DEGREE PROJECT FOR MASTER OF SCIENCE WITH SPECIALIZATION IN MANUFACTURING
DEPARTMENT OF ENGINEERING SCIENCE
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Investigation of reinforcing strategies for vacuum chamber sizing optimization

- from a Structural Performance Perspective

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UNIVERSITY WEST

Summary

Vacuum testing/ tightness control field plays important part of the modern technological evaluation which required to induced vacuum conditions across multiple industries such as aerospace, defence, space, energy etc. Therefore, different size and shapes of vacuum chambers are in demand based on required test space and test objects. Sizing and reinforcing vacuum chambers are step by step process for the customized vacuum chambers which follows the simulations and optimizing mass, cost and favourable structural response.

This study was conducted to investigate variation of chamber related parameters (Width, Height, Depth and Shell thickness) and reinforcement related parameters (Reinforcement Height, Number of reinforcements and reinforcement spacing) are affect the stress response and deformation response of non-reinforced chambers and each reinforcement arrangement.

In order to achieve the target of the study, a number of finite element analysis simulations are performed respect to the change of parameters for different six phases. Post processed results shows that the depth to chamber wall thickness ratio dominates the stress and deformation response of the chamber. Also, results in this study conclude that Width to Height aspect ratio of the chamber does have less effect compared to the depth to thickness ratio for the selected size range. The non reinforced set of chamber simulation suggested that reinforcement is essential for most of the chamber sizes due to exceeding 27% of defined stress (Yield stress of materials) and 81% of deformation limits (1mm). Further, that all reinforcement strategies show reduction of stress response between 14% to 63% and deformation response than 85% compared to the non-reinforced chambers. The hybrid reinforcing method (welded flat plate with bolted support profile) shows the strongest reinforcing strategy with increased mass.

Findings of the project suggested that practical and quantitative base for selecting reinforcing strategy for rectangular vacuum chambers instead of relying on the experience itself. However, analysis also shows the importance of reinforcing door adjacent to the chamber shell suggesting increase of deformation shift towards door with reinforced chamber. Future work involving the physical testing of manufactured chambers are recommended to validate regression trends.

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Affirmation

This master degree report, *Investigation of reinforcing strategies for vacuum chamber sizing optimization*, was written as part of the master degree work needed to obtain a Master of Science with specialization in manufacturing engineering technology degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

Signature by the author

Date

Lalitha Srilal Kannangara Arachchige

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Symbols and glossary

CC-depth	Center to center spacing of reinforcement along depth direction (mm)
CC-height	Center to center spacing of reinforcement along height direction (mm)
D/t ratio	Chamber depth to thickness ratio (dimensionless)
DoE	Design of Experiment
FEA	Finite Element Analysis
H-profile	Bolted hollow profile height (mm)
LHS	Left Hans Side
MPa	Megapascal, unit of stress (1MPa=1N/mm^2)
W/H ratio	Chamber width to height ratio (dimensionless)
Nos-depth	Number of reinforcements along depth direction (-)
Nos-height	Number of reinforcements along height direction (-)
R^2	Coefficient of determinant of regression model
RH	Welded rib reinforcement height(mm)
RHS	Right Hand Side
RMSE	Root Mean Square Error
t-profile	Bolted hollow profile thickness (mm)
Von Misses Stress	Equivalent stress to predict yielding (MPa)

1 Introduction

1.1 Background

Tightness control systems (Vacuum Systems) are critical component in industrial tightness control where sealed/controlled components such as pumps, tanks, cameras are tested using tracer gases to achieve sensitivity down to 10^{-10} Pa.m^3/s even in chambers exceeding volume of 10m^3[1]. Vacuum environment is created inside of vacuum chambers where objects are placed for testing. These chambers are subjected to atmospheric pressure when vacuum conditions applied internally which leads to structural challenges such as deformation, stress concentration and buckling.

In industrial practice, chamber sizes and geometry are defined by the application requirement. For smaller chambers, structural integrity can be achieved without additional reinforcements with selection of suitable sheet metal thickness. Plate theory describes behaviour of rectangular plate under uniform pressure develops bending stress and deformation that proportional to span to thickness ratio non-linearly[2].

However, when chamber size increased with demand of the application, structural response due to vacuum conditions become highly non-linear requiring additional support for to reinforce structural integrity of the chamber(s)[2]. Introducing welded rib reinforcement, including size of reinforcement, number of reinforcement and spacing of reinforcement has a first order effect on stiffness and stress distribution. Previous studies show that the effective reinforcement layout is non-uniform and introduced to places where the deformation is highest [3],[4], [5]. Finite Element Analysis in combination of Design of experiment (DoE) combined can effectively study effect of these different design parameter by using statis structural simulation and linear/non-linear regression models[6].

The physical connection method between reinforcements and chamber also plays the important role where euro code 3 classified that the joints as rigid, semi-rigid and pinned based on connection stiffness[7]. Studies also shows that the bolted joints are not always reflect the stiffness equivalent to the welded joints[8]. This interaction behaviour further described by partial interaction theory for mechanically fastened composite sections

Manufacturing of vacuum chamber(s) involve with trade-off between structural integrity (deformation, stress), sustainable material usage, economic constrains, weight constrains and manufacturing complexity. In recent practice reinforcements of vacuum chambers are based on empirical methods and experience methods rather than systematic quantitative method.

1.2 Aim

The aim of this study was to develop a quantitative and simulation-based design methodology for vacuum chamber design, including both non reinforced and reinforced configurations in order to optimize structural performance and sustainable material usage.

1.2.1 Research question

The following research questions were formulated to execute the study;

1. What is the influence of chamber size (depth to thickness ratio) on stress and deformation under induced vacuum conditions, and what size does reinforcement become necessary?
2. How effective are welded reinforcements (rib) and hybrid reinforcement strategies at reducing stress and deformation, com-pared with each other and with the non-reinforced baseline?
3. Which reinforcements returns the best trade-off between structural performance and material usage?

2 Methodology

A structural engineering approach in combination with statistical post processing of finite element analysis was used to answer research questions defined in section 1.2.1. Three major design phases were evaluated including non-reinforced baseline, welded reinforcement and hybrid reinforcement scenarios. Each reinforcement method was simulated for different chamber size and reinforcement associated parameters.

The resulting structural responses, including maximum von mises stress and total deformation were analysed relative to the baseline non reinforced scenario using regression analysis and probe-based hotspot ranking.

2.1 Material and Software

The following material assignments were used in the simulations;

- **Stainless steel** was assigned to the main chamber structure excluding the door of the chamber and to the welded reinforcements (excluding door reinforcements)
- **Aluminium alloy** was assigned to the chamber door and door reinforcements
- **Structural steel** was assigned to the support profiles used in Phase 3

The loads and boundary conditions were defined as follows;

- The analysis was performed within the linear elastic range of all materials while non-linear, thermal and dynamic loads were not considered in this study.
- Gravitational acceleration and a constant inwards atmospheric pressure (0.101325 MPa) were applied as external stimuli.

The chamber geometry was developed parametrically using SolidWorks. Furthermore, FEA simulations were performed using SolidWorks static structure simulation and parametric design studies.

Post-processing, regression analysis and data visualization were performed using Microsoft Excel, Claude and MATLAB.

2.2 Mesh generation and adaptive mesh refinement

The chamber models in each phase were meshed using the adaptive meshing function to generate a refined mesh in SolidWorks static simulation. A h-adaptive mesh refinement function was performed over three loops with a target accuracy of 98%. A blended curvature-based mesh was used with element sizes ranging from 3 to 20 mm with a growth ratio of 1.2 to provide a gradual transition between different mesh sizes.

The mesh quality was evaluated using 16 Jacobian points with a minimum of eight elements in a circle. These settings were kept consistent over the different design configurations to provide a comparable basis for the stress and deformation results.

The adaptive mesh was particularly useful in areas where the geometry transitions or locations where high stress gradients were expected (such as chamber rear side and door flange side). Representative mesh views for the baseline and reinforced chamber configurations are presented in Figures. The adaptive mesh control method allows the mesh to become finer in areas requiring greater resolution while avoiding unnecessary refinement of the entire model resulting in reduced computational power and analysis time. The resulting meshes were then used for the static structural analyses to obtaining the structural responses used in the design study.

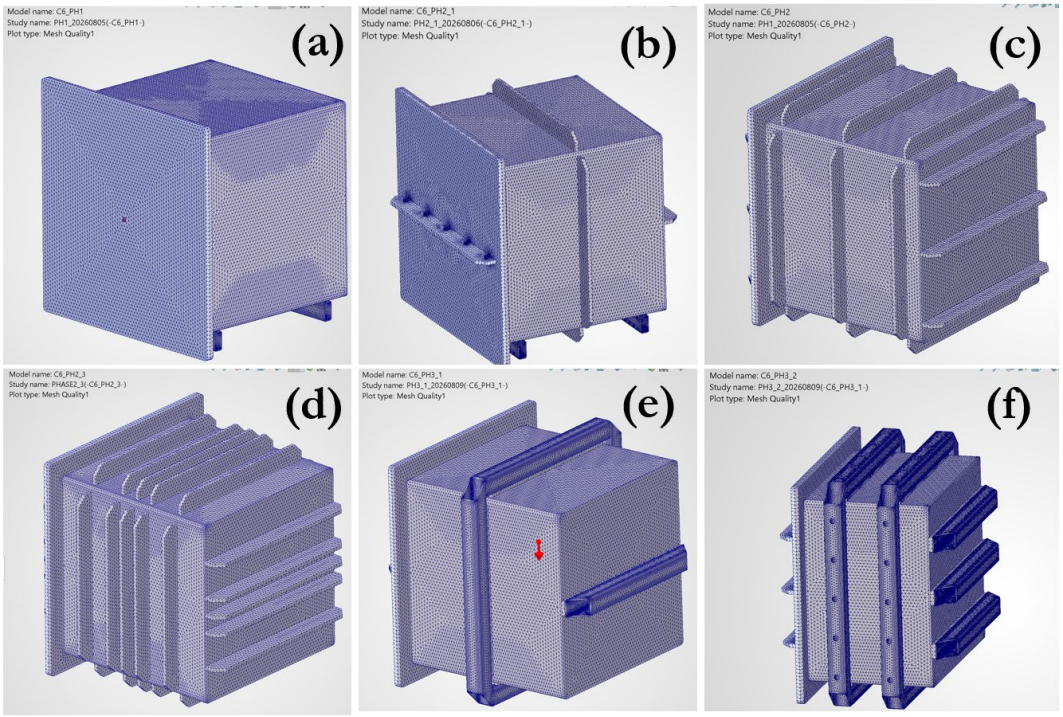

Figure 1: Representative adaptive mesh configuration for the different reinforcement strategies: (a) non-reinforced baseline, (b) Phase 2.1, (c) Phase 2.2, (d) Phase 2.3, (e) Phase 3.1, (f) Phase 3.2

2.3 Design of Experiments (DoE)and procedure

For each design phases, a set of geometrical parameters associated with the chamber and its reinforcement system were defined.

The vacuum conditions inside the chamber are generated using a pump system consisting of rotary vane backing pumps (such as MIL's Evisa E400, E200 with E100 depending on chamber size) and a compound Roots blower package (such as Pedro Gil RVB 23.20, 2000m^3/h and RVB 21.20, 500m^3/h). A roots blower is a positive displacement pump that uses two synchronized lobed rotors to transfer gas from inlet to outlet without compressing gas internally (with compression occurs at the discharge side, driven by back pressure of the backing pumps). Due to this reason, a roots blower

cannot be started directly at atmospheric pressure, since the differential pressure across its rotors would be too large and would draw excessive current which can result in overheating of motor. Therefore, the rotary vane backing pumps run at the initial stage to pump the chamber down from atmospheric pressure to rough vacuum range. Roots blowers are engaged once the pressure inside chamber is low enough for the chamber to be further pump down into medium vacuum (millibar range) due to high operating speeds.

Since the internal pressure of the chamber is reduced close to zero pressure (MPa) while the surrounding atmosphere remains at standard pressure. The resulting pressure difference across the chamber walls approaches the full atmospheric a pressure of 0.102325 MPa was applied in every simulation to represent this worst-case loading condition (near full vacuum).

