Failure Assessments for MQXF Magnet Support Structure with a Graded Approach

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Abstract—The High-Luminosity Large Hadron Collider (HL-LHC) upgrade requires new quadrupoles, MQXF, to replace the present LHC inner triplets. The MQXFA magnet is the first prototype that has a 150 mm aperture and uses Nb3Sn superconducting technology in a 4.2 m magnetic length structure. The support structure design of the MQXFA magnet is based on the bladder-and-key technology, where a relatively low pre-stress at room temperature is increased to the final pre-load targets during the cool-down by the differential thermal contraction of the various components. The magnet support structure components experience different load levels from pre-load to cool-down and excitation. Consequently, a few parts experience high stresses that may cause localized plastic deformations or internal fracture development. The concept presented in this paper for the failure assessment of support structures integrates nonlinear finite element analysis with detailed sub-models and fracture mechanics into an advanced engineering tool. The nonlinear FE solutions enable estimations of the structural response to the given loads, and the advanced fracture analysis with failure assessment diagram (FAD) assesses the structure safety index of results obtained from the FE model. The paper describes how the MQXFA shell end segments are being optimized based on the failure analyses.

Index Terms—High Luminosity LHC, Low-\(\beta\) quadrupole, Fracture analysis, Nb3Sn magnet, Mechanical Model, FAD

I. INTRODUCTION

The Large Hadron Collider Luminosity upgrade (HiLumi) program requires new low-\(\beta\) triplet quadrupole magnets, called MQXF, in the Interaction Region (IR) to increase the LHC peak and integrated luminosity [1]. The MQXF magnets designed and fabricated in collaboration between CERN and the U.S. LARP, will serve as focusing elements in the interaction regions of the HiLumi LHC. The MQXF long model, referred as MQXFA, is a quadrupole using the Nb3Sn superconducting technology with 150 mm aperture and a 4.2 m magnetic length and is the first long prototype of the final MQXF design [2].

The design for MQXF magnets uses a shell-based support structure with the “bladder and key” concept to counteract nominal forces of \(+2.47/-3.48\) MN/m \((F_x/F_y)\) without overstressing the brittle Nb3Sn coils. The MQXFA magnet support structures (as shown in Fig. 1) are loaded in tension to preload the magnet coils at room temperature, and then the final pre-load is achieved by thermal contraction during the cool-down phase. The tie rods are also tensioned to load the magnet coils axially [3].

The MQXF magnet undergoes four primary load conditions [4]:

1. Assembly loading (1a) and room temperature load (1b). The load(s) are typically associated with preload operations. Loading 1a represents loadings when the pressurizing the bladders, and load (1b) is the static load after the preload operation.
2. Cool-down to 1.9 K. The resulting load case includes the room-temperature loadings and thermal stresses induced by the differential thermal contraction of the structure components.
3. Operation. The magnet is subject to full Lorentz forces in normal operations. The loading includes load 1b, load induced in cooldown and the Lorentz forces associated with energization.
4. Fault loads that outside of usual fabrication and operations.

As a result, the mechanical structure of MQXF magnet is subject to different load levels from pre-load to cool-down and excitation. Some parts, such as the aluminum shell and iron yokes, experience high stresses in the primary load cases as defined above.

In order to analyze the potential mechanical failures such as plastic deformation and fracture development, a graded approach is used for the MQXF magnet. Different criteria are defined in this approach. If criteria defined at each grade are exceeded, it will trigger the next level of analysis and/or require modifications to the design. In this paper we describe the graded approach combined with FE models of MQXFA magnet for the parts experiencing stress concentrations.
II. GRADED MECHANICAL ANALYSIS PROCURES

For MQXF magnets, structural failures can occur via one of the followings:

1. Plastic collapse typically associated with "tough" materials that yield in a smooth manner under the influence of large loads;
2. Linear elastic fracture, typically associated with brittle materials under significant loads coupled with stress concentration factors such as defects or voids;
3. Ductile tearing, i.e. materials are subjected to a combination of the elements above.

Failure assessments for MQXFA structure account for the failures above by referencing ASME FFS-1 as a standard to accept use of nominally 'brittle' materials with assumed flaws. The graded approach, shown in Fig. 2, is expected to yield structural designs that are safe for operation in the Large Hadron Collider, and is used in MQXFA designs.

