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STRUCTURAL VALIDATION OF INTRAMEDULLARY NAILS: FROM EXPERIMENTATION TO VIRTUAL TESTING

D. Croccolo, M. De Agostinis(*), S. Fini, S. Funaioli, G. Olmi, F. Robusto
Department of Industrial Engineering, University of Bologna, Italy
(*)*Email:* m.deagostinis@unibo.it

ABSTRACT

Closed intramedullary nailing has become the “gold standard” in the treatment of displaced fractures of the tibial shaft. The material of choice for the manufacturing of intramedullary nails is Ti-alloy, while the structural performance requested to these components is steadily growing. Validation procedures pertaining to these components comprehend both compression and torsion tests. Finite element analysis could help shrinking down the time required for new product development, as fewer full scale experimental tests would be needed in the early design stages. In order for numerical models to be representative of the actual test, a number of parameters has to be accurately chosen: particularly, contact modeling must be fine-tuned based on experimental data. This contribution provides guidelines for the correct contact settings to use, referring to the Ansys software.

Keywords: intramedullary nail***,*** FEA***,*** contact, joint.

INTRODUCTION

Closed intramedullary nailing has become increasingly popular in the treatment of displaced fractures of the tibial shaft [Leung *et al*., 2006]. Due to their comparatively compact dimensions, intramedullary nails require high performance materials in terms of mechanical properties. Both titanium alloys and stainless steels have been used for the construction of such devices, even if, there has recently been evidence of better performance of titanium alloy nails, versus stainless-steel counterparts [Riemer *et al*., 1995]. In accordance with relevant international standards, two tests are required for the validation of a new nail: a static four-point bending test and a torsional test. Moreover, manufacturers usually run internal validation tests also for the loading case of axial compression. The development of an accurate finite element analysis would allow performing a quick identification of the most critical combination of nail size and testing conditions. This would in turn mean to shrink down the development time needed for the release of new products. Besides adequate modeling of the material response, a proper contact modeling strategy is critical in order for the numerical model to accurately represent the experimental test. The present contribution focuses on non-linear contacts and their formulation: although some authors provided contributions describing finite element models of intramedullary nails [Simpson *et al*., 2008], none focused on how to properly choose the contact settings between the nail and the fixtures. This contribution aims at filling such a lack of information. Although the data provided in the present contribution is referred to the Ansys software, it can easily be extended to other commercial FEA softwares.

MATERIALS AND METHODS

The intramedullary nail object of the present investigation is made of Ti6Al4V ELI [ASTM, 2013] according to the general dimensions reported in Figure 1. The test fixtures used in the experimentation, are manufactured from AISI 304 [EN, 2014]. The mechanical properties of the materials are reported in Table 1.

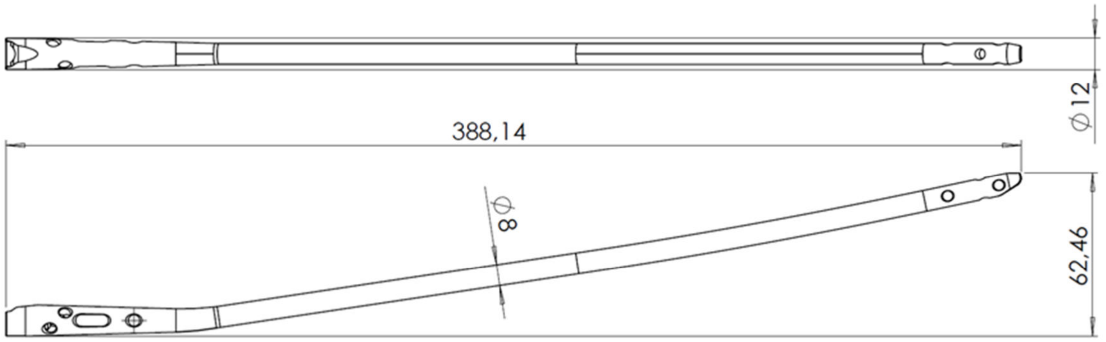

Fig. 1 - Geometry of the tibial intramedullary nail object of this study

Table 1 - Mechanical properties of the materials

Ti6Al4V ELI

$\boldsymbol{S_u}$ [MPa]	$\boldsymbol{S_y}$ [MPa]	$\boldsymbol{E}$ [GPa]	$\boldsymbol{\nu}$	$\boldsymbol{\rho}$ [kg/m^3]
860	795	114	0.31	4430

AISI 304

$\boldsymbol{S_u}$ [MPa]	$\boldsymbol{S_y}$ [MPa]	$\boldsymbol{E}$ [GPa]	$\boldsymbol{\nu}$	$\boldsymbol{\rho}$ [kg/m^3]
500	190	200	0.29	7900

Torsional tests have been performed on a “MTS 858 mini bionix II” axial and torsional servohydraulic machine. Three repetitions for each of the following constraint configurations were executed, using nominally identical specimens: (i) proximal pins and distal pins (PP_DP), (ii) proximal pins and distal screws (PP_DS), (iii) proximal screws and distal pins (PS_DP), (iv) proximal screws and distal screws (PS_DS). The rationale behind this different configurations is that, during testing, the screws (which are actually used to secure the nail to the bone) may be conveniently replaced by parallel pins. Then it is interesting to check whether the simplifications adopted during testing entail significant differences in terms of overall stiffness with respect to the actual application.