The chamber parameters included the chamber width, height, depth and shell thickness, while the reinforcement parameters included reinforcement height, center to center spacing between reinforcements and number of reinforcements along depth and height direction. The combination of defined configurations was evaluated using static structural analysis design of experiments (DoE).

This investigation of effect or reinforcements divided in to three main phases following by sub divisions in phase 2 and 3 as described below;

2.3.1 Phase 1- Non reinforced chamber (baseline scenario)

Phase 1 investigated the structural response of the vacuum chamber without any extra external reinforcement

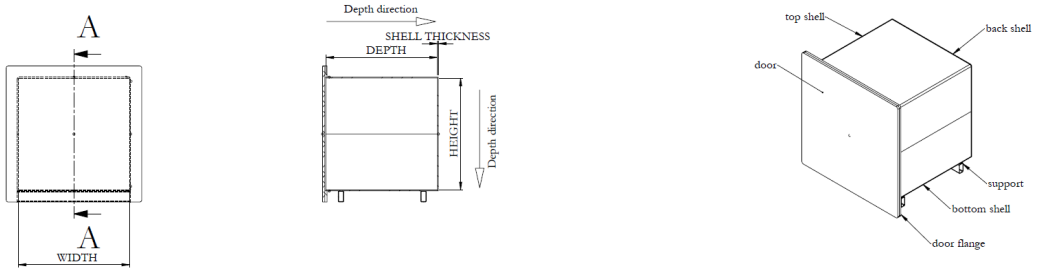

Figure 2: Non-reinforced chamber model

Table 1: Phase 1 design parameter

Parameter	Value (mm)
Width	400, 700, 1000
Height	400, 700, 1000
Depth	400, 700, 1000
Shell thickness	6, 8, 10

The purpose of Phase 1 was to establish baseline case for structural behaviour of the chamber and to determine influence of the defined primary chamber parameters on stress and deformation under the induced vacuum conditions.

A total of 81 (3x3x3x3) design configurations were evaluated.

2.3.2 Phase 2- Welded rib reinforcement

Phase 2 investigated influence of reinforcement on stress and deformation of the chamber under induced vacuum conditions. The chamber reinforced with welded ribs in top, bottom, LHS, RHS and back surface of the chamber shell. The door reinforcement was fastened to the door using bolts mechanically. The bolted reinforcements (see Figure 2) were modelled as bonded contacts in the simulation model for the numerical simplification.

Further, Phase 2 was divided into three sub parts based on the reinforcement arrangement.

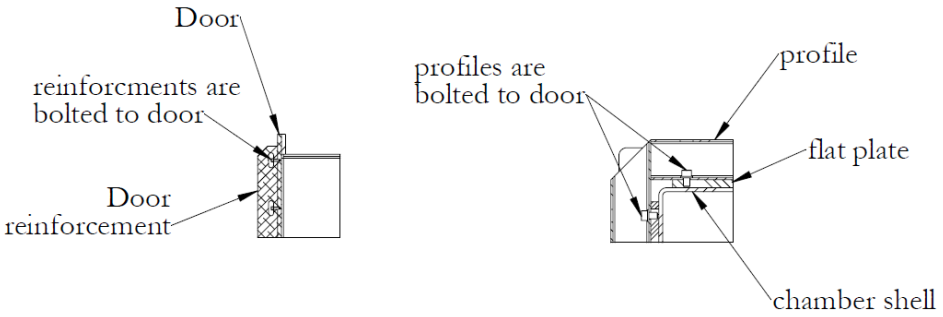

Figure 3: Door reinforcement (applicable for Phase 2 and 3) and support profile(applicable for Phase 3) fastening method

2.3.3 Phase 2.1- Single central welded rib reinforcement

A single reinforcement was positioned at the middle of each relevant external chamber surfaces with the reinforcement rib height varies (50 and 100mm) to investigate its influence on the structural response (stress and deformation) of the chamber. The door reinforcement was bolted to the chamber physically and modelled as bonded contact for the simplification of simulation.

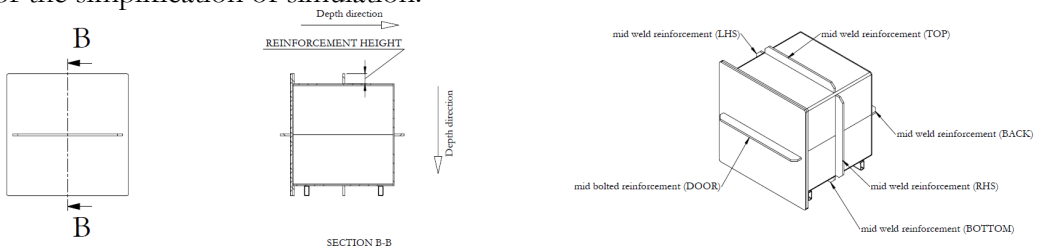

Figure 4: Single central welded rib reinforced chamber model

Table 2: Phase 2.1 design parameter

Parameter	Value (mm)
Width	400, 700, 1000
Height	400, 700, 1000
Depth	400, 700, 1000
Shell thickness	6, 8, 10
Reinforcement height	50, 100

The objective was to evaluate the effect of presence of reinforcement at most vulnerable unsupported areas and reinforcement height on resulting stress and deformation response compared with baseline scenario investigated in Phase 1.

A total of 162 (3x3x3x3x2) design configurations were evaluated

2.3.4 Phase 2.2-Multiple welded rib reinforcement with equal spacing

Phase 2.3 investigated multiple desecrate number of welded rib type reinforcements with equal center to center spacing in each surface of the chamber along the depth and height directions. The reinforcements were welded to the top, bottom, LHS, RHS of the chamber along depth direction, while reinforcements in the back of the chamber welded with equal center to center spacing along depth direction. The door reinforcements were bolted to the door in height direction and represented using bonded contact in the simulation model.

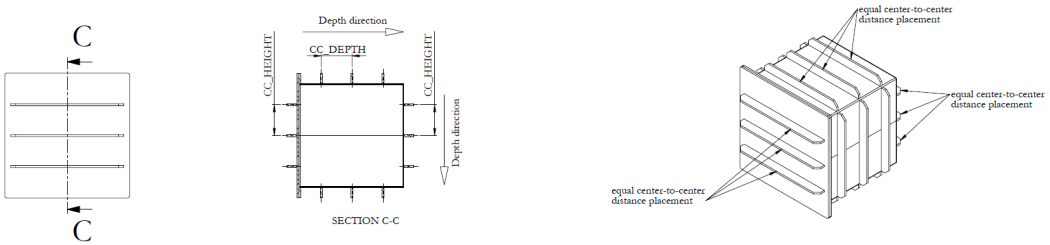

Figure 5: Equally spaced welded reinforced chamber model

Table 3: Phase 2.2 design parameter

Parameter	Value
Width (mm)	400, 700, 1000
Height (mm)	400, 700, 1000
Depth (mm)	400, 700, 1000
Shell thickness (mm)	6, 8, 10
Reinforcement height (mm)	50, 100
Center to center spacing (mm)	200, 300
Number of reinforcements	2, 3

The objective was to investigate how the equal arrangement and number of reinforcements influence the stress and deformation response of the chamber under the induced conditions.

Feasible center to center spacing and number of reinforcements placed in each depth and height direction were obtained with conditional MATLAB script total of 288 design configurations were evaluated.

2.3.5 Phase 2.3- Multiple welded rib reinforcement with unequal spacing

This phase was an extended version of Phase 2.1. In this phase, alternative reinforcement strategy was investigated in which the unequal center to center reinforcement arrangement in each depth and height direction. Initially single reinforcements were placed in each surface of the chamber as per Phase 2.1 while the remaining 4 reinforcements were distributed away from the central reinforcement with increasing center to center spacing symmetrically.

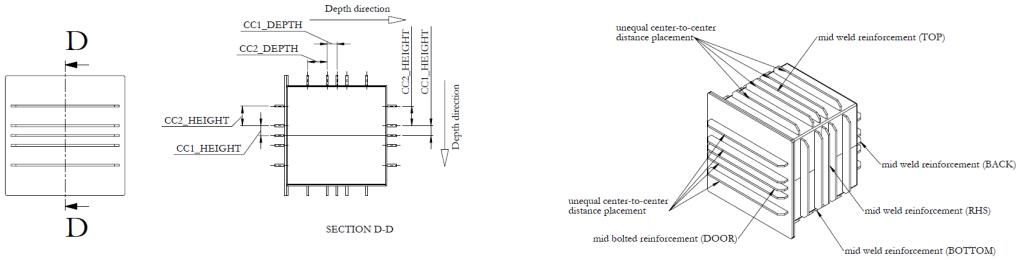

Figure 6: Unequally spaced welded reinforced chamber model

Similarly, all reinforcements were welded to the chamber excluding door reinforcements. Door reinforcements were bolted to the door and designed as bonded connection for the simulation purpose.

Table 4: Phase 2.3 design parameter

Parameter	Value
Width (mm)	400, 700, 1000
Height (mm)	400, 700, 1000
Depth (mm)	400, 700, 1000
Shell thickness (mm)	6, 8, 10
Reinforcement height (mm)	50, 100
Center to center spacing level 1(mm)	75, 100
Center to center spacing level 2(mm)	150, 200

The unequal spacing strategy was designed to investigate whether concentrating reinforcements near center of the chamber surfaces could provide a more efficient reinforcement strategy than equal spacing reinforcement.
A total of 81 design configurations were evaluated based on feasibility of reinforcement position along given depth and height values limited to the study.

2.3.6 Phase 3- Hybrid reinforcement

Phase 3 investigated a hybrid reinforcement concept where combination of welded flat plate to the chamber with additional support profile bolted for more rigidity over induced vacuum conditions. The hybrid reinforcement concept was applied at the all surfaces of the chamber along depth and height except door reinforcement where same bolted rib reinforcement concept was employed as stated in Phase 2.

Unlike Phase 2, Phase 3 divided to two sub-phases due to depth and height limitation of the study where unequal reinforcement strategy was not feasible for the given depth and height values selected in the study.

2.3.7 Phase 3.1- Single central hybrid reinforcement

A single hybrid reinforcement was positioned at the middle of each surface in depth and height direction excluding door reinforcements where usual bolted rib reinforcements were employed as phase 2. The height of support profiles (SHS or RHS) varied to investigate its influence on the stress and deformation response of the chamber.

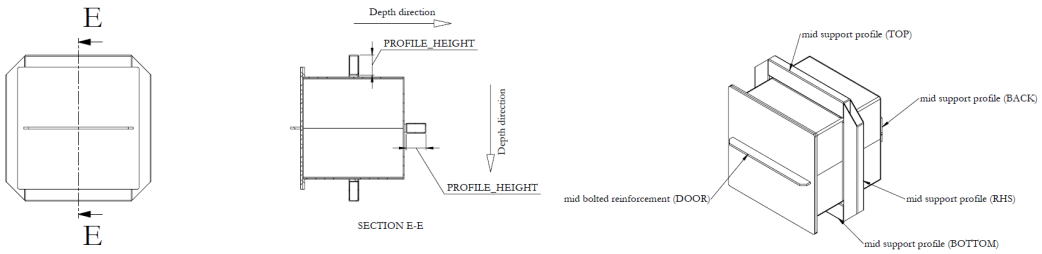

Figure 7: Single central hybrid reinforced chamber model

Table 5: Phase 3.1 design parameters

Parameter	Values
Width (mm)	400, 700, 1000
Height (mm)	400, 700, 1000
Depth (mm)	400, 700, 1000
Shell thickness (mm)	6, 8, 10
Profile height (mm)	100, 200

The objective was to evaluate the influence of hybrid reinforcement and profile height in structural response of the chamber.
A total of 162 (3x3x3x3x2) design configurations were evaluated.

2.3.8 Phase 3.2- Multiple hybrid reinforcement with equal spacing

Phase 3.2 investigate multiple desecrate number of hybrid type reinforcements with equal center to center spacing in each surface of the chamber along depth and height directions. The reinforcements were welded and supported by support profile to the top, bottom, LHS, RHS of the chamber along depth direction, while reinforcements in the back of the chamber placed with equal center to center spacing along depth direction. The door reinforcements were mechanically bolted to the door in height direction and represented using bonded contact in the simulation model.

