Comparison of Numerical and Experimental Analysis of Plates Used in Treatment of Anterior Surface Deformity of Chest

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Abstract. The work discusses the results of numerical and experimental research of the plates for treatment of deformations of the frontal wall of chest. The conducted analyses included determination of: within numerical research, the state of displacement, strain and reduced stresses as well as reactions and moments of forces in supports, while within experimental research, the values of displacements at characteristic points of the system.

Keywords: Biomaterials, Biomechanical analysis, MES.

1 Introduction

Deformation of the anterior surface deformity of chest has been an important therapeutic problem for years. This practically concerns two pathologies, which is pectus excavatum and pectus carinatum. In 1949 Ravitch published a historically ground breaking operational technique of pectus excavatum consisting in resection of parasternal rib fragments, crosswise osteotomy of sternum and lifting of the sternum above the "funnel" as well as resection of xiphoid process [1]. For many years, operation with classical Ravitch's method has been a "golden standard" in case of therapy of patients with pectus excavatum. The principles of Ravitch's technique applied in the treatment have also been used in treatment of pectus carinatum deformation type. The technique similarly assumed subperiosteal resection of the deformed parasternal rib fragments with suturing and "gathering" in place of the removed ribs [2]. The most important problem following operations based on this technique was the recurrence of deformations and significant disfigurement in the form of flat chest [3]. In May 1997, during the session of American Paediatric Surgical Association, Donald Nuss presented for the first time the results of surgical treatment of chest necessitating no resection procedures of osteocartilaginous parts of the anterior surface of chest, and

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he published these data in 1998 [4]. This technique opens a new chapter in the history of surgical treatment of pectus excavatum; it proves that it is possible to perform a surgical procedure correcting this defect in a way less traumatic for patients. The introduction in recent years of new, less invasive surgical techniques using special correction plates, accelerated healing and rehabilitation processes. However, high costs of the plates and equipment used in western countries and manufactured by Walter Lorenzs Surgical, Jaksonville, FL practically made impossible propagation of this method in Poland to a degree corresponding to frequency of the defect occurrence [5]. The provisional preparation of plate stabilizers and surgical instruments by the Centre for Biomedical Engineering of Silesian University of Technology as well as implementation of their production at BHH Mikromed significantly reduces costs of surgical procedure. The plate of Polish production is 20 times cheaper and the instruments necessary for the procedure 6 times cheaper [6]. This resulted in the possibility of application of this less invasive technique in other centres in Poland [7,8,9].

The effects of the so far conducted stabilizations with Nuss' method are very positive in clinical evaluation. However, a tendency to the plate rotation has been observed in some cases, which was temporarily corrected with additional support sutures, but caused destabilization and pains. Nonetheless, current analyses of clinical experiments are very encouraging with regard to design of a new generation plate of diverse reinforcement and geometry state and a new fastening way preventing loosening of the plate and its rotation, which in consequence shall create new possibilities of correction of the anterior surface of chest in a wider population of patients. This will undoubtedly increase post-operative comfort in children as well as elderly patients, ensuring proper correction of the defect [10].

Computer calculation methods commonly used in biomechanics contribute to quicker elaboration and implementation into clinical practise of new, refined surgical instruments and implants improving treatment quality and patient's comfort during their use. Biomechanical systems are constructed on the basis of physical and mathematical models, while finite element method allows for determination of displacement, strain and stress state under conditions similar to the real ones [11,12,13,14,15,16].

The obtained results constitute the initial point of a subsequent stage which is actual making of an implant. They form the basis for optimization of structural characteristics of the individual elements of stabilizing system as well as selection of suitable mechanical properties of biomaterial [17].

The next stage includes experimental research constituting verification of the obtained results of numerical analyses. It is necessary to prepare a research post reflecting conditions of the investigated implant functions to the most possible degree of accuracy. It is also necessary to make the actual implant intended for clinical application, which will be subject to experimental research [18,19,20,21,22].

Comparison of the results obtained in both research methods allows for verification of the proposed numerical method giving indications for its optimization.

