Relation between I_c degradation due to pressure in magnets and experimental data

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Contents

Abstract

The following work indagates critical current degradation of Nb_3Sn cables due to transverse pressure. The experimental setup apparently gives very different values of degradation compared to actual magnet results. This work tries to understand why it happens and to suggest some parameters that must be taken into account in order to better reproduce with the experimental setup the real stress condition of the magnet.

1 Introduction

The critical current of superconductive cables depends on many physical quantities such as temperature, magnetic field and stress. Stress dependence of critical current has been investigated by several experiments, which basically consist in applying a transverse pressure on a sample and measuring its critical current degradation. After applying pressure, there are two kinds of critical current degradation: a reversible one and a permanent one. Reversible degradation is seen measuring degradation while applying pressure; permanent degradation is seen measuring degradation after applying pressure, with no pressure applied on the cable.

FermiLab has an experimental setup (Figure 1) used to evaluate reversible and permanent degradation due to applied azimuthal pressure. It consists of a plate (2) driven up by a rod assembly (3) wich presses a two impragnated and insulated cables (1) sample with a pressure up to 200 MPa. This simulates an up to 200 MPa azimuthal stress condition in the magnet. In order to prevent current sharing, all the strands of the sample are made of copper except one which is superconductive.

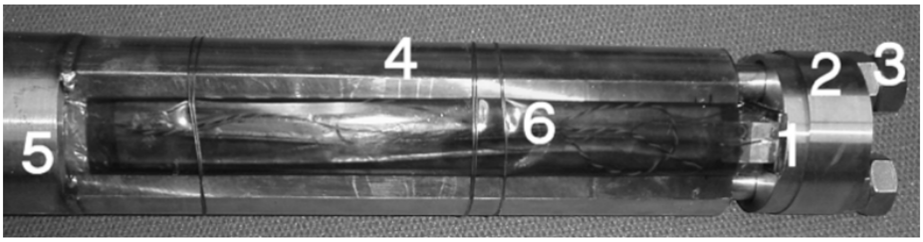

Figure 1: Experimental setup.

Both reversible and permanent degradation have been measured. Unfortunately, compared to experimental data, magnets seem to withstand higher loads without degradating (Figure 3).

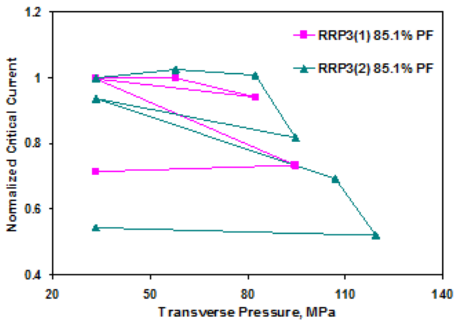

Figure 2: Some of latest experimental results.

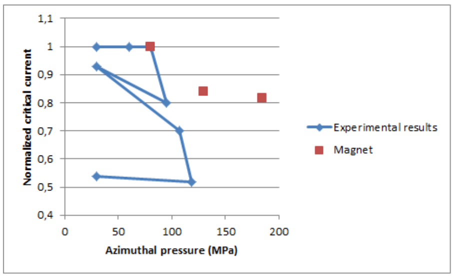

Figure 3: Comparison between experimental results and magnet data; the latter are plotted against maximum azimuthal stress reached during pre-load.

2 Comparison between experimental data and magnets' behaviour

The transverse pressure applied on the cable wants to simulate a condition of azimuthal stress on the magnet. Pre-loads on the magnet are applied both at room temperature and after cooling down at 4.2 K, and the magnet is also loaded when it is powered.

First af all, it must be noticed that critical current depends on magnetic field (Figure 4); critical current degradation due to magnetic field is even more intense than the one due to applied pressure. So we can assume that the lowest critical current will be in the area in which there is the highest field.

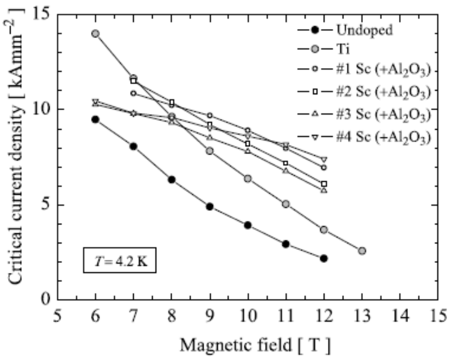

Figure 4: Critical current degradation due to magnetic field.

As we can see in Figure 5, the highest field is located on the pole, so we should be interested in the stress reached in that area of the magnet.

As we can see in Figure 6, when the magnet is powered, the pole is unloaded, so there will not be any reversible degradation. During pre-load, azimuthal stress on the pole is higher but the maximum value of azimuthal stress on the magnet is still not there.

After these observations we compare experimental permanent degradation with the stress reached on the pole and we see that some results seem to fit better, but other are still far (Figure 7).

