Advances in Science and Technology
Research Journal

Advances in Science and Technology Research Journal 2023, 17(3), 31–39
https://doi.org/10.12913/22998624/162998
ISSN 2299-8624, License CC-BY 4.0

Received: 2023.03.07
Accepted: 2023.05.10
Published: 2023.06.01

Analysis of Mechanical Properties of External Unilateral Fixation Device in the Case of Torque Load

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ABSTRACT

Analysis of mechanical properties of external unilateral fixation device „*Ultra X*", in the case of torque load, is presented in this paper. Fixation device is applied on lower leg in the case of unstable fracture. Computer aided design (CAD) model and finite element model (FEM) are developed according to the dimensions and material properties of real fixation device. In the next step principal stress and deformation analysis is performed in CATIA V5 software. During numerical analysis values of stresses at critical places are monitored and analyzed. In addition, values of displacements are measured on important places on fixation device and bone fracture. Using values of displacements at the place of bone fracture, stiffness of the fracture is calculated. The same methodology is used to calculate stiffness of the fixation device. Using obtained results, several conclusions about the mechanical properties of the fixation device "Ultra X" are formulated at the end of the paper.

Keywords: unilateral external fixation device, stiffness analysis, interfragmentary displacements, principal stresses.

INTRODUCTION

Purpose of external fixation devices is to enable basic function of broken bone as soon as possible by adding necessary strength and stiffness to the bone, and to give the bone its normal shape. Stability of bone fracture is especially important in the early stage of healing process. Mechanical properties of fixation device have a big influence on biomechanical properties of fracture. Also it effects osteotomies or pseudarthrosis during the healing process. In the case of biomechanical research of external fixation devices important factor is to define influence of design parameters on the device stability [1, 2]. Design parameters are dimensions and places and shape of device components. A lot of research about design parameters of different fixation devices are done in the past.

In addition, a lot of experimental research about mechanical properties of different fixation devices are carried out in the past. Vossoughi, et al. [3] carried out research about the influence of number of pins, number of trees and places of couplings on stiffness for Hofmann unilateral and uniplanar fixation device. Moroz, et all. [4] done comparison analysis of the stability for two different external fixation devices, Hofmann device and AO tubular fixation device for four different designs. Paley, et all. [5] also carried out experimental comparison analysis of biomechanical properties of Ilizar fixation device in comparison to other most common fixation devices. Simpson, et all. [6] carried out research about maximal values of axial forces between broken bone segments at the place of fracture for different patients and different fracture cases.

In the last decade, except experimental research, researchers start to use CAD modeling and numerical analysis for the analysis of mechanical properties of external fixation devices. Researchers like Radke, et all. [7], Meleddu, et all. [8], Oh, et all [9], and a lot of others developed numerical modes using FEM methods for biomechanical analysis of fixation devices. Using numerical analysis, it is possible to obtain values of displacements at the critical places and then to calculate stiffness of the device and stiffness of bone segments at the place of fracture. Watson, et all. [10] used FEM model and experimental testing to analyze influence of tightening force on the stiffness of Ilizar external fixation device.

Except mechanical properties, biomechanical research can give answers to the lot of questions regarding the success of the healing process and possible complications. It is well known that mechanical properties of external fixation device and bone fracture have an effect on the quality of callus formations, especially in the early stage of healing process. If the specific load is known, stiffness of the fixation device can be adjusted to allow necessary interfragmentary displacements during bone consolidation [11]. Influence of interfragmentary displacements on the healing process of bone can be better understood if places and directions of load and stiffness of external fixation device is well known. [12].

Goal of this paper is to analyze mechanical properties of external unilateral fixation device „Ultra X“ applied on the lower leg in the case of unstable fracture and in the case torque load. Design parameters which are taken in consideration are stiffness of the device, values of maximal von Mises stresses and displacements at critical places.

DEVELOPMENT OF CAD/FEM MODEL

During war periods more injured patients arrive in hospitals. These patients usually overreach hospital capacity and they need immediate medical care. This medical care is usually performed by young surgeons with little or no experience in the conditions which are less than ideal. In this ceases the question is which fixation technique needs to be used. External fixation is much simpler to implement because it has smaller amount of parts and it requires less surgeons work. One of the external fixation devices which was used by military during the gulf war (beginning of 1991) is “Ultra X” external unilateral fixation device manufactured by Howmedica company (Figure 1).

