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Experimental and numerical study on the re-anchoring of wire in grouted prestressed tendons

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ABSTRACT

Some recent researches have focused on strand wire damage in external prestressing tendon. When some strand wires of a grouted prestressing cable are damaged, the tension in the cable can be preserved due to the re-anchoring phenomenon. For safety issues, it is important to study the damage limit that a tendon can suffer before the rupture. While the re-anchoring of a strand is well studied, there is less literature on wire re-anchoring. In this study, we tested grouted seven-wire strands which are put under tension and then cut out wire by wire to simulate the wire damages. The re-anchoring is observed by strain gauges installed in the strands and on the sheath. In addition, a numerical model has been developed with the help of FEM to analyse the mechanical phenomenon during and after the wire cuts. The results show that the tendon is bent and twisted because of the loss of tension and moment when one or several wires are cut off. Moreover, the strand strain is various following the gauge position in each wire and its distance to the cut section. This result contributes to the comprehension of the wire damages in grouted tendons, and could be extended to grouted multiple-strand tendons.

Keywords: external prestressing, prestressed tendon, strand wire damage, wire re-anchoring

1 INTRODUCTION

The re-anchoring of tendons with a whole broken strand was reviewed by Abdelatif, Owen and Hussein (2017). The re-anchoring occurs due to friction. The mechanical characteristics of steel and concrete turn out to be the main parameters influencing the re-anchoring length. This result was confirmed by experimental studies of Watanabe et al. (2011). The re-anchoring is similar to a pretensioned strand bond, studied in some articles such as Oh, Kim, and Choi (2006) or Ramirez-Garcia et al. (2016), which take into account loss of grout strength due to cracking. It suggests that the stress of the strand changes exponentially from 0, at the cutting position, to the final stress value, at a distance called transfer length from the cut strand. The Poisson's effect causes the cut end to adopt a wedge-like form that leads to friction with the other wires and the grout. Furthermore, the loss of tension in the wire unfolds the wire and thus increases the contact with the concrete; this is called the Hoyer effect, Briere et al. (2013). The re-anchoring of a whole strand is presented in several

construction codes such as American Concrete Institute 2011, Eurocode EN-1992-1-1(2004) (§8.10.2), and British code CS 455 (§8.3.1). According to these codes, the re-anchoring length of a cut strand is of the order of one meter.

Ghoreishi et al. (2007) have reviewed the difference generalized stiffness models for 7 wires strand. In those model, individual wires are modelled as beam in the Frenet coordinate system. Depending on the model, the friction, Poisson effect, and the wire flattening are considered. 3D finite element models of strand with contact conditions have been developed by de Menezes and Marczak (2021), Zhang and Ostoja-Starzewski (2016), Judge et al. (2012) or Karathanasopoulos et al. (2017). These articles focus on the generalised mechanical behaviour of the strand.

When no wire is cut, each helical wire has the same tension, which is proportional to the central wire tension Foti and Martinelli (2019). Otherwise, the re-anchoring of a strand wire has been studied by MacDougall and Bartlett (2006). This study shows that the cutting of a wire of a strand not subjected to radial confinement but deflected leads to a re-anchoring length of more than 10 meters. When a wire is cut on a monostrand, the stress in the wire is redistributed according to the angle made by the wire, the central wire and the cut wire, as shown in FIGURE 1. The re-anchoring is partial and the strand tension decreases by 2-4 % for each cut (in a seven-wire strand, each wire account for around 14% of the tension). They assume that stress redistribution is symmetric but non-homogeneous.

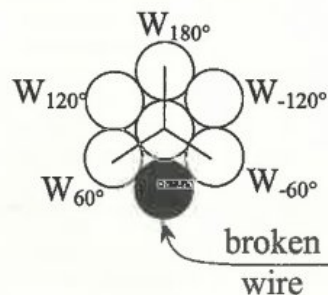


Fig. 9—Coordinate axes describing location of unbroken outer wires.

