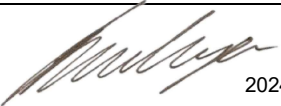






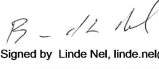





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REVISIONS

This document has been revised in accordance with the following schedule:

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1.0	31/03/2023	First issue	WJ Jarvis
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1 EXECUTIVE SUMMARY

The concept design of an Overpack is developed into a final design in this report. This includes the simplification of the design for the ease of manufacturing, introducing of lifting points of ease of handling and the tie-down points for securing an Overpack in the truck during transportation.

Additional to the static structural analysis for the above-mentioned cases, a drop test and thermal analysis was performed to meet the requirements of the NNR as required by the IAEA SSR-6 document. Lastly, the bolt sizing and weld strength calculations were carried out.

ANSYS 2022 R2 software was used for the finite element analysis of the Overpack detailed design to calculate the stresses, deformations, reaction forces, temperatures, heat flux and linearized stresses due to imposed loads and boundary conditions.

In summary, the ultimate goal for achieving the stress of less than 20 MPa on the Pecron container was achieved during the drop test analysis, the transient thermal analysis resulted in the temperature of 22.3 °C which is less than 50 °C specified by the SSR-6, while 20 M12 Grade 8.8 bolts are found to be adequate for lifting the Overpack and can be reused after an accidental drop event of an Overpack.

2 INTRODUCTION

This report refines the final concept of a Pecron Cask Overpack that was developed in the concept report [1] to a detail design.

The following activities are carried out in this report:

- i. Simplification of the model, specifically the impact absorbing profiles for the ease of manufacturing,
- ii. Drop test analysis,
- iii. Static analysis,
 - a. Including lifting points, tie-down points
- iv. Vibration analysis- modal calculations
- v. Weld strength calculations
- vi. Bolt sizing calculations
- vii. Fire Test: Thermal calculation for the container and Overpack combination

2.1 Concrete Containers

Historical concrete containers, illustrated in Figure 1, manufactured for NTP (Pecron containers) do not meet NNR/Transport requirements in terms of the availability of process

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control information for the manufacturing process of the containers. There are more than 900 of these containers on Necsa site which need to be transported to Vaalputs [3]. The “Overpack” in combination with the Pecron container should comply with the IAEA transport requirements, SSR-6 [7], which will enable NLM to transport these packages to Vaalputs.

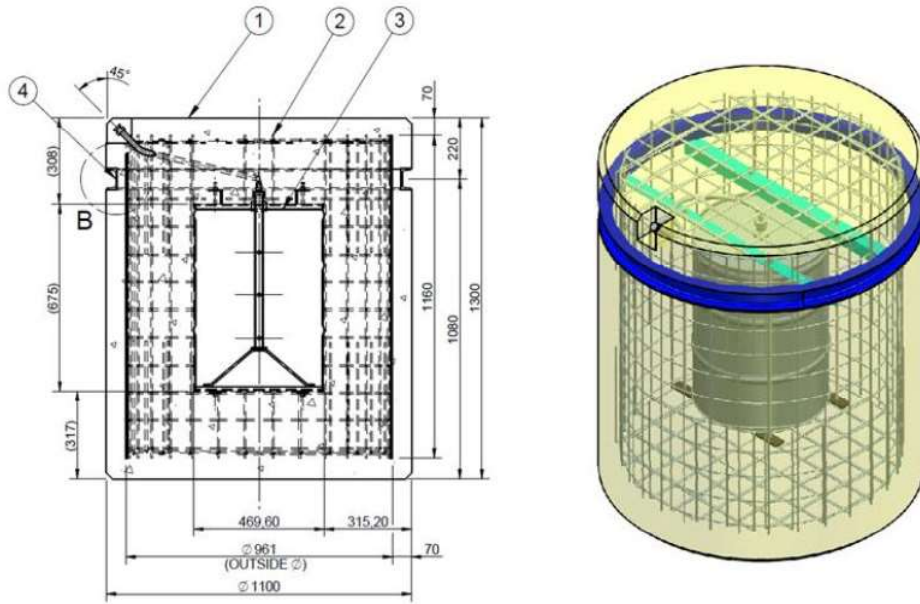


Figure 1: Concrete Cask dimensions (left) and model (right) [3]

2.2 Overpack

The Overpack will be used to contain the concrete container and it will be made of the five parts, the bottom and top lid, bottom and top inner and main shell. During transportation, the Overpack will be lifted onto the truck at Necsa and off-loaded at Vaalputs. The container will be packed into the overpack which will then be lifted into its transport position. The lifting points on the lid will allow for lifting onto the truck and for off-loading at the Vaalputs.

The model of the overpack which was developed during the concept design [1] will be further developed in this report to include the bolting, lifting points for handling and for ease of manufacturing.

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Document Title	Document No.	Rev
[1] Pecron Cask Overpack Concept Design	NM-17880-REP-0001	1.0
[2] Big Square Location Frame	PRE-ENG-REP-23001	1.0
[3] User Requirements Specification for an Overpack Conceptual Design for Concrete Containers	NLM-SPE-00035	00
[4] Accuracy of computational welding mechanics methods for estimation of angular distortion and residual stresses	J ZHU, M Khurshid, Z Barsoum	May 2019
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[6] Drawing NNDD-IP2TRANS-M-115	NNDD-IP2TRANS-M-115	1.0
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[8] Shigley's Mechanical Engineering Design	ISBN 978-0-07-352928-8	9 th Edition
[9] Design of Below-the-Hook Lifting Devices	BTH-1	2017
[10] ASME Boiler and Pressure Vessel Code, Section III, Appendices	ASME III, Appendices	2021
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[15] Eurocode 3: Design of Steel Structures- Part 1-2: General rules- Structural Fire Design	EN 1993-1-2	2005
[16] Eurocode 3: Design of Steel Structures- Part 1-9: Fatigue	EN 1993-1-9	2005
[17] ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Alternative Rules	ASME VIII, Div. 2	2019
[18] https://www.matweb.com/search/DataSheet.aspx?MatGUID=d5d5cd7c01b34df98f9466bfbc64236d	Material Property Data	26 August 2022
[19] ANSYS	Ansys Mechanical	Release 2022 R2

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Document Title	Document No.	Rev
[20] Structural Steel Connections: The Green Book		2012

4 DEFINITIONS AND ABBREVIATIONS

4.1 Abbreviations

Term	Definition
3D	Three Dimensional
ANSYS	A Finite Element Analysis Software Package
ASME	American Society for Mechanical Engineers
FEA	Finite Element Analysis
IAEA	International Atomic Energy Agency
ISO	International Organization for Standardization
Necsa	South African Nuclear Energy Corporation
NLM	Nuclear Liabilities Management
NNR	National Nuclear Regulator
NTP	Nuclear Technology Products
PSD	Power Spectral Density
URS	User Requirements Specifications

4.2 Nomenclature

Symbol	Definition	Units
a	M12 bolt diameter divided by 2	mm
A	Initial yield stress (based on 1/s strain rate)- Johnson Cook strength model	MPa
A _d	Major diameter of a fastener	mm ²
A _t	Tensile area	mm ²
A _v	Total area for the two shear planes	mm ²
b _e	Actual width of the plate	mm
b _{eff}	Effective width	mm
c	Bolt compression cone area	mm ²
C	Stiffness constant	-
C _p	Specific heat capacity	J/kg.°C
D ₁	Damage constant 1- Johnson Cook failure model	-
D ₂	Damage constant 2- Johnson Cook failure model	-
D ₃	Damage constant 3- Johnson Cook failure model	-
D ₄	Damage constant 4- Johnson Cook failure model	-

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Symbol	Definition	Units
D ₅	Damage constant 5- Johnson Cook failure model	-
d	Nominal major diameter	mm
D _h	Hole diameter	mm
d _m	Mean diameter	mm ²
d _r	Minor diameter	mm
d _p	Pitch diameter	mm
D _p	Pin diameter	mm
E	Modulus of elasticity	GPa
F _i	Pretension load	N
F _p	Proof load	N
F _u	Minimum ultimate strength	MPa
F _y	Minimum yield strength	MPa
g	Gravitational acceleration	m/s ²
l	Grip length	mm
l _d	Length of unthreaded portion of grip	mm
l _t	Length of threaded portion of grip	mm
m	Total mass of the Overpack	kg
N _d	Design factor	-
k _b	Bolt stiffness	MPa
k _m	Spring rate	MPa
w	Total weight of the Overpack	N
S _p	Proof strength	MPa
S _y	Yield strength	MPa
p	Bolt pitch	mm
P	Force on each bolt	N
P _b	Allowable single plane fracture strength	MPa
P _v	Allowable double plane shear strength	MPa
P _t	Allowable tensile strength through the pin hole	MPa
t	Plate thickness	mm
T	Required bolting torque	N.m
t ₁	Flange 1 thickness	mm
t ₂	Flange 2 thickness	mm
t _w	Washer thickness	mm
R	Actual plate width	mm
V	Volume of Pecron container	mm ³
ρ	Density of Pecron container	kg/m ³
σ _b	Tensile stress in the bolt	MPa
φ	Shear plane locating angle	°

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5 DESIGN INPUT INFORMATION

5.1 Overpack Diameter Spacing

The container has an outer diameter of 1100 mm. The spacing between the container and the overpack shall be 5 mm on each side totalling 10 mm. This spacing is applicable to each layer of the overpack and the locator [3].

5.2 Overpack Skirt Height

The skirt height should be such that it clears the depth of the locating ring. The locating ring shown in ref. [1] has a depth of 54 mm. Therefore, a skirt height of minimum 60 mm will be sufficient to clear the locating ring. The skirt height is also influenced by its ability to absorb impact. Therefore, a skirt height of more than 60 mm is desirable. During the concept design phase [1], a skirt height of 150 mm was found to be sufficient.

5.3 Cask Mass and Density

From a sample of 420 weighed Pecron containers the average measured container mass was found to be 4311 kg with a maximum of 4718 kg [3].

Using the concrete model as described in the Concept report, the mass of a Pecron container is 2855.6 kg. The density of the concrete model as described in the Concept report therefore needs to be adjusted to increase the mass to match that of what was measured.

The volume of a Pecron container is:

$$V = \pi \left(\frac{1.1}{2} \right)^2 \times 1.3 = 1.2354 \text{ m}^3$$

Using the maximum mass as reference, the density of a Pecron container is then:

$$\rho = \frac{4718 \text{ kg}}{V} = 3819 \frac{\text{kg}}{\text{m}^3}$$

5.4 Loading Scenarios

5.4.1 Drop Test

5.4.1.1 Drop Height

The total mass of the Overpack assembly is between 5000kg and 10000kg and therefore the drop height will be 0.9 m in accordance with SSR-6 [7].

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5.4.1.2 Drop Orientation

The drop orientation is such that the centre of mass of the Pecron Container is above its corner. The drop angle is then

$$\tan^{-1}\left(\frac{1.1}{1.3}\right) = 40.24^\circ$$

5.4.2 Fire Test

This analysis shall be based on the IAEA SSR-6 [7] thermal test, where the package is exposed to 800 °C for 30min followed by a cooling period until equilibrium is reached. The cooling period shall be no longer than 12 hours. The purpose of the thermal test is to impose on the package damage equivalent to that which would be observed if the package were to be involved in a severe accident.

5.4.3 Stacking

Two testing loads are applicable:

- A stacking test prescribed by SSR-6 [7]. It involves the stacking of 5 packages onto top of one another.
- Trench placement load.

5.4.4 Lifting of the Overpack Components, Contents and Assembly

All the components of the overpack, namely, the Top Lid, Top Inner, Shell, Bottom Inner and the Bottom Lid requires to be lifted in the following sequence prior the transporting the Overpack to the Vaalputs:

- i. Bottom lid lifting on the floor using eyebolts
- ii. Bottom inner lifting into the bottom lid using eyebolts
- iii. Pecron container lifting into the bottom inner using lifting clamp
- iv. Shell lifting using eyebolts
- v. Top inner lifting using the eyebolts
- vi. Top lid lifting using the lifting holes
- vii. And lastly bolting of the components to make it an overpack assembly before lifting it onto the transportation truck.

All these activities require stress/reaction forces analysis on the lifting points and bolt sizing calculations.

5.4.5 Retention Loads

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The tie down lugs of the Overpack must withstand the loads induced by the accelerations as specified in SSR-6 [7] which have been reproduced in Table 1.

Table 1: Acceleration Factors for the Package Retention System Design

Direction	Value	Unit
Longitudinal	2	g
Lateral	1	g
Vertical (Up)	2	g
Vertical (Down)	3	g

5.4.6 Tie Down Loads

The resultant forces of the tie-down points are calculated using Figure 2 below found in SSR-6 [7].

