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Original Article

# FEM Experimental Study in Surgical Treatment of Humeral Shaft Pseudarthrosis

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**Abstract**

***Finite Element Method*** *was used to determine the state of stress of the humeral cortical, which is made when fixing a steel plate provided with six fixing holes and compression (installation) is provided by a Müller compactor. There were considered three cases of resection: straight parallel resection (humeral shaft angle of approximately 90°), oblique parallel resection (angle of approximately 75°) and resection in "opposite scale steps ", comparing the states and distribution of stress and strain. The study was conducted with the computer program ANSYS finite element V14.*

**Keywords**: *pseudarthrosis, humerus, surgical treatment, osteosynthesis, the finite element method.*

## 1. Introduction

In humeral shaft pseudarthrosis, the method of metal plate fixation of bone fragments plays an important role in the recovery and healing of bone tissue. This is because during installation, it can cause a local tension too high or too low, tension that require bone structure (living tissue) to respond to these requests by increasing or decreasing bone density. Another important factor is that the metal plate change tension "path", so around the cortical plate tensions are lower, leading to bone resorption. By mathematical simulation (FEM), the material properties of cortical and cancellous bone being determined by bone density, we are able to calculate the risk of fractures. Currently there are known bone recovery mechanism and the factors that contribute to faster healing. There have been studies on mathematical models that highlight the link between stress and bone density values, but we do not know exactly the limit values.

## 2. Method

In this study, finite element method was used to determine the state of stress of the humeral cortex, which is made when fixing a steel plate provided with six fixing holes and compression (installation) is provided by a Müller compactor. There were considered three cases of resection: resection parallel straight (humeral shaft angle of approximately 90°), parallel oblique resection (angle of approximately 75°) and resection in "opposite scale steps", comparing the states and distribution of stress and strain. The study was conducted with the computer program ANSYS finite element V14.

The method was developed based on the classical equations known in materials resistance, applicable for objects with constant section, for which, knowing the dimensions and material properties, can be determined response under the action of known tensions.

Starting from the idea that some form of a body can be approximated by smaller, finite, regular-shaped (bolt) bodies and with the development of computing power (matrix calculation) of computers, finite element generated in the beginning to beam type elements (bar with constant section), has developed rapidly and can be successfully applied to almost any complex structure. In fact, the method entails the generation of a mathematical model, three-dimensional, in which are known:

- length, area, bodies volume, by reporting lines points to a global coordinate system (the body is positioned against a known reference) ;
- to each studied body structure is assigned a material characterized by minimum elasticity modulus (Young's modulus), transverse contraction coefficient (Poisson's ratio) and material density;
- is necessary to know the operating conditions, which consist of information on the way of support (fixing, supporting) the structure and the tasks to which the structure is subjected;

When all this information is known and put in the program, three-dimensional mathematical model (a system of differential equations) can be generated and solved. As a result of the solutions there are determined the primary unknowns (such as the displacement, force, temperature, speed, etc.) and then by specific mathematical operation are determined and the secondary unknowns (stresses, strains, etc.).

The experimental study had the following steps:

*Step 1. Geometric model.* Obtaining a three-dimensional geometric model, virtually, for the humerus, plate, fixing screws and Müller compactor, characterized by points in space, surfaces and solids;

*Step 2. Finite element model.* Geometry obtained in step 1 is divided (discretized) into hexahedral bodies (FE), regular, connected through nodes to give a mathematical model characterized by geometric properties in space (position, size, area, volume), elastic properties (by assigning appropriate material properties - cortical bone, cancellous bone, ligaments, etc.). This gives a finite element model which will generate a system of differential equations. The first two stages are generally known as the "pre-processing".

*Step 3. Boundary conditions.* The system of equations obtained in the previous step is characterized by the fact that the system is undetermined. In order to solve the system of differential equations, additional equations are created by introducing "boundary" conditions, known conditions, referring to the bearing / retaining structure mode and its stress tasks.

*Step 4.* The last step is to solve the system and the interpretation of results.

## 2.1. The geometric model

Some of the components which were considered are more regular in shape, and can be measured with simple measuring devices (like caliper). We are talking about the metal plate, the Müller compactor and the screws. Thus, based on the dimensional measures geometry was generated directly in ANSYS Design Modeler. However, the virtualization of the complex geometry of the humerus, which has variable cortical thickness and irregular shapes, require special devices. In the practical are carried out transverse CT scan, with varied axial increments, depending on the complexity of bone surface.

### 2.1.1 The humeral geometric model

For the experimental study, the geometry of the external surface of the left humerus, generated in another specialty papers, has been adopted. In the reminded study, the external surface of the humerus was considered as a rigid body. Therefore, this area, imported by STEP format in ANSYS, was further processed.

In this paper, the contour lines corresponding to the internal surface of the cortex **(Figure 1)** were introduced into the ANSYS DM and led to the generation of the humerus geometric model with variable cortical thickness.

Contour lines were simplified, their number was reduced, while keeping sufficient as will produce more accurate cortical thickness. Based on these lines (cross section) were generated cross areas.

These surfaces, together with the external surface further processed, in particular shaft of the humerus, generated the humeral geometric model **(Figure 2).** Surfaces, both external, internal and transverse are quadrilateral surfaces (consisting of four lines), form that facilitates division in regular hexahedral bodies. Proximal and distal ends of the humerus were further processed, but did not put much emphasis on highlighting all significant bone form because, for this study is very important the diaphyseal area.

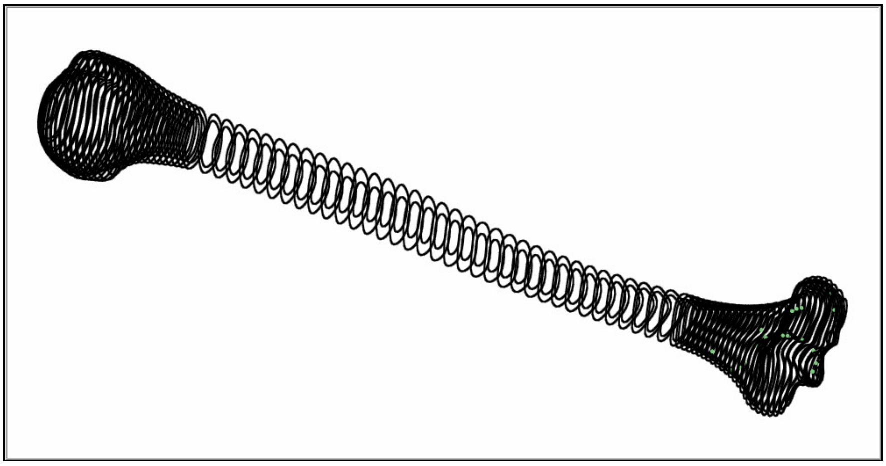

**Figure 1:** ***Contour lines obtained after processing. It highlights the cortical thickness variation. Only the inner contours will be processed and assembled with the existing exterior surfaces. Isometric view.***