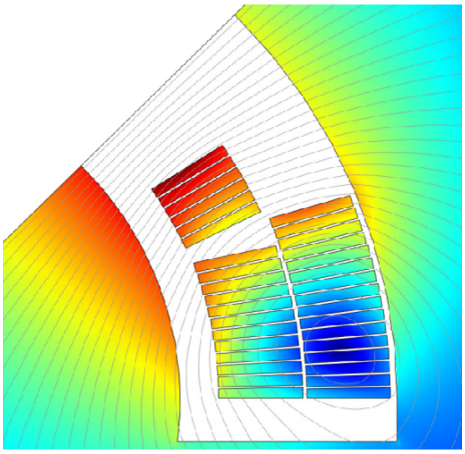

Figure 5: Field distribution on the magnet.

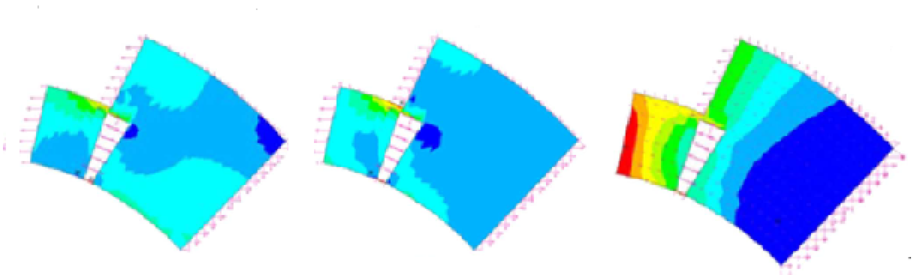

Figure 6: Stress distribution on the magnet: at room temperature, at 4.5 K and when powered.

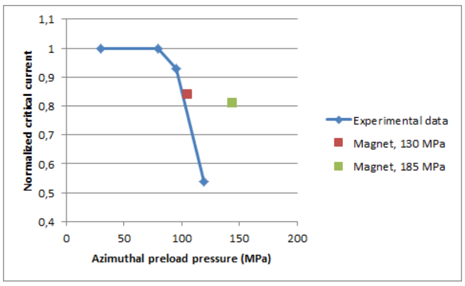

Figure 7: Experimental permanent degradation and magnet data; the latter are plotted against maximum stress reached where stress is maximum.

3 ANSYS model of the section

In order to better understand the physics of the problem, a simple ANSYS model of the section has been developed. Because of the high uncertainity and non-reproducibility of the geometry of the cable and because of the fact critical current (which is the quantity we want to study) is not evaluable, the model has been created in order to be as simple and fast to run as possible, without any corrections that would make the simulation much slower (even if probably more similar to the reality) without correcting significantly the result. That's why the model is bidimensional, every material is modelled as linear, elastic and isotropic, there is no friction between strands (they are glued to the epoxy) and mechanical and thermal properties of the material do not vary with temperature. This model is wanted to be an indicator of the order of magnitude of local stress in the cable and should be used to see qualitatively how differents loading conditions can change local stress values and so, probably, critical current. Section is shown in Figure 8.

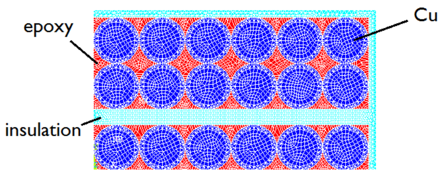

Figure 8: Section modelled.

The model is bidimensional, so we need to evaluate the behaviour in axial direction in order to choose the correct elements that better represent the phenomenon. A plane stress model does not seem to be correct, because it allows the material to deform in axial direction as much as it wants; this does not respect the integrity of the material, because if the axial strain was not the same all over the section, two adjacent section would compenetrate or separate. A plane strain model does not seem to be correct either, because it forces the axial strain to be zero, even if the sample is not axially constrained. A generalized plane strain model forces the axial strain to be constant all over the section, keeping the integrity of the material without forcing it not to deform in axial direction. So generalized plane strain seems to be the best assumption.

In order to verify it, a simple ANSYS model of a compound material has been performed. The model wants to represent an ortogonal section that allows us to evaluate the axial behaviour of the sample. Figure 9 and Figure 10 show that axial stress is not zero on the section (so plane stress is not correct), while axial strain is constant (but not zero) all over the section, so a generalized plane strain model seems to reproduce the sample in the best way.

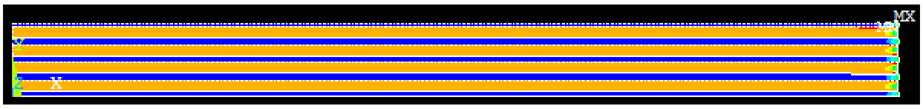

Figure 9: Axial stress: it is not zero all over the section.

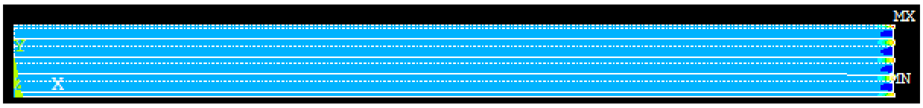

Figure 10: Axial strain: it is constant (but not zero) all over the section.

4 Effect of radial stress

In order to understand if the radial stress in the magnet can explain the difference between magnet and sample degradation, a constant compressive radial stress on the cable has been simulated. Infact, the coupling of two compressive stresses should bring smaller shear deformation than only one. Radial stress has been simulated by applying on the lateral side of the sample a constant pressure.