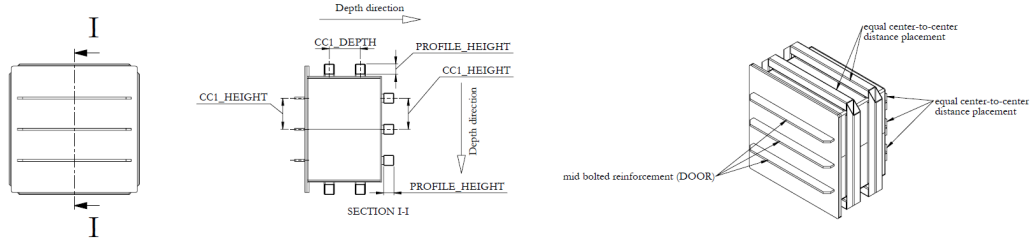

Figure 8: Equally spaced hybrid reinforced chamber model

Table 6: Phase 3.2 design parameters

Parameter	Values
Width (mm)	400, 700, 1000
Height (mm)	700, 1000
Depth (mm)	700, 1000
Shell thickness (mm)	6, 8, 10
Profile height (mm)	100, 200
Center to center spacing (mm)	200, 300
Number of reinforcements	2, 3

The configurations including 400mm depth and height were excluded from Phase 3.2 because the availability of space was insufficient to accommodate hybrid reinforcements effectively. In addition, configurations with 400mm depth and height were created economically unsustainable configurations where exposed spacing between two reinforcement entities were less than reinforcement width itself (in case of two of SHS of 100x100x5 reinforcement placement along 400mm of depth/height provides clearance of 66.67mm).

2.3.9 Recorded FEA responses and probe responses

For each design configurations of relevant phase, the following responses were recorded from FEA simulations. Largest configuration of chamber 1000x1000x1000, t10 simulated using SolidWorks static structural study and configuration were simulated with design study.

1. Maximum von mises stress
2. Total deformation
3. Twenty-three discreate probe values representing local stress (Von mises stress) and deformation responses at predefined locations of door, back plate and sections of chamber shell

The probe locations were defined to investigate consistent comparison of local structural behaviours between different chamber geometries against reinforcement strategies compared to base case scenario (Phase 1). The probe location distributed across chamber as follows (see Figure 1);

- Middle face of the door (DOOR)
- Front cross section of chamber (F1-F7)
- Front cross section of chamber (M1-M7)
- Front cross section of chamber (R1-R7)
- Middle face of the back plate (BACK)

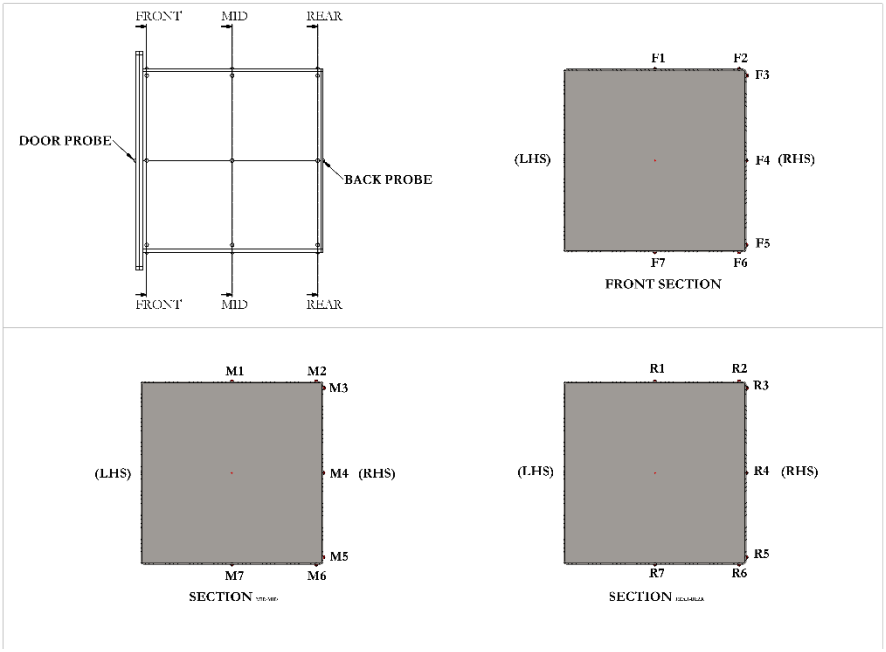

Figure 9: Probe location selection and sectional visualization

Half of chamber (RHS) was probed due to symmetric behaviours of chamber simulation with symmetric loading and boundary conditions. These recorded results set of probe measurement locations could be consistently applied despite the reinforcement strategy across different design configurations.

Further, to facilitate the analysis, MATLAB script was developed to extract, organize and compare the simulation results. The probe locations values were normalized to a common reference system to enable direct comparison of local stress and deformation responses across the different configurations despite variation in chamber dimensions and reinforcement placement.
This data process approach enabled systematic comparison of both predefined local probe measurement and global structural responses represented by maximum von mises stress and total deformation.

2.4 Data analysis

Linear regression and non-linear regressions were performed for each phase where stress and deformation response of both regressions compared directly on R^2. Furthermore, the linear model was preferred for simplicity unless R^2 of non-linear regression was noticeable and supported by significant coefficient.

Material specific yield checks were performed for every probe location (except door probe) was checked against the stainless stell yield strength while door probe location was checked against aluminium yield strength. Local stress and deformations observations of support profiles were not feasible due to lack of dedicated probe locations (applicable to Phase 3).

Two deformation limits (1mm and 2mm) were checked in analysis for obtain two design criteria rather than a single limit. This allowed to perform design decisions against

chamber sizes (under 2mm allowance for larger chambers and 1mm allowance for smaller chambers)

Standardized sensitivity analysis, probe to probe peak ratio hotspot ranking and parameter correlation analysis were performed.

3 Results

This chapter presents the results of finite element analysis and post processed analysis for each six phases followed by common configuration cross comparison and probe analysis.

3.1 Phase 1, non-reinforced baseline

Mean peak stress is found out 287.5 MPa across the 81 design configurations and mean peak deformation is found out 6.44mm.

Table 7: Linear regression coefficients of Phase 1 (Stress R2=0.494, Deformation R2=0.381)

Response	Parameter	Coefficient	p-value	Significance
Max. stress	D/t ratio	+2.92 MPa/unit	$3.8x10^{-13}$	Yes
Max. stress	W/H ratio	-10.9 MPa/unit	0.6	No
Max. deformation	D/t ratio	+0.083 mm/unit	$1.1x10^{-13}$	Yes
Max. deformation	W/H ratio	-0.048 mm/unit	0.95	No

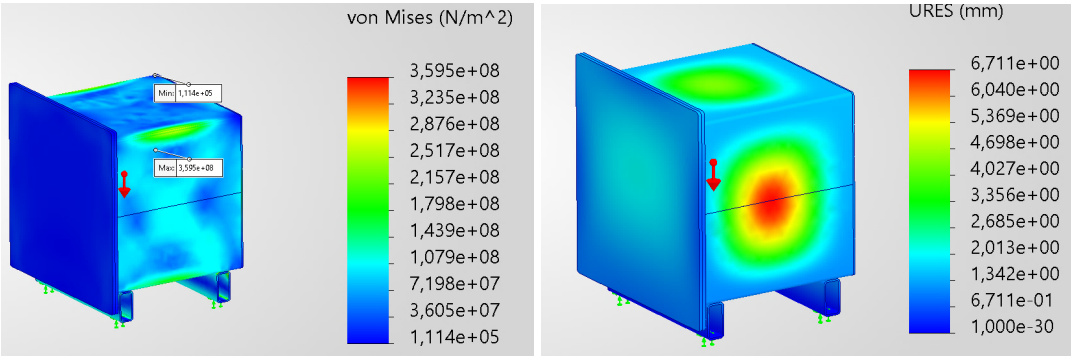

Figure 10 : Stress(left) and deformation(right) colour map for 1000W x 1000H x 1000D chamber in Phase 1 (shell thickness=10 mm)

The baseline structural response is exceeding predefined limits across majority of the parameterized configuration tested in Phase 1 where 22 out of 81 scenarios (27%) exceeded the yield strength of stainless steel (205 MPa). In perspective of deformation, 66 out of 81 scenarios (81%) exceed a 1mm deformation limit while by 59 out of 81 scenarios (73%) are exceeding a 2mm deformation limit. These observations are directly proved that introducing of reinforcement is essential for chambers sizes beyond the smallest sizes analysed.

The dominant stress probe hotspot is R4 (rear section, RHS-middle) carrying average 44.7% of the global peak stress where the largest probe hotspot concentration among phases of this study. The dominant deformation hotspot is the back plate probe (dBACK) averaging 62.4% of peak deformation where the back plate being a large only edge supported flat sheet with no reinforcement in the baseline phase.

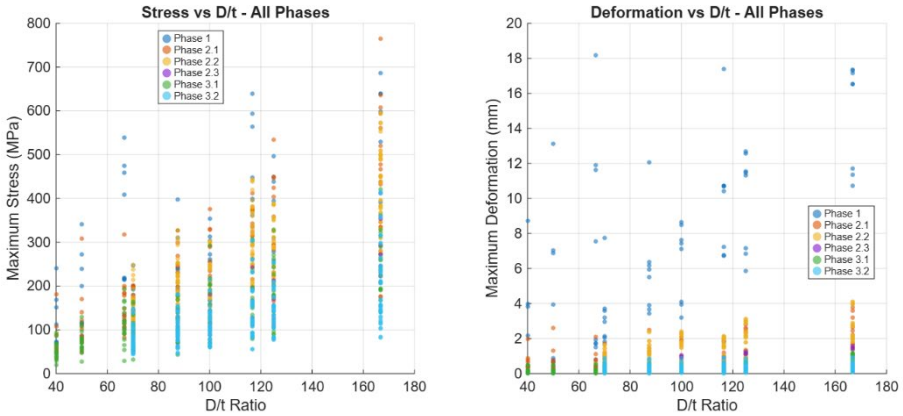

Figure 11: Maximum stress vs D/t ratio (left), deformation vs D/t ratio (right) across all six analysed phases (Phase 1 illustrate in blue)

Table 8: Effect of shell thickness on stress and deformation (non-reinforced baseline, matched chamber geometries, 6 configurations per thickness)

Thickness (mm)	Mean stress (MPa)	Mean deformation (mm)	Mean mass (kg)	Exceed yield (205 MPa)	Exceed 1mm limit
6	533.7	12.614	279.6	6 of 6	6 of 6
8	332.2	8.161	333.1	5 of 6	6 of 6
10	237.9	5.094	386.	3 of 6	6 of 6

Table 8 shows the effect of increasing shell thickness alone without reinforcement for the matched chamber geometries discussed in section 3.7.1. Increasing the thickness from 6mm to 10 mm reduced the mean peak stress by 55.4% and mean deformation by 59.6% for a mass increase of 38.4%. However, all six configurations exceed the 1mm deformation even at 10 mm and 3 of 6 configurations exceeds the yield stress (the analysis include 18 common configurations, with 6 configurations evaluated at each thickness value). This shows that increasing shell thickness alone cannot bring these chamber sizes within the stress and deformation limits.

3.2 Phase 2.1-Single central welded rib reinforcement (bonded)

Introducing single central reinforcement per face as per section 2.2.3 results the reduction of D/t ratio coefficient dominant where shows a clear effect with reinforcement height. Reinforcement height (RH) shows coefficient of -1.06 MM per mm ($p=8.3x10^{-5}$) and -010125mm per mm for the deformation ($p=7.6x10^{-11}$). This proves that the taller reinforcement reduces both stress and deformation responses. D/t ratio show significant relationship (+2.84 MPa/unit and $p \approx 0$) while W/H ratio shows lack of significance as same as Phase 1. Linear stress regression model fit improves ($R^2=0.644$) over the baseline Phase 1 ($R^2=0.494$) while the non-linear model for deformation ($R^2=0.529$) shows improvement over the linear regression model ($R^2=0.506$). This non-linear relationship describes the RH integration with chamber geometry where RH becomes proportionally less effective as the chamber depth grows in size.

