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Mechanical Qualification of the Support Structure for MQXF, the Nb_3Sn Low-β Quadrupole for the High Luminosity LHC

M. Juchno, G. Ambrosio, M. Anerella, H. Bajas, M. Bajko, N. Bourcey, D. W. Cheng, H. Felice, P. Ferracin, P. Grosclaude, M. Guinchard, J. C. Perez, H. Prin and J. Schmalzle

***Abstract*— Within the scope of the High Luminosity LHC project, the collaboration between CERN and U.S. LARP is developing new low-β quadrupoles using the Nb_3Sn superconducting technology for the upgrade of the LHC interaction regions. The magnet support structure of the first short model was designed and two units were fabricated and tested at CERN and at LBNL. The structure provides the preload to the collars-coils subassembly by an arrangement of outer aluminum shells pre-tensioned with water-pressurized bladders. For the mechanical qualification of the structure and the assembly procedure, superconducting coils were replaced with solid aluminum "dummy coils", the structure was preloaded at room temperature, and then cooled-down to 77 K. Mechanical behavior of the magnet structure was monitored with the use of strain gauges installed on the aluminum shells, the dummy coils and the axial preload system. This paper reports on the outcome of the assembly and the cool-down tests with dummy coils, which were performed at CERN and at LBNL, and presents the strain gauge measurements compared to the 3D finite element model predictions.**

***Index Terms*— High Luminosity LHC, Low-β Quadrupoles, Nb_3Sn magnets, short model, support structure.**

I. Introduction

THE NEW Nb_3Sn low-beta quadrupole magnets are being developed and built [1] by the collaboration between CERN and US LHC Accelerator Program (LARP). This 150 mm single aperture magnet called MQXF will provide a nominal field gradient of 132.6 T/m and will be installed in the LHC interaction regions during the High Luminosity LHC upgrade [2]. Its design is based on the 120 mm quadrupole magnet called HQ [3], which was developed by LARP, and utilizes the same bladder and key technology [4] for providing the coil preload. Fig. 1 shows the cross-section of the MQXF magnet.

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M. Juchno (e-mail: mariusz.juchno@cern.ch), H. Bajas, M. Bajko, N. Bourcey, P. Ferracin, P. Grosclaude, M. Guinchard, J. C. Perez and H. Prin are with CERN, 1211 Geneva, Switzerland.

G. Ambrosio is with FNAL, Batavia, IL 60510 USA.

D. W. Cheng and H. Felice are with LBNL, Berkeley, CA 94720 USA.

M. Anerella and J. Schmalzle are with Brookhaven National Laboratory (BNL), Upton, NY 11973 USA.

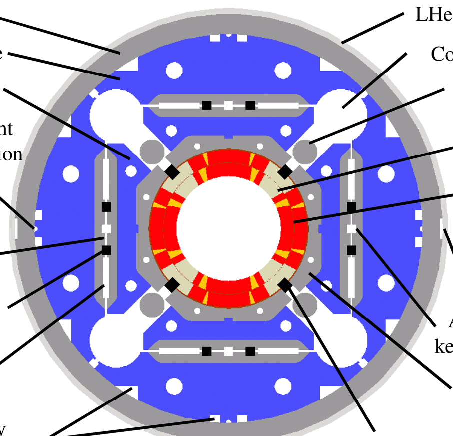


Fig. 1. MQXF magnet cross-section.

This paper focuses on the mechanical qualification of the short model (MQXFS) structure. For the purpose of the test, the support structure is assembled with four solid aluminum inserts ("dummy coils") replacing the superconducting coils and cooled-down with liquid nitrogen to 77 K. Mechanical behavior of the structure is monitored during the assembly and the cold test with strain gauges and the measurement data is compared with results of the 3D finite element analysis [5]. Two such structures, which are shown in Fig. 2, were assembled and tested in parallel; one at CERN called MQXFSD0 and one at LBNL called MQXFSD1.