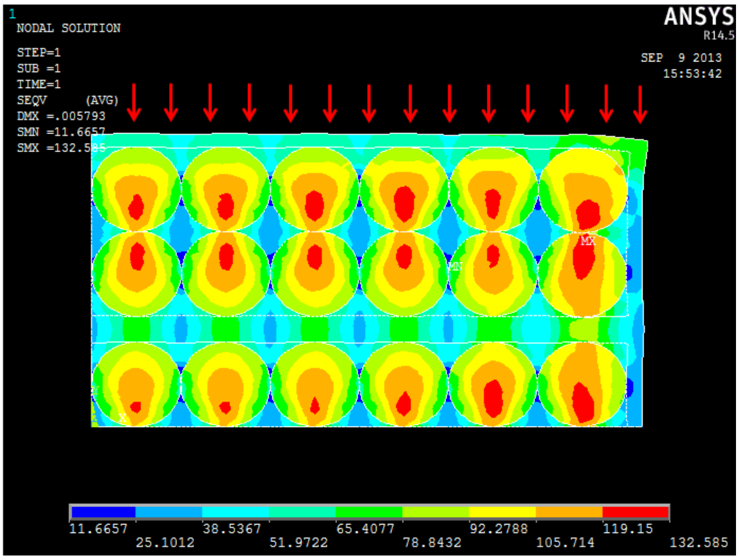

Figure 11: $\sigma_{\theta\theta} = 80$ MPa, $\sigma_{rr} = 0$.

Von Mises stress in a sample loaded with an azimuthal stress $\sigma_{\theta\theta} = 80$ MPa and a radial stress $\sigma_{rr} = 0$ is plotted in Figure 11. We can see a local Von Mises stress higher than 80 MPa (more than 130 MPa) in the strands. This is the current situation in the experiment, in which is not possible to give a lateral radial load to the sample.

FIGURA shows Von Mises stress for a $\sigma_{\theta\theta} = 80$ MPa coupled with a $\sigma_{rr} =$ 40 MPa. We can see in Figure 12 that local maximum Von Mises stress decreases to less than 120 MPa, and it moves to the external part of the strand. This situation is common in magnets, in which usually radial stress is around half of the azimuthal stress.

The following situations have also been plotted:

- $\sigma_{\theta\theta} = 80$ MPa, $\sigma_{rr} = 80$ MPa;
- $\sigma_{\theta\theta} = 40$ MPa, $\sigma_{rr} = 80$ MPa;
- $\sigma_{\theta\theta} = 0$ MPa, $\sigma_{rr} = 80$ MPa.

In order to complete the qualitative evaluation of the effect of radial stress, a loop of simulation has been performed with all the possible couplings between azimuthal stress and radial stress from 0 to 150 MPa every 10 MPa. Maximum Von Mises stress has been plotted for each load in Figure 16 and Figure 17. As

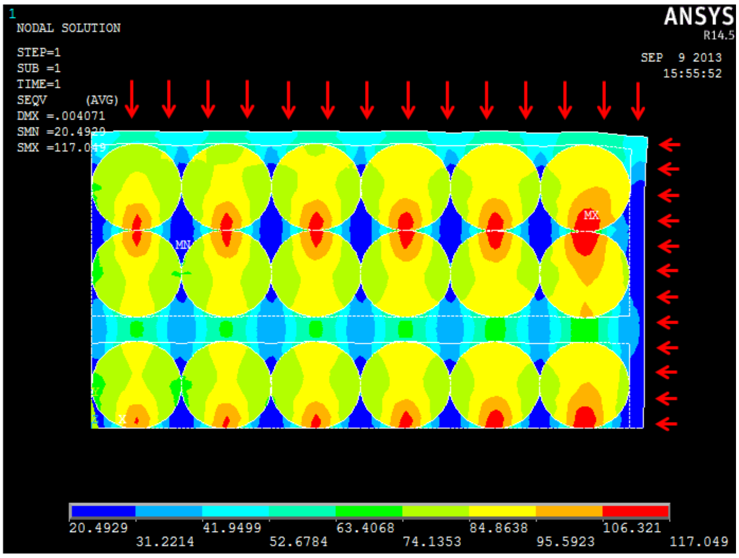

Figure 12: $\sigma_{\theta\theta} = 80$ MPa, $\sigma_{rr} = 40$ MPa.

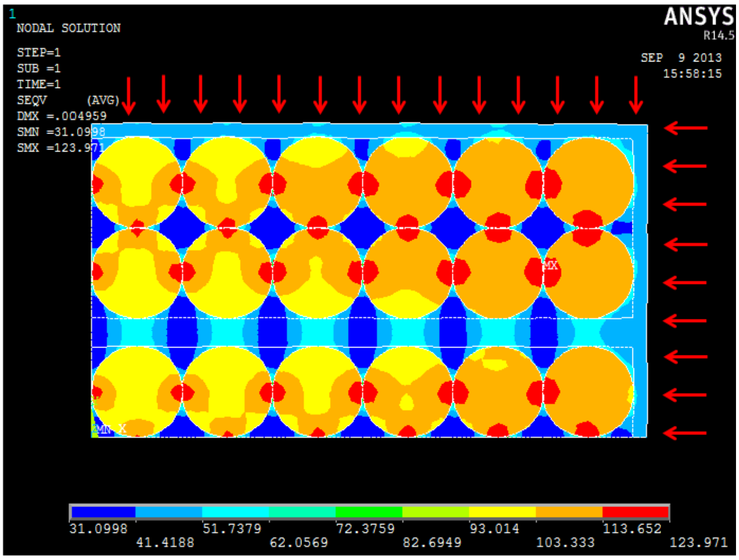

Figure 13: $\sigma_{\theta\theta} = 80$ MPa, $\sigma_{rr} = 80$ MPa.

expected and as we have seen before, azimuthal stress being equal, an increasing radial stress (lower than a trashold value) makes maximum Von Mises stress in the strand decrease.

