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STRUCTURAL ANALYSIS OF MAIN FIXATION ELEMENTS OF THE APPARATUS FOR EXTERNAL OSTEOSYNTHESIS

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Abstract. In order to determine the degree of osteosynthesis stability, four basic fixation systems can be identified depending upon the correlation of the fixator and bone fragments. The first level corresponds to fixator–bone connection and determines the element which is directly connected to a bone. The second level – intermediate element which specifies the space between the bone and the supporting part of the fixator. Level 3 includes connections and joints between different parts of the apparatus. The fourth level unifies all the apparatus parts defining bone-to-bone fixation through the fixator. This work reviews the main methods and approaches based on structural mechanics' principles that can be used to construct the first-fixation-level (fixator–bone level). These methods can be applied to select the components of the external fixation device to provide the required stiffness and strength of the apparatus. The paper provides calculation schemes and constitutive equations to calculate stress-strain state of the apparatus elements to provide its effective attachment to the bone. This paper includes graphs and tables for selecting external fixator elements elaborated as the result of calculations. In addition, it determines deformations of the components if they are under loading condition.

Key words: external fixation of fractures, Illysarov's apparatus, strength, rigidity, deformations, transosseous osteosynthesis.

INTRODUCTION

Nowadays, there are plenty of research studies dedicated to numerical simulation of external osteosynthesis apparatus stress-strain state as well as the works devoted to the identification of Illizarov apparatus stiffness and strength by using finite element method [2, 4, 5, 6, 7, 9, 15]. This method (finite element method) is also used to produce new construction schemes for interbone osteosynthesis [1, 8]. Nevertheless, finite element method is just one of the methods to solve the problems of structural mechanics and undoubtedly, is not "panacea" since finite element method has a number of shortcomings that hinder its wide application in clinical practice. The main shortcomings behind this method are the requirement to the qualification of the specialists in the fields of solid and structural mechanics along with the complexity to create a numerical model that would ensure satisfactory degree of accuracy. At the same time, the existing works dedicated to numerical simulation of transosseous osteosynthesis by the use of finite element method are usually limited to particular apparatus constructions and do not provide general recommendation for a new apparatus design accounting for the weight, age and bone condition of the patient.

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One of the few studies representing a complex experimental and theoretical analysis of the apparatus construction is [11], where the author provides practical guidelines towards constructive schemes according to the weight and age of a patient. This work covers the problem of the Illizarov apparatus stiffness, although its strength properties are not analyzed.

In the present work, the stiffness and strength of the first fixation level elements, which ensure the apparatus–bone connection of the osteosynthesis apparatus are studied. These results have the recommendations on the practical selection of fixator–bone elements, such as Schanz pins and needles, depending on the weight and bone tissue of the patient. The elements redistributing the loading (2 and 3 levels), such as vertical bars and rings (semicircles) are not studied, as their stress-strain state hugely depends not only on the loading applied on the apparatus, but also on its structural scheme, which is beyond the scope of this research and can be considered as a future prospective of the present work.

MAIN DESIGNATIONS AND DEFINITIONS

External bone fixation apparatus for transosseous osteosynthesis may be divided into two main part: receiving the loading from the bone part (I) and part transferring the loading to another bone part (II). Both parts are located on different sides of a fracture. The first part (I) is located on the upper zone of a fracture and receives the loading while the limbs move. The second part (II) is located on the other side of the fraction line and respectively transfers the stress on the other part of the limb below the fracture.

In the case of two-lever fractures [10] when each fracture is fixated by two levels of rings (Fig. 1), the part of the apparatus above the fracture including two ring levels and the elements ensuring apparatus–bone connection corresponds to the first part (I) (Fig. 2). Whereas the two lower ring levels form the second part of the apparatus (II), which transfer the loading to the limb part below the fracture (Fig. 2). This division of the apparatus into 2 parts is needed for accurate simplification of internal forces calculation in the elements of the apparatus and to provide recommendations to orthopedic surgeons so that they might select the best fixator layouts.

Furthermore, the middle level of vertical bars located on the fracture level (Fig. 1) may be specified as a separate part of the apparatus because it unifies the parts I and II and transfer the loading between these two parts (transferring part). Thus, the assessment of stress and strain in the external bone fixation apparatus can be performed partially by the following steps:

- analysis of the I apparatus part;
- analysis of the II apparatus part;
- analysis of the transferring part.

Transferring part is not considered in this work. Meanwhile, the loading upon the elements of (I) and (II) parts are assumed to be identical. This quite evidently follows from the apparatus equilibrium condition.

Additionally, it is important to determine and underline the concepts of stiffness and strength of the apparatus. This is related to the fact that apparatus configuration attached to a bone with Schanz pins provides higher stiffness [11], however, its strength is lower than the one of the classic Illizarov construction using the spokes to connect to a bone. Thus, the design of the apparatus for the transosseous osteosynthesis including the method of its connection to a bone for a specific fracture should rely on:

- required stiffness of apparatus;
- required strength of apparatus.

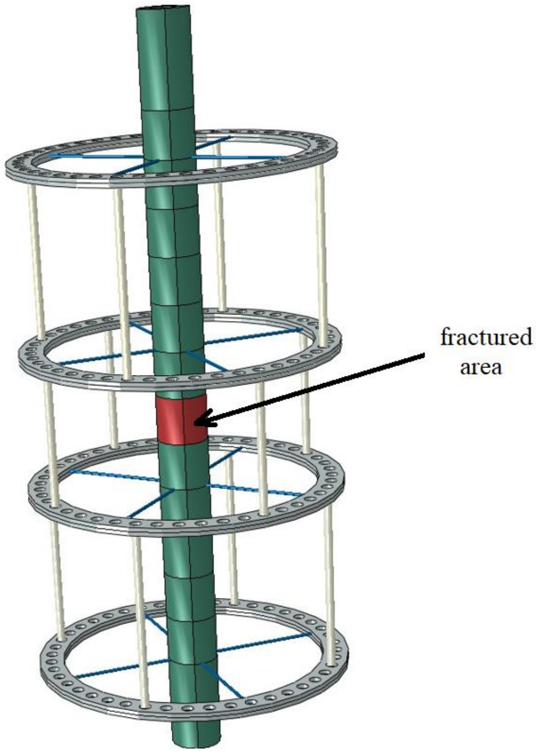


Fig. 1. The scheme of the Illizarov apparatus attached to a bone. Two upper ring levels correspond to the first part of the apparatus which receives loading; two lower ring levels correspond to the second part of the apparatus transferring pressure on lower part of the limb