Parts of fixation devices are mostly manufactured using different types of metal materials (steel, aluminum, alloys, etc.), plastic materials, polymers or carbon fiber materials. Carbon fiber especially gain popularity in last few years. In the case of “Ultra X” fixation device, according to the data from the manufacturing company, tree of the device is manufactured using austenitic stainless steel X2CrNiMo17-12-2. Couplings and big and small spheres are manufactured using polymer material which have low values of strength, Young Modulus of elasticity, and density, but in the same time it has low value of specific weight and great shaping properties. Upper part of the coupling and head for screw tightening are manufactured using Polyvinyl chloride (popularly called PVC) which have high value of hardness and good mechanical properties in comparison to other polymers. Mechanical properties of PVC can be drastically reduced in the case of high temperatures. Big and small spheres are manufactured using Polybutylene (PB) polymer. PB polymer have similar properties as PVC, both of them can be manufactured using any type of thermal manufacturing process which gives endless possibilities for production of different shapes and sizes. Mechanical properties of basic parts of unilateral fixation device Ultra X are given in Table 1 [13]. For CAD and FEM model development of

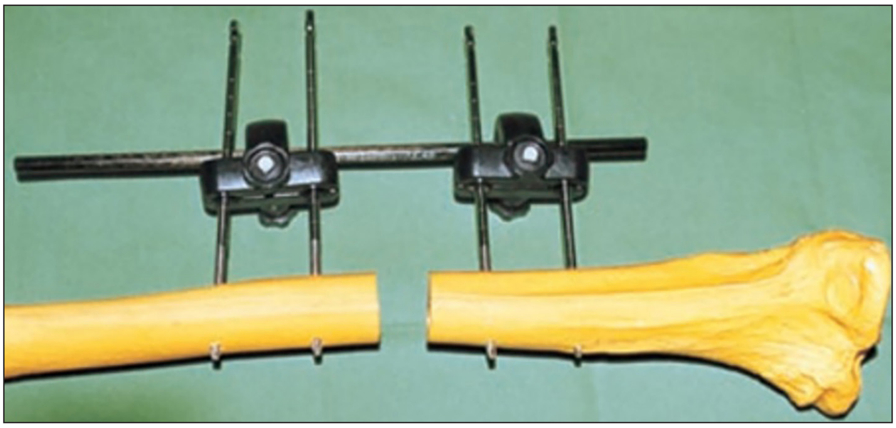

Figure 1. “Ultra X” external unilateral fixation device

Table 1. Mechanical properties of “Ultra X” fixation parts

Part name	Standard marks (EN)	Modulus of elasticity E (GPa)	Poisson coefficient υ	Density ρ(kg/m^3)	Yield strength σ_V(MPa)
Tree	X2CrNiMo17-12-2	230	0.29	8000	620
Spheres	>PB<	2.9	0.4	1290	-
Couplings	>PVC<	3.3	0.38	1380	0.2
Screws for couplings	X5CrNi18-10	193	0.29	7900	205
Half pins	X2CrNiMo18-14-3	196.4	0.3	8000	800

unilateral fixation device “Ultra X”, software package CATIA V5 was used. In the process of development of 3D CAD models of a device, first step is to develop all individual parts. In Part Design module of CATIA V5 software all individual parts are developed (tree, spheres, couplings, half pins and two parts of the bone, upper and lower part). In Assemble Design module of the same software all parts are assembled in one assembly and CAD model of fixation device is developed.

After development of CAD model of fixation device, in the next step FEM models of all components needs to be done in CATIA V5 software. Before FEM modeling in Generative Structural Analysis module, materials for all components must be applied. Materials for fixation device parts are applied according to Table 1 and materials for bone models are simulated as orthotropic material according to Table 2 [14, 15].

After material definition, next step is to make a discretization and chose type and size of finite elements. Finite elements are chosen in a form of linear (TE4) and parabolic (TE 10) tetrahedron. Linear tetrahedron is used for modeling of small and big spheres and parabolic tetrahedron is used for the rest of the parts. Next step is to define connections between components of fixation device. During assembly design process connection between all parts are defined. Fixed connection are defined between bone segment and half pins (Figure 2a). Contact constrains are defined between all other parts of fixation device (Figure 2b). After connection definition constrains must be applied to the model. Constrains are applied according to the Figure 3.

