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SCUOLA DI INGEGNERIA INDUSTRIALE
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EXECUTIVE SUMMARY OF THE THESIS

Modellazione agli elementi finiti per lo studio del processo di piegatura di barre spinali in flessione a 4 punti: analisi di sensitività

TESI MAGISTRALE IN BIOMEDICAL ENGINEERING – INGEGNERIA BIOMEDICA

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ACADEMIC YEAR: 2020-2021

1. Introduction

The spinal column could be affected by many pathologies such as tumors, osteoporosis and deformities. In the worst cases a surgery is needed, and the implantation of spinal fixation devices is considered to be the main solution for the treatment of severe deformities and the stabilization of bone osteotomies [1]–[4]. Spinal rods are a primary element inside fixation devices and they typically undergo a bending process (called "contouring") to match the deformed spine curvature and allow the recovery of the physiological one. The rods contouring could be carried out at the end of the manufacturing step or during the surgery. Depending on this, different tools are used, which can achieve many types of curvature.

Clinical evidences point out rod breakage as the main cause of implant failure primarily due to mechanical fatigue [2], [4]–[6]. As a matter of fact, there are a lot of experimental analysis that focus on mirroring "in vivo" loads on spinal fixation devices. However, just a few of them investigate how the display of residual stresses within the rod as an aftermath of contouring could affect the fulfillment of the implant. Increasing awareness on how the contouring process is led would be very useful to avoid failures, reduce procedure costs and improve patient's life quality.

Hence, the aim of this thesis is to lead a sensitivity analysis on a titanium spinal rod by FE modelling of a uniform contour throughout a 4-points bending set up, modifying the radius of the rod contact elements (i.e.: rollers) and their material. Secondly, based on the results of sensitivity analysis, a best fitting phase is held, in order to get correlation between input and output variables related to the bending process.

2. Materials and Methods

This work is based on FE simulations that took place in ABAQUS (*Dassault Systemes Ri, Simulia Corp. Providence, RI*), where only a single bending technique has been modeled, a 4-points bending set up, some characteristics of which come from a previous study [1]. This method allows a uniform curvature on a large span along the rod length throughout the presence of four rollers. Two of them are named "support" rollers: they are kept fixed and the rod is placed on them; the others two are called "load" rollers: a straight downward movement is imposed on them in order to push the rod and producing a bending moment. In **Figure 1** the distribution of the bending moment in a 4-points bending configuration is schematized.

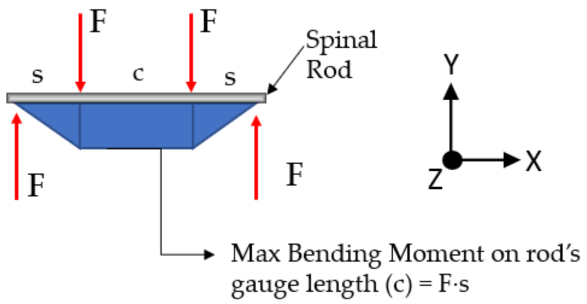

Figure 1: Representation of the bending moment acting on a rod due to a 4-points bending system.

2.1. Numerical Simulations

ABAQUS presents a user-friendly interface represented by different setting modules, where each aspect of the simulations is taken into account one by one.

The first step in the creation of FE models consists in the definition of the geometry of the parts involved. Rod is meant to be 100 mm in length and have a solid circular cross section (diameter = 5.5 mm), but it has been reduced to one fourth by means of symmetry planes. Rollers instead are designed with a semicircular cross section and reduced to half for the same reasons (**Figure 2**).

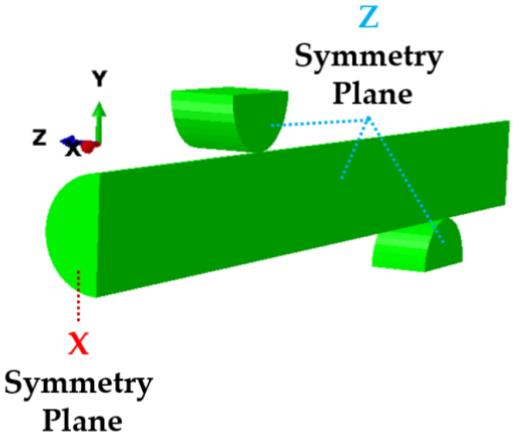

Figure 2: FE modelization of the 4-points bending set up: geometries are reduced by means of symmetry planes.

