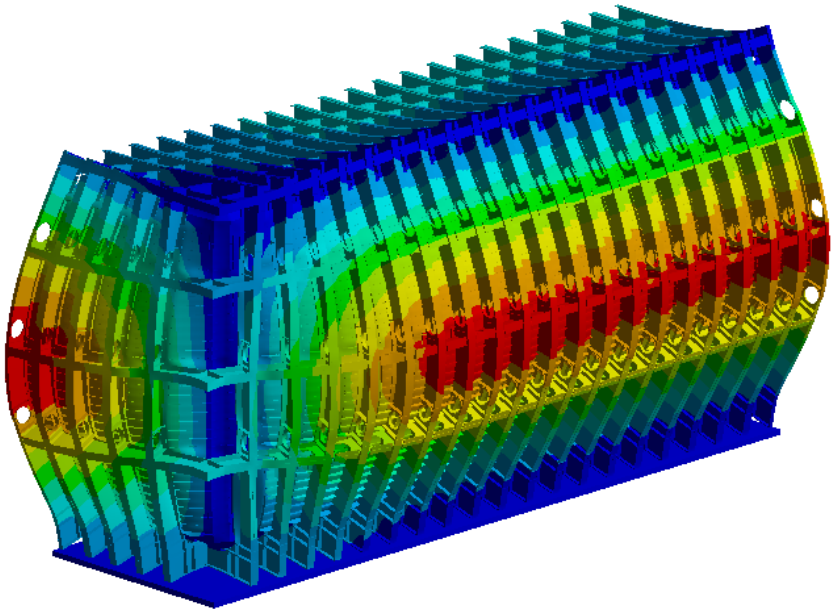
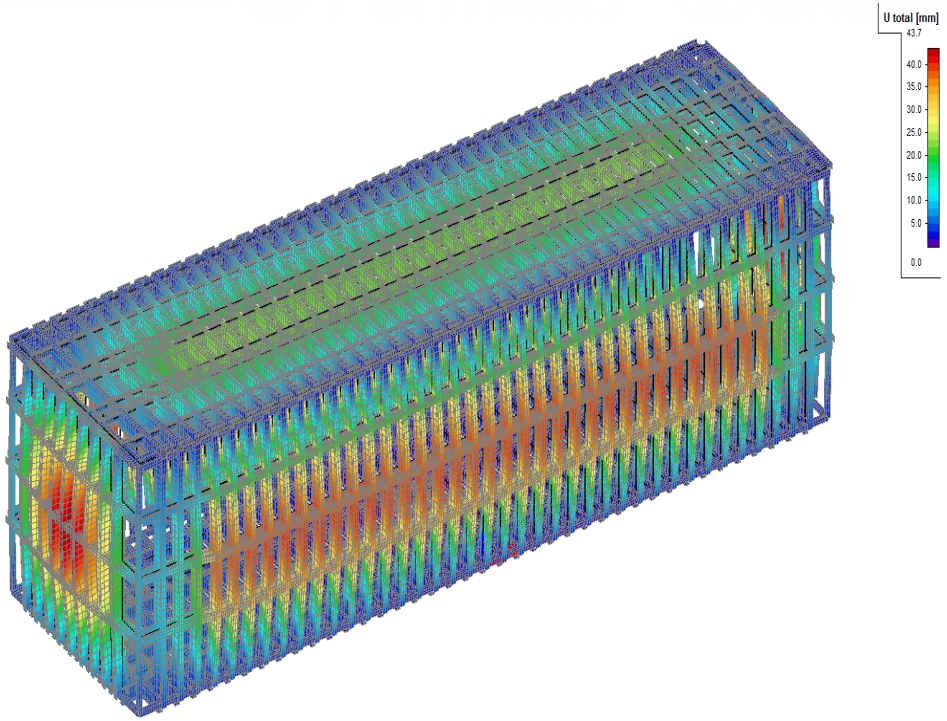




LBNF Structural analysis strategy

Andrea Catinaccio (CERN-EP-DT)

LBNF Cryostat, final design review

SURF, 21-22 August 2017

CERN

Fermilab

Sanford Underground Research Facility

Outline

- Introduction on models
- Eurocode3 verification: Analytical - SCIAengineer – FEA
- External consultant calculations on connections
- FEA models for the reinforced membrane
- Testing of main connections at Coimbra, Dept. of Civil Engineering

Calculation models implemented

Several models have been implemented and results compared:

- Analytical (EC3 code based) analyses of main structural elements and connections
- SCIAengineer analyses (EC3 code based) with load combinations and imperfections
- FEA models (beam, shell and solid element formulation) in order to:
  - Verify results obtained with SCIA global model
  - Detail study/analysis of critical areas of the LBNF cryostat
    - Beam Connections (welded and bolted)
    - Warm membrane and reinforcements
    - Floor reactions and support conditions
    - Local reinforcements (e.g. for access openings)

Testing of most critical connections planned to validate FEA and Analytical models

Calculation models implemented

The analyses have covered:

- Load combinations and initial sway imperfections
- Static and dynamic (seismic) stress-deflection behaviour
- Global and local Stability
- Evaluation against plastic collapse, by linear and non linear analyses (ANSYS, SCIAeng)

Loading and Materials

- Static head of LAr: 14m (~100% filling ratio, ρ=1400kg/m^3)
- Top pressure: 130mbar to 350mbar (valve opening)
- Weight of members:

Design Pressure

– Self-weight of composing members. Main beam members: HL1100M (433 kg/m)
– Insulation plus inner corrugated membrane 105 kg/m2 (800 mm total thickness)
– Stiffened warm membrane of 12 mm, 131 kg/m2
– Detector weight (dry) 200 tons distributed on the roof

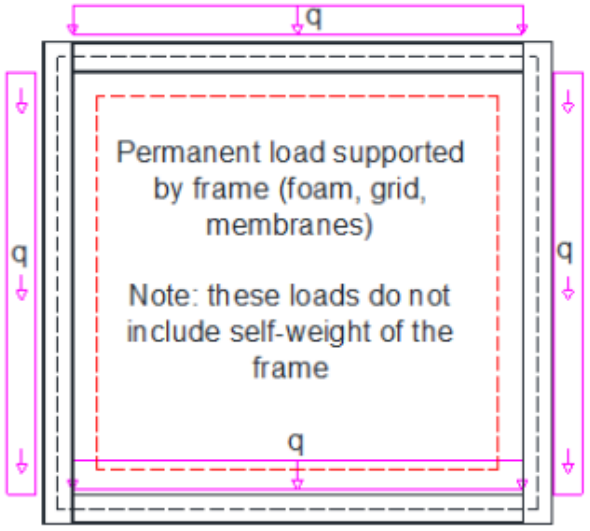
Assumes uniform load transfer to warm membrane

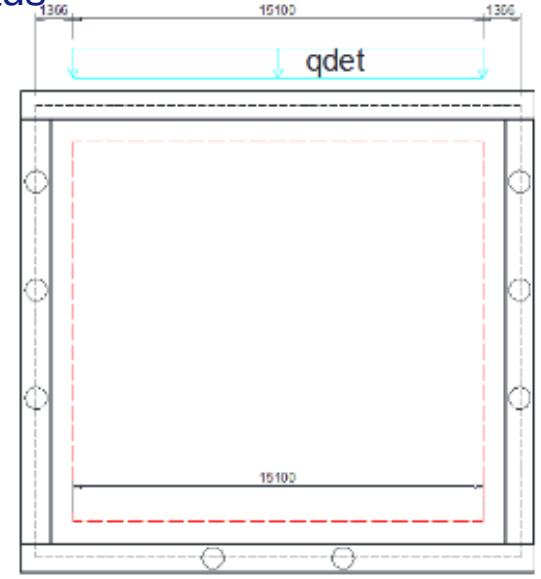
- Load cases with Seismic loads

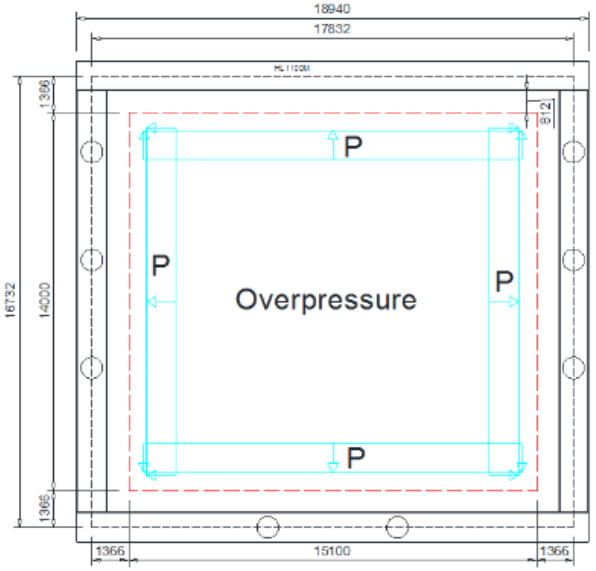
New HL1110M*433 beams and news dimensions of portals

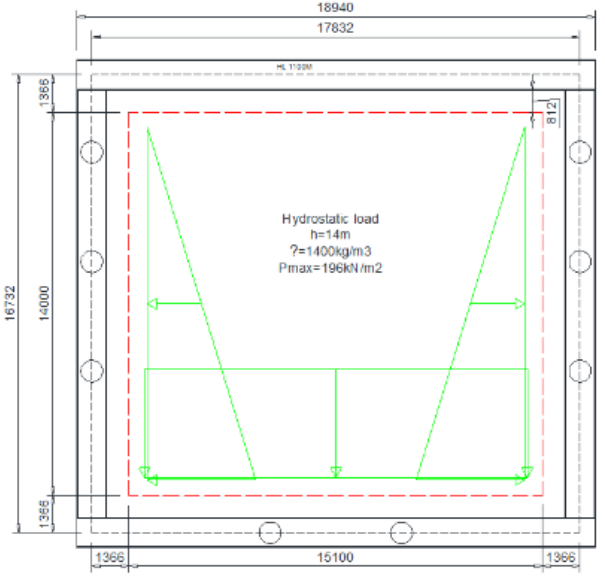
- Baseline Material: Grade S460ML (σy=440 MPa; UTS=540MPa) for main beams and membrane
- Bolt grades 10.9 **(preloading qualified bolts)**