Table 2. Mechanical properties of bone models

Property	Value
Longitudinal modulus of elasticity	22900 MPa
Tangential modulus of elasticity	10500MPa
Normal modulus of elasticity	14200 MPa
Poisson coefficient in XY plane	0.29
Poisson coefficient in XZ plane	0.19
Poisson coefficient in YZ plane	0.31
Sliding modulus in XY plane	6480 MPa
Sliding modulus in XZ plane	6000 MPa
Sliding modulus in YZ plane	3700 MPa
Density	1850 kg/m^3

Final step, before analysis can be started, is to define loads. Tongue load is defined at the upper bone segment at the top flat surface. Axis of the torque is the axis of the bone segments. Except

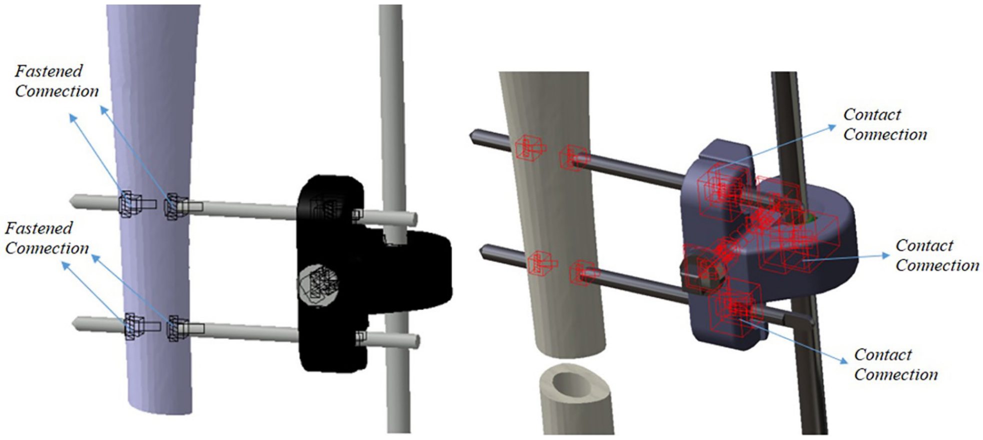

Figure 2. Definition of connections between components, (a) fix connection, (b) contact connection

torque definition, it is important to define cylindrical joint connection at the same place where torque is applied. Cylindrical joint connection enables only one rotation around bone axis (z-axis). At the bottom of the lower bone segment fix constrain is applied. At this place all translations and all rotations are constrained (Figure 4). According to the orthopedic suggestions from clinical practice and according to the other similar research, from other authors, value of torque is selected in the interval from 0 to 10 Nm [2, 16].

After definition of materials, connections, constrains and loads, numerical structural analysis using CATIA can be initiated. During structural analysis, values of generated principal and von Mises stresses are monitored. Values of equivalent one axis stress, also known as von Mises stress is usually used in solid mechanics. It is defined as [17, 18]:

$$\sigma_e = \sigma_{vm} = \sqrt{3J_2} = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]} \quad (1)$$

In addition to stress monitoring, displacements of point at the place of load are also monitored in x and y direction (Figure 5). Using values of this displacements stiffness of the device can be calculated as [19]:

$$C_u = \frac{M_u}{R} \quad (2)$$

where: M_u – value of torque (Nm), R – vector of resulted relative displacement at the place of load (mm).

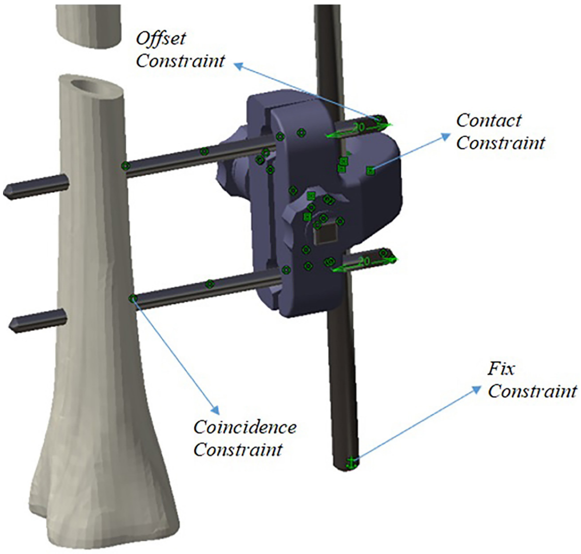

Figure 3. Constraints definition

It is well known that stiffness of the device is important but value of stiffness does not give direct information about movement in the area of bone fracture. It is important to observe values of relative displacements at the end of bone segments in the area of fracture. With a goal to calculate stiffness of the fracture, value of displacements in the x, y and z direction of two selected points at separate side of bone segments in the area of fracture are taken. Vector of resulted displacement (R) for these points have maximal values. Relative displacements ($r_{D(x)}$, $r_{D(y)}$, $r_{D(z)}$) of observed points at end planes of proximal (upper) and distal (lower) segment of bone model in x, y, and z direction are defined as: [20, 21]:

$$\begin{aligned} r_{D(x)} &= D_{p(x)} - D_{d(x)} \\ r_{D(y)} &= D_{p(y)} - D_{d(y)} \\ r_{D(z)} &= D_{p(z)} - D_{d(z)} \end{aligned} \quad (3)$$

