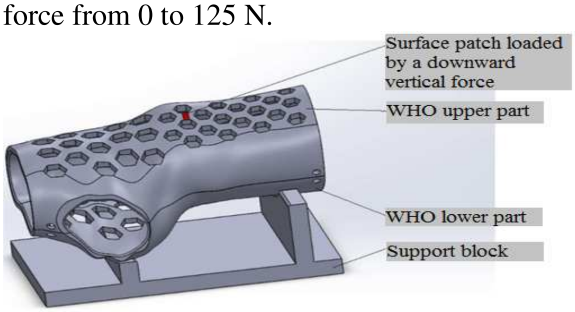

Fig. 2. Principle of the three-point bending test

The finite element model of the three-point bending test has been developed by considering that the top and bottom parts of the orthosis are made of ABS exhibiting isotropic linear elastic properties as defined by the material parameters listed in Table 1 and Figure 3. As for the support block (Fig. 2), this component of the finite element model has been considered as being a perfectly rigid body.

Table 1

Material parameters of ABS [14] – see also Figure 3

Density ρ	1070 kg/m^3
Elastic modulus E	1990 MPa
Poisson's ratio ν	0.365
Yield strength Y	31.2 MPa

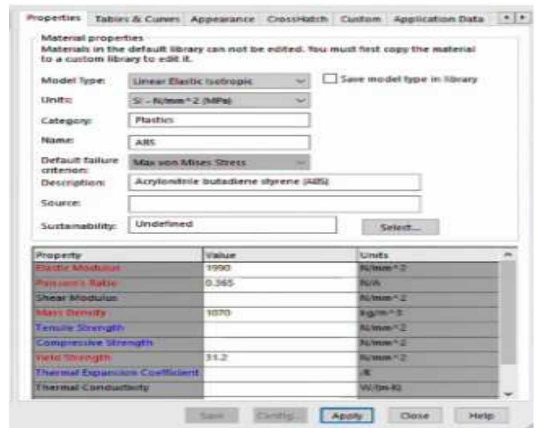

Fig. 3. Characteristics of the ABS material associated to the top and bottom parts of the orthosis during the preparation of the finite element model

The top and bottom parts of the orthosis have been considered as being bonded along their contact surfaces. The contact interaction between the lower part of the orthosis and the support block has been assumed to be of sliding type, its frictional component being neglected.

The finite element model of the three-point bending test (Fig. 4) has been prepared in the following sequence of steps:

a) Defining the support block as a perfectly rigid component of the finite element model

b) Assigning the ABS material characteristics listed in Table 1 to the top and bottom parts of the orthosis

c) Defining the frictionless sliding contact between the support block and the lower part of the orthosis

d) Defining the bonded contact between the top and bottom parts of the orthosis

e) Defining a kinematic constraint that fully restricts the motion of the support block on its lower surface

f) Defining a downward vertical unit force applied to the top part of the orthosis. The actual values of this force have been provided in step (h) by using the load case facility of the SOLIDWORKS Simulation program

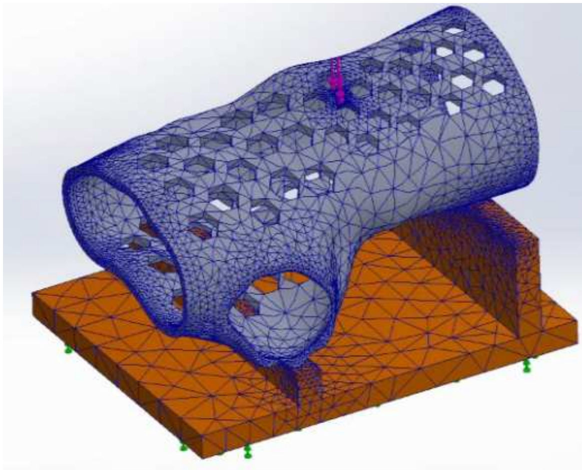

Fig. 4. Finite element model of the three-point bending test prepared with SOLIDWORKS Simulation

g) Specifying the average size of the finite elements and generating the mesh

h) Defining the actual values of the downward vertical force applied to the top part of the orthosis (Fig. 5): 25 N (load case 1), 50 N (load case 2), 75 N (load case 3), 100 N (load case 4), and 125 N (load case 5).

