Gurit
Engineered Structures

Technical Report

Hemo Gorge Sculpture

Design Report

GU6706-6002 A1

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Issue and Amendments

ISSUE	AMENDMENTS	DATE	APPROVED	INITIAL
A	First Issue	5/06/2019	Thomas Basset	T.B.
A1	Minor updates to reflect design basis revision change	2/02/2021	Thomas Basset	T.B.

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Summary

Kilwell Fibretube is to build a composite sculpture for installation as the centre artwork in the recently completed Hemo Gorge traffic roundabout at the southern entrance to Rotorua, New Zealand.

The sculpture consists of a series of concentric spiral forms constructed from braided and unidirectional carbon fibre and e-glass reinforcements over a 3d printed non-structural former.

The sculpture will be submitted for building consent.

This present report summarises the structural performance of the sculpture against the requirements set out in 'GU6706-6002 Rev A Hemo Gorge Sculpture Design Basis Report.pdf'.

The composite parts of the structure have been shown to meet or exceed the requirements set out in the Design Basis Report.

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1. Introduction

The spiral sculpture shown in Figure 1 has been selected as the centrepiece for a new roundabout at the Hemo Gorge intersection in Rotorua. The sculpture is 12m tall and consists of multiple interconnected spiral tubes. The tubes are separated into inner and outer sets, with internal diameters of 100 and 150mm respectively. Adjacent tubes are connected via small chevron shaped plates interspersed along their length. Additional support is provided by short connecting tubes where the main spiral tubes cross each other. Four decorative/carved panels will be attached in the openings between the tubes as shown below.

The tubes are constructed using woven e-glass and carbon sock and carbon unidirectional reinforcements, laminated over a male former.

Kilwell Fibretube Ltd are manufacturing and assembling the sculpture at their Rotorua factory, before transporting it (while assembled) to the installation site.

This report documents the global analysis undertaken to validate the structural performance of the sculpture. The structural analysis has been undertaken using a Limit State Design approach, using factors defined in the Gurit report: 'GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf'.

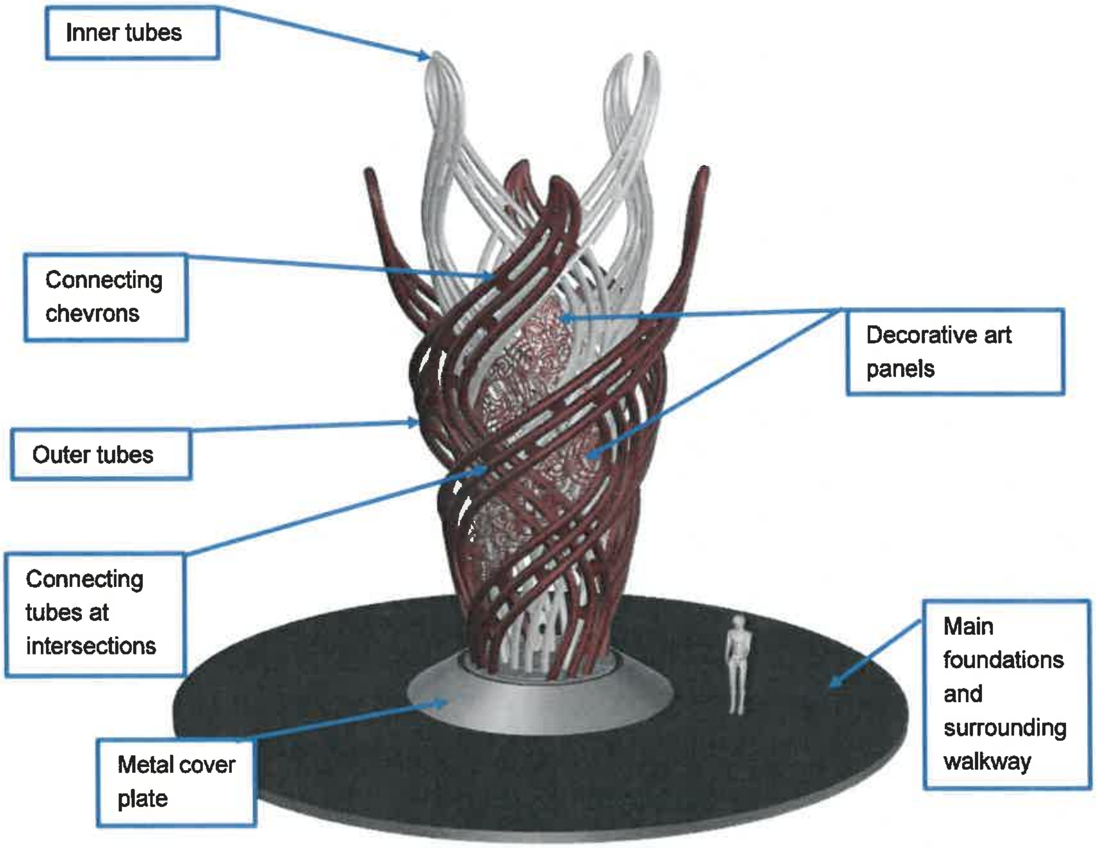

Figure 1. Sculpture general arrangement

2. Summary of Results of Global Analysis

A summary of the design criteria, results of the global analysis and reserve factors is given below.

Load State	Criteria		Value Achieved	Reserve factor
	Description	Requirement		
ULS long-term	Material ultimate strength	Material utilisation <1.0	0.99	1.01
	Buckling stability	Load factor >1.5	76.0	50.7
ULS short-term	Material ultimate strength	Material utilisation <1.0	0.99	1.01*
	Buckling stability	Load factor >1.5	6.55	4.37
ULS accidental	Material ultimate strength	Material utilisation <1.0	0.99	1.01*
	Buckling stability	Load factor >1.5	5.84	3.89
SLS	Principal strain	<0.45%	0.34%	1.33
	Proof test standard chevron	Withstand SLS loading	Passed	2.59
	Proof test through chevron	Withstand SLS loading	Passed	2.00
	Proof test tube connection	Withstand SLS loading	Passed	2.99
	Proof test base fitting	Withstand SLS loading	Passed	1.94
	Maximum deflection	<250mm	169	1.48
	Natural frequency	>2Hz	2.49	1.25

** Excluding some areas due to modelling inaccuracies discussed in sections 6.1.2 and 6.1.3*

Table 1: Summary of global analysis results

3. Structural overview

The sculpture is made up of an inner and outer set of spiralling tubes, which are then repeated about 180° to give a rotational symmetry of order two. Each set (total four sets) consists of 15 tubes, of which six are attached to the foundations. Short joining tubes between the inner and outer tube sets provide structural connections linking the inner and outer tubes together. The inner and outer tubes have inner diameters of 100mm and 150mm respectively.

All the tubes consist of a monolithic (single skin) laminate over a 3D printed male former. The formers are produced in ≈500mm sections, which are then joined into a continuous length representing each tube. The laminates are a combination of e-glass and carbon woven sock and carbon unidirectional plies infused with epoxy resin.

A different laminate is used for the inner and outer tubes and this is constant across all inner/outer tubes. Local patching laminate is added in areas of high stress. Adjacent tubes and chevrons are connected via a combination of adhesive bonding and taping plies.

For further descriptions of the sculpture assembly and structural drawings refer to:

-GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf
-GU6706-0000_RevA Material Properties.dwg
-GU6706-1001_RevA Sculpture Laminate.dwg
-GU6706-1002_RevA Tubes Mounting Hardware.dwg
-GU6706-1006_RevA Sculpture Laminate Details.dwg
-GU6706-2001_RevA Chevrons and Art Panels Layout.dwg

4. Analysis model

4.1 Modelling Approach

The global structural analysis of the sculpture has been undertaken using Altair Hyperworks Finite Element (FE) analysis software. The model was constructed using Altair Hypermesh 2017.3 and analysed using Altair Hyperworks 2017.3 using linear static, linear buckling and normal modes analyses.

4.2 Model Geometry

The geometry for the analysis model was supplied by Kilwell Fibretube Ltd on 20-11-2017 as a 3D CAD file "Entire Sculpture.stl".

Since the analysis model was constructed the overall height of the outer tubes was reduced by 700mm (7%). Modelling the original taller outer tubes is deemed to be conservative compared to the updated shorter tubes. As such the reduction in height of the outer tubes has not been effected in the analysis model.

4.3 Coordinate System and Units

Units used in the FE model are millimetres (mm), Newtons (N), seconds (s) and tonnes (T), to form a consistent set satisfying the equation Force = Mass x Acceleration.

The global co-ordinate system was set as shown below. Orientations are described relative to the location of the art panels, being either parallel, or normal, to the panels.

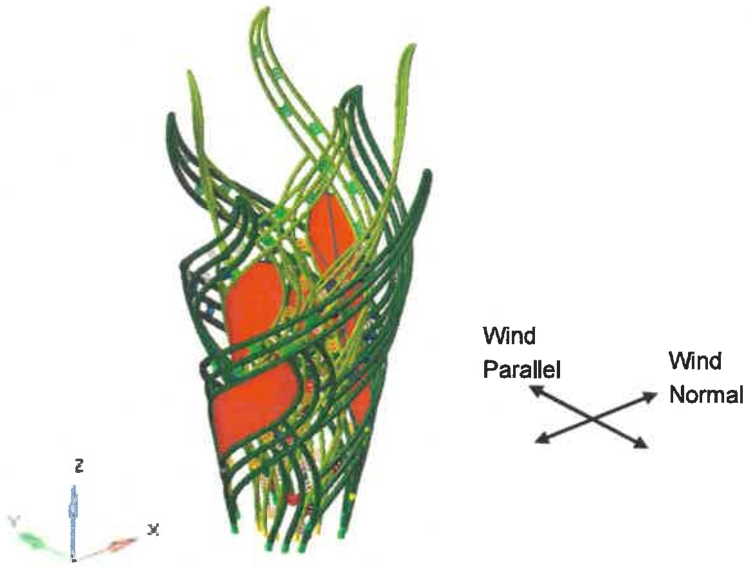

Figure 2. Model co-ordinate system

A variable co-ordinate system was used for applying the laminates to the tubes, whereby the primary axis (0° orientation) follows the tube axis.

4.4 Model Mesh

The FE model of the sculpture is composed of approximately 330,000 first-order composite shell elements and 32 1D elements (Rigids) representing the foundation attachments and art panels. Element size targets were set at 30mm for general areas and 15mm for areas surrounding tube joins and the chevrons themselves.

Figure 3 below shows a more detailed view of the mesh.

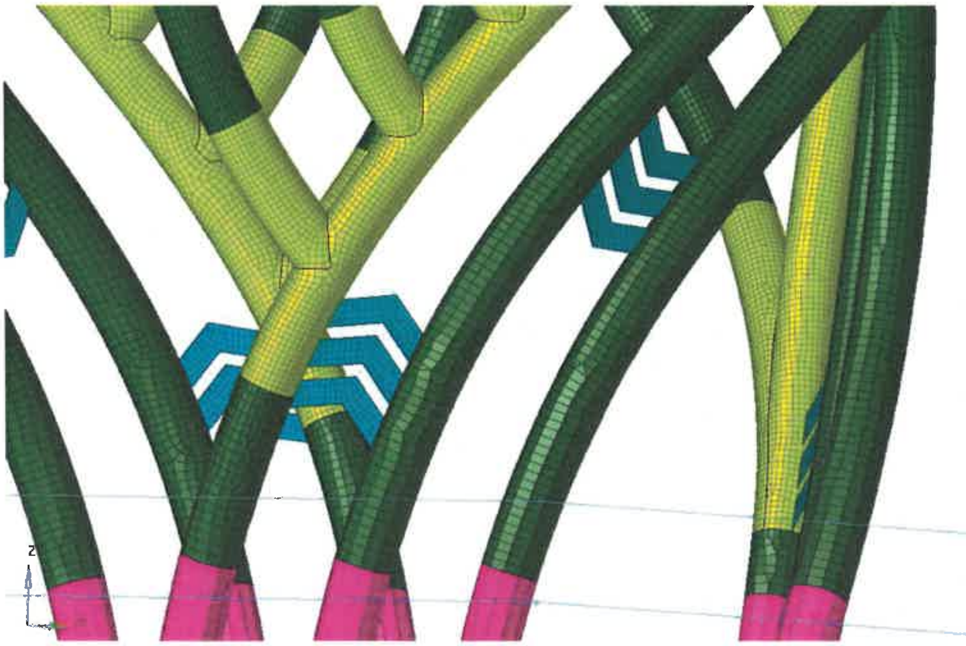

Figure 3. Model mesh – Outer tubes

4.5 Material properties

In general material properties used in the analysis were taken from *GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf*. However, materials testing was subsequently carried out on the individual plies to confirm key mechanical properties, as indicated by Table 2 below. In these cases the characteristic value determined from testing was used in the analysis.