It is also possible to improve the applied technique of experimental research on this basis and allow for extension and adaptation of the post in order to more accurately simulate function of the implant under real conditions [22].

2 Materials and Methods

The work presents the results of numerical and experimental research of a new solution of the plates for treatment of anterior surface deformity of chest. Numerical research allowed for optimization of structural characteristics of the plate, which was subject to experiments following its elaboration.

A numerical model as well as the post for experiments on the investigated implant was prepared in order to conduct comparative analysis of both methods.

2.1 Finite Element Method Analysis

A geometrical model of the plate, bars and screws prepared on the basis of BHH Mikromed documentation with Inventor software was used for numerical analysis. Next, the models were used for construction of plate - bars - screws system with Ansys - Workbench software. The plate of 340x11x2.5 mm was subject to testing. The following material properties corresponding to Cr-Ni-Mo steel were assumed for the analysis [23]:

- E $= 1.93 \cdot 10^5$ MPa,
- Poisson ratio $\nu = 0.31$,
- $R_{p0,2} = 690$ MPa,
- $R_m = 1200$ MPa.

A geometrical model of the analyzed plate - bars - blocking screws system considering recommendations of surgical technique was presented in figure 1.

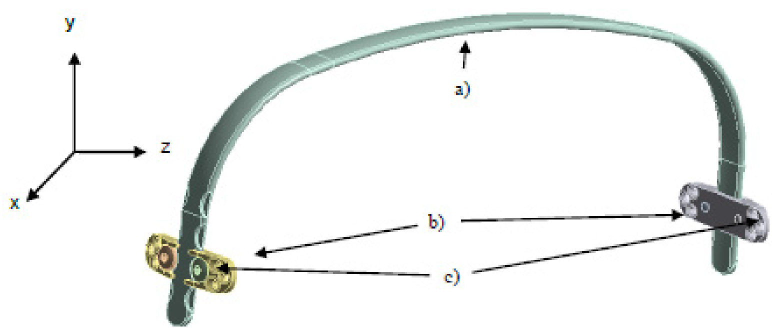

Fig. 1. Geometrical model of the system: plate (a), bars (b), locking screws(c)

The nets of finite elements, presented in figure 2, were generated basing on geometrical models. The finite element of SOLID187 type, used for analysis of spatial bodies was used for discretization of the model.

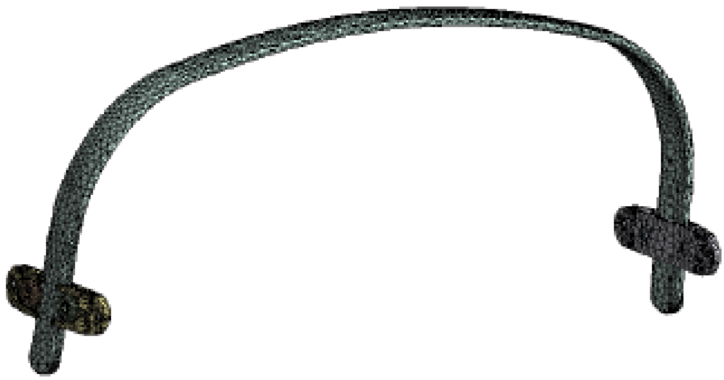

Fig. 2. Discrete model of the system. Finite element - SOLID187

The state of displacement, strain and stress in the elements of the system and reaction in the supports of plate - bar - screws system was determined during research. In order to conduct calculations it was necessary to determine and assign initial and boundary conditions reproducing phenomena occurring in the real system. The following assumptions were adopted for the analysis:

– at the bar location (points B and C - Fig. 3) all degrees of freedom in the nodes placed on the pane have been taken away which didn't allow for displacement of the plates and simulated the method of fastening of the bars to ribs,
– contacts have been installed between the plates, bars and screws, allowing for analysis of mutual influence of these elements. All slacks present in the system have been disregarded considering the real object,
– calculations for loading force F (point A - Fig. 3) have been conducted in 5 steps - from 250 N up to 1200 N at the intervals of 250 N.