Loading corresponding to Unit Cell **(pitch 1.6m)**









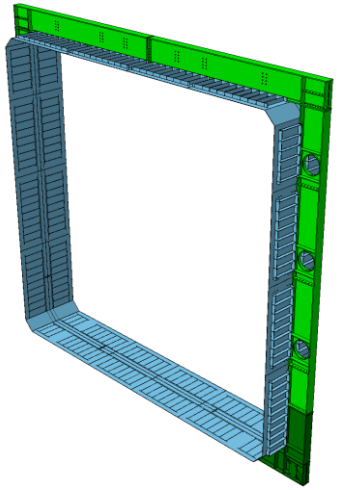
2D and 3D Calculation models

As presented at the end of 2016

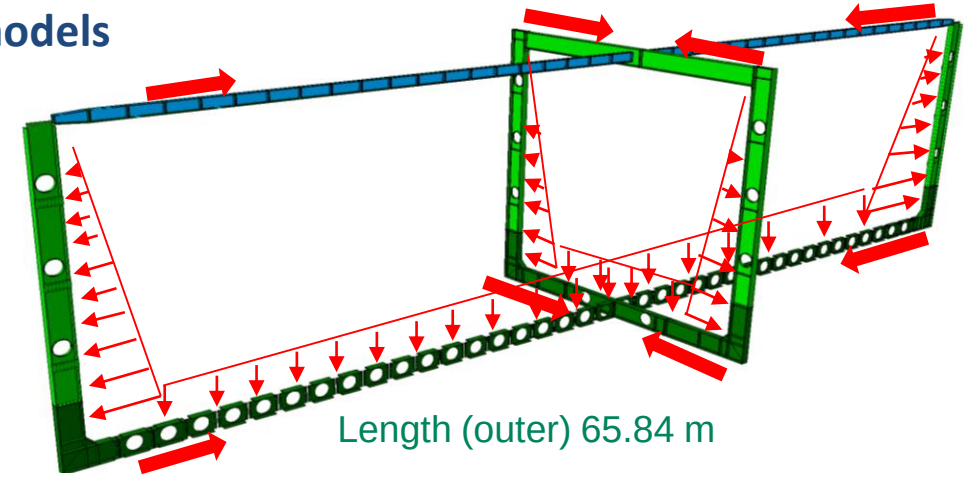
- This basic unit cell is the "portal". It takes the principal load - fluid pressure and weight
- The standard cell is then completed by the longitudinal belts, to compose the main holding frame box
- The warm membrane, reinforced with ribs, holds the pressure between the main beams, provide the tightness, and does not contribute to the strength of the main holding structure

2D Portal models

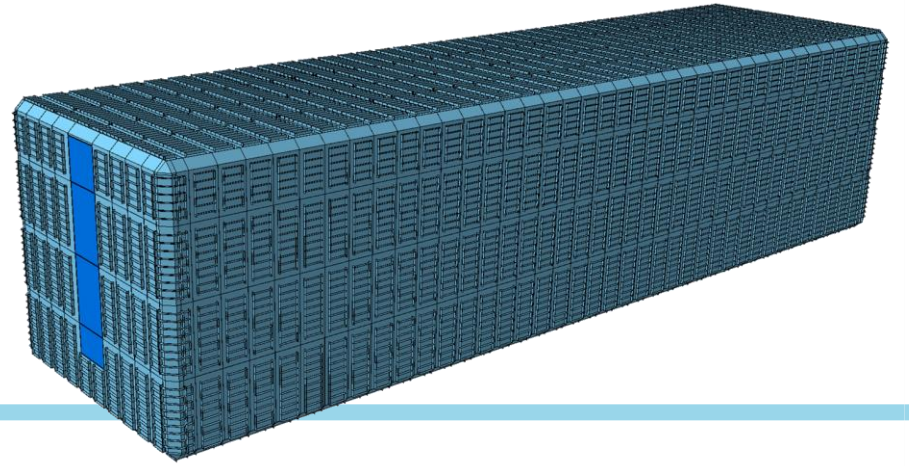
Unit Cell
(1.6m pitch)



3D models



Length (outer) 65.84 m



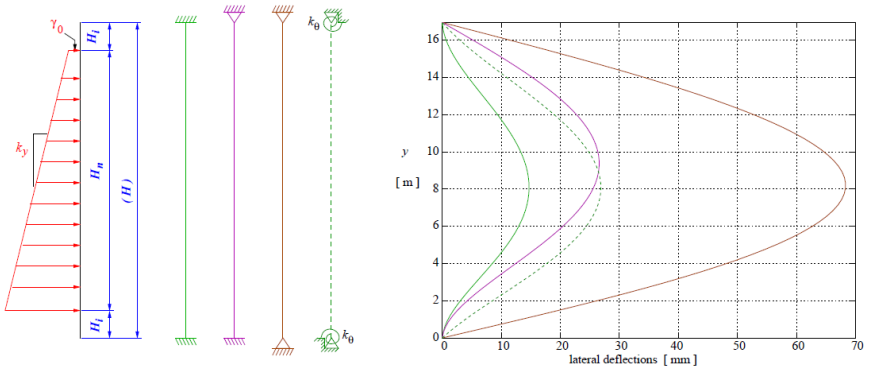
Initial comparison portal beam vs SCIAeng

- Results from the beam model for a direct comparison.

  *Calculations in EDMS doc. 1547687 (2nd assessment), with a load multiplier of 1.35 for permanent actions and hydrostatic pressure and of 1.4 for the design pressure of 350 mbar. Comparison with Ansys analysis EDMS doc. 1550696. HL1110M*433 beams*

	Beam model	Scia model	Δ %
Vertical beam side displacement	56.7 mm	55.6 mm	1.9 %
Top beam vertical displacement	19.65 mm	19.1 mm	2.8%
Vertical beam mid span moment	5.02 MN m	4.996 MN m	0.5%
Vertical beam bottom corner moment	6.76 MN m	6.74 MN m	0.3%
Vertical beam bottom corner shear	2.64 MN m	2.632 MN m	0.3%

Displacements: ANSYS run with EC3 load multipliers for comparison with EC3 calculations



Presented at Initial design review in 2015
Initial studies for thicker beam and nominal loads as benchmark

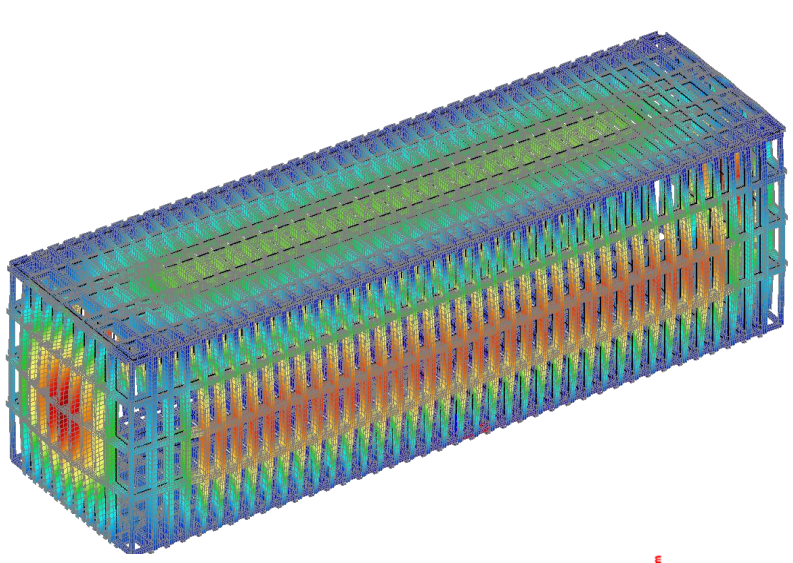
Ref. documents:
https://edms.cern.ch/document/1835609

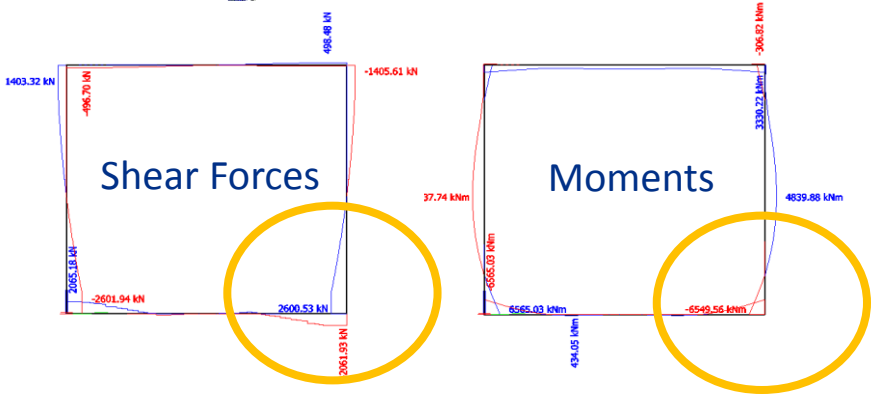
Analytical and FEA models: ref. material Joao

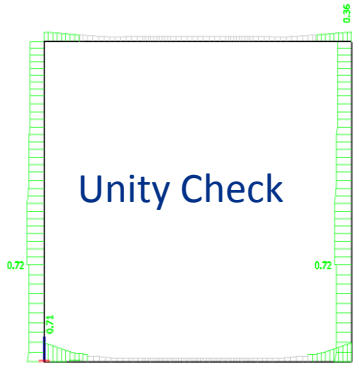
- EC3 SCIAengineer global models
- Analytical calculations of members, connections, local openings
- Seismic analysis

Calculations model: 3D beam (SCIAeng)

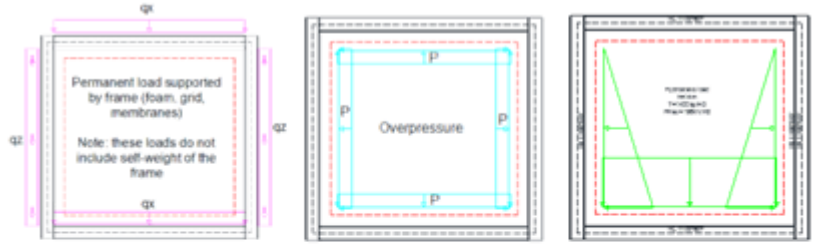
- SCIAengineer full verification according to Eurocode 3 (dedicated software).