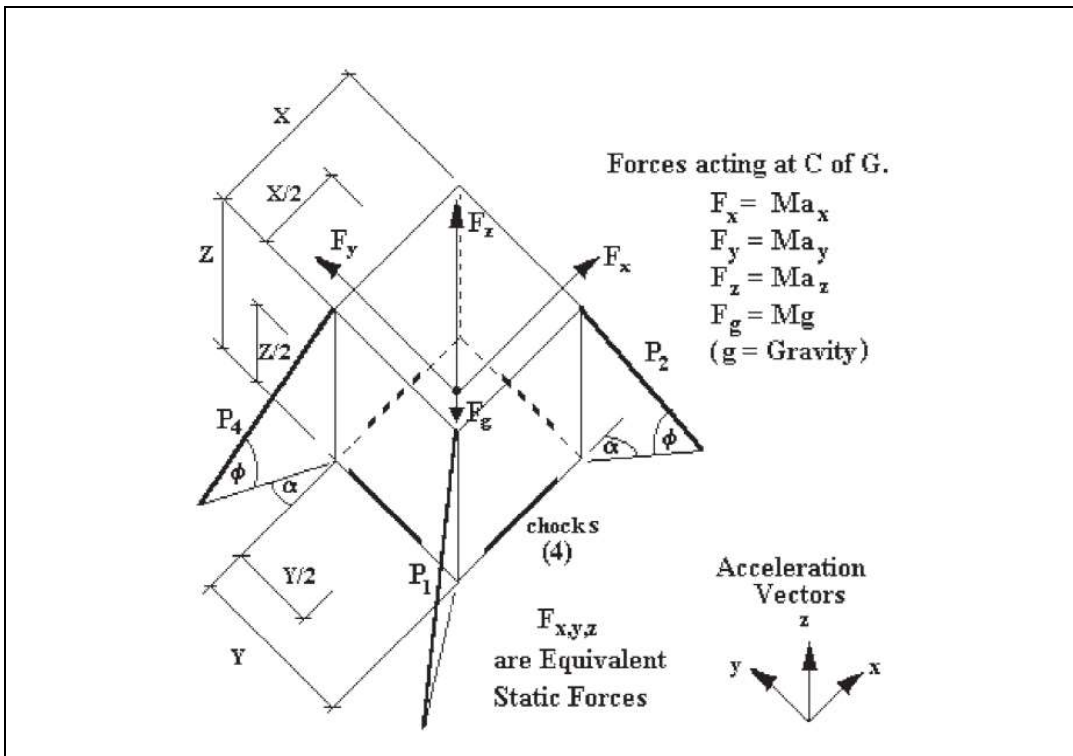


Figure 2: Graphical Depiction of Tensile Tie-Down System with Chocks

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Since the Overpack is cylindrical, dimensions X and Y as shown in Figure 2 is the same.

5.4.7 Fatigue Loading

The fatigue curve used for the carbon steel (S355J2G3) is selected from the Eurocode (EN 1993-1-9 2005 [16]) which is illustrated in the Figure 3. It is assumed that the curve remains flat as more loading cycles are applied. The curve flattens at a point of 110 MPa.

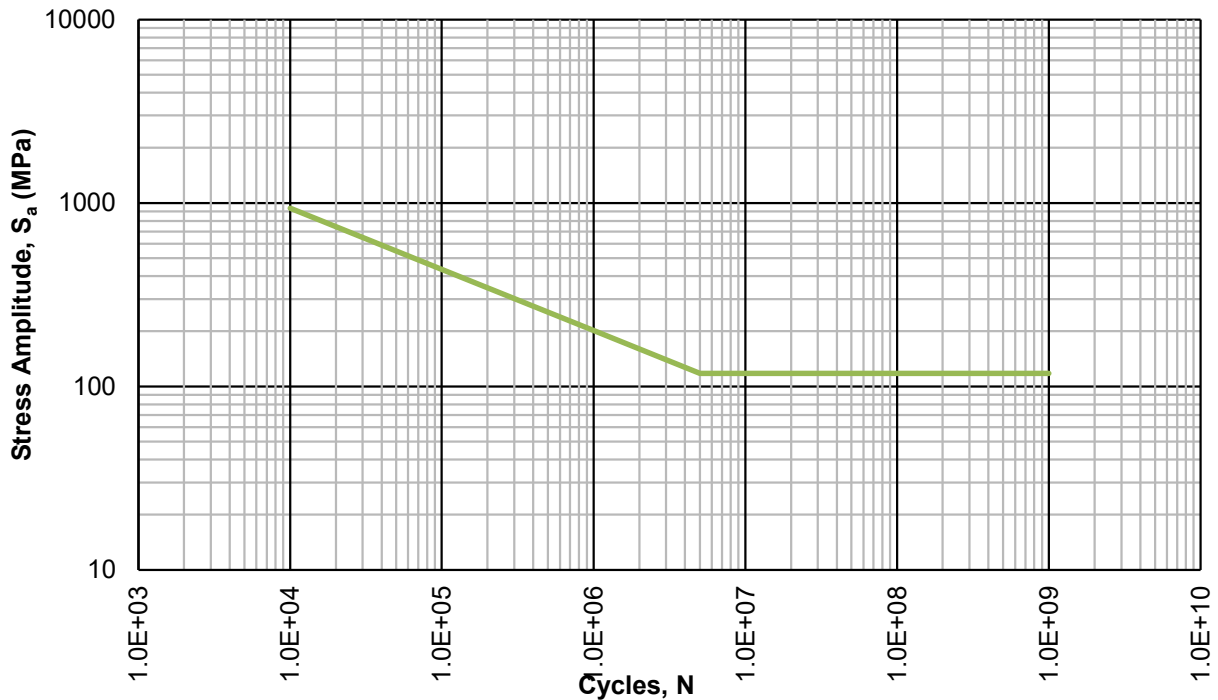


Figure 3: Fatigue Curve for S355J2G3

The fatigue curve used for the stainless steel (304/304L) is selected from ASME (ASME Section VIII, Division 2 [17]) which is illustrated in the Figure 4. It is assumed that the curve remains flat as more loading cycles are applied. The curve flattens at 94.7 MPa.

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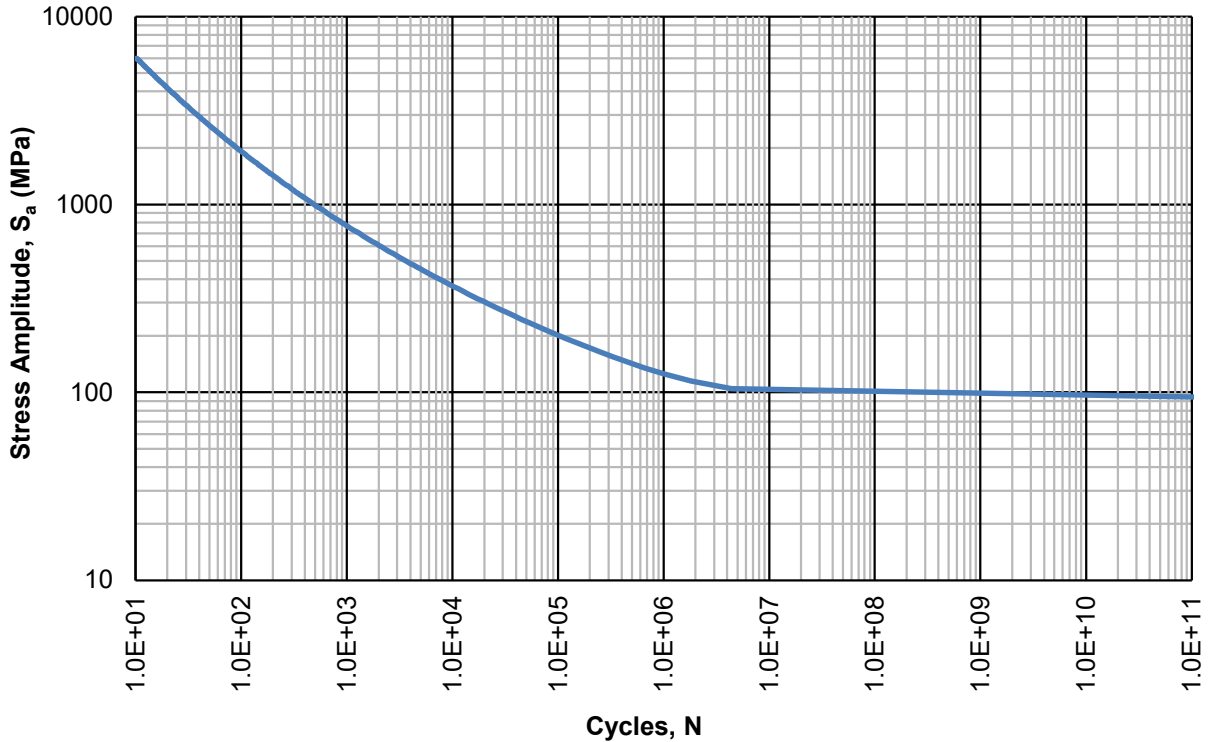


Figure 4: Fatigue Curve for Stainless Steel

5.4.7.1 Tie Down Points

Fatigue loading on the tie down points must be considered in accordance with IAEA regulations.

5.4.7.2 Vibration Loading

In order to simulate the vibration caused by the travel from Necsca to Vaalputs, a Power Spectrum Density (PSD) must be developed. The concept design report [1] addresses how the PSDs are developed.

The trip is broken into three different sections as presented in Table 2. The road conditions assumed are conservative.

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Table 2: Trip Schedule Based on Road Roughness Classification Data.

Description	Assumed ISO 8608 Road Class	Expected Vehicle Speed (km/h)	Segment Length (km)	Segment Duration (hh:mm)
Necsa to Brandvlei (N14)	C	80	60	00:45
N14 to Turn off	B	80	1040	13:00
Unpaved Section to Vaalputs	H	60	90	01:30

The PSDs for the sections are illustrated in Figure 5. These are then weighted by travel time spent in each section and added together to generate a single PSD for the total trip. The weighted PSDs are shown in Figure 6 and the PSD for the total trip is shown in Figure 7.