					Stiffness (GA)				Strength (% strain)			
Material	Method	Orientation	Fvf	E1	E2	G12	v12	ε1t	ε1c	ε2t	ε2c	Y12
Sock_E332	Epoxy, infused	0/90	0.46	20.8	20.8	3.4	0.12	1.50	1.50	1.20	1.20	1.41
		+45/-45	0.46	10.5	10.5	9.3	0.56	0.90	0.90	0.90	0.90	**2.56**
Sock_C610	Epoxy, infused	0/90	0.53	**62.7**	**62.7**	4.2	0.04	0.96	0.67	0.96	0.67	1.36
		+45/-45	0.53	14.7	14.7	25.4	0.73	0.79	0.79	0.79	0.79	**0.76**
UC450	Epoxy, infused	0	0.55	**11.9**	7.0	4.1	0.34	**1.64**	**0.37**	0.45	1.50	1.20

Table 2. Tested material properties

As per the Eurocomp design code, verification of material properties via testing allows a reduction in the gm1 partial material factor due to the increased confidence in the material strengths. The material factors shown in Table 8 of *GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report* have been updated as follows:

Partial factor	Description	Long Term Factor	Short Term Factor	Accidental Factor
gm1	Properties of individual plies from test specimen data. Properties of laminate, panel or pultrusion from theory.	**1.50**	**1.50**	-
gm2	Panels to be manufactured by resin transfer moulding, Fully post cured.	1.20	1.20	-
gm3	Resin system HDT 55-80deg, operating in 25-50deg environment	3.00	1.20	-
gm	**Total material factor**	**5.40**	**2.16**	**1.50**

Table 3. Material factors for analysis

4.6 Restraints

Refer to *GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf* for a description of the physical systems providing support to the sculpture.

The connection between the composite tubes and the steel base fitting has been modelled using a freeze contact (infinitely rigid interface) between the two components over the length of the steel fitting. The connections to the foundations are then realised by restraining the bottom edge of the steel fitting using infinitely rigid RBE2 element 'spiders' with the central nodes connected to single point constraints (SPC) fixed in all 6 directions.

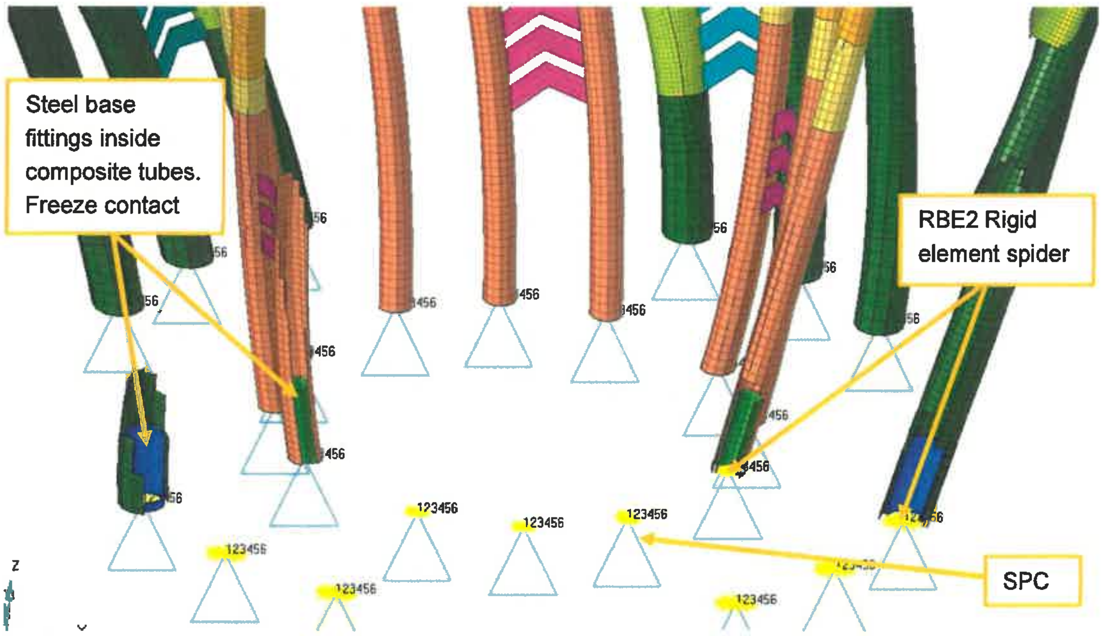

Figure 4. Sculpture base supports (partial section)

4.7 Additional Masses

In addition to the materials explicitly included in the FE model, masses have been included to represent manufacturing details that are not modelled, such as join taping, and non-structural masses such as the 3D printed formers and paint. These masses have been modelled as distributed masses applied evenly over the surface area of the tubes. A summary of these masses is shown below in the table below.

Item	Inner Tubes		Outer Tubes	
	Weight (kg)	FE model distributed mass (T/mm²)	Weight (kg)	FE model distributed mass (T/mm²)
Manufacturing masses (taping, glue)	250.0		300.0	
3D printed former	200.5		327.5	
Paint (Clear coat and Nyalic resin coating)	15.0		20.0	
Total	**465.5**	**6.45e-9**	**647.5**	**6.26e-9**

Table 4. Distributed non-structural masses

Point masses of 48kg and 37kg (per panel for outer and inner panels respectively) have been used to represent the weight of the art panels. These masses are applied at the centre of gravity of each art panel and attached to the surrounding tubes via a rigid RBE3 elements (zero stiffness elements).

4.8 Model Mass

The overall modelled composite mass (including manufacturing, former and paint weights as above) is 2960kg

A detailed weight estimate of the sculpture estimates the composite mass at 2792kg, 6% lighter than the modelled mass. Refer to section 10.2 for further details.

5. Applied loadings

Refer *GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf* for characteristic values of actions, load combinations and factors.

6. Results – Global FE analysis

6.1 Structural response to ULS loading

The Failure Index (FI) measures whether or not the laminate will fail at the load applied in the FEA model. The Maximum Strain, First Ply Failure criteria is used in this analysis. As such the Failure Index plotted in the FEA results presented in this section is:

$$Failure\ Index = Max\left(\frac{Measured\ Strain}{Ultimate\ Strain}\right)_{For\ each\ plies, for\ each\ failure\ mode}$$

The FEA output is the maximum of this ratio across each individual ply, in each individual failure mode (tension, compression and shear). Otherwise said, when the FI reaches 1, one of the plies in the laminate stack has reached its failure strain in one of the failure mode, and the laminate is considered "failed" (this is conservative as the laminate may still be able to maintain load carrying ability after only 1 ply has failed)

A FI greater than 1 means the laminate has "failed".

In order to evaluate whether or not the design is compliant, the Reserve Factor is used:

$$Reserve\ Factor = \frac{Allowable\ Strain}{Design\ Strain}$$

A RF greater than 1 means the design is compliant (The design strain hasn't exceeded the allowable level).

The material utilisation factor is the inverse of the RF, a material utilisation factor lower than 1 means the design is compliant.

The Design Strain must be calculated from a factored load, with load factors presented in *GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf*. The loads are entered into the FEA model in their factored state, as such:

$$Measured\ Strain = Design\ Strain$$

The Allowable Strain must be calculated from a knocked down material property, with material factors (MF) presented in *GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf.*

$$Allowable\ Strain = \frac{Ultimate\ Strain}{Material\ Factor}$$

The following equation presents how the Reserve Factor is calculated:

$$Reserve\ Factor = \frac{Allowable\ Strain}{Design\ Strain} = \frac{\frac{Ultimate\ Strain}{Material\ Factor}}{Measured\ Strain} = \frac{1}{Material\ Factor} \times \frac{Ultimate\ Strain}{Measured\ Strain} = \frac{1}{MF} \times \frac{1}{FI}$$

If we introduce $FI_{Target} = \frac{1}{MF}$ in the above, then

$$RF = \frac{FI_{Target}}{FI}$$

Otherwise said, for a design to be compliant, the FI should not exceed a set value, $FI_{Target} = \frac{1}{MF}$.

Figure 5 below demonstrates a graphical explanation of the above.

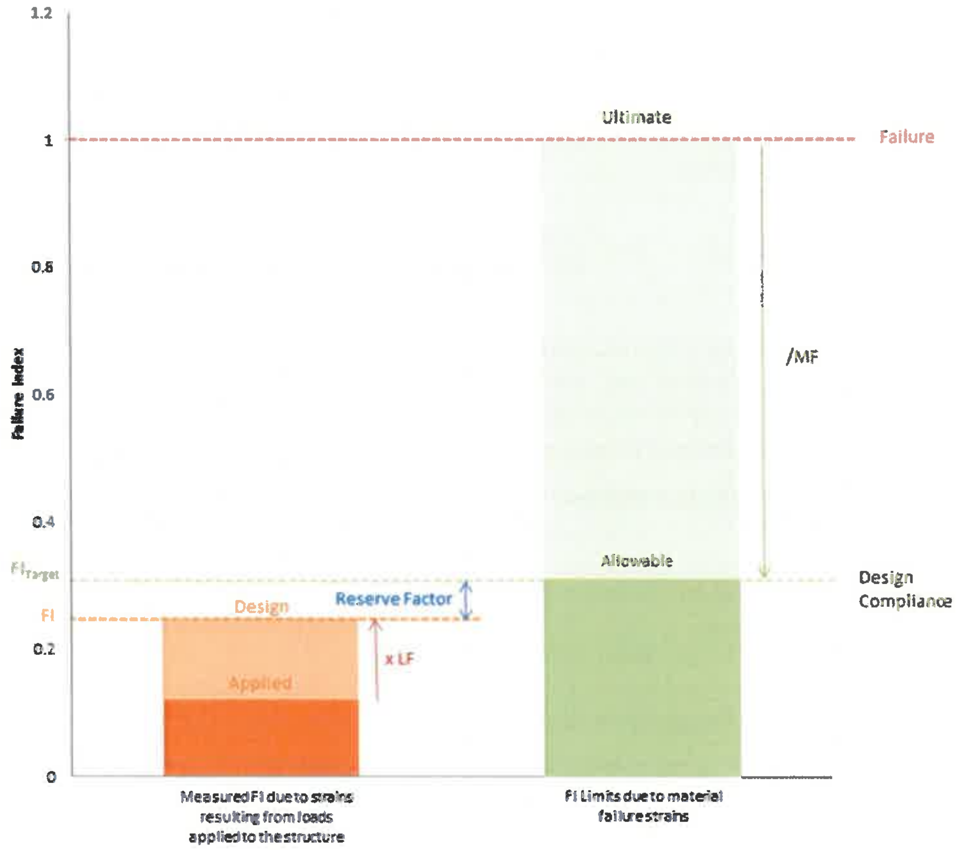

Figure 5: Diagram presenting the Failure Index

For this project we have the following set of FI_{Target}:

Long term loading: ULS 20001 Self-weight

$$\left(FI_{Target}\right) = \frac{1}{MF_{Skin}} = \frac{1}{5.4} = 0.185$$

Short term loading: ULS 20002-20003 (Wind IL= 1)

$$\left(FI_{Target}\right) = \frac{1}{MF_{Skin}} = \frac{1}{2.16} = 0.463$$

Accidental loading: ULS 20004-20005 & 21001-21002 (Wind IL= 2, Seismic)

$$\left(FI_{Target}\right) = \frac{1}{1.5} = 0.667$$

The evaluation of the RF is realised graphically by setting the contour scale with a threshold at the FI_{Target}, as shown on Figure 6 below.