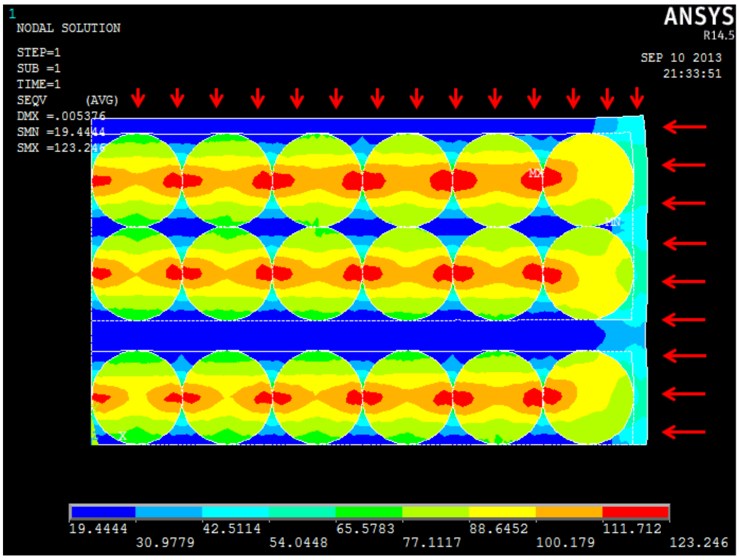

Figure 14: $\sigma_{\theta\theta} = 40$ MPa, $\sigma_{rr} = 80$ MPa.

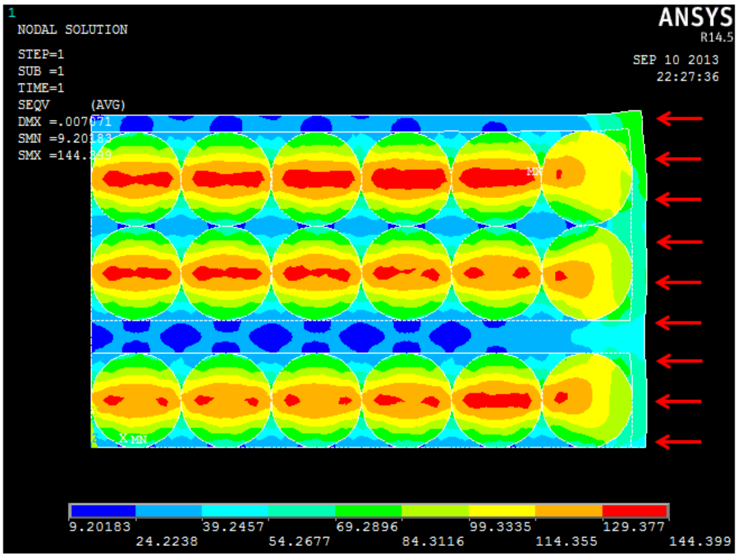

Figure 15: $\sigma_{\theta\theta} = 0$, $\sigma_{rr} = 80$ MPa.

5 Effect of different geometrical and material configurations

Geometry can change a lot from cable to cable and it is not easily reproducible in a ANSYS model. Infact, strands are not circular and epoxy is not always filling the cable without voids; strands have some Nb_3Sn wires composing an exagon before being manufacted. After the plastic deformation occurred with the manufacturing process, strand geometry changes a lot.

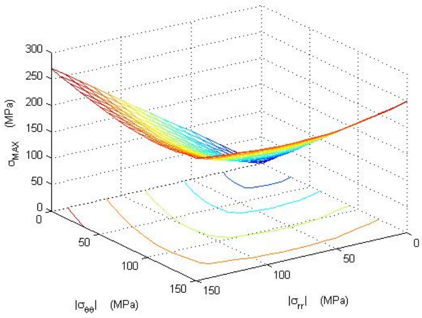

Figure 16: $\sigma_{MAX}(\sigma_{\theta\theta}, \sigma_{rr})$: 3D view.

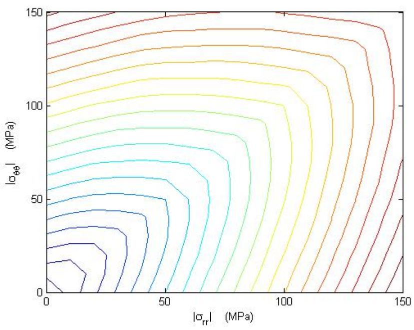

Figure 17: $\sigma_{MAX}(\sigma_{\theta\theta}, \sigma_{rr})$: top view.