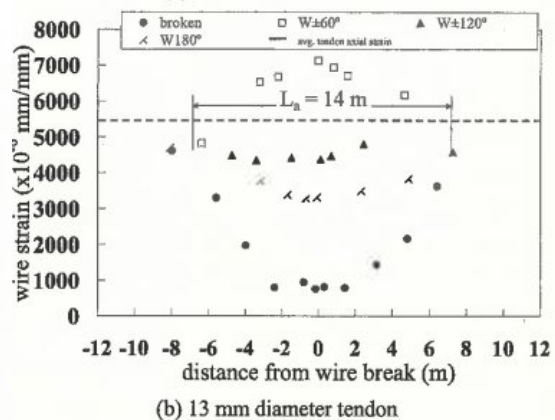


FIGURE 1 Left different class of symmetry in a strand with one broken wire. Right strain in the different wire after breaking of a wire. Both extracted from MacDougall and Bartlett (2006)

Beltran et al. (2018) used analytical and FE models to derive the static response of a strand with broken wires. Other finite element models of strands with broken wires have been developed by Abdullah et al. (2016a and b). In the second article, wires are cut with radial confinement done by other steel strands tied together. This radial confinement is less efficient than the one presented in the present paper. The measured transfer length between the cut and the end of the bench is more than 30 meters.

The study proposed in this paper aims at understanding the mechanical evolution of a grouted monostrand in which the steel wires were damaged. Three 50 m long grouted monostrands were built and damaged until the rupture of the cable. The tendons were monitored while they were damaged. A numerical model faithful to the built tendons was created to further enhance the understanding of the mechanical behaviour of a monostrand.

2 EXPERIMENTAL CAMPAIGN

The experimental tests were performed on a 200 m bench at Gustave Eiffel University (UGE) in Nantes - France (see Figure 3). This campaign was funded by the AFSA (Association des sociétés françaises d'autoroutes). Three tendons were built by Freyssinet company. First, the strands were put through the anchoring system and HDPE sheaths. In the first two tests, the central sheath was transparent PVC in order to be able to visually follow the propagation of the cracks in the grout. The PVC and HDPE sheaths were linked with a screw connection. The anchoring systems were installed at the two ends of the tendon with a force sensor at the passive end. Then, the tension was applied with a jack at the active end to a tension of 70 % of the strand strength and the tendon was injected with Superstressem grout. The tension of the monostrands before the cut test was between 186 kN and 204 kN. The tendon have a length of 46.6 m and the grout rested for 7 days before the cutting. A 20 cm hatch (10 cm for the third tendon) was made in the sheath by removing the grout in order to access the strand wires. The wires were cut manually, one by one, with of a rotating Dremel (see Figure 2).The tension was measured by a dynamometric cell at the tendon passive end. Some strain gauges are glued on the wires and the HDPE sheath.