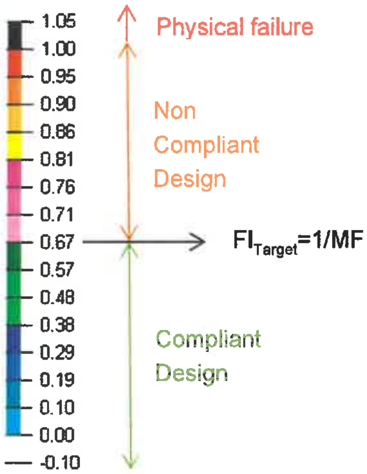

Figure 6: Failure Index contour scale threshold (accidental FI example)

Stability (buckling resistance) of the structure has been checked with a linear buckling analysis. For buckling,

$$Reserve\ Factor = \frac{Achieved\ Buckling\ factor}{Required\ Buckling\ factor}$$

As the buckling factor requirement for all ULS load cases is 1.5 (refer *GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf*), a buckling factor >1.5 indicates that the structure satisfies the design requirements for buckling resistance.

The natural frequency of the structure has also been checked with a frequency analysis. A first natural frequency mode greater than 2Hz is considered to satisfy the design requirements, as per 8.2.3 in *GU6706-6001 Rev C Hemo Gorge Sculpture Design Basis Report.pdf.*

6.1.1 Long term strength and stability

Figure 7 shows the failure index for the ULS_20001 load case (Self weight 1.35G). As can be seen the failure index, is low with a peak value of 0.184 at the connection between outer tubes 9 and 10 (refer to GU6706-1001_RevA Sculpture Laminate.dwg for tube numbering convention). There is a minimum reserve factor of 0.185/0.184 = 1.01 (utilisation factor of 0.99) over the safety factors defined in the design requirements.

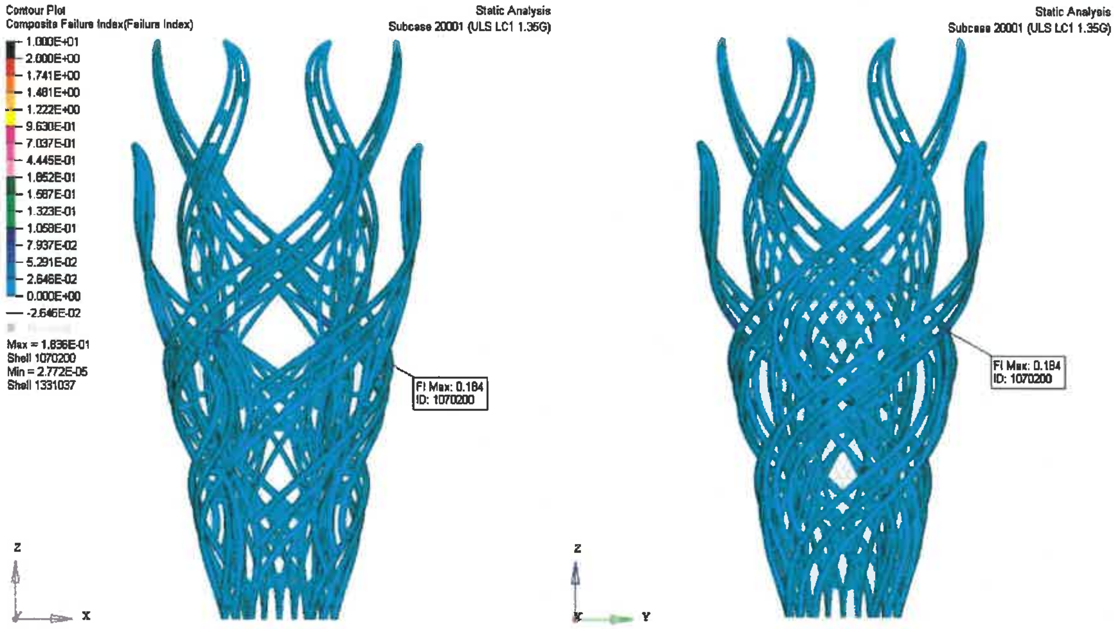

Figure 7: ULS_20001. FI for long term loading

(Note: To aid in interpretation of the results the same contour plot is shown on both sides of the image, but the 2nd view is orthogonal to the first)

The first linear buckling mode of the sculpture under ULS_30001 is shown below in Figure 8 below. The outer tube set consisting of tubes 7,8, and 9 can be seen to buckle through the unsupported tip region. The load factor for this buckling mode is 76.0 (i.e. the predicted load to cause buckling is 7600% higher than the applied ULS load), thus giving a reserve factor of 50.7, against the target minimum load factor of 1.5.

Figure 8: ULS_30001 (1.35g self-weight) first buckling mode

6.1.2 Short term strength and stability

For clarity the failure index results of the inner and outer tubes are viewed separately in sections 6.1.2.1 and 6.1.2.2 below.

As is explained in the following sections there are elements in the model with a failure index greater than the target maximum. Upon review the high failure index in all these elements has been accounted for either because of modelling inaccuracies, or due to additional structural elements that have not been modelled (e.g. bonding coves and taping laminates). Excluding these elements, and the immediately adjacent elements, the maximum failure index for the entire sculpture under short term loading is 0.459. This gives a minimum reserve factor of 0.4630/0.459 = 1.01 (utilisation factor 0.99) over the design requirements.

6.1.2.1 Inner tubes

The failure index for the inner tubes under short term loading is shown in Figure 9 below.

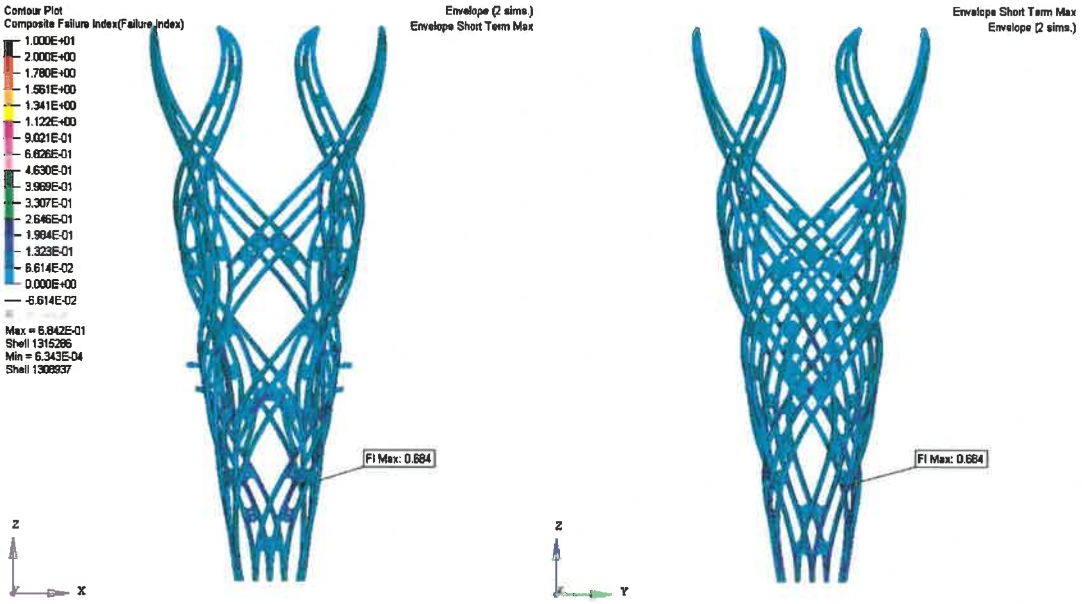

Figure 9. Envelope plot of FI for short term load cases. Inner tubes only

For the most part the FI is well below the target maximum. However, there are 30 elements exceeding the FI as highlighted below in Figure 10, with the highest element at 0.684 (target FI 0.463). Locations of the failed elements are highlighted in red. These elements have been reviewed and considered safe, based on the justifications in the following paragraphs. The failed elements can be grouped into three areas, of which typical examples are shown further below in Figure 11.

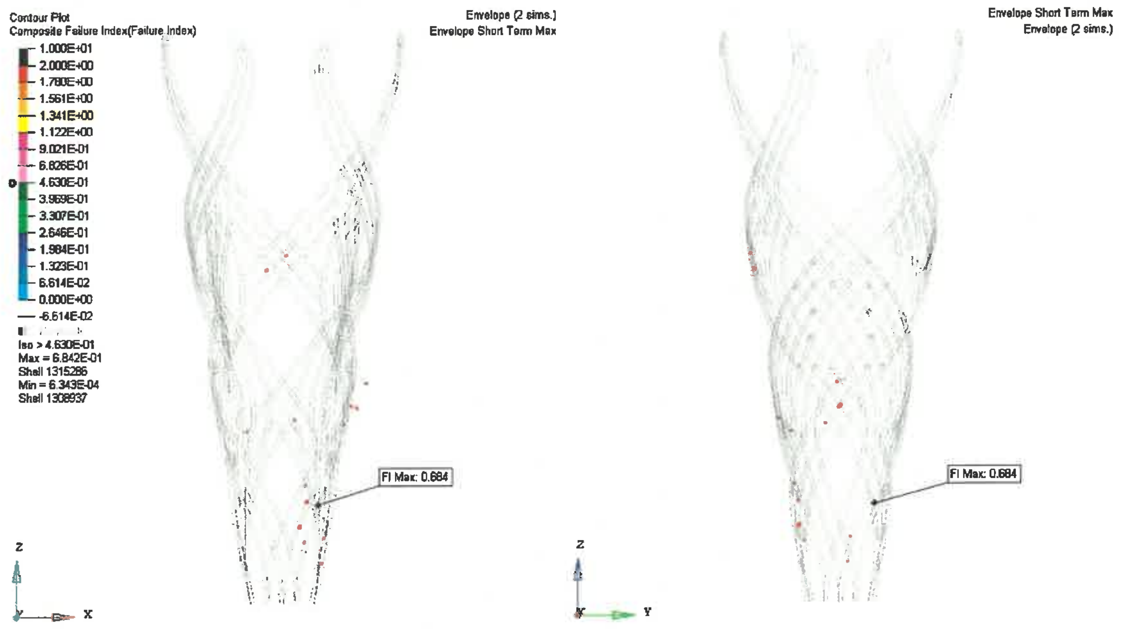

Figure 10. Envelope plot of elements exceeding FI for short term load cases. Inner tubes only