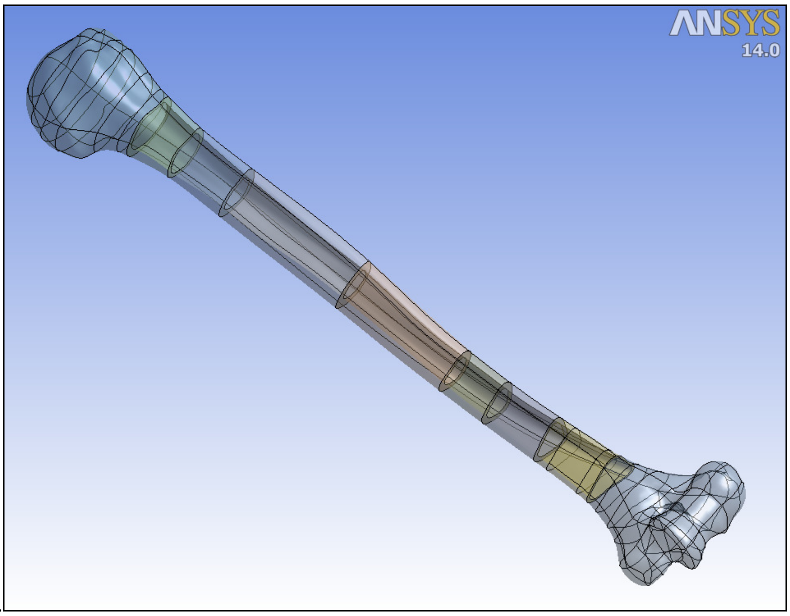


**Figure 2:** ***Geometric model for the humerus, with variable cortical thickness obtained in ANSYS Design Modeler program. Isometric view.***

### 2.1.2 The geometric mode for plate, fixing screws and Müller compactor.

For the virtualization of geometric model of fixation plate were measured the dimensions and geometry of the physical model, and the geometry was obtained by specific commands in ANSYS Design Modeler program. In generating the model was took into account the creation of that regular surfaces which will then allow hexahedral elements discretization. **Figure 3** shows the metal plate with 6 holes, highlighting the points, lines and areas that were the basis of this geometry.

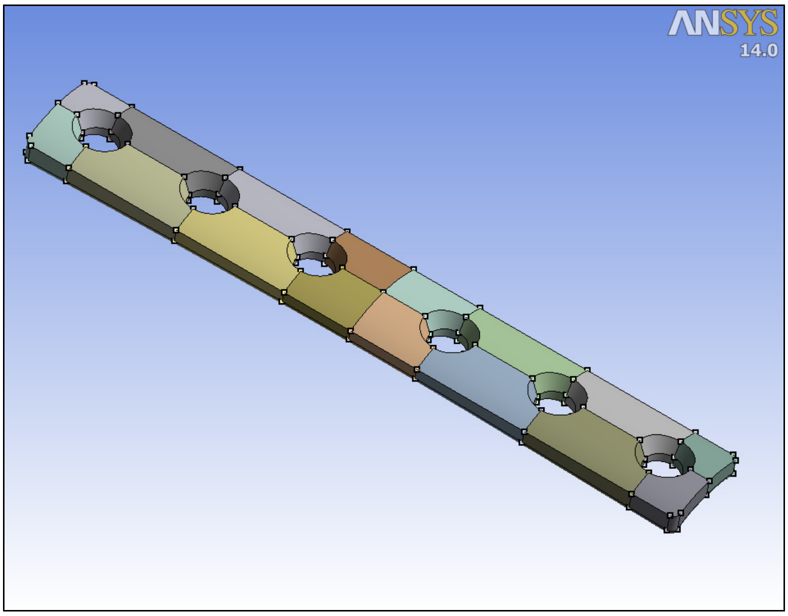


**Figure 3:** ***Geometric model for fixation plate, generated in ANSYS DM software based on dimensional measurements. Isometric view.***

Similarly was done for the Müller compactor, consisting of a perforated body that secures the humerus, a guide roller and a hexagonal screw **(Figure 4).** There have been highlighted in this case too, the points, lines and areas of geometry.

These models were then placed in a common basis for their assembly and set an initial relative position. This "whole" can be viewed in **Figure 5,** figure that highlights the three screws located opposite to the roller.

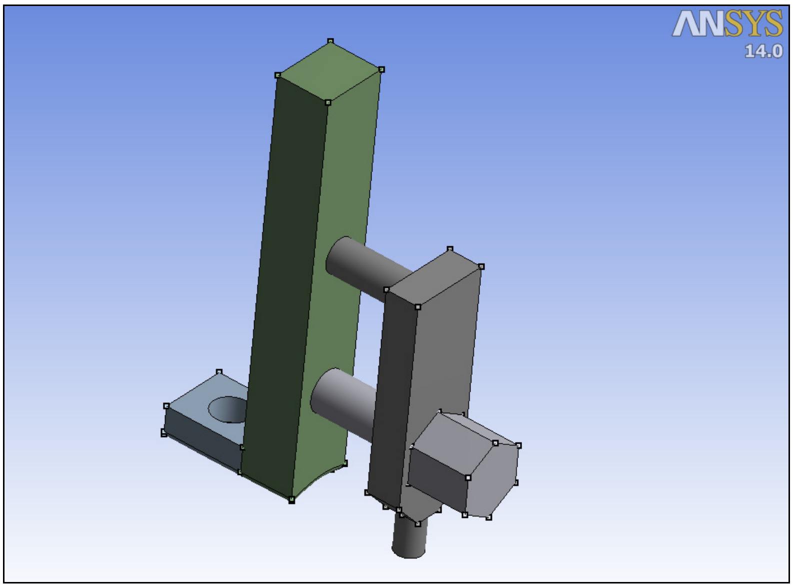


**Figure 4:** ***The compactor geometric model generated in ANSYS DM program, based on dimensional measurements. Isometric view.***

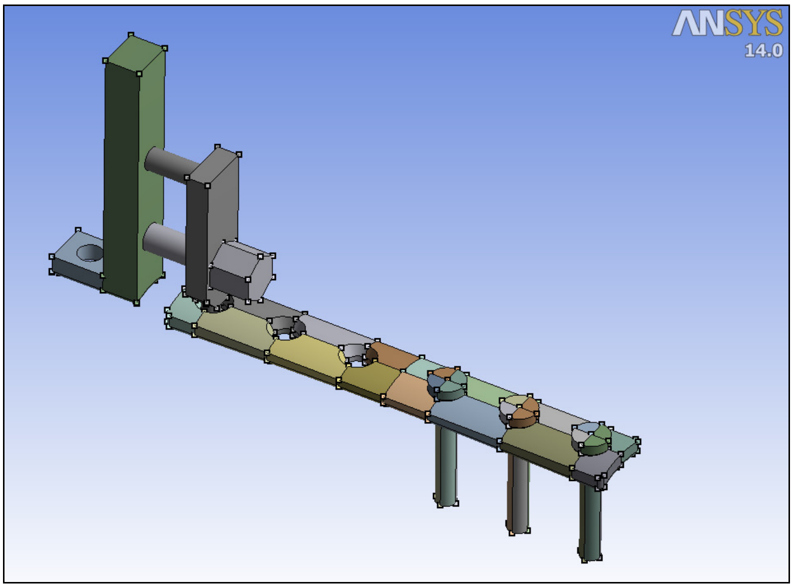


**Figure 5:** ***The plate geometric model (with 3 screws) positioned relative to the compactor (located in the maximum open position). Isometric view.***

All these geometries were inserted into one base and the plate with the compactor positioned on the external side of the humerus, such that the plate is in a stable position of contact with the humerus, a position can be seen in **Figure 6.**