Power Spectrum Density for the Three Types of Road Roughness on the Trip

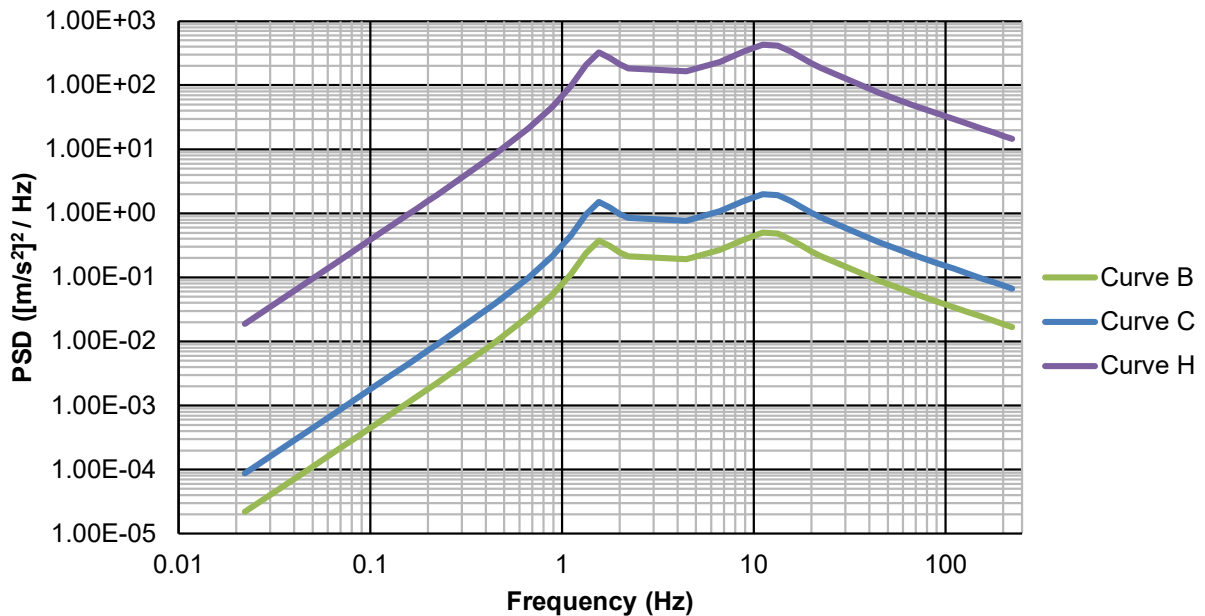


Figure 5: PSDs for the Three Types of Road Roughness Experienced on the Trip

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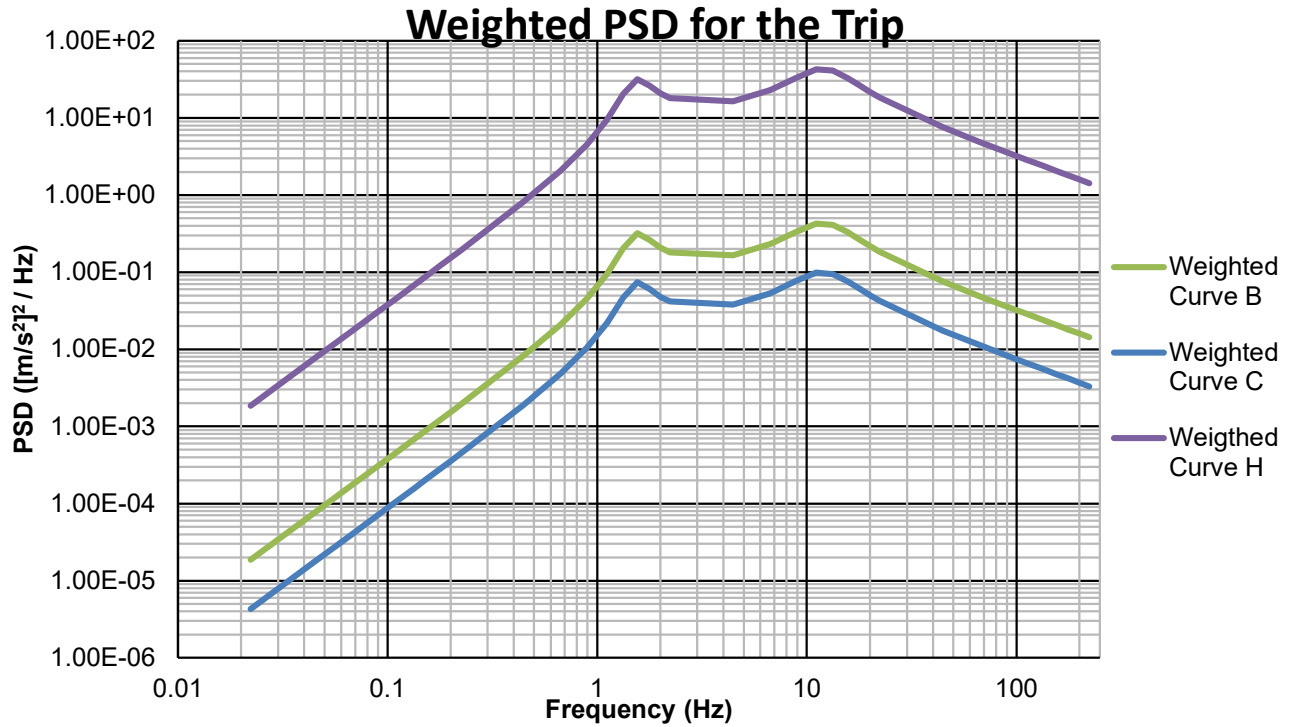


Figure 6: Weighted PSD for the Trip to Vaalputs

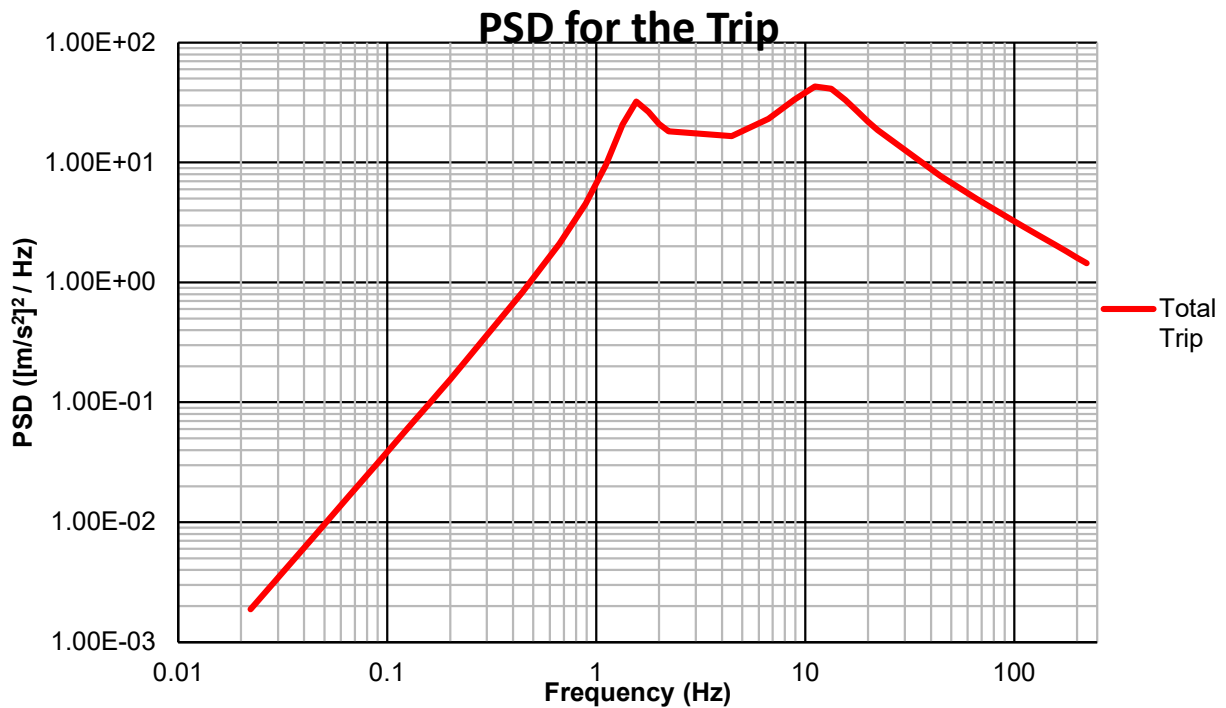


Figure 7: Total PSD for the Trip

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5.5 Design Acceptance Criteria

All of the following minimum requirements in Table 3 below shall be met for the design of an Overpack to be adequate.

Table 3: Design acceptance criteria

Design activity	Acceptance criteria	Reference
Drop test analysis	Maximum von Mises stress in the Pecron container should be less than 20 MPa at a distance of 300 mm from the 100 l solidification drum	URS [3]
	The maximum von Mises stress on the bolt should not exceed allowable/proof strength of the bolt	Shigley's Mechanical Design [8]
Thermal test analysis	The maximum temperature on the drum must be less than 50 °C	SSR-6 [7]
Lifting	The maximum von Mises stresses on the lifting holes shall not exceed the allowable stresses	ASME BHT-1 [9] ASME III [10]
	The maximum von Mises stress on the bolt should not exceed allowable strength of the bolt	Shigley's Mechanical Design [8]
Vibration	The maximum von Mises stresses on the Overpack shall not exceed the material allowable stresses and the stresses shall allow for a reasonable fatigue life	EN 1993-1-9 [16], ASME III [10]
Static	The maximum von Mises stresses on the Overpack shall not exceed the material allowable stresses	ASME III [10]
Tie-down	The maximum von Mises stresses on the Overpack shall not exceed the material allowable stresses and the stresses shall allow for a reasonable fatigue life	EN 1993-1-9 [16], ASME III [10]

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6 FINITE ELEMENT ANALYSIS

The overpack design was modelled (using dimensions found in Drawing [6]) in Design Modeller and analysed using Workbench of ANSYS 2022 R2 software [19]. The software has been verified for use on the computer described below and is presented in NM-DES-REP-0003 [5]. The computer has the Hostname VH-MES2 and the MAC address of D8-5E-D3-83-9B-B6

6.1 Models

A full 3D model of the Overpack and concrete container assembly was used for all load cases except the drop test. For the drop test, a half model was created using symmetry to reduce total elements and runtime time. The two models are shown in Figure 8.

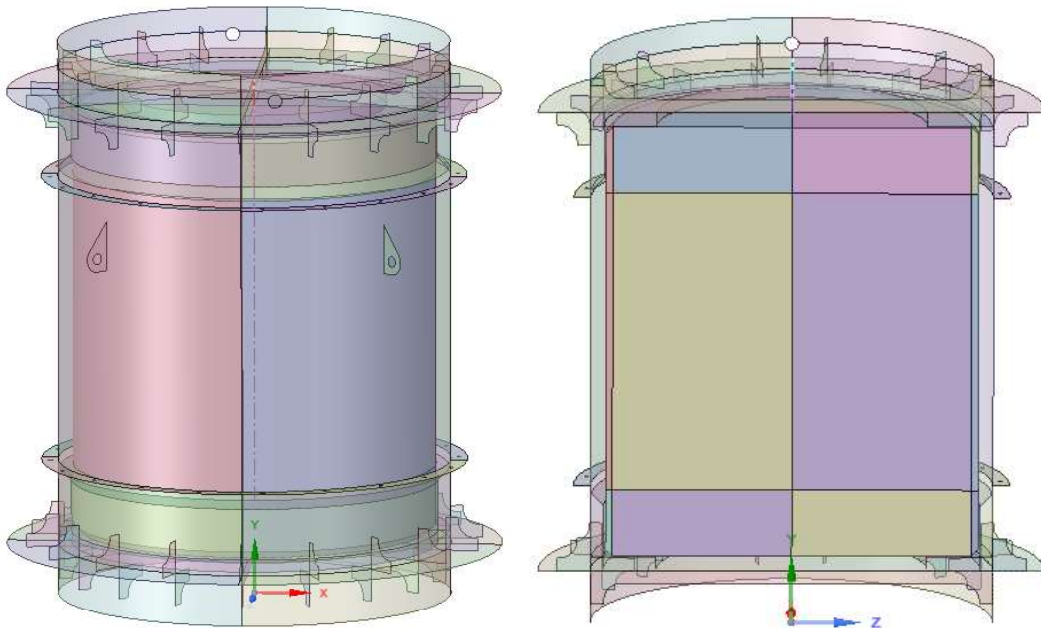


Figure 8: Overpack Full and Half Model

6.2 Drop Test Analysis

6.2.1 Modelling

Rotated to an angle of 40.2° relative to the X-axis, a half model of an Overpack was used in the drop test analysis with the ground surface modelled as a rigid body plate as shown in Figure 9. The numbers displayed in the image is the thickness of the elements.

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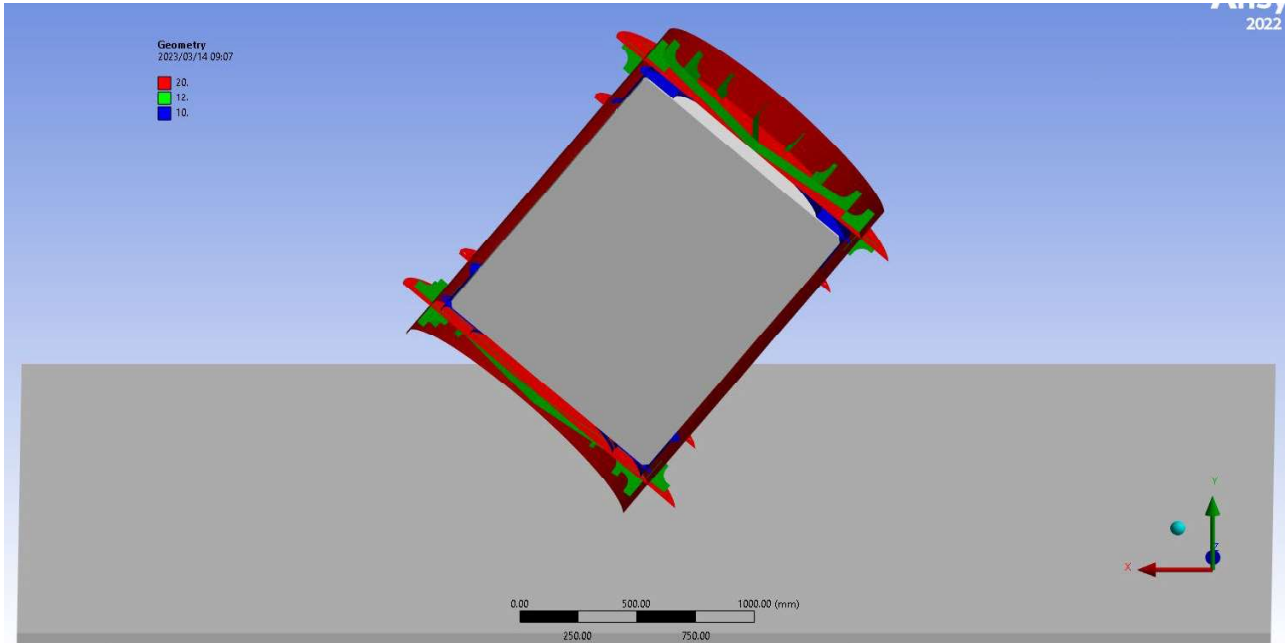


Figure 9: Drop Test Model

6.2.2 Mesh

A mesh size of 30mm was used on the container while the Overpack has a mesh size of 7 mm to 12 mm depending on the element. This has resulted in a model of 120181 nodes and 108386 elements. This mesh is shown in Figure 10.