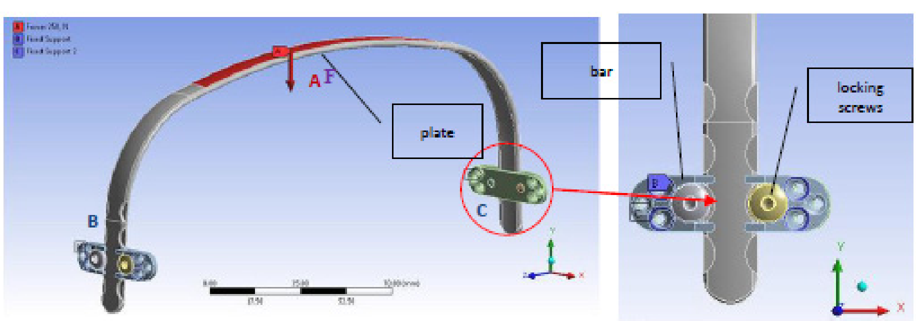

Fig. 3. Geometrical model of the system and schematic presentation of the boundary conditions used in numerical analysis: point A- loading force F, points B and C- the point of attaching fixed support

Strain and stress obtained as a result of the conducted numerical analysis are the values reduced according to Huber - Mises - Hencky hypothesis.

2.2 Biomechanical Analysis

The experimental analysis was performed on the two plates - Fig. 4a, of Cr-Ni-Mo steel for treatment of chest deformations marked as:

- Plate no 1, of 16 x 2.5 x 340 mm dimensions - rigidly fastened,
- Plate no 2, of 16 x 2.5 x 340 mm dimensions - one movable support simulating chest movements during breathing.

The way of the plate bending depends on anthropomorphic characteristics of the patient. For this reason, it is fitted individually for every patient, so that when the plate is put into place according to surgical technique the chest would be characterized by a correct position. Considering that each treated, deformed chest has a different geometry, the plates of various bending curvatures are obtained following the final shaping, which may result in obtaining unique values of forces and displacements in case of the plates intended for different patients. Therefore, in order to simulate a correct stabilization of the deformed chest, the plates had been properly bent with specialist surgical instruments - Fig. 4b, according to anatomical curvature before embarking on the research.

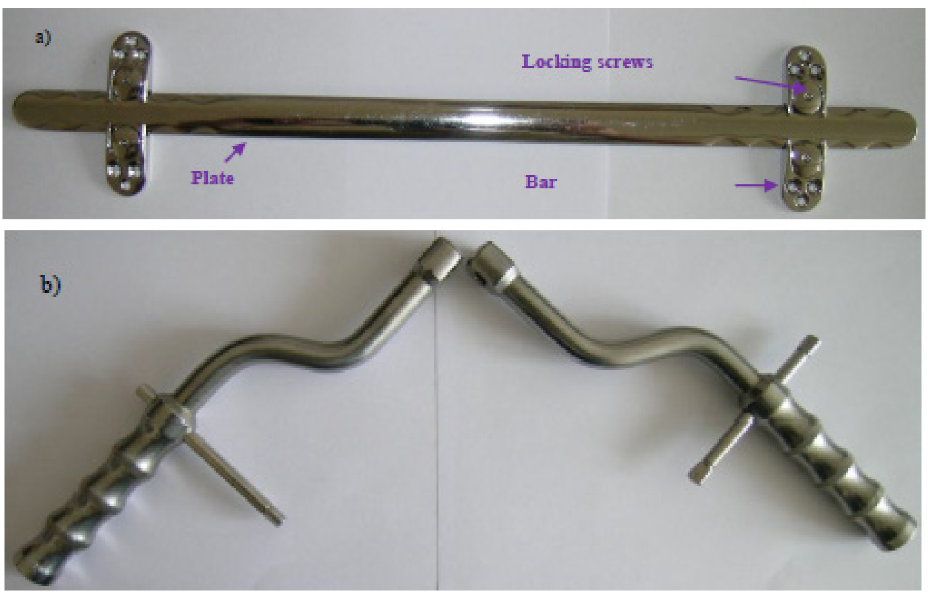

Fig. 4. The construction of the plate stabilizer - a), bender - b)