Table 9: Regression coefficients of Phase 2.1 (Stress R2=0.644(linear), Deformation R2=0.506(linear)/0.529(non-linear))

Response	Parameter	Coefficient	p-value	Significance
Max. stress	RH	-1.06 MPa/unit	$8.3x10^{-5}$	Yes
Max. stress	D/t ratio	+2.84 MPa/unit	$<10^{-35}$	No
Max. deformation	RH	-0.0125 mm/unit	$7.6x10^{-11}$	Yes
Max. deformation	D/t ratio	+0.0124 mm/unit	$5.2x10^{-20}$	No

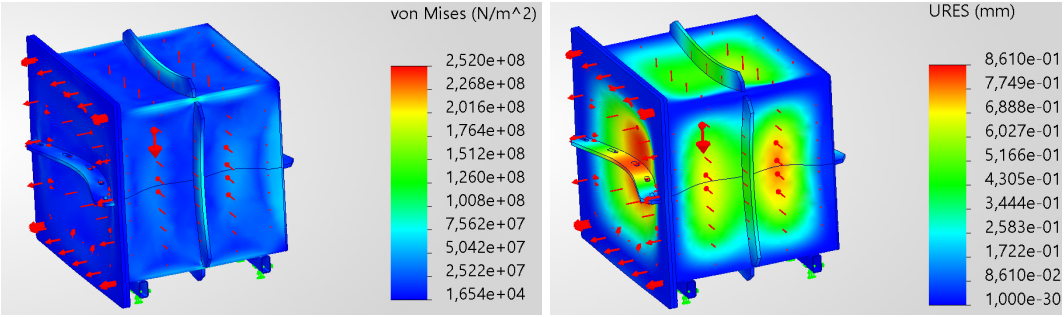

Figure 12: Stress(left) and deformation(right) colour map for 1000W x 1000H x 1000D chamber in Phase 2.1 (shell thickness=10 mm, reinforcement height=100 mm)

Introduction of single central reinforcement improves structural response by 5 out of 162 scenarios (3%) exceeds the yield strength of the stainless steel while 51 out of 162 scenarios (31%) for the 1mm design limit and 19 out of 162 scenarios (12%) for the 2mm deformation limit. The dominant stress hotspot shifts from R4 (rear section, RHS-middle) to R1 (mean ratio of 0.249). This observation shows that single central reinforcement relocates and reduces the peak stress. Other hand the dominant deformation hotspot become dM1(mean ratio of 0.444).

3.3 Phase 2.2-Multiple welded rib reinforcement with equal spacing (Bonded)

This phase with multiple welded rib reinforcements with equal center to center spacing 288 design points trends significant relationship with non-linear regression model for both stress (R^2=0.986 (non-linear)/0.939(linear)) and deformation responses (R^2=0.94 (non-linear)/0.77(linear)) confirming significant effect on Phase 2.2 reinforcement arrangement. Number of reinforcements along the depth direction shows the largest linear coefficient among other factors of this phase (-79 MPa/unit, $p<10^{-30}$) than the effect of RH (-0.87 MPa/mm, $p<10^{-29}$). This observation identifies the number of reinforcements along depth direction as the most impactful design parameter of this phase.
Both coefficient corelate with CC-height and Nos-height show the significance, but do not show the expected physical direction. These behaviours can be concluded that as artifact due to only two discrete values of reinforcement height (RH) and limited number of centers to center spacing in height direction (CC-height) due to limited design space of this phase rather than the real structural response.

Table 10: Selected regression coefficients of Phase 2.2 (Stress R2=0.939(linear)/0.986(non-linear)

Response	Parameter	Coefficient	p-value	Direction
Max. stress	Nos-depth	-79 MPa/unit	$<10^{-30}$	expected
Max. stress	RH	-0.87 MPa/mm	$<10^{-29}$	expected
Max. stress	Nos-Height	+120.8 MPa/unit	$<10^{-69}$	Not expected
Max. stress	CC-Height	+1.19 MPa/mm	$<10^{-93}$	Not excepted

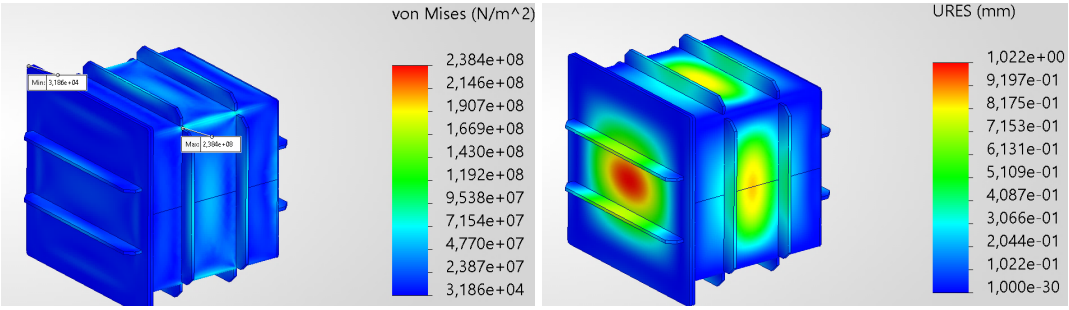

Figure 13: Stress(left) and deformation(right) colour map for 1000W x 1000H x 1000D chamber in Phase 2.2 (shell thickness=10 mm, reinforcement height=100 mm, Center to center spacing=400 mm)

Yield stress exceeds 12 out of 288 (4%) and deformation exceeds 214 of 288 (43%) for 1mm limit while 46 of 488 (16%) configurations for the 2mm design limit. This phase structural response reduces peak stress and produce the most evenly distributed stress field of reinforced phase so far. The domination hotspot probe (M2) carries 14.1% of the global peak stress on average where far improves than response of Phase 1 (44.7%) and Phase 2.1(24.9%). These results verify that the spreading reinforcement across multiple discreate locations improves the distribution of stress evenly throughout the chamber shell.

3.4 Phase 2.3- Multiple welded rib reinforcement with unequal spacing

In this phase feasible 36 design configurations are evaluated due to selected design spectrum for height and depth. Even the results show the trend, but more design configurations required to get proven statistical conclusion which is opening for the future work on this study. Similarly to Phase 2.1, analysis shows a significant negative coefficient for stress (-0.517Mpa/mm, p=0.0003) and deformation (-0.0110 mm/mm, $p=5.4x10^{-7}$) for reinforcement heigh (RH) confirming the significant effect of the RH. The linear regression model follows the data set for stress response (R^2=0.937) while the non-linear regression shows relatively low effect (R^2=0.941). Therefore, non-linear stress regression does not provide significant interpretation for the Phase 2.3 as regression comparison of Phase 2.2. Meanwhile, non-linear deformation regression shows improvement from linear regression model (R^2=0.691(linear)/0.714(non-linear)).
Further, this phase shows the best deformation response so far compared to the smaller (36 design points) sample space where 7 out of 36 (19%) exceeds the 1mm deformation design limit while none out of 36 exceeding 2mm deformation design limit. In stress response, only 1 out of 36 (3%) exceeds the yield stress limit.

The dominant stress probe hotspot is M4 (mid-section, RHS-middle of ratio 0.235) and dominant deformation hotspot is dM4 ((mid-section, RHS-middle of ratio .0788). This is the highest recorded probe deformation concentration recorded out of phases so far suggesting that mid-section side location remain the deformation critical location even after the most targeted reinforcement placement strategy.

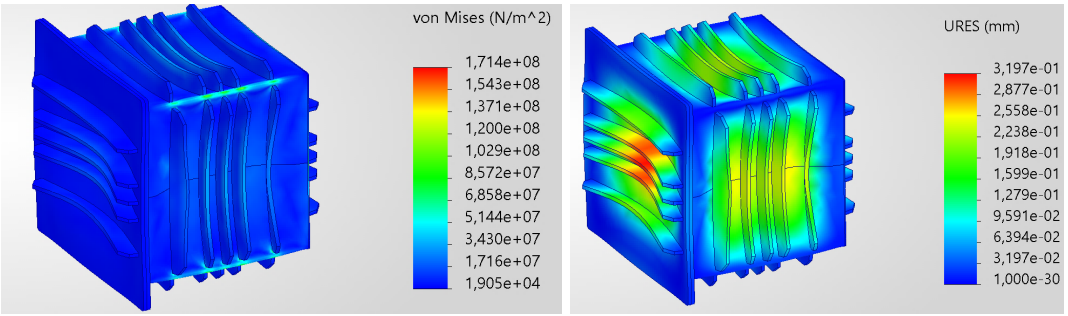

Figure 14: Stress(left) and deformation(right) colour map for 1000W x 1000H x 1000D chamber in Phase 2.3 (shell thickness=10 mm, reinforcement height=100 mm, Center to center spacing level 1=100 mm and Center to center spacing level 2=200 mm)

3.5 Phase 3.1- Single central hybrid reinforcement (Bonded)

Introducing bolted support profile to the welded flat plate (162 design configurations) fundamentally affects the sensitivity of D/t ratio. The stress response coefficient drops to +1.49 MPa/unit ($p=2.6x10^{-31}$) which is 50% less of the baseline phase (+2.92 MPa/unit. This demonstrate that the central hybrid reinforcement strategy significantly reduces chamber's sensitivity to its own D/t ratio. The higher profile height desired to provide less stress, but shows the positive stress coefficient of +0.384 MPa/mm ($p=1.6x10^{-6}$) which is not far significant but consistent with the earlier analytical findings. However, this can be concluded that as artifact due to only two discrete values of profile height (100 and 200mm) which is required to investigate further with more design values. The profile height effect is negative and significant for deformation response (-0.00036 mm/mm) and the non-linear($R^2=0.809$) model shows substantial improvement than the linear($R^2=0.677$) regression model reflecting that relationship between profile height and D/t ratio is non-linear.

Table 11: Phase 3.1 linear regression coefficients (Stress R2=0.606, deformation R2=0.677(linear)/0.809(non-linear))

Response	Parameter	Coefficient	p-value
Max. stress	D/t ratio	+1.49 MPa/unit	$2.6x10^{-31}$
Max. stress	Profile height	+0.384 MPa/mm	$1.6x10^{-6}$
Max. deformation	D/t ratio	+0.00638 mm/unit	$<10^{-40}$
Max. deformation	Profile height	-0.00036 mm/unit	0.18

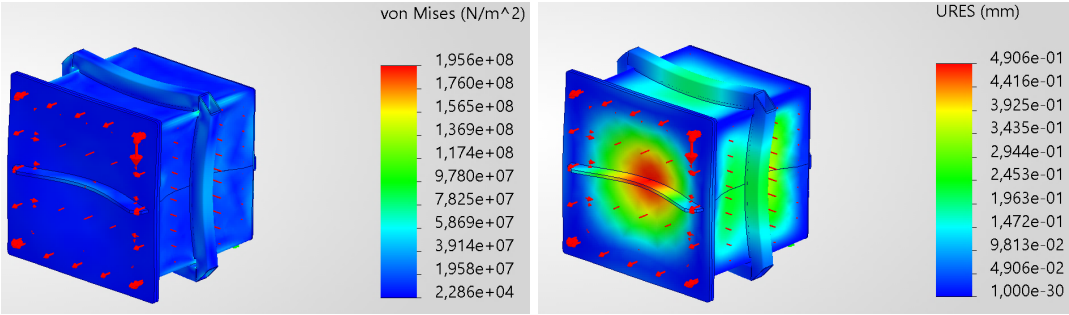

Figure 15: Stress(left) and deformation(right) colour map for 1000W x 1000H x 1000D chamber in Phase 3.1 (shell thickness=10 mm, profile height=100 mm)

This phase shows noticeable improvement with zero stainless steel yield acceptance across all 162 design scenarios while deformation limit exceeds by zero out of 162 design scenarios for the 2mm design limit (only 10 out of 162 (6%) are failed of 1mm design limit). Dominant stress hotspot is R1 (rear-section, top middle with ratio of 0.277) which shows the matching trends compared to seen in Phase 2.1. The dominant deformation hotspot shifted to dDOOR (center of door with ratio of 0.494) which demonstrates the requirement of more rigid type of reinforcing method for the door itself after well-reinforced chamber shell.