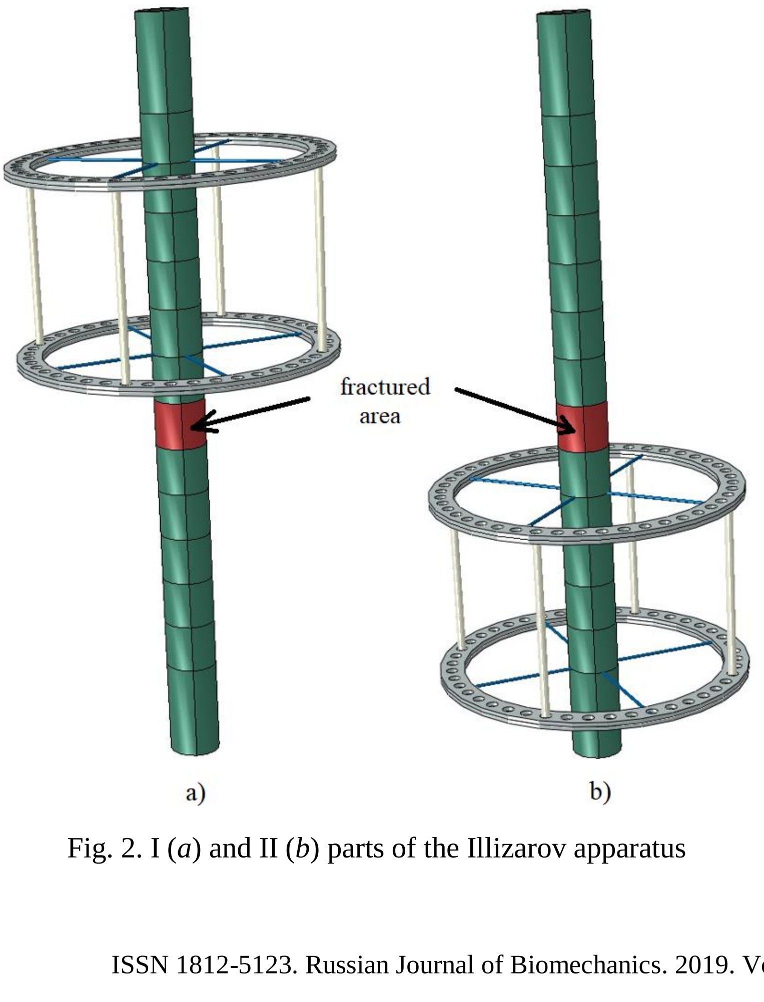


Fig. 2. I (*a*) and II (*b*) parts of the Illizarov apparatus

The first criterion corresponds to the maximum force value that can be applied to the apparatus during the process of the treatment. This can be produced by controlling the internal forces in the fixator elements. Limit stress value in the apparatus elements should be determined according to one of the strength theories [3, 13]. The methods provided in this works are based on the energy strength theory.

This theory states that while equivalent stress in the apparatus elements (3) do not exceed material yield stress (Fig. 3), the damage does not take place. This criterion gives an appropriate degree of precision for steel like material and allow us to determine plastic yielding (in this work the apparatus material is steel 17X18H9 according to Russian standards). It is worth noting that the destruction criteria (plastic yielding) for the elements made of other materials can differ from the considered one.

The second criterion determining the limits upon the value of deformation (strain) in the area of fracture. As there are no recommendations and works towards desirable value of strain or displacement in the fracture zone, the present paper provides strains and displacements in spokes and Shanz pins as contour plot and tables according to the loading value and element properties. Then, these results should be used by an orthopedic surgeon to design the most appropriate apparatus construction and control the deformation in the fracture zone.

BASIC FORCES THAT APPEAR IN THE APPARATUS ELEMENTS

In the following, it is important to introduce principal internal forces that take place in the apparatus elements and are used to connect the apparatus to bones (spokes and Schanz pins). These elements are analyzed in the framework of beam theory, according to which in cross- sections of the apparatus elements the following stresses can appear (Fig. 3):

- N is axial force;
- M_y is bending moment with the defining vector along Y axis;
- Q_z is shear force which is parallel to Z axis and corresponding to the moment M_y;
- M_z is bending moment with the defining vector along Z axis;
- Q_y is shear force which is parallel to Y axis and corresponding to the moment M_z.

Positive force directions in rods are taken as follows: shear forces Q_z and Q_y are positive if they act in the positive directions of the axes Z and Y; bending moments M_x, M_y, M_z are positive if they rotate a cross-section counterclockwise around the corresponding axis X, Y, Z respectively; axial force N is positive if it elongates the rod.

The positive directions for the internal forces in the element's sections are shown in Fig. 3. Displacements in the sections of elements are denoted as follows:

- u is displacement along the local X axis (directed along the axis of the rod);
- v is displacement along the local Y axis (perpendicular to the axis of the rod);
- w is displacement along the local Z axis (perpendicular to the axis of the rod).

Rings and semicircles should be considered in the framework of plate theory with the corresponding shape functions for finite element method. However, these elements are outside the scope of this work.