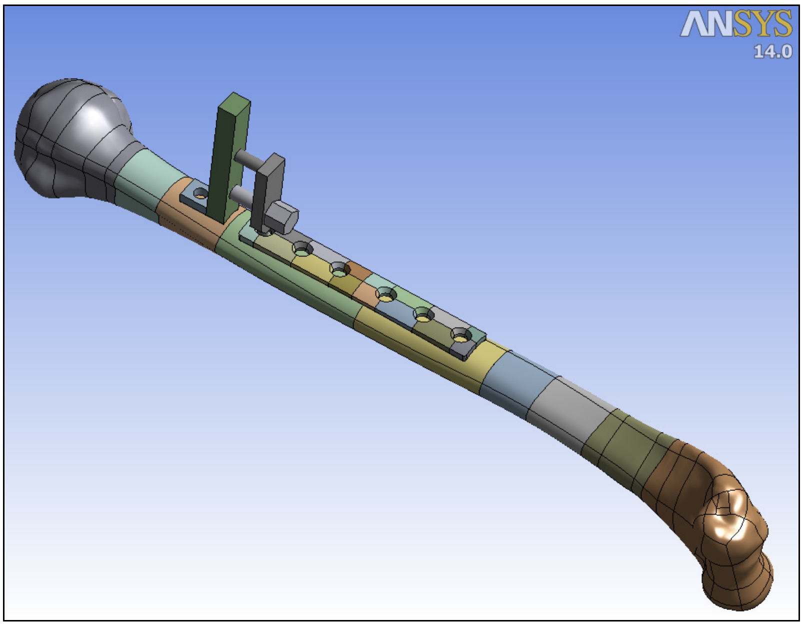


**Figure 6:** ***Geometric model of the humerus with fixation plate and compactor. Isometric view. Observe the relative position of the plate and compactor to humerus.***

After having determined the initial relative position of the plate to the humerus, in the region of plate half, was created a fracture (resection) of the shaft of the humerus, width 2 mm, having 3 different forms:

- Fracture (resection) generates straight parallel surfaces (at 90 degrees) transverse to the longitudinal axis of the humerus **(Figure 7);**

- Fracture (resection) generates parallel surfaces which are inclined (at an angle of 15 degrees) to the longitudinal axis **(Figure 8);**

- Fracture (resection) surfaces arranged in "opposite scale steps" **(Figure 9).**

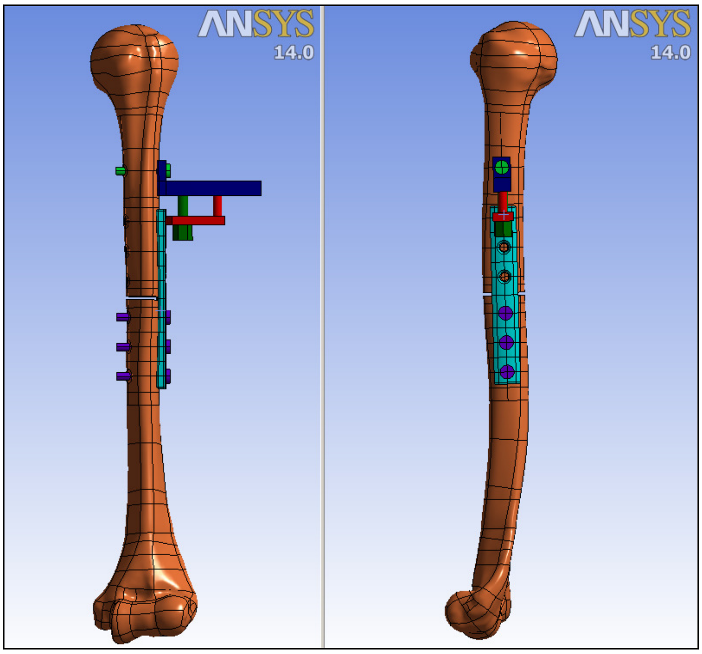


**Figure 7:** ***Geometric model of the humerus of with resection in parallel surfaces (straight resection) with fixing plate, screws and compactor. Left-front view, right - external side view.***

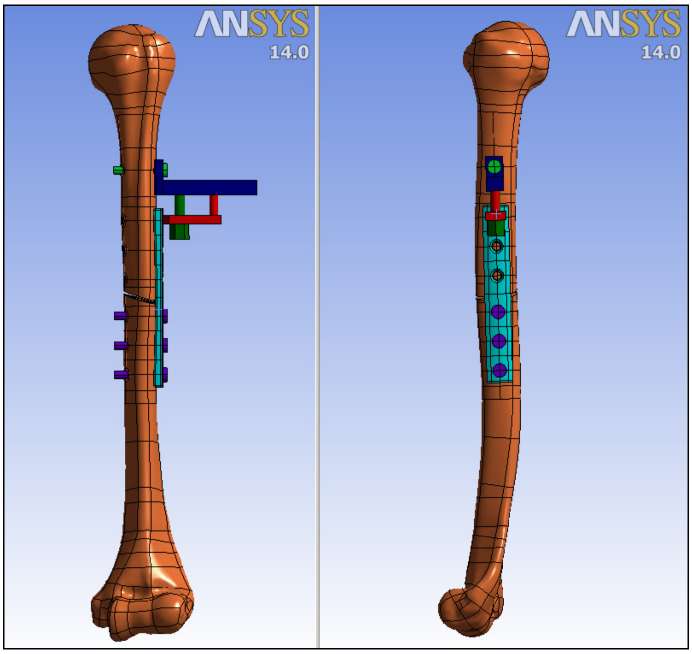


**Figure 8:** ***Geometric model of the humerus of with resection in parallel surfaces (where surfaces are inclined, oblique to the axis of humerus), with the plate, screws, and the compactor. Left-front view, right - external side view.***

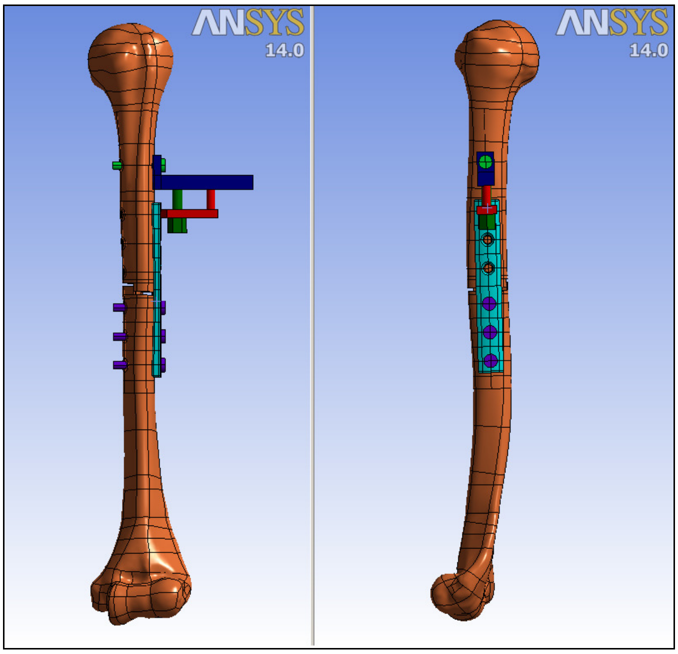


**Figure 9:** ***Geometric model of the humerus of with resection in "opposite scale steps ", with the plate, screws, and the compactor. Left - front view, right - external side view.***

### 2.1.3. The Finite Element Model

Based on the above geometric patterns, were generated models with finite element for all the components which have been considered in this study. These models are shown in figures 10-13. The material properties used are taken from the literature (49):

- fixation plate, compactor elements and screws are stainless steel. For this material was used elasticity modulus (Young's modulus) E = 186000 MPa and Poisson's ratio (ratio of transverse contraction) of 0.3.