3.6 Phase 3.2- Multiple hybrid reinforcement with equal spacing (Bonded)

Introducing multiple hybrid reinforcements (welded flat plates with bolted support profiles) with equal spacing (288 design configurations) produces the strongest non-linear regression improvement of both stress(R^2=0.834(linear)/0.965(non-linear)) and deformation (R^2=0.73 4(linear)/917(non-linear)). This analysis demonstrates the placement of multiple hybrid reinforcements produced a significant trend consistence with patten shows in the Phase 2.2. All of 288 scenarios retain within the defined yield stress and deformation (1mm and 2mm) design criteria where full compliance across the all-tested design spaces.

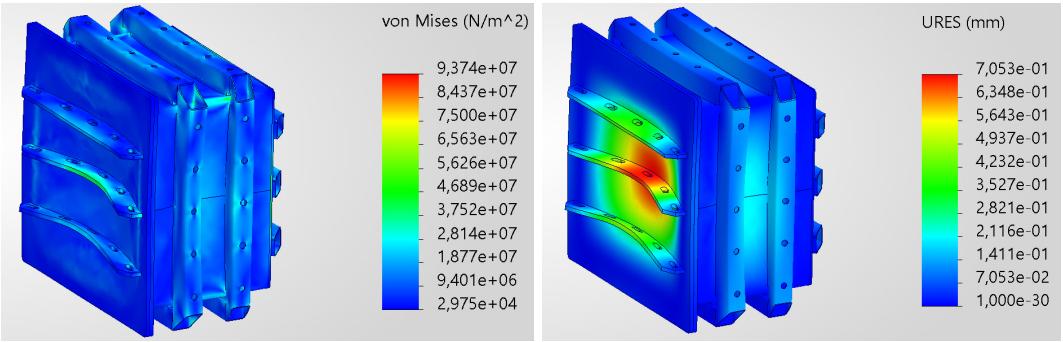

Figure 16: Stress(left) and deformation(right) colour map for 1000W x 1000H x 700D chamber in Phase 3.2 (shell thickness=10 mm, profile height=100 mm, Center to center spacing=300 mm)

The dominant stress probe hotspot is R1 (ratio of 0.189) showing the lowest peak stress concentration among all six phases. The dominant deformation probe hotspot is dDOOR with increased ratio of 0.702 compared to Phase 3.1 which is highest among

the tested design space. This observation also demonstrates the same conclusion as Phase 3.1 which is relatively disproportional reinforced door becomes the majority deformation carrier among the well reinforced chamber shell causing large majority of remaining deformation.

3.7 Cross phase comparison across common configurations

Comparing linear and non-linear regression models across all six phases shows clear trend (see Figure 10). The unreinforced base line in Phase 1 and the central single reinforcement strategy in Phase 2.1 are described by linear regression model with less than 0.02 R^2 improvement contributes by the non-linear regression model. Each phase introducing multiple reinforcements (Phase 2.2, 2.3, 3.1 and 3.2) shows the significant and statistically justified non-linear improvement which dramatically in Phase 2.2 and 3.2 (combining reinforcement height (RH), number of reinforcements and center to center spacing) with non-linear R^2 exceeds 0.96 for the stress response.
The practical conclusion that the reinforcement height/profile height parameter behave close to linear regression model while the introducing multiple reinforcements (Nos-depth, Nos-height. Center to center spacing) shifts regression model to fit close to non-linear. Ultimately this describes that the introducing more design parameters leads to the complexity and hence the non-linear models are mor appropriate for the interpretation of design space.

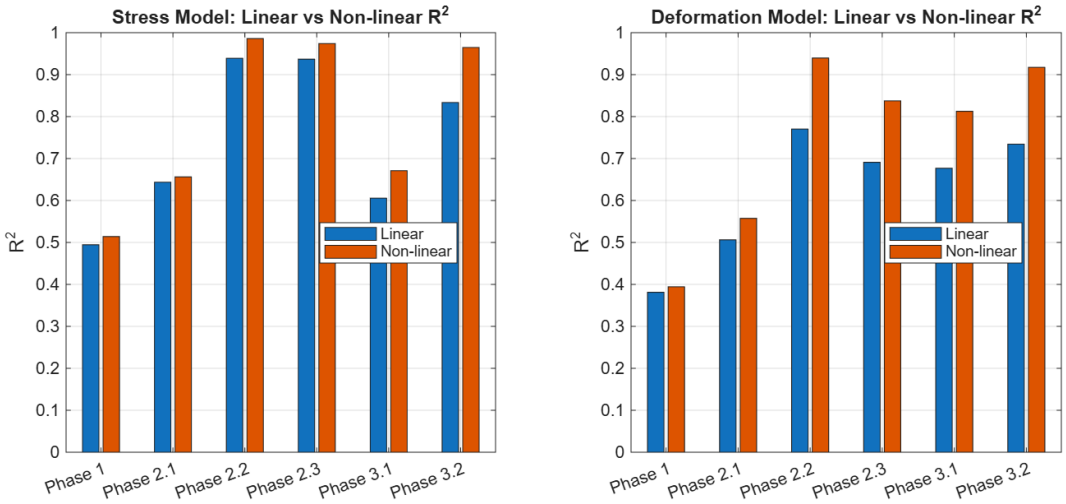

Figure 17: Linear vs non-linear regression R2 across all phases, stress (left) and deformation (right)

3.7.1 Common configuration (geometrically identical chamber) comparison

Direct comparison of overall phase average of Phase 2.2, 2.3 and 3.2 would not provide fair comparison due to evaluated in limited narrower depth and height (700 and 1000mm) range. Common configuration limited to 18 design configurations across six phases with identical Depth, Height, Width and shell thickens to ensure analysis consistency. This approach provides the matched geometrical comparison across each

phase of the study. In these 18 scenarios, baseline (Phase 1) had a mean stress of 367.9 MPa and the mean deformation of 8.62mm. These values are higher than the compared to the overall Phase 1 averages because common configuration contains mainly the large chamber geometries which justifiably for the resultant stress and deformation results.

Table 12: Common geometry configuration comparison (18 shaped identical design points per phase)

Phase	Mean Stress (MPa)	Stress change compared to baseline	Mean deformation	Deformation change compared to baseline
Phase 1	367.94	-	8.6231	-
Phase 2.1	316.80	-13.9%	1.2573	-85.4%
Phase 2.2	254.17	-30.9%	1.2134	-85.9%
Phase 2.3	147.22	-60.0%	0.4985	-94.2%
Phase 3.1	180.43	-51.0%	0.4169	-95.2%
Phase 3.2	136.58	-62.9%	0.2834	-96.7%

.

This matched configuration comparison also changed the ranking of stress response where Phase 2.2 improves reduction of 13.9% (Phase 2.1) compared to raw comparison to 30.9% when using the matched geometries. Therefore, the final ranking of stress and response is:

Phase 3.2 > Phase 2.3 > Phase 3.1 > Phase 2.2 > Phase 2.1

The deformation ranking of matched configuration also follows nearly identical ranking.

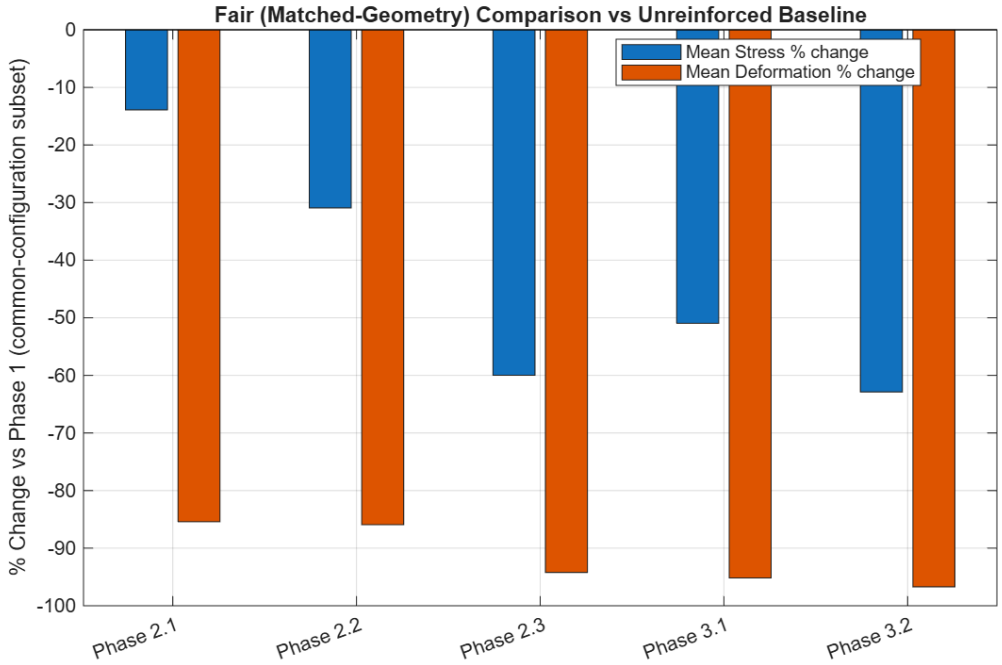

Figure 18: Common geometry configuration stress and deformation reduction compared to baseline (Phase 1)

3.7.2 Mass efficiency

Reduction of stress itself does not provide the best design criteria considering the material cost. Normalizing chamber stress reduction respect to mass increase (see Table 1)provides the material efficiency ranking where Phase 3.1 provides the best efficiency (1.52% stress reduction per 1% of mass) followed by Phase 2.2, Phase 2.1and Phase 2.3.

The Phase 3.2 gives the least mass efficient (0.72) phase despite the highest stress reduction recorded due to 86.9% of increased mass (including profile mass). Therefore Phase 3.1 becomes the most efficient among all phases in perspective of mass related cost perspective unless larger geometrical chamber sizes are associated.

Table 13: Mass efficiency of each reinforcement strategy (for common chamber configurations)

Phase	Mass change compared to baseline	Stress change compared to baseline	Efficiency (% reduction per 1% mass)
Phase 2.1	+13.9%	-13.9%	1.00
Phase 2.2	+30.3%	-30.9%	1.02
Phase 2.3	+60.8%	-60.0%	0.99
Phase 3.1	+33.5%	-51.0%	1.52
Phase 3.2	+86.9%	-62.9%	0.72

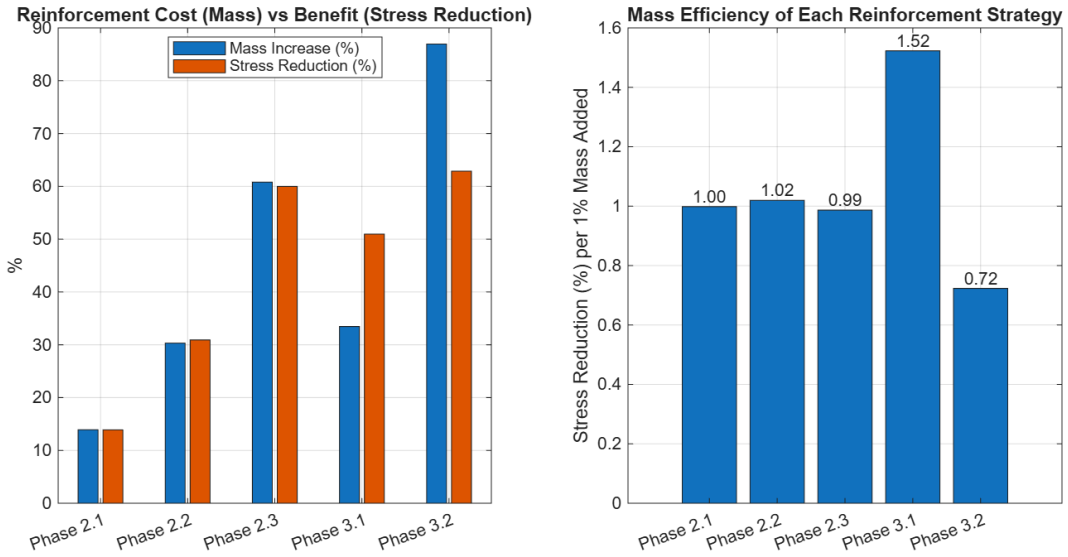

Figure 19: Mass % increase vs. stress change(left) and mass efficiency (right), for Phase 2.1, 2.2, 2.3, 3.1 and 3.2

3.8 Probe layout analysis

Total of 23 probe stress across front, middle, back, door and back plate with symmetrical assumption reveals two consistent patters across all phases.
The introducing reinforcements reduced the magnitude of highest-stress ratio while shifting the highest-stress position. Stress hotspot shifted to top-middle from RHS, middle-side introducing reinforcements in Phase 2.1, 3.1 and 3.2 while in Phase 2.2 and 2.3 it remains at the same spot with lower ratio compared to baseline.