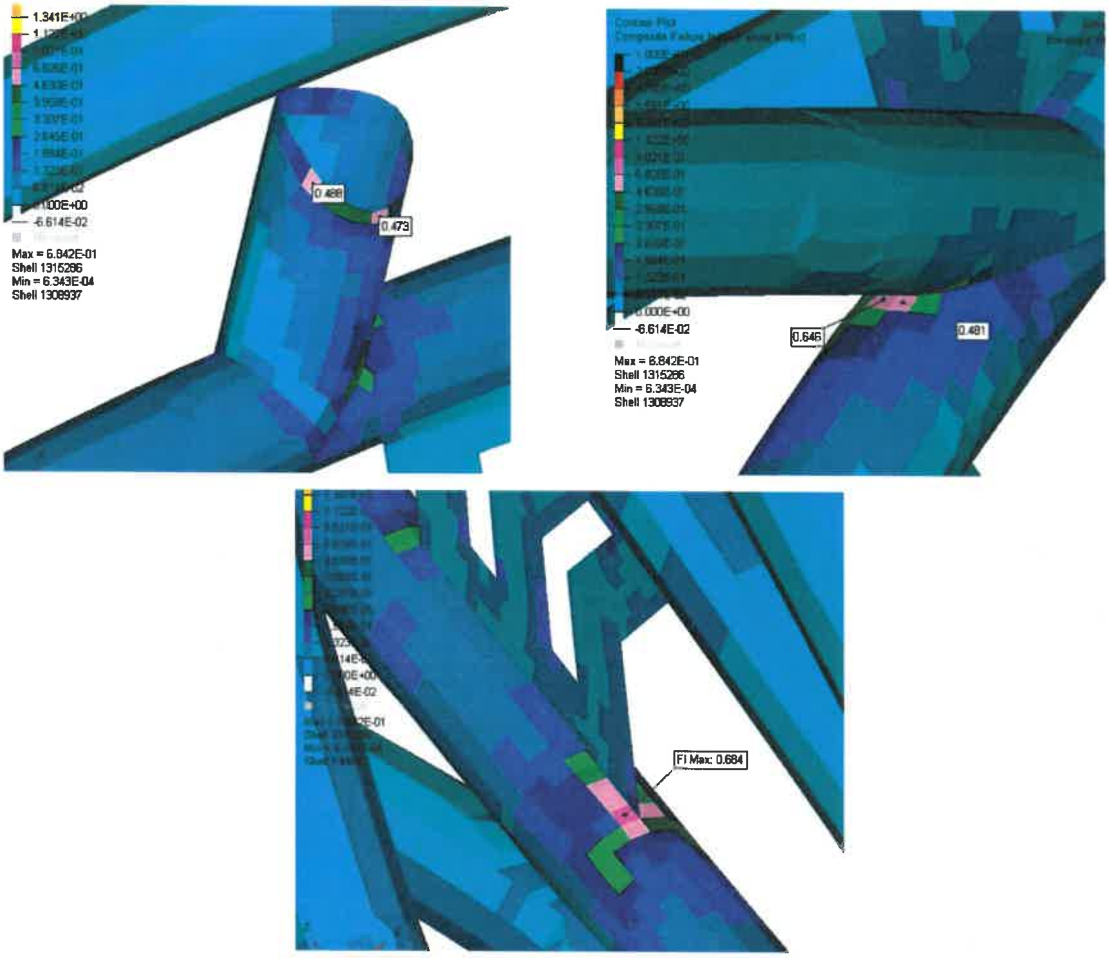

Figure 11. Local areas where FI is exceeded. Short term load cases. Inner tubes only. Clockwise from top left: Inner to outer tube joiner, connection between tubes 4 and 7, typical chevron connection

Five individual elements are located on the tubes joining the inner and outer tubes. The presence of low FI in the adjacent elements suggests that the high FI is due to meshing artefacts and can be ignored. These areas will also have a glue cove and taping which is not modelled, which will further distribute any local stress concentrations.

There are three elements overall at the connections between tubes that are exceeding the target FI. This is a result of the same situation as explained in the previous paragraph. Therefore the high FI in these three elements can be ignored.

The majority of the remaining elements (22) are located at the ends of the chevrons, where they contact the tubes. These areas have been reviewed and the high FI has been attributed to modelling restraints. The thickness of the chevron and the glue cove and taping used to attach it to the tube are not modelled. These features would have the effect of distributing the load from the chevron over a larger area of the tube, reducing the stress. The adjacent elements generally have a low FI, and thus the capacity to support a more distributed load without exceeding the FI. As such the high FI in these elements can be ignored.

6.1.2.2 Outer tubes

The Failure Index for the outer tubes under short term loading is shown below in Figure 12.

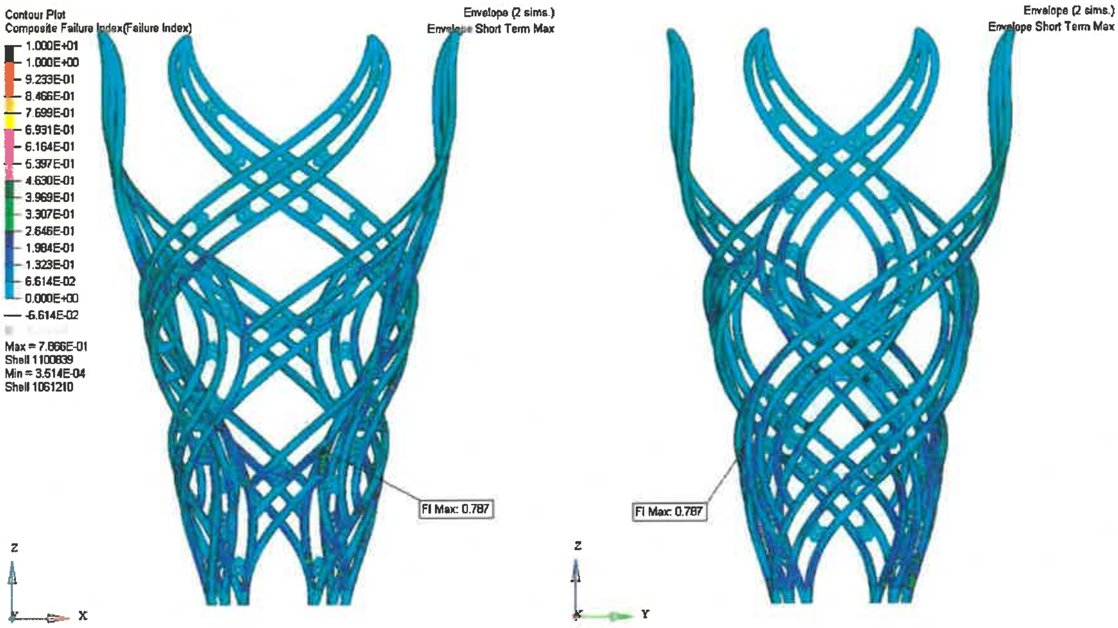

Figure 12. Envelope plot of FI for short term load cases. Outer tubes only

Most of the outer tube elements have a low failure index, <0.200, but there are some that exceeding the target failure index (0.463). These are highlighted below in Figure 13 and occur at the chevrons and tube to tube intersections.

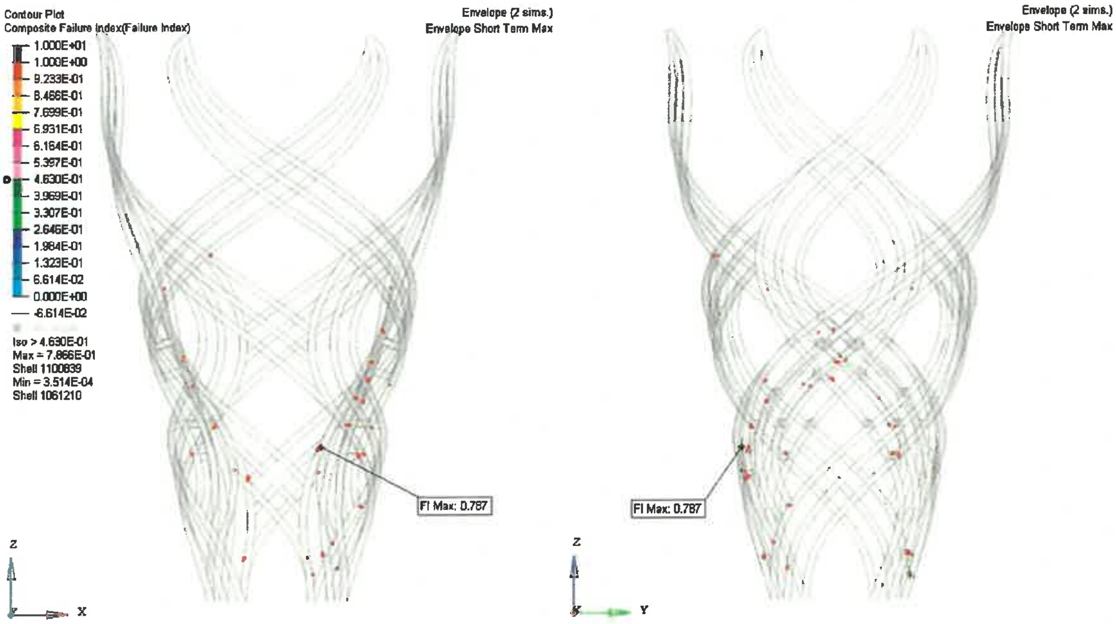

Figure 13: Envelope plot of elements exceeding FI for short term load cases. Outer tubes only

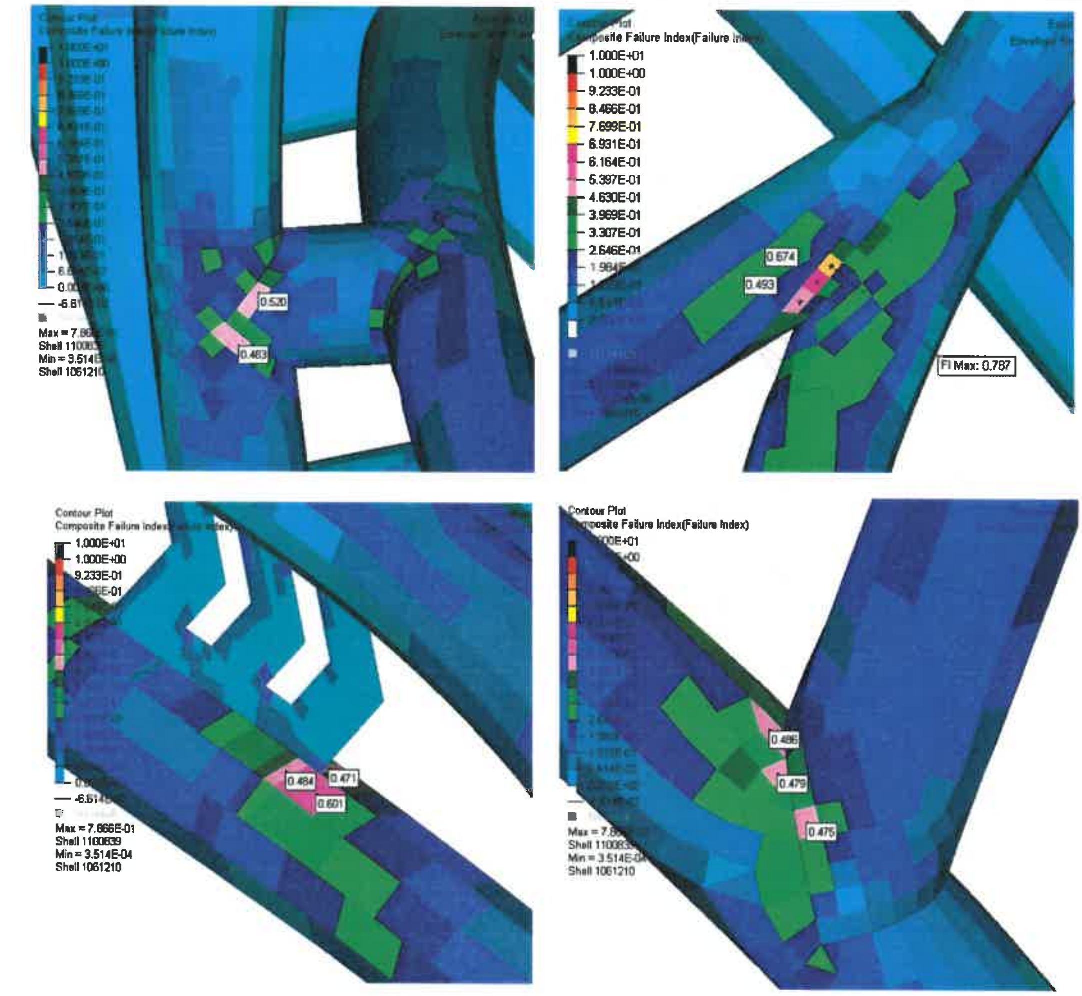

Figure 14. Local areas where FI is exceeded. Short term load cases. Outer tubes only. Clockwise from top left: Outer tube joiner, connection between tubes 5 and 7, connection between tubes 3 and 6, typical chevron connection

In total there are 78 elements above the target failure index (0.463) with a maximum FI of 0.787.