Stiffness of the fracture is defined as relation between value of load and resulted relative displacement for observed points (Figure 6, detail A):

$$C_{pu} = \frac{M_u}{R} = \frac{M_u}{\sqrt{\left(r_{D(x)}\right)^2 + \left(r_{D(y)}\right)^2 + \left(r_{D(z)}\right)^2}} \quad (4)$$

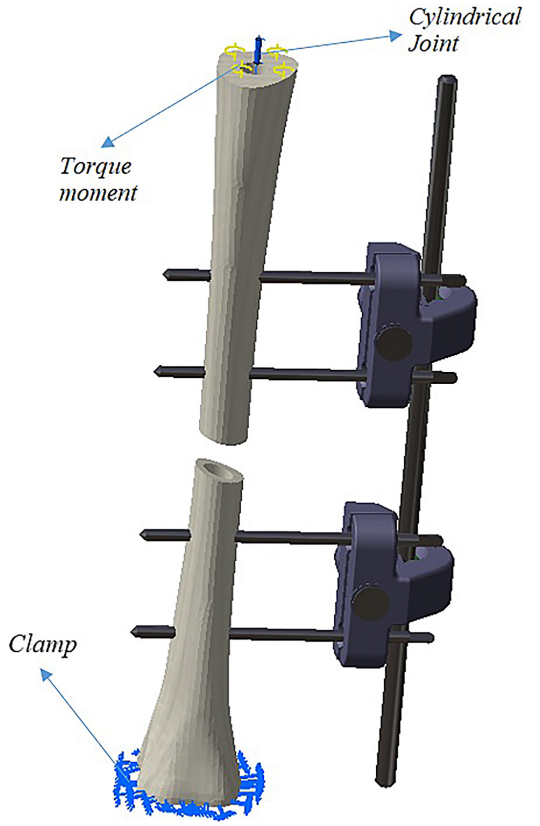

Figure 4. Loads definition

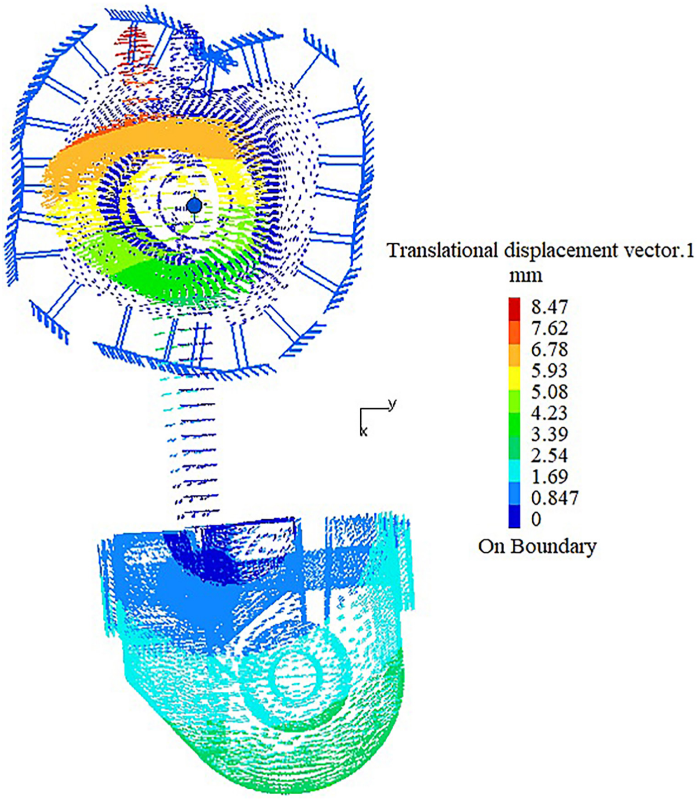

Figure 5. Vectors of displacements at the place of load for maximal torque value

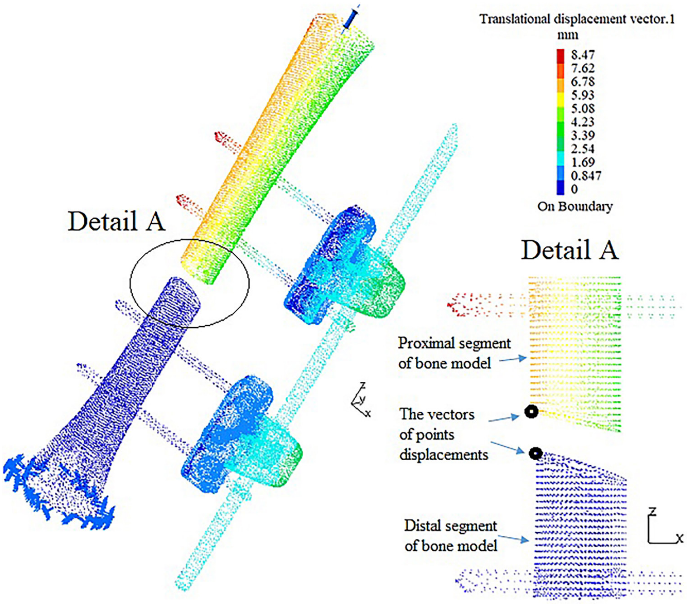

Figure 6. Displacement vectors of observed points for maximal torque load

Table 3. Values of displacements for maximal torque load (Mt=10Nm)

Displacements of proximal bone segment [mm]						Displacement of distal bone segment [mm]			Stiffness of the fracture [Nm/mm]	Stiffness of the fixation device [Nm/mm]
Place of loads			Place of fracture			Place of fracture				
x	y	z	$D_{p(x)}$	$D_{p(y)}$	$D_{p(z)}$	$D_{d(x)}$	$D_{d(y)}$	$D_{d(z)}$	C_{pu}	C_{u}
0.788	-6.93	0	0.457	-6.178	-0.004	0.001	-0.032	0.0001	1.6226	1.4327

RESULTS

Figure 5 shows vectors of points displacements for maximal torque load. Direction and intensity of displacement vector can be clearly seen. In addition, it is possible to determine components of displacement vectors (Table 3). Values of displacements for maximal torque load (Mt=10Nm) are given in Table 3.

