Structural Optimization and Experimental Assessment of a CFRP–Nomex Pressure Vessel for the EPIC dRICH Detector

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Abstract

The dual-radiator Ring Imaging Cherenkov detector of the EPIC experiment requires a gas enclosure that combines low mass, pressure resistance and dimensional stability. This work investigates a 1:10-scale vessel prototype manufactured with carbon-fibre-reinforced polymer monolithic regions and CFRP–Nomex sandwich panels. A static finite-element model was developed in COMSOL MULTIPHYSICS Workbench on one quarter of the geometry, using symmetric conditions, anisotropic laminate properties, bonded interfaces and uniform internal pressures from 0.2 to 0.5 MPa. The baseline 4 mm Nomex core was compared with 5 mm and 3 mm alternatives, the latter combined with thicker CFRP skins. Experimental pressurization cycles of 24 and 48 h were conducted up to 3.5 bar, with pressure, temperature and local displacement monitored in the monolithic and sandwich regions. The numerical study identifies interfaces and geometric transitions as the dominant stress-concentration zones. Among the investigated layups, the 3 mm core with 1.30 mm skins provides the lowest deformation and the most stable safety margin: at 0.3 MPa it gives 14.34 mm maximum directional deformation, 1550 MPa equivalent stress and a safety factor of 1.61. At 0.4 MPa its safety factor falls to 1.20, below the design target of 1.5, while at 0.5 MPa it falls below unity. Experiments reproduce the predicted sequence from elastic response to sandwich-panel bulging and local distress, but the available data support qualitative rather than fully calibrated quantitative validation. The results therefore favour the 3 mm-core configuration for further development while requiring local reinforcement and model calibration before defining the final pressure envelope.

Keywords: composite pressure vessel; CFRP; Nomex honeycomb; finite-element analysis; dRICH; structural optimization.

1 Introduction

The Electron–Ion Collider will investigate the quark and gluon structure of matter through polarized electron–proton and electron–ion collisions. Within the EPIC detector, the dual-radiator Ring Imaging Cherenkov system provides charged-particle identification over a broad momentum range. Its optical and tracking performance depends on a stable gas volume; consequently, the surrounding vessel must retain its geometry under pressure while contributing as little passive material as possible.

Composite construction is attractive because high specific stiffness can be combined with tailored reinforcement. The dRICH shell considered here includes monolithic CFRP regions and larger sandwich surfaces formed by CFRP skins bonded to a Nomex honeycomb core. This hybrid architecture introduces discontinuities in stiffness and load transfer, particularly at bonded joints, pipe transitions and the boundary between monolithic and sandwich regions. These features make simplified thin-shell formulas insufficient for design verification and motivate a finite-element and experimental approach.

The objectives are to characterize the pressure-dependent response of a scaled prototype, compare three sandwich layups and identify a configuration suitable for further engineering. The study also distinguishes between numerical trends that are experimentally supported and quantities that still require direct calibration.

2 Prototype Geometry and Materials

The full vessel is approximately 4 m in diameter and 1.5–2 m long. The 1:10 prototype preserves the principal curvature, modular subdivision and transition between structural regions while omitting the aluminium frame, bolted details and quartz window. The reduced diameter is approximately 400 mm. The two manufactured portions were joined by adhesive bonding, which also permits direct observation of interface behaviour during pressure testing.

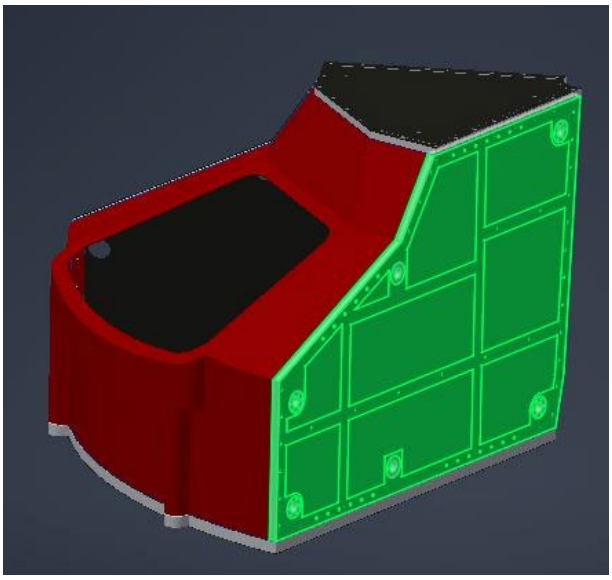


Figure 1. Full dRICH vessel geometry used as the basis for the scaled prototype.