Further, we shall introduce the principal notation for stress and strain tensors, which are used in the study to determine failure stress and strain. The symmetric stress tensor takes the following form:

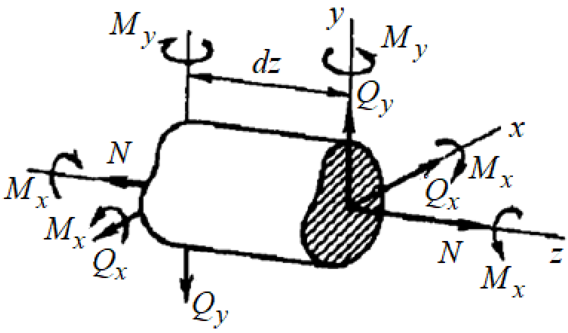


Fig. 3. Distribution of internal forces in a rod (spoke) cross-section [3]

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}, \tag{1}$$

or $\sigma=\sigma_{ij}$, where components with indices $i=j$ correspond to normal stresses and components with indices $i\neq j$ correspond to shear stresses respectively (in this work the indexes correspond to the local axes of the elements).

Symmetric strain tensor can be introduced similarly:

$$\varepsilon = \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{pmatrix}, \tag{2}$$

where components with indices $i=j$ correspond to tension / compression strain and components with indices $i\neq j$ correspond to shear deformations respectively (similarly to stresses, the strain tensor components indexes correspond to the local axes of the elements).

Energy based strength criterion is adopted to determine the failure of the apparatus elements:

$$\sigma_T = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6\left(\sigma_{12}{}^2+\sigma_{23}{}^2+\sigma_{31}{}^2\right)}, \tag{3}$$

where σ_T is the equivalent Mises stress which corresponds to material plastic yielding. This criterion is well suited for steel like materials and can be used to identify whether plasticity in the element takes place or not.

The corrosion-resistant steel 17KH18N9 is considered as the material to be used for the elements of the apparatus. In order to simulate its stress-strain state, the Prandtl's bilinear stress-strain diagram is used (Fig. 4).

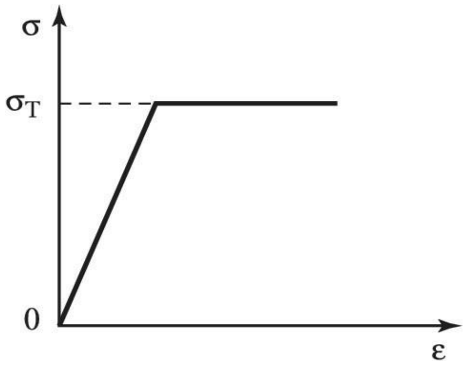


Fig. 4. Prandtl stress vs. strain diagram [2]

The process of deformation of the apparatus elements in the zone of inelastic deformation is not taken into account, since frequent overloading beyond yield stress will lead to accumulation of irreversible plastic deformations. Eventually, apparatus deformation will become too large to ensure stable apparatus durability. For example, when stresses in the apparatus element exceed σ_T followed by the loading removal, the residual stress in the apparatus element will take place. When many loading cycles take place, the device is deformed to such a degree (become “loose”) that it can cause considerable inconvenience to the patient.

In order to develop the methodic of the external fixation apparatus (Illizarov) design and structural analysis the following assumptions are made:

1. Elements of the system are considered separately not taking into their mutual interaction.

2. There is no loss of stiffness in the joints.

3. The failure is assumed to take when the element cross-section is in fully plastic state.

4. The loading on the elements corresponding to one part (receiving or transmitting the loading) is equally distributed between all the elements of the part.

The first two assumptions allow us to determine the distribution of displacements, stresses and strains in an analytical form and to assess the effect of the element parameters on the general apparatus stiffness. As a result, optimal cross-sections and lengths of the elements can be selected. At the same time, the calculated value of stress will be less than those evaluated using full structural scheme of the apparatus with account of the mutual effect of the elements.

The third assumption is made to avoid residual strains, which, in the case of cyclyc action on the apparatus (for example walking), can lead to significant apparatus shape change affecting the overall strength and stiffness of the external fixator.

The fourth assumption is based on the fact that the stiffness of the bone is much higher than the stiffness of the general receiving and transmitting parts of the Illizarov apparatus.

STRUCTURAL ANALYSIS OF THE SPOKES. EVALUATION OF MAXIMUM PERMISSIBLE SHEAR FORCE AND DISPLACEMENT IN THE SPOKES

According to the principal apparatus design, the spoke length used in the structural analysis L equal to $L = 135 - 215$ mm. The spoke undergoes longitudinal transverse bending and can be analyzed in the framework of the beam model (Fig. 5). The force acting on the spoke can be simulated as a point-loading P in the center (see Fig. 5). It is worth noting that the problem of the external fixator elements deformation is studied in [16, 17], however, these works do not provide any recommendations regarding practical apparatus design and element selection. Pinned fixation is selected for one side of the spoke, while another one is fixed in vertical direction. Tension force N acts on the side which is fixed only in vertical direction.

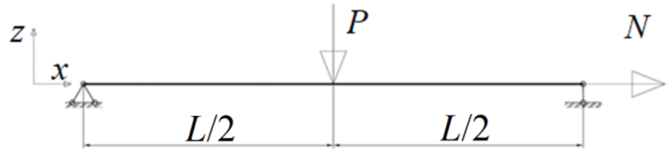


Fig. 5. Structural scheme of the spoke

As the moment of inertia of the spoke cross-section $I = \frac{\pi D^4}{64}$ (for the most commonly applicable spokes with a diameter equaling to 2 mm ($I = 7.85 \cdot 10^{-13}\ \mathrm{m}^4$) it is possible to simulate spoke behavior in the framework of thin thread. Assuming vertical displacements of the spoke $u(x)$ to be small, the equilibrium equation can be written in the form:

$$N_0 \frac{du(x)}{dx} + P(x) = 0, \tag{4}$$

with the following boundary conditions:

$$u(0) = u(L). \tag{5}$$

In (4), N_0 and $P(x)$ are the tension and shear force. In agreement with the principal assumptions:

$$P(x) = \begin{cases} P, & x = \frac{L}{2}, \\ 0, & x \neq \frac{L}{2}. \end{cases} \tag{6}$$

Therefore, an analytical solution for the bending of the spokes is difficult to obtain. Eq. (6) solved numerically. As a result, the values of displacements in the spoke are obtained at various values of shear and tension forces acting on the spoke.

