Structural Engineering

Technical Report

Hemo Gorge Sculpture
As Built Testing and Installation Report

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This Report has been Prepared For

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SUMMARY

Rotorua Lakes Council commissioned Gurit to retrospectively issue a PS4 document in respect of the manufacture of the Hemo Gorge Sculpture constructed by Kilwell Fibretube. This involved Gurit making on-site inspections of the completed sculpture just prior to, and during installation, along with a review of any supporting material and QA information in order to verify that the sculpture was built to specification.

Tolerancing issues during installation meant that several of the sculpture inner tubes had to be cut and removed. A visual inspection of the ends of the cut tubes indicated that the laminate was very dry, with several layers peeling apart easily. Based on these observations Gurit initiated a testing program to determine whether the as built laminate was achieving the design strengths. Of the two parameters tested, the interlaminar shear strength (ILSS) achieved a corrected value 44% of the target