The monolithic region consists of GG380T-12K-2×2T carbon fabric with 42% IMP503Z resin. A balanced sequence containing 0°, ± 45° and 90° plies was adopted to carry longitudinal, shear and transverse loads. In the prototype, this region was represented with a nominal thickness of 1.60 mm. The sandwich region contains outer and inner CFRP skins and a CNX3.2 Nomex honeycomb core. The baseline prototype thickness was 5.60 mm, including a 4 mm core. Two alternatives were assessed numerically: a 5 mm core with 0.30 mm skins and a 3 mm core with 1.30 mm skins. The design comparison therefore concerns the complete distribution of core and face-sheet material rather than core thickness alone.

3 Finite Element Model

The CAD model was prepared in Autodesk Inventor and imported into COMSOL MULTIPHYSICS Workbench for static structural analysis. Only one quarter of the vessel was retained because of radial and longitudinal symmetry. Symmetry constraints were imposed on the cut planes, and a radial support condition was applied to the cylindrical boundary. Uniform internal pressure was applied to all wetted surfaces at 0.2, 0.3, 0.4 and 0.5 MPa. Temperature was held at 20 °C. CFRP and honeycomb domains were represented with anisotropic properties and multilayer orientations; skin-to-core and structural interfaces were treated as bonded. Curved tetrahedral elements were used, with local refinement at interfaces, joints and geometric transitions. The reported element size range was 0.8–4 mm with a grading factor of 1.5.

The extracted responses were maximum directional deformation along the vessel Y axis, equivalent stress and stress intensity. A scalar safety factor was calculated as

$$SF = 2500\ MPa / \sigma_{eq,max}$$

where 2500 MPa was used in the thesis as a reference strength. This screening metric is retained for consistency across the design variants. It should not be interpreted as a complete composite failure criterion: ply-level stresses, orthotropic strength allowables, adhesive failure and honeycomb crushing require separate verification. This limitation is especially important where peak stresses occur at bonded transitions.

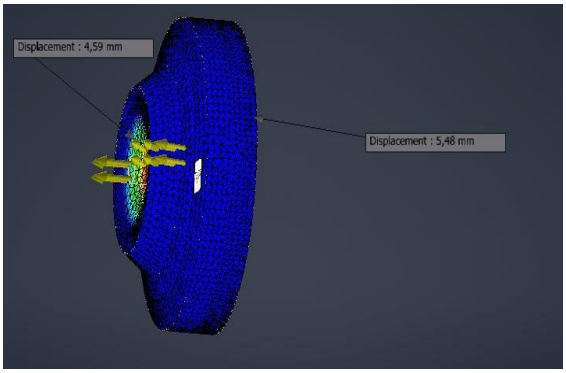


Figure 2. Quarter-symmetry finite-element model with virtual probes located at the experimental measurement positions.

4. Experimental Program

The physical prototype was equipped with a pressure transducer and datalogger for continuous monitoring. Two dial indicators, with 0.01 mm resolution, were subsequently positioned on the monolithic and sandwich regions to quantify their different responses. Helium pressurization cycles were maintained for 24 and 48 h at nominal pressures of 2.5, 3.0 and 3.5 bar. Temperature and humidity were recorded because daily temperature variation affects gas pressure and composite dimensions.



Figure 3. Manufactured 1:10 CFRP–Nomex vessel prototype.