Stress intensities are variable throughout the entire fixation device. They are mostly influenced by the shape and place of device components. From the aspect of von Mises stress critical places of the fixation device are *Schanz* screws and tree of the fixation device (Figure 7). Looking to the whole design it can be noticed that maximal von Mises stress are at first Schanz screw with the values of (Figure 8). In the case of fixation device tree, maximal *von* Mises stress is the middle of the tree (on the outside surface of the tree). It have value of (Figure 9). Intensity and direction of principal stresses are monitored at 4 critical places in the case of maximal torque load (Figure 10). Results are shown in Table 4.

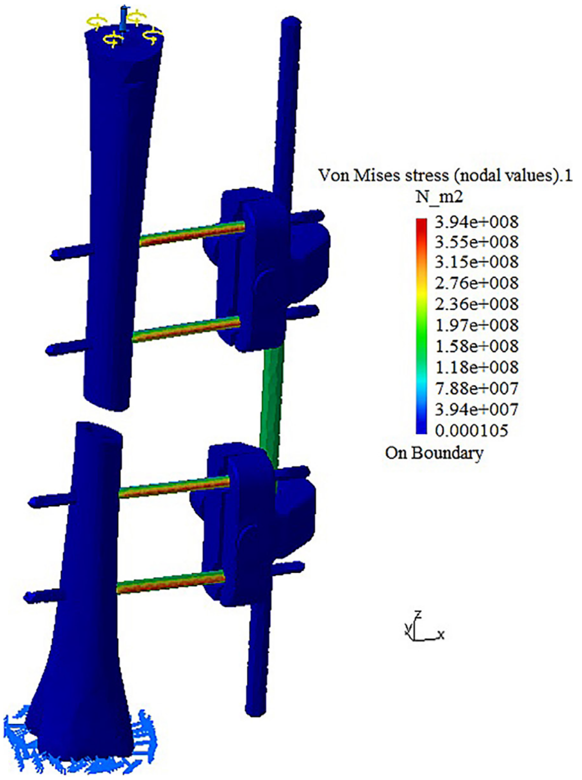

Figure 7. Distribution of von Mises stress in the case of torque load

DISCUSSION

Looking to the results of the numerical FEM analysis of Ultra X external fixation device, it can be noticed that maximal displacement is at the end of first Schanz screw and its value is 8,47 mm. (Figure 6). For the place of fracture maximal displacement is at the edge of proximal and distal segment of the bone (Figure 6, detail A), values of these displacements are given in Table 3. In the case of comparison of these results with the results from other research, for other fixation devices, it can be noticed that Ultra X fixation device have significantly bigger values of displacements, even 80% bigger displacements in comparison to the similar fixation devices for the same value of load [22].