The tests were conducted with universal testing machine manufactured by MTS Insight. The properly prepared plates were fixed at the specially designed experimental post, which allowed for various methods of the plate fastening - using permanent supports (with little possibility of displacement of the lateral part of the plate during loading resulting from the structure flexibility) - Fig. 5a as well as using movable support (assuming limitation of displacement to a maximum of 10 mm on one side) - Fig. 5b. The plates were fastened to a newly designed bar with surgical wire of 1.2 mm diameter, according to surgical technique. Measurements of loading force F and the values of displacements in the direction of "x" axis read from Sensors 1 and 2, were conducted for the values of axial displacements from z = 1 mm to z = 10 mm at every 1 mm.

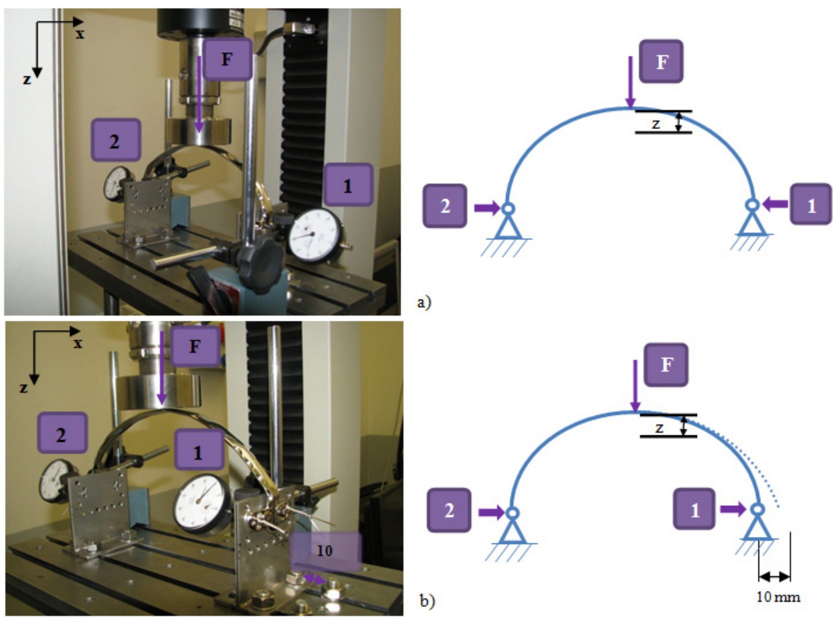

Fig. 5. Research stand, fixing with the use of support: a) fixed b) one mobile support

3 Results

3.1 Results of Numerical Analysis

The obtained values of displacement, strain and reduced stresses as well as the values of reactions and moments in the bars have been collected in table 1 and presented in figure 6a and b.

The analysis of the obtained results demonstrated that a maximal load, which in case of Cr-Ni-Mo steel doesn't cause exceeding of the assumed conventional plasticity limit $R_{p0.2}$ = 690 MPa is 300 N. The reduced displacement corresponding to this load is 2 mm, reaction value in the supports is R = 250 N, while reaction moment M = 4250 N mm - Fig. 6a and b.

Table 1. The results of the numerical analysis of the system plate - bars - locking screws

step	Loading force, F	Displacements, l	von Misses strains, ε	von Misses stresses, σ	Reaction in support, R	Moment reaction in supports, M
	N	mm	mm/mm	MPa	N	N·mm
1	250	1.700	0.002	461.110	208.070	3452.400
2	500	3.401	0.004	746.500	416.130	6902.700
3	750	5.105	0.004	795.040	624.020	10343.000
4	1000	7.030	0.005	891.390	827.660	13556.000
5	1250	11.323	0.005	953.450	1026.800	16711.000