- for humerus material was considered the elastic modulus E = 17000 MPa and the coefficient of contraction (Poisson) of 0.3.

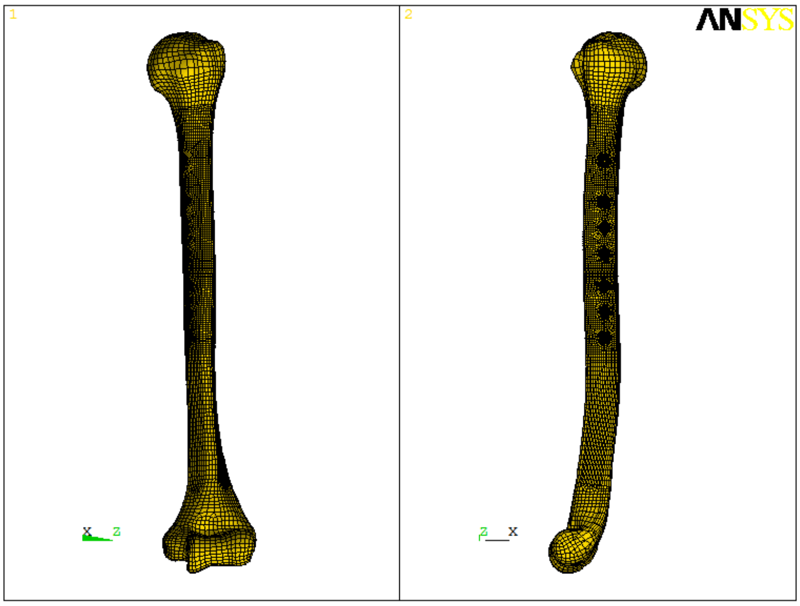

**Figure 10:** ***The finite element model for the humerus. Left - front view, right - external side view.***

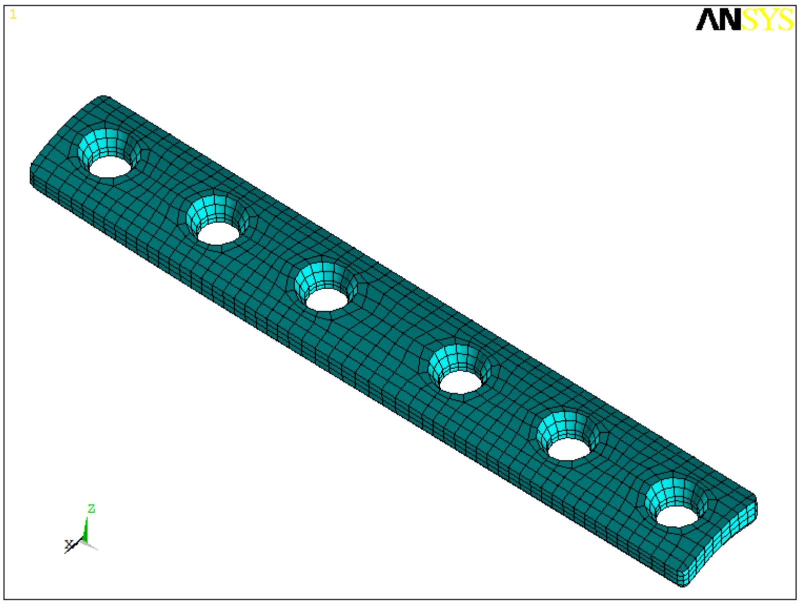

**Figure 11:** ***The finite element model for the plate. Isometric view.***

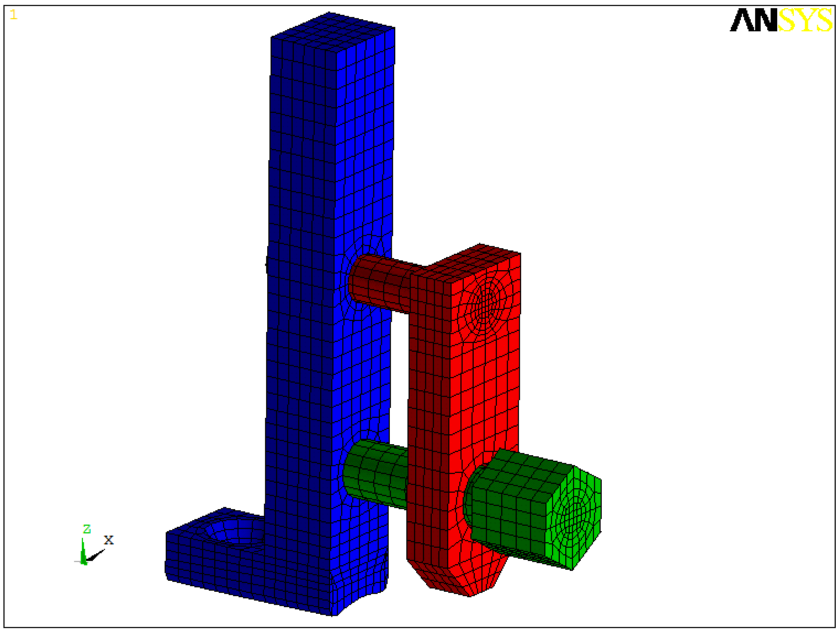


**Figure 12:** ***The finite element model for the Müller compactor elements. Isometric view***

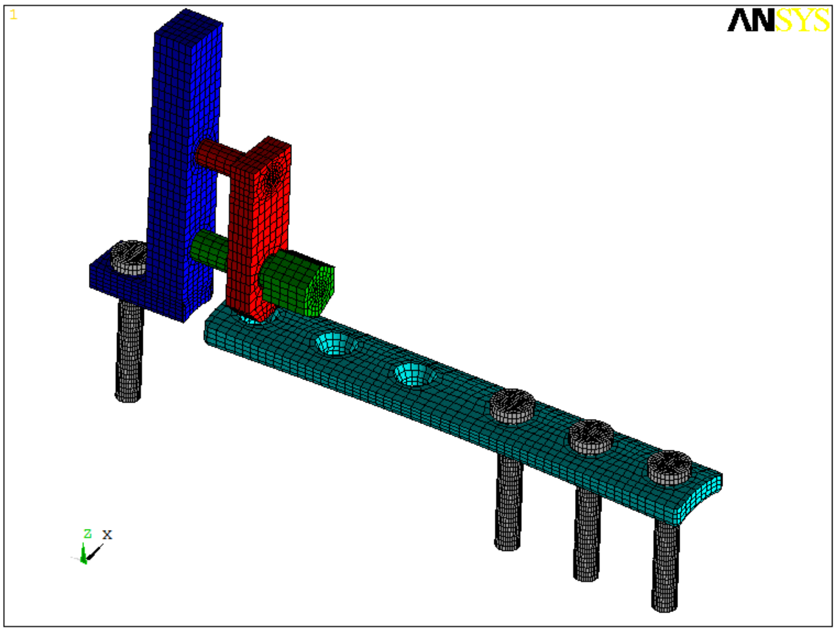


**Figure 13:** ***Finite element model for plate screws, and Müller compactor, assembled in position to be mounted on the humerus. Isometric view.***

In the experimental study were considered and analyzed three models of resection, depending on the surfaces form: straight resection, oblique resection, opposite steps resection. Even though there are 3 models, as mentioned, the difference between created finite element models is very small.