Covers full load combinations (example below out of 32 combinations by now):



Load case 1: q=3.5kN/m

Load case 2: p=20.8kN/m
Load case 3: p=56kN/m

Load case 4 p=-307.5kN/m

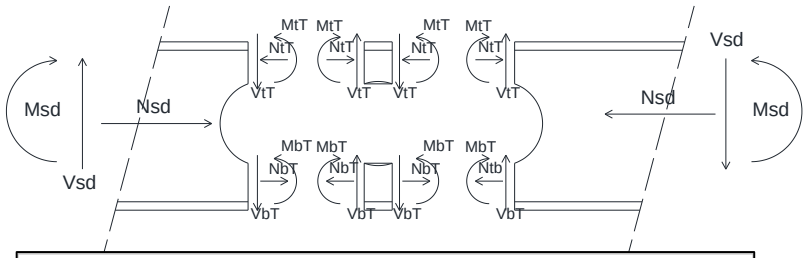
	ULS Combinations	SLS Combinations
1- permanent action	1.35*LC1	1.0*LC1
2- Hydrostatic	1.35*LC1 + 1.35*LC4	1.0*LC1 + 1.0*LC4
3- Operation	1.35*LC1 + 1.35*LC4 + 1.4*LC2	1.0*LC1 + 1.0*LC4 + 1.0*LC2
4- Accident	1.35*LC1 + 1.35*LC4 + 1.4*LC3	1.0*LC1 + 1.0*LC4 + 1.0*LC3

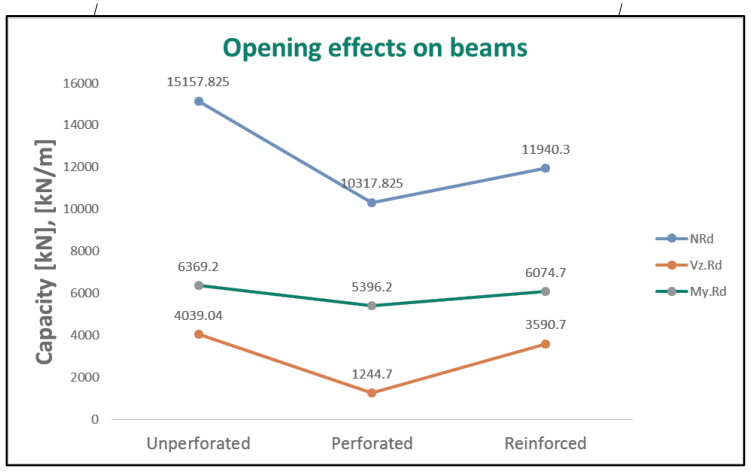
SCIAengineer **envelope** verification according to Eurocode 3 (main transversal portal).

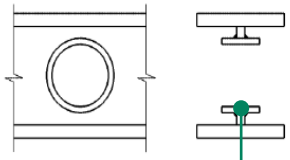
Envelope results used for Unity check verification and sizing of connections.

Calculations model: EC3 Analytical

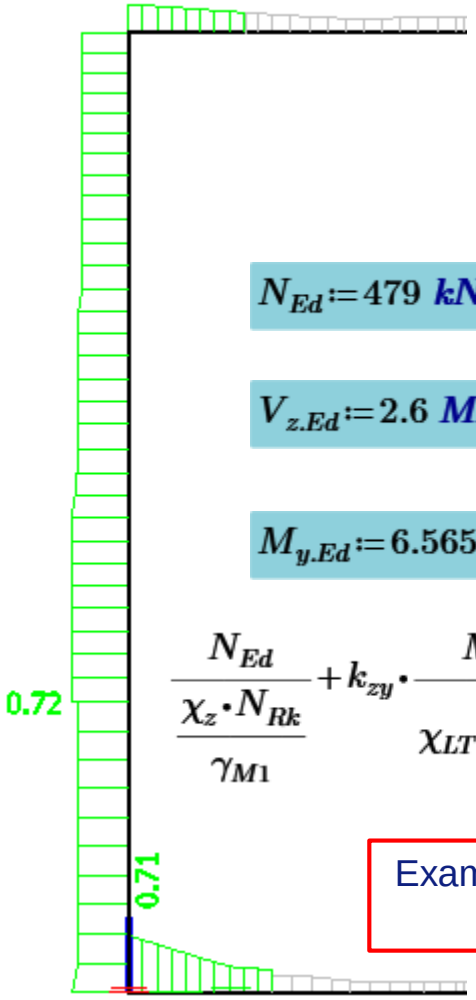
Analytical calculations of openings







25mm



$N_{Ed} := 479\ kN$

$V_{z.Ed} := 2.6\ MN$

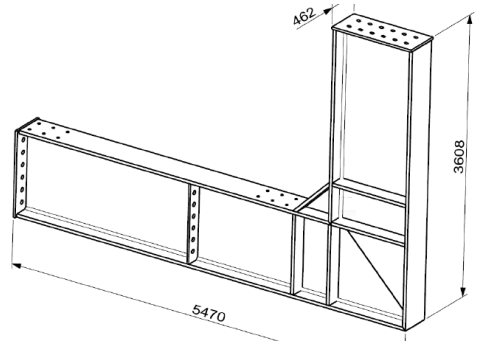
$M_{y.Ed} := 6.565\ MN \cdot m$

$$\frac{N_{Ed}}{\frac{\chi_z \cdot N_{Rk}}{\gamma_{M1}}} + k_{zy} \cdot \frac{M_{y.Ed}}{\chi_{LT} \cdot \frac{M_{y.Rk}}{\gamma_{M1}}} + k_{zz} \cdot \frac{M_{z.Ed}}{\frac{M_{z.Rk}}{\gamma_{M1}}} = 0.8$$

Example of main frame analytical end verification: Unity Check

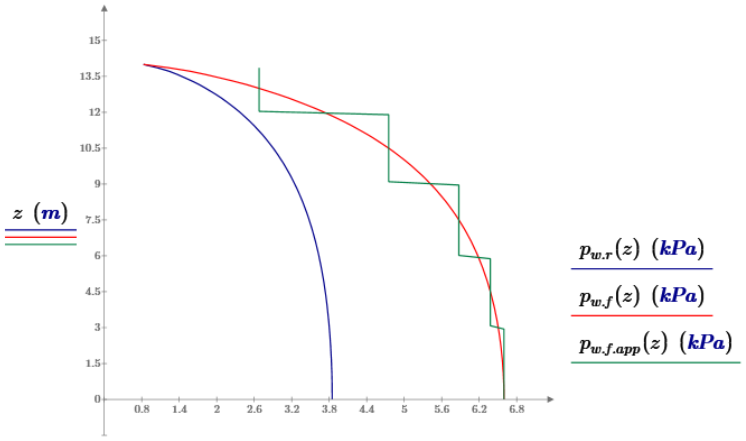
Examples of results from analytical calculation of connections

Stiffener	M_{jRd} (kNm)	V_{Rd} (kN)	Stiffness
TC	5897	5875	rigid
TCS	9264	5875	rigid
TCH	8574	5875	rigid
TCSH	13470	5875	rigid



Seismic Calculations : EC3 Analytical and FEM

Hydrodynamic components:
Rigid impulsive component (fraction of the fluid that moves together with the wall of the vessel)
Convective pressure distribution corresponds to the distribution due to the sloshing of the fluid.
Inertia effects:
Additional uniformly distributed load on the structural elements.



Total pressure distribution on the wall

- Impulsive mass (that move with walls) *[(A.4) EN 1998-4]*

$$m_i := m \cdot 2 \cdot \gamma \cdot \sum_{n=0}^{50} \frac{I1\left(\frac{2 \cdot n+1}{2} \cdot \frac{\pi}{\gamma}\right)}{\left(\frac{2 \cdot n+1}{2} \cdot \pi\right)^3 \cdot \left(I0\left(\frac{2 \cdot n+1}{2} \cdot \frac{\pi}{\gamma}\right) - \frac{I1\left(\frac{2 \cdot n+1}{2} \cdot \frac{\pi}{\gamma}\right)}{\frac{2 \cdot n+1}{2} \cdot \frac{\pi}{\gamma}}\right)} = 13663513.63 \ kg$$

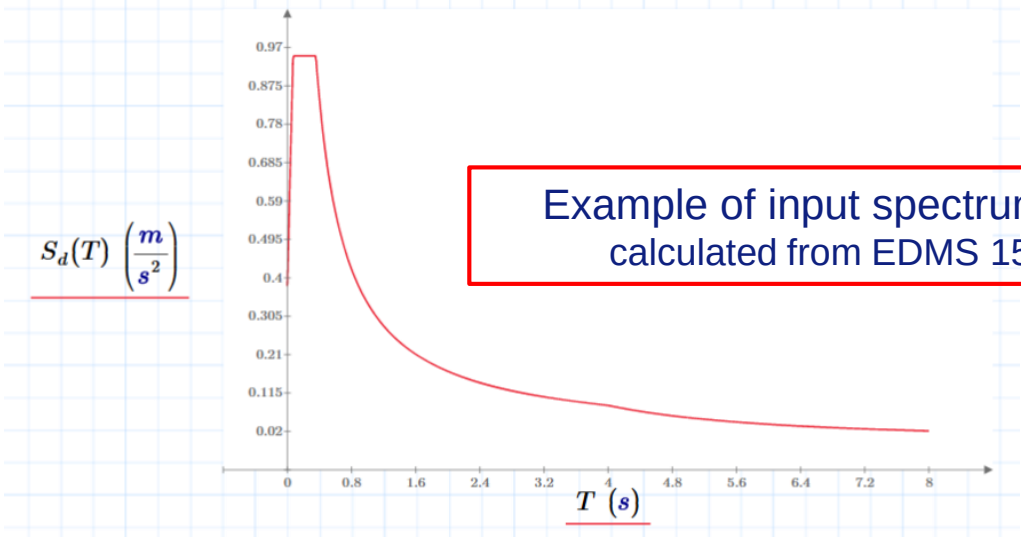
- *[IITK-GSDMA]*

$$m_{iI} := m \cdot \frac{\tanh\left(0.866 \cdot \frac{2 \cdot L}{H}\right)}{0.866 \cdot \frac{2 \cdot L}{H}} = 14389631.464 \ kg$$

- Percentage of impulsive mass

$$\frac{m_i}{m} \cdot 100 = 74.463$$

examples of seismic analytical calculations



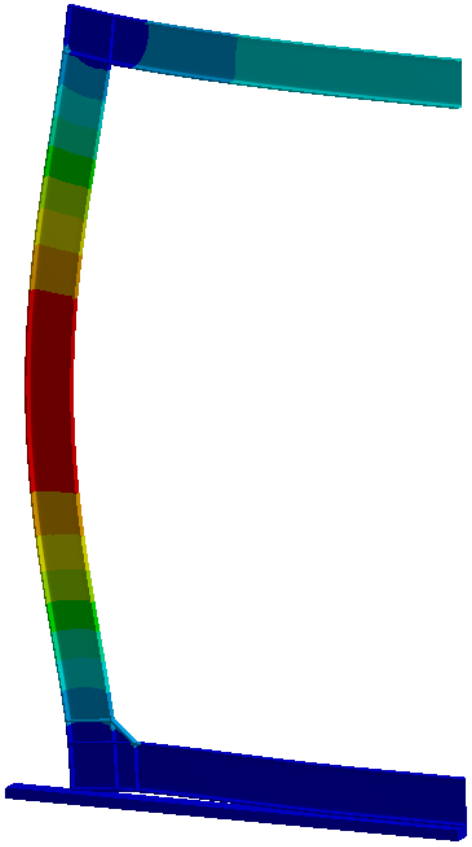
Example of input spectrum for FEA
calculated from EDMS 1510132