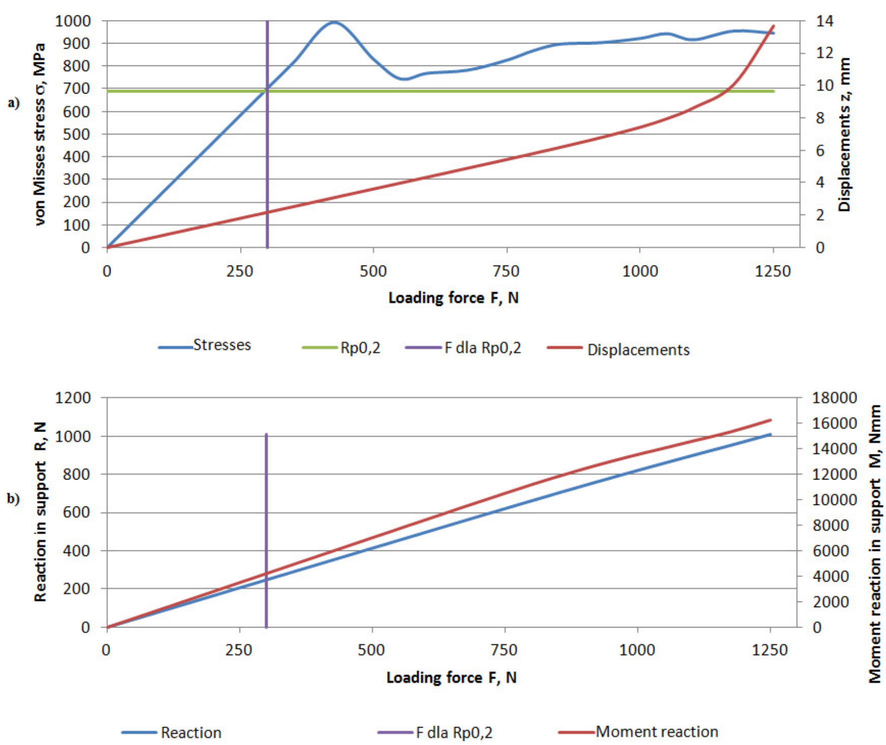

Fig. 6. Graphical representation of obtained results: a) reduced stresses and displacement in the function of loading force, b) reactions and moments in support in the function of loading force

The areas especially prone to damage were located in the place of force application and especially in the place of bars' fixing to the plates with blocking screws - Fig. 7a, b and c. Also, the obtained values of reactions and moments in the place of bars' fastening to ribs, indicate at the possibility of damage to bone structure in case of strong forces influencing the plate.

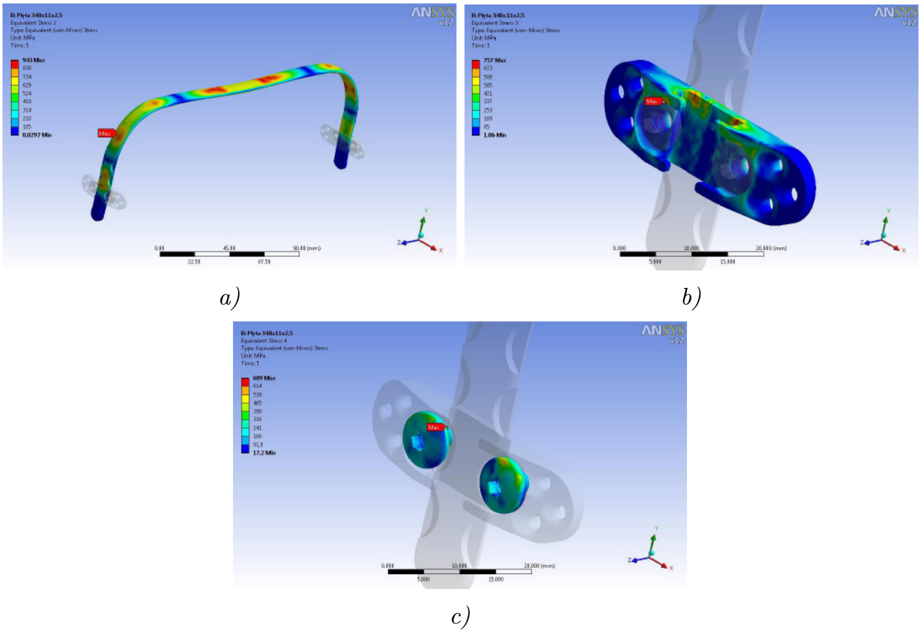

Fig. 7. Sample scheme of von Misses stresses in the elements of the system plates - bars - locking screws for loading force F=1250N: a) plate, b) bar, c) locking screws