At 2.5 bar the pressure was essentially stable over 24 h and decreased by about 0.06 bar after 48 h, a variation compatible with thermal effects, micro-

permeability and structural settling. At 3.0 bar the pressure remained stable, but the first acoustic emissions and visible sandwich-panel bulging appeared. At 3.5 bar the pressure decreased from 3.500 to 3.462 bar after 48 h, crackling became more frequent and deformation extended over a larger part of the sandwich region. No gross loss of containment was observed, although the combination of pressure drift, sound and persistent deformation indicated entry into a more critical regime.

Pressure	24 h Δp	48 h Δp	Main observation	
2.5 bar	+0.006 bar	−0.019 bar	Time-dependent bulging	
3.0 bar	−0.020 bar	−0.004 bar	Acoustic emissions	
3.5 bar	−0.019 bar	−0.027 bar	Persistent deformation	
Pressure	**Mon. 24 h**	**Mon. 48 h**	**Sand. 24 h**	**Sand. 48 h**
2.5 bar	−0.06 mm	−0.05 mm	+0.02 mm	+0.58 mm
3.0 bar	−0.13 mm	−0.11 mm	+0.19 mm	+0.47 mm
3.5 bar	−0.05 mm	−0.10 mm	+0.27 mm	+0.32 mm

Table 1. Pressure stability and local displacement changes reconstructed from the start and end readings reported in the thesis.

5 Validation Approach

The numerical model predicted larger deformation in the sandwich region, smaller and more linear movement in the monolithic region, and stress localization at stiffness transitions. These features are consistent with the experimental observations. Virtual probes were placed at the dial-indicator locations to support a location-matched comparison. However, the thesis reports global or model-scale maximum numerical displacements of 9–38 mm, whereas measured incremental local displacements are mostly below 0.6 mm. Because the reference states, probe values, load histories and geometric scaling are not tabulated in a common form, the present dataset does not establish numerical agreement in magnitude. Accordingly, validation is described here as qualitative: the model correctly ranks sensitive regions and reproduces the pressure-driven evolution, while quantitative calibration remains future work.

This distinction does not reduce the utility of the model for relative design screening, because all three layups were compared using the same geometry, loads and output definitions. It does, however, limit claims about absolute displacement prediction and allowable operating pressure.

6 Numerical Results and Structural Optimization

The baseline 4 mm core shows an approximately linear increase in maximum directional deformation from 15.17 mm at 0.2 MPa to 37.95 mm at 0.5 MPa. Its safety factor falls below the target value of 1.5 above 0.2 MPa and below unity at 0.4 MPa. Increasing the core to 5 mm while reducing each skin to 0.30 mm decreases deformation by about 10–13% relative to the baseline, but it also produces the lowest safety margin at the two higher pressures. Thus, deformation reduction alone does not indicate an improved design.

The 3 mm core combined with 1.30 mm CFRP skins produces the lowest deformation at every pressure. Compared with the baseline, maximum deformation is reduced by approximately 37% across the complete pressure range. The corresponding equivalent stresses are also lower, and the safety factor remains above the 1.5 design target through 0.3 MPa. At 0.4 MPa, however, the value is 1.20—not ≥1.5—and therefore the configuration does not satisfy the adopted target. At 0.5 MPa the equivalent stress exceeds the 2500 MPa reference strength and the safety factor decreases to 0.96. [1,2]

Baseline 4 mm core

P (MPa)	Def. (mm)	Stress (MPa)	SF
0.2	15.17	1520	1.64
0.3	22.76	2281	1.09
0.4	30.35	3041	0.82
0.5	37.95	3801	0.66

5 mm core and 0.30 mm skins

P (MPa)	Def. (mm)	Stress (MPa)	SF
0.2	13.62	700	3.57
0.3	19.75	2000	1.25
0.4	26.33	3500	0.71
0.5	32.91	4800	0.52

3 mm core and 1.30 mm skins

P (MPa)	Def. (mm)	Stress (MPa)	SF
0.2	9.56	1033	2.42
0.3	14.34	1550	1.61
0.4	19.12	2067	1.20
0.5	23.90	2584	0.96

Table 2. Summary of finite-element results for the three sandwich configurations.