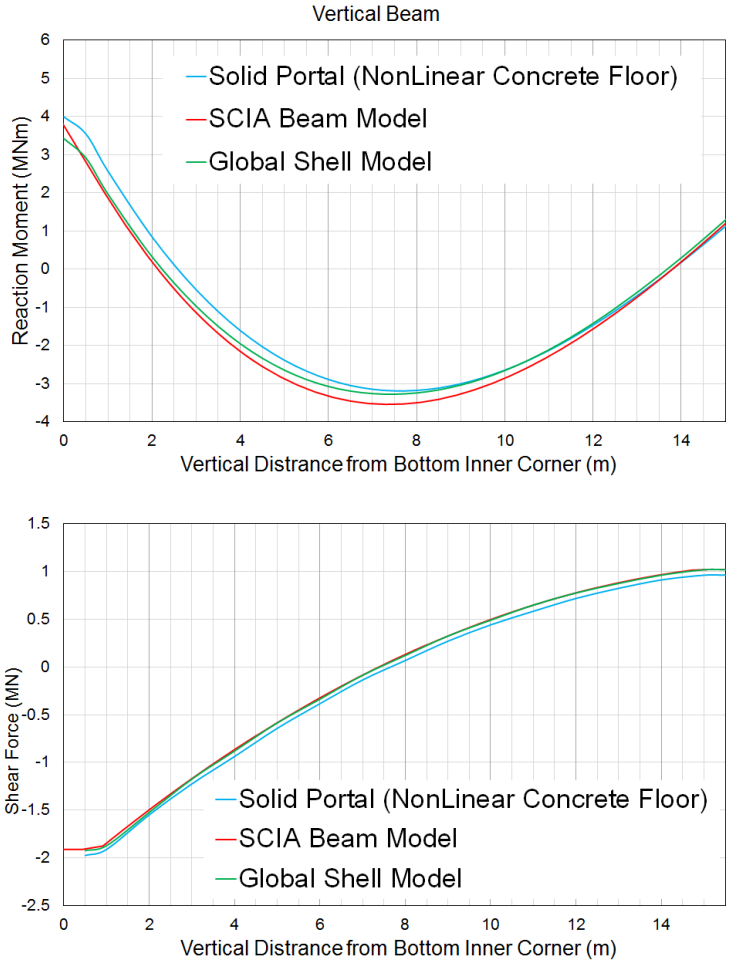
FEA ANSYS models: ref. material Diego

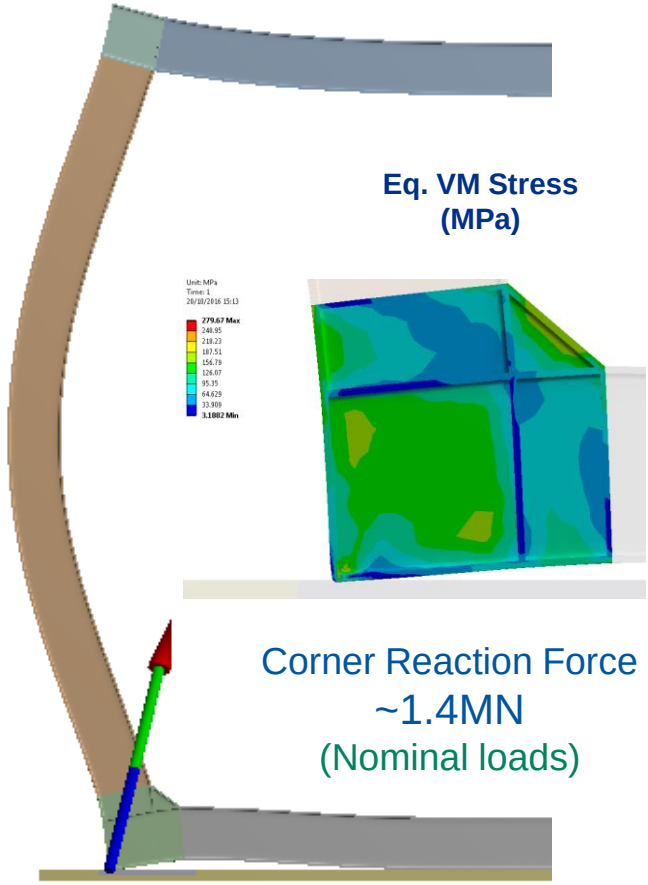
- FEA global models: main holding structure with warm membrane
- FEA local models:
  - Floor reactions and support conditions
  - Connections (welded and bolted)
  - Local reinforcements (e.g. for access holes)

FEA Single Portal Frame Model

- Very good agreement with ANSYS Global (shell) model and SCIA models
- Floor Analysis + BC input for beam connections' sub-models



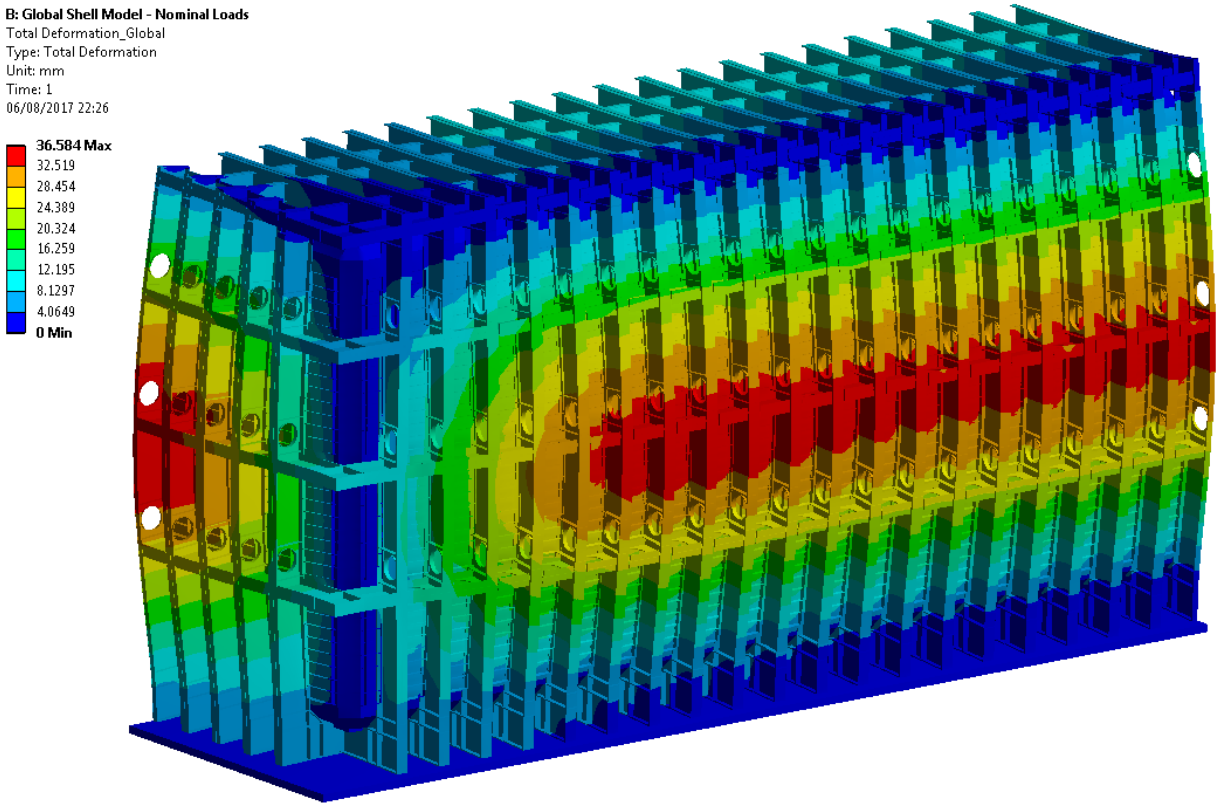


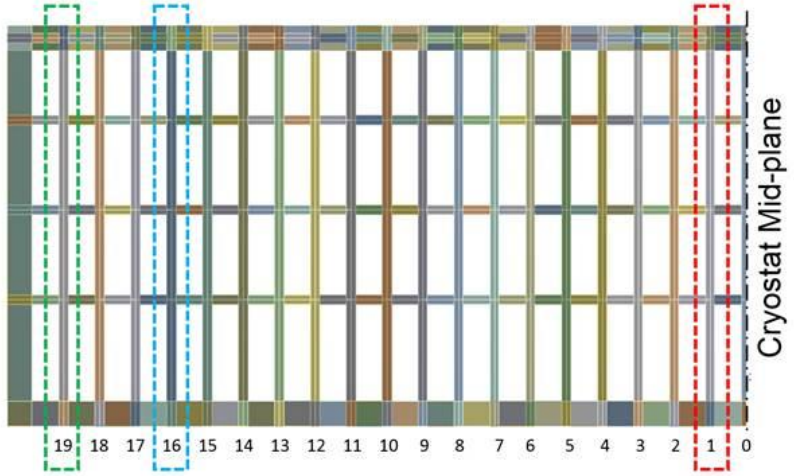


FEA global models

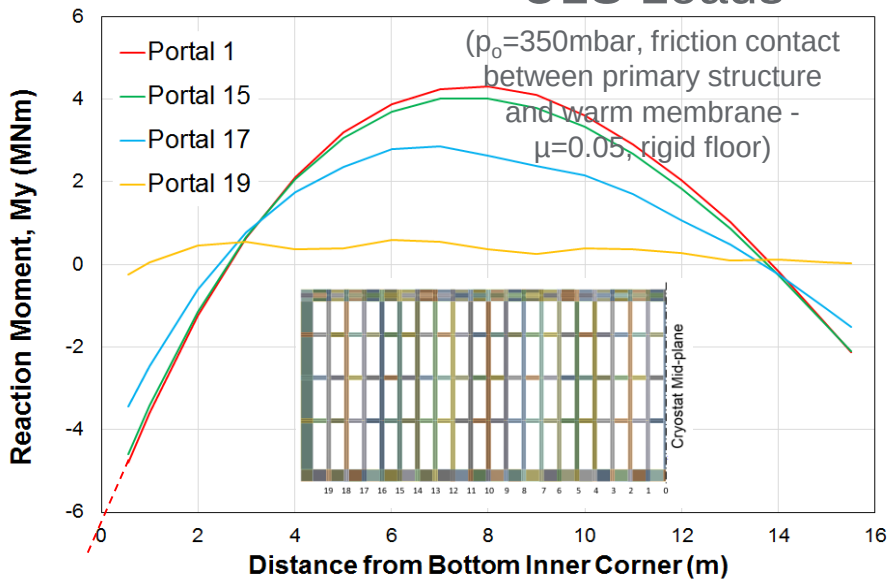
Nominal Loads

(p_o=350mbar, friction contact between primary structure and warm membrane - μ=0.05, rigid floor)