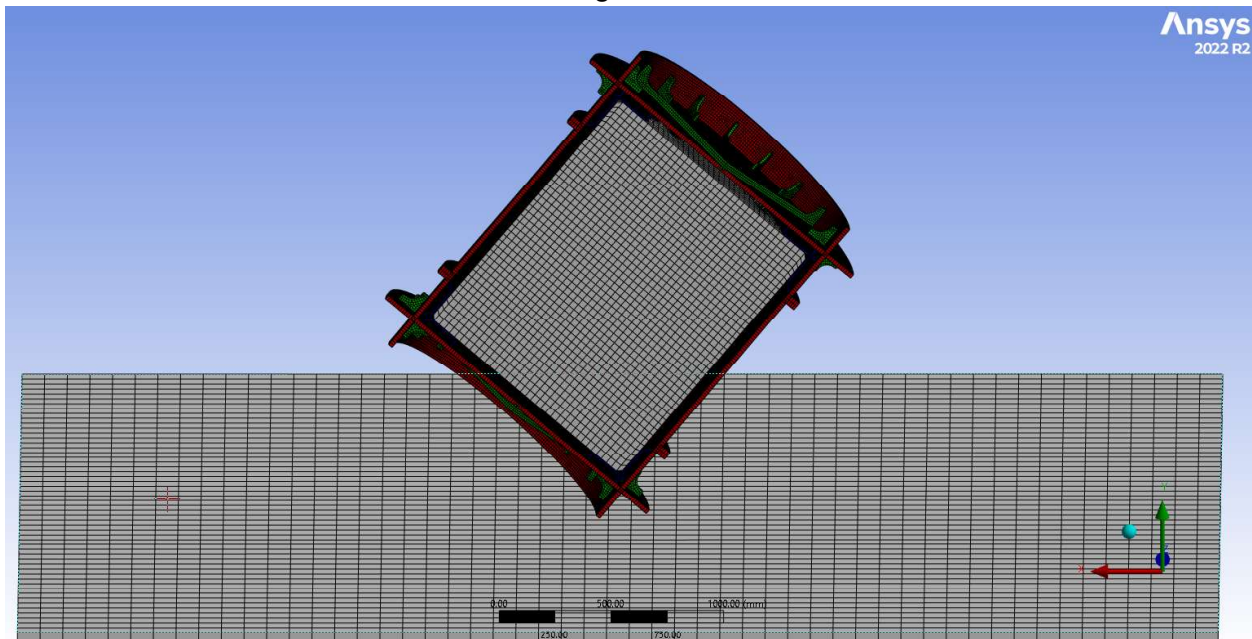


Figure 10: Mesh for Drop Test Analysis

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6.2.3 Materials

Drop test is an energy-limited event (strain-based) that requires the material characteristics that will vary with change in energy/temperature. Jonson-Cook method was found to be accurate in the concept development of an Overpack. The Johnson-Cook material model and failure model parameters are shown in Table 4 and Table 5 [1].

Table 4: Johnson-Cook model parameters [1]

Material Model Parameter	Value		Unit
	S355	304/304L	
A	448	208.22	MPa
B	782	1194.63	MPa
n	0.562	0.6097	Not Applicable
C	0.0247	0.022993	Not Applicable
m	0.45	0.5658	Not Applicable
$\dot{\epsilon}_{p0}$	1	1	1/s
T_r	20	25	°C
T_m	900	1450	°C
C_p	480	490	J/kg°C
ρ	7850	8030	kg/m ³
ϑ	0.3	0.31	Not Applicable

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Table 5: Johnson-Cook failure model parameters [1]

Material Model Parameter	Value		Unit
	S355	304/304L	
D_1	0.15	0.05	N/A
D_2	2	2.947	N/A
D_3	-1.5	-2.186	N/A
D_4	0.002	0.002	N/A
D_5	0.6	0.61	N/A

6.2.4 Loads and Boundary Conditions

The Overpack is dropped from a height of 0.9 m at a gravitational acceleration of 9.81 m/s² to a rigid surface.

6.2.5 Results

The acceptance criteria for the drop test (Table 3) is to have the stress in the concrete container be less than 20 MPa at 300 mm from the metal drum contained within. The equivalent stress in the container is shown in Figure 11. The red represents the areas in which 20 MPa is exceeded. From Figure 11, the furthest into the container where the stress is over 20 MPa, is 2.5 elements which is equivalent to 75mm. The following calculation shows that this is still 397.72 mm from the drum. This result is than accepted.

$$d = \sqrt{(315.20 - 75)^2 + (317)^2} = 397.72mm$$

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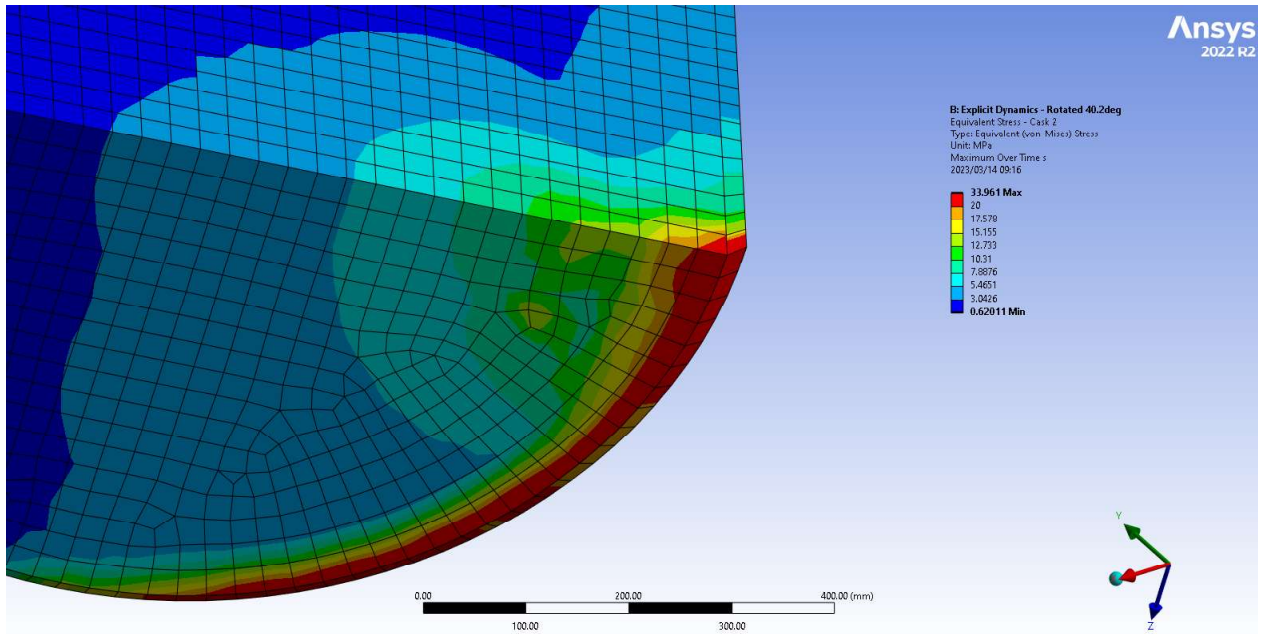


Figure 11: Equivalent stress on a concrete cask

The other aspect of interest is the stress found in the bolts. Figure 12 shows that the maximum stress in the bolt is found in the one closest to the ground and the stress is 432.8 MPa, which is significantly less than the 800 MPa ultimate failure strength of each bolt.

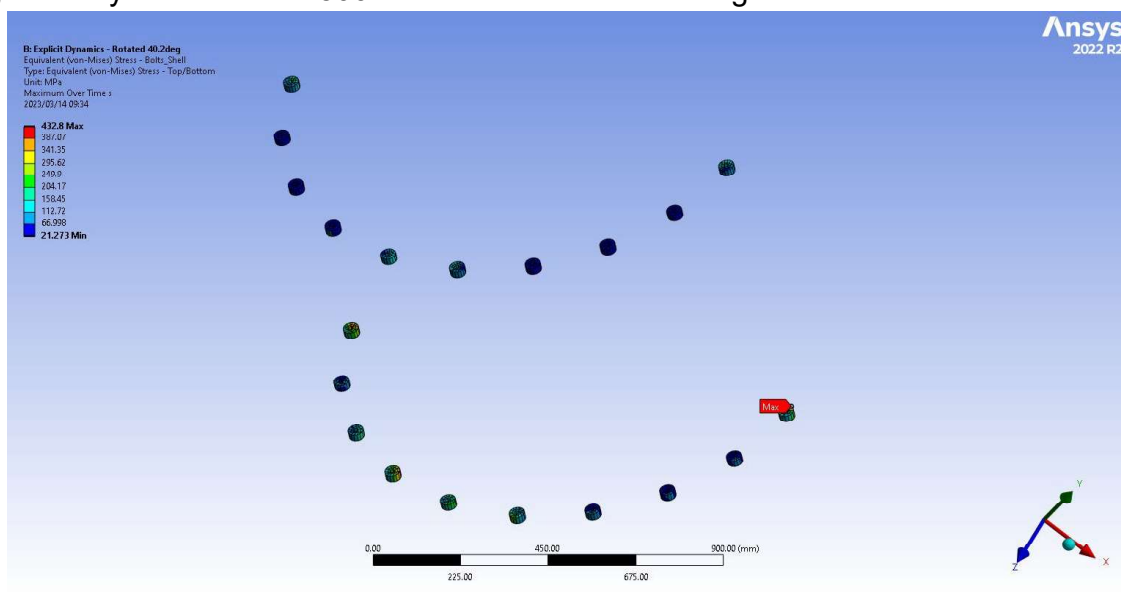


Figure 12: Stress in the Bolts

6.3 General Model

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The following model was used for the thermal, static, modal and PSD analyses. The full 3D model was used as shown in Figure 8.

6.3.1 Material Properties

The material properties at ambient conditions for structural steel S355, stainless steel 304/304L and Concrete are as follows:

Table 6: Material properties at ambient conditions [11], [12], [18].

Material property	S355	304/304L	Concrete
Modulus of elasticity (GPa)	210	195	30
Density (kg/m ³)	7850	8030	3820
Yield strength (MPa)	355	210	N/A
Tensile strength (MPa)	470	564	N/A
Thermal conductivity (W/m·K)	45	16.3	2
Specific heat capacity (J/g·°C)	0.48	0.5	1

6.3.2 Mesh Generation

The quadratic mesh was used with varying sizes depending on whether it is an area of interest. These areas of interests are any connection points and the impact absorbing fins. These areas were sized at 5 mm while the rest of the model was meshed at 30 mm. This resulted in the mesh seen in Figure 13. This resulted in a model of 389078 nodes and 213116 elements. A mesh convergence study was performed on the frequency of important modes and on the stress along a bottom rib. The findings are presented in Table 7 and Figure 14. The mesh is considered converged as the change in mesh does not relate a significant change in result.

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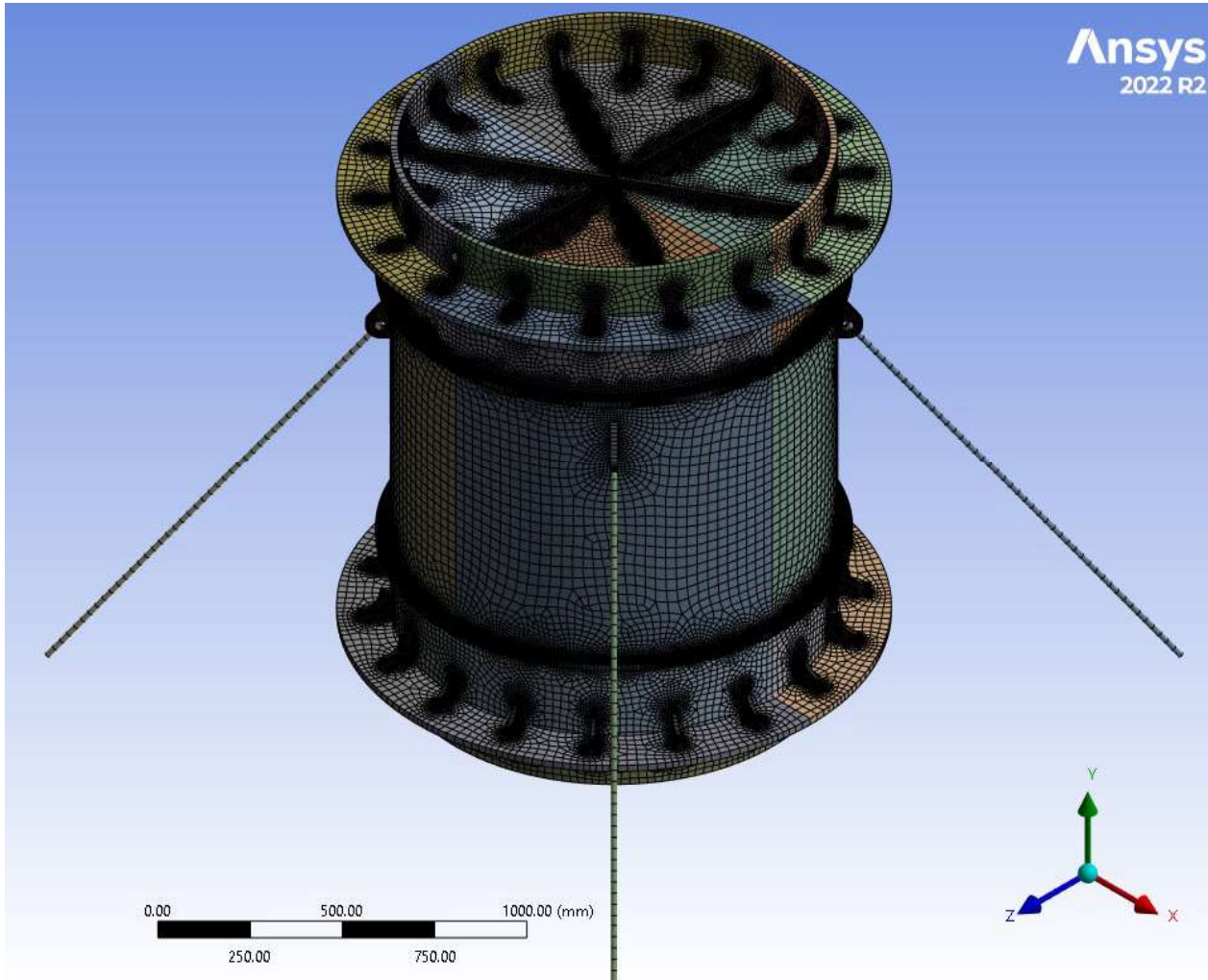