3.2 Results of Biomechanical Analysis

The results of the experiments for two analysed cases (Plate 1 - permanent supports, Plate 2 - movable supports) were presented in tables 2 and 3 as well as in figures 8 and 9.

Table 2. The values of the force F and displacement "x" registered at the axial displacement values "z"- from 1mm to 10mm (Plate 1)

No.	Displacements, mm	Force, N	Sensor 1, mm	Sensor 2, mm
1	1	45	0.140	-0.050
2	2	80	0.190	-0.100
3	3	111	0.230	-0.160
4	4	180	0.350	-0.220
5	5	270	0.520	-0.285
6	6	355	0.670	-0.330
7	7	440	0.810	-0.370
8	8	510	0.950	-0.330
9	9	580	1.120	-0.520
10	10	640	1.270	-0.630

Table 3. The values of the force F and displacement "x" registered at the axial displacement values "z"- from 1mm to 10mm (Plate 2)

No.	Displacements, mm	Force, N	Sensor 1, mm	Sensor 2, mm
1	1	12	0.490	-0.020
2	2	17	0.240	-0.050
3	3	27	0.430	-0.090
4	4	55	0.920	-0.130
5	5	99	2.180	-0.180
6	6	143	3.300	-0.230
7	7	188	4.450	-0.260
8	8	226	5.600	-0.290
9	9	266	6.800	-0.320
10	10	303	7.950	-0.360

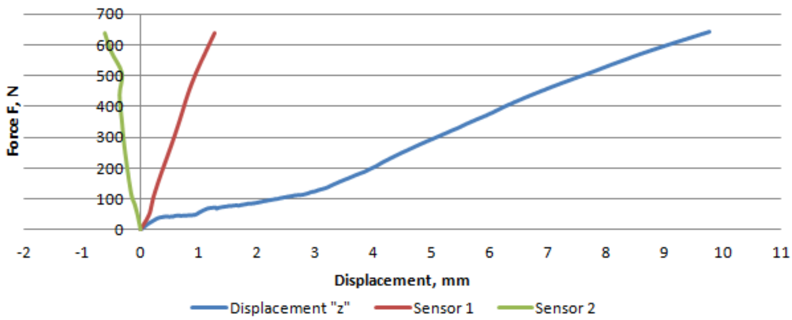

Fig. 8. The diagram of the dependence of the values of the displacements in axis "x" and "z" on the F force - fixed support

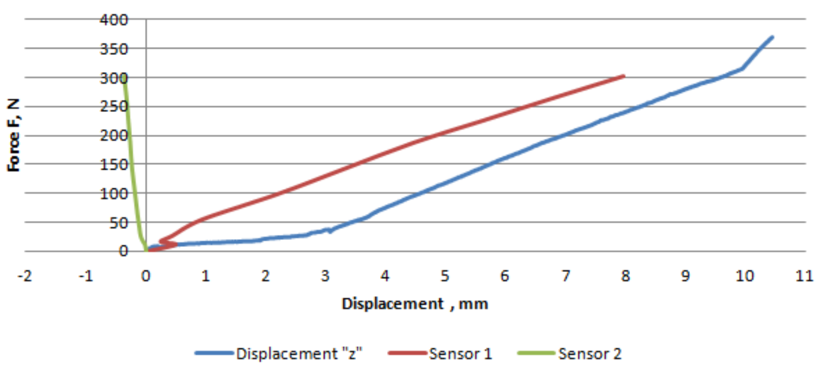

Fig. 9. The diagram of the dependence of the values of the displacements in axis "x" and "z" on the F force - mobile support