Presence of voids in the epoxy matrix has been simulated as in Figure 18. Comparing with Figure 11, it can be seen that maximum Von Mises stress in the strand is higher.

More compact strands have been simulated as in Figure 19. In this case a lower maximum Von Mises stress is reached. It is located on the external part of one of the strands, and the central strands are very less stressed than the strands of Figure 11.

Voids in compact strands have been simulated as in Figure 20. As in Figure 18, the presence of voids increases very much local stress.

From these first simulations, we can stand that geometry affects very much local stress; so the numbers obtained in simulations should not be trusted in too much, and simulations should be intended just to give a qualitative idea of how different loading conditions can affect local stress and so critical current degradation.

In order to see if differences between magnets and experimental data can be caused by the fact that experimental sample is made of copper strands instead of superconductive strands, a simulation of a cable made with superconductive strands is shown in Figure 21. Local values of stress does not change very much, so we can state that it is correct to substitute superconductive strands with copper ones.

Another difference between magnet azimuthal stress and the transverse pres-

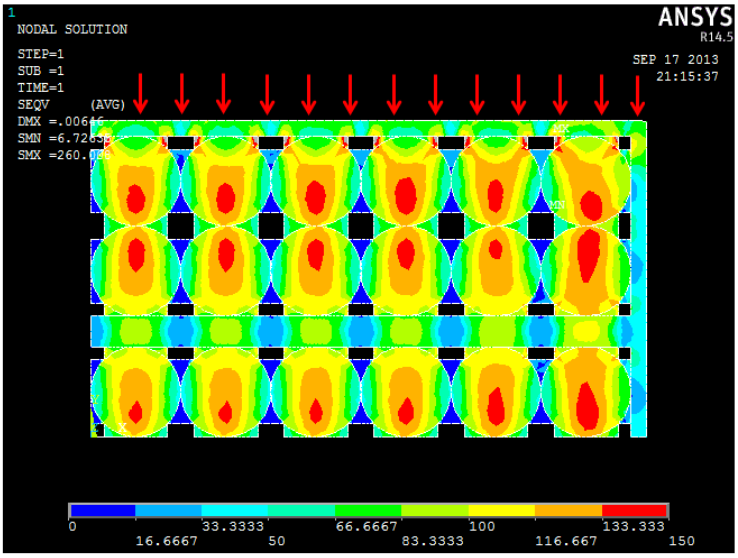

Figure 18: Voids in epoxy.

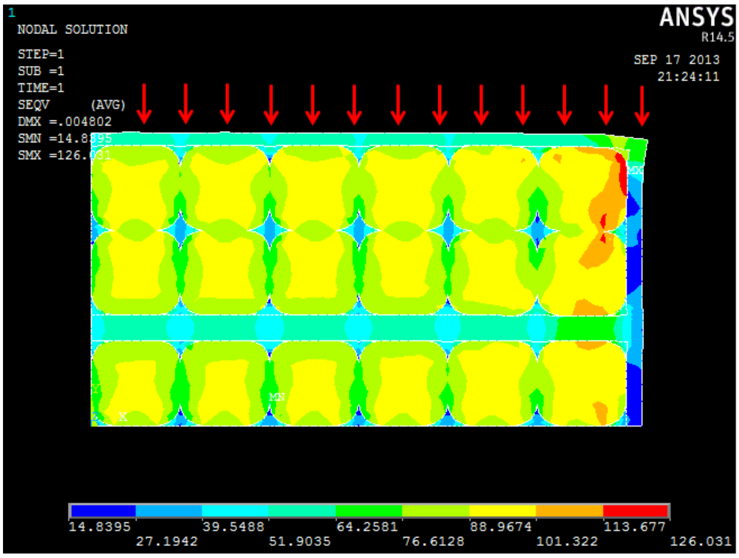

Figure 19: Compact strands.

sure on the sample is that the first is not always constant all over the cable, while the latter is forced to be a constant value. Figure 22 and Figure 23 show that if the cable is loaded with $\sigma_{\theta\theta} = 80$ MPa just in a restricted area of the cable (central in Figure 23 and external in Figure 22) local stress does not change very much, so we can state that it is correct to reproduce a non-uniform azimuthal stress in the magnet with an uniform transverse pressure on the sample.

As previously stated, to reproduce a radial stress in the magnet, a lateral pressure should be applied to the sample. It will not be easy to apply this

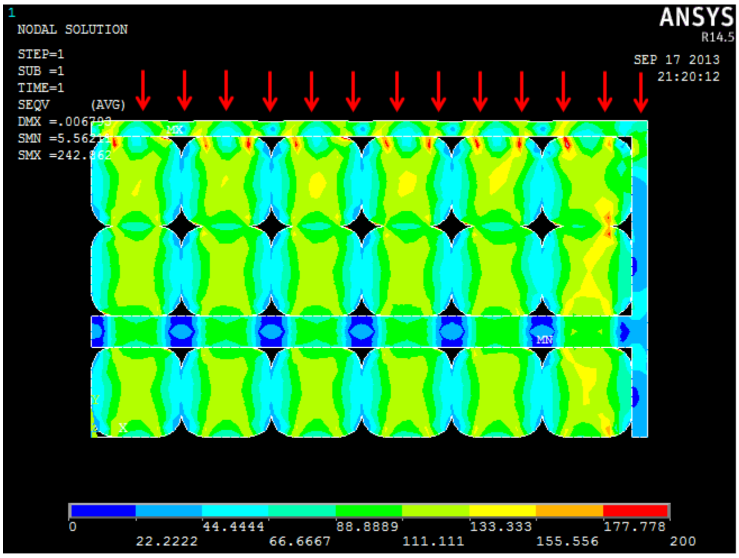

Figure 20: Compact strands with voids.