In **figures 14-16** are the three study designs. As can be seen, in the same region of bone (8 mm wide), we performed a 2 mm thick cutting, cropping direction is almost perpendicular to the longitudinal axis of the humerus. Thus obtained finite element model for a study case. The link between the "resection" regions with bone was performed with common nodes.

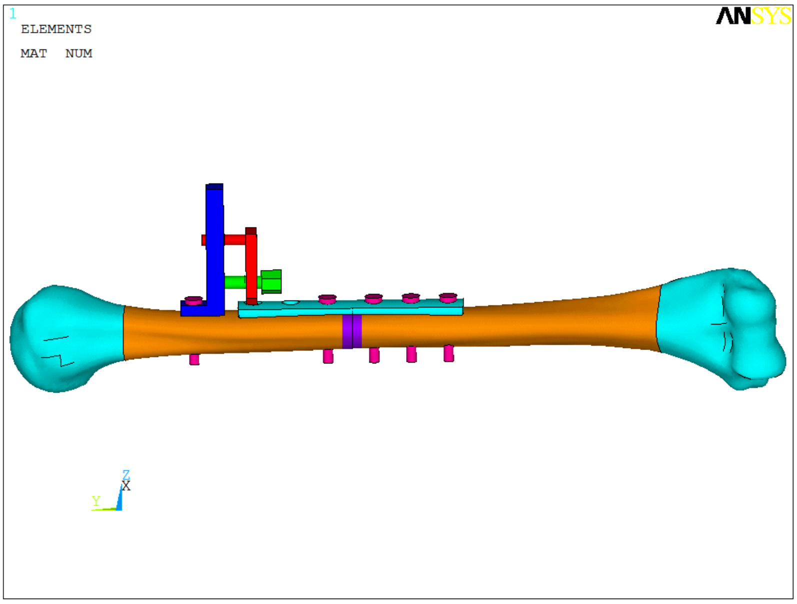


**Figure 14:** ***The finite element model used for the straight resection. Front view. In the middle of the shaft, magenta colored area is the area where the resection was performed, and the two bones were contacted.***

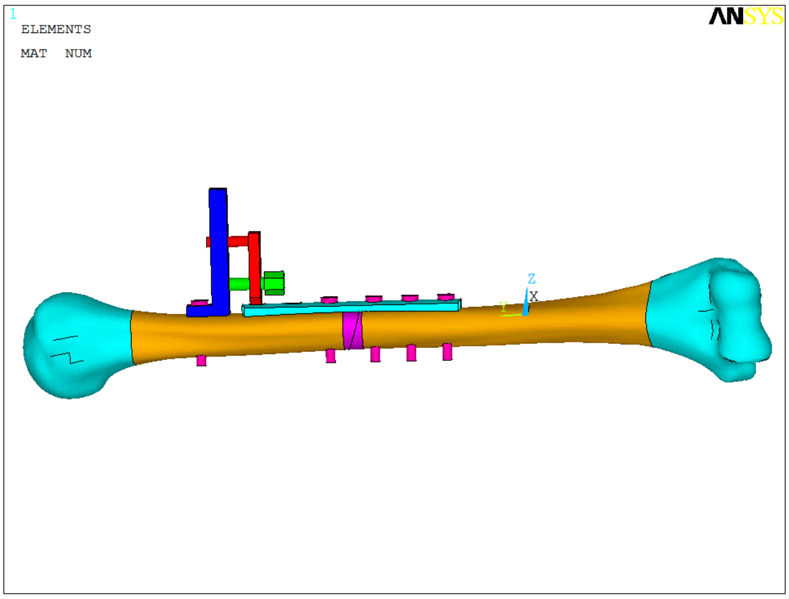


**Figure 15:** ***The finite element model used for oblique resection. Front view. In the middle of the shaft, the color pink is the area where the resection was performed, and the two bones were contacted.***

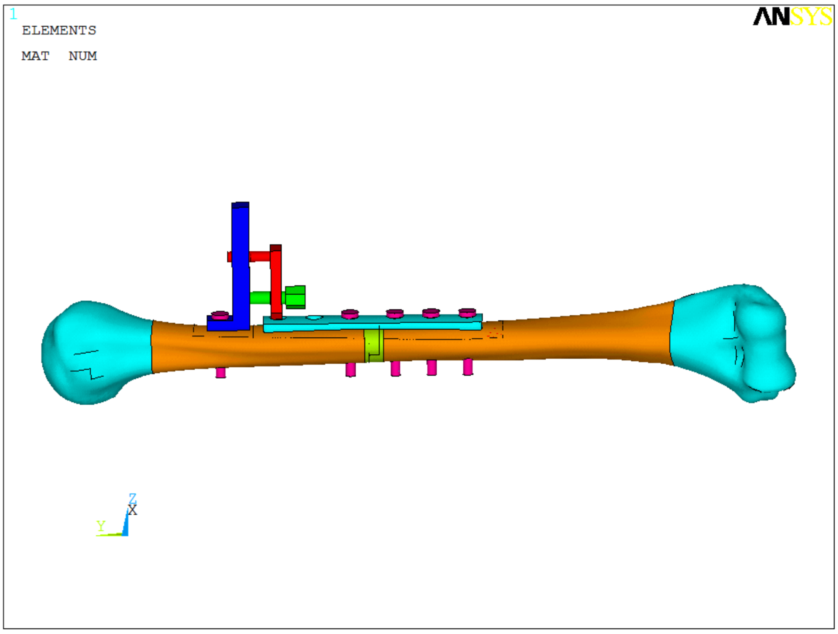


**Figure 16:** ***The finite element used for "in steps" resection. Front view. In the middle of the shaft, the light green color is where the resection was performed, and the two bones were contacted.***

### 2.1.4. Boundary conditions

Each of the three mathematical study models were solved in four steps of loading. Loads or boundary conditions are identical for all 3 models and consist of (Figure 17):

- Step 1. In the first step, it was considered that two screws are inserted into the bone, one that secures the metal plate and the second is fixing the compactor. It was considered that fixing is done with a screw pretension force of 100 N. Thus, it was considered that the two screws located on the extremities (the Figure 112 pink color) are used simultaneously;

- Step 2. Insert the second screw (blue) in the metal plate and bone, by applying pretension force of 100 N.

- Step 3. The third screw is inserted (green) in the metal plate and in the bone, also by means of pretension force of 100 N.

- Step 4. After the first steps, the plate is fixed to the bone fragment located at the distal humerus. It required a translational movement (along the positive Y axis) of the compactor guide, simulating rotation of the screw. With this translation, the guide pulls the plate, and the plate pulls the bone, with the compression of the resection zone.

