Fracture Failure Analysis for MQXF Magnet Aluminum Shells

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Abstract: **The High-Luminosity LHC Accelerator Upgrade Project (HL-LHC AUP) is approaching the production phase of the US-contributed Q1 and Q3 Interaction Region Quadrupoles (MQXFA). The structures for the MQXFA prototypes were design and inspected by the US-LARP (LHC Accelerator Research Program), AUP developed criteria, which will be used for the pre-series structures. As the first two full-length prototypes with 4.2 m magnetic length, MQXFAP1 and MQXFAP2, were designed and assembled at Lawrence Berkeley National Laboratory (LBNL), and tested at Brookhaven National Laboratory (BNL). The end aluminum short shell of MQXFAP2 was fractured along the shell length during the test, and tests were stopped. Analytical and Finite Element analysis were performed in light of the graded procedure defined in the Structure Design Criteria to investigate the fracture failure for MQXFAP2.**

In this paper, we report the fracture analysis of the current shell design, including the elasto-plastic simulations with sub-model technique, and calculations with Linear Elastic Fracture Mechanics (LEFM). Test material properties are also presented. The results of this analysis explain why the end shell of MQXFAP2 failed, and suggest fillets on the end shell notches to meet the margin specified in the Structural Design Criteria.

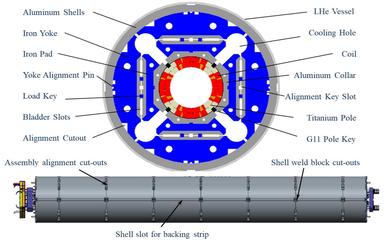
Introduction

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.

As same as the previous LARP HQ and MQXFS magnets, MQXFA magnet has the same cross section, and relies on the pre-tension of the aluminum 7075-T6 shell, which is pre-loaded at room temperature with the bladder-and-key technology.

The cold test of MQXFAP2 was stopped by a notable unstable structure behavior, which was identified fracture failure on the end shell. A longitudinal crack was plainly evident in the RE end shell. The shell displaced by approximately 15 mm axially, and rotated also about 0.5° . The fractured surface appears rough, and no "fatigue-induced" cyclic rubbing appears present based on microscope checks.

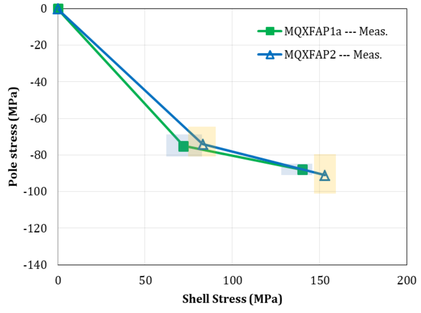
MQXF Magnet Parameters



COIL AND MAGNET PARAMETERS

Parameter	Unit	
Coil clear aperture diameter	mm	150
Magnet (LHe vessel) outer diameter	mm	630
No. turns in layer 1/2 (octant)		22/28
Operational temperature T_{op}	K	1.9
Magnetic length (Q1-Q3)/(Q2)	M	4.20/7.15
Nominal gradient G_{nom}	T/m	132.6
Nominal current I_{nom}	kA	16.47
Nominal conductor peak field B_{op}	T	11.4
I_{nom} / I_{ss} at 1.9 K for RRP/PIT (specs.)	%	77/79
Ultimate gradient G_{ult}	T/m	143.2
Ultimate current I_{ult}	kA	17.89
Ultimate conductor peak field B_{ult}	T	12.3
I_{ult} / I_{ss} at 1.9 K for RRP/PIT (specs.)	%	84/86
Stored energy density at I_{nom} (Q1-Q3)/(Q2)	MJ/m	1.17
Differential inductance at I_{nom}	mH/m	8.21
Stored energy at I_{nom} (Q1-Q3)/(Q2)	MJ	4.91/8.37
F_x / F_y (per octant) at I_{nom}	MN/m	+2.47/ -3.48
F_y layer1/layer2 (per octant)	MN/m	-1.84/-2.14
F_y (whole magnet) at I_{nom}	MN	1.17