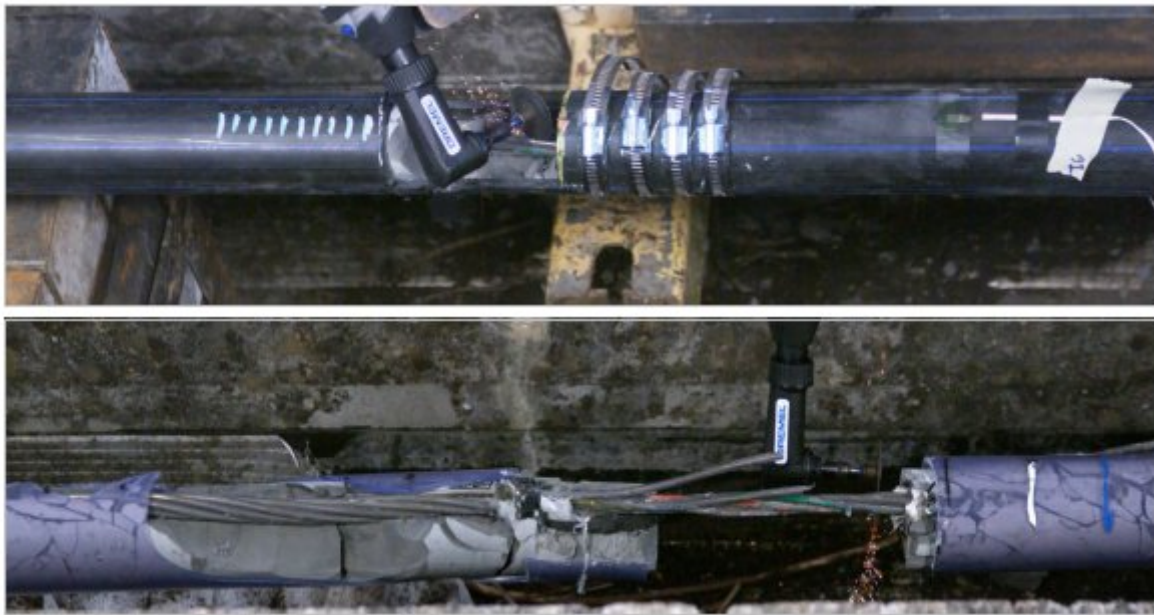


FIGURE 2 Cutting of wires on the 3rd and 2nd tendon

A limit of this experiment is that we cannot reproduce the corrosion in the strands. The wire breaking occurs due to mechanical cutting and not corrosion. Another limit is that only monostrands were tested. Grouted prestressed tendons are mostly composed of multiple strands, usually 19. Furthermore, a 10 cm hatch was done to reach the wires with the saw, which has a mechanical impact.