- Step 5. After reaching a maximum, it is introduced and the fourth screw in plate and bone, all simulated by pretension force of 100 N. During these steps, the humerus is considered concealed on the proximal end and simply supported at the distal end, ends represented by light blue (cyan) in **Figure 17.**

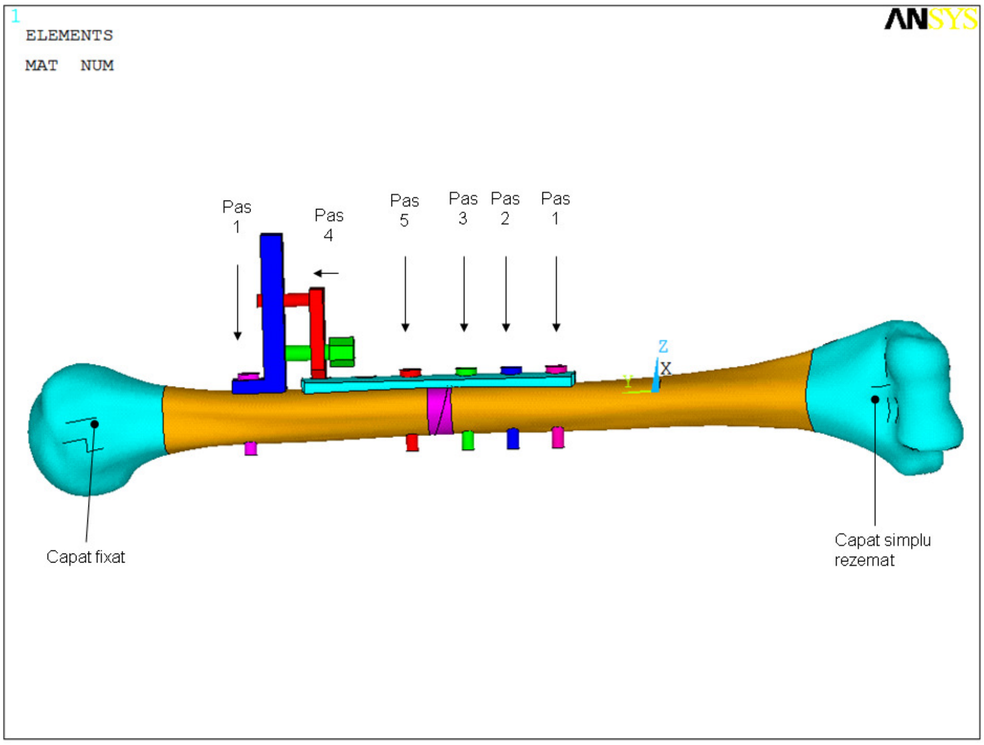


**Figure 17:** ***The boundary conditions applied to each of the three study designs.***

### 2.1.5. Results

In order to compare the three variants of resection for each studied model, the results will be highlighted as color maps with equivalent stress distribution (von Mises), the maximum principal stress (tensile), compression stress, movement distribution, the contact in the "fracture" (resection) zone and frictional pressure developed, for each studied step.

Research studies have shown that the level of stress (main or equivalent) in the body, determines the response of bone tissue, meaning the change in bone density, by bone loss or material input. Li et al (2007) (132) even created a mathematical model that traced the curves in **Figure 18,** curves that show that the stress must not be less than 2-3 MPa or greater than 8 MPa.

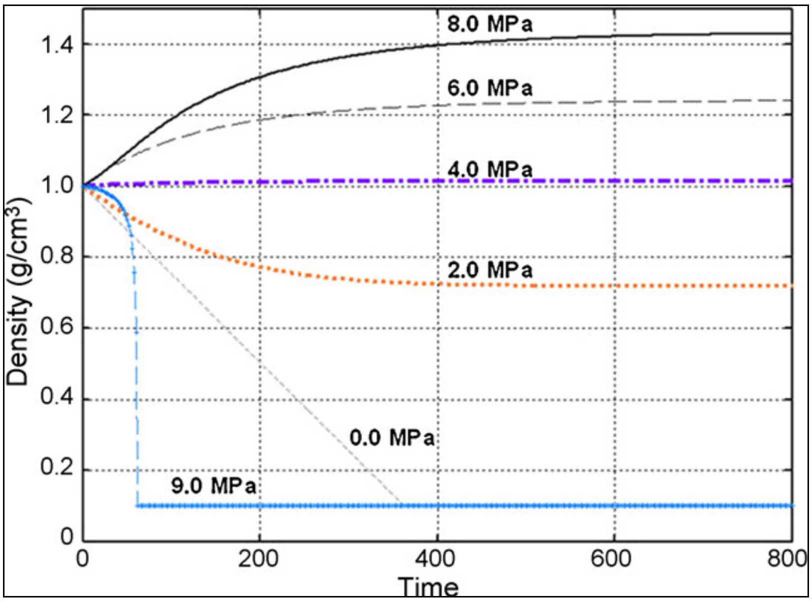


**Figure 18:** ***Curve of change in bone density over time for different levels of stress application*** **(after Li J. et al.).**

For this reason, the results will be directed to highlight the level of stress (main or equivalent) of the resection zone.

### 2.1.5.1. Straight resection zone.

In the straight resection case, after the first three steps, the two bone segments were not in contact over a large area (**Figure 19**). But after the final step, the contact is closed on the entire section, but the pressure is not uniform, being eccentric, as shown by **Figure 20.**

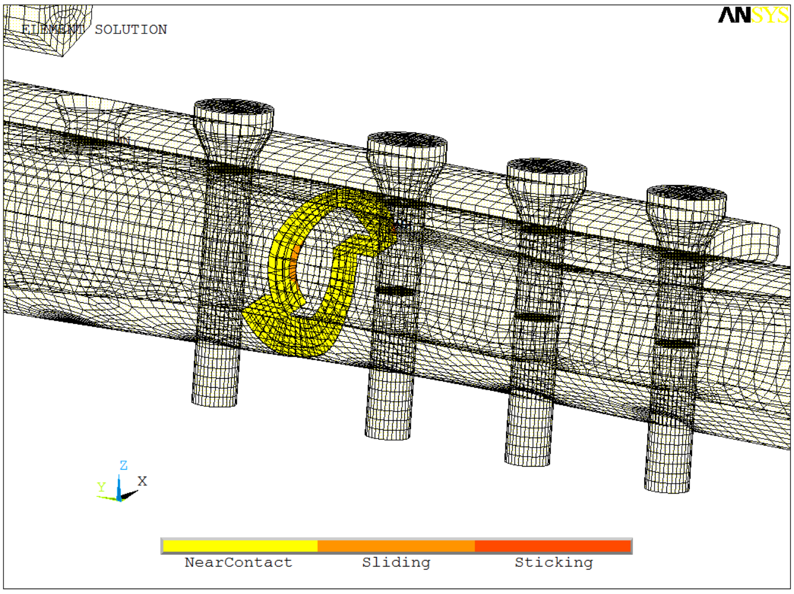


**Figure 19:** ***At the end of step 3, the contact between the two segments is achieved in part, only on a very small portion (orange portion).***