Fracture Failure of the MQXFAP2 End-Shell



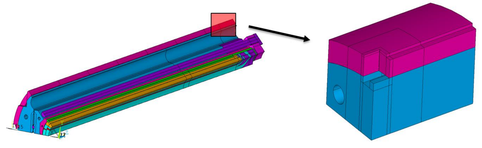
SHELL MATERIAL INSPECTION RESULTS

Magnet	Material	Ave. shell stress (MPa)	Corner radii (mm)
MQXFAP1	Al 7075-T6	137	0.03-0.14
MQXFAP2 (End shells)	Al 7075-T652	152	0.02 (Broken shell), >0.75 (LE shell)
MQXFAP2 (other shells)	Al 7075-T6	152	>0.75

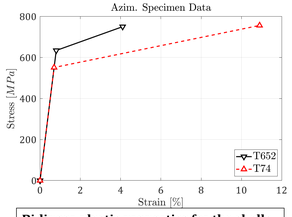
There are two non-conforming parameters of the fractured shell:

- (a) the shell material;
- (b) the corner radii of the cut-outs.

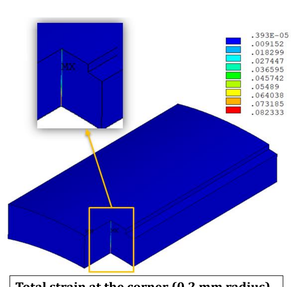
Plastic Analysis for the MQXFAP2 End-shell



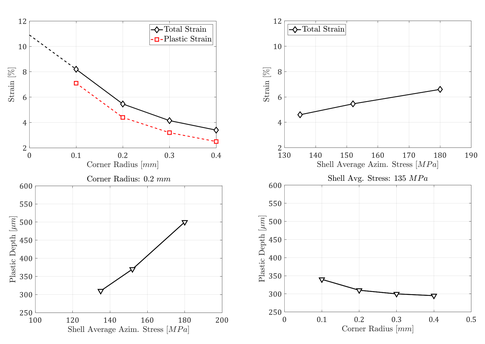
Sub-model for the weld block cut-out



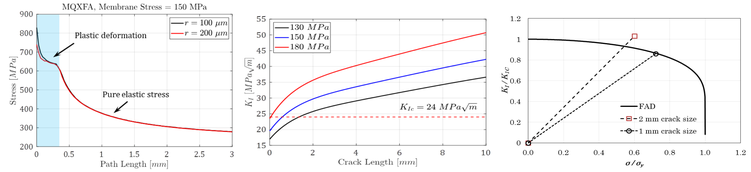
Bi-linear plastic properties for the shells



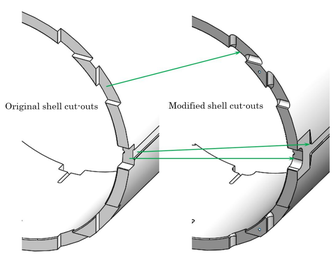
Total strain at the corner (0.2 mm radius)

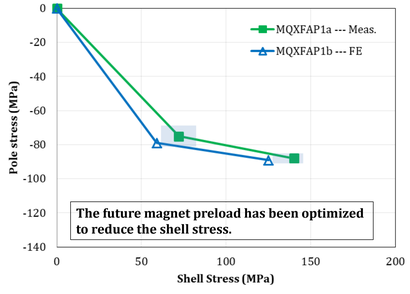


Fracture Analysis and Shell Redesign

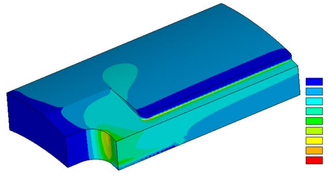


- The size of the plastic zone of the cut-out of the MQXFAP2 end shell is close to the critical flaw size with a real corner radius on the level of 0.02 mm.
- It's apparently that the weld block cut-out of the MQXFAP2 end shell does not meet the load factor requirement.





The future magnet preload has been optimized to reduce the shell stress.



Von Mises stress with the new shell cut-out designs