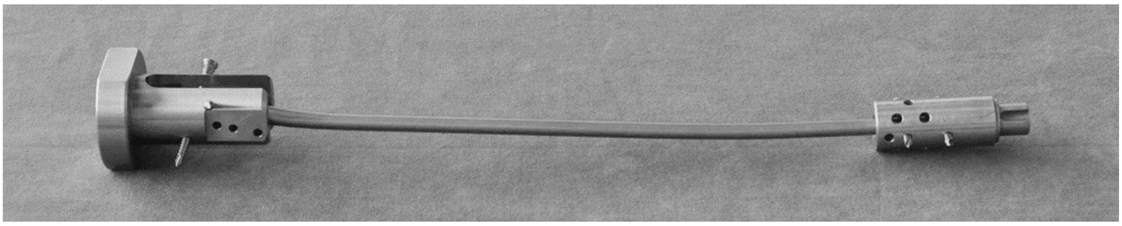

Fig. 2 - Fixtures configuration for the torsional test: a screw mounting is depicted here.

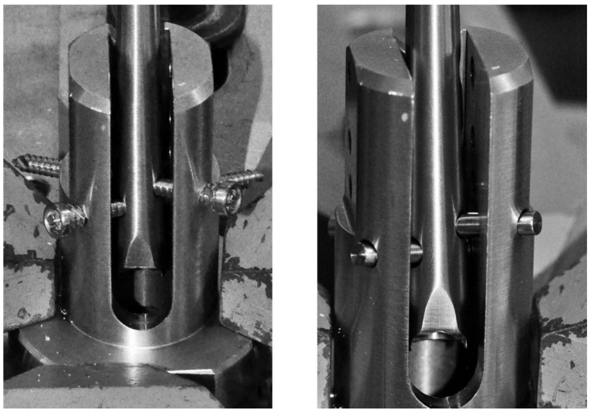

Fig. 3 - Proximal constraints - Screws (left) and pins (right)

A screw mounting of the nail can be seen in Figure 2, whereas the difference between screw and pin mounting at the distal end of the nail can be appreciated by looking at Figure 3.

In order to avoid a statically indeterminate system, the distal end has been connected to the actuator by a double universal joint. The tests have been executed under displacement control, by imposing a rotation equal to Θ = 5 ° at a constant angular velocity of ω = 5 °/min. Results in terms of torsional moment Mt at the fixed end have been measured.

Finite element analyses have been carried out by the ANSYS Workbench R17 software. The results in terms of torsional reaction moment obtained by FEA have been compared with the torsional moment experimental reading. This comparison guided the choice of the proper contact parameters in the numerical model. Contacts between pins and fixtures have been set as bonded, whereas contacts between pins and nail have been set as frictional. The “Adjust to touch” option has been enabled and the friction coefficient has been set to 0.3 [Croccolo, 2017]. The distal fixture has been fixed at the bottom, whereas a rotation of Θ = 5 ° has been imposed to the upper face of the proximal fixture.