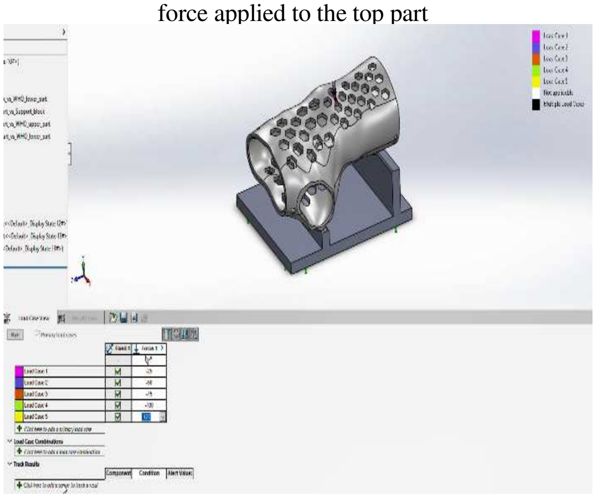

Fig. 5. Defining the actual values of the downward vertical force applied to the top part of the orthosis by using the load case facility of the SOLIDWORKS Simulation program

Figure 6 shows the most significant result of the finite element analysis namely, the distribution of the von Mises equivalent stress in the top and bottom parts of the orthosis as predicted by SOLIDWORKS Simulation for the fifth load case (testing force of 125 N).

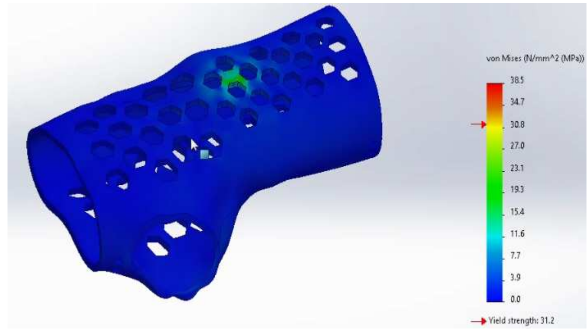

Fig. 6. Distribution of the von Mises equivalent stress within the top and bottom parts of the orthosis

Figure 7 illustrates the relationship between the maximum equivalent stress ($\sigma_{eq,max}$) and the testing force (F) associated to different load cases. The data plotted in the diagram have been extracted from the numerical results of the finite element analysis.

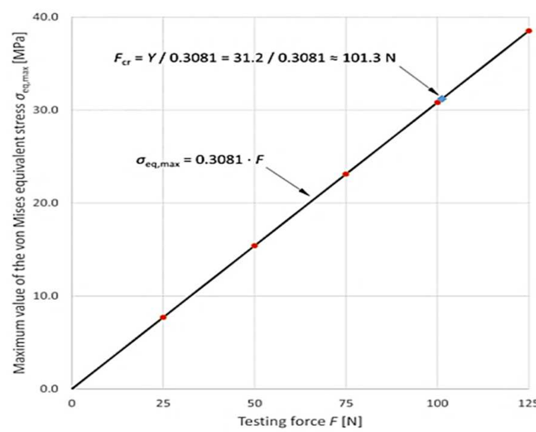

Fig. 7. Maximum values of the von Mises equivalent stress corresponding to various testing forces: red dots – numerical results provided by SOLIDWORKS Simulation; black path – approximation of the numerical results by a linear regression; blue diamond – testing force causing the failure of the wrist-hand orthosis

The diagram in Figure 7 allows formulating the following conclusions:

a) The mechanical response of the orthosis is well approximated by the linear regression $\sigma_{eq,max} = 0.3081 \cdot F$ (displayed as a black path in Figure 7).

b) This regression can be used to determine the testing force F_{cr} at which the maximum von Mises equivalent stress reaches the yield strength of the ABS material (31.2 MPa – see Table 1): $F_{cr} = 101.3$ N (represented by the blue diamond in Figure 7).

3. MANUFACTURING THE WRIST-HAND ORTHOSIS BY FDM

After the FEA validation, the 3D model of the wrist-hand orthosis has been converted to the STL format and transferred to the UltiMaker Cura software for being printed on an FDM equipment (Fig. 8).