Thirteen elements are located at the joining tubes where the outer tubes cross each other. Refer Figure 14 below for an example. Like the inner tubes these elements with a high failure index can be ignored. The surrounding elements have a low failure index, and taping laminates and structural adhesive coves which are not modelled here will act to distribute any local stress concentrations.

Twenty-two elements located at tube to tube intersections have a high failure index. These areas initially had a high failure index due to the local bending action as the applied loads attempted to open/close the angle between the tubes. The design of the connection was modified to use a larger cove in these areas, distributing the load and providing a more efficient load path through the taping, due to the smaller change in angle. This was modelled by adding RBE2 infinitely rigid elements to represent the taping. The high failure index is occurring in the elements that are connected to the nodes used for the RBE2. In reality this load will not be concentrated at a single point and the high failure index observed in these elements can be considered spurious. This is confirmed by the low failure index in the adjacent elements.

As seen on the inner tubes most elements (43 elements) with a high failure index are located within the tubes adjacent to where the chevrons end. The same modelling restraints as described for the inner tubes apply here, therefore the high failure index can be ignored.

The first linear buckling mode of the sculpture for the short term load cases occurs in load case ULS_30002 (Wind Normal) and is shown below in Figure 15. Buckling occurs in the lowest chevron between inner tubes 11 and 12 at a load factor of 6.55, thus giving a reserve factor of 4.37.

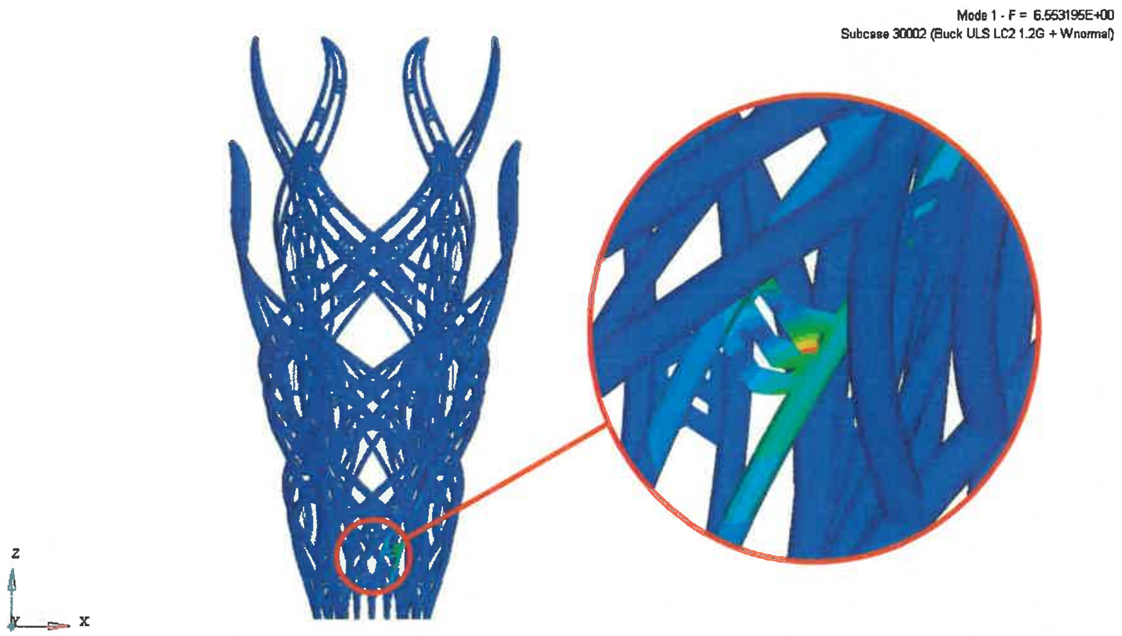

Figure 15: ULS_30002 (Wind Normal) first buckling mode

6.1.3 Accidental cases strength and stability

The Failure Index for the entire sculpture under accidental loading is shown over the page in Figure 16.

Like the other ULS cases the accidental load cases also see a small number of elements exceeding the target failure index. In this case there are 14 elements in total that have a high failure index: 6 are located at the tube to tube joins, and 8 are located at the ends of chevrons.

These elements are all in identical locations to those described in section 6.1.2.2 above and their high failure index is a result of the same modelling inaccuracies. They can therefore be ignored based on the same justifications.

Excluding these 14 elements and those immediately adjacent the maximum failure index is 0.662. This gives a reserve factor of 0.6667/0.662 = 1.01 (utilisation factor 0.99).

Figure 16, Figure 17 and Figure 18, below, show the overall failure index plot, the location of the elements exceeding the failure index, and examples of the local areas where the high failure index elements are.

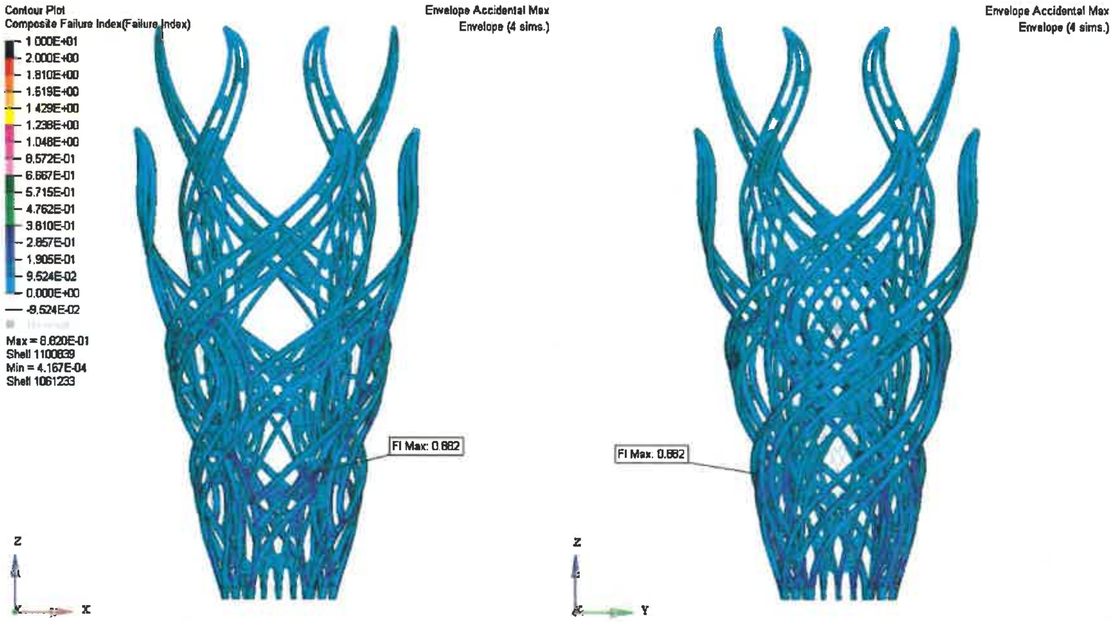

Figure 16. Envelope plot of FI for accidental load cases.

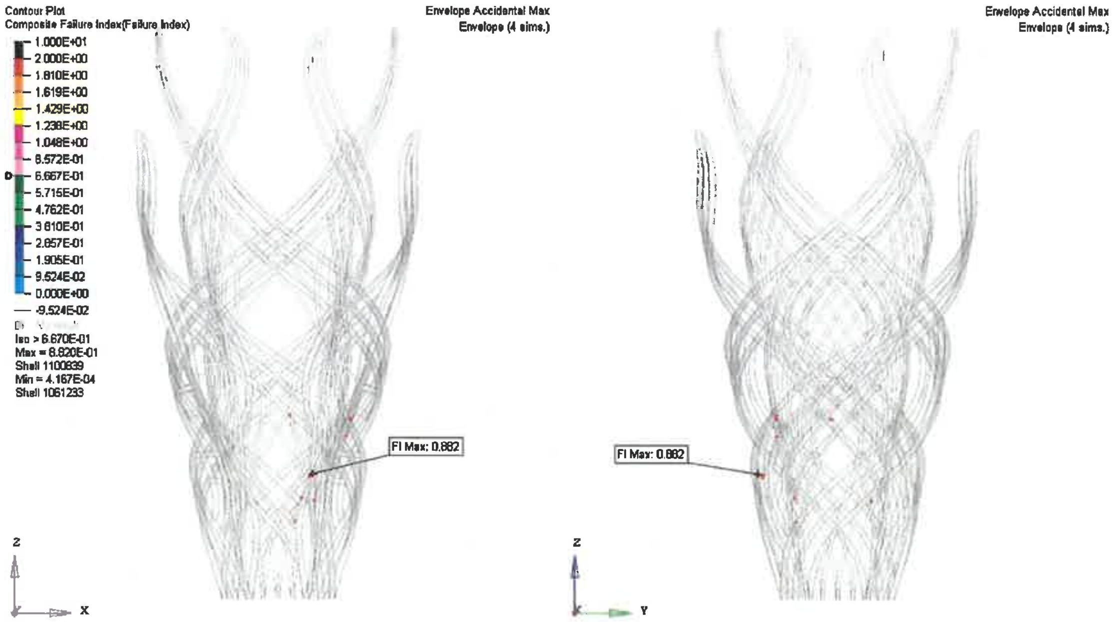

Figure 17. Envelope plot of elements exceeding FI for accidental load cases.

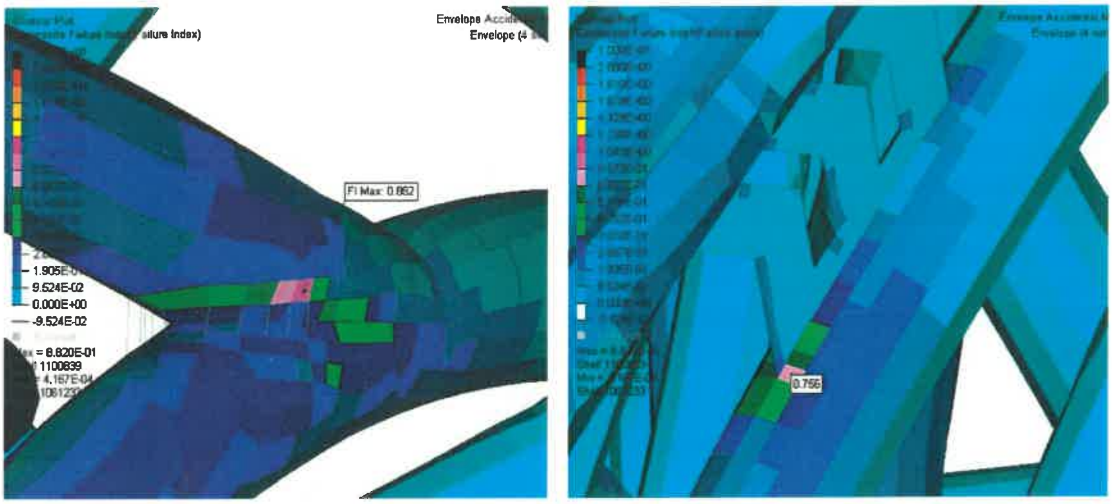

Figure 18. Local areas where FI is exceeded. Accidental load cases. Left to right: Connection between tubes 5 and 7, typical chevron connection

The first linear buckling mode of the sculpture under accidental load cases (Wind loading to Importance Level 2, and Seismic loading) occurs for load case ULS_30004 (IL = 2, Wind Normal), and is shown below in Figure 19 occurring at the lowest chevron between inner tubes 11 and 12 at a load factor of 5.84, thus giving a reserve factor of 3.89.

