# Spinal rods contouring: an experimental and finite element study to control fatigue

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***Abstract*****—French bender is the clinical gold standard for spinal rod contouring. Despite it allows the surgeon in achieving any desired shape, it is believed to weaken the implants, finally promoting fatigue failure. The current study proposes a new method combining non-linear FE models and experimental tests to better understand the role of residual stresses resulting from contouring. Learning how to control this phenomenon may contribute in reducing the high failure rate met during clinical use, as well as improving the usage of current implants.**

***Keywords*****— Spine rod contouring, French bender, residual stresses, fatigue.**

## I. Introduction

POSTERIOR spinal fixation through long constructs represents the gold standard for a variety of clinical disorders. Long deformities (e.g. scoliosis) or the stabilization of bone osteotomies represents few examples [1, 2]. In all these cases, the surgeon is expected to adapt the rod to restore the natural spine curvature through *contouring* [3].

Despite preformed spinal rods with *uniform curvature* are available in the market, the clinical gold standard for contouring is *French bender*, which allows achieving even sharper angles.

Clinical experience demonstrated high failure rate of contoured spinal rods due to the cyclical loads occurring in everyday life, i.e. mechanical fatigue [2, 3]. However, such events cannot be explained only due to the relatively low loads met during clinical use [1, 4].

Among the key factors influencing fatigue failure, very little attention was directed towards the comprehension of how alternative contouring methods affect the residual stress field within the implant [5]: understanding and controlling these factors would be decisive to prevent hardware failure in clinical practice.

The aims of current study is to test the contribution of residual stress introduced through contouring obtained with a French bender on the fatigue behaviour of spinal rods.

## II. Material and Methods

### A. Static French bender contouring

To study the contribution of contouring, the available Ti6Al4V spinal rods (diameter 5.5 mm) were divided into different groups. Straight rod (n=5) served as a reference. FB rods (n=10) were contoured using the French bender on ad-hoc guides to achieve a desired 150 mm curvature radius (Fig.1, top-left).

The FE model of French bender contouring (Fig.1, bottom-left) was virtually reproduced in Abaqus Standard CAE 6.14-1 (Dassault Systemes Ri, Simulia Corp. Providence, RI, USA). The experimental elasto-plastic material properties characterized through tensile tests were assumed (E=110 GPa, $\nu$=0.3, $\sigma_Y$=886 MPa, $\sigma_U$=1134 MPa, $\varepsilon_U$=5.35%). Contouring step was simulated applying a vertical displacement to obtain a local curvature radius of 150 mm [5]. Residual stress distribution (following release) and maximum equivalent stress components (upon loading) were compared across each group.

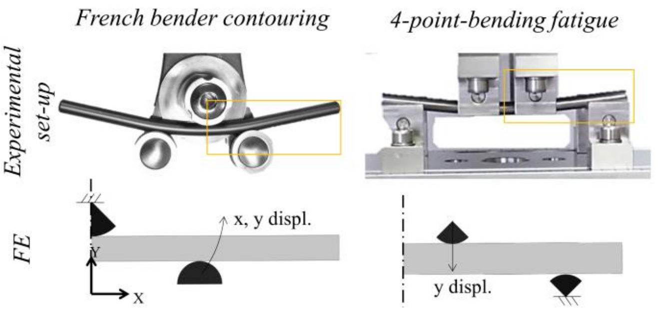


Fig. 1: French bender contouring (left) and 4-point-bending fatigue (right): Experimental set-ups (top) and FE model (bottom). contouring (top) and FE model (bottom).

### B. 4-point-bending fatigue

Spinal rods were experimentally tested on a custom-made 4-point-bending jig (Fig.1, top-right) [6] applying a sinusoidal load with a maximum of 930 N (load ratio R of 0.1) up to 1 Mcycles (run-out). Mann-Whitney statistical test allowed to highlight differences in the number of cycles to failure among groups ($p \leq 0.05$ significance level).

To describe thoracic and lumbar implantation sites, two loading configurations were considered for FB rods (Fig. 2):

- FBL (n=5): representative of a bending moment in flexion on lumbar region,
- FBK (n=5): representative of a bending moment in flexion on thoracic regions.