ULS Loads

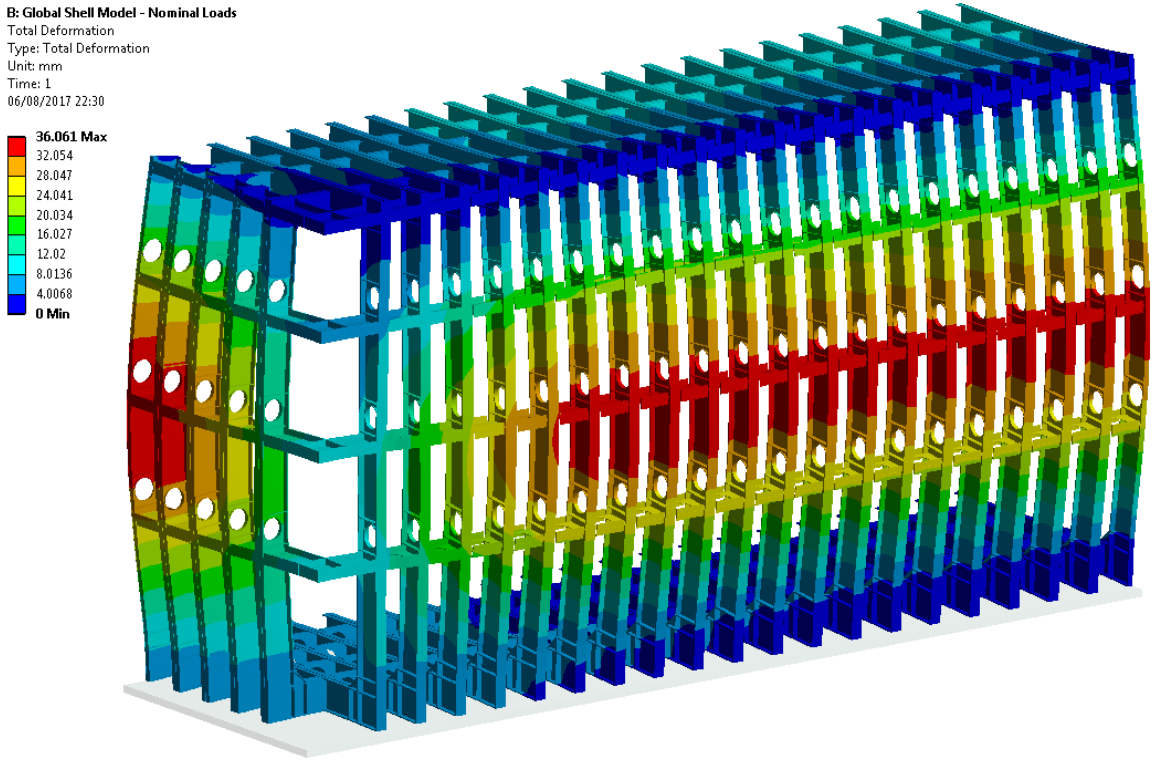


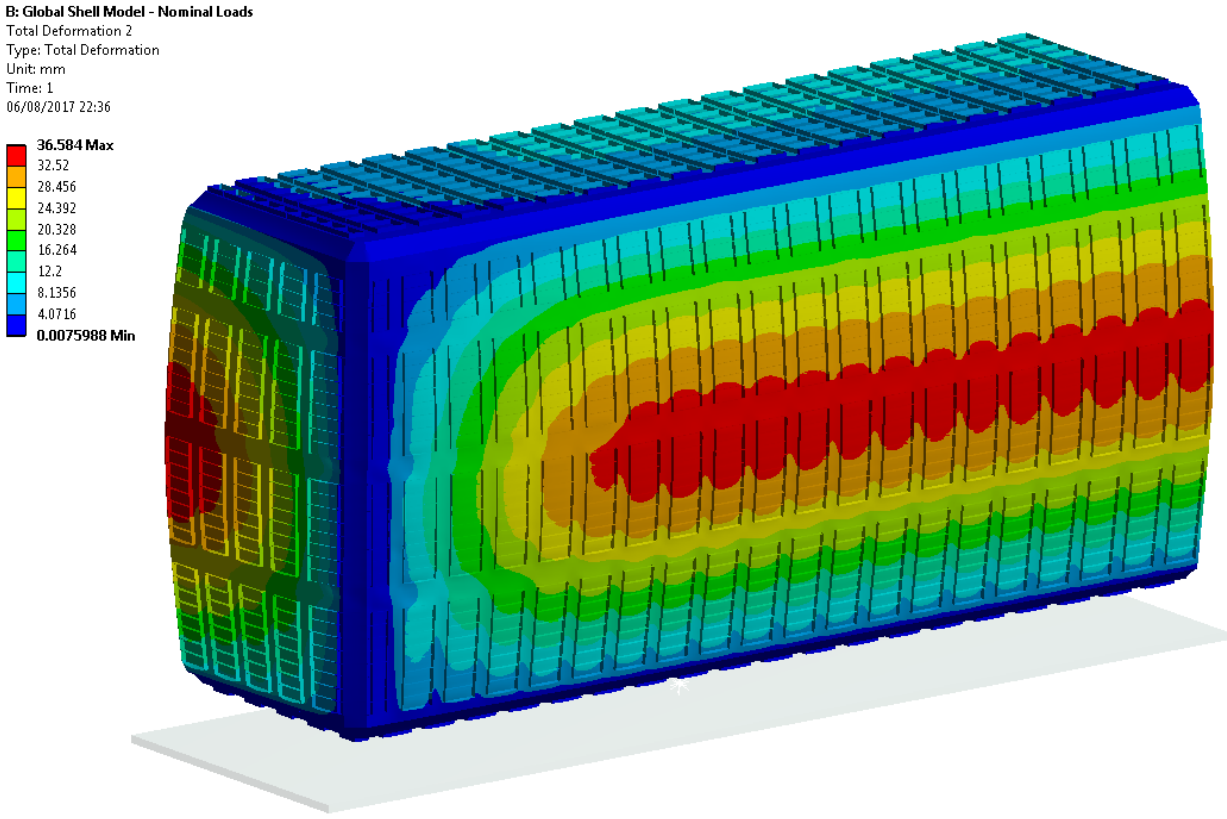
Portal at the centre of the cryostat represents the worst case scenario

FEA global models: Main Structure and Warm membrane

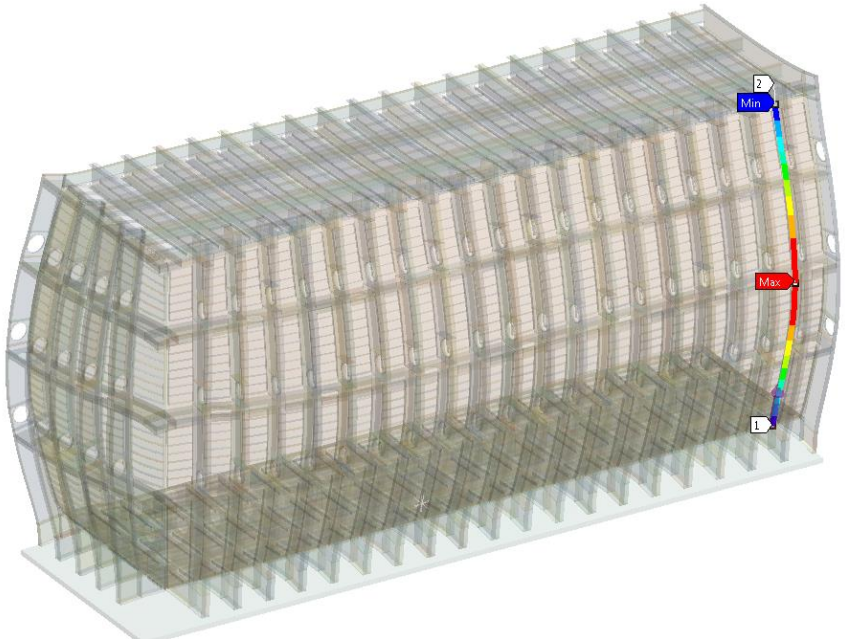
Nominal Loads

(p_o=350mbar, friction contact between primary structure and warm membrane - μ=0.05, rigid floor)

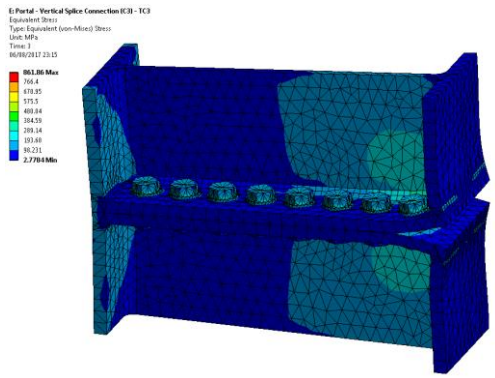


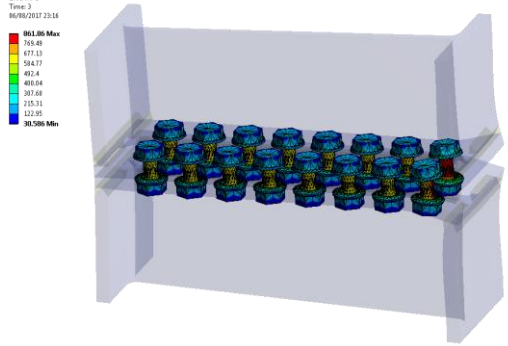


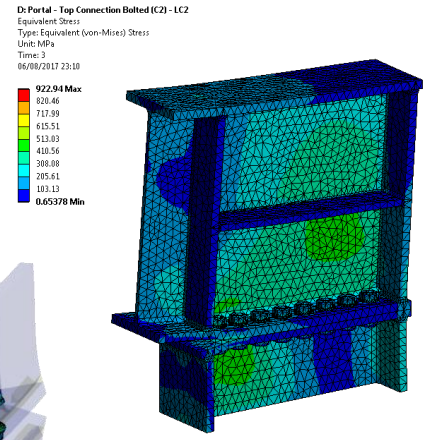
FEA local models: Connections and Openings