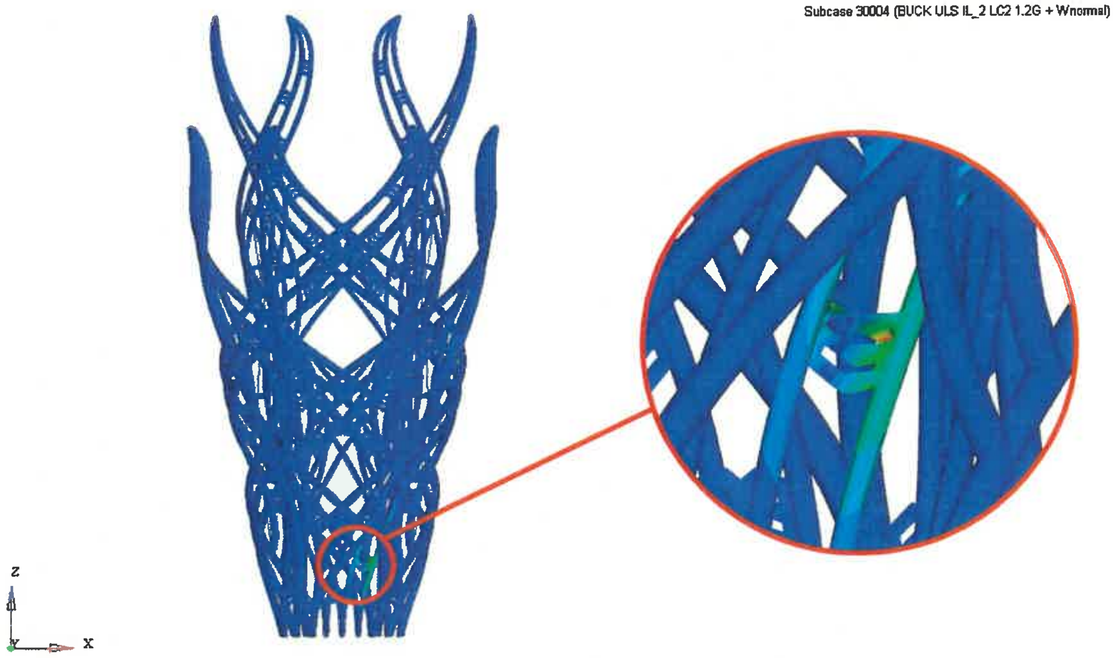

Figure 19: ULS_30004 (IL=2, Wind Normal) first buckling mode

6.2 Structural response to SLS loading

6.2.1 Stiffness – Deflection of components

The following three figures show the deflection for each of the SLS load cases.

Deflections for the lower 2/3 of the sculpture are low due to the well-connected nature of the structure. This support reduces over the upper 4-5m of the outer and inner tubes and most of the deflection therefore occurs in this region. The overall maximum deflection is 169mm and occurs at the uppermost tip of the inner tubes under load case 10002 (Wind Normal). Refer Figure 21. Preliminary design work compared maximum deflection vs cost/weight for a range of laminates. The outcome of this work was the decision for a strength critical design allowing for a max deflection of 250mm. The maximum deflection observed is therefore within the requirements.

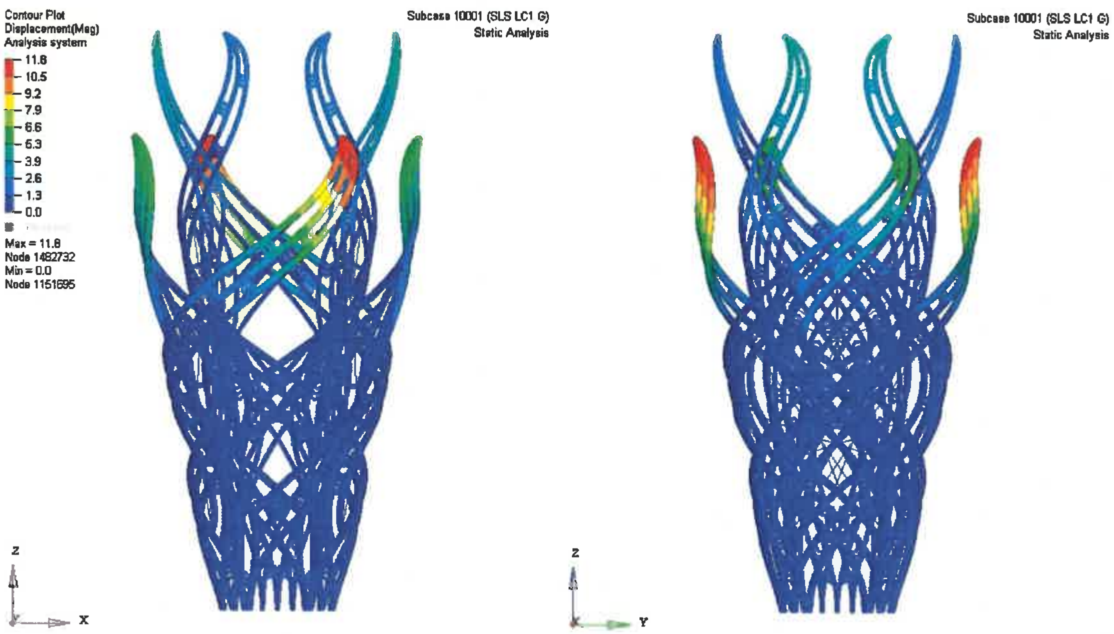

Figure 20: Deflection Load case 10001 (SLS, Static)

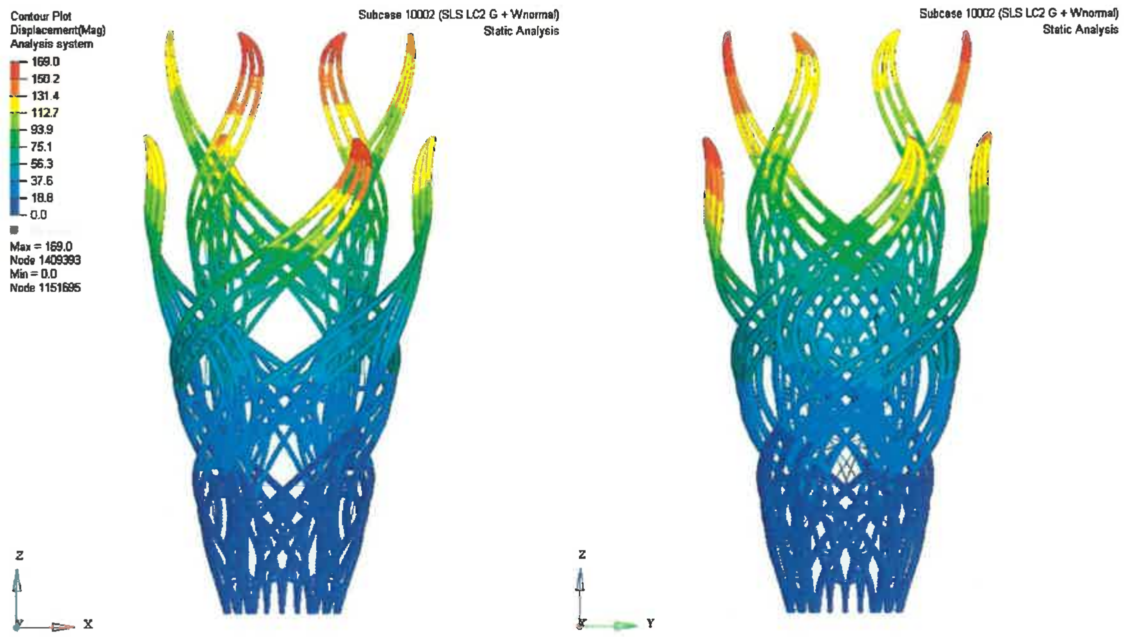

Figure 21. Deflection. Load case 10002 (SLS, Wind Normal)

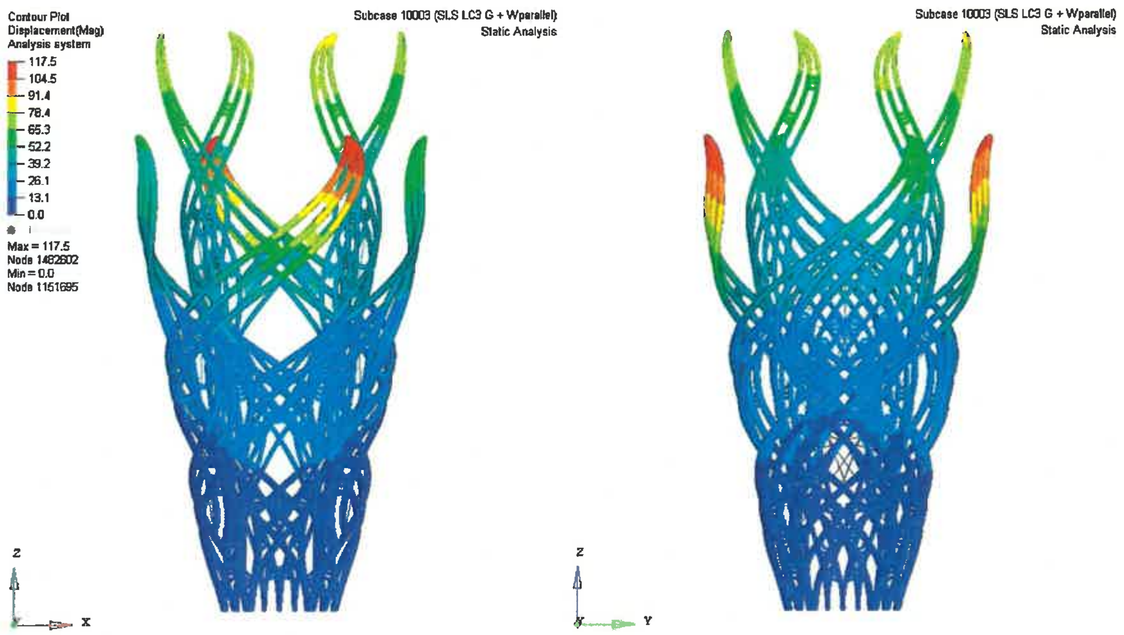

Figure 22. Deflection. Load case 10003 (SLS, Wind Parallel)

6.2.2 Maximum Principal Strain

Figure 23 below shows the maximum principal strain across an envelope of all SLS load cases. The peak value of 0.337% occurs low down in the outer tubes at the connection between tubes 7 and 10. This gives a reserve factor of 0.45/0.337 = 1.33.

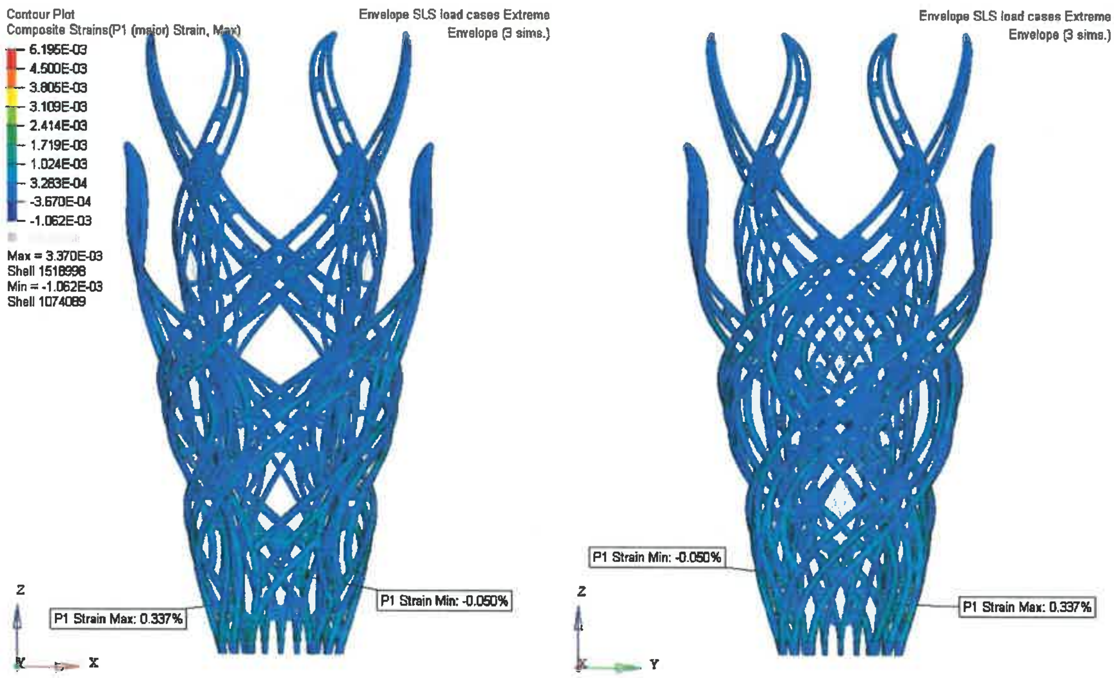

Figure 23: SLS cases – Maximum Principal Strains. Envelope plot.