These results also shows that door become critical area when chamber becomes rigid with the reinforcement strategies. The mean deformation of door increases from ratio of 0.142(baseline) to ratio range of 0.371-0.436 in welded rib reinforcement phases, 0.494 in Phase 3.1 and 0.702 in Phase 3.2. This provides the insight of introducing more rigid reinforcements to the door adjacent to stiffer chamber reinforcements.

Table 14: Worst stress position and sectional averages across all phases

Phase	Worst position	Ratio	Front average	Mid average	Rear average
Phase 1	RHS, side-middle	0.303	0.095	0.278	0.132
Phase 2.1	Top-middle	0.132	0.058	0.055	0.116
Phase 2.2	RHS, side-middle	0.100	0.036	0.104	0.054
Phase 2.3	RHS, side-middle	0.154	0.033	0.099	0.077
Phase 3.1	Top-middle	0.146	0.083	0.053	0.100
Phase 3.2	Top-middle	0.098	0.059	0.064	0.064

These results also shows that door become critical area when chamber becomes rigid with the reinforcement strategies. The mean deformation of door increases from ratio of 0.142(baseline) to ratio range of 0.371-0.436 in welded rib reinforcement phases, 0.494 in Phase 3.1 and 0.702 in Phase 3.2. This provides the insight of introducing more rigid reinforcements to the door adjacent to stiffer chamber reinforcements.

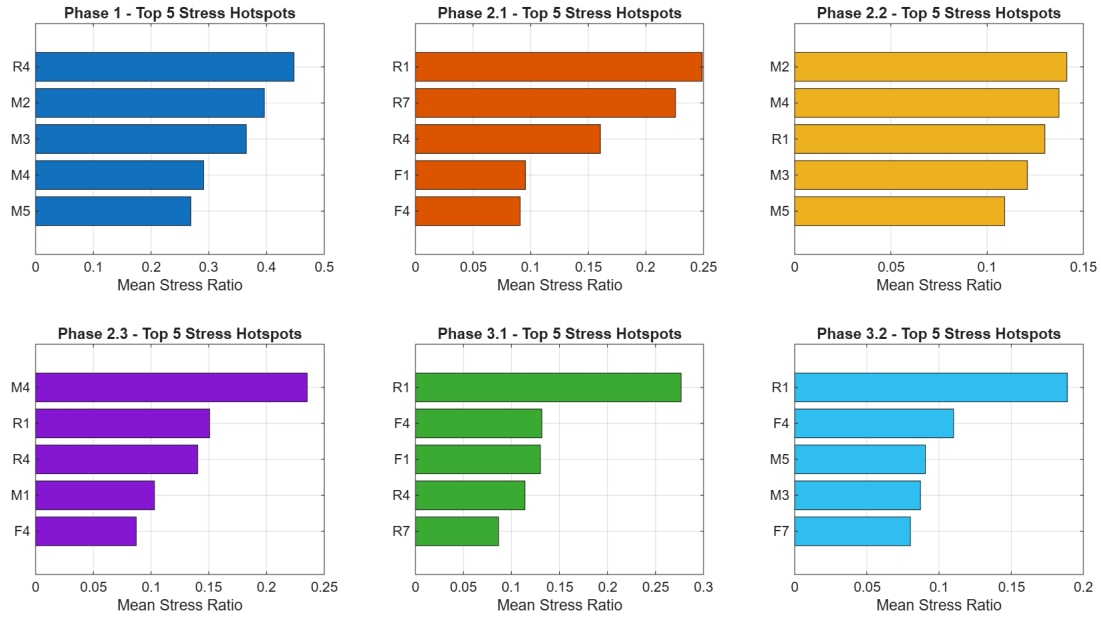

Figure 20: Top 5 stress hotspot probes across all phases

4 Discussion of Results

This chapter discusses the results presented in chapter 3 in relation to research questions formulated in chapter 1, section 1.2.1.

4.1 Dominance of depth to thickness ratio (RQ1)

The D/t ratio parameter is the most dominant across all phases which is the significant statistically driver of the peak stress (see Table 7, Table 8, Table 9 and Table 10). The W/H ratio of chamber does not show a significant effect across phases. This provides the direct answer to the research question 1 where the chamber size interpreted through the D/t ratio rather than the W/H aspect ratio is the primary parameter driving the stress and deformation (in each unreinforced and reinforced phases includes in design space). The magnitude of the D/t ratio coefficient is not consistent across all phases; however, the values drop to +1.49 MPa/unit in the Phase 3.1 from +2.92 MPa/unit in the baseline Phase 1. This provides the evidence that the introduction of reinforcements potentially reduces the sensitivity of D/t ratio of the chamber.

4.2 Reinforcement necessity and comparative effectiveness (RQ2)

The Phase 1 study shows the direct and quantitative baseline for the research question 1 where 27% and 81% of tested chamber geometries exceed the yield stress and 1mm design limit respectively. Therefore, this data suggests that the reinforcements are necessary for the majority of geometrical sizes of the tested spectrum. Meanwhile, all of reinforcement strategies produced statistically significant improved responses compared to baseline phase which answers the research question 2.

Common configuration (geometrically identical chamber) comparison evaluated in the section 3.7.1 (see Table 11 and Figure 11) indicates that the hybrid reinforcement strategy provides the most effective among other strategies. Further, this ranking differs from the raw value ranking comparison where Phase 2.2 stress reduction improves from 13.9% (raw values) to 30.9% when comparing with matched geometrical chamber sizes. This fair comparison between all six phases is employed due to selected narrower field of depth and height (700 and 1000mm) parameters used in the phase 2.2, 2.3 and 3.2.

4.3 Reinforcement placement (Density, center to center spacing)

Nos-depth shows a significant coefficient (-79.0 MPa/unit) than RH parameter (-0.87 MPa/mm) in Phase 2.2 which identifies the number of depth side reinforcement count as impactful parameter. However, CC-height and Nos-height also significantly associate with increased stress and deformation which is opposite response to the expected physical behaviour. This could be investigated further with the larger geometrical chamber sizes with wide range of Nos-height rather than adopted as design insight (only 2 or 3 reinforcements in height direction is considered in the study).
The linear vs non-linear regression model comparison (see Figure 10) demonstrates a consistent and clear trend where RH change (Phase 2.1 and 2.3) was described by a linear model and different reinforcement placements (number of reinforcements and center to center spacing) were described by a non-linear regression model. These methodological findings show that non-linear regression model is more suitable for the multiple reinforcement placement used as parameters in combination with other design parameters.

4.4 Reinforcement placement and stress/deformation hotspots

The probe layout analysis (see Table 14 and Figure 13) shows peak stress location and magnitude. The baseline stress hotspot at the RHS side-middle shifted to top-middle in both welded rib and hybrid single central reinforcement scenarios while the stress hotspot remains at the RHS side-middle probe location with reduced magnitude level in the both welded rib and hybrid multiple reinforcement placement scenarios. Therefore, it is recommended to consider reinforcement structure hotspot analysis in combination of chamber hotspot analysis.
Ultimately, this analysis also shows the door shows larger deformations ratio compared to chamber deformation with stiffer reinforcement applied to the chamber shell. The mean door deformation ratio increased from baseline ratio of 0.142 to 0.702 in Phase 3.2. Since door reinforcement remain the consistence across all phases (excluding baseline) it is recommended to improve reinforcement adjacent to the chamber shell reinforcements.

4.5 Optimal combination for material sustainability and cost

Table 12 and Figure 12 directly addresses the research question 3. The Phase 3.2 provides the highest stress reduction, but at the cost of the largest mass increase due to weight of support profiles (+86.9%). Meanwhile, the Phase 3.1(central hybrid reinforcement placement) provides a stress reduction of 1.52% stress reduction per increase of unit percentage of mass. Therefore, Phase 3.1 is the better choice compared to both structural performance and material efficiency unless chamber size parameters are larger compared to the design space.

The alternative of increasing shell thickness instead of adding reinforcements can be assessed from the Phase 1 results (see Table 8). Increasing thickness from 6 mm to 10

mm gives a stress efficiency of 1.44% reduction per unit percentage of mass increase, close to the 1.52% stress reduction achieved by hybrid reinforcements of Phase 3.1. However, thickness increase does not satisfy the defined deformation limits where all matched configurations in Phase 1 exceeds 1mm deformation limit even at 10 mm of shell thickness, compared with only 6% exceeding it in Phase 3.1. Therefore, reinforcement is the most suitable strategy for the chamber size studies, since increasing shell thickness alone cannot bring deformation within the defined design limit.

4.6 Analytical estimation of reasoning for D/t ratio dominates over W/H aspect ratio.

Classical plate theory[2] provides deflection and stress for rectangular shape plate under uniform pressure loading as;

Deformation (w)

$$w \propto \frac{b^4}{Plate\ Bending\ Stiffness}$$

$$w \propto \frac{12\ b^4(1-v^2)}{Et^3}$$

Stress (σ)

$$\sigma \propto \frac{b^2}{t^2}$$

$$Plate\ Bending\ Stiffness = \frac{Et^3}{12(1-v^2)}$$

Where;

b=shorter plate span, t=plate thickness, E=Young's modulus, v=Poisson's ratio, D= plate bending stiffness, W/H= aspect ratio

The equations stated above shows that both plate thickness and W/H aspect ratio affect the stress and deformation. However, thickness provides stronger effect in both deformation and stress by $1/t^2$ and $1/t^3$ respectively. As an example, reducing of thickness by half results stress increase by four times and deformation increase by factor of eight.

The effect of W/H ratio is smaller compared to the D/t ratio due to change in plate coefficients which change linearly as Width and Height changes. This supports the FEA results where W/H ratio (0.4 to 2.5) was insignificant compared to D/t ratio and provides an analytical explanation for the answer to research question 1.

5 Conclusions

This study investigates reinforcement strategies and their effects on both structural responses of stress and deformation dividing to six phases including one baseline phase and five reinforced phases. From the study, research questions are defined in section 1.2.1 are answered as follows

- **RQ1: What is the influence of chamber size (depth to thickness ratio) on stress and deformation under induced vacuum conditions, and what size does reinforcement become necessary?**

The D/t ratio provides significant effect on stress and deformation across all phases while W/H ratio remains comparatively less significant. Classical plate theory supports this finding since stress scales with $1/t^3$ and deformation scales with $1/t^2$. In the non-reinforced base case study, 27% of configurations and 81% of configurations exceed yield stress of stainless steel and 1mm deformation limit respectively. Therefore, reinforcements are essential across most of the analyzed design spectrum and only the smallest chambers with sufficient wall thickness can withstand vacuum loads without reinforcements.

- **RQ2: How effective are welded reinforcements (rib) and hybrid reinforcement strategies at reducing stress and deformation, compared with each other and with the non-reinforced baseline?**

All reinforced strategies contribute to the reduction of stress and deformation compared with baseline scenario. For matched chamber size geometries, the ranking of stress reduction is Phase 3.2 > 2.3 > 3.1 > 2.2 > 2.1. Hybrid reinforcement is more effective than welded rib reinforcements, but at the trade-off of additional mass increase due to support profiles. The door becomes dominant deformation location with the stiffer reinforcement of chamber shell, where door reinforcements should be improved parallel with the chamber shell reinforcement.