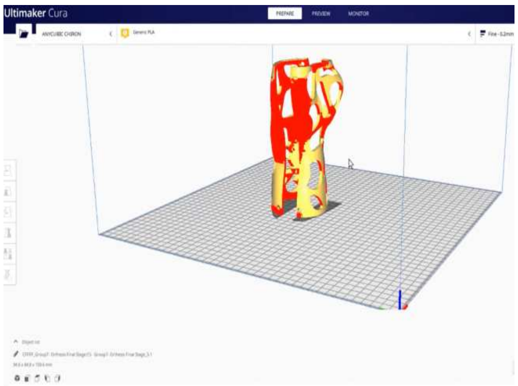

Fig. 8. 3D model of the wrist-hand orthosis loaded in the Cura software

The following parameters have been defined when preparing the 3D printing process with the UltiMaker Cura software:

- Base material: ABS
- Nozzle temperature: 250°C.
- Bed temperature: 100°C
- Printing speed: limited to 50 mm/s – in order to minimize the warping of the printed part
- Layer height: 0.2 mm
- Infill ratio: 30 %.

The wrist-hand orthosis has been manufactured using a Zortrax M200+ 3D printer (Fig. 9). After finishing the printing process and cooling the bed, the orthosis components have been detached from the building platform and extracted from the 3D printer (Fig.10).

Post-processing procedures have also been performed: removing support structures, polishing the orthosis components to eliminate sharp edges and rough surfaces, applying foam linings in specific areas to enhance the comfort of the patient wearing the orthosis, and incorporating mounting elements to securely fasten the orthosis components (plastic cable ties and Velcro straps – see Figure 11).

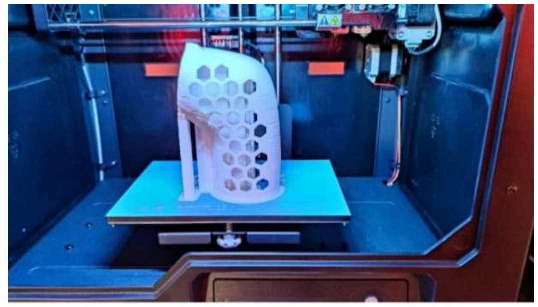

Fig. 9. Wrist-hand orthosis manufactured with the Zortrax M200+ 3D printer

Fig. 10. Wrist-hand orthosis manufactured by FDM

Fig. 11. Post-processing the wrist-hand orthosis manufactured by FDM

Finally, a 26-year-old patient suffering from an injury (fracture) of his right wrist has tested the fit and functionality of the orthosis manufactured by FDM (Fig. 12).

Fig. 12. Wrist-hand orthosis tested by a patient

4. CONCLUSIONS

The finite element analysis performed with SOLIDWORKS Simulation has allowed the evaluation of the mechanical strength of a wrist-hand orthosis by simulating a three-point bending test. Among the results provided by the FEA program, the most important has been the distributions of the von Mises equivalent stress in the orthosis components for different values of the testing force. By analyzing this data, the authors have noticed that the mechanical response of the orthosis is well approximated by a linear regression. This regression is a valuable tool that can be used to determine the critical testing force at which the maximum von Mises equivalent stress equals the yield strength of the ABS material.

After its validation by FEA, the wrist-hand orthosis has been manufactured using a Zortrax M200+ 3D printer. The orthosis has been tested by a 26-year-old patient suffering from a wrist fracture before being its clinical use.

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CERCETĂRI PRIVIND PROIECTAREA ŞI FABRICAȚIA UNEI ORTEZE PERSONALIZATE DE MÂNĂ PRIN DEPUNERE DE MATERIAL PLASTIC TOPIT

Rezumat: Această lucrare se concentrează asupra utilizării analizei cu elemente finite pentru evaluarea rezistenței mecanice a unei orteze de mână fabricate prin depunere de material topit (FDM) pentru un pacient suferind de o fractură care necesită stabilizare. Analiza cu elemente finite a fost realizată prin simularea unei încercări de încovoiere în trei puncte, aceasta fiind metoda cea mai relevantă pentru evaluarea caracteristicilor de rezistență ale unor asemenea dispozitive medicale. Rezultatele numerice au permis examinarea distribuției tensiunii echivalente von Mises pentru diferite nivele ale solicitării la încovoiere, dar și determinarea solicitării critice la care nivelul maxim al acestei tensiuni egalează limita de curgere a materialului de bază. După validarea proiectului său prin analiză cu elemente finite, orteza a fost fabricată prin procedeul FDM.

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