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Shear stress in LQ coils

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Abstract

This note presents the computation of the shear stress in the coils of the LARP Long Quadrupole (LQ) during assembly, cooldown and at 240 T/m operation. It also reports some results of compression and shear strength tests performed on cable stacks and coil samples fabricated using the same (or similar) materials and procedures adopted for the insulation and impregnation of LARP magnets.

Computation of shear stress in the LQ coils

The shear stress in the coils of the LQ, adopting a shell-based structure, has been calculated during bladder and key operations, cool-down, and excitation (240 T/m) with a 2D finite element model (see Fig. 1). The shear stress has been computed in two coordinate systems: cylindrical (see Fig. 2) and Cartesian (see Fig. 3).

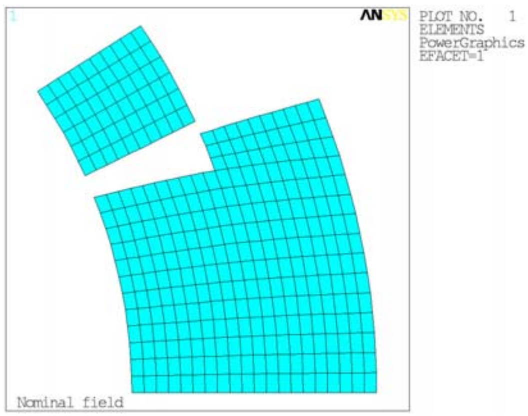

Fig. 1. 2D finite element model of the LQ coil.

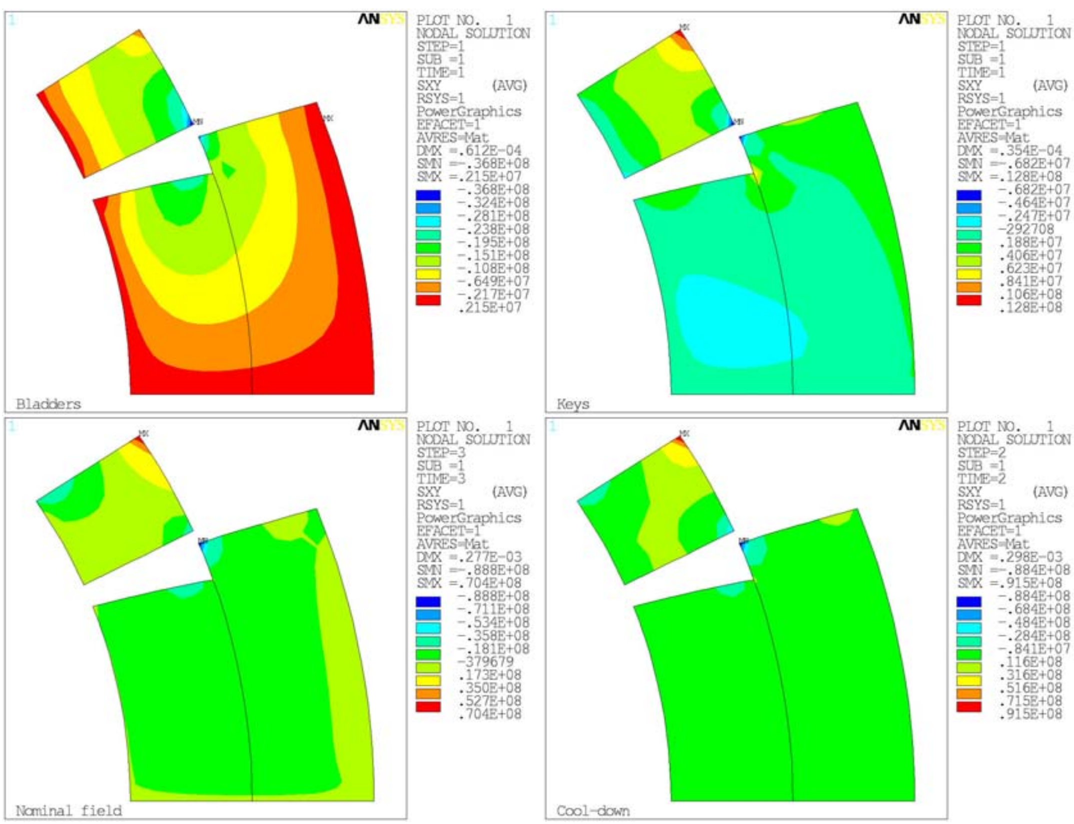

Fig. 2. Shear stress (Pa) in the coil during bladder pressurization (top left), key insertion (top right), cool-down (bottom left), and excitation (bottom right) at 240 T/m. Results are plotted in a cylindrical coordinate system.