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- **RQ3: Which reinforcements returns the best trade-off between structural performance and material usage?**

The Phase 3.1(single central hybrid reinforcement) gives the best trade-off between stress reduction and mass efficiency (1.52%) while the Phase 3.2 gives the largest stress reduction but with the lowest mass efficiency (0.72%). Increasing the shell thickness of the chamber is the basic alternative to introducing reinforcements. Increasing the shell thickness from 6mm to 10 mm gives a comparable stress efficiency (1.44% per unit percentage of mass) but increasing the thickness does not satisfy deformation limits where all matched configurations exceed 1mm deformation limit even at thickness of 10 mm.

Thickness alone is therefore not sufficient for the largest chambers (which are common in industrial applications), since the added material by thickness

increase is distributed over the whole shell instead of the regions with the highest deformations. Reinforcement is the more suitable option for the largest chamber sizes investigated, while a thicker shell can be remaining practical choice for smaller vacuum chambers as per fabrication simplicity and applications requirements.

– **Methodological findings**

Non-linear regression models are required to represent the responses once multiple reinforcement placement parameters are introduced, while reinforcement height alone is described well by linear models.

5.1 Generalization of the result

Since the D/t ratio was identified as a key parameter affecting peak stress for all analysed phases suggest that these findings are related to rectangular vacuum chamber designed in same geometrical parameter sizes and materials.
However, extrapolation of regression coefficients obtained during the analysis should not be used directly without validation beyond dimensions, boundary conditions, loadings and material used in this study.

5.2 Limitations of the study

- Welded and bolt connections behaviour modelled as bonded for analytical simplicity and to conserve computational power per project scope.
- Material selection was limited to stainless steel for main chamber shell and weld reinforcements, aluminium alloy for door and door reinforcement and structural steel for the profiles and supports)
- Linear elastic range of material models were accounted.
- Thermal and dynamic loading effects were neglected.
- The study was limited to narrower size range of rectangular chambers for simplicity (width, height, depth values of 400,700 and 1000mm and shell thickness values of 6,8 and 10 mm)
- Phases 2.2, 2.3 and 3.2 were simulated over a limited Depth/Height size than Depth/Height sizes simulated in Phase 1, 2.1 and 3.1. This limits direct stress and deformation comparison between common configurations.
- Center to center spacing values and number of reinforcements in Phase 2.3 (36 design points) are tied to fixed Depth/Height values due to physical feasibility. Therefore, regression and sensitivity results pattern may not be strong enough to claim the relationship are statistically proven.
- Effect of manufacturing and fabrication defects such as material defects, welding distortion and welding defects were not accounted.

5.3 Future work and research

- Expand and reevaluate design phases to wide feasible geometric values (Width, Depth and Height from 1000mm to 3000mm and thickness values of 8,10,12mm) of the chamber to get identical configuration comparisons in between phases.

- Run FEA study with the actual welded and bolted connection to confirm and compare results with the existing study accuracy.
- Conduct small set of matched comparison of each phase with higher number of geometrical configurations.
- Verify the results with several real-time physical models matched to the modelled configurations.

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A. Phase 1: Regression Analysis Results

========== STRESS ANALYSIS ==========

Stainless: 22 of 81 exceed yield (205 MPa). Aluminium (door): 0 of 81 exceed yield (150 MPa).

--- LINEAR stress model ---

MaxStress ~ 1 + Dt_ratio + WH_ratio

Number of observations: 81, Error degrees of freedom: 78
Root Mean Squared Error: 114
R-squared: 0.494, Adjusted R-Squared: 0.482
F-statistic vs. constant model: 38.1, p-value = 2.79e-12

--- NON-LINEAR (quadratic) stress model ---

MaxStress ~ 1 + Dt_ratio*WH_ratio + Dt_ratio^2 + WH_ratio^2

Number of observations: 81, Error degrees of freedom: 75
Root Mean Squared Error: 114
R-squared: 0.514, Adjusted R-Squared: 0.482
F-statistic vs. constant model: 15.9, p-value = 1.22e-10
Linear R^2 = 0.4945 | Quadratic R^2 = 0.5141

========== deformation ANALYSIS ==========
66 of 81 exceed 1mm; 59 of 81 exceed 2mm.

--- LINEAR deformation model ---

Maxdeformation ~ 1 + Dt_ratio + WH_ratio

Number of observations: 81, Error degrees of freedom: 78
Root Mean Squared Error: 4.07
R-squared: 0.381, Adjusted R-Squared: 0.365
F-statistic vs. constant model: 24, p-value = 7.39e-09

--- NON-LINEAR (quadratic) deformation model ---

Maxdeformation ~ 1 + Dt_ratio*WH_ratio + Dt_ratio^2 + WH_ratio^2

Number of observations: 81, Error degrees of freedom: 75
Root Mean Squared Error: 4.11
R-squared: 0.394, Adjusted R-Squared: 0.354
F-statistic vs. constant model: 9.77, p-value = 3.24e-07
Linear R^2 = 0.3813 | Quadratic R^2 = 0.3944

B. Phase 2.1: Regression Analysis Results

========== STRESS ANALYSIS ==========
Stainless: 5 of 162 exceed yield. Aluminium (door): 0 of 162 exceed yield.

--- LINEAR stress model ---

MaxStress ~ 1 + ReinforcementHeight + Dt_ratio + WH_ratio

Number of observations: 162, Error degrees of freedom: 158
Root Mean Squared Error: 83.7
R-squared: 0.644, Adjusted R-Squared: 0.637
F-statistic vs. constant model: 95.1, p-value = 3.19e-35

--- NON-LINEAR (quadratic) stress model ---

MaxStress ~ 1 + ReinforcementHeight + Dt_ratio + WH_ratio + ReinforcementHeight^2 + Dt_ratio^2 + WH_ratio^2

Number of observations: 162, Error degrees of freedom: 156
Root Mean Squared Error: 83.9
R-squared: 0.646, Adjusted R-Squared: 0.635
F-statistic vs. constant model: 57, p-value = 1.82e-33
Linear R^2 = 0.6437 | Quadratic R^2 = 0.6461

========== deformation ANALYSIS ==========
51 exceed 1mm; 19 exceed 2mm (of 162).

--- LINEAR deformation model ---

Maxdeformation ~ 1 + ReinforcementHeight + Dt_ratio + WH_ratio

Number of observations: 162, Error degrees of freedom: 158
Root Mean Squared Error: 0.569
R-squared: 0.506, Adjusted R-Squared: 0.497
F-statistic vs. constant model: 54, p-value = 4.44e-24

--- NON-LINEAR (quadratic) deformation model ---

Maxdeformation ~ 1 + ReinforcementHeight + Dt_ratio + WH_ratio + ReinforcementHeight^2 + Dt_ratio^2 + WH_ratio^2

Number of observations: 162, Error degrees of freedom: 156
Root Mean Squared Error: 0.56
R-squared: 0.529, Adjusted R-Squared: 0.514
F-statistic vs. constant model: 35, p-value = 6.55e-24
Linear R^2 = 0.5062 | Quadratic R^2 = 0.5290

C. Phase 2.2: Regression Analysis Results

========== STRESS ANALYSIS ==========
Stainless: 12 of 288 exceed yield. Aluminium (door): 0 of 288 exceed yield.

--- LINEAR stress model ---

MaxStress ~ 1 + ReinforcementHeight + CCDepth + NosDepth + CCHeight + NosHeight + Dt_ratio + WH_ratio

Number of observations: 288, Error degrees of freedom: 280
Root Mean Squared Error: 28.6
R-squared: 0.939, Adjusted R-Squared: 0.937
F-statistic vs. constant model: 615, p-value = 5.95e-166

--- NON-LINEAR (two-way interaction) stress model ---

MaxStress ~ [Linear formula with 36 terms in 7 predictors]

Number of observations: 288, Error degrees of freedom: 257
Root Mean Squared Error: 14.3
R-squared: 0.986, Adjusted R-Squared: 0.984
F-statistic vs. constant model: 601, p-value = 6.73e-220
Linear R^2 = 0.9390 | Non-linear R^2 = 0.9859

========== deformation ANALYSIS ==========
124 exceed 1mm; 46 exceed 2mm (of 288).

--- LINEAR deformation model ---

Maxdeformation ~ 1 + ReinforcementHeight + CCDepth + NosDepth + CCHeight + NosHeight + Dt_ratio + WH_ratio

Number of observations: 288, Error degrees of freedom: 280
Root Mean Squared Error: 0.397
R-squared: 0.77, Adjusted R-Squared: 0.765
F-statistic vs. constant model: 134, p-value = 1.35e-85

--- NON-LINEAR (two-way interaction) deformation model ---

Maxdeformation ~ [Linear formula with 36 terms in 7 predictors]

Number of observations: 288, Error degrees of freedom: 257
Root Mean Squared Error: 0.212
R-squared: 0.94, Adjusted R-Squared: 0.933
F-statistic vs. constant model: 133, p-value = 8.11e-139
Linear R^2 = 0.7703 | Non-linear R^2 = 0.9396

D. Phase 2.3: Regression Analysis Results

========== STRESS ANALYSIS ==========
Stainless: 1 of 36 exceed yield. Aluminium (door): 0 of 36 exceed yield.

--- LINEAR stress model ---

MaxStress ~ 1 + ProfileHeight + Dt_ratio + WH_ratio

Number of observations: 36, Error degrees of freedom: 32
Root Mean Squared Error: 19.1
R-squared: 0.937, Adjusted R-Squared: 0.931
F-statistic vs. constant model: 158, p-value = 2.82e-19

--- NON-LINEAR (quadratic) stress model ---

MaxStress ~ 1 + ProfileHeight + Dt_ratio + WH_ratio + Dt_ratio^2 + WH_ratio^2

Number of observations: 36, Error degrees of freedom: 30
Root Mean Squared Error: 19
R-squared: 0.941, Adjusted R-Squared: 0.932
F-statistic vs. constant model: 96.5, p-value = 1.47e-17
Linear R^2 = 0.9369 | Non-linear R^2 = 0.9415

========== deformation ANALYSIS ==========
7 exceed 1mm; 0 exceed 2mm (of 36).

--- LINEAR deformation model ---

Maxdeformation ~ 1 + ProfileHeight + Dt_ratio + WH_ratio

Number of observations: 36, Error degrees of freedom: 32
Root Mean Squared Error: 0.265
R-squared: 0.691, Adjusted R-Squared: 0.662
F-statistic vs. constant model: 23.9, p-value = 2.68e-08

--- NON-LINEAR (quadratic) deformation model ---

Maxdeformation ~ 1 + ProfileHeight + Dt_ratio + WH_ratio + Dt_ratio^2 + WH_ratio^2

Number of observations: 36, Error degrees of freedom: 30
Root Mean Squared Error: 0.263
R-squared: 0.714, Adjusted R-Squared: 0.666
F-statistic vs. constant model: 15, p-value = 2.16e-07
Linear R^2 = 0.6910 | Non-linear R^2 = 0.7140

E. Phase 3.1: Regression Analysis Results

========== STRESS ANALYSIS ==========
Stainless: 0 of 162 exceed yield. Aluminium (door): 0 of 162 exceed yield.

--- LINEAR stress model ---

MaxStress ~ 1 + ProfileHeight + Dt_ratio + WH_ratio

Number of observations: 162, Error degrees of freedom: 158
Root Mean Squared Error: 49.1
R-squared: 0.606, Adjusted R-Squared: 0.598
F-statistic vs. constant model: 80.9, p-value = 9.38e-32

--- NON-LINEAR (quadratic) stress model ---

MaxStress ~ 1 + ProfileHeight + Dt_ratio + WH_ratio + ProfileHeight^2 + Dt_ratio^2 + WH_ratio^2

Number of observations: 162, Error degrees of freedom: 156
Root Mean Squared Error: 49
R-squared: 0.612, Adjusted R-Squared: 0.6
F-statistic vs. constant model: 49.3, p-value = 2.02e-30
Linear R^2 = 0.6056 | Non-linear R^2 = 0.6124

========== deformation ANALYSIS ==========
10 exceed 1mm; 0 exceed 2mm (of 162).