Using values of displacements at the place of load, stiffness of the fixation device is calculated, in this case its value is 1.43 N/mm. In comparison to the other similar fixation devices stiffness is significantly smaller, even 9 do 10 times smaller in comparison to other fixation devices for the same load conditions. Same case is with the stiffness at the place of fracture, its value is 1.62 N/

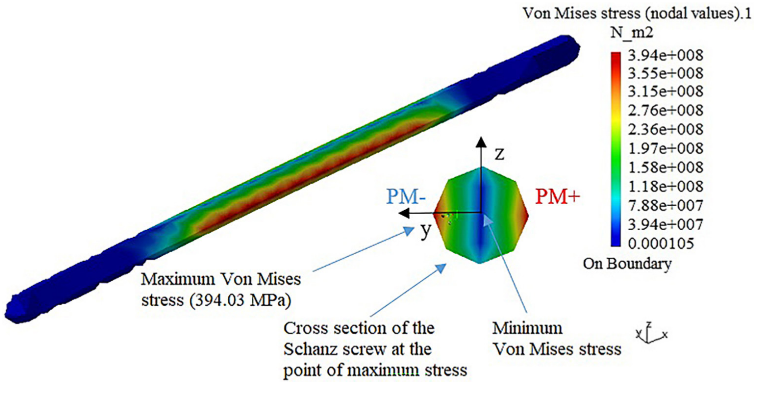

Figure 8. Schanz screw, distribution of von Mises stress

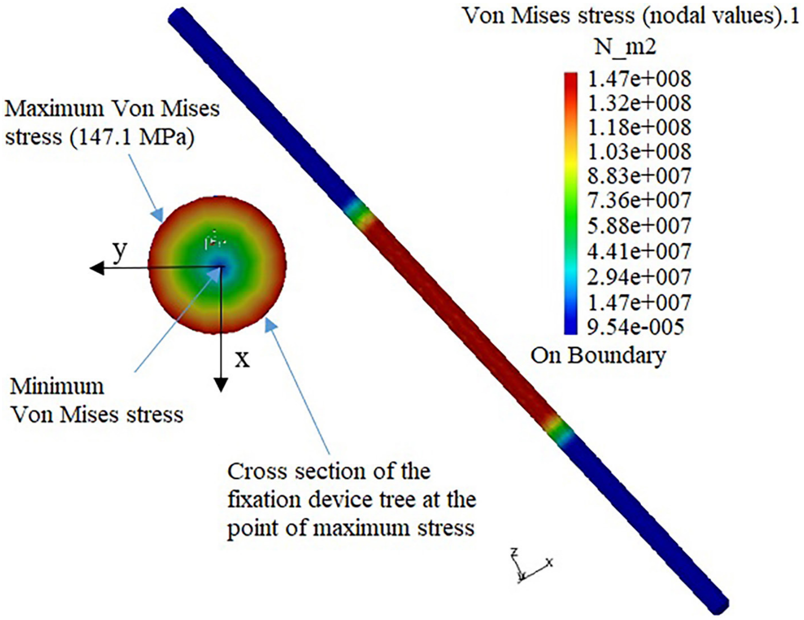

Figure 9. Fixation device tree, distribution of von Mises stress

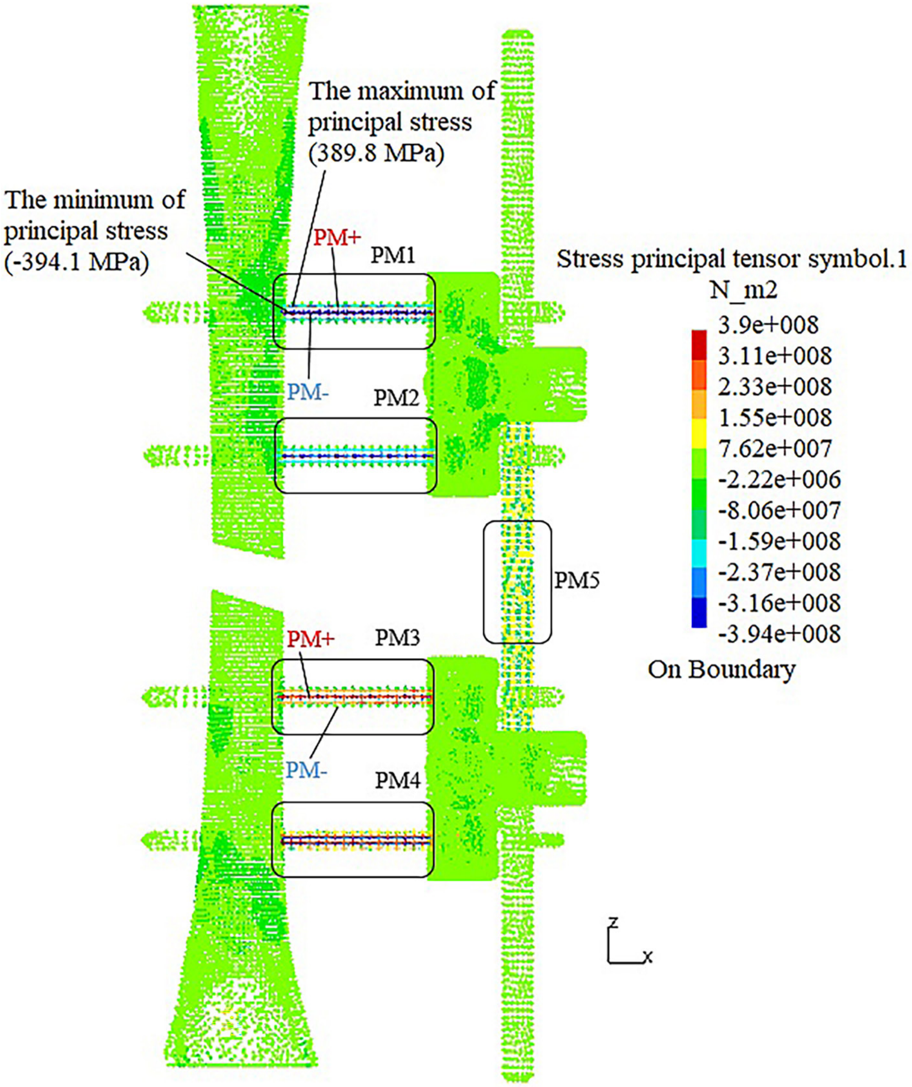

Figure 10. Principal stresses at critical places of the design

Table 4. Values of principal stresses for maximal torque load

Place on the fixation design	Values of principal stresses at critical places of the design [MPa]						Von Mises stresses at critical places [MPa]	
PM	PM+			PM-			PM+	PM-
-	σ_1	σ_2	σ_3	σ_1	σ_2	σ_3	σ_{vM}	σ_{vM}
1	389.8	3.493	1.584	-3.839	-4.483	-394.1	391.9	394.03
2	350.6	3.917	3.439	-3.454	-4.014	-353.2	353.7	354.5
3	356.9	3.564	3.383	-2.421	-3.453	-351.6	357.9	352.5
4	369.2	3.675	2.774	-4.173	-4.242	-365.4	370.8	366.3

mm, which is from 2,5 up to 12 times smaller in comparison to the similar devices for the same load conditions [22].

In the case of principal stresses, critical places are Schanz screws and tree of the device (Figure 10). Value of main positive principal stress, looking to the whole design, is , which represent global maximum. Maximal value of main principal negative stress (global minimum) is . Both of these stresses accrue at Schanz screws, more precisely at the place of connection between first Shanz screw and upper bone part. Value of both of these stresses are up to 25% bigger in comparison to the similar fixation devices for the same load conditions [22]. It is important to notice that values of all stresses which accrue on the design are lower than allowed stress for the material of the fixation device parts.

CONCLUSION

Mechanical properties of external fixation device have significant impact to the healing process of broken bone, especially in the area of fracture. To test mechanical properties of unilateral external fixation device FEM model was developed. Developed FEM model can be used for simulation of displacements in the area of fracture, for calculation of fracture and device stiffness and to test stresses at the critical places of the device.

Taking in consideration obtained results it can be concluded that Ultra X fixation device have worst mechanical properties in comparison to the rest of the similar external fixation devices for the same load conditions.

However, it should be taken into account that this system is designed and manufactured in the 90s of the last century, so it is not surprise that new fixation device have better mechanical properties. Most of the new fixation devices have more compact design and bigger value of stiffness which is achieved using new better materials, especially using composite materials which have great relation between stiffness, strength and weight.