The graded procedure consists of four levels analysis from 'hand calculations' to FEA, advance FEA to Linear Elastic Fracture Mechanics (LEFM)—in order of complexity. MQXFA structural design uses FEA for every structural component; In the grade I and II analysis, the FEA results will be evaluated with the material properties, parts could be reported to be satisfactory when the results meet Von Mises criteria; Grade III will be required when the results show stress singularity or concentration, or any other cases that exceed the Von Mises criteria. Sub-model will be used in this grade to determine the stress concentration factor. Grade IV analysis will be triggered when the material is brittle and fracture failure mode dominants. This approach relies on the R6 design criteria approach [5], which has been adopted by ASME FFS-1, Fitness for Service standard [6]. Failure Assessment Diagram (FAD) is key technique used in Grade IV since it includes the full range of failure modes listed above. Associate with grade III and IV analysis, mitigations were performed as well to ensure the design is deemed appropriate.

Due to the complexity of the magnet design and the various load conditions encountered during fabrication, assembly, and operation, the results of 3D FE models are used for the failure assessments of the MQXFA structural elements.

III. MECHANICAL ANALYSIS AT GRADE II

The MQXFA magnet has been analyzed at Grade II in the FE model described in [3]. The model applies the azimuthal interference of 750 µm as defined for MQXFAP2 magnet. Axial preload is provided by pre-tensioning -580 µε on the axial steel rods.

The simulations include the primary load conditions: load (1b), load from cool-down, and load in normal operations. Table I lists the peak stresses in the primary structural components.

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Principal Stress</th>
<th>Von Mises Stress</th>
<th>von Mises</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collar</td>
<td>Al 7075</td>
<td>293 K 1.9 K</td>
<td>293 K 1.9 K</td>
<td>293 K 1.9 K</td>
</tr>
<tr>
<td>SS Pad</td>
<td>SS 316</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Iron Pad</td>
<td>ARMCO</td>
<td>98 152</td>
<td>-</td>
<td>223 (7)</td>
</tr>
<tr>
<td>Yoke</td>
<td>ARMCO</td>
<td>246 306</td>
<td>-</td>
<td>223</td>
</tr>
<tr>
<td>Shell</td>
<td>Al 7075</td>
<td>280 610</td>
<td>320 573</td>
<td>420 550</td>
</tr>
<tr>
<td>Endplate</td>
<td>Nitronic 50</td>
<td>-</td>
<td>137 333</td>
<td>517 -</td>
</tr>
</tbody>
</table>

Please note, ARMCO steel is ultra-low carbon steel with low very impurities produced by AK steel, was tested at CERN at both room temperature and 4 K. It shows purely
brittle at 4 K thus no yield strength was determined. As seen in Table I, most of the structural components are within the yield limits, which meet the criteria defined at this grade level; those parts can stop with a report after a successful Grade II analysis is completed. The shell and yoke clearly exceed their yield limits at either room temperature or 1.9 K. The shell is loaded in tension, and the end shell with cut-outs tends to bend the cut-out corner, which referred as “end effect”; The Yoke is loaded in compression by the shell. The yoke lamina sees bending in the azimuthal direction that yields a tensile load around the top cut-out corner. The peak stresses in the end shell and yoke locate at the cut-out inner corners, as shown in Figure , which are considered stress concentrations due to the sharp corners in the model.

Figure 3: Peak Von Mises stress (Pa) in the end shell (Left) and peak principal stress (Pa) in yoke(Right)

The stress concentration can not readily resolved when increased the local mesh density; it usually means the model needs to include the actual geometry features such as fillets or chamfers. On the other hand, Al 7075 and ARMCO steel are considered as brittle material due to low fracture toughness. Therefore, the end shell and yoke need to be analyzed in Grade III with detailed features and mesh refinements, and then Grade IV is also triggered for fracture assessment.

IV. ADVANCED FEA FOR THE FAILURE ASSESSMENT

For components exhibiting stress concentrations that cannot be readily resolved via routine mesh refinement studies in the primary FEA model, sub-modeling was employed to evaluate the stress distribution around the particular concerning area.

Sub-model is a separate finite element model of the local region of interest, which imposes displacements on the cutting boundaries from the original model. The basis of a sub-model is St. Venant’s principle when picking the cutting boundary locations from the original model. The acceptance criterion for a sub-model solution is the resolved stresses are negligibly affecting the stress distribution in the original FEA model. The requirement can be expressed:

$$\left\| \left( \sigma_{ij} + \sigma_0 \right) \cdot n \right\| \ll \left\| \sigma_{ij} \cdot n \right\|| \ll 1$$  \hspace{1cm} (1)

where $\sigma$, is the calculated stress tensor after refinement in the sub-model, and $\sigma_0$ is the "Baseline" stress tensor from the original full model.