Figure 13: Mesh for Static, Vibration and Thermal Analysis

Table 7: Frequency Changes due to Mesh Size Changes

Mode	Mesh Size [mm] Frequency [Hz]				
	5	5>10	10	10 > 15	15
9	111.85	0.38%	111.42	0.07%	111.5
10	112.35	0.37%	111.93	0.10%	112.04
23	206.72	0.11%	206.49	0.15%	206.79
27	207.01	0.07%	206.86	0.40%	207.68

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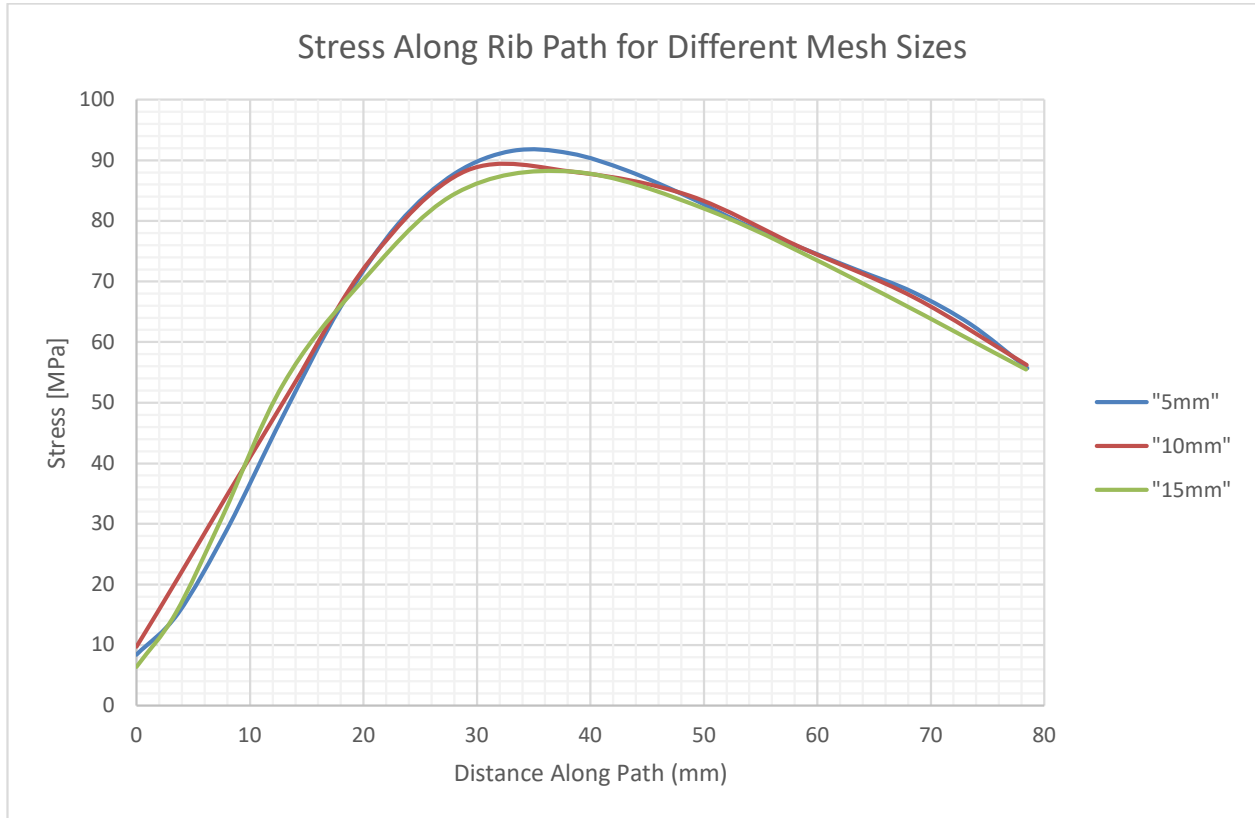


Figure 14: Stress along the Edge of a Support Rib

6.4 Thermal Analysis

Transient thermal analysis was performed using ANSYS code and it was carried out as detailed in this section. The modes of heat transfer such as Convection, Conduction and Radiation were considered.

6.4.1 Assumptions

- i. All the outside surfaces of an Overpack are subjected to a maximum temperature.
- ii. A thermal conductivity of S355 at minimum temperature was used, i.e., maximum thermal conductivity and therefore conservative results.
- iii. A constant specific heat capacity of concrete was used irrespective of temperature changes.
- iv. The inside surface of an Overpack is modelled as a blackbody radiating with an emissivity of 1, which is greater than 0.9 specified by the SSR-6, and therefore more conservative.
- v. The heat generation due to radiation inside the package is low enough to ignore [1].

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6.4.2 Thermal Loads and Boundary Conditions

As defined in Section 2, the outside surface of the Overpack was exposed to a temperature of 800 °C for 30 minutes followed by a cool of period. The inside surface of an Overpack was modelled as a radiation surface with an emissivity of 1.

The temperature-dependent material properties such as the thermal conductivity and the specific heat are defined as shown in APPENDIX D through APPENDIX F

6.4.3 Thermal Results

6.4.3.1 Temperature on the Inside of the Overpack

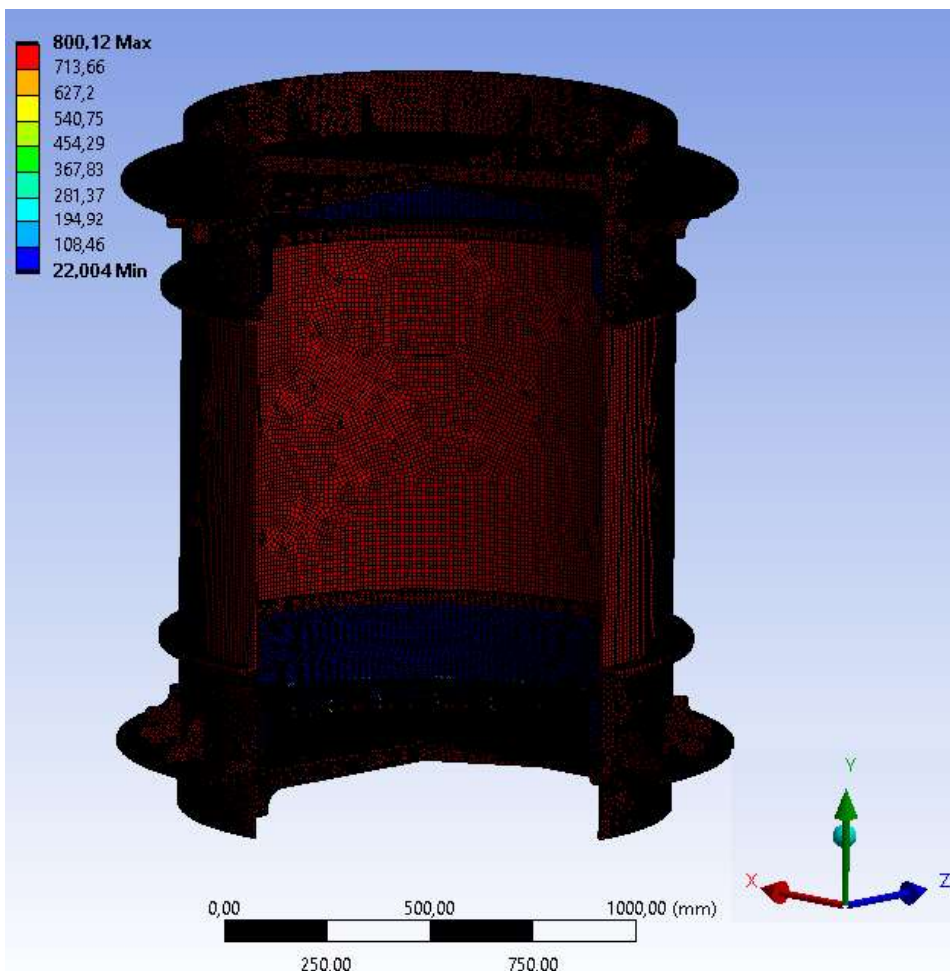


Figure 15: Resultant Temperature Distribution

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6.4.3.2 Temperatures on the Inners

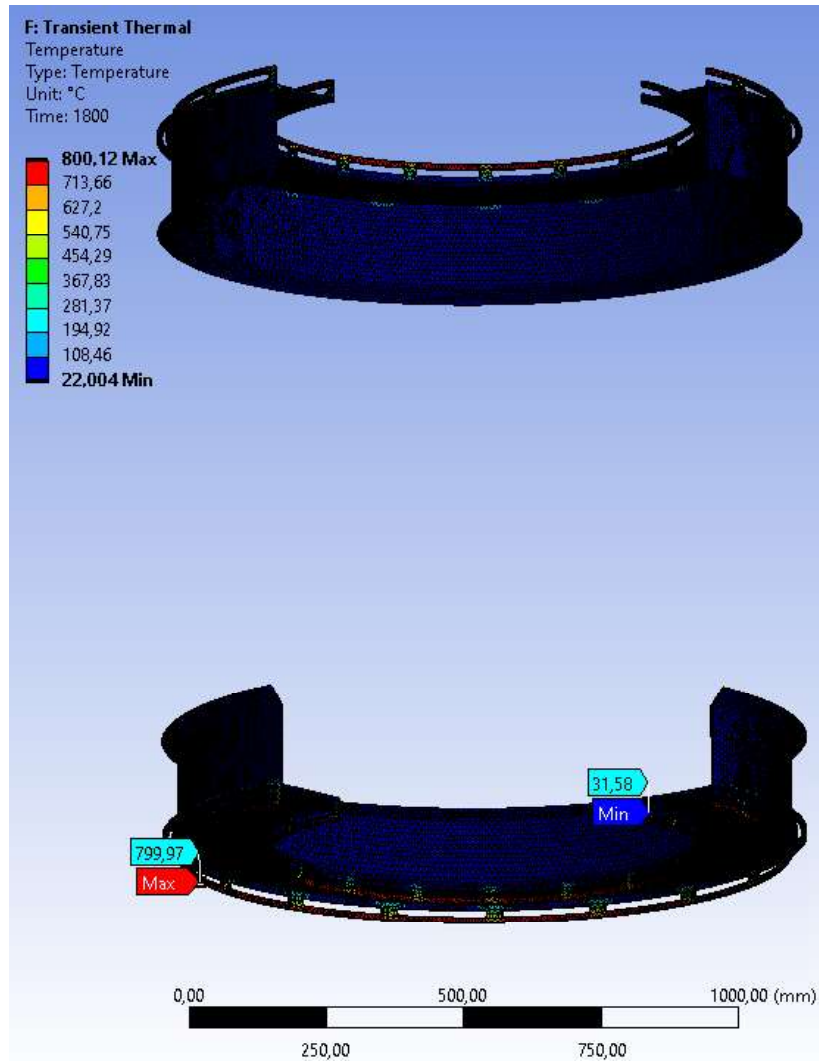


Figure 16: Maximum Temperature on the Bottom Inner due to Conduction

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6.4.3.3 Temperatures on the Concrete

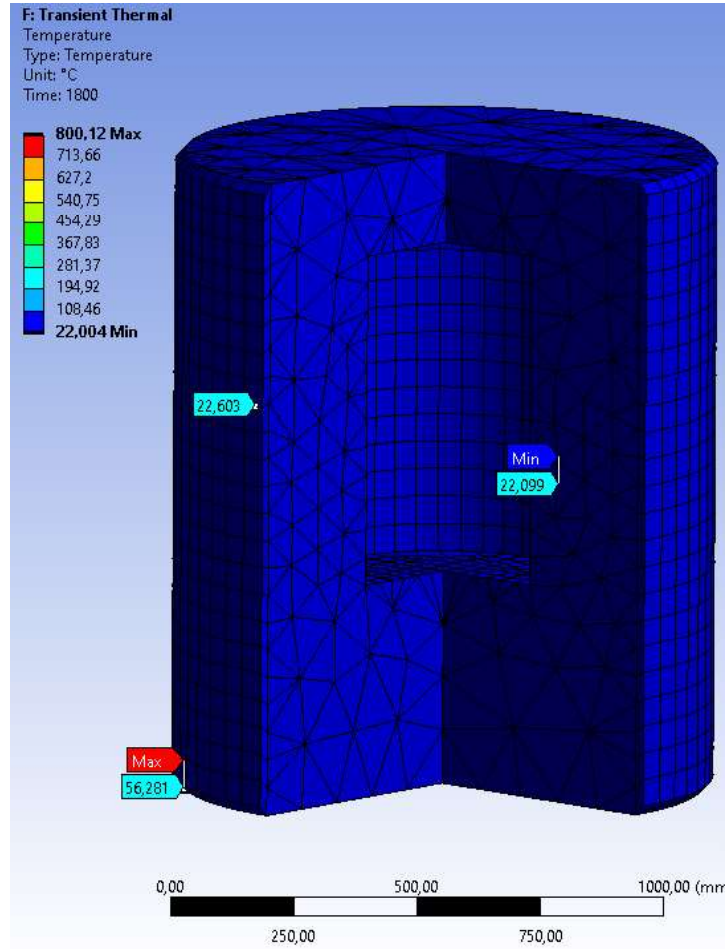


Figure 17: Maximum Temperature on the Drum

Table 8: Summary of thermal results

Location	Temperature (°C)
Overpack Outside Surface	800
Overpack Inside Surface	799.98
Concrete Outside Surface	56.28
Concrete Inside Surface	22.30

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Based on these results, the fire load will raise the temperature of the drum by 3 degrees Celsius which is acceptable.