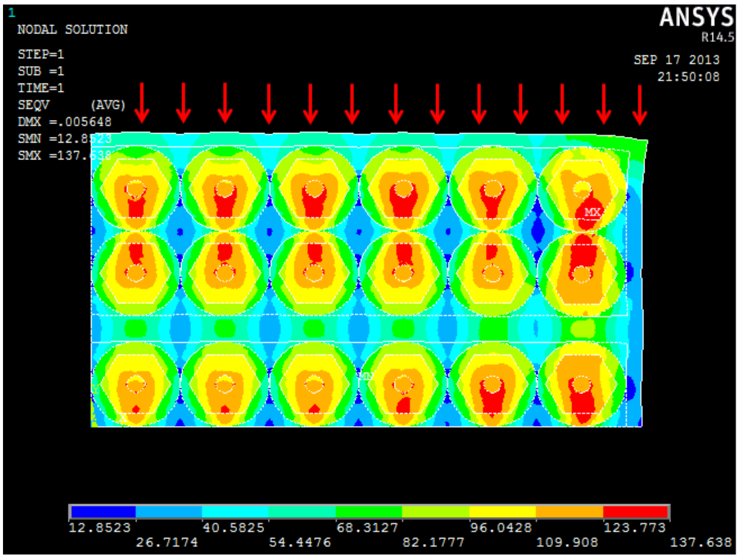

Figure 21: Nb_3Sn strands.

pressure along the whole height of the cable, so it has been simulated a sample partially loaded in Figure 24 ($\sigma_{\theta\theta}$ = 80 MPa, $\sigma_{\theta\theta}$ = 40 MPa). Compared to Figure 12, we see that local stress does not change too much.

6 Thermal loads

A compound material subject to high variation of temperature forces the materials that compose it to expand or contract in the same way, and this induces

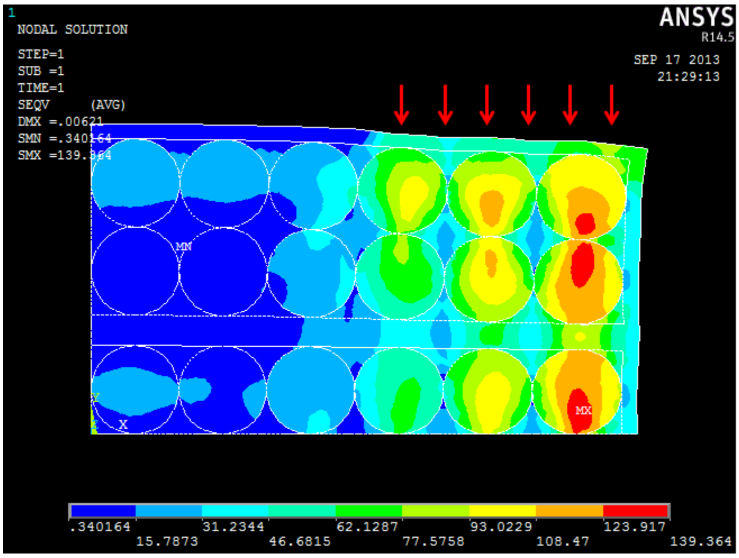

Figure 22: External load.

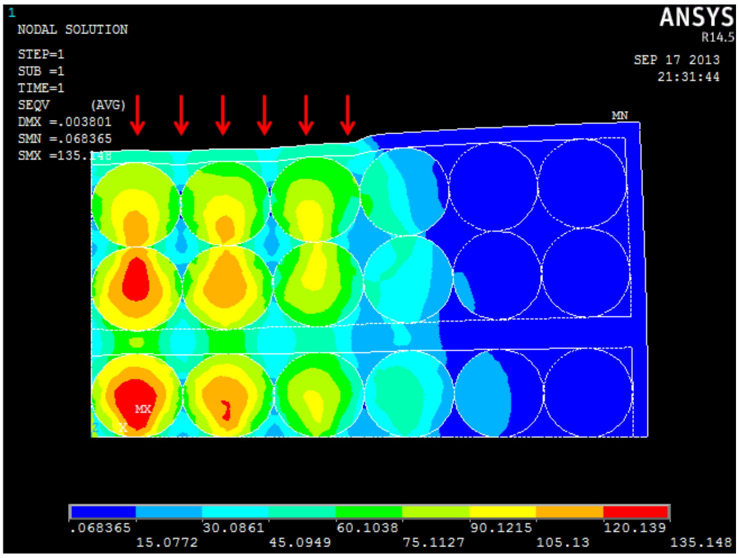

Figure 23: Central load.

stress due to the fact that they have different thermal expansion coefficient.