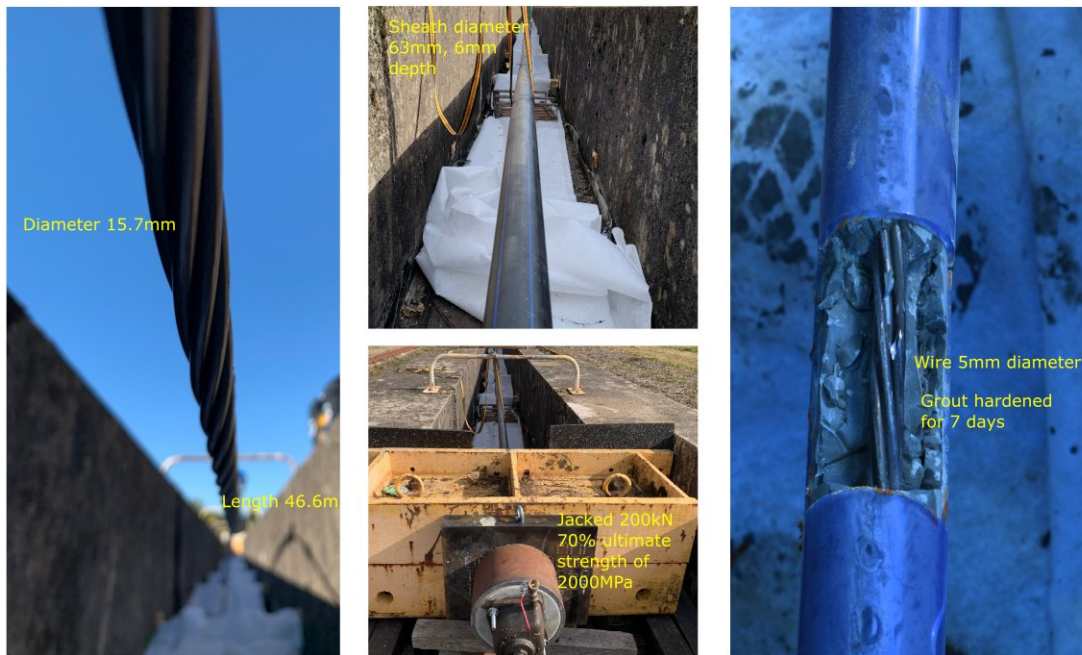


FIGURE 3 Set up of the experimental bench

3 NUMERICAL MODEL

A FEM model was developed using Abaqus to study the behaviour of tendons during and after the wire cuts. In this model, the wires are modelled by Timoshenko beam elements and the other tendon components (grout, HDPE sheath) are 3D elements. The wire diameters are 5.4 mm and 5.2 mm for the central and the outer wires respectively. An offset of 0.1 mm is set between wires and no offset between the outer wires and the grout. The lay angle of the helix is 7.8° and the pitch is 243.9 mm. This model does not take into account wire flattening and Poisson's effect but it allows the modelling of multiple lay length which would otherwise be too computationally expensive.

The material property were taken from the reference sheets when available. Poisson coefficients used are usual values (0.45 for HDPE, 0.3 for steel, and 0.2 for grout). The only remaining unknown is the grout Young's modulus but it was tested in the sensibility analysis. The contact between the wires and the grout is achieved with the generalised contact law implemented in Abaqus, allowing contacts between edges of two elements and between an edge and a face. A dynamic analysis with mass scaling is performed which is equivalent to a quasi-static analysis.

The two main simplifying assumptions are that wire are modelled as 1D Timoshenko beam and that the material density is changed in order to speed up computations by using mass scaling as done by de Menezes and Marczak (2021). Mass scaling change the density of the elements in order to reach a target stable increment. Thus the model is not accurate for the dynamic effect but remain accurate for the equilibrium once the computation has converged. Poisson effect is not taken into account. The re-anchoring of wires only occurs due to the Hoyer effect. According to Foti and Martinelli (2019), wire flattening and Poisson effect have little effect on the mechanical behaviour of the strand for low lay angle. This leads to a necessary overestimation of the friction coefficient. No breaking of the grout was considered in the simulation.

4 RESULTS

4.1 Loss of tension

This study shows experimentally and numerically that loss of tension related to wire damage is small enough to be within accuracy of most of tension measurement methods. However, an important damage will lead to a tension variation sufficient to be detectable. A very small loss of tension implies that most of the energy and strength in the cut wire is transferred to the other wires of the tendon (FIGURE 4).

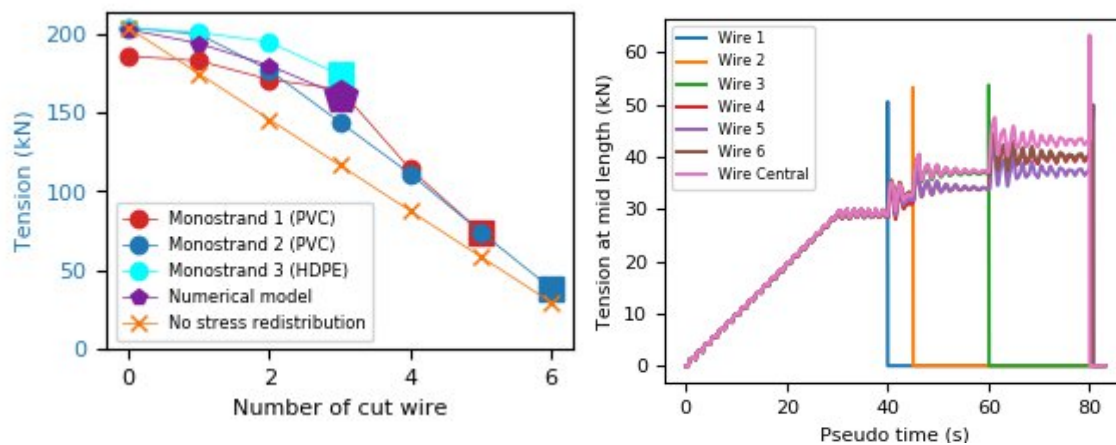


FIGURE 4 Experimental and numerical results of the tendon tension in function of the number of wire cuts (left) and Tension in each wire in numerical pseudo-time by the numerical model (right)

A numerical sensitivity analysis is performed to highlight the dependencies of the numerical model to different parameters (TABLE 1). The weak influence of the Young's modulus of the grout shows either that the re-anchoring is mostly due to inter-wire friction rather than grout-wire friction, or that the numerical model is not able to capture grout-wire friction. This could explain why the tension loss is higher in the numerical model than in the experimental tests.