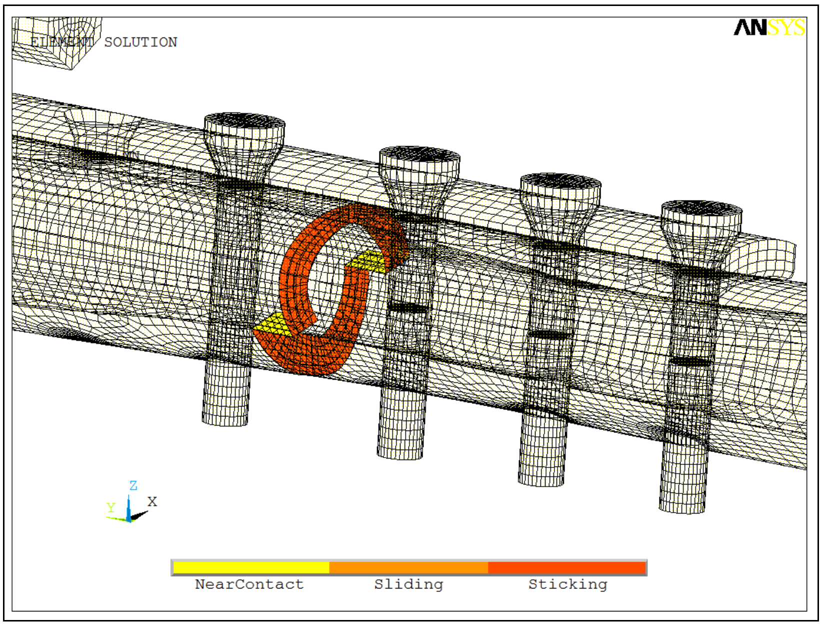


**Figure 20:** ***At the end of run, contact between the two segments is performed on the entire surface, but red indicates that the pressure is higher in that area.***

#### 2.1.5.2. Oblique resection case

The values of tensions at the sections in the region of resection, as calculated after charge step 3, is from 2.4 to 3.7 MPa, are similar to those calculated in the case of straight resection. Instead, these values increase dramatically (from 5.9 to 16.6 MPa) at the final step. The results show that in this case there is no contact between the surfaces before using the compactor, making a uniform game between surfaces. One reason is that, when entering and tightening the fixation screws, loose bone segment tends to make a translation away of contact area.

#### 2.1.5.3. "Opposite steps" resection case

There will be a graphic exemplification of “opposite steps” resection case. And in this case will be highlighted Von Mises stress and principal stress (tension-compression) that develop in the "fracture". In terms of contact, in this case the results show that even if the contact between the two sections was not achieved at the end of step 3 (**Figure 19**) after compactor action the contact of two sections was done and is even uniformly, so as shown in **Figure 20**. In this case, the main stress and the von Mises stress is higher than in the case of straight resection: 3.2 to 4.7 MPa values were calculated for the portion of the "bone" of 8 mm (used to perform the virtual resection) at end of step 3 and increase to 3.3 to 8 MPa at the end of load steps (**Figure 21-26**).

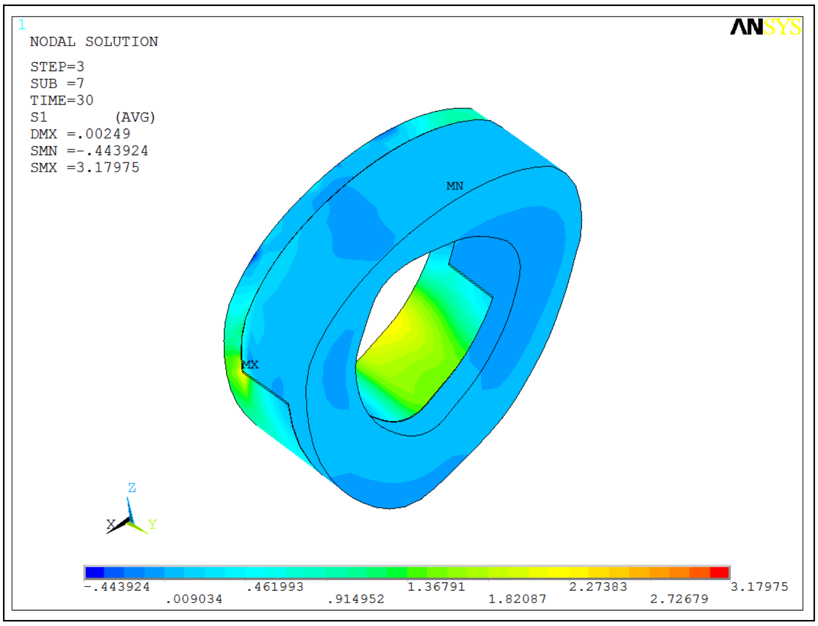


**Figure 21:** ***Distribution of the maximum principal stress (tensile) - [MPa], calculated at the end of loading step 3.***

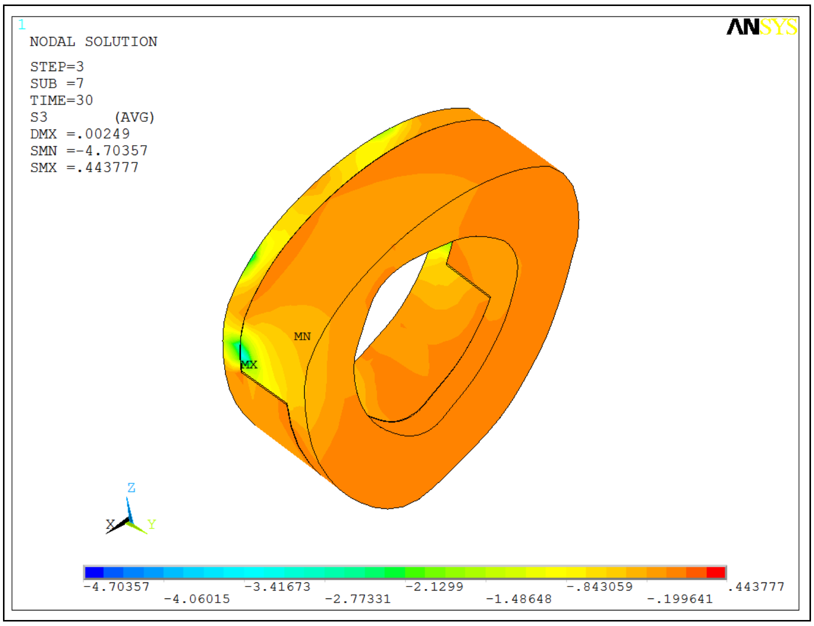


**Figure 22:** ***The distribution of the minimum principal stress (compression)*** **- [MPa]** ***calculated at the end of the loading step 3.***