6.5 Stacking Test

SSR-6 [7] specifies a compressive load of 5 times the mass of the actual package: thus $5 \times 6\,715\text{kg} = 33\,575\text{kg}$.

This mass is also conservative as the expected “real life” load in the trench at Vaalputs disposal site on the worst case container will be lower than the SSR-6 required test load as calculated below:

The Vaalputs trenches are 8m deep, and allow a waste fill height of 5.2 m. This means that the Overpacks (1.7 m high) will be stacked maximum 3 tiers inside the trench.

The Overpack weight with concrete container is 6 715kg.

Typical Vaalputs capping density is 1.8 g/cc. The total cap weight, and the non-used waste fill height weight, on top of a stack Overpack would be 5.99 ton (1.23 m diameter, 2.8 m cap height).

MAN tipper (single back axel), tare mass of 13 200 kg and sand load capacity of 6 300 kg. Thus the maximum point load will be below the back wheels when the sand is tipped. It is assumed that 70% of the total truck weight will be concentrated on the back axel during tipping (significant load needs to remain on the front wheels otherwise the truck will tip over backwards). Only one wheel can practically be positioned on a Overpack top surface. Thus maximum load on a back wheel:

$$(13\,200\text{ kg} + 6\,300\text{ kg}) \times 0.7 / 2 \text{ back wheels} = 6\,850\text{ kg}$$

Thus total trench placement load on the container in the bottom of the trench is calculated as follows:

$$\begin{aligned} &= 3 \times (\text{Overpack}) + \text{cap soil weight} + (\text{max load of capping equipment}) \\ &= 3 \times 6\,715\text{ kg} + 5\,985\text{ kg} + 6\,850\text{ kg} \\ &= 32\,980\text{ kg} \end{aligned}$$

It should be noted that this is a very conservative approach since the vertical load resistance due to the sideways pressure dispersion effect of soil above the submersed Overpack, as

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well as the lateral resistance of soil and other Overpacks beside the Overpack being analyzed is not considered.

Based on the above is the Stacking load of 5 Overpacks the most limiting.

The stacking test was performed by fixing the bottom edge of the Overpack and applying a force equal to 5 times the mass of the Overpack to the top edge of the Overpack. The equivalent stress is shown in Figure 18. This result is well within the allowable stress for the materials.

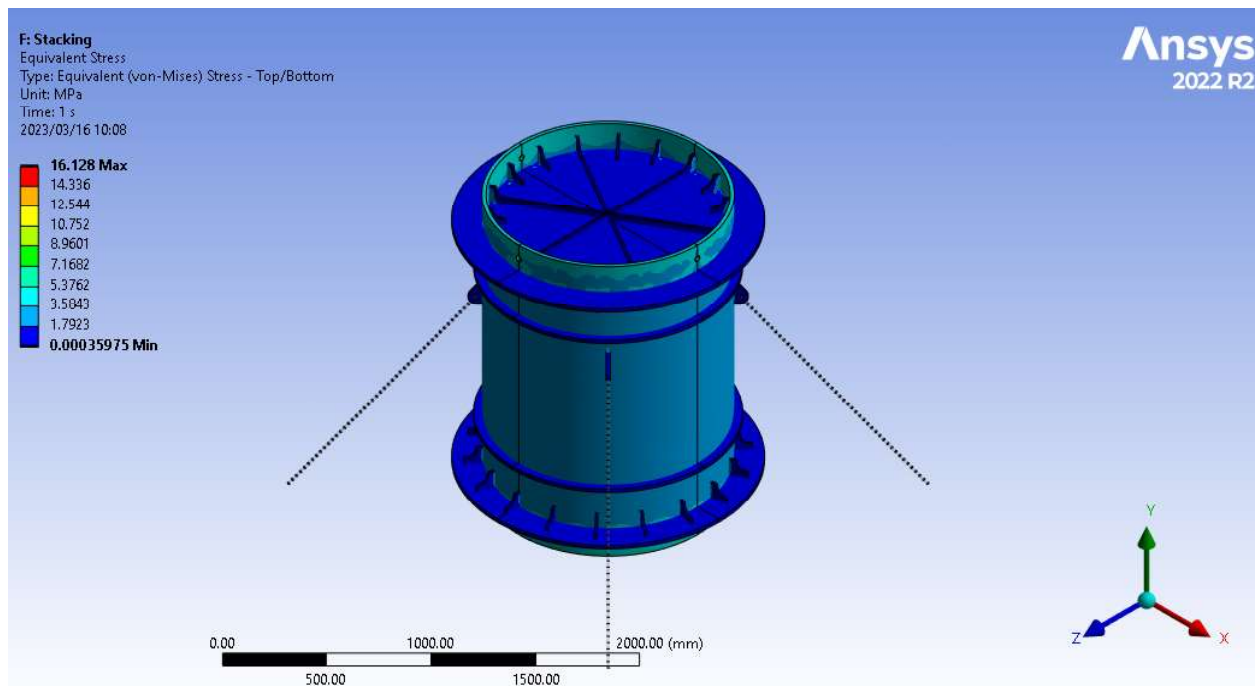


Figure 18: Stacking Test Results

6.6 Lifting Point Analysis

In this section, the lifting points of the bottom/top lid (601 kg each), shell (653 kg), top/bottom inner (115 kg each) will be analysed. This section deals with each individual part and the Overpack with container (as a whole. Section 7.1 performs a theatrical calculation on the main lifting points.

6.6.1 Assumptions

- i. The lifting of components listed in Section 6.6 will be on the ground
- ii. Four M12 Eyebolts will be used for lifting and are modelled as cylinders in the analysis.
- iii. All 4 Eyebolts will be equally lifting the load

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iv. The lifting from the bolts will be vertical

6.6.2 Loads and Boundary Conditions

For this analysis, the lifting points were fixed and the gravitational acceleration (-Y) was applied to represent the self-weight of the components.

6.6.3 Results

As the bottom and top lid are practically identical, only the bottom lid was analysed. The same applies to the bottom and top inner. The results of the analyses are presented in Table 9. Based on these values, the Overpack components can be lifted without issue.

Table 9: Summary of Lifting Results

Component	Equivalent stress (MPa)
Bottom lid	21.70
Bottom inner	12.04
Shell	18.70
Overpack with Container	16.54

6.7 Retention Loads

In this section, the retention loads described in Section 5.4.5 was applied to the model including the tie-down loads.

6.7.1 Boundary Conditions

Two load cases were considered in this section. Both load cases applied the horizontal accelerations in both directions. The difference between the two cases comes when applying the vertical accelerations. The first load case considered the downwards acceleration, while the second load case applies the upwards acceleration.

Each Tie-Down point has the tie-down load applied of 68.6 kN as calculated using the method described in SSR-6 [7].

6.7.2 Results

The results of both load cases can be seen in Figure 19 and Figure 20 for retention down and up respectively. This shows that the stress in the tie-down point is well below the allowable stress for S355 steel.

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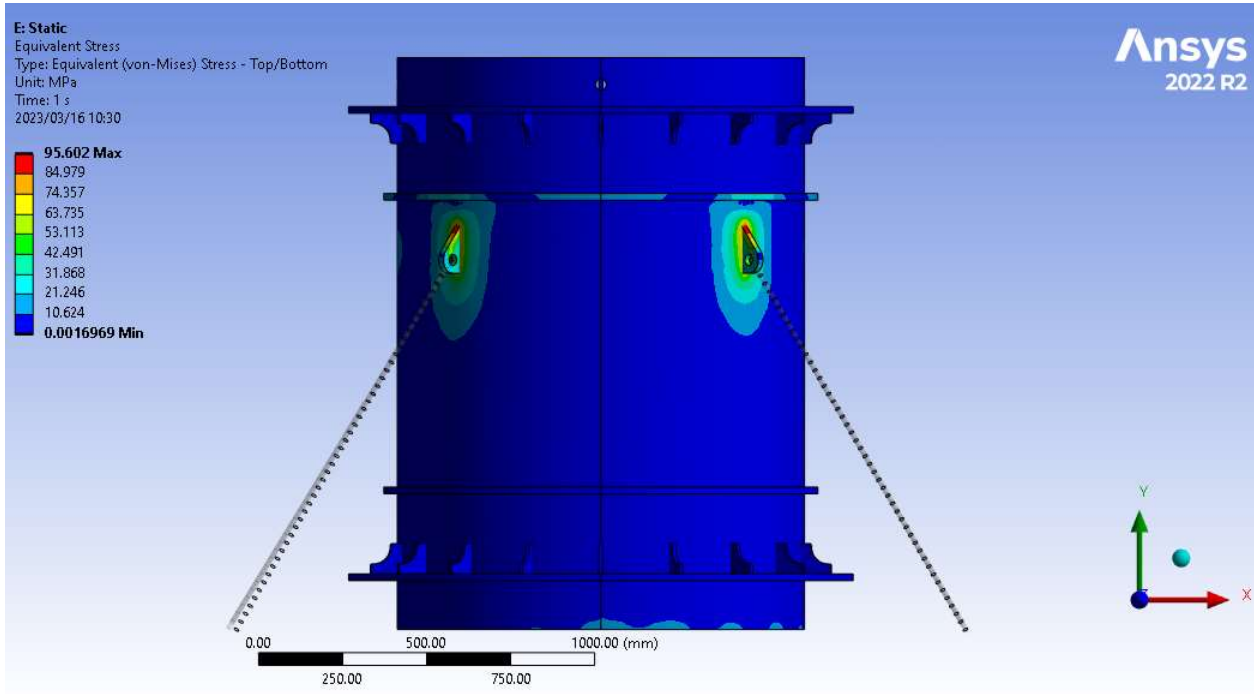


Figure 19: Retention Load Down Results

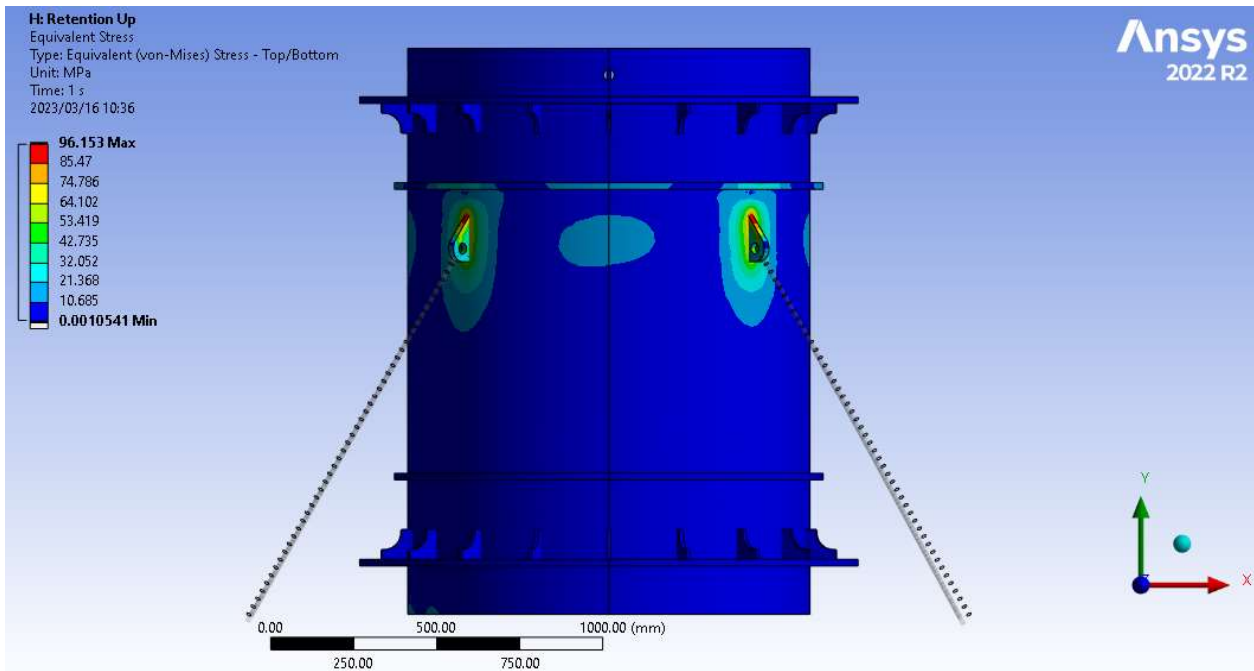


Figure 20: Retention Load Up Results

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6.8 Fatigue

In this section, fatigue was considered by checking the tie-down points and the full vibration analysis.