Reduced models & sub-modelling approach

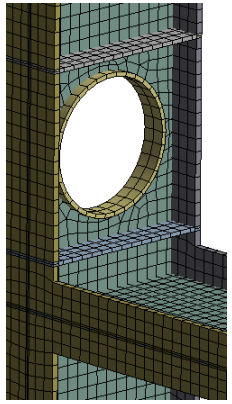




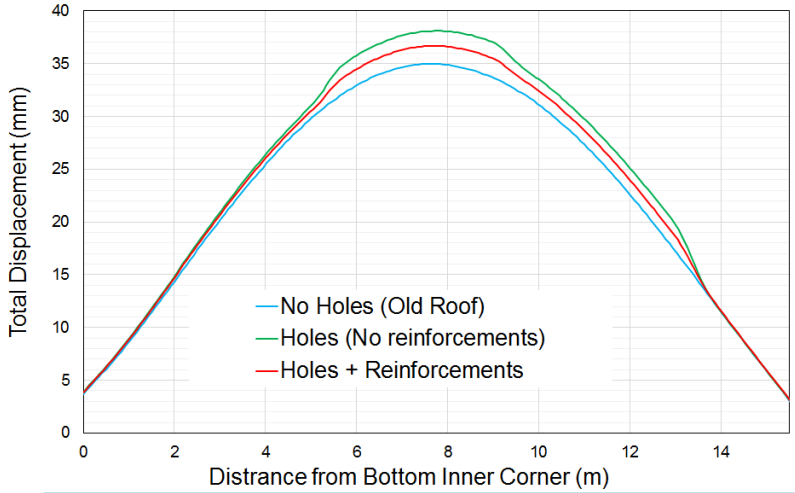


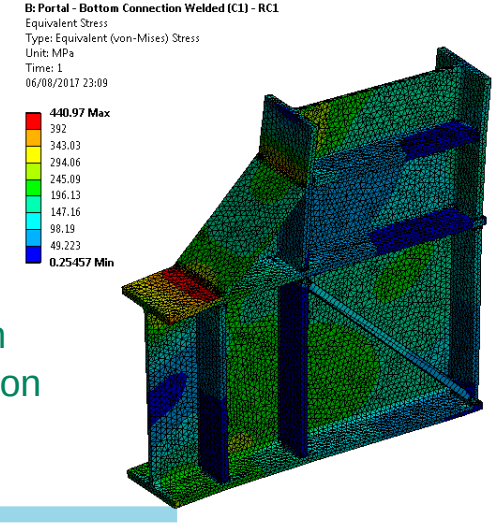
Top Connection

Splice Connection



The local reinforcements help recovering part of the stiffness lost with the access openings



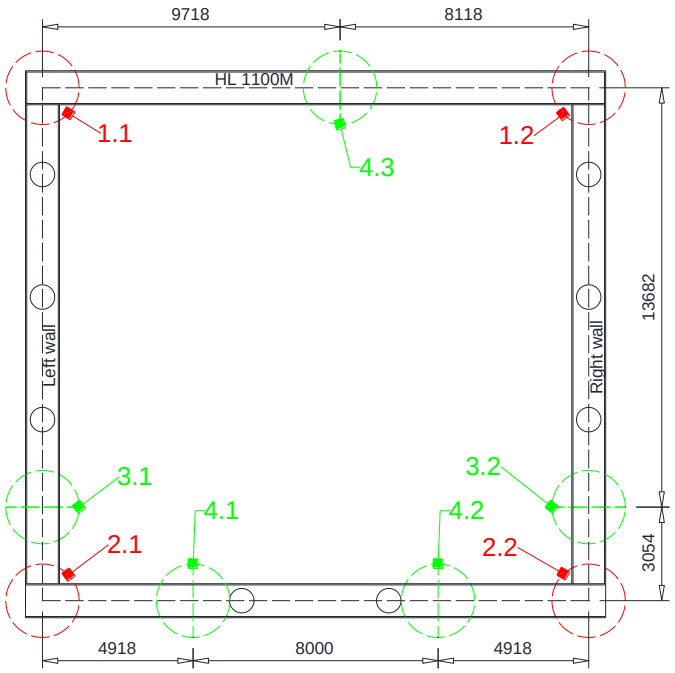


Bottom Connection

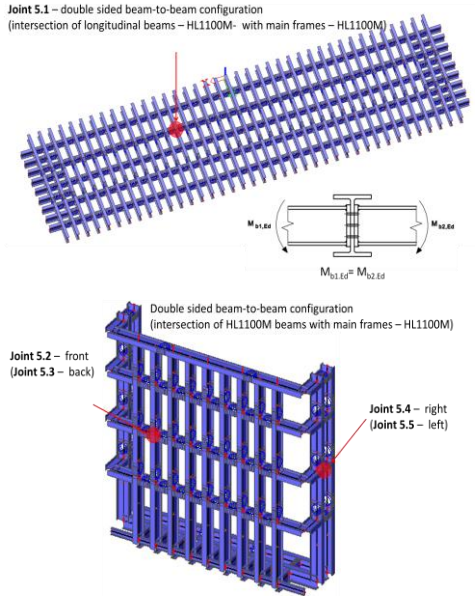
Effects on the local instability is evaluated analytically (and in SCIA)

Joint Capacity - calculations by consultant

structurame
rue de zurich 15, geneve 1201
www.structurame.com



2.3 - on front wall 3.3 - on front wall
2.4 - on back wall 3.4 - on back wall



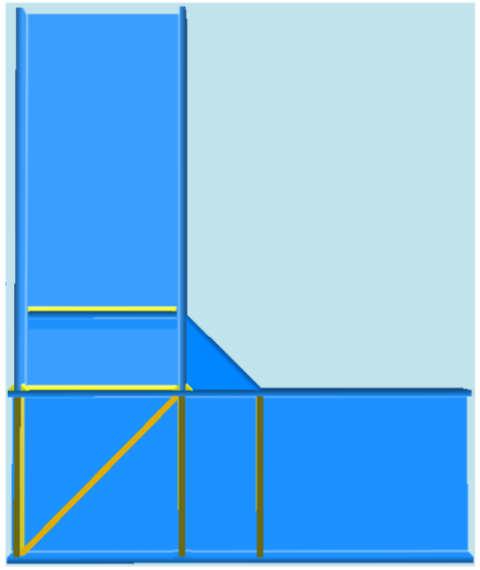


Figure 3.2: Connection W-HLM1100-TCSH-S460 geometry.

Full report EDMS 1756431 on joint analysis available at: https://edms.cern.ch/document/1835609

The table below summarizes the main results:

Table 3.2: Variant for the Joints 2.1, 2.2, 2.3 and 2.4. Main results.

a_w (mm)	a_f (mm)	Stiffener	M_{jRd} (kNm)	V_{Rd} (kN)	Stiffness
F.P	F.P	TC	5897	5875	rigid
F.P	F.P	TCS	9264	5875	rigid
F.P	F.P	TCH	8574	5875	rigid
F.P	F.P	TCSH	13470	5875	rigid

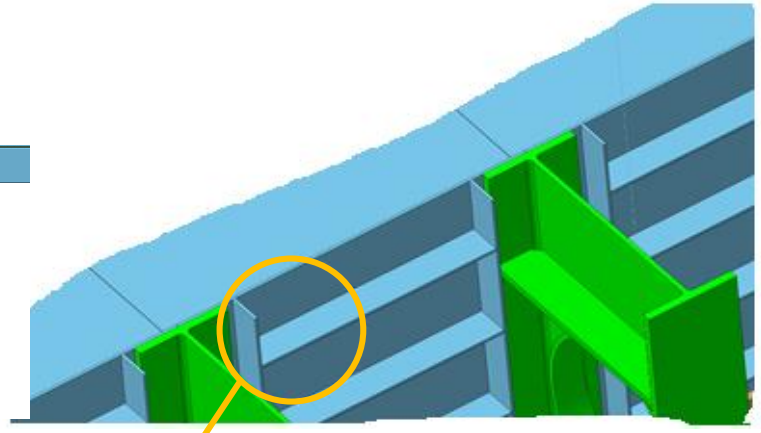
Examples of specifications provided to the consultant for joint capacity calculations (8 main joints plus fin plate connection).

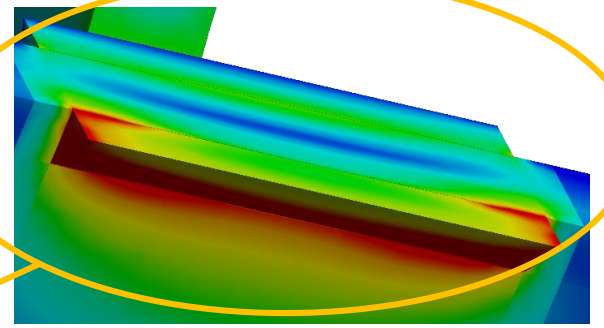
Examples of analytical calculations done by the consultant on the joint capacity. Verified analytical by Joao, and by FEA by Diego and Luca

Local Analyses: ref. material Luca

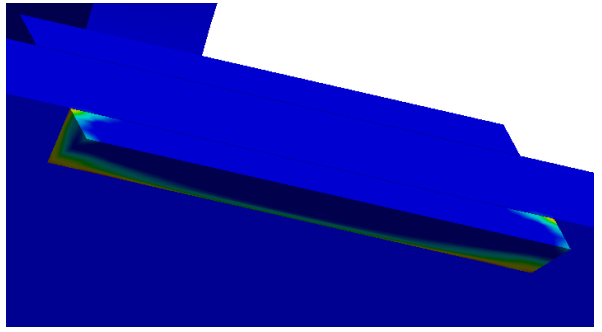
- EC3 and FEA analyses for
  - the reinforced membrane (main cryostat and door)
  - the membrane support brackets