The cable is a epoxy and copper compound; epoxy can't withstand the high tensile stress that there wuold be, so it is going to crack and to follow the deformation of the copper. So these kind of thermal load must not be taken into account.

The strand is a copper and Nb_3Sn compound and stress is plotted in Figure 25 (unloaded) and Figure 26 ($\sigma_\theta\theta = 80$ MPa), considering a variation of temperature from 293 K to 4.2 K. We can see that there is an intrinsic stress

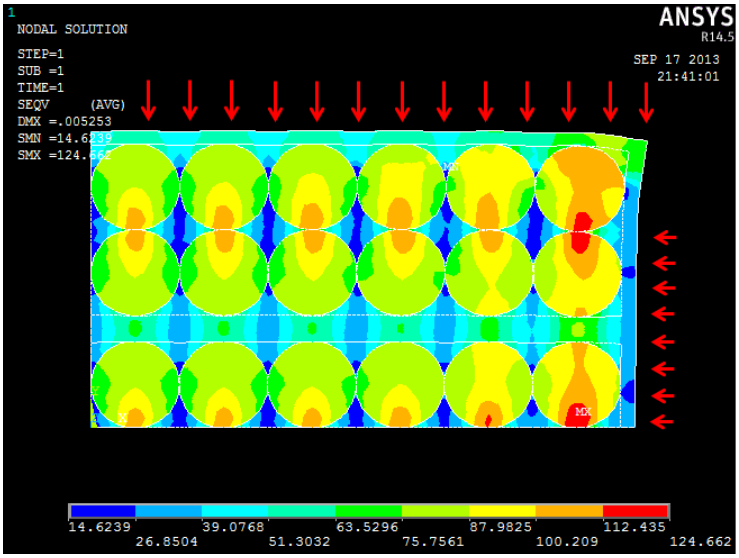

Figure 24: Partial radial load.

even if the cable is not pressed.

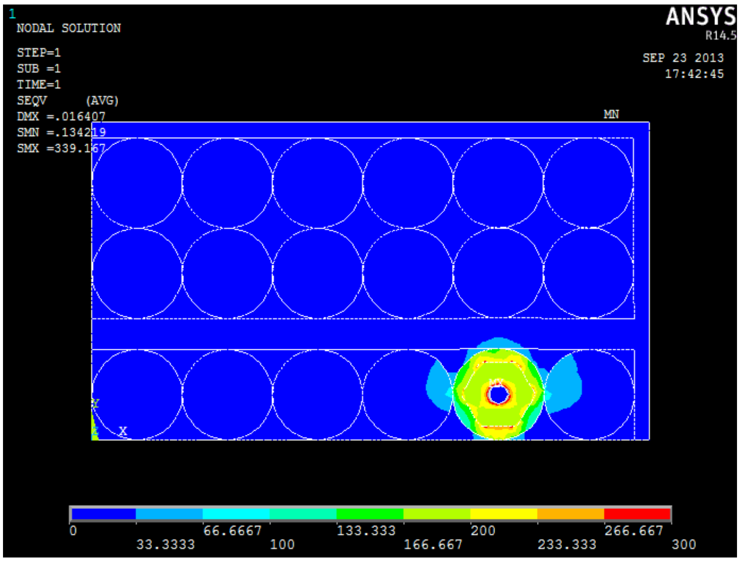

Figure 25: Stress after cooling down while unloaded.

In order to have a complete idea of the effect of radial and azimthal stress on critical current degradation while considering thermal effects, a loop of simulation has been performed with all the possible couplings between azimuthal stress and radial stress from 0 to 150 MPa every 10 MPa. For each load case, it has been considered the maximum Von Mises stress reached in the area shown in Figure 27, in order not to consider singularity zones (near the corners and the central zone). Results are shown in Figure 28 and Figure 29.

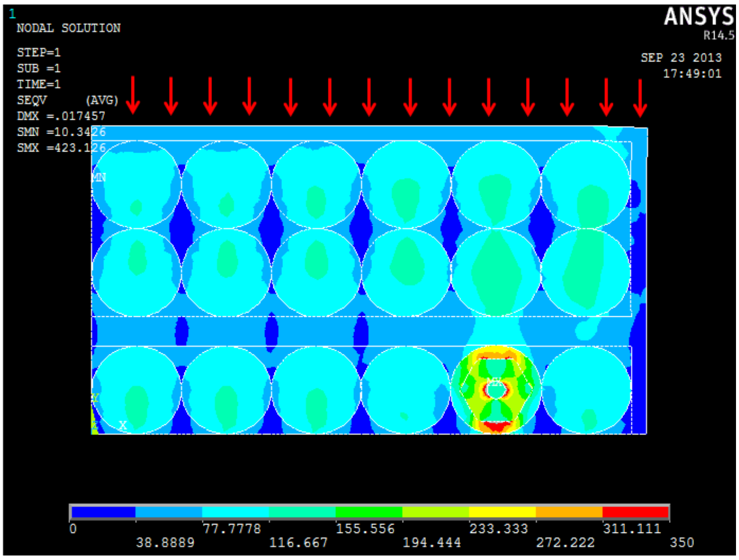

Figure 26: Stress after cooling down with $\sigma_{\theta\theta} = 80$ MPa.