--- LINEAR deformation model ---

Maxdeformation ~ 1 + ProfileHeight + Dt_ratio + WH_ratio

Number of observations: 162, Error degrees of freedom: 158
Root Mean Squared Error: 0.17
R-squared: 0.677, Adjusted R-Squared: 0.671
F-statistic vs. constant model: 110, p-value = 1.46e-38

--- NON-LINEAR (quadratic) deformation model ---

Maxdeformation ~ 1 + ProfileHeight + Dt_ratio + WH_ratio + ProfileHeight^2 + Dt_ratio^2 + WH_ratio^2

Number of observations: 162, Error degrees of freedom: 156
Root Mean Squared Error: 0.131
R-squared: 0.809, Adjusted R-Squared: 0.803
F-statistic vs. constant model: 133, p-value = 2.65e-54

Linear R^2 = 0.6768 | Non-linear R^2 = 0.8095

F.Phase 3.2: Regression Analysis Results

========== STRESS ANALYSIS ==========
Stainless: 0 of 288 exceed yield. Aluminium (door): 0 of 288 exceed yield.

--- LINEAR stress model ---

MaxStress ~ 1 + ProfileHeight + CCDepth + NosDepth + CCHeight + NosHeight + Dt_ratio + WH_ratio

Number of observations: 288, Error degrees of freedom: 280
Root Mean Squared Error: 26.2
R-squared: 0.834, Adjusted R-Squared: 0.829
F-statistic vs. constant model: 200, p-value = 4.4e-105

--- NON-LINEAR (two-way interaction) stress model ---

MaxStress ~ [Linear formula with 36 terms in 7 predictors]

Number of observations: 288, Error degrees of freedom: 257
Root Mean Squared Error: 12.6
R-squared: 0.965, Adjusted R-Squared: 0.961
F-statistic vs. constant model: 234, p-value = 1.38e-168
Linear R^2 = 0.8335 | Non-linear R^2 = 0.9647

========== deformation ANALYSIS ==========
0 exceed 1mm; 0 exceed 2mm (of 288).

--- LINEAR deformation model ---

Maxdeformation ~ 1 + ProfileHeight + CCDepth + NosDepth + CCHeight + NosHeight + Dt_ratio + WH_ratio

--- NON-LINEAR (two-way interaction) deformation model ---

Maxdeformation ~ [Linear formula with 36 terms in 7 predictors]

Number of observations: 288, Error degrees of freedom: 257
Root Mean Squared Error: 0.0598
R-squared: 0.917, Adjusted R-Squared: 0.908
F-statistic vs. constant model: 95.2, p-value = 1.7e-121
Linear R^2 = 0.7344 | Non-linear R^2 = 0.9174

G. Probe layout analysis

Section	Position	ProbeID
{'Front'}	{'top-middle'}	{'F1'}
{'Front'}	{'top-RHS'}	{'F2'}
{'Front'}	{'RHS side-top'}	{'F3'}
{'Front'}	{'RHS side-middle'}	{'F4'}
{'Front'}	{'RHS side-bottom'}	{'F5'}
{'Front'}	{'bottom-RHS'}	{'F6'}
{'Front'}	{'bottom-middle'}	{'F7'}
{'Mid'}	{'top-middle'}	{'M1'}
{'Mid'}	{'top-RHS'}	{'M2'}
{'Mid'}	{'RHS side-top'}	{'M3'}
{'Mid'}	{'RHS side-middle'}	{'M4'}
{'Mid'}	{'RHS side-bottom'}	{'M5'}
{'Mid'}	{'bottom-RHS'}	{'M6'}
{'Mid'}	{'bottom-middle'}	{'M7'}
{'Rear'}	{'top-middle'}	{'R1'}
{'Rear'}	{'top-RHS'}	{'R2'}
{'Rear'}	{'RHS side-top'}	{'R3'}
{'Rear'}	{'RHS side-middle'}	{'R4'}
{'Rear'}	{'RHS side-bottom'}	{'R5'}
{'Rear'}	{'bottom-RHS'}	{'R6'}
{'Rear'}	{'bottom-middle'}	{'R7'}
{'Plate'}	{'Back plate center'}	{'BACK'}
{'Plate'}	{'Door plate center'}	{'DOOR'}

Figure 21: Probe location definition

Phase	WorstPosition	WorstPositionRatio	FrontAvg	MidAvg	RearAvg
{'Phase1'}	{'RHS side-middle'}	0.30299	0.094916	0.27799	0.13176
{'Phase2_1'}	{'top-middle'}	0.13178	0.057621	0.055208	0.11576
{'Phase2_2'}	{'RHS side-middle'}	0.099504	0.036249	0.10398	0.053585
{'Phase2_3'}	{'RHS side-middle'}	0.15428	0.033296	0.098565	0.076601
{'Phase3_1'}	{'top-middle'}	0.14571	0.082523	0.052531	0.099625
{'Phase3_2'}	{'top-middle'}	0.098058	0.058681	0.063973	0.064416

Figure 22: Probe analysis

H. Cross Phase Comparison

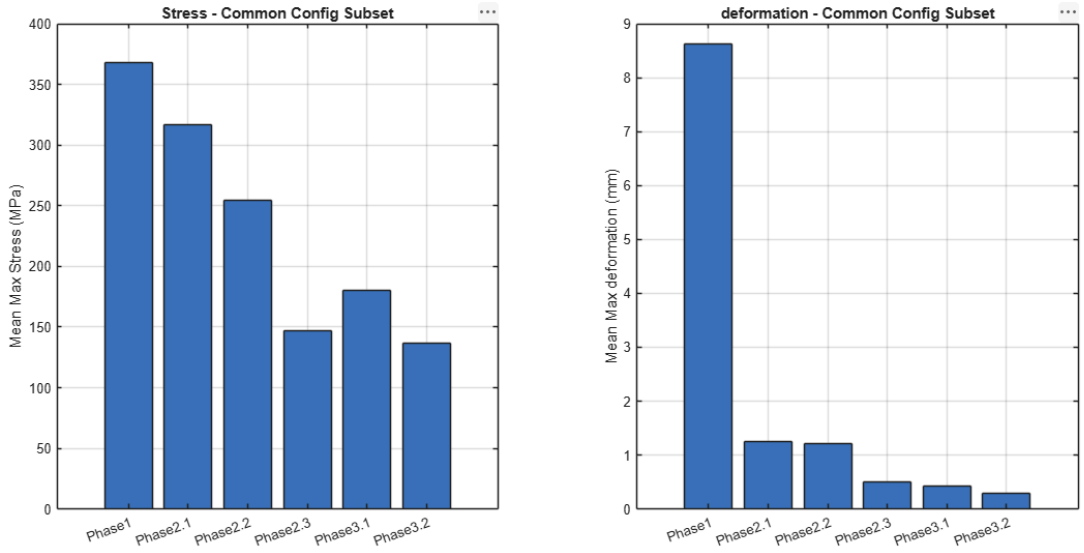

Figure 23: Stress (left) and Deformation(right) of common configuration across all six phases

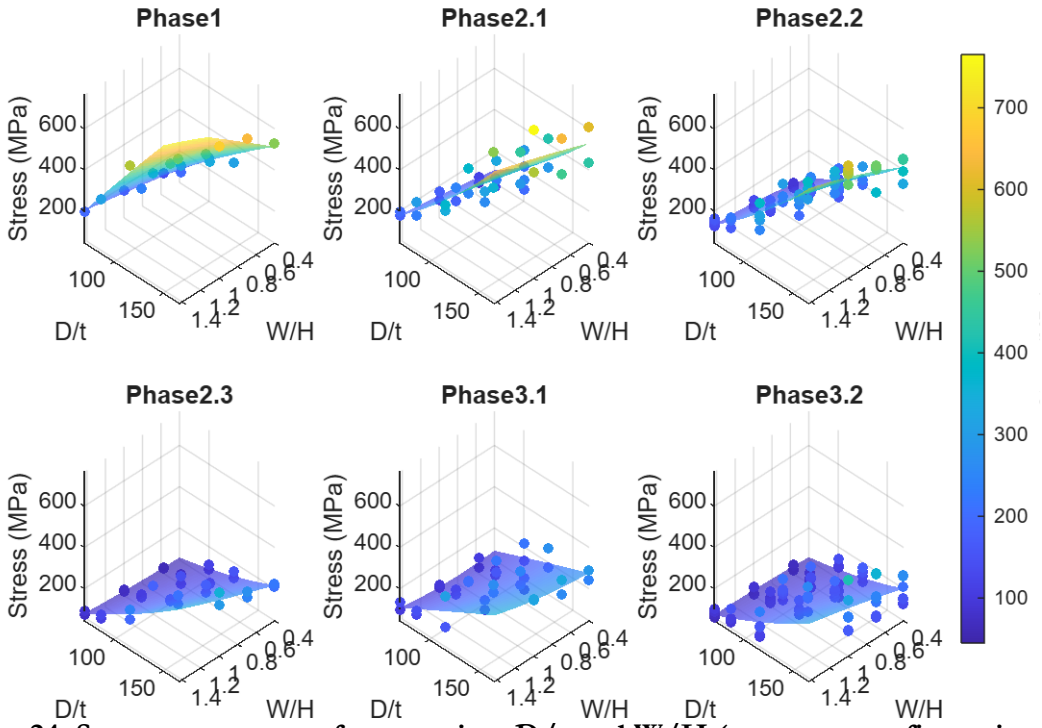

Figure 24: Stress response surfaces against D/t and W/H (common configuration for all six phases)

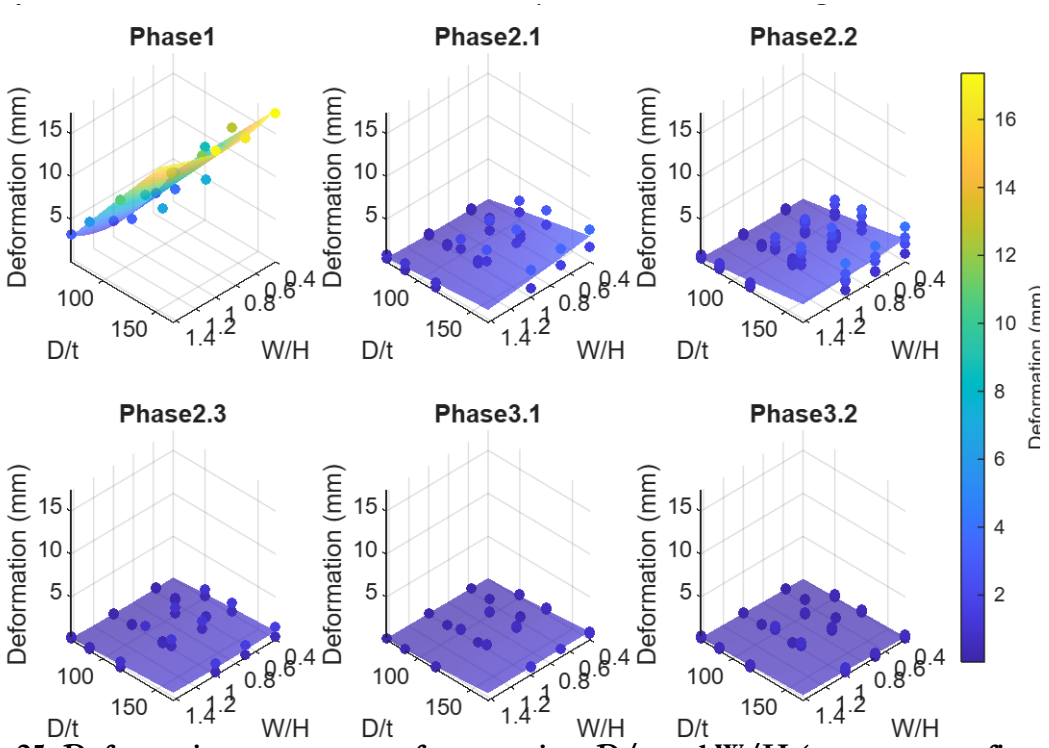

Figure 25: Deformation response surfaces against D/t and W/H (common configuration for all six phases)