II. Details of the Design and the Assembly

A. *Yoke and shell assembly*

The yoke-shell sub-assembly consist of four iron quarter-yokes that are inserted in vertical position into a stack of aluminum shells and locked against them with temporary yoke-keys. The CERN structure was assembled using two identical aluminum shells of a length of 755 mm while the LBNL structure used an optimized shell configuration with the central 755 mm long shell and two outbound shells each 377.5 mm long. For the second test, the CERN structure will be upgraded to the new shell configuration, which minimizes the stress variation along the coil as well as the peak stress in the coil ends.

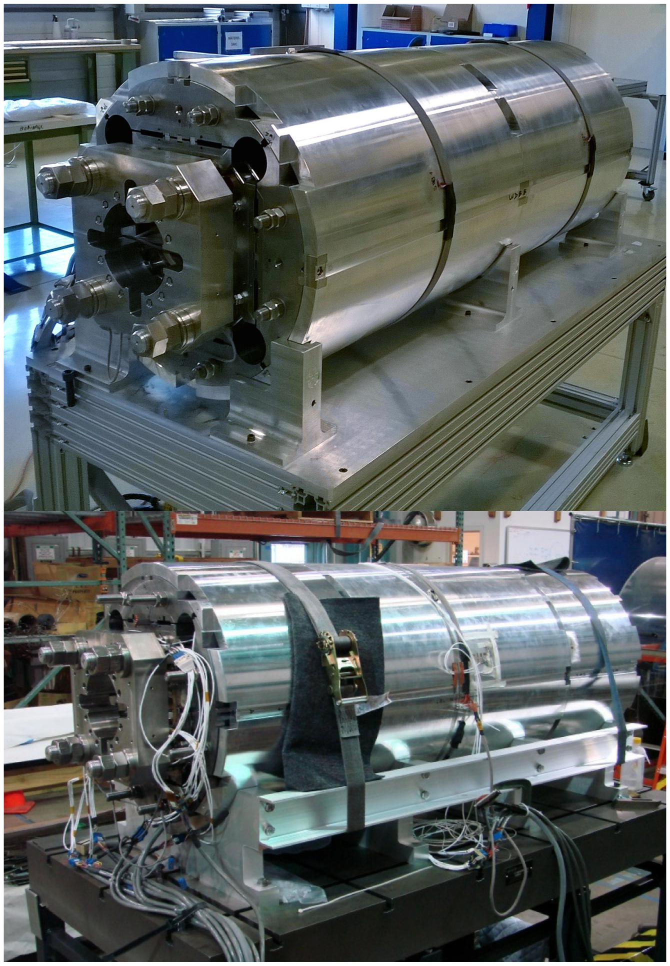


Fig. 2. MQXFSD0 structure assembled at CERN (top) and MQXFSD1 structure assembled at LBNL (bottom)

B. Coil-pack sub-assembly

The coil-pack consist of four coils held together by four sub-assemblies of aluminum collars and iron load-pads bolted together to provide rigidity and to ensure dimensional uniformity. For the purpose of the mechanical qualification of the structure, four aluminum dummy coils were used instead of the Nb_3Sn coils. The assembly is performed in several sub-steps to assure proper thickness of the radial and the pole-key shims. Prior to the assembly, a Coordinate Measuring Machine (CMM) inspection of the parts is performed to estimate the actual outer diameter of the coil and the thickness of the radial shims to be inserted between coils and collars. The first step of the assembly is performed with pressure sensitive sheets of Fuji Prescale film replacing a radial shim of the same thickness and without shimming the pole-key. After tightening the coil-pack bolts, its overall dimensions are measured as well as the distance between collars, which is used to estimate the actual thickness of the pole-key shims needed. The final assembly step is performed with the Fuji paper replaced with the proper radial shim and the pole-key shimmed to proper thickness.

For the CERN structure, the total thickness of radial shims inserted was 1.575 mm while the nominal thickness was 1.625 mm. The total pole-key thickness inserted was 14.95 mm while nominal was 15 mm. The average width of the assembled coil-pack was within 30 µm from the nominal while its height was oversized by about 200 µm.