The maximum force in the thread cross-section can be calculated in the following way:

$$N = \sqrt{N_0^2 + P^2}. \tag{7}$$

The dependence of the maximum permissible tension force N_0 on the value of shear force $P(x)$ is shown in Fig. 6. Contour plots representing maximum displacement in the spoke at different values of shear force and initial tension (in relation to the maximum admissible tension, Fig. 6) are shown in Fig. 7.

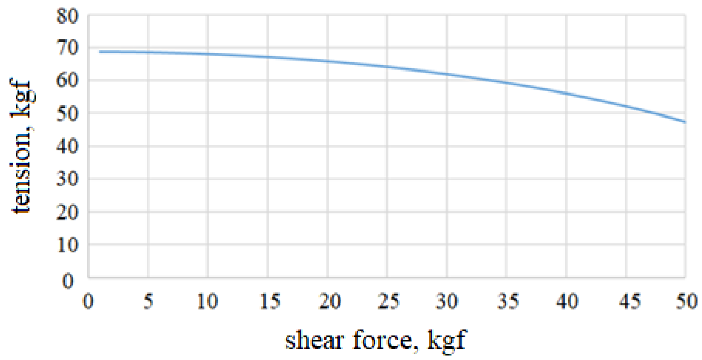
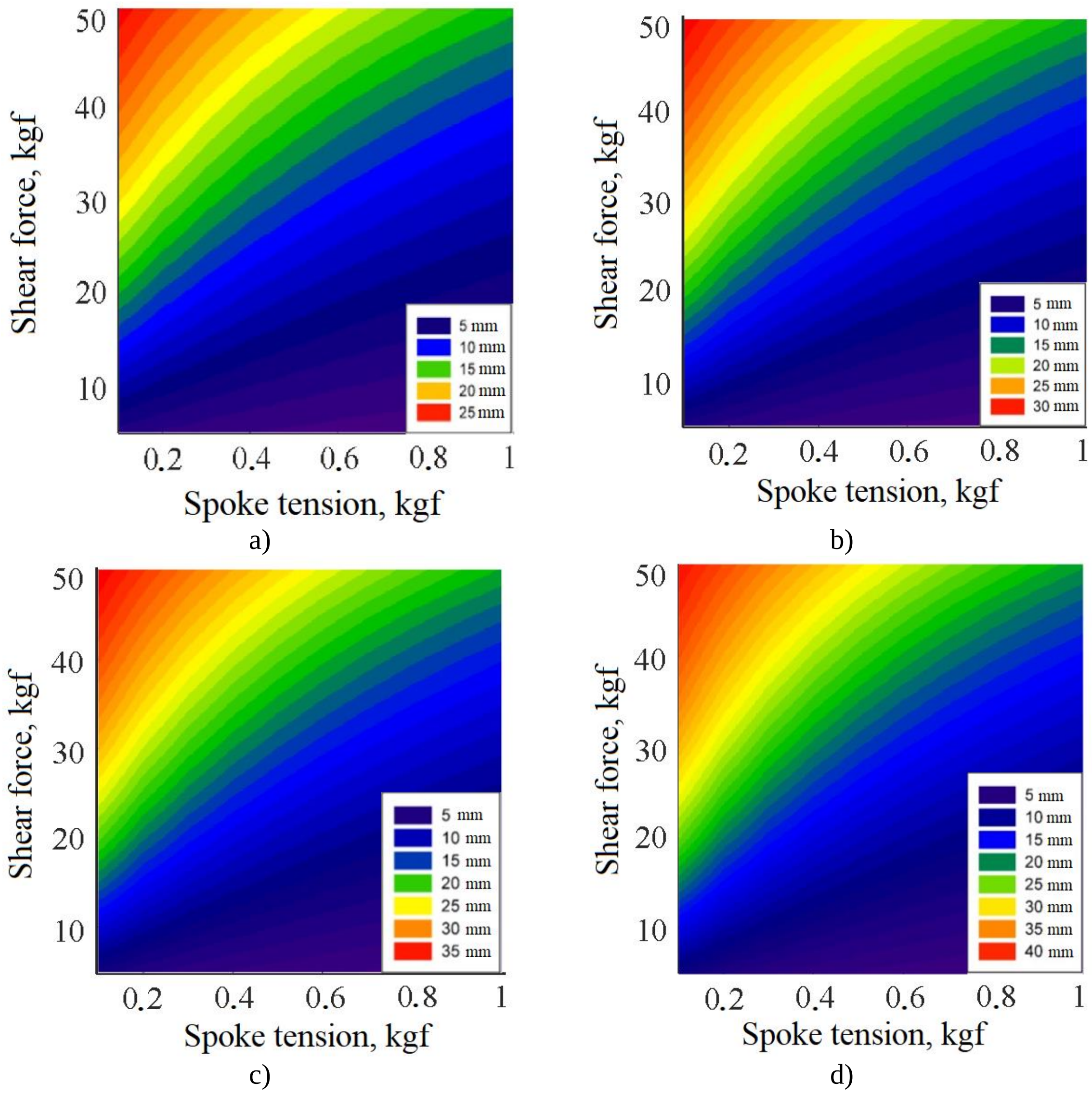
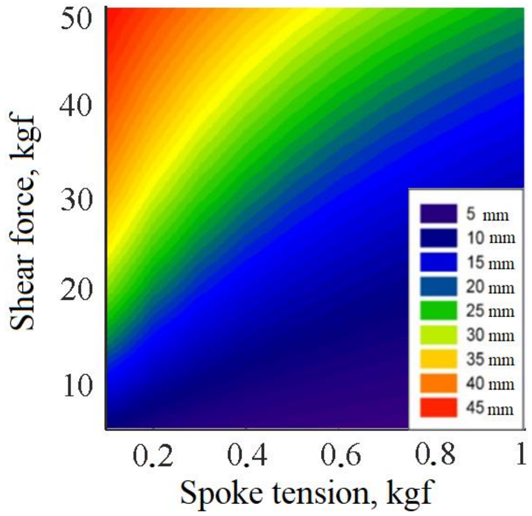