Calculations models: Warm Membrane with ribs

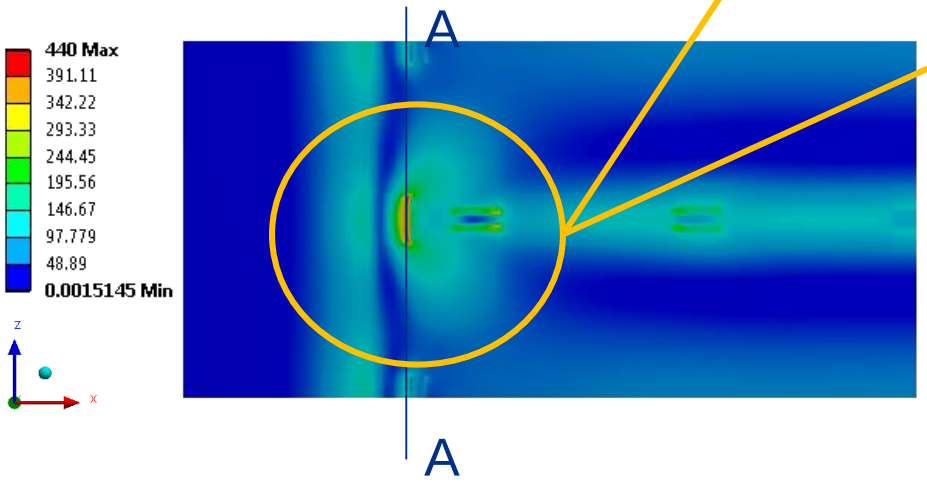


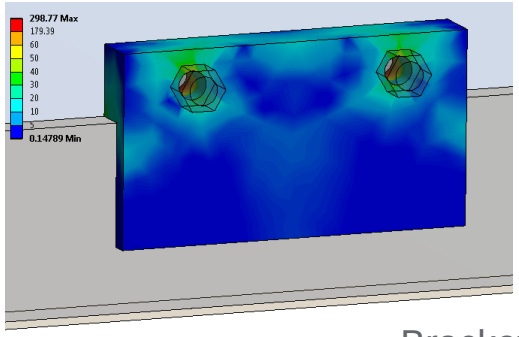


Elastic Stress



Equivalent plastic strain < 0.8%



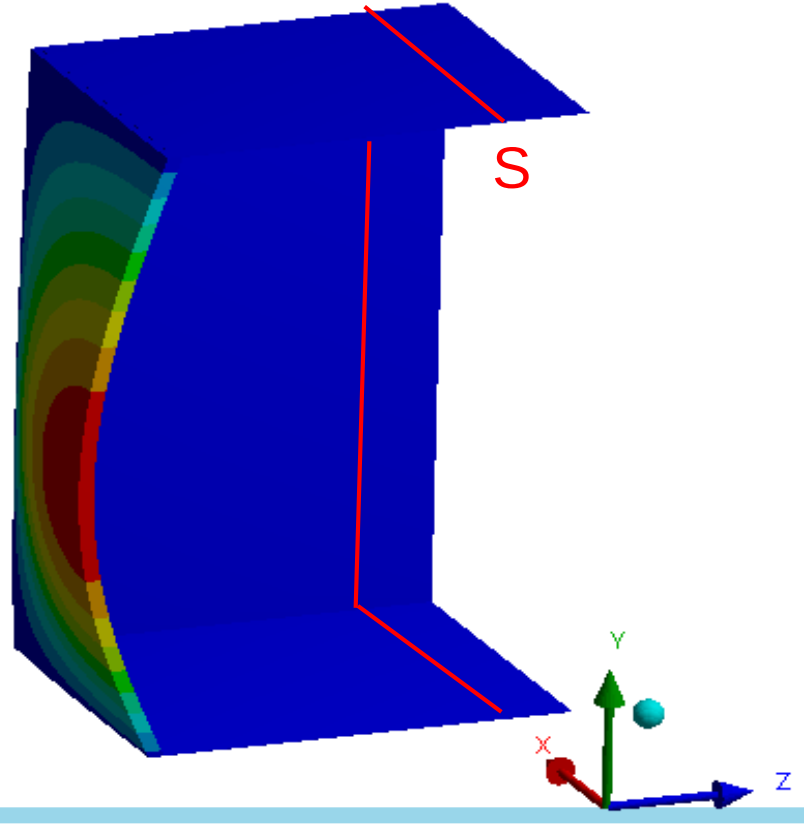


Brackets VM stresses

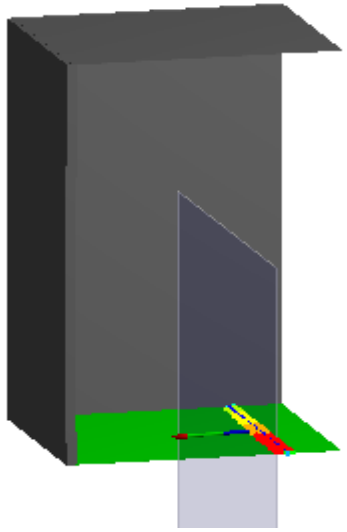
Calculations models: Warm Membrane

Model: selection of 1/4th of the full cryostat membrane:

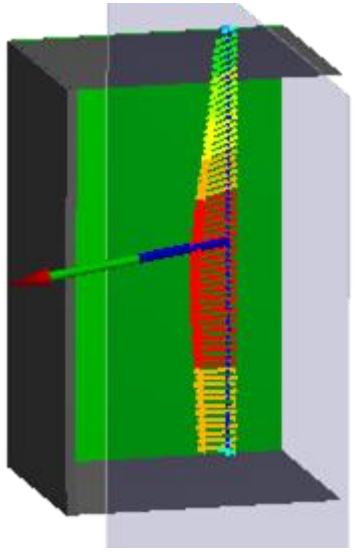
Assumption here: all forces from the short walls passing through the membrane (no contribution by the longitudinal belts).



F_{Ed}=6.7 MN



F_{Ed}=9.2 MN



F_{Ed}=3.6 MN

Design Force acting on the membrane sections

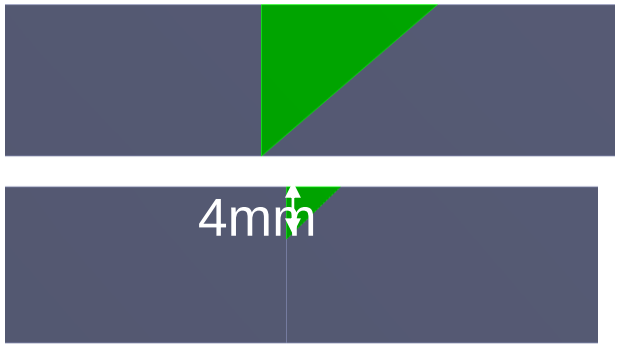
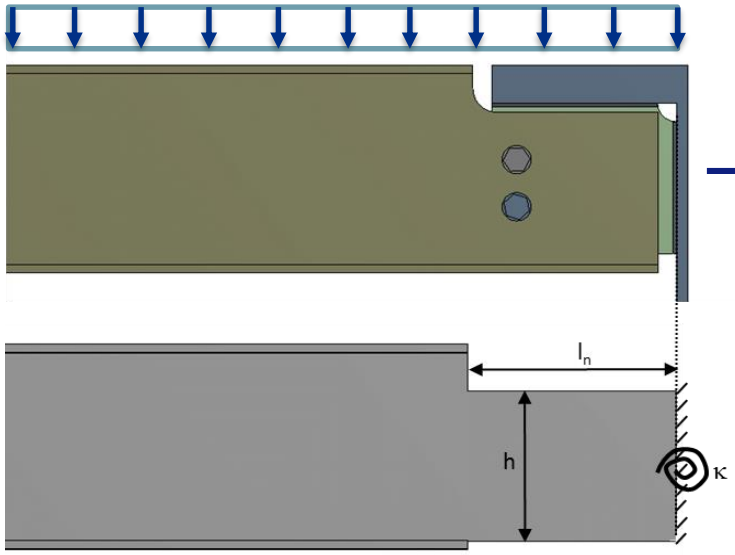


Plate-to-plate butt weld sizing:

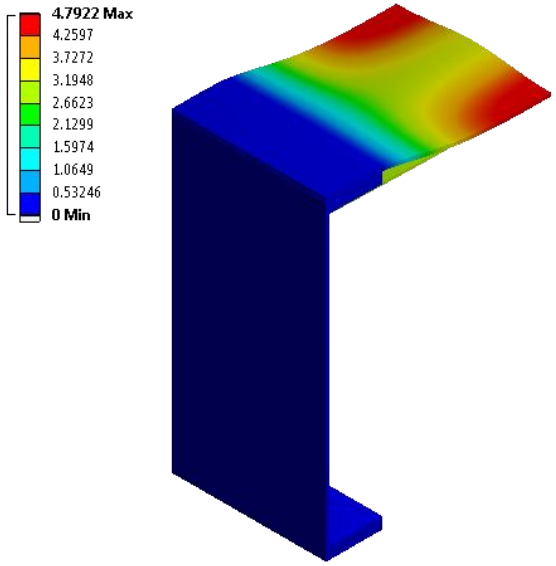
Full penetration weld: 17% utilisation factor;

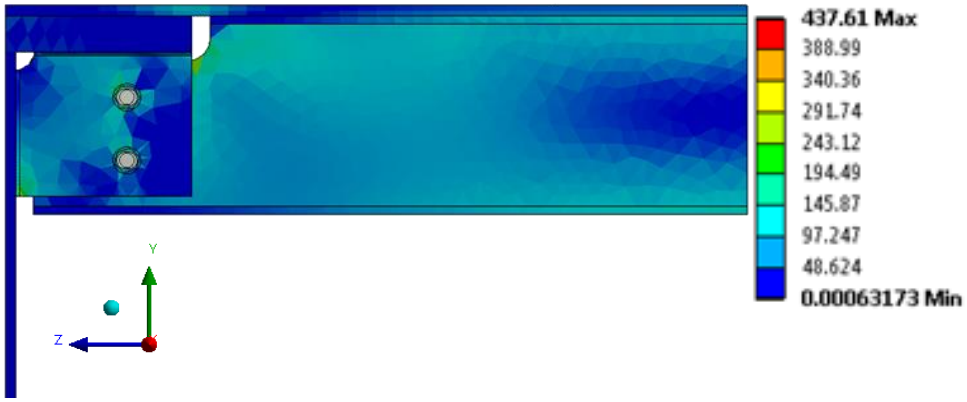
4 mm min required for full strength with partial penetration

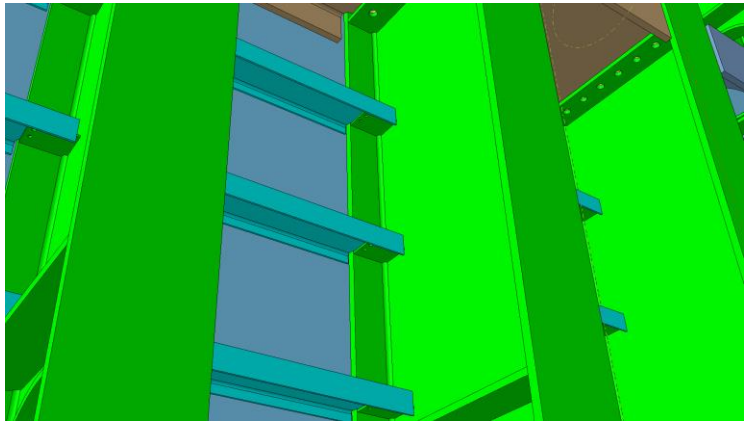
Door opening - IPE reinforcement



→ Rigid fin plate





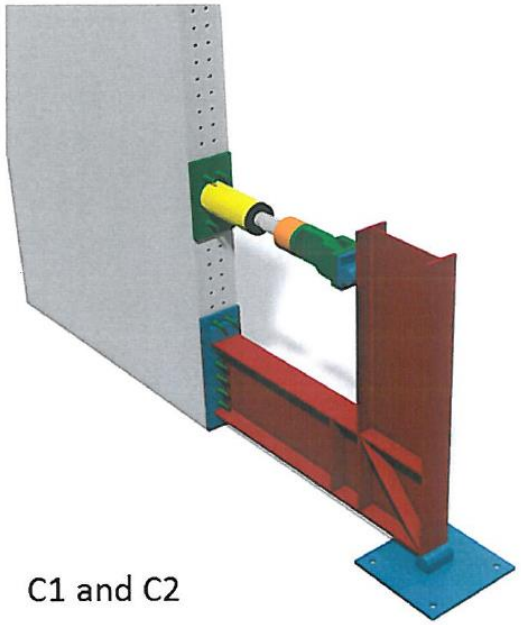


Verified by EC3, by FEA and by Consultant.
EDMS 1808385
https://edms.cern.ch/document/1808385