The LBNL assembly was performed with a radial shim thickness of 1.57 mm and the pole-key stack of 15 mm. Measurement of the coil-pack dimensions showed that it was smaller than nominal by about 150 µm per side.

C. Coil-pack insertion and room temperature assembly

The coil-pack is inserted into the yoke-shell sub-assembly in the horizontal position and centered by using bladders and initial loading keys. Room temperature preload is performed by pressurizing the bladders and shimming the load keys quadrant by quadrant. The axial loading system is installed after the azimuthal loading operation, and the rods are pre-tensioned using a hydraulic piston loading rig attached via rod extensions.

III. Strain Gauge Instrumentation

The assembly and the cool-down tests are monitored with the use of strain gauges. They are installed on the external surface of the aluminum shell, the bore surface of the dummy coil and on all four aluminum axial rods, as shown in Fig. 3. Measured strain values are compared with the result of the numerical analysis in order to validate the support structure behavior as well as its finite element model.

A. Instrumentation of the aluminum shells

Each 755 mm long aluminum shell is equipped with four half-bridge strain gauge stations. They are located 90º from one another, along the outer circumference of the central cross-section of the shell, starting from the 15º above the magnet mid-plane. Locations are labeled as “Left”, “Right”, “Top” and “Bottom” (letters L, R, T and B) in a chosen assembly reference frame. Each half-bridge is temperature compensated with an additional one, which is glued on a floating aluminum sample. The strain is measured in two directions: azimuthal (ε_θ) and axial (ε_z). The azimuthal and the axial stress (σ_θ and σ_z) are obtained using the following relation

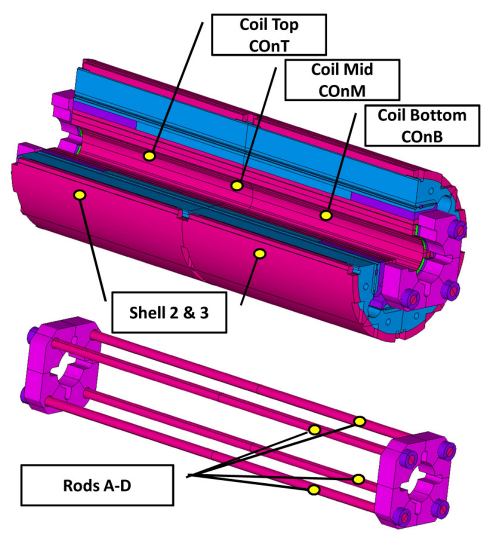
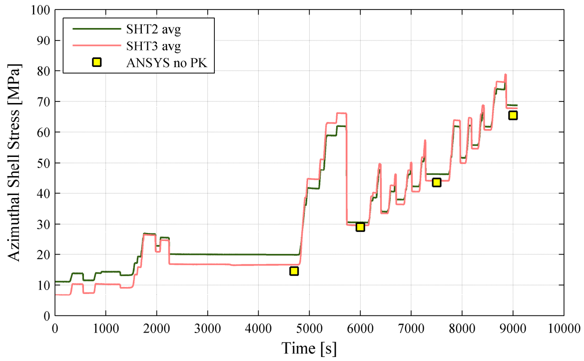


Fig. 3. Locations of the strain gauge stations on aluminum shells and dummy coils (top) and axial rods (bottom) in the CERN structure MQXFSD0.



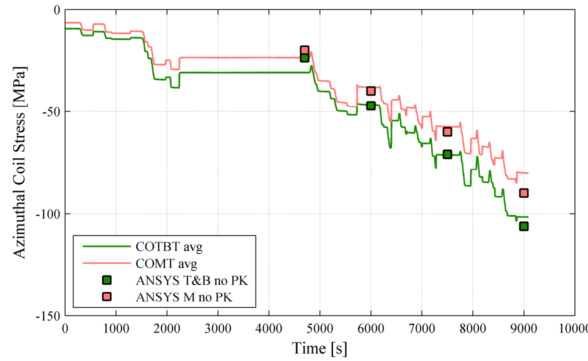


Fig. 4. Azimuthal stress in aluminum shells (left) and aluminum dummy coils (right) during the first room temperature azimuthal pre-loading of the CERN MQXFSD0 structure. Shell stress was averaged from four strain gauge location separately for each of the shell segments. Coil stress was averaged from "Top" and "Bottom" strain gauge locations (COTBT and ANSYS T&B) as well as "Mid" locations (COMT and ANSYS M) of all dummy coils.