In the first case (cylindrical coordinate system), the computations provide an estimate of the shear between adjacent turns, between the bronze wedge and its adjacent turns, and between the pole turn and the titanium alloy pole. Shear stress values vary in the ± 30 MPa range with the exception of a few corners (the outer corner of layer 1 pole turn and the inner corner of layer 2 pole turn).

In the Cartesian coordinate system, the shear stress can be seen as the results of the horizontal (x) and vertical (y) components of the azimuthal (θ) stress of the coil. Therefore, in the Cartesian coordinate system, the shear is identical to the cylindrical shear on the mid-plan, and it reaches it maximum values towards the coil pole (45º angle). In the Cartesian coordinate system the theoretical value at 45º with 150 MPa of pure azimuthal compression is 75 MPa (based on the fact that $\tau = \sigma/2$ on a plan at 45º in case of uniaxial load at 90º).

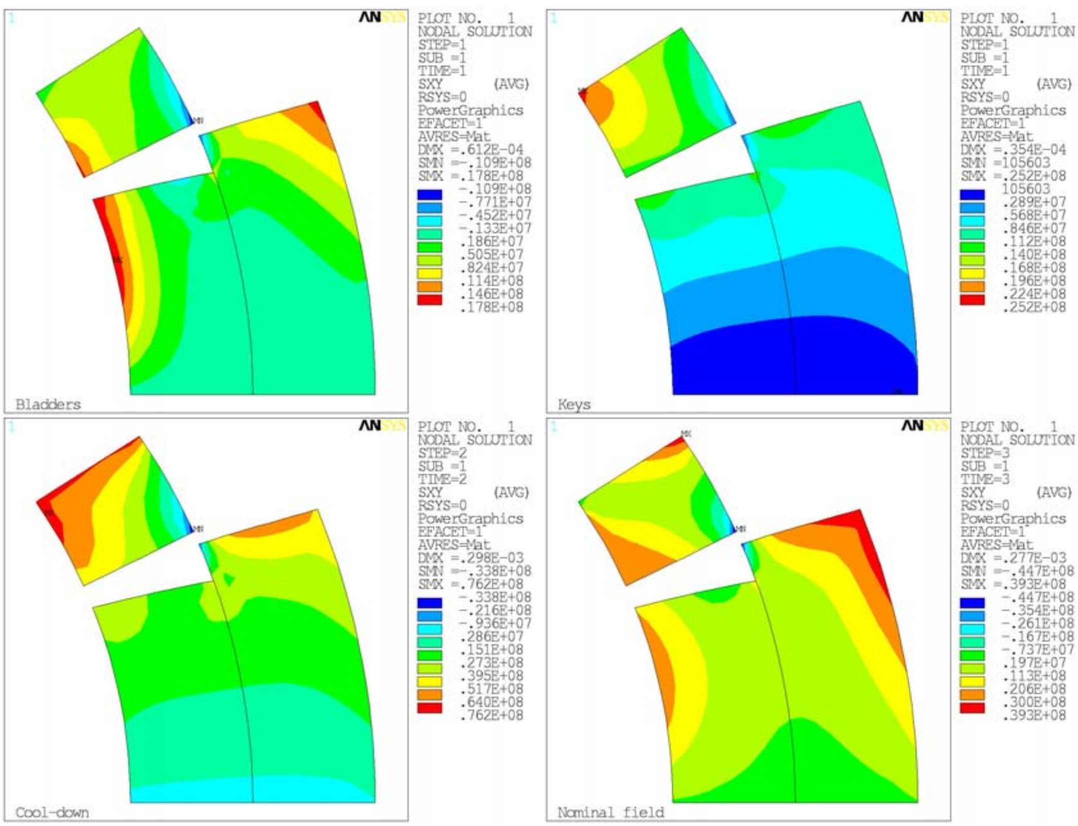

Fig. 3. Shear stress (Pa) in the coil during bladder pressurization (top left), key insertion (top right), cool-down (bottom left), and excitation (bottom right) at 240 T/m. Results are plotted in a Cartesian coordinate system.