FE parts are then coupled with different materials, which are defined by their elastic properties (E, ν) and by a plastic curve that explains their behavior beyond the yield stress.

Load and support rollers were placed at a distance of 15mm and 40mm from the rod x symmetry plane (**Figure 2**) respectively, setting the relative distance between them at 25mm. The rod-roller interactions were defined as "surface-to-surface" contacts, and two different friction coefficients were used depending on the materials involved (see paragraph 2.3).

The contour procedure was divided into two steps:

- **Load step**: the load upper roller moves downward until it reaches the preset drop value;
- **Unload step**: the load roller ascends to its original position.

This is made possible through the definition of proper boundary conditions on each part of the model:

- **Load roller**: vertical displacement (U_Y=-2mm, -3mm, …, 8mm, -8.25mm, -8.5mm, -9mm) on rectangular face; Z-symmetry ($U_Z = 0$, $UR_{X,Y} = 0$);
- **Support roller**: encastre ($U_{X,Y,Z}=0$) on rectangular face; Z-symmetry ($U_Z = 0$, $UR_{X,Y} = 0$);
- **Rod**: X-Symmetry: $U_X = 0$, $UR_{Y,Z} = 0$; Z-Symmetry $U_Z = 0$, $UR_{X,Y} = 0$).

The last module is about parts meshing. The rod and the rollers parts are discretized with linear hexaedral elements with incompatible nodes (C3D8I) and reduced integration (C3D8R) respectively. The mesh design strategy is focused on the optimization of elements distribution: a greater number of elements is present at the contact regions both on rod and rollers, as well as on the edges of the rod x symmetry plane, where a more accurate description of results is needed.

2.2. Mesh Convergence

Before starting with the simulations execution a mesh convergence analysis has been carried out. Firstly, it was created a reference mesh that contained a considerable amount of elements (called "X1"). On its basis, three other meshes were defined multiplying the element sizes for a factor 1.5, 2 and 4 (named X15, X2, X4 respectively).

Then, for each mesh type a simulation was run, modifying roller material (steel or aluminum: see paragraph 2.3) and contact properties (frictionless or with a friction coefficient), for a total of sixteen jobs. The rollers radius (3mm) and the drop level of the load roller were kept fixed (-8mm). For mesh convergence analysis purposes were considered the maximum and minimum values of three quantities (Max Principal stresses, Von Mises stresses and Plastic Equivalent Strains - PEEQ), taken from rollers and rod x symmetry plane. Convergence was achieved when a difference lower or equal than 5% was found between subsequent mesh refinements. Equation 2.1 is an example:

$$\frac{X1-X1.5}{X1.5} * 100 < 5\% \qquad (2.1)$$

2.3. Sensitivity Analysis

The sensitivity analysis is focused on studying the 4-points contour technique on a titanium (Ti6Al4V; E=110GPa, ν=0.3) spinal rod with a solid circular cross-section (diameter = 5.5mm) in which the relative distance between load and support rollers was kept fixed. The influence on the results of the process is seeked by selectively modifying the materials and the radius sizes associated with the rollers.

Data extraction focused on four main dimensions: Stresses (S, Max Principal, Abs), Reaction Forces (RF), PEEQ (Equivalent Plastic Strain), and NFORC (Nodal forces due to element stresses), thanks to which is possible to evaluate a number of quantities in order to study many aspects of the rod contour process:

- Maximum stress inside the rod during load, [MPa];
- Vertical reaction force component acting on rollers (RF2, [N])
- Theoretical bending moment: vertical reaction force component (RF2) x rollers distance, [Nmm]; effective bending moment (NFORC 3, [Nmm]).
- Plasticized area at the x symmetry plane, [%];
- Rod residual radius of curvature, [mm];
- Localized plastic deformations (PEEQ) at rod-roller contact region and at the x symmetry plane, [-];
- Residual stresses, [MPa].