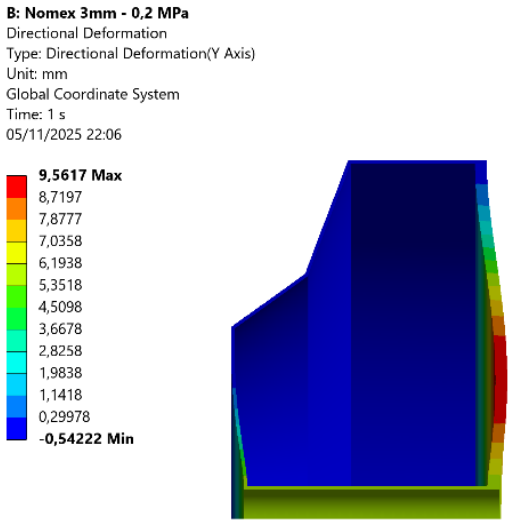


Figure 4. Directional deformation of the 3 mm-core configuration at 0.2 MPa; maximum reported value 9.56 mm.

Stress maps consistently place the most severe gradients at the interfaces between monolithic and sandwich construction, along outer edges and at pipe junctions. These localized peaks may partly reflect geometric singularities or idealized bonding, but they also identify the correct regions for physical reinforcement. A robust next iteration should use smoother transitions, locally increased skin thickness, adhesive characterization and mesh-convergence checks based on stress away from singular edges. [3]

7 Discussion

The comparison demonstrates that the response is governed by the combined core–skin architecture. The nominally thinner 3 mm core is the stiffest option because its 1.30 mm CFRP skins dominate flexural response. Conversely, the 5 mm core is paired with only 0.30 mm skins; it limits global deflection relative to the baseline but develops higher effective stresses and a rapidly decreasing safety margin. Core thickness should therefore not be optimized independently of face-sheet thickness, layup, joint geometry and mass budget.

The experimental campaign supports three design conclusions. First, the sandwich zone is more sensitive to sustained pressure than the monolithic zone. Second, a transition occurs near 3 bar, where visible bulging and acoustic emissions begin even without a substantial pressure loss. Third, the 3.5 bar condition produces persistent deformation and a small pressure decline, so operation in this range requires additional evidence. These trends are consistent with the numerical identification of the sandwich region and its interfaces as critical areas.

Several limitations remain. The safety-factor calculation uses a single equivalent-stress limit for an anisotropic composite assembly and does not evaluate ply failure, core shear, face wrinkling, delamination or adhesive damage. Some 5 mm-core safety factors are based on an “effective” value read from the plotted colour range rather than the reported singular maximum, which introduces analyst judgement. The experimental and numerical displacements also lack a complete common reference definition. Finally, dynamic, cyclic, thermal and accidental loads were not included. The reported values should therefore guide comparative optimization, not final qualification of the pressure boundary.

8 Conclusions

A combined finite-element and experimental study was performed on a 1:10 CFRP–Nomex prototype for the EPIC dRICH gas vessel. The main findings are:

- the 3 mm Nomex core with 1.30 mm CFRP skins provides the lowest deformation and the highest stable safety margin among the configurations tested;
- this configuration satisfies the adopted safety-factor target of 1.5 only up to 0.3 MPa; its safety factor is 1.20 at 0.4 MPa and 0.96 at 0.5 MPa;
- bonded interfaces and geometric transitions govern the peak-stress response and should be the first targets for reinforcement and geometric refinement;
- pressurization testing confirms the relative sensitivity of the sandwich region and identifies a behavioural transition near 3 bar, but further calibration is required before claiming quantitative FEM validation.

The next design stage should incorporate orthotropic failure criteria, cohesive or experimentally calibrated interface laws, mesh-convergence assessment and additional displacement measurements at matched numerical probe locations. After these steps, the pressure envelope can be reassessed using service, cyclic and proof-load cases.

References

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