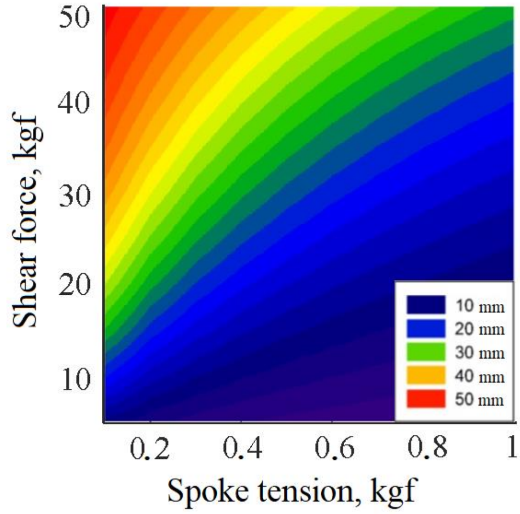
Fig. 6. Maximum admissible tension in the spoke element at various values of the shear force

The obtained results reveal that one spoke can carry a shear loading of up to 50 kgf, however, the displacement in the spoke exceeds 8 cm. At the same time, the value of initial tension in the spoke should not exceed the limit value that can be determined from Fig. 6. Therefore, the value of initial tension force in the spoke should be controlled by special device so that its value does not decrease significantly. If the value of initial tension in the spoke decreases by 10 times, its displacement increases up to 5–6 times. Hence, loading on the fracture area will be inappropriate. At the same time, it is possible to decrease the tension in the spokes to increase the loading on the fracture area causing hypertrophy of the "regenerate" in the fracture zone and improving bone regeneration. This effect of hypertrophy is confirmed in the study [5]. However, as there are no clear recommendations and only few research can be found, it is necessary to control the initial tension in the spokes so that it should be equal to N_0 according to the graph (Fig. 6).



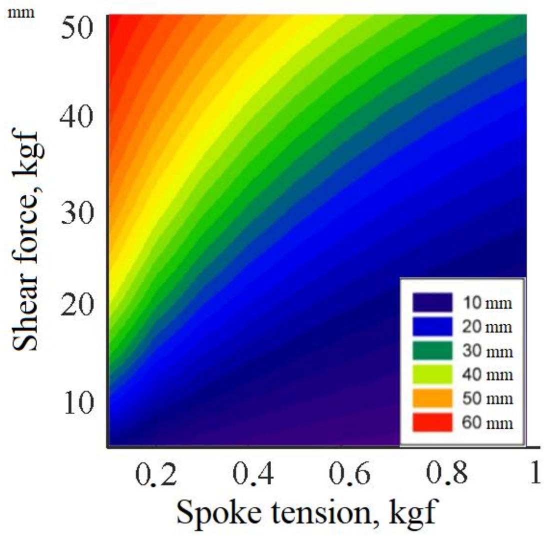


e)



f)

Fig. 7. The dependence of the spoke displacements on the magnitude of the shear load and its tension in fractions of the limiting value of the spoke (kgf): 90 (a); 100 (b); 110 (c); 120 (d); 130 (e); 140 (f); 160 (g); 180 (h); 200 (i)



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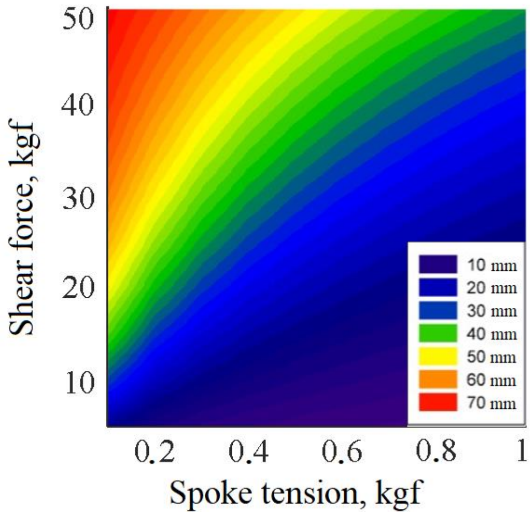

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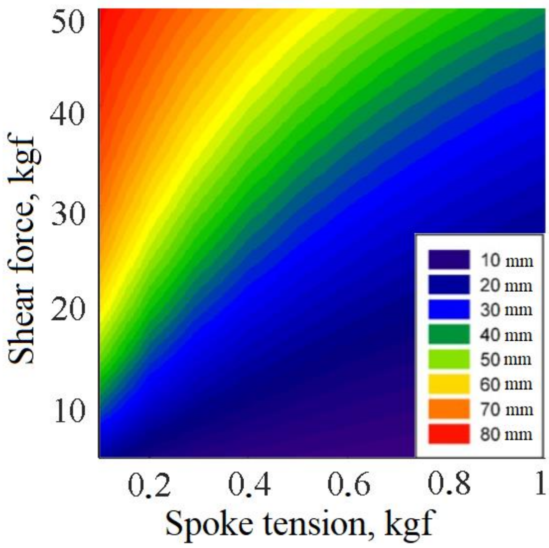

i)

Fig. 7. Ending

Thus, the spokes should be used for patients with large weights, while during the treatment procedure, the initial tension in the spokes should be controlled and when it decreases to the values at which the displacements in the fracture area are significant (according to the results in Fig. 7), it is necessary to stretch spokes.