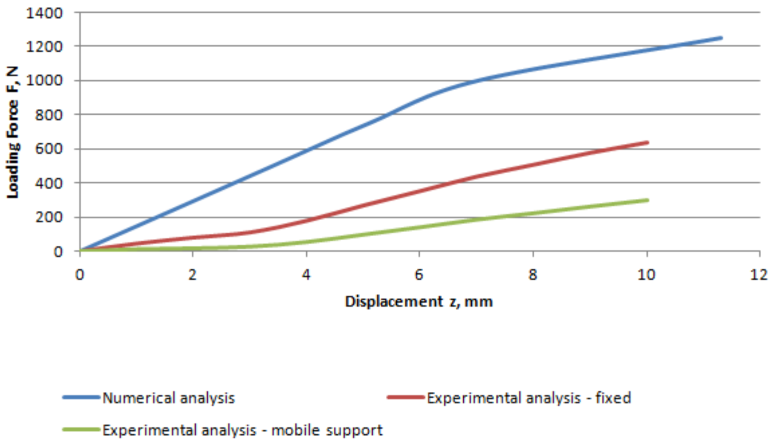

Fig. 10. Comparasion of results set in numerical and experimental analysis

4 Conclusion

The Authors conducted investigation of chest rigidity in children of school age (7-9 years) and demonstrated that maximal bending not causing pains fluctuates within a range of z = 10 mm to z = 20 mm, while the forces resulting in such bending were up to 100 N [17,24].

Loading of the system with force up to 1250 N value was simulated during the first stage of the work. Assumption of such maximal force was intended to indicate places exposed to permanent damage and the possibility of the whole system destabilization. Simultaneously the analysis of the obtained results demonstrated that loading with force up to 250 N did not result in permanent deformation of the system elements, while indicating at its high rigidity resulting from low value of the plate displacement z = 1.7 mm in comparison to the values obtained during chest rigidity measurements in children.

Measurements of loading force F and displacement values in the direction of "x" axis read from Sensors 1 and 2 were performed from 1 mm to 10 mm with interval of 1 mm during the second stage of the experiment. It was demonstrated on the basis of the conducted research that in case of maximal value of axial displacement z = 10, axial forces F are obtained respectively for:

- Plate no 1, F = 640 N while assuming rigid supports,
- Plate no 2, F = 303 N while assuming one movable support.

It was demonstrated basing on the observation of the plates following tests, that the method of fastening with surgical wires of 1.2 mm diameter ensured a proper stabilization of the system. The wires were not damaged and the fastening did not become slack. No plate rotation during the experiment was observed, which happened in clinical practice in case of stabilization with plates without bars with blocking screws. Additionally, it could be stated that in case of the assumed loading way, no damage of the fastening elements (plate bar, blocking screws) has been observed as well as no shifting of the plate in the bar.

The results obtained during numerical analysis were strongly influenced by the assumed boundary conditions. In a real object, the individual cooperating elements are fixed together in the way ensuring proper slack, and the whole structure is prone to deformations. There were no slacks assumed in mathematical model, and all elements were rigidly fixed together with possible contact. This caused rising of the obtained strain and stress and reaction force values in supports while simultaneously limiting the possibility of the plate displacement - Fig. 10. Moreover, the plate fastening to ribs under clinical conditions is flexible, made with surgical wire ensuring proper connection with bone.

It should be stated while summarizing that the presented comparative analysis of numerical and experimental research of the plates for treatment of chest deformations demonstrated, that numerical research results are burdened with error resulting from application of boundary conditions, which inaccurately simulate the real ones. That is why it was necessary to conduct experimental verification test under conditions simulating the implant function during patient's convalescence.

Considering the discussed limitations, it is necessary to conduct additional experiments taking osseous structures into account. In order to do it the plate will be implanted in the pig's chest with clinical recommendations and surgical technique. Next, displacement characteristics of plate stabilizer - porcine chest system will be determined with a universal testing machine. The obtained results will fully allow for characterization of the proposed new solution and optimization of geometry in order to select the proper rigidity of the tested implant.

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