REFERENCES

1. Mešić E., Avdić V., Pervan N. and Repčić N. Finite element analysis and experimental testing of stiffness of the Sarafix external fixator. Procedia Engineering 2015; 100: 1598–1607.
2. Mešić E., Pervan N., Repčić N., Muminović A. Research of influential constructional parameters on the stability of the fixator Sarafix. Annals of DAAAM for 2012 & Proceedings of the 23rd International DAAAM Symposium Intelligent Manufacturing & Automation: Focus on Sustainability, Editor: Katalinic B., Zadar, Croatia, October 24th–27th, 2012; 561–564.
3. Vossoughi, J., Youm, Y., Bosse, M., Burgess, A.R., Poka A. Structural Stiffness of the Hoffmann Simple Anterior Tibial External Fixation Frame, 5th Southern Biomedical Engineering Conference, Louisiana, October 20 and 21, 1986.
4. Moroz, T.K., Finlay, J.B., Rorabeck, C.H., Bourne R.B. Stability of the Original Hoffmann and AO Tubular External Fixation Devices, Medical & Biological Engineering & Computing 1988; 26: 271–276.
5. Paley, D., Fleming, B., Kristiansen, T., Pope M. A biomechanical analysis of the Ilizarov external fixator, Operativni principi metode Ilizarov, A.S.A.M.I. grupa, Zagreb 1995.
6. Simpson, A.H.R.W., Cunningham J.L., Kenwright J. The Forces which Develop in the Tissues During Leg Lenghtening”, A Clinical Study, Nuffield Othopaedic Centre, Oxford, England, British Editorial Society of Bone and Joint Surgery 1996.
7. Radke, H., Aron, D.N., Applewhite, A., Zhang G. Biomechanical Analysis of Unilateral External Skeletal Fixators Combined with IM-Pin and without IM-Pin Using Finite-Element Method, Veterinary Surgery 2006; 35: 15–23.
8. Meleddu, A., Barrault, S. andZysset P.K. A Rigor-

ous Method for Evaluation of the 6D Compliance of External Fixators, Biomechanics and Modeling in Mechanobiology, Springer-Verlag 2006; 6(256).

9. Oh, J.K., Lee, J.J., Jung, D.K., Kim, B.J., Oh, C.W. Hybrid External Fixation of Distal Tibial Fractures: New Strategy to Place Pins and Wires without Penetrating The Anterior Compartment, Arch Orthop Trauma Surg., Springer-Verlag 2004; 124: 542–546.
10. Watson, M.A., Mathias, K.J., Maffulli N. External Ring Fixators: an Overview, Proc Instn Mech Engrs 2000; 214(Part H): 459–470.
11. Behrens F. General Theory and Principles of External Fixation. Clin Orthop 1989; 241: 15–23.
12. Remiger, A.R. Mechanical Properties of the Pinless External Fixator on Human Tibiae, The British Journal of Accident Surgery Injury, 1992; 23(3): 28–43.
13. Bosse, M.J., Holmes, C., Vossoughi, J., Alter, D. Comparison of the Howmedica and Synthes military external fixation frames. J Orthop Trauma. 1994; 8(2): 119–126.
14. Dehankar R., Langde A.M. Finite element approach used on the human tibia: a study on spiral fractures. Journal of Long Term Effects of Medical Implants. 2009; 19(4): 313–321.
15. Pervan, N., Muminović, A.J., Mešić, E., Delić, M., Muratović, E. Analysis of Mechanical Stability for External Fixation Device in the Case of Anterior-Posterior Bending. Advances in Science and Technology Research Journal 2022; 16(3): 136–142.
16. Đozić Š., Shetty A.A., Hansen U., James K.D. Biomechanical Test Results of the Sarafix – External Fixator, Imperial College, London 2004.
17. Pervan N., Mesic E., Colic M. Stress analysis of external fixator based on stainless steel and composite material. International Journal of Mechanical Engineering & Technology 2017; 8(1): 189–199.
18. Mešić, E., Pervan, N., Muminović, A.J., Muminović, A., Čolić M. Development of Knowledge-Based Engineering System for Structural Size Optimization of External Fixation Device. Applied Sciences 2021; 11(22): 10775.
19. Mešić E., Muminović A., Čolić M., Petrović M., Pervan, N. Development and Experimental Verification of a Generative CAD/FEM Model of an External Fixation Device. Tehnicki glasnik-Technical Journal 2020; 14(1): 1–6.
20. Mesic E., Avdic V., Pervan, N. Numerical and experimental stress analysis of an external fixation system. Folia Medica Facultatis Medicinae Universitatis Saraeviensis 2015; 50(1): 52–58.
21. Mesic E., Avdic V., Pervan N., Muminovic, A. A new Proposal on Analysis of the Interfragmentary Displacements in the Fracture Gap. TEM Journal 2015; 4(3): 270–275.
22. Pervan N., Muminović A.J., Mešić E., Muratović E., Delić M. Analysis of the Mechanical Behaviour for the External Fixation Device under the Impact of Torque. Tehnicki glasnik-Technical Journal 2023; 17(1): 20–25.