STRUCTURAL ANALYSIS OF SHANZ PIN. EVALUATION OF MAXIMUM ADMISSIBLE SHEAR FORCE AND DISPLACEMENTS IN THE PIN

Shanz pin (Fig. 8) in the apparatus for external osteosynthesis acts as a cantilever bar with the following equilibrium equation:

$$\frac{\partial^{III} u(x)}{\partial x^{III}} = P(x), \quad u(0) = u'(0), \quad u''(L) = 0. \tag{8}$$

The structural scheme in Fig. 9 can be used for structural analysis of the pin with maximum internal force in the zone of its connection to the ring (half-ring):

$$M = PL. \tag{9}$$

Meanwhile, the stress in this zone can be determined as follows:

$$\sigma = M \frac{r}{I_z}. \tag{10}$$

Assuming the length of the pin is equal to the radius of the ring (half-ring) and the diameters of the pins M5 and M6 is equal to 5 and 6 mm respectively, it is possible to fill the table with the maximum permissible shear force that can be applied on the pin. Maximum displacement in the Shanz pin can be calculated as follows

$$v = \frac{Pl^3}{3EI}. \tag{11}$$

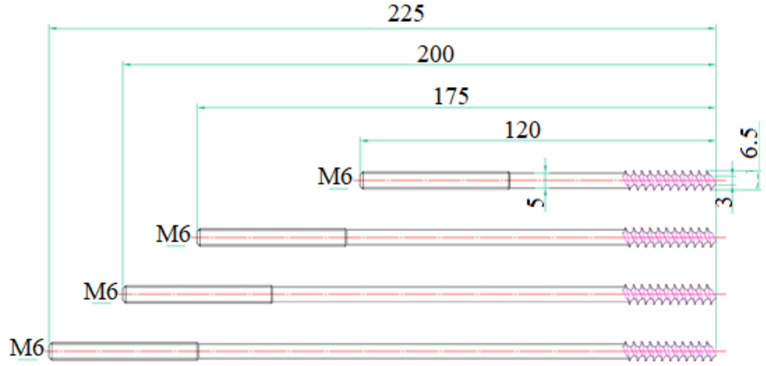

Fig. 8. Shanz pin with deep thread

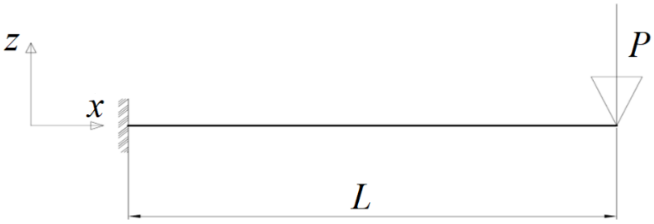

Fig. 9. Structural scheme of the Shanz pin

Table 1

Stress and maximum displacement in the Shanz M6 at different ring (semicircle)

P, kgf	Half-ring diameter, mm								
	90	100	110	120	130	140	160	180	200
stress, MPa									
10	242.6	265.7	288.8	311.9	335.1	358.2	404.4	450.6	496.8
15	363.9	398.6	433.3	467.9	502.6	537.2	**606.6**	**675.9**	**745.2**
20	485.2	531.5	**577.7**	**623.9**	**670.1**	**716.3**	**808.7**	**901.2**	**993.6**
25	**606.6**	**664.3**	**722.1**	**779.9**	**837.6**	**895.4**	**1010.9**	**1126.5**	**1242.0**
30	**727.9**	**797.2**	**866.5**	**935.8**	**1005.2**	**1074.5**	**1213.1**	**1351.8**	**1490.4**
35	**849.2**	**930.1**	**1010.9**	**1091.8**	**1172.7**	**1253.6**	**1415.3**	**1577.0**	**1738.8**
40	**970.5**	**1062.9**	**1155.3**	**1247.8**	**1340.2**	**1432.6**	**1617.5**	**1802.3**	**1987.2**
maximum displacement, mm									
10	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.002	0.003
15	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.004	0.005
20	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.005	0.006
25	0.001	0.001	0.002	0.002	0.002	0.003	0.004	0.006	0.008
30	0.001	0.001	0.002	0.002	0.003	0.004	0.005	0.007	0.010
35	0.001	0.002	0.002	0.003	0.003	0.004	0.006	0.008	0.011

Note: here and in Table 2: The stress in the ring that exceed material strength are highlighted

Table 2

Maximum displacement (mm) in Shanz rod M5 at various diameters of the ring (semicircle)

P, kgf	**Half-ring diameter, mm**								
	90	100	110	120	130	140	160	180	200
stress, MPa									
10	419.5	459.4	499.4	539.3	**579.3**	**619.2**	**659.2**	**699.1**	**739.1**
15	**629.2**	**689.1**	**749.0**	**809.0**	**868.9**	**928.8**	**988.7**	**1048.7**	**1108.6**
20	**838.9**	**918.8**	**998.7**	**1078.6**	**1158.5**	**1238.4**	**1318.3**	**1398.2**	**1478.1**
25	**1048.7**	**1148.5**	**1248.4**	**1348.3**	**1448.2**	**1548.0**	**1647.9**	**1747.8**	**1847.6**
30	**1258.4**	**1378.2**	**1498.1**	**1617.9**	**1737.8**	**1857.6**	**1977.5**	**2097.3**	**2217.2**
35	**1468.1**	**1607.9**	**1747.8**	**1887.6**	**2027.4**	**2167.2**	**2307.1**	**2446.9**	**2586.7**

40	**1677.9**	**1837.7**	**1997.5**	**2157.2**	**2317.0**	**2476.8**	**2636.6**	**2796.4**	**2956.2**
maximum displacement, mm									
10	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.004	0.004
15	0.001	0.002	0.002	0.002	0.003	0.004	0.005	0.005	0.006
20	0.002	0.002	0.003	0.003	0.004	0.005	0.006	0.007	0.008
25	0.002	0.003	0.003	0.004	0.005	0.006	0.008	0.009	0.011
30	0.002	0.003	0.004	0.005	0.006	0.007	0.009	0.011	0.013
35	0.003	0.004	0.005	0.006	0.007	0.009	0.011	0.013	0.015
40	0.003	0.004	0.005	0.007	0.008	0.010	0.012	0.014	0.017

According to the obtained results about maximum load bearing capacity of Shanz rods M5 and M6, they can be used only at body less than 20 kg. However, even for the loading values presented in the tables, irreversible plastic deformations can take place.