6.2.3 Vibration

The first normal mode of the sculpture is shown in Figure 24 below. It shows the whole sculpture bending in the XZ plane, the direction normal to the art panels. This mode occurs at 2.49 Hz, offering a reserve factor of 1.25 versus the 2Hz requirement.

Figure 24: First normal mode

7. Analysis of connections

7.1 Chevrons

The chevron plates between the tubes are a key structural component of the sculpture. When the sculpture is loaded the chevrons act as shear webs between the adjacent tubes, allowing the structure to act as a series of connected beams. As a result, high shear force is present across many of the chevrons. This also generates significant peel forces (tensile force normal to the tube, in the plane of the chevron) at opposite corners of the chevrons.

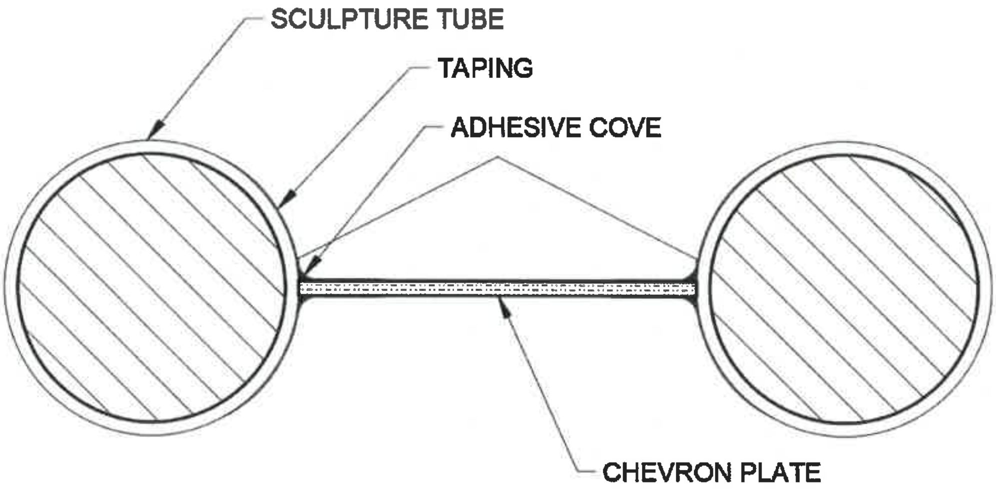

Figure 25. Standard chevron detail

The initial chevron attachment design was for a simple bonded and taped 'T' connection. In this design shear forces are transferred through the taping and peel forces are resisted by the bonding coves.

To evaluate the chevron connections the peel and shear forces along the length of each chevron at the interface between the chevron and the adjacent tube were extracted from the FEA model.

The taping shear calculations are summarised overleaf for the inner and outer chevrons.

	ULS Short term	ULS Accidental	
Maximum shear force at edge of chevron	300*	336*	N/mm
Taping material	XC411 Infused Epoxy	XC411 Infused epoxy	
Ultimate shear strength	329.5	329.5	MPa
Material factor	2.16	1.5	
Allowable shear strength	**152.6**	**219.7**	MPa
Number of layers	3	3	
Taping thickness per side	1.26	1.26	mm
Number of sides	2	2	
Chevron length	305	305	mm
Chevron applied shear stress	**119.3**	**133.7**	MPa
RF ON APPLIED SHEAR STRESS	1.28	1.64	

Table 5. Inner tube chevrons. Taping shear calculations

**there are three elements with a shear force above this value in the FEA model. These are isolated individual elements with adjacent shear stresses <100N/mm. The high shear stress in these elements has therefore been considered spurious and the overall maximum shear stress set at the next highest value of 300N/mm and 336N/mm for the short term and accidental load cases respectively.*

	ULS Short term	ULS Accidental	
Maximum shear force at edge of chevron	283	317	N/mm
Taping material	XC411 Infused Epoxy	XC411 Infused epoxy	
Ultimate shear strength	329.5	329.5	MPa
Material factor	2.16	1.5	
Allowable shear strength	**152.6**	**219.7**	MPa
Number of layers	3	3	
Taping thickness per side	1.26	1.26	mm
Number of sides	2	2	
Chevron length	305	305	mm
Chevron applied shear stress	**112.5**	**126.0**	MPa
RF ON APPLIED SHEAR STRESS	1.36	1.74	

Table 6. Outer tubes. Taping shear calculations

The achievable peel strength of such a design is very dependent on the adhesive application and manufacturing process, both of which can see a significant amount of variation when not machine controlled. Calculations based on typical peel values achievable showed that peel failure was the critical failure mode of the connection and that the design would be unlikely to achieve the target reserve factor across all chevrons.

A second chevron design was therefore developed, which involved continuing the chevron through the adjacent tubes and allowing for attachment to the opposite side of the tube, such that the peel force was reduced.

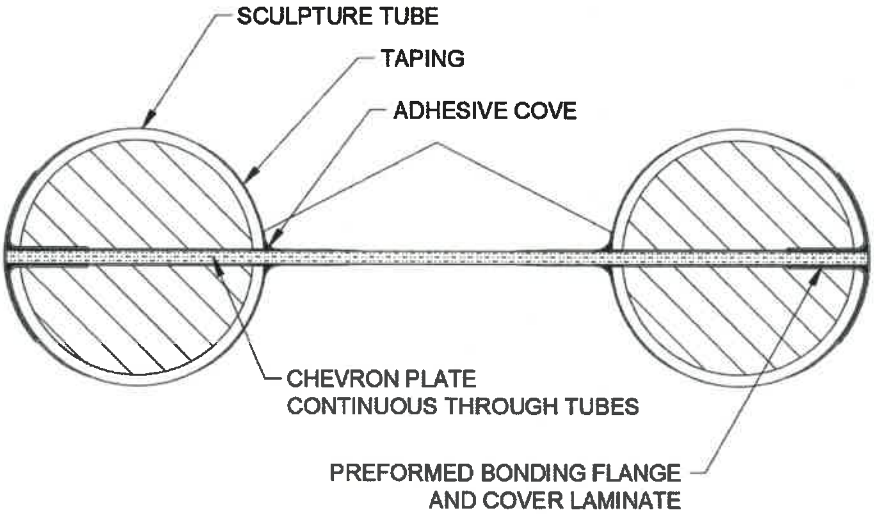

Figure 26. Through chevron detail

This design, referred to as the 'through chevron' design, is costlier than the initial standard chevron solution, due to increased material quantities and labour time. It was not viable to utilise this design over the entire sculpture. As such it was necessary to determine a transition point below which the standard chevron design could be used and above which the through chevron design would be required.

Proof testing of the standard chevron design established a maximum peel force at limit state of 572N/mm (Refer section 8.1 below). This value was conservatively used as an ultimate limit state value to determine the transition from standard chevrons to through chevrons.

Peel force at ULS from standard chevron testing	572	N/mm
Material Factor	2	
Design allowable peel force at ULS	286	N/mm

All chevrons in the FEA model with a peel force greater than 286N/mm under ULS loading must therefore use the through chevron design. This resulted in 8 of the outer tube chevrons and 12 of the inner tube chevrons using the through chevron design. These chevrons were predominantly the lowest chevrons in the sculpture, where the bending and shear loads are highest.

The stronger through chevron design was validated by proof testing. Refer section 8.2 below.

7.2 Tube intersections

At each of the tube intersections the discontinuous tube was mitred to the continuous tube and then the joint was bonded, coved, and taped. The typical tube to tube connection detail is shown below.

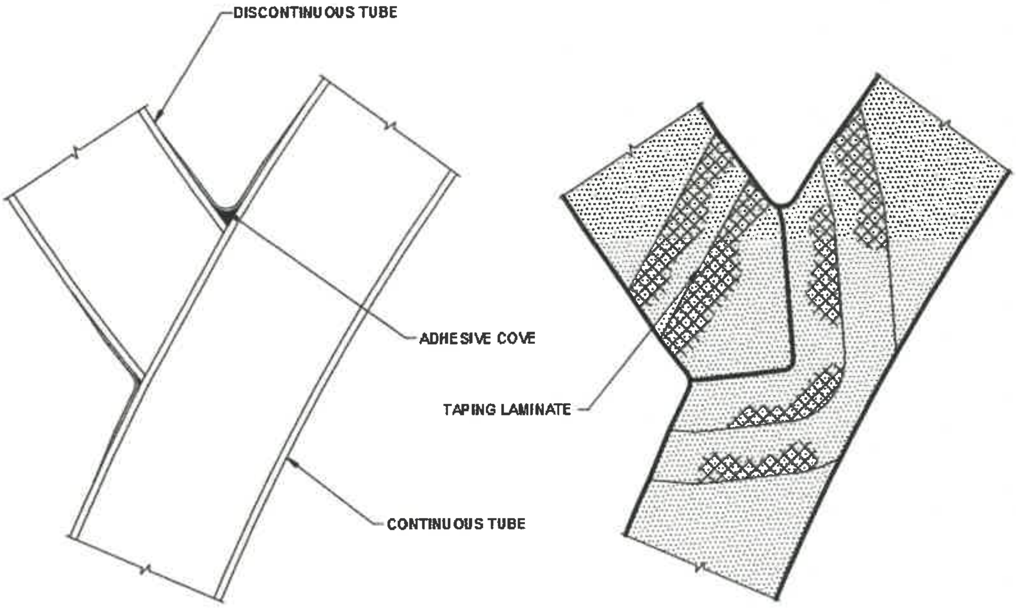

Figure 27. Tube to tube connection

The angle between connected tubes ranges from near parallel to perpendicular. The extremes of this range produce two different loading scenarios: when the tubes are near parallel tensile loads produce in plane shear in the taping laminate, and when the tubes are perpendicular this changes to an out of plane peel force along the axis of the continuous tube, along with a tensile force in the taping at the sides.

The taping specification of the joint was conservatively designed to carry the combined worst case of tensile and shear forces. Taking into account the material factor, the ULS short term load cases were found to be the most onerous for the taping laminate and their reserve factor calculations are summarised in Table 7 below.

The taping laminate stack for both inner and outer tubes consisted of:

4 x RC200 Wet Vac Epoxy AT 0/90°, interleaved with

3 x XC411 Wet Vac Epoxy AT ±45°

	ULS Short term loading – Outer Tubes	ULS Short term loading – Inner Tubes	
Maximum shear force	80.0	117.2	N/mm
Maximum tensile force	238.7	211.6	N/mm
Resultant maximum laminate fibre tensile strain	0.28	0.25	%
Resultant maximum laminate resin shear strain	0.39	0.35	%
Laminate ultimate fibre tensile strain	0.96	0.96	%
Laminate ultimate resin shear strain	2.15	2.15	%
Material factor	3.24	3.24	
Allowable laminate fibre tensile strain	0.30	0.30	%
Allowable laminate resin shear strain	0.66	0.66	%
RF on laminate fibre tensile strain	1.05	1.18	
RF on laminate resin shear strain	1.69	1.89	
TAPING LAMINATE MINUMUM RF	1.05	1.18	

Table 7. Tube connection. Taping laminate calculations

Peel forces in the tube to tube connections were also checked. The peel force achieved in the standard chevron proof test was used as the design allowable peel force due to the similarity in the joint geometry and manufacturing method between the two components.