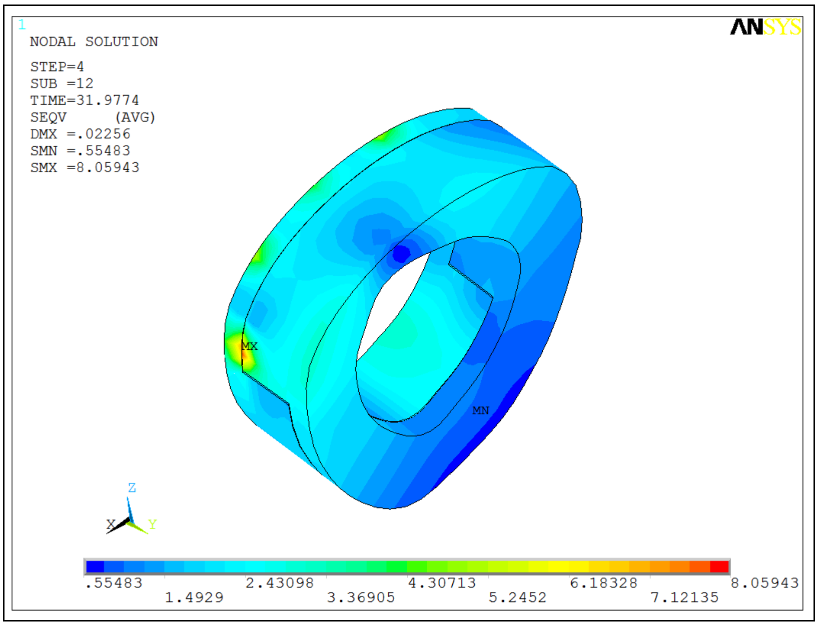


**Figure 23:** ***Von Mises stress distribution*** **[MPa]** ***calculated at the final step.***

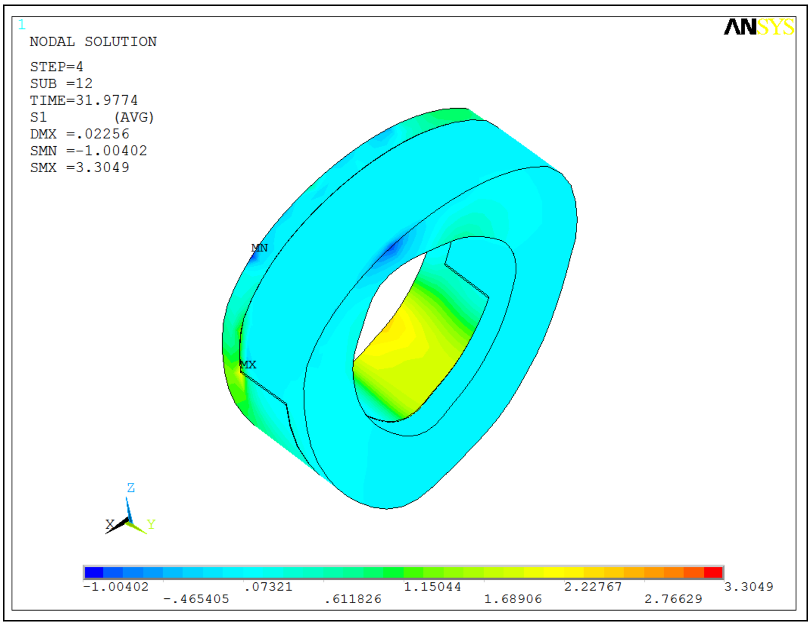


**Figure 24:** ***Distribution of the maximum principal stress*** **(tensile) - [MPa],** ***calculated at the final step.***

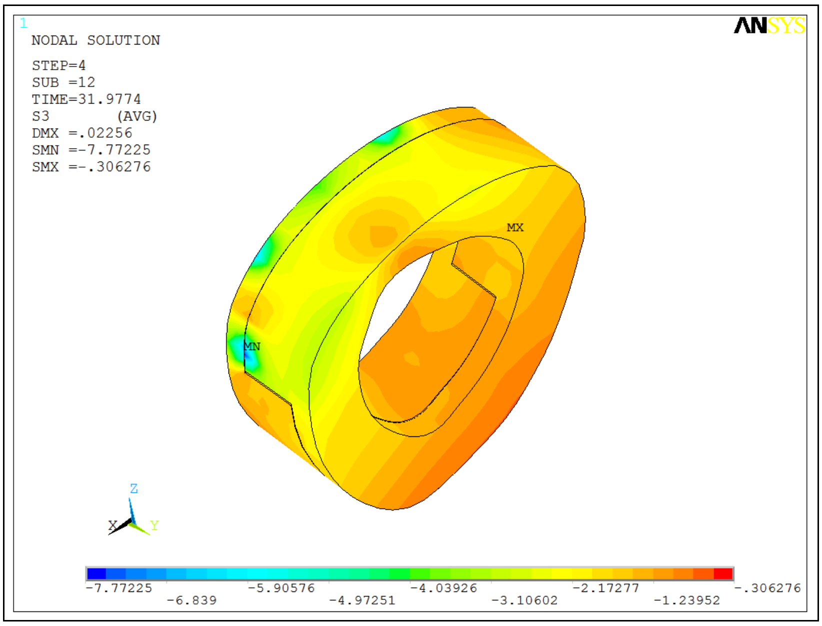


**Figure 25:** ***Distribution of the minimum principal stress*** **(compression) - [MPa],** ***calculated at the final step.***

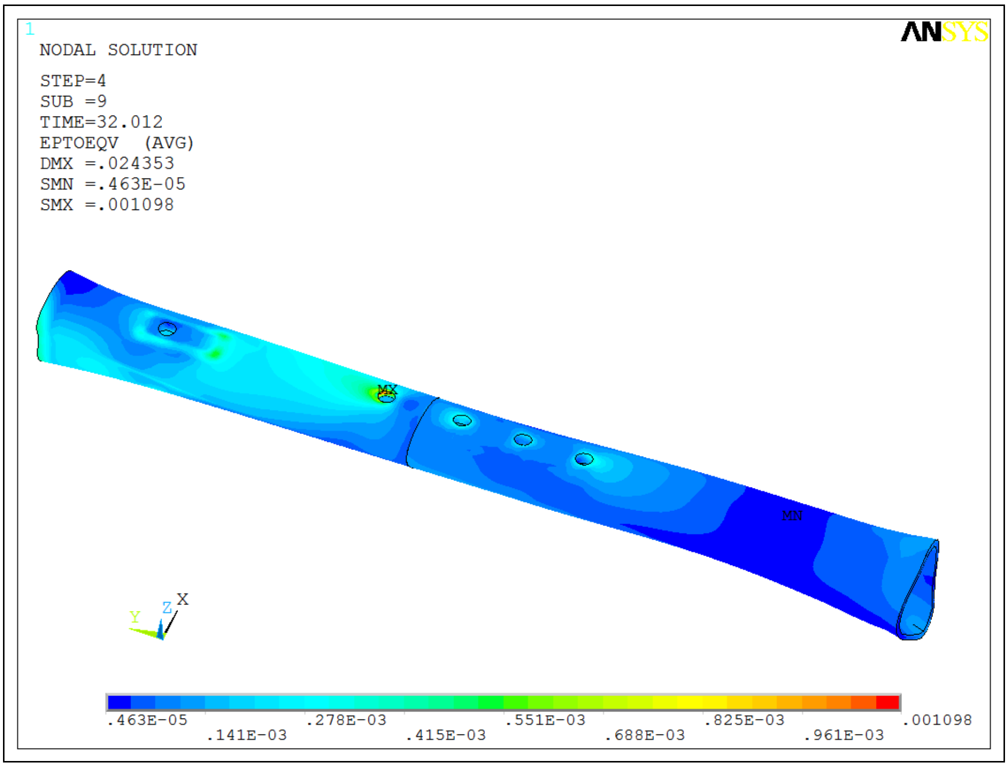


**Figure 26:** ***Von Mises specific strains distribution*** **[MPa]** ***calculated at the final step for both segments of bone.***

## Conclusions

1. Stress values calculated for the humeral shaft are in the range of values (2-8 MPa) beneficial for bone reconstruction.

2. It is noted that the use of compactor increase the tension of the screw surrounding cortical bone, used for its fixing.

3. The resulting finite element model provided results comparable to those presented by other authors. Thus, this model can be improved by assigning orthotropic material characteristics and used for other biomechanical studies.

4. It was noted that the fixation of those screws located closer to the fracture, determines to the bone a remoteness movement from conjugate bone. Therefore, a recommendation is that after using the compactor, plate fixation to be made starting with the farthest hole.

5. At the end of compaction common structures state recovers, such as bone work as a whole, which recommend compactor use.

6. The most uniform contact was achieved in "step resection" and the worst in oblique resection.

7. It was observed that the use of pretension force of 100 N, determines the acceptable bone tensions (7-10 MPa).

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