It is worth noting the possibility to use the combination of spokes and pins to connect to a bone. Nevertheless, the overall loading on the apparatus is not distributed equally among the pins and spokes but it depends on the stiffness ratios of these elements. The distribution of forces in the elements with a combined (hybrid) fixation to a bone (spoke-rod) will be investigated in subsequent works.

Remark 1. Stress values calculated in the work will be less than the real ones, which is caused by deformability of the apparatus connections and spatial stress distribution in the apparatus structure. Hence, the obtained values can be considered as the upper bound. Therefore, apparatus design based on the values calculated in this work ensure the durability of the device and safety during operation. At the same time, the calculated values of displacements are the lower estimation of the final displacements, since they do not take into account the deformability of the device and apparatus elements mutual interaction.

Remark 2. The limit stress for estimation of Shanz pins load bearing is considered to be equal to the material strength. However, as the stiffness of the connection is not infinite, final stress value will be lower than the one calculated from the cantilever beam structural scheme. Thus, the results of calculation will be revised after spatial analysis of the apparatus.

THE ANALYSIS OF STRESSES IN BONE TISSUE IN THE AREA OF ATTACHING FIXING ELEMENTS OF THE APPARATUS

In the following text, stress in the bone tissue caused by Schanz pin and spokes connections are considered. Finite element models are presented in Fig. 10. The bone tissue material is assumed to be orthotropic and linear elastic with the characteristics according to the works [12, 13]. Vertical load equaling to 1 kgf and acting along the *Z* axis is applied on top of the bone (Fig. 10) (the load value in this case is not critical, since the calculation is performed for linearly elastic deformation of the apparatus and bone tissue materials).

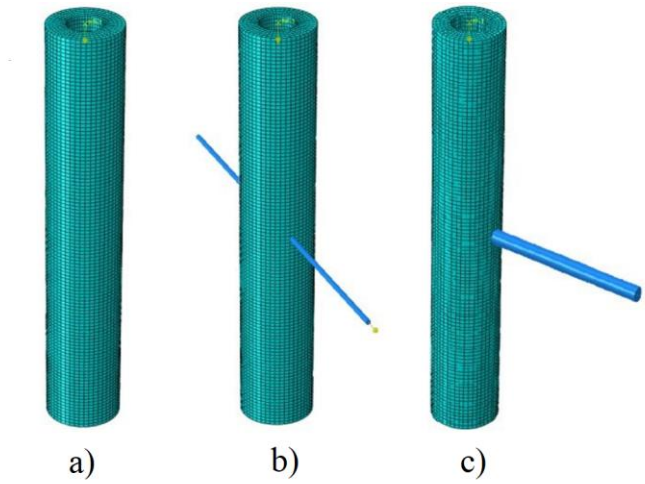

Fig. 10. Finite element models for calculation of stress in bone tissue caused by different methods of fixation

In the case of the bone without external fixation, the lower part of the model is fixed along the *X*, *Y* and *Z* axes. In the case of a bone with external fixation, the lower part of the model is free and the entire load is distributed to a spoke or Shanz pin. To ensure the geometrical immutability of the scheme, the rotations around the *X* and *Y* axes are fixed. The contour plots in Fig. 11–13 represent volumetric and shear stress in the bone tissue for each considered case.

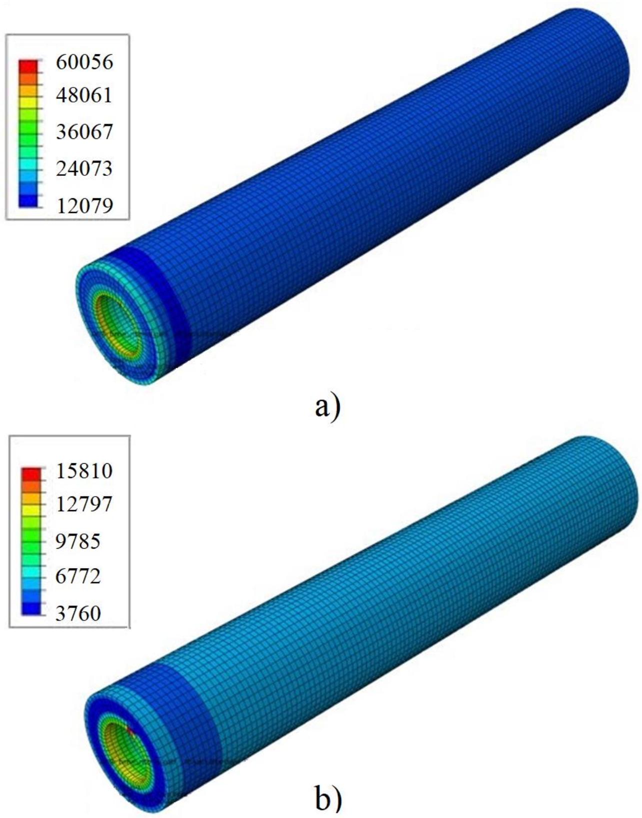

Fig. 11. Equivalent Mises stress (*a*) and pressure (*b*) in bone tissue in the case of Shanz pin fixation (for case in Fig 10, *a*)