$$\sigma_{\theta,z} = \frac{E}{\left(1-\nu^2\right)}\left(\varepsilon_{\theta,z} + \nu\varepsilon_{z,\theta}\right), \tag{1}$$

where E and ν are, respectively, the elastic modulus and the Poisson's ratio.

B. *Instrumentation of the aluminum dummy coil*

The four aluminum dummy coils are equipped with three half-bridge strain gauge stations each. These stations are located along every quarter of the coil length, on the central point of the inner surface, and are labeled as "Top", "Mid" and "Bottom" (letters T, M and B). Each station is temperature compensated and it measures two directions: azimuthal and axial.

C. *Instrumentation of the aluminum axial rods*

Each aluminum axial rod is equipped with one full-bridge strain gauge station. They do not require any additional temperature compensation and are measuring the strain only in the axial direction. Strain gauges on the axial rods are identified with letters from A to D.

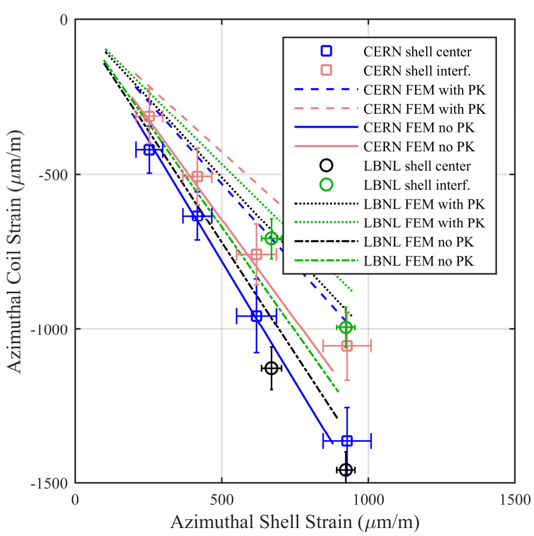


Fig. 5. Room temperature loading behavior of the CERN and the LBNL structure. Measurement data is shown in the area corresponding to the center of the shell segment ("Top" and "Bottom" coil strain gauges in Fig. 3) and in the area corresponding to the interface between two shells segments ("Mid" coil strain gauges). Results of the FEM analysis are shown for the same locations. Two different FEM models were analyzed for each structure, with and without pole-keys (PK) between the collars.

IV. Room Temperature Assembly and Pre-Loading

Fig. 4 shows the state of the CERN MQXFSD0 structure during the first room temperature pre-loading. During the initial centering of the coil-pack with respect to the yoke-shell sub-assembly, the maximum bladder pressure of 100 bars was used to replace the initial 12.8 mm thick keys with 13 mm keys. The insertion of 13.1 mm keys was performed by pressurizing all four quadrant bladders at the same time. Required bladder pressure was 260 bars and the stress level in aluminum shells was about a factor of two higher than with the inserted keys. The consecutive key increments were performed by pressurizing bladders in a single quadrant at the same time. The final key, 13.35 mm thick, was reached with a maximum pressure of 300 bars. All reported measurement values are provided as an average of all corresponding strain gauge stations along with a standard deviation. The average azimuthal stress in the aluminum shells after the first pre-loading was 67±6 MPa with 13.35 mm keys and only 12% stress over-shoot was required during the bladder operation.