Rollers material sensitivity

In order to investigate the effect of rollers material on the bending process, two metal alloys are considered: stainless steel (AISI 1010; E=210GPa, ν=0.3; Ti6Al4V-steel friction coefficient = 0.175) and aluminum (Al 2024-T3; E=70GPa, ν=0.3; Ti6Al4V-aluminum friction coefficient = 0.4). For each of the aforementioned couples of quantities is held a comparison between the data coming from simulations run with steel and aluminum rollers.

Rollers radius sensitivity

Similarly to the material sensitivity, to analyze the effect of rollers dimensions, three rollers radius sizes equal to 3mm, 4mm and 5mm are contemplated.

According to rollers material and radius the simulations are splittable into six sets (**Table 1**) including eight simulations each.

A simulation is marked by the drop value the load roller should reach at the end of the loading step (-2mm, -3mm, …). The highest drop value in a set of simulations corresponded to the maximum stress the rod material could bear (1133MPa). In this way a range of action has been delimited, in which is possible to investigate the effects of contouring at many load levels.

Table 1: Simulations planning based on rollers materials and radii.

		Rollers materials	
		Steel	**Aluminum**
Rollers radii	**3mm**	**3mm Steel**	**3mm Aluminum**
	4mm	**4mm Steel**	**4mm Aluminum**
	5mm	**5mm Steel**	**5mm Aluminum**

2.4. Best Fitting

Throughout MATLAB it is possible to achieve some analytic equations able to best fit the extracted data. This phase could be useful to provide a easy-to-use tool able to anticipate the rod contouring outcomes. In order to do that, three types of equation are selected as the most appropriate to best fit the available data: both three (2.2) and two (2.3) coefficient power laws [7]:

$$f(x) = a\cdot x^{b} + c \;; \tag{2.2}$$

$$f(x) = a\cdot x^{b} \;; \tag{2.3}$$

and a two coefficients polynomial equation (2.4):

$$f(x) = p1\cdot x + p2 \;; \tag{2.4}$$

Load roller drop and bending moment were selected as input variables, while the output ones were chosen to be bending moment (when roller drop is used as input), rods residual radius of curvature and the % of plasticized area at the rod x symmetry plane.

3. Results and Discussion

3.1. Mesh Convergence

Figure 3 shows the computational time that occurred to run each of the sixteen simulations.

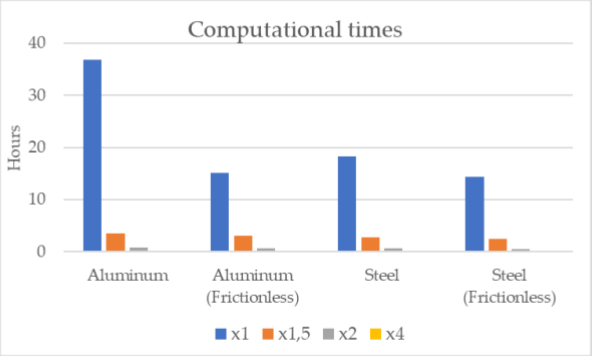

Figure 3: Computational times for each of the sixteen simulations executed for the mesh convergence analysis.

It's very remarkable the difference between mesh X1 and X4; but also considering the same mesh type, especially for the aluminum case (36h 52 minutes for X1 and 18h 14 minutes for frictionless X1). A more deformable roller material together with friction forces induce rollers to experience a severe plastic deformation of the contact region along the bending process. This is represented by a greater mesh distortion that could make increase computational efforts.

Regarding the rod, convergence has been achieved in almost every case, considering PEEQ and Principal Stresses values on the x symmetry plane.

Von Mises stresses instead did converge limitedly to maximum values. On the other hand, convergence is hardly achieved with rollers, which undergo a plastic deformation localized in the contact region.

By looking at these results mesh X1.5 was chosen as the solution that could give the best description of results in a reasonable amount of time. So, it has been selected to carry on the sensitivity analysis.

3.2. Sensitivity Analysis

Rollers material sensitivity

Roller Drop vs Maximum stress

Steel rollers allowed to reach higher levels of roller drop (9mm, average) with respect to aluminum ones (8.3mm, average) before the rod reached the limit stress value of 1133MPa.