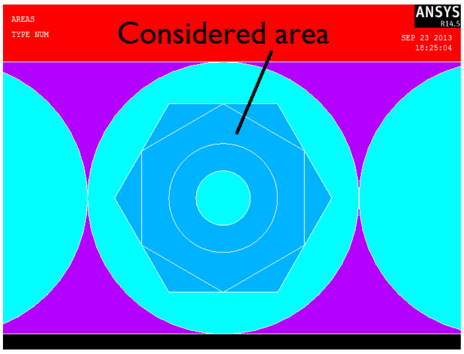

Figure 27: Considered area for maximum Von Mises plots.

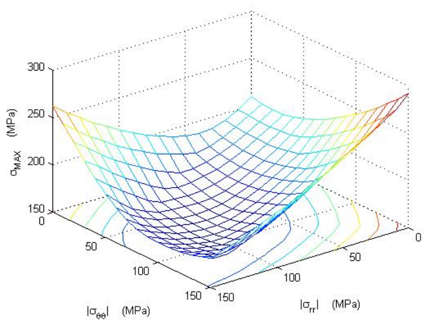

Figure 28: $\sigma_{MAX}(\sigma_{\theta\theta}, \sigma_{rr}, 4.2 \text{ K})$: 3D view.

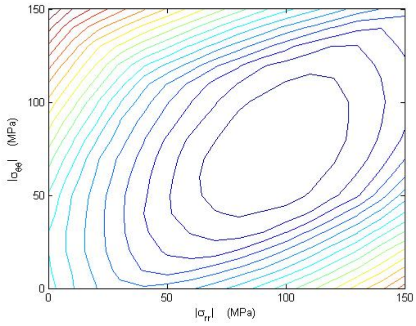

Figure 29: $\sigma_{MAX}(\sigma_{\theta\theta}, \sigma_{rr}, 4.2 \text{ K})$: top view.

Under the hypothesis that critical currents depends on maximum Von Mises stress and that a maximum Von Mises stress lower than the one reached at 4.2 K without external load does not bring any degradation, a qualitative prevision of critical current degradation is shown in Figure 31 and Figure 30.

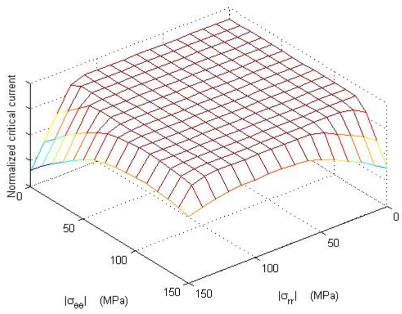

Figure 30: Room temperature preload expected degradation.

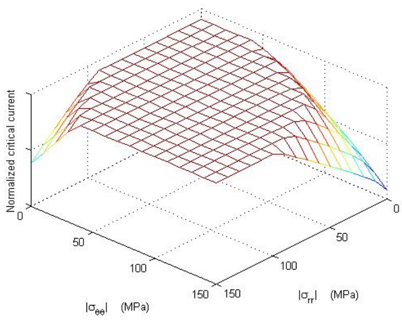

Figure 31: Cold preload expected degradation.

A fit to experimental data has been made under the following hypothesis:

- $I_c = k\sigma_{MAX} + q$

- $I_c(\sigma_{MAX}(0, 0, 4.2K)) = 1$

Among the curves shown in Figure 32, the one that fits best is the RRP 85.0% PF. The best fit is shown in Figure 33.

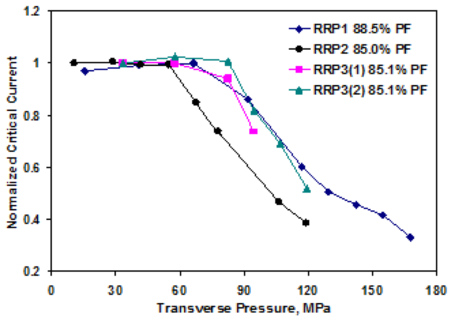

Figure 32: RRP experimental results.

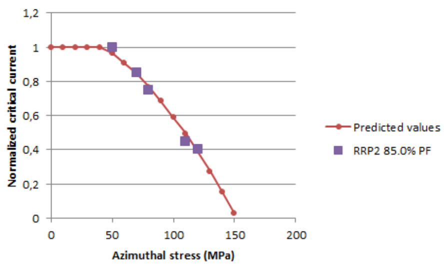

Figure 33: Best fit.

It must be underlined again that the prediction made with these results should not be quantitave, but just qualitative. The fact that it is possible to fit some experimental data, make it look more verosimile and encourages to permorm different kinds of experiments.

7 Conclusions and further developments

This work shows that thermal loads and radial stress affect local values of stress in the strands, and so they are going probably to affect also critical current degradation.

Differences between a warm preload and a cold preload should be taken into account and experimental setup able to apply radial stress should be developed. A lateral load can be given by forcing the cable in a seat, but small errors on dimensions of seat or cable can bring loads higher or lower than expected. A spring system can avoid this, but forces needed seem to be to high for the space at our disposal.