Fatigue loading following French bender contouring was also simulated in 4-point-bending, reproducing the loading-unloading cycles applied during tests (Fig.1, bottom-right). The predicted stress components upon loading and unloading were used as an input for a Matlab script V.15 (Mathworks, Natick, Massachusetts) to calculate the maximum equivalent stress according to *Sines* criterion:

$$\sigma_{Sines} = \sigma_{VM,a} + K \cdot I_m \tag{1}$$

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where $\sigma_{VM,a}$ = alternate component of von Mises stress, K= $\sigma_{FA,f}$ / $\sigma_U$ = 0.6 and $I_m$ = average component of the first stress invariant. The maximum equivalent stress was compared to the fatigue limit at 1 Mcycles ($\sigma_{FA,f}$), while its location was compared with the experimental fracture points.


Fig. 2: Configurations compared during 4-point-bending fatigue.

## III. Results and Discussion

### A. Static French bender contouring

The FE model was used to tune the proper boundary conditions to apply on the rods: the experimentally-contoured rods resulted in a satisfactory local curvature radius of 154.0±5.8 mm.

The FE model predicts extensive sections undergoing yielding upon contouring, resulting in a tensile residual stress after release at the concave side, conversely compression is reached at the convex side (Fig. 3). Numerical predictions are significantly affected by the assumed post-yielding properties [5].

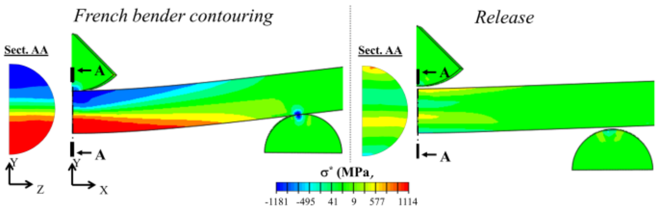


Fig. 3: Configurations tested during fatigue tests.

### B. 4-point-bending fatigue

Experiments demonstrated a significant reduction in fatigue resistance for lordotic rods (FBL) compared to straight ones ($p<0.05$), while kyphotic rods (KBL) reached the run-out (Table 1).

TABLE I
Experimentally-measured number of cycles to failure ($N_F$) and numerically-predicted equivalent stress ($\sigma_{Sines}$)

| | $N_F$ *(# of cycles)* | $\sigma_{Sines}$ *(MPa)* |
|---|---|---|
| *Straight* | *305894 ± 236623* | *728 §* |
| *FBL* | *21789 ± 4616 ** | *932 §* |
| *FBK* | *run-out* | *651* |

**: $p<0.05$ compared to straight rods. §: >$\sigma_{FA,f}$.*

Coupling FE models with Sines criterion correctly predicts the experimental site of fracture initiation and propagation, as well as helping interpreting the effect of tensile residual stresses. In FBL configuration, the effect of fatigue loading superposes to the tensile residual stress at the concave side, involving higher mean hydrostatic stress components (+55% in $I_m$ compared to straight rod). In FBK configuration, the effect of fatigue loading superpose to the compressive residual stress at the convex side, involving lower alternate stresses and lower mean hydrostatic stress components (respectively, -28% in $\sigma_{VM,a}$, -55% in $I_m$ compared to straight).

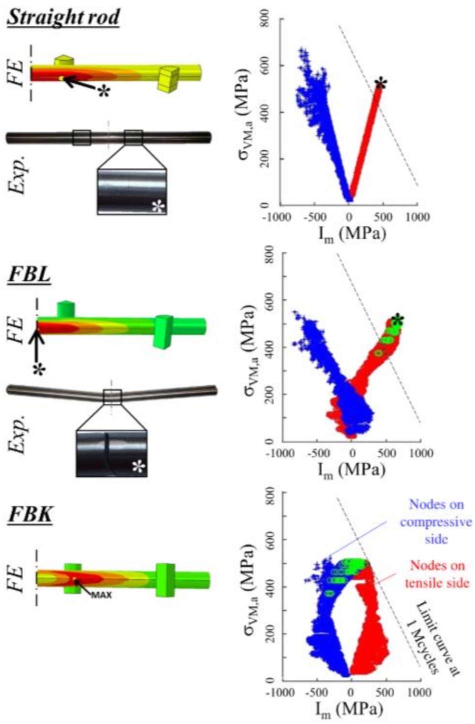


Fig. 4: Comparison between the predicted most stressed region (top-left) and the experimental fracture location (bottom-left): * indicates where the equivalent stress reaches its maximum. Haigh diagram (right).

## IV. Conclusion

The validated FE models here presented allow describing the important role of local residual stresses due to spinal rod contouring on static and fatigue behaviour in simplified controlled-conditions. Such procedure may be easily extended to study other elasto-plastic material, as well as to optimise the mechanical/thermal treatments to apply on spinal rods before clinical use.

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