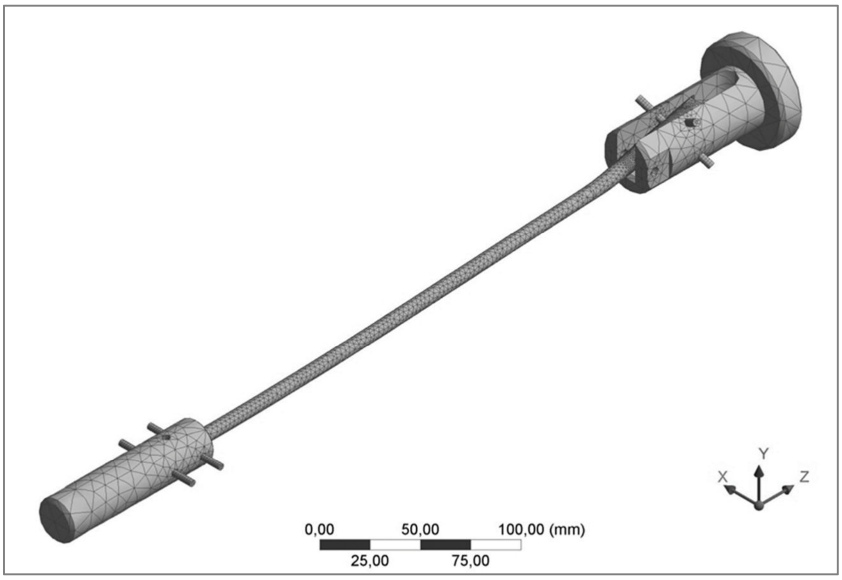

Fig. 4 - FEA model of the nail

Frictional contacts have been detected on Gauss' points. The mesh has a general element size equal to 3 mm: a refinement in the contact regions has been applied, with an element size of 1 mm. The result is a total element count of 49,415 SOLID186 and SOLID187, for a total number of nodes equal to 83,697: the meshed geometry is shown in Figure 4. By tuning the normal stiffness factor of the frictional contacts, a comparison with the experimental results has been carried out.

RESULTS AND CONCLUSIONS

Table 2 reports the experimental results in terms of torque reaction for the different constraint options. An analysis of variance applied to the experimental data, allows to state that the constraint methodology does affect the torsional stiffness: in fact, with a F_{calc}=5.73, and a significance level of 5%, a p-value=2.2% can be calculated. Particularly, it can be noticed that combination between proximal pins and distal pins (PP_DP) is the stiffest assembly condition.

Table 2 - Experimental moment reaction as a function of the constraint type

Proximal pins and distal pins	**Test N.**	**θ [°]**	***Mt* [Nmm]**
	1	5	4301
	8	5	4341
	9	5	4345
	Mean	5	4329
	St. Dev.	-	24
Proximal pins and distal screws	**Test N.**	**θ [°]**	***Mt* [Nmm]**
	2	5	4213
	7	5	4203
	10	5	4233
	Mean	5	4216
	St. Dev.	-	15
Proximal screws and distal pins	**Test N.**	**θ [°]**	***Mt* [Nmm]**
	3	5	4237
	6	5	4295
	11	5	4341
	Mean	5	4291
	St. Dev.	-	52
Proximal screws and distal screws	**Test N.**	**θ [°]**	***Mt* [Nmm]**
	4	5	4299
	5	5	4232
	12	5	4269
	Mean	5	4267
	St. Dev.	-	34

As for the fine tuning of the FEA model, Pure Penalty and Augmented Lagrange formulations have been analyzed for the contact areas, showing that there is no significant difference between these two approaches in terms of stresses on the nail. Nonetheless, the Augmented Lagrange formulation was preferred, because it favors convergence. The normal stiffness factor FKN resulted to be the most important contact parameter that governs the contact response. In particular, a normal stiffness factor equal to FKN = 0.04 shall be adopted, in order to accurately represent the global torsional stiffness response of the nail, as shown in Figure 5.

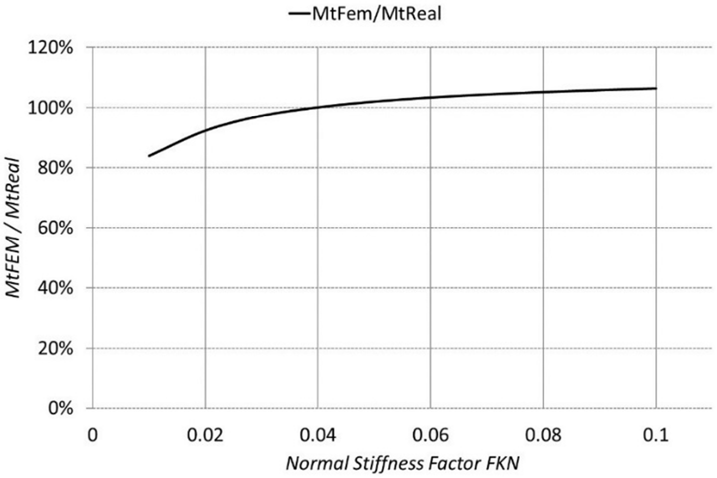

Fig. 5 - FEM torque to experimental torque ratio versus normal stiffness factor FKN

As a double check, under the same contact settings, an axial compression test has been run. A comparison between the experimental and numerical results for this load scheme is reported in Table 3: the same contact settings provide a good agreement between FE and experimental results, in this loading scenario as well.

Table 3 - Axial compression test: FEM displacement versus experimental displacement (FKN=0.04)

	F_Z [N]	Δz [mm]	***Error***
Experimental results mean	500	1.143	-
Finite element analysis	500	1.042	-8.8%

The FEA model defined according to the aforementioned specifications would allow performing a quick identification of the most critical test condition and/or combination between testing condition and nail size. Such a model will help shrinking down the development time of new products.

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