6.8.1 Tie-Down Points

The fatigue experienced by the tie-down points when considered independently does not represent a logical loading scenario as the tie-down loads will be experienced while traveling to Vaalputs. Therefore, this will be checked during the PSD analysis for the road roughness.

6.8.2 PSD Analysis for Vibration

The vibration analysis will be carried out by using a Power Spectral Density (PSD) analysis. The PSD curve was shown in Section 5.4.7.2.

6.8.3 Boundary Conditions

The base of the overpack is simulated to be fixed and the tie-down forces are applied to the tie-down points. A modal analysis, results found in APPENDIX A, was then performed in order to then perform the PSD analysis. The PSD curve was applied to the base.

6.8.4 Results

The results of the PSD analysis can be seen in Figure 21 and Figure 22 for the entire model and a targeted area of a rib on the bottom lid respectively. The results show that the stress in the bottom lid exceed the targeted 110 MPa for fatigue. A closer look at Figure 22 shows that the areas where the stress exceeds the target is at a discontinuity. This stress concentration can be ignored for two reasons. The first is that the area under consideration is a discontinuity which will always cause a concentration. The second reason is that this area will be welded. This will cause a thicker area of material which in turn will result in lower stresses. Regular tests on the welds in this area will ensure that it does not become an issue.

It should be noted that although these calculations indicate that the design life of the Overpack is effectively infinite except in the weld area of the support ribs, assumptions have been made regarding the road surface and the vibrations. Special care should be taken in the inspections of the Overpack after each trip.

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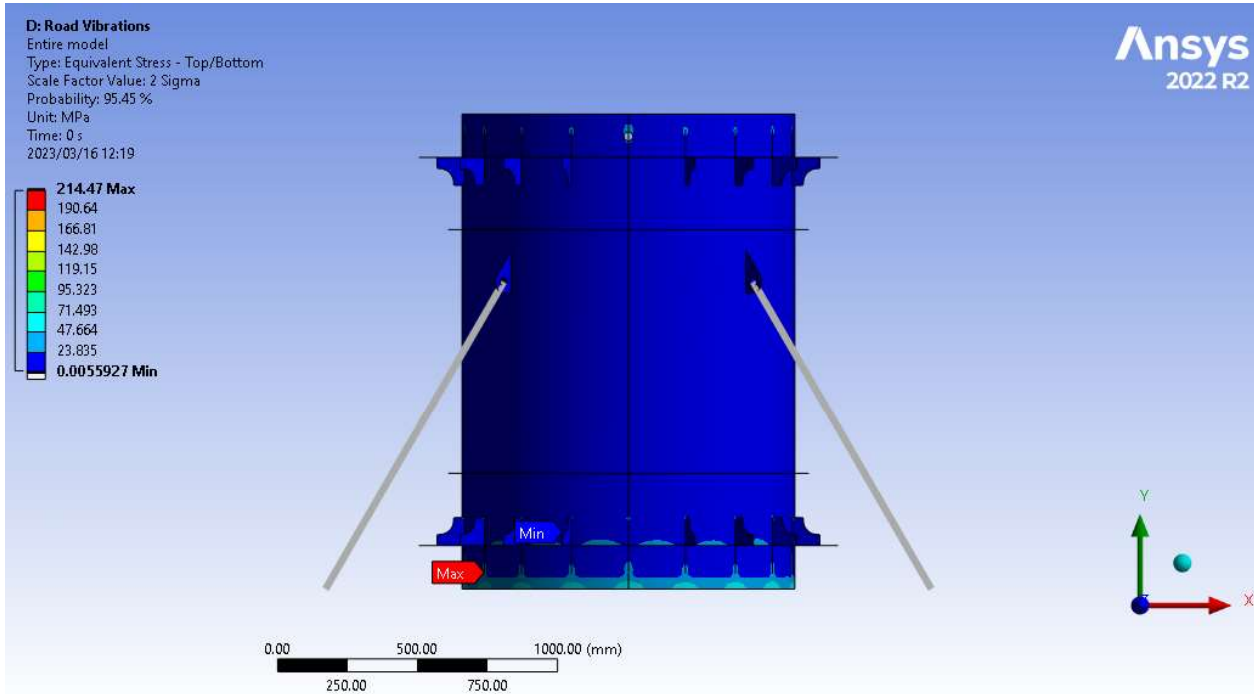


Figure 21: PSD Analysis Results of the Entire Model

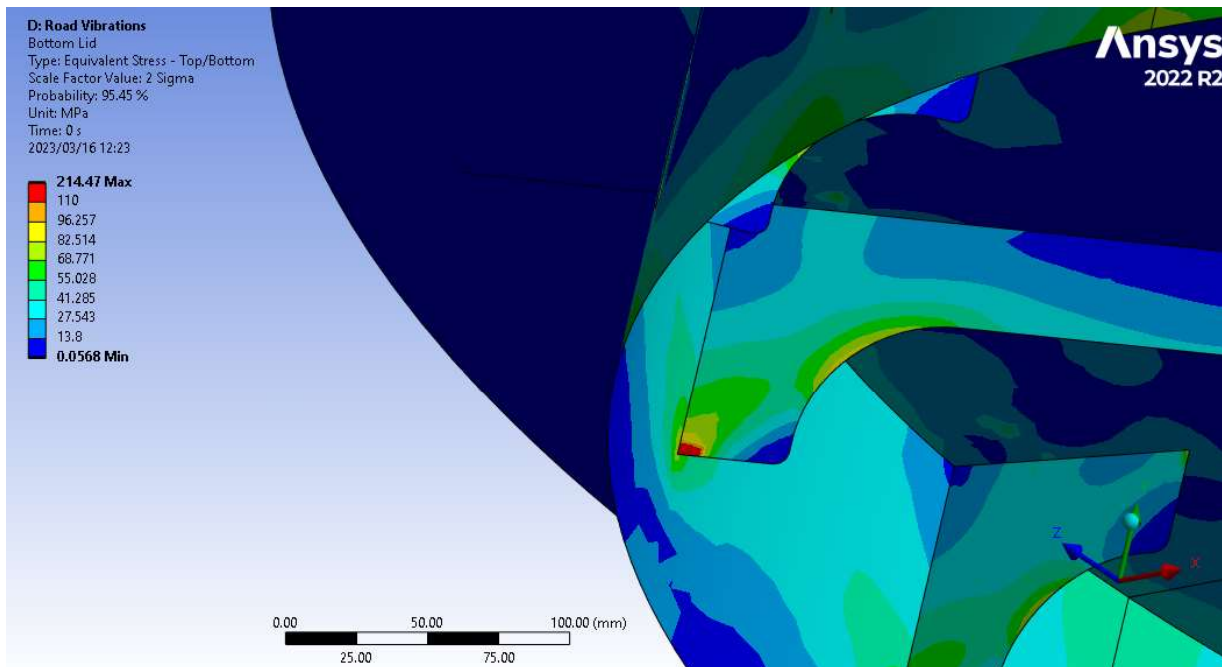


Figure 22: PSD Analysis Results Showing Area of Interest on the Bottom Lid

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7 THEORETICAL CALCULATIONS

7.1 Overpack Lifting Holes Sizing

The top lid of an Overpack will have 4 lifting holes with a diameter of 40 mm for loading and off-loading the Overpack.

ASME BTH-1 was used and the following assumptions were made:

- i. The pin diameter will be at least 38 mm
- ii. Two lifting points are used instead of all four and therefore conservative.
- iii. The load will be applied vertical, i.e., no bending of the top skirt plates.

See APPENDIX B for a detailed stress calculation on the lifting holes. The calculated force on each hole is 16.47 kN while the allowable force on each hole is 278.28 kN resulting in a safety factor of 16.9.

7.2 Weld Strength Calculations

Due to static loading of the Concrete container on the Overpack, the bottom inner (which is made of sub-parts welded) will experience the excessive loads in the welds. The weld strength calculation is carried out in detail in APPENDIX C. The applied stress is 21.51 MPa while the allowable stress is 56.0 MPa. This is a safety factor of 2.6.

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8 RECOMMENDATIONS

Due to the nature of the fatigue analyses, it is recommended that an inspection and testing schedule is put in place for the Overpack.

8.1 Inspections

Visual inspections shall take place after every trip. The visual inspection shall focus on the tie-down points, the support ribs on the bottom lid and the bottom inner. If there is any indication of damage, especially to the welds, non-destructive testing shall be carried out.

8.2 Testing

There shall be non-destructive tests carried out on all welds on the bottom lid, bottom inner and tie-down points after every 5 trips. All other welds shall be tested after every 10 trips. The frequency of the non-destructive testing frequency will be adapted based on operational performance of Overpack.

8.3 Bolting Torque

The bolts used on the Overpack are Ordinary Bolts as defined by the “Green Book [20]” and as such must be tightened to a “snug tight”. This is defined as “tight as an ordinary steelworker can tighten with an ordinary podger spanner or the normal setting on an impact wrench” [20].

8.4 Lifting Bolts

When lifting each of the components, all four lifting points shall be used. The lifting capacity of the four bolts together shall be larger than the weight of the component it is lifting.

8.5 Tie-Down Forces

The tie-down force applied to each tie-down point shall be 68.6 kN as calculated using SSR-6 [7].

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9 CONCLUSIONS

The detailed design of the Overpack is successfully carried out in this document and presented in Drawing NNDD-IP2TRANS-M-115 [6]. The different cases as outlined in the SSR-6, i.e., the drop test, fire test and static analysis were all considered in this design and the design of the Overpack proves to be adequate for different possible loading conditions.

Design activity	Acceptance criteria	Requirement Met?	Section
Drop test analysis	Maximum von Mises stress in the Pecron container should be less than 20 MPa at a distance of 300 mm from the 100 l solidification drum	Yes	6.2
	The maximum von Mises stress on the bolt should not exceed allowable/proof strength of the bolt	Yes	6.2
Thermal test analysis	The maximum temperature on the drum must be less than 50 °C	Yes	6.4
Lifting	The maximum von Mises stresses on the lifting holes shall not exceed the allowable stresses	Yes	6.6
	The maximum von Mises stress on the bolt should not exceed allowable strength of the bolt	Yes	6.6
Vibration	The maximum von Mises stresses on the Overpack shall not exceed the material allowable stresses and the stresses shall allow for a reasonable fatigue life	Yes	6.8
Static	The maximum von Mises stresses on the Overpack shall not exceed the material allowable stresses	Yes	6.7
Tie-down	The maximum von Mises stresses on the Overpack shall not exceed the material allowable stresses and the stresses shall allow for a reasonable fatigue life	Yes	6.8.1

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APPENDIX A MODAL ANALYSIS RESULTS

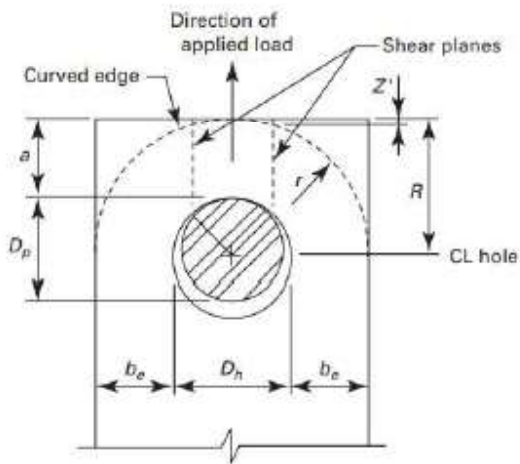
MODE	FREQUENCY [Hz]	MODAL MASS	X-DIR	RATIO%	Y-DIR	RATIO%	Z-DIR	RATIO%
1	36.64	0.003675	2.04E-03	0.03	3.03E-11	0.00	0.00	0.03
2	36.64	0.003835	2.75E-05	0.00	6.63E-13	0.00	0.00	0.00
3	36.64	0.00221	1.47E-03	0.02	5.51E-11	0.00	0.00	0.02
4	36.64	0.002172	5.78E-04	0.01	1.14E-11	0.00	0.00	0.01
5	36.71	0.005913	1.18E-04	0.00	2.62E-03	0.04	0.00	0.00
6	36.71	0.007285	6.79E-05	0.00	5.00E-05	0.00	0.00	0.03
7	36.71	0.00531	2.08E-03	0.03	1.19E-04	0.00	0.00	0.00
8	36.71	0.007976	2.83E-06	0.00	6.25E-09	0.00	0.00	0.00
9	111.90	0.1738	1.92E+00	28.59	1.70E-05	0.00	2.95	43.93
10	112.40	0.1191	2.92E+00	43.57	2.14E-05	0.00	1.90	28.35
11	114.80	0.003643	1.82E-06	0.00	6.34E-11	0.00	0.00	0.00
12	114.80	0.00342	4.51E-05	0.00	9.54E-10	0.00	0.00	0.00
13	114.80	0.003453	1.13E-02	0.17	1.45E-07	0.00	0.06	0.95
14	114.80	0.00376	8.14E-02	1.21	7.33E-07	0.00	0.02	0.33
15	115.00	0.008005	1.68E-05	0.00	4.29E-04	0.01	0.00	0.00
16	115.00	0.007784	6.95E-06	0.00	1.38E-08	0.00	0.00	0.00
17	115.00	0.00409	1.04E-02	0.16	6.10E-07	0.00	0.02	0.23
18	115.00	0.004382	2.52E-02	0.37	4.76E-07	0.00	0.02	0.25
19	206.40	0.003347	1.28E-09	0.00	8.00E-06	0.00	0.00	0.00
20	206.40	0.002806	6.01E-07	0.00	2.20E-05	0.00	0.00	0.00
21	206.40	0.001978	5.49E-08	0.00	4.84E-05	0.00	0.00	0.00
22	206.40	0.001743	4.31E-07	0.00	3.83E-05	0.00	0.00	0.00
23	206.70	0.01111	2.22E-05	0.00	2.15E+00	31.99	0.00	0.00
24	206.80	0.005334	2.71E-05	0.00	3.95E-04	0.01	0.00	0.00
25	206.80	0.005215	3.98E-07	0.00	6.98E-06	0.00	0.00	0.00
26	206.80	0.006566	6.51E-09	0.00	2.12E-05	0.00	0.00	0.00
27	207.00	0.01783	3.48E-05	0.00	3.40E+00	50.58	0.00	0.00
-----	-----	-----	-----	-----	-----	-----	-----	-----
sum			4.98	74.16	5.549	82.63	4.979	74.13