Parameter	Initial value	1 wire broken	2 wires broken	3 wires broken	Remark
Experiment	204	201	195	174	
Reference	203	194	180	161	
Grout Young modulus double	202	193	180	161	
50m length	231	213	194	0	Far more stiff
Wire mesh twice coarser	203	194	179	160	Mesh converged
Friction coefficient half	204	190	169	144	More tension loss
Free rotation at the end	196	187	173	155	Major side effect as the tendon unwind close to the end

TABLE 1 Evolution of tension (kN) due to the variation of different parameters of the numerical model

4.2 Reanchoring (stress distribution in wires)

Friction causes the cut wire to regain its stress at a distance from the cutting position. This phenomenon, called re-anchoring, was previously studied with cut strand but sparsely with cut wire. The re-anchoring occurs because of the confinement of the strand in the grout. The re-anchoring of wire for an ungrouted tendon is of the order of 10 m. Contrary to the article of MacDougall and Bartlett (2006), the cut was performed while the strand is loaded, thus allowing a loss of tension. Cuts of the wires of the numerical model were simulated until the rupture of the tendon. FIGURE 5 shows that the grout confinement allows re-anchoring over lengths less than 10 m. The numerical model successfully captures the re-anchoring of a wire and the redistribution of the stresses inside the strand.

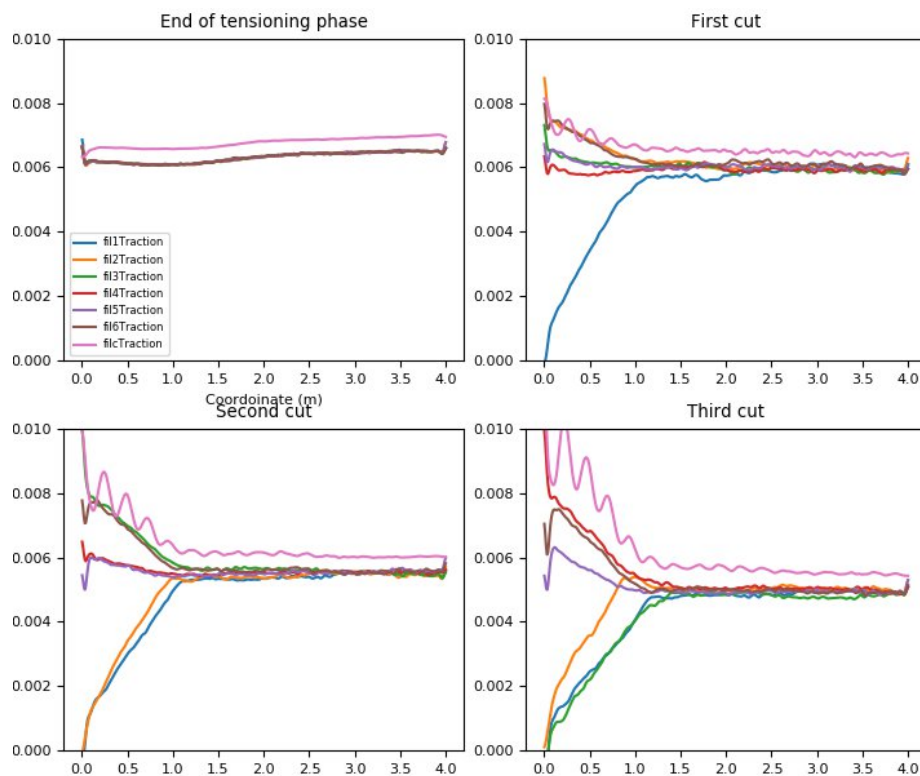


FIGURE 5 Strain on the wire according to the state of the strand and the distance to the cut

4.3 Damage of the grout and the sheath

The sheath of the first monostrand, chosen transparent to follow the propagation of the cracks, is brittle. The sheath was found to be more brittle than the grout and so the cracks could be traced directly to the sheath. Cracks on the grout and the sheath follow the same helical geometry as the geometry of stress on the numerical model (FIGURE 7). This result is important because it shows that the cracks follow the helical geometry of the wires caused by the damage part. The experimental and numerical results show that the strain on the sheath has a lay length periodicity and is exponentially decreasing, as shown FIGURE 6.