The LBNL MQXFSD1 structure underwent a series of similar operations. The average azimuthal stress after the pre-loading was 69±3 MPa with 13.55 mm keys inserted using a maximum bladder pressure of 276 bars. The difference in the key thickness between the CERN and LBNL structure is consistent with measured dimensions of assembled coil-packs. The measured strain values indicate that the CERN coil-pack is oversized and the LBNL coil-pack is undersized by approximately 100 µm, with the assumption that yokes and shells have nominal dimensions. Stress values obtained with the use of the finite element model with an effective key thickness of 13.45 mm were 65 MPa and 67 MPa in case of the CERN and the LBNL structure correspondingly.

Due to a different configuration of aluminum shells, it is more appropriate to compare the stress level in the aluminum dummy coils at a location corresponding to the center of the shell segment. The average azimuthal stress in the CERN structure was -100±8 MPa and in the LBNL structure -107±5 MPa. The numerically predicted stress level was -105 MPa and -101 MPa in the CERN and the LBNL structure correspondingly.

The relationship between the shell and the aluminum

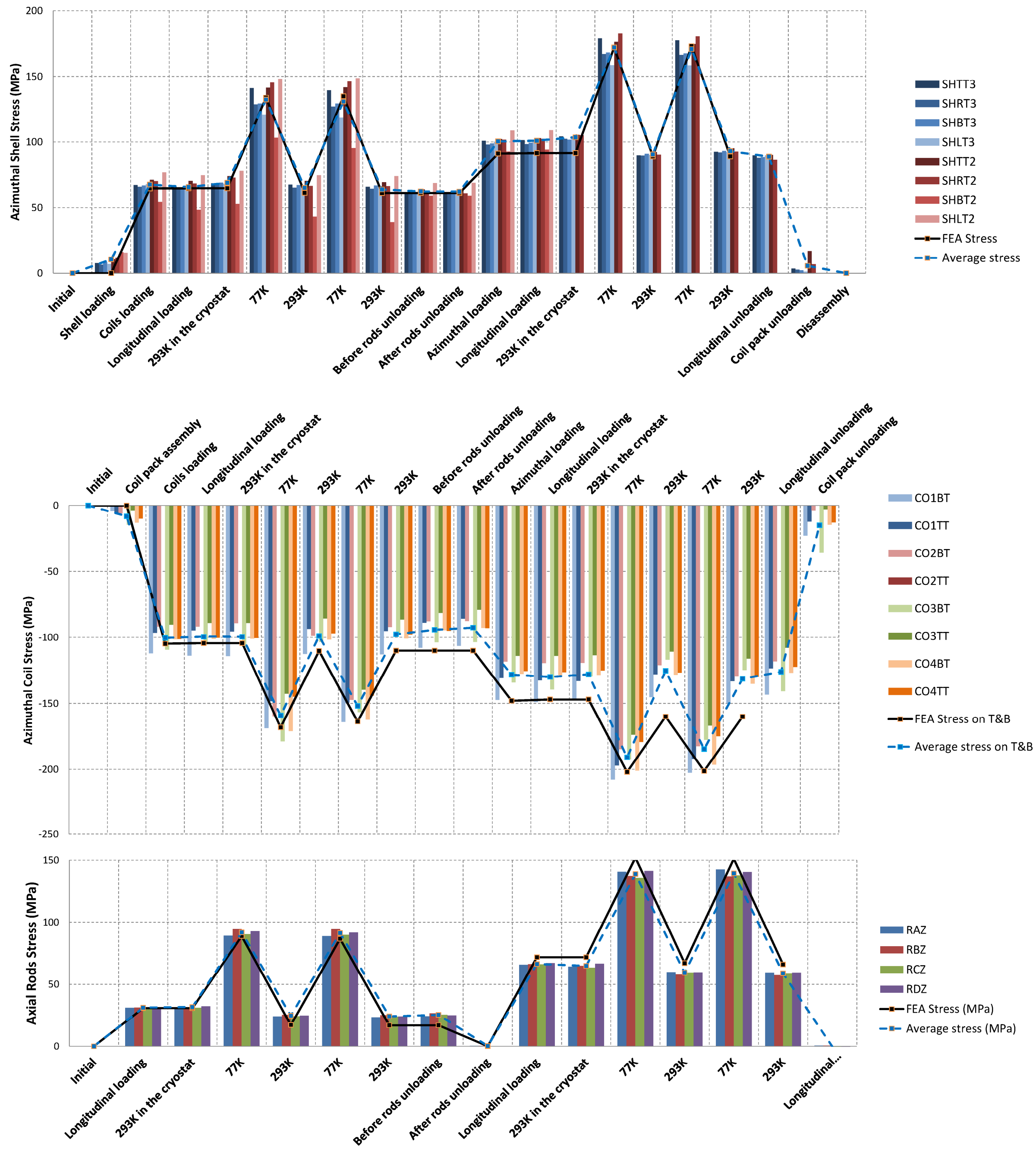


Fig. 6. Azimuthal stress in aluminum shells (top), azimuthal stress in dummy coils ((middle) and axial stress in the rods (bottom) of the CERN structure MQXFSD0 at the consecutive test steps. State of the dummy coil is presented in the location corresponding to the center of the shell segment (“Top” and “Bottom” coil strain gauges in Fig. 3).

dummy coil strain during the warm preload operation is presented in Fig. 5. The measurement results indicate that the pole-key (PK) gap between the collars was not sufficiently shimmed, which resulted in the higher force level being intercepted by the coil with respect to the nominal design case. This aspect of the structure behavior will be investigated and corrected during future coil-pack assembling operations, however, even at this state, the estimated alignment of the aluminum dummy coils is within 60 µm.

Axial pre-load was set on the conservative level with the intention of increasing it during consecutive tests. The axial rods of the CERN structure were pre-tensioned at room temperature to 32±0.4 MPa, while in the LBNL structure this was done to 58±2 MPa.

After performing the cold test at 77 K, the LBNL structure MQXFSD1 was disassembled in preparation for the assembly with Nb_3Sn coils [6]. After a similar cold test, the pre-load in the CERN structure MQXFSD0 was increased to the level corresponding to the nominal design. The final keys inserted with a maximum bladder pressure of 390 bars were 13.55 mm thick. The average shell and coil stress after the loading was 100±4 MPa and -128±10 MPa, while axial rods stress was increased to 66±1 MPa. Results of the numerical analysis were 91 MPa for the shell, -148 MPa for the dummy coil and 72 MPa for the axial rods.