The MQXFA end shell and yoke were analyzed in their sub-models. Fig. 4 illuminates the example of the end shell of the verification for the end shell sub-model. The Von Mises stress on the picked locations of the cutting boundary has compared with the stress on the same locations of the original model. The agreement of the two sets of stress indicates that the cutting boundaries are remote enough to meet St. Venant’s principle. Same verification process has been performed on the yoke sub-model.

Fillets features were added to the end shell and yoke sub-models as shown in Fig. 5. Once the sub-models have been verified, mesh refinements have been performed on the sub-models.

Figure 4: End shell sub-model verification using St. Venant’s principle, the pink part is the sub-model of the end shell.

Figure 5: Sub-models of End shell and yoke with fillets according to the machining capability.

A. Results of the End shell sub-model

The initial elements size in the original global model was 8 mm. relative mesh density is designed as:

$$m_l = \frac{\delta_0}{\delta_l}$$

where $\delta_0$ and $\delta_l$ are the element size in the original global model and the sub-model, respectively. $\delta_0$ is 8 mm for the end shell in the original model.

Fig. 6 Relationship between the peak Von Mises stresses at the stress concentration area and the relative mesh density. The stress is calculated at 1.9 K. Marks of circle, diamond, and square represent fillet radius of 3 mm, 5mm, and 6 mm at that corner.

Fig. 6 shows the mesh density study of the end shell sub-model. The peak stress in end shell increases and converges finally when the mesh density is over 10. Thus, the subsequent studies then used element size as of 0.8 mm. Elasto-plastic
study has been performed for the end shell sub-model at 1.9 K to obtain the plastic zone size.

Three fillet radii are taken into account in the mesh refinement studies. Fillet certainly reduces stress concentrations at the local corner.

The peak stress decreases to 490 MPa with 5 mm fillet at 1.9 K, which dropped within the yield limits of 550 MPa for Aluminum 7075. However, 7075 T6 alloy does not exhibit significant strain hardening [8] and the fracture toughness is low at both room temperature and 1.9 K. LFEM with the sub-model at Grade IV is needed to assess the failure of flawed end shell for flaw sizes determined by the quality assurance process.

B. Results of the yoke sub-model

The yoke is considered brittle at room temperature and 1.9 K according to the test results conducted by CERN [7]. Sub-model was used to determine the plastic deformation and stress on the likely path if part-through a crack presents. Similarly, the yoke sub-model also includes different fillet radii (Fig. 7).

![Fig. 7 Relationship between the peak principal stresses at the stress concentration area and the relative mesh density. The stress is calculated at room temperature. Marks of circle, diamond, and square represent fillet radius of 0.6 mm, 1mm, and 2 mm at that corner.](image)

The yoke peak stress also shows similar trends with the mesh densities as seen on the end shell. The subsequent studies used the relative mesh density of 10 as well.

Adding fillet lowers the peak stress at the corner, too; however, plastic deformation still occurs at room temperature. As a material that fracture dominates, yoke will be analyzed in Grade IV to determine the plastic deformation and load factor with fillets.

V. Fracture Failure Assessment

Grade III failure assessment for the end shell and yoke shows that fillets around the corner are recommended. The shells and yoke will be inspected by non-destructive evaluation for flaws of a given size as part of the quality assurance process.

A. Fracture Analysis Method

As the materials exhibit fracture failure modes at both room and cryogenic temperature, fracture failure assessments for the end shell and yoke with given flaw sizes were performed at Grade IV (as seen in Fig. 2).

As mentioned in section II, the fracture failure assessment in this step relies on the R6 FAD, which captures failure by LEFM (elastic fracture), and plastic collapse simultaneously.

For the purposes of design, semi-elliptic part-through cracks are assumed with flaw features intersecting and centered on the components surface as these typically have the highest stress intensities. The major process is to determine the applied stress intensity \( K_I \). For part-through cracks subject to primary stresses, \( K_I \) can be written in the following form [9]:

\[
K_I = F(x) \sqrt{\frac{\pi a}{Q}}
\]

where \( a \) and \( c \) are the elliptical radius of a crack, \( F(x) \) is geometry constants that can be obtained from FEA or published data. \( \sigma(x) \) can be approximated as a cubic expansion of a load profile extracted from an unflawed elastic analysis in the direction of assumed crack propagation through part thickness \( x = \) a direction. \( F(x) \) can be approximated as:

\[
F(x) = \sum_{i=0}^{3} G_i A_i x^i
\]

where \( G_i \) is an influence coefficient for a part-through internal flaw in a cylinder; \( A_i \) is the curve-fitting coefficient of the stress long the path of assumed crack propagation. The stress on the crack path is defined in the end shell and yoke sub-models. The path starts the stress concentration point, and is along the direction of the lowest stress gradient, which is normal to the maximum principal stress and in the most energetic direction.