Roller Drop vs Bending Moment

After the yield point is reached on the x symmetry plane, the theoretical bending moments for the aluminum rollers are growing faster with respect to the steel ones. This evidence it's not expected since steel is a stiffer material. Rollers indeed are undergoing a deformation process (as mentioned in the convergence analysis), which is more prominent for aluminum ones. This aspect, together with the plasticization of the rod, is thought to bring a quick increment of the contact region that may lead to higher reaction forces and thus, momentum.

Bending moments computed using NFORC shows instead a different behavior with respect to the previous case, in which slightly higher values are achieved with the steel roller (14327Nmm vs 13820Nmm: values averaged at the end of the load step). This consideration matches with the expected bending moment trend during the load phase.

As a support of this, it should be taken into consideration the percentage of plasticized area at the rod x symmetry plane, which reached the 70.92% with steel rollers at the end of the bending process and the 65.2% with aluminum. It seems more realistic to achieve an higher plasticization level when a greater load is imposed indeed.

For this reason, the bending moment computed multiplying RF2 by the rollers distance is considered to be not a proper way to measure the acting moment on the rod

Bending Moment (NFORC) vs Residual Curvature Radius

This couple of variables highlights the differences between the two materials of rollers mentioned in the previous paragraph.

In the case of steel rollers, there are higher bending moments related to a certain roller drop level and residual curvature radii are lower (which means higher rod curvatures). For example, with steel rollers, at a drop level of -8mm, the mean bending moment is equal to 14127 Nmm and the associated radius of curvature is 104mm; for the aluminum case the bending moment reaches a mean value of 13760Nmm for a mean radius of curvature of 120mm. These results show how, at the same drop level, steel rollers are able to produce a higher bending moment acting on the rod, which causes more evident contour effects.

Bending Moment (NFORC) vs PEEQ Max

The results shows that steel rollers produce higher PEEQ values at the contact region at a certain bending moment with respect to aluminum. This is an expected evidence mainly due to the lower deformability of steel.

However, the PEEQ values extracted from the symmetry plane can confirm and expand the previous results regarding the percentage of plasticized area. The steel rollers generated a mean maximum PEEQ value of 3.40 at the end of the load step, while aluminum ones only reached 2.60. This is another indicator that shows how the contouring is being effective on the "gauge length" of the rod.

Residual Stresses

With respect to aluminum ones, steel rollers axhieved better results in terms of plastic deformation of the rod (radius of curvature, % plasticized area at the x symmetry plane). However, residual stresses mirrors this condition with a more intense state of stress all along the gauge length of the rod (steel max values: 562MPa/-524MPa; aluminum max values: 501MPa/-517MPa), (**Figure 4**). Moreover, still concerning steel rollers, the rod-rollers contact regions are characterized by a more intense and wide concentration of tensile (load roller) and compressive (support roller) residual stresses.

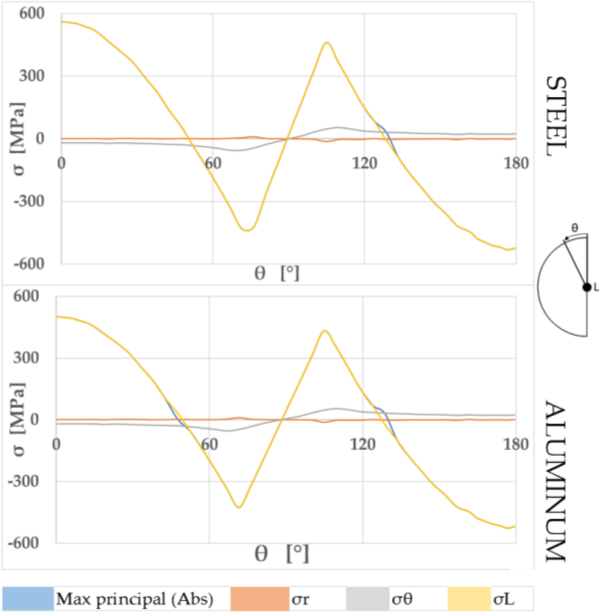

Figure 4: Residual stresses components profiles (based on a cylindrical reference frame) computed along a circumferential path along the x symmetry plane of the rod.