Experimental results

The computed values can be compared with shear and compression tests performed on cable stacks and coil samples fabricated using the same (or similar) materials and procedures adopted for the insulation and impregnation of LARP magnets. The cable insulation used for LARP magnets consists of an S2-glass sleeve reinforced by ceramic binder. Palmitic acid used as sizing agent is removed during reaction in argon flow. CTD-101 epoxy (type A or K) is used for vacuum impregnation. More details about LQ coils insulation and impregnation can be found in [1].

Standard tests of coil samples under uniaxial compression can be used to estimate the shear strength at 45º (shear across the cables samples on 45º planes is the typical failure mode under uniaxial compression as shown in Fig 4). LQ cable stacks and LQ coil samples have been tested under uniaxial compression in order to evaluate the limits for mechanical and electrical breakdown. As reported in [2] LQ coils samples didn't show signs of mechanical or electrical failure up to 190 MPa of transverse compression at room temperature.

Cable stacks made with different insulation and the same epoxy used for LARP magnets (CTD-101k) reached 180 MPa without any failure at room temperature [3]. Same cable stacks showed electrical failure at 210 MPa, and a few of them showed mechanical failure at the same pressure. Cable stacks with S2-glass sleeve (LARP standard) were among the best performing samples.

Fig. 4. Fixture used for electrical test under compression (left), and example of mechanical failure (right).

Tests of shear failure between adjacent turns (Fig. 5) have been performed at Texas A&M University [4]. Test performed on cable stacks insulated using a silane-sized S2-glass braided on the cables showed failure around 30 MPa at room temperature (preliminary results, the apparatus calibration is still in process). The same test performed on samples insulated with the same S2 sleeve used for LARP magnets showed failure at about 25 MPa at room temperature [5] (these samples didn't have the ceramic binder reinforcement).

Measurement of shear strength at 77 K of insulation samples (S2-glass fabric reinforced by ceramic binder and impregnated with CTD-101k) showed shear strength of ~ 100 MPa [6]. This value dropped significantly after irradiation (~ 30 MPa after 20 MGy dose).

Fig 5. Fixture used for test of shear strength between adjacent turns at room temperature (courtesy of P. McIntyre).

Conclusions

The measurement presented, although incomplete, show that the standard LARP insulation-impregnation scheme can withstand at room temperature compression loads up to 180 MPa (and the corresponding shear stress on the 45º plans up to 90 MPa) without electrical or mechanical failures. The shear strength between adjacent turns is about 25 MPa at room temperature, and the shear strength of the insulation is ~100 MPa at 77 K.
Several questions remain to be addressed, such as the maximum acceptable compression and shear stress at cold temperature (from the point of view of electrical insulation performance, conductor degradation, and effect on training), and the safety factors to be applied to these values in order to assure reliable magnet performance. Cable tests under variable compressive load (such as the test performed at the NHMFL) could address most issues and are highly recommend to be performed on TQ/LQ cables with the standard LARP insulation-impregnation scheme.
The effect of radiation dose on the shear strength should be carefully taken into account in the design of the whole magnet system (magnet, absorbers, and liners) for operation in high dose regions.

References

[1] G. Ambrosio, et al., "Design of Nb_3Sn coils for LARP long magnets", *IEEE Trans. on App. Supercond.*, vol. 17, no. 2, pp. 1035-1038, June 2007

[2] D. Tooke, G. Ambrosio, N. Andreev, R. Bossert, *"Test of Insulation Electrical Strength of LARP Technological Quadrupoles (TQ)"*, FNAL Technical Division note TD-06-52.

[3] R. Bossert, G. Ambrosio, N. Andreev, G. Whitson, and A. Zlobin, “TESTS OF INSULATION SYSTEMS FOR Nb3Sn WIND AND REACT COILS”, Presented at *CEC07*, to be published in Advances in Cryogenic Engineering.

[4] R. Blackburn, N. Diaczenko, T. Elliott, A. Jaisle, A. McInturff, P. McIntyre, and A. Sattarov, “Fabrication of “TAMU3”, a “Wind/React” Stress-Managed 14T Nb3Sn Block Coil Design” presented at EUCAS07, to be published in the *Proceedings of EUCAS 2007* - Journal of Physics: Conference Series (JPCS).

[5] A. McInturff, private communication.

[6] M. Hooker (CTD) “Radiation-Resistant Insulation For High-Field Magnet Applications” presented at the *Radiation-Hard Insulation Workshop,* Fermi National Accelerator Laboratory, April 2006.