B. Fracture Assessment for the End Shell

As analyzed in Grade II and III, the end shell presents high stress at 1.9 K. Use the path as described above, the total Von Mises stresses on this path of the end shell with different fillets at 1.9 K are shown in Fig. 8. The path of a crack likely grow along on the end shell is stress concentration around the cut-out corner to the inner surface of the shell with a depression angle of 20°.

The local stress concentration results in local plastic deformations that limit the effective stress state. The fully elastic analysis will coincide with the elasto-plastic model at some distance from the structural discontinuity. The distance to the coincidence is considered as the plastic depth on the defined path. With 3 mm fillet, plastic deformation occurred around the stress concentration area, results in a 0.6 mm plastic depth along the path; the peak stress dropped when increasing the fillet radius.

Take the total stress illustrated in Fig. 8 and a given crack length, the “load point” of each case can be determined in FAD. Load points inside of the FAD curve are safe from failure, load points falling outside or on the curve may fail. Each load point determines a “load line” by connecting the original point. The load factor in the plot is defined as:
where $L$ is the length from the original point to the load point; $L'$ is the length from the original point to the “projected load point”, which is the intersection of load line and the FAD curve. A flaw is considered critical in size if its Load Factor is unity.

![Fig. 8 Total stress on the path of a crack is most likely to propagate](image)

$Load \ factor = \frac{L}{L'}$

The fracture toughness $K_{IC}$ used for the FAD is 20 MPa*√m [11]. The critical flaw sizes at 1.9 K for 5 mm fillet is 2 mm. Accordingly, critical flaw sizes are 1.6 mm and 2.5 mm for 3 mm and 6 mm fillet end shell, respectively. This means flaw less than the critical size should not propagate. Assuming 2 mm crack started at the stress concentration spot, the load points in FAD of the stress concentration area of different cases can be seen in Fig. 9.

The plastic deformation depth in the case of 3 mm fillet is less than the critical flaw size of 1.6 mm, thus the plastic deformation will not affect the crack propagation. However, according to the flaw sizes correlated to Inspection Grades for Aluminum Forgings [10], if a flaw is 2 mm, an inspection Class of “AA” is required; a higher Class of “AAA” is required if a flaw is less than 1.77 mm.

As a reminder, the $K_{IC}$ used in these assessments is the lowest reported value for plate materials. It is possible that a higher value may be achieved in the actual forgings employed; it is also possible that it may be lower. This assessment will be repeated with measured data for the forgings.

Based on the calculations above, the end shell cut-out corners were rounded up to 5 mm fillet radius, each batch of the forging material will be inspected in the Class of “AA”. Please note that the load factor of 1 is only at this stress concentration area, load factor in the major part of shells are larger than 1.4.

C. Fracture Assessment for the yoke

The yoke yields at the notch corner at room temperature in the cases of fillet radius from 0.6 mm to 2 mm. Because the top notch experiences bending due to the compression form the shell, the path of a crack likely grow along on the yoke is from the notch corner (stress concentration) to the hole (Fig. 5).

Fig. 10 shows the total principal stress on the path at room and cryogenic temperature. The yield depths at room temperature of the cases are 2.1 mm and 0.8 mm for 1 mm and 2 mm fillet radius, respectively. Please note, because there are no measured yield strength at 1.9 K, there are no derived yield depths at cold.

![Fig. 9 FAD for 2 mm crack in stress concentration area of end shell with different fillet sizes, $\sigma_y$ is the yield stress](image)

![Fig. 10 Total stress on the path at room temperature and 1.9K with fillet radiiuses of 1 mm and 2 mm.](image)

The fracture toughness of iron is selected the lowest value of 24.1 in the measurements reported in [12]. According to the total stress illustrated in Fig 10, the critical flaw sizes for the case of 1 mm fillet are calculated as 8.6 mm and 5.5 mm at room temperature and 1.9 K. The calculated critical flaw size is much larger than the plastic zone seen on yoke.
Failure assessments for the MQXFA magnet structural metallic parts have been performed in light of a graded approach. Most of the structural components meet the design criteria at grade II level; End shell and yoke presented stress concentration in Grade II analyses, Grade III advanced mechanical analysis and Grade IV fracture assessments were then performed. The analysis suggests adding fillets on the cut-out corners of these components to reduce the stress concentration and release the elastic energy if a local flaw presents. The end shell eventually added 5 mm fillet on the corner; and yoke added 2 mm fillet according to the Grade IV fracture assessments.

REFERENCES