Rollers radius sensitivity

Roller Drop vs Maximum stress

The effect of rollers sizes seems to be strictly dependent from their material: only regarding aluminum, 3mm rollers allowed slight higher roller drop (8.5mm) with respect to 4mm and 5mm (8.25mm).

Roller Drop vs Bending Moment

Only considering the theoretical bending moment (computed through RF2) can be seen a difference between the three rollers dimensions: 5mm rollers achieve higher values, followed by 4mm and 3mm.

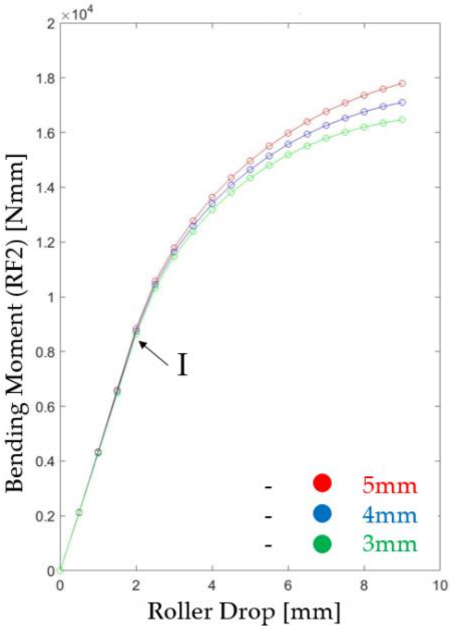

Figure 5: Bending Moments during load step: roller radius effect.

Yet, this is true only after the first plasticization of the rod x symmetry plane occurs (**Figure 5**, (I)). The fact that bigger rollers show higher values of bending moment at a certain drop level is reasonable, since the system has increased its overall stiffness. However, this difference should be visible from the beginning of the bending process. For this reason, considering RF2 bending moments, the role of rollers radius seems to be related to the rod deformation. In addition, the boundary conditions set on the rollers doesn't mirror the reality of a 4-points bending set up, in which cylindrical rollers are free to rotate and are subjected to a bending moment. In this case, the whole system stiffness would be more evident, as well as the effect of the rollers size.
For what concerns NFORC bending moments, they are not sensitive to rollers dimensions since are extracted from the x-symmetry plane, and so, an evident difference is not visible.

Bending Moment (NFORC) vs Residual Curvature Radius
The same explanation holds also for this couple of quantities, for which no relevant effects could be found.

Bending Moment (NFORC) vs PEEQ Max
3mm rollers leads to higher values of maximum PEEQ in the rod-roller contact region with respect to 4mm and 5mm. This is an expected result since smaller rollers provide a tighter contact region, where stresses are more concentrated and local deformations could easily take place.

Residual Stresses
Once again, the effect of rollers dimensions is limited to very small differences, such as the intensity and the width of tensile and compressive stresses at the rod-roller contact regions. Anyway, it's not evident a correlation with roller size.

3.3. Best Fitting

For the couples of quantities that involved roller drop as the input variable, the three coefficients power law (2.2) allowed the best fitting of data; instead, for "bending moment – % plasticized area" and "bending moment - residual curvature radius" couples the two coefficients polynomial (2.4) and two coefficients power law (2.3) equations were needed respectively. For each case the coefficient of determination R^2 and adjusted-R^2 is greater than 0.99, so it could be concluded that the chosen analytical expressions fulfill their best fitting purpose.

4. Conclusions

This thesis study focused on a single contouring method and tried to analyze the effects by changing some parameters involved in it.
The roller material is found out to be the most important aspect that could affect the procedure. In particular, steel rollers seem to work more efficiently with respect to aluminum ones because at a certain roller drop level they generate higher bending loads with which is possible to achieve greater curvature effects. Nonetheless, the steel roller solution could easily bring to a more intense residual state of stress inside the rod for which more awareness in its use may be recommended.
On the other hand, the roller size doesn't seem to affect much the process. This may be mainly due to the simplifications made while setting the geometry and the boundary conditions of the rollers in the FE model.

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