Peak peel force for all tube connections at ULS	139	N/mm
Design allowable peel force at ULS (from chevron testing)	286	N/mm
Reserve Factor on peel force at ULS	2.05	

Proof testing was also carried out on a perpendicular tube connection to verify the design strength. Refer section 8.3.

7.3 Foundation attachment

The composite tubes are attached to the foundations via welded stainless steel foot plates and spigots.

Design of the attachment was by ASP OPUS using reaction loads extracted from the FEA model. A table of reaction loads can be found in appendix 10.1 on page 42.

The composite tubes are bonded to the stainless steel spigots using structural adhesive. Peak glue stresses were extracted from the FEA model and compared with the allowable glue strength:

Peak glue shear stress in bond between tubes and foundation attachment under ULS loads	12.8	MPa
Ultimate shear strength HPR5 structural adhesive	28.9	MPa
Material Factor	2.16	
Allowable shear strength HPR5 structural adhesive	13.4	MPa
Reserve Factor on glue shear strength at ULS	1.05	

Proof testing was also carried out to validate the strength of the bond between the foundation attachment and a partial length of outer tube. Refer to section 8.4 below for details.

8. Proof testing

Proof testing was carried out on representative models of the main structural connections to verify their strength. Of particular interest was the capacity of the chevron connections to withstand the expected peel forces which were calculated to be the limiting failure mode.

The following connections were tested:

- Standard chevron plate in outer tubes
- High strength 'through' chevron plate in outer tubes
- 'Tube to tube' connection using outer tubes
- Base plate fitting to outer tube bond

All tests were carried out at the SCION Crown Research Institute in Rotorua.

An FEA model of each test was used to calibrate the loads and results between the physical test models and the full sculpture FEA model. The worst case stress state of each connection, at SLS, was extracted from the full FEA model. Loads were then applied to the FEA model of the test such that the stress state was replicated. These loads were then used to guide the maximum loads used in the physical proof test.

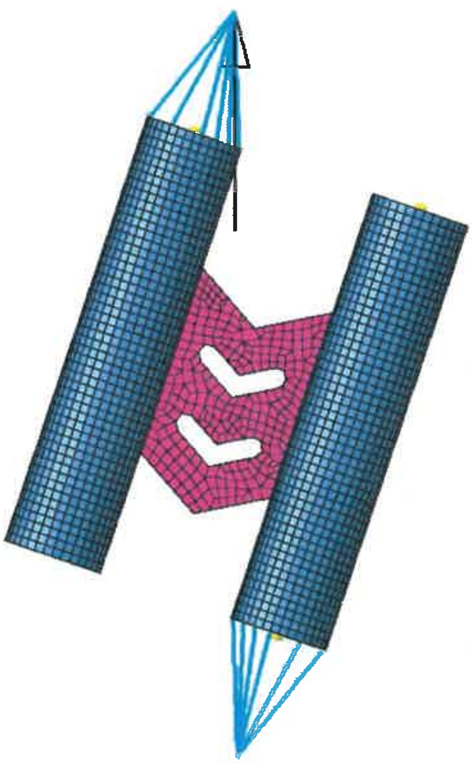

Figure 28. Standard chevron proof test model

8.1 Standard chevron

The standard chevron test was conducted using two parallel lengths of outer tube and a chevron that was bonded and taped to the tubes. The outer tubes were chosen for the test as, due to their larger radius, they were determined to be more peel critical than the inner tubes with a smaller radius.

The components were tested using an offset tensile load to generate the correct ratio of peel and shear forces determined from the FEA modelling.

Six components were tested such that a characteristic value could be calculated. The limit load (load at first sign of load decease), along with the corresponding allowable peel force were calculated as follows:

Applied test load at Limit state (characteristic value)	27,438	N
Resultant peel force in FEA model of test (Limit state)	572	N/mm
Maximum allowable peel force for standard chevron design at SLS	572	N/mm

From the full FEA model, the peak peel force seen in the standard chevrons under SLS loading was = 221N/mm. The proof test achieved a limit peel strength of 572N/mm, thus the connection passes the proof test with reserve factor of 2.59.

Figure 29. Standard chevron proof test setup

8.2 Through chevron

The chevron calculations showed that the standard chevron design was no capable of carrying the loads in the most highly loaded chevrons and that it would be necessary to utilise the stronger through chevron design in these areas. The through chevron proof tests were conducted in a similar manner to the standard chevron tests.

The through chevron tests were limited to a maximum applied load of 71,000N due to the end fitting capacity. All specimens were loaded above 71,000N and held for 120 seconds with no signs of failure.

Applied test load	71,000	N
Resultant peel force in FEA model of test (limit state)	1207	N/mm
Allowable peel force for through chevron design at SLS	1207	N/mm

From the full FEA model, the peak peel force seen across all chevrons under SLS loading was = 603N/mm. The proof test achieved a limit peel strength of 1207N/mm, thus the through chevron connection passes the proof test with reserve factor of 2.00.

Figure 30. Through chevron proof test setup

8.3 Tube to tube connection

The tube to tube proof test utilised two lengths of outer tube joined in a 'T' configuration. The discontinuous tube length and target applied load were specified to generate a stress state in the "t" connection equivalent to the worst SLS stress state from the FEA modelling. This resulted in a requirement for the test to exceed a 16,700N load to validate the connection strength.

Three identical connections were tested. Two specimens were loaded to 50kN and held for one minute, without failure. A third specimen was loaded to 77kN, before the test was stopped due to damage to the test rig.

The connection therefore passed the proof test with a reserve factor of at least 2.99.

Figure 31. Tube to tube connection proof test setup

8.4 Foundation attachment

A proof test was carried out on the foundation attachment primarily to validate the strength of the adhesive bond between the metal fitting and the composite tube. As per the tube to tube proof test above, a lever arm and applied load were determined such that the same peak reaction loads as seen in the FEA model were achieved. With the calculated lever length, the applied load necessary to reach SLS is 15,690N.

The test exceeded the target SLS load without failure and continued to a load of 30,380N at which point the bolts in the foundation attachment began to yield. The connection passed the proof test and achieved a reserve factor of at least 1.94.

Figure 32. Foundation attachment proof test setup

9. Dependant systems

9.1 Art Panel Attachment

The following table shows the maximum relative deflections of the art panels under SLS loading of the tubes. These values represent the in-plane displacement that the surrounding tubes will apply to the art panel boundary. This information should be used to inform the design of the art panel attachments such that they allow enough freedom of movement of the panels to prevent them from acting as part of the structure.

It is assumed that the art panels are sufficiently compliant that any out of plane displacement will be accommodated by bending of the panels.

	Maximum relative displacement	
	Horizontal (mm)	Vertical (mm)
LC1 10001 (SLS Self Weight)	0.1	1.3
LC2 10002 (SLS Wind Normal)	6.1	0.3
LC3 10003 (SLS Wind Parallel)	6.4	0.7

Table 8. Relative displacements at art panels

10. Appendices

10.1 Reaction forces at foundations

A summary of the extreme forces at the sculpture base supports is given in Table 9 below.

	Maximum forces and moments at base					
	Fx N	Fy N	Fz N	Mx Nmm	My Nmm	Mz Nmm
Outer Tubes						
Max	5866	8542	41214	9038900	4596900	3816300
Min	-18165	-9590	-36487	-3021600	-12162000	-3898300
Max Abs.	**18165**	**9590**	**41214**	**9038900**	**12162000**	**3898300**
Inner Tubes						
Max	5454	4982	51598	3327700	1419200	943920
Min	-7550	-6561	-45283	-344620	-5032600	-900570
Max Abs.	**7550**	**6561**	**51598**	**3327700**	**5032600**	**943920**

Table 9: Maximum forces at foundations

10.2 Sculpture masses

The total modelled mass of the sculpture is 2960kg including all non-structural masses and contingency (as shown in the table below). A detailed weight study was carried out for the sculpture and adjusted based on the weights of as built tubes available at the time. The expected weight of the sculpture is 2792kg. The modelled sculpture is therefore 6% heavier than the estimated weight, which is within acceptable tolerances.

(Note: none of the weights mentioned above include the metal foundation attachment fittings. These are estimated to weigh a total of 501kg)

	w/o NSM	with NSM	Non-Structural Mass (NSM)				
			Total	3D Printed Formers	Paint	Taping, Coving and Contingency	
Composite Components	**1695**	**2960**	**1265**	**528**	**35**	**702**	**kg**

Table 10. FEA model weight breakdown

10.3 Tube repair specification

Manufacturing tolerances resulted in the finished shape of some tubes differing from their intended shape. These tubes required corrections to their shape in order to interface correctly with the adjacent tubes and maintain the overall shape of the sculpture. These corrections were made by cutting and repairing the tubes at appropriate locations.

In order to minimise the visual impact of the repairs (preventing additional thickness build up), repair of the unidirectional material in the tube laminate was engineered based on the required strength, rather than the strength capacity of the laminate. The tubes are stiffness driven to limit tip deflections. As such the tensile and compressive strength capacity of the laminate is higher than required in most areas, making it unnecessary to match the original capacity with the repair.

This is not the case for the off axis material. Repair of the off axis material matched or exceeded the strength capacity of the original laminate.

For the inner tubes two repair laminates were developed for the different axial strain levels identified in the tubes:

1. Cuts to tubes below 4.5m

   Maximum axial strains in inner tubes, across all ULS load cases, including relevant material factors, determined to be 0.2% tensile and -0.15% compressive, for regions below 4.5m. These occurred in the short term load cases. Reserve factor calculations for number of unidirectional repair layers and lap shear strength are shown below.

	Tension	Compression	
Applied strain	0.200%	-0.150%	
Base laminate modulus	65.1	65.1	GPa
Base laminate thickness	6.75	6.75	mm
Resultant stress	130.2	-97.6	MPa
Resultant force	**879**	**-659**	N/mm
Repair material	UC300 infused, epoxy	UC300 infused, epoxy	
Ply thickness	0.3	0.3	mm
Material strength	1819	410	MPa
Material strength/ply	551	124	N/mm
Number of plies	6	6	
Repair force capacity	**3307**	**746**	N/mm
RF ON APPLIED FORCE	3.76	1.13	
Ultimate lap shear strength	**30**	**30**	MPa
Material Factor	4.5	4.5	
Design allowable lap shear	6.7	6.7	MPa
Total UC300 lap length (per side)	400	400	mm
Design allowable lap shear force	2680	2680	N/mm
RF ON LAP SHEAR	3.05	4.07	

2. Cuts to tubes above 4.5m

Maximum axial strains in inner tubes, across all ULS load cases, including relevant material factors, determined to be 0.1% tensile and -0.1% compressive, for regions above 4.5m. These occurred in the short term load cases. Reserve factor calculations for number of unidirectional repair layers and lap shear strength are shown below.

	Tension	Compression	
Applied strain	0.100%	-0.100%	
Base laminate modulus	65.1	65.1	GPa
Base laminate thickness	6.75	6.75	mm
Resultant stress	65.1	65.1	MPa
Resultant force	439	-439	N/mm
Repair material	UC300 infused, epoxy	UC300 infused, epoxy	
Ply thickness	0.3	0.3	mm
Material strength	1819	410	MPa
Material strength/ply	551	124	N/mm
Number of plies	4	4	
Repair force capacity	2205	497	N/mm
RF ON APPLIED FORCE	5.02	1.13	
Ultimate lap shear strength	30	30	MPa
Material Factor	4.5	4.5	
Design allowable lap shear	6.7	6.7	MPa
Total UC300 lap length (per side)	320	320	mm
Design allowable lap shear force	2144	2144	N/mm
RF ON LAP SHEAR	4.88	4.88	

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