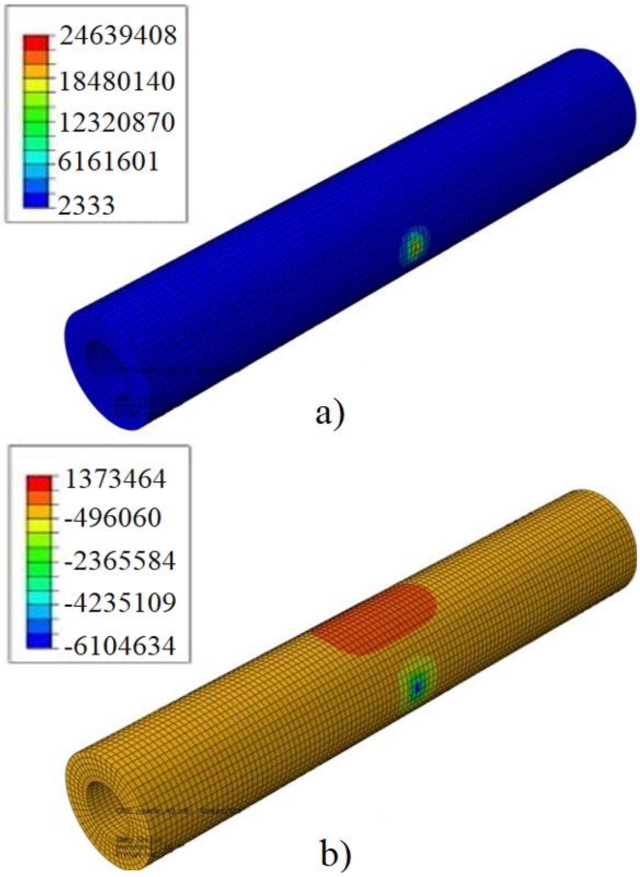

Fig. 12. Equivalent Mises stress (*a*) and pressure (*b*) in bone tissue in the case of Shanz pin fixation (for case in Fig 10, *b*)

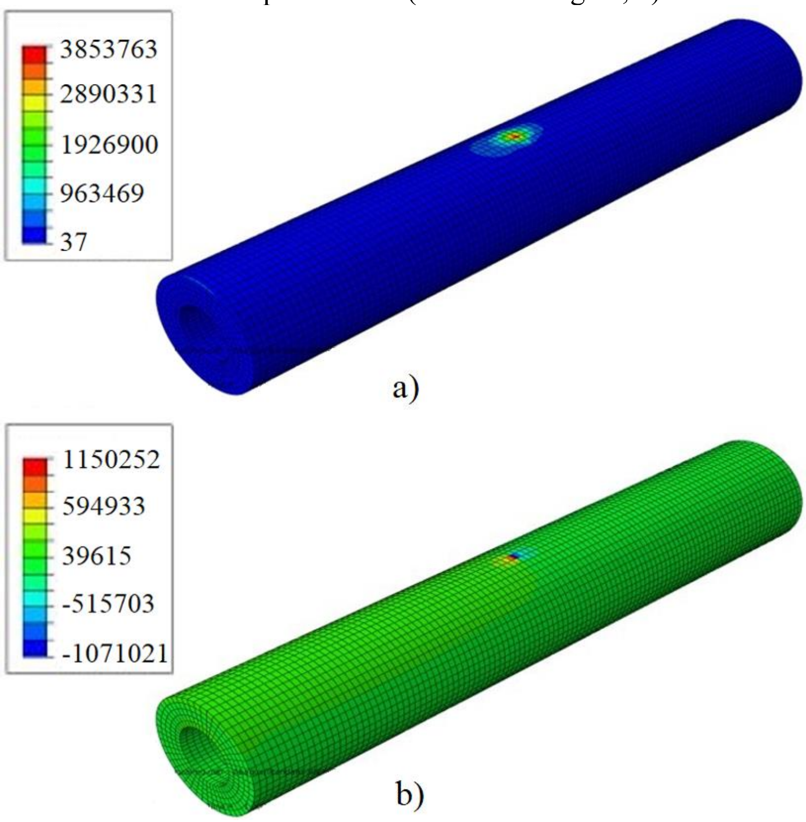

Fig. 13. Equivalent Mises stress (*a*) and pressure (*b*) in bone tissue in the case of Shanz pin fixation (for case in Fig 10, *c*)

According to the obtained contour plots of volumetric (pressure) and shear (equivalent Mises) stresses external fixation with spokes caused significant stress concentration in the bone tissue. Hence, when local bone degradation takes place (decrease in bone density, osteoporosis), it is necessary to install the spokes outside the affected areas, or to combine the spoke method of attachment with the pin method of attachment in order to partially relieve the load and reduce the stress concentration in the area where the spoke passes, or, if possible, abandon the spoke method of attachment in favor of the pin (rod) method.

The presence of such stress concentrations is caused by the fact that the diameter of the spokes is smaller than the diameter of the Shanz rod, which leads to higher pressure on the bone tissue in the area of the fixation zone. At the same time, the attachment with Shanz pins provides more even stress distribution in the bone with less rapid stress increase in the area of attachment.

Conclusions

Based on the analysis of the elements of the external fixation apparatus, the following conclusions can be drawn:

1. The attachment with Shanz pins provides higher stiffness with lower strength than the one with the spokes. Thus, if the weight of patient exceeds 80 kg and 4 Shanz pins can be installed to attach the apparatus to the bone, irreversible plastic strain in the apparatus take place. This will lead to the loose of strength and stiffness.
2. The attachment to a bone with spokes provides better strength, but its stiffness is lower and it is necessary to control the tension in the spokes during treatment process. Nevertheless, this method is suggested for the patient with heavy weight.
3. Real stress values in the elements of the apparatus will be lower that the calculated ones which is caused by the deformability of the joints and mutual deformation of the apparatus elements. At the same time, this assumption can compensate poor quality of the apparatus and a possible surgeon mistake.
4. Real values of strain and displacement in the apparatus elements will be higher than those calculated in the presented paper, which requires accuracy in limiting the deformation of the device.
5. Both types of attachments lead to the formation of stress concentrators in the bone tissue under loading. Meanwhile, the attachment with spokes produces several times higher stresses with more rapid stress change than the Shanz pin fixation.

Thus, in the case of a decrease in the density and strength of the bone tissue (osteoporosis), it is recommended to use either a rod (Shanz pin) fixation method (if possible) or to combine the spoke and rod fixation methods. In this case, the spokes and rods should be located outside the damaged areas of the bone tissue.

Design guidelines

1. To determine the weight of the patient and calculate the load on one element, assuming even load distribution among all the elements of the apparatus.
2. According to the calculated load on the element to choose the type of attachment (spoke or Shanz pin).
3. In the case of spoke attachment to control initial tension in the spoke according to Fig. 6. Then, the control of tension during the treatment process is required to prevent significant deformations and pressure on fracture (Fig. 7).
4. In the case of Shanz rod attachment to check that the loading does not exceed the maximum admissible value.

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