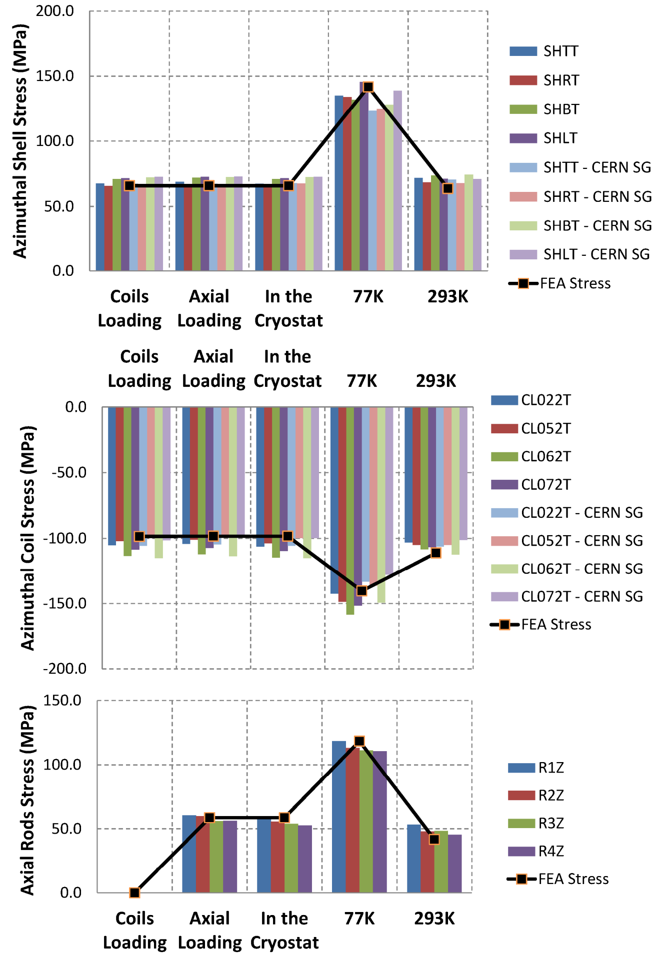


Fig. 7. Azimuthal stress in aluminum shells (top), azimuthal stress in dummy coils (middle) and axial stress in the rods (bottom) of the LBNL structure MQXFSD1 at the consecutive test steps. State of the dummy coil is presented in the location corresponding to the center of the shell segment.

V. Cold Test at 77 K and Results

After each room temperature pre-loading, the CERN structure was installed in the cryostat and subjected to two thermal cycles, by cooling it down with liquid nitrogen to 77 K and warming it up to room temperature. The LBNL structure was cooled down pre-loaded and tested at cold only once. The aim of this test was to monitor the coil pre-load provided by the shrinkage of the aluminum shell in cryogenic temperature and to acquire data necessary to fully validate the finite element model of the structure.

The analysis of the measurement results from the first cool-down showed that the numerical model was underestimating the influence of friction between components of the structure. Increasing the friction coefficient used in the model from 0.2 to 0.3 significantly reduced discrepancies in the azimuthal strain of the shell and the coil.

Fig. 6 shows the measured and the modelled stress level in the aluminum shells and the aluminum dummy coils of the CERN structure along the whole assembly and cold testing process. The strain gauges used at CERN were calibrated for use in cryogenic temperatures and appropriate correction of -6.5% was applied to the results at 77 K. The average tension in the shell increased at cold to 132±14 MPa during the first series of cold tests and to 172±8 MPa during the second series. Corresponding stress values obtained with the numerical model were 134 MPa and 172 MPa. The average compression of the dummy coil measured during the cold test was -152±9 MPa and -185±2 MPa, while corresponding values obtained with the numerical model were -164 MPa and -201 MPa.

Tension in the axial rods increased during cool-down by 60 MPa after the first room temperature preload and by 74 MPa after the second, to values of 92±2 MPa and 139±2 MPa. The increase of tension predicted by the numerical model was 58 MPa and 80 MPa. This gives an increase of the axial force acting on the dummy coil by about 240 kN and 300 kN. In the structure assembled with the Nb_3Sn coils, the predicted increase of the axial force due to the cool-down is around 530 kN.

The state of the LBNL structure is shown in Fig. 7. The strain gauges used at LBNL are not calibrated for cryogenic use, therefore, in addition to them, calibrated strain gauges (SG) of the CERN type were also installed in selected locations. Both types of strain gauges gave almost identical results during the room temperature pre-loading. The average stress measured in the shell at cold was 137±6 MPa (128±7 MPa with CERN SG) while the value obtained with the numerical model was 142 MPa. The average compression of dummy coils was -150±7 MPa (-137±9 MPa with CERN SG) and modelled value was -140 MPa. Tension in the axial rods increased during cool-down by 58 MPa to the value of 113±3 MPa. The increase of tension predicted by the numerical model was 60 MPa.

VI. Conclusion

The process of the MQXFS structure qualification is so far very successful. It provided valuable information regarding the assembly process and the mechanical behavior of the structure. Gathered measurement data allowed to validate the numerical model of the structure and improve some of the modelling aspects such as the applied friction coefficient.

The LBNL structure MQXFSD1 is now disassembled in preparation for the assembly with Nb_3Sn coils. The CERN structure MQXFSD0 will also be disassembled and assembled again with dummy coils along with the updated aluminum shells configuration and geometry. This new structure, which will be designated as MQXFSD2, will be used to further investigate some aspects of the assembly, such as radial and pole-key shimming, and to provide more data on the behavior of the structure.

Acknowledgment

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