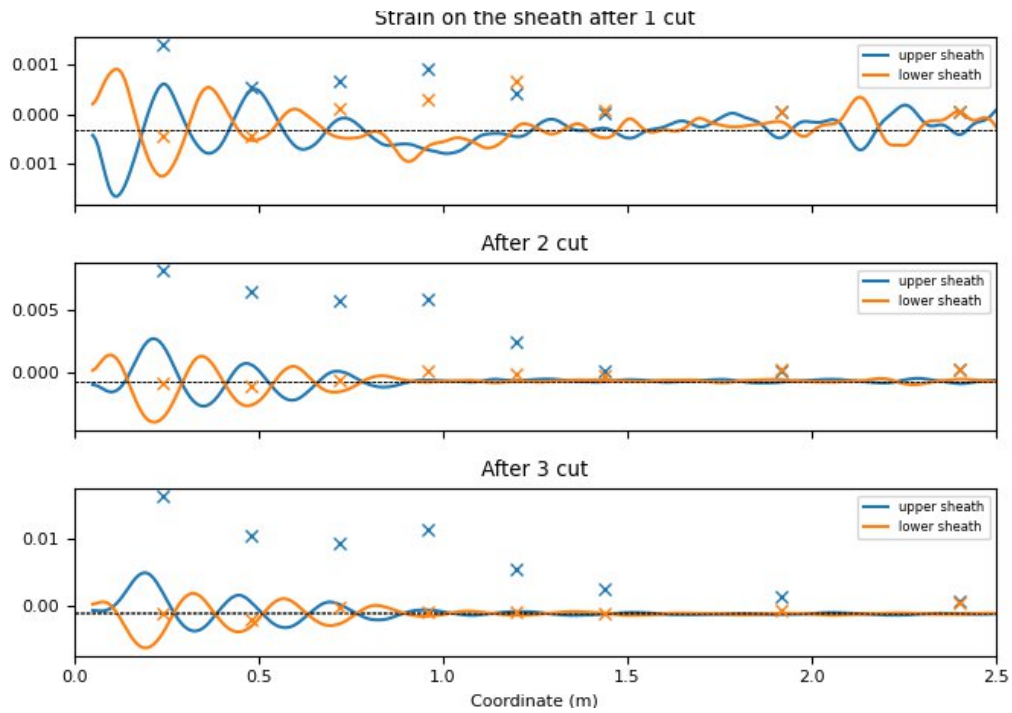


Figure 6 Strain on the upper and lower line of the sheath

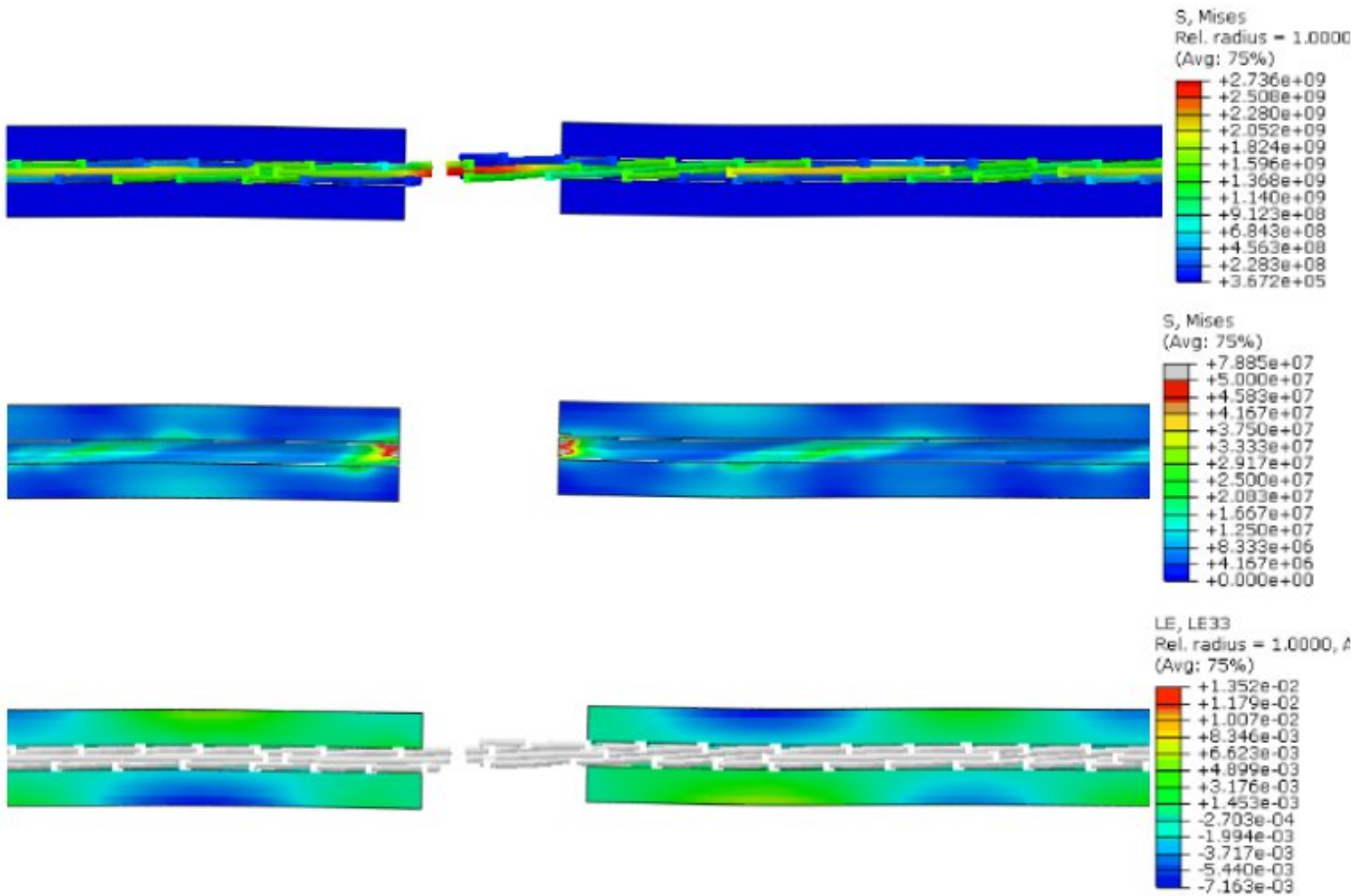


FIGURE 7 Stress in the wires and stress and strain in the sheath and the grout after the third cutting

5 CONCLUSION

Experimental tests were carried out by cutting one by one the wires of a grouted monostrand. The results show that a stress redistribution occurs inside the strand. A FE numerical model was developed by using beam element for the wires and 3D elements for the grout and the sheath. The numerical results agree well with the experimental results. Then, the model is used to analyse the sensitivity of the model parameters and to study how the stresses are redistributed between the wires. The re-anchoring of wires is different from strand re-anchoring due to the helical geometry of the cut wires. The tension loss is all the more important as the radial confinement is degraded. In the experimental tests, the degradation of the grouting was responsible for the different values of tension loss. The impact of wire damage on sheath strain was also explored. In future works, we will present the experimental and numerical results achieved on 5-strand tendons to contribute more on the understanding of the re-anchoring behaviour of prestressed tendons.

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