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APPENDIX B LOADED OVERPACK LIFTING POINTS DESIGN

LOADED OVERPACK LIFTING POINTS DESIGN

Thickness Calculations:



ASME BTH-1: 2017

3-3.3 Pinned Connections

1. Static Strength of the plates

Material := S355JR

Minimum Ultimate strength $F_u := 470 \text{ MPa}$

Minimum Yield strength $F_y := 355 \text{ MPa}$

For Design Class A,

Design factor $N_d := 2.0$

Plate thickness $t := 20 \text{ mm}$

Hole diameter $D_h := 40 \text{ mm}$

Actual width of the plate $b_e := 50 \text{ mm}$

$$R := b_e + \frac{D_h}{2} = 0.07 \text{ m}$$

Effective width is calculated as follows:

$$b_{eff1} := 4 \cdot t = 0.08 \text{ m}$$

$$b_{eff2} := b_e \cdot 0.6 \cdot \frac{F_u}{F_y} \cdot \sqrt{\frac{D_h}{b_e}} = 0.0355 \text{ m}$$

Total mass to be lifted $m := 6715 \text{ kg}$

Gravity $g := 9.81 \text{ m s}^{-2}$

Vertical Force $W := m \cdot g = 65874.15 \text{ N}$

Number of lifting holes $n := 4$

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$$b_{eff} := b_{eff2} = 0.0355 \text{ m}$$

smallest of the two, beff1 & beff2

Allowable Tensile Force through the Pin Hole

$$P_t := \frac{F_u}{1.2 \cdot N_d} \cdot 2 \cdot t \cdot b_{eff} = 278.2802 \text{ kN}$$

Allowable single plane fracture strength

$$P_b := \frac{F_u}{1.2 \cdot N_d} \cdot \left(1.13 \cdot \left(R - \frac{D_h}{2} \right) + \frac{0.92 \cdot b_e}{1 + \frac{b_e}{D_h}} \right) \cdot t = 301.3657 \text{ kN}$$

$$a := b_e = 0.05 \text{ m} \quad \text{Pin diameter} \quad D_p := 38 \text{ mm}$$

Shear plane locating angle

$$\phi := 55 \text{ deg} \cdot \frac{D_p}{D_h} = 0.9119$$

Total area for the two shear planes

$$A_v := 2 \cdot \left(a + \frac{D_p}{2} \cdot (1 - \cos(\phi)) \right) \cdot t = 0.0023 \text{ m}^2$$

Allowable double plane shear strength

$$P_v := \frac{0.7 \cdot F_u}{1.2 \cdot N_d} \cdot A_v = 314.5672 \text{ kN}$$

The actual force in each hole is

$$P := \frac{F}{n} = 16.4685 \text{ kN}$$

The smallest strength is due to tension and is therefore used to calculate the safety margin as follows,

$$SF := \frac{P_t}{P} = 16.9$$

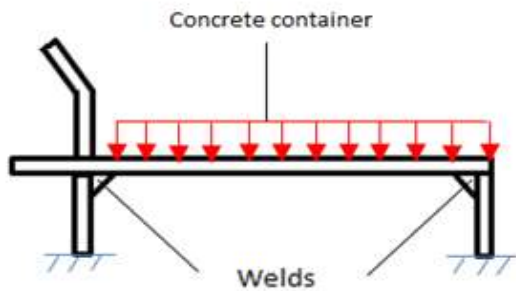
The Bearing stress was not considered as this design is Service Class 0

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APPENDIX C WELD STRENGTH CALCULATIONS

This calculation assumes that all the weight is on the inner weld and on no other. Even with this conservative assumption, the weld stress is less than the allowable.

Weld Strength Calculations- Static

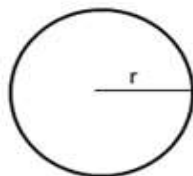


Mass of the concrete $m := 5000 \text{ kg}$

Gravitational acceleration $g := 9.81 \frac{\text{m}}{\text{s}^2}$

Weight

$W := m \cdot g = 49050 \text{ N}$



Radius to a circumferential weld $r := 403 \text{ mm}$

Weld throat $h := 4 \text{ mm}$

$A_w := 1.414 \cdot r \cdot h = 0.0023 \text{ m}^2$

Stress on the weld

$\tau := \frac{W}{A_w} = 21.5191 \text{ MPa}$

+

Yield stress $S_y := 140 \text{ MPa}$

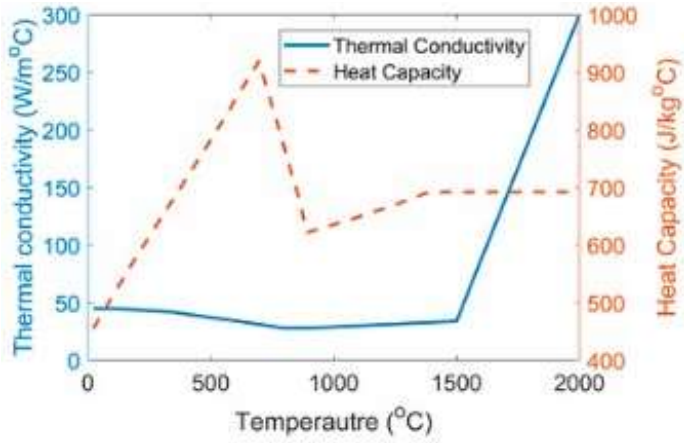
Allowable stress

$\sigma_A := 0.4 \cdot S_y = 56 \text{ MPa}$

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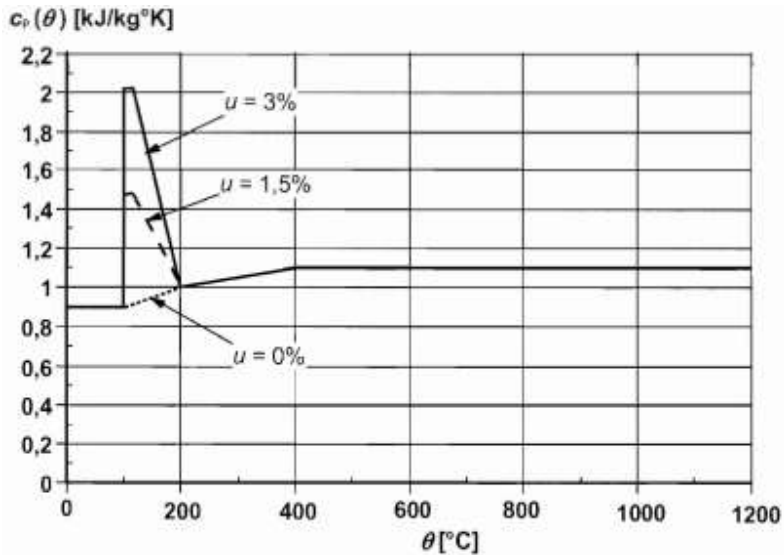
APPENDIX D THERMAL CONDUCTIVITY AND SPECIFIC HEAT OF S355 STEEL AS A FUNCTIONS OF TEMPERATURE



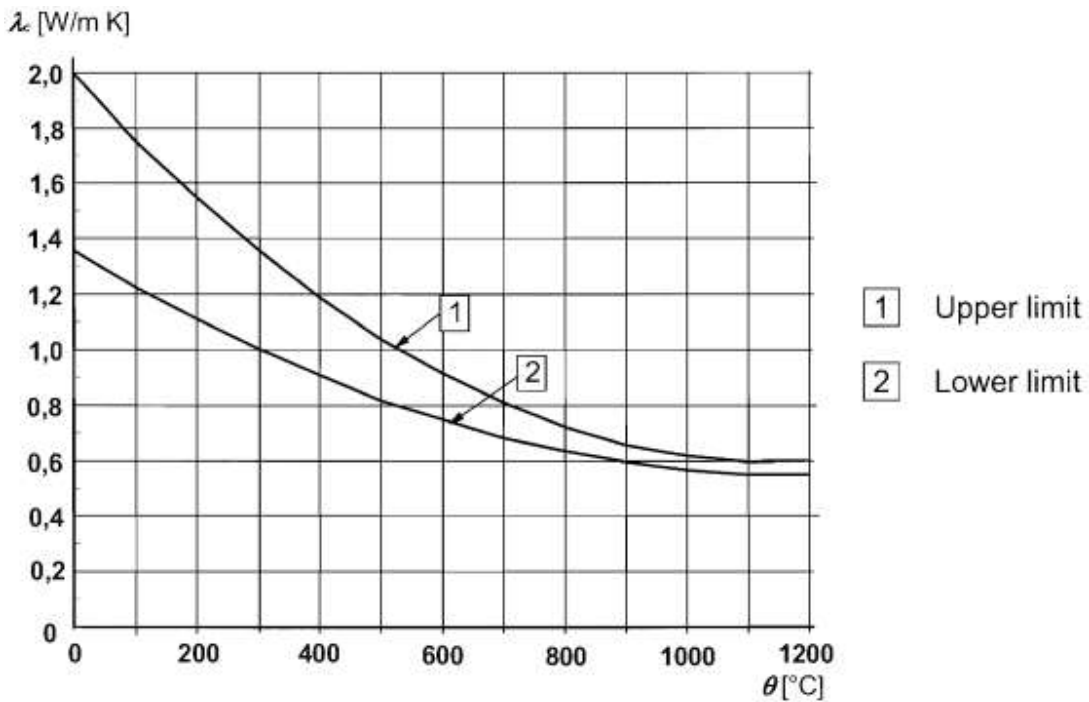
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APPENDIX E THERMAL PROPERTIES OF CONCRETE AS A FUNCTION OF TEMPERATURE

E.1 SPECIFIC HEAT OF CONCRETE AS A FUNCTION OF TEMPERATURE



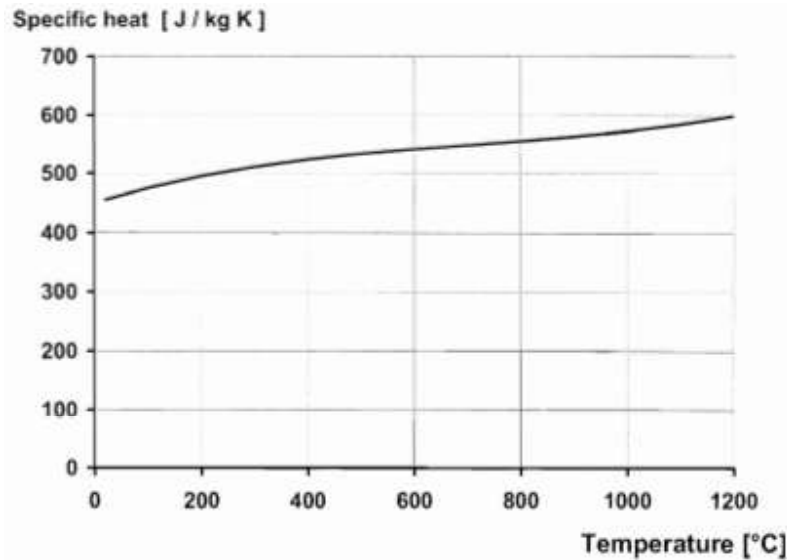
E.2 THERMAL CONDUCTIVITY OF CONCRETE AS A FUNCTION OF TEMPERATURE



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APPENDIX F THERMAL PROPERTIES OF STAINLESS STEEL AS A FUNCTION OF TEMPERATURE

F.1 SPECIFIC HEAT OF STAINLESS STEEL AS A FUNCTION OF TEMPERATURE



F.2 THERMAL CONDUCTIVITY OF STAINLESS STEEL AS A FUNCTION OF TEMPERATURE