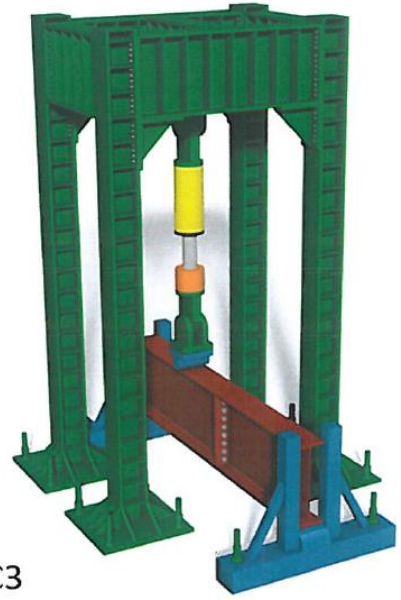
Full Scale Testing of Structural Connections

https://www.isise.net

- Collaboration with Coimbra Civil Engineering Test Lab
- Tests will be carried out on full scale samples, max load at 125% of max envelope loads
- 6 MN actuators procured

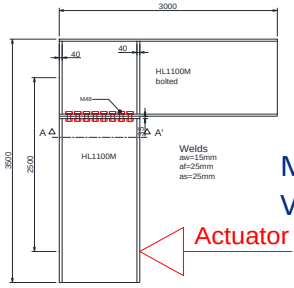


C1 and C2



C3

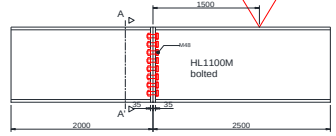
Images from Coimbra offer: red (concerns all test joints) and bleu components to be provided by CERN



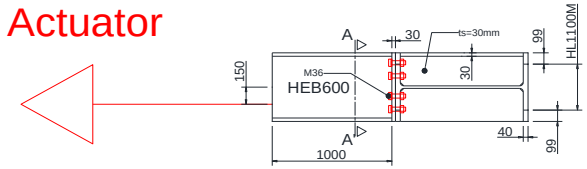
Msd=4.2MN
Vsd=2.65MN

Msd=3.8MN
Vsd=1.5MN

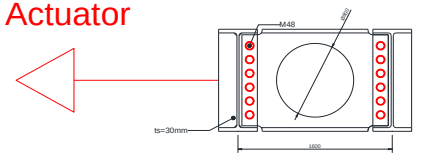
C2- Top corner



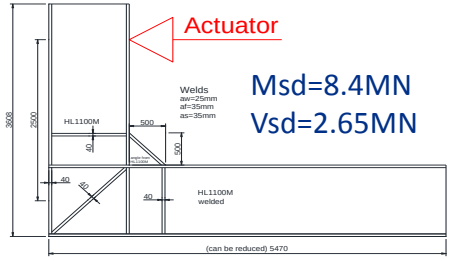
C3- Splice



C5- Slice

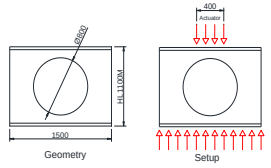


C6- Pinned connection

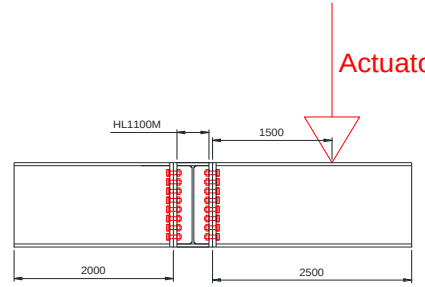


Msd=8.4MN
Vsd=2.65MN

C1- Bottom corner (welded)



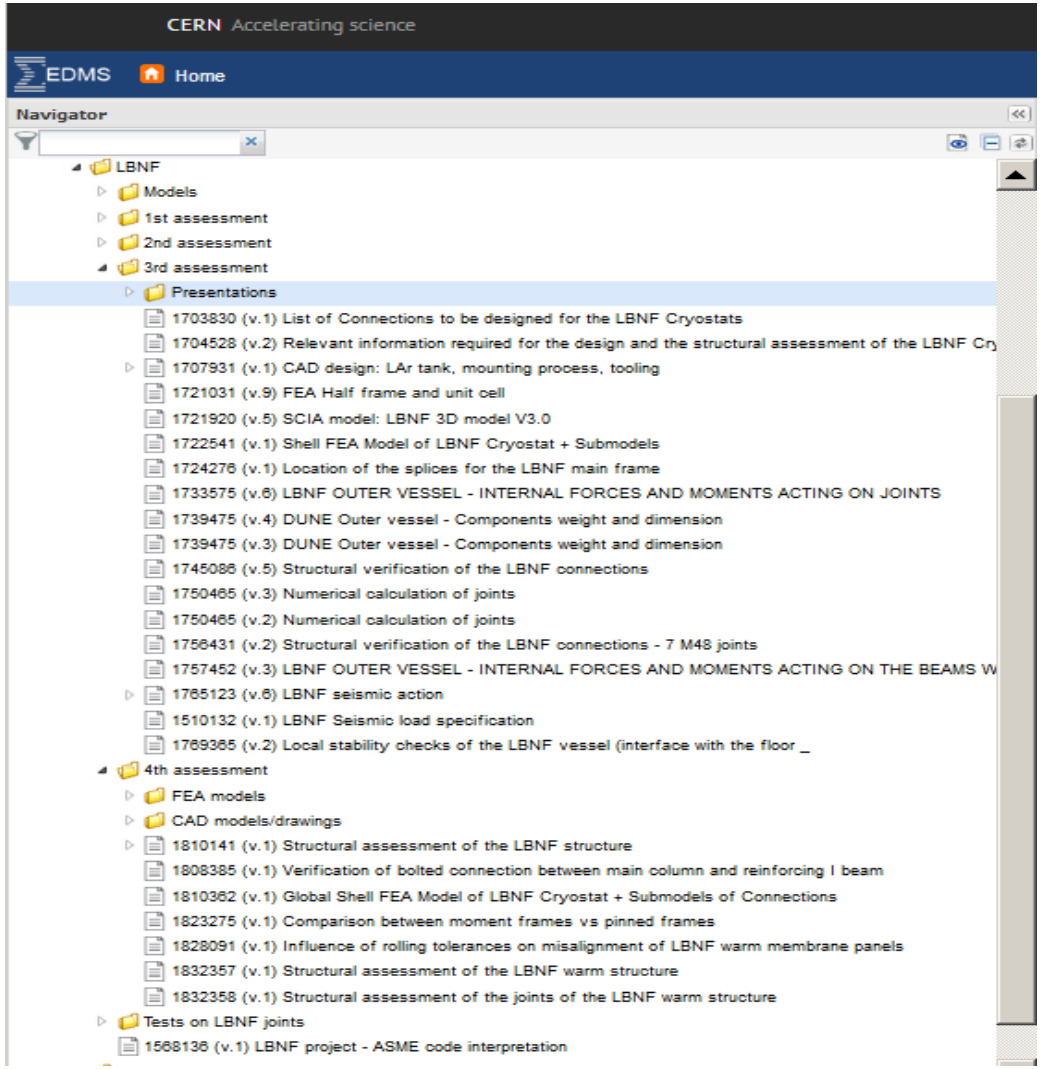
C0-web opening



C4- Splice

ACIV - Associação para o Desenvolvimento da Engenharia Civil – UNIVERSITY OF COIMBRA
Department of Civil Engineering - FCTUC * Rua Luís Reis Santos | Pólo II da Univ. Coimbra | 3030-788 COIMBRA
ISISE SMCT – Institute for Sustainability and Innovation in Structural Engineering
Firelab – Fire Engineering laboratory of the University of Coimbra

Documentation and References



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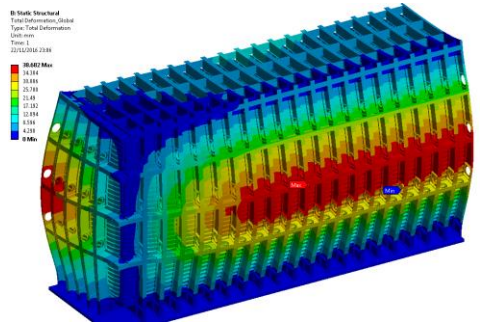
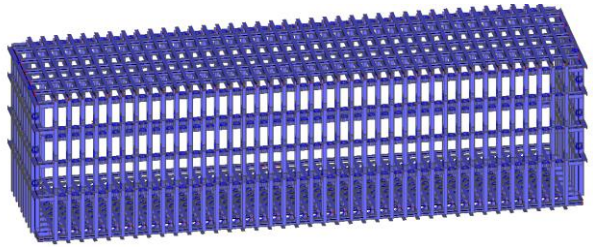
Summary

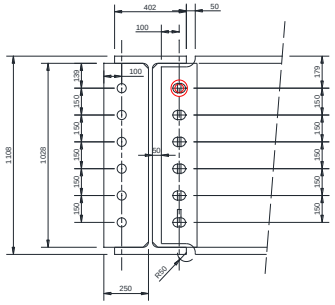


- Optimisation of the load-carrying structure and Warm Membrane (4 assessments)
  - Selection of lighter standard beams.
  - Stronger longitudinal bracings
  - In depth verification of connections.
  - Stiffened membrane for easier assembly
  - Support conditions



- Models developed for detailed analyses
  - Main portal (Beam models; Shell model; Solid Model)
  - Unit Cell (Beam Model; Beam + Shell Model)
  - Global Cryostat Model (Beam models; Beam + Shell Models)
  - Bolted & Welded Connections (Detailed solid Sub-models)
  - Reinforced Membrane (Global, sub-models)

Analytical & Numerical (ANSYS, SCIA) Studies



- Independent Eurocode 3, FEA and Consultant validation of the final design
- Fully coherent results compliant with Eurocode 3
- Final further validation of critical connections planned by full scale testing and FEA correlation

Material

List of symbols according to Eurocode 1990 and Eurocode 1993-1-9

E_k: Characteristic value of effect of actions

R_k: Characteristic value of resistance

E_d: Design value of effect of actions ($E_k \cdot \gamma_F$)

R_d: Design value of resistance (R_k/γ_M)

γ_F: Partial factor for actions, which takes account of the possibility of unfavourable deviations of the action values from the characteristic values. This factor accounts also for model uncertainties and dimensional variations

γ_M: Partial factor for a material property, also accounting for model uncertainty and dimensional variations

f_y: Yield strength

f_u: Ultimate strength

σ_{VM}: Von Mises stress

w: Deflection

w_{lim}: Maximum allowable deflection

Serviceability Limit State (SLS) verification:

$\gamma_F = 1.0$

$\gamma_M =$ not applicable

Example of verification: $w(E_k) \leq w_{lim}$

Ultimate Limit State (ULS) verification:

$\gamma_F = 1.35$ for self weight, insulation, hydrostatic pressure
$= 1.40$ for over-pressure

$\gamma_M = 1.10$ for section resistance (γ_{M_0})
$= 1.25$ for connection resistance (γ_{M2})

Example of verification: $\sigma_{VM}(\gamma_F \cdot E_k) \leq \frac{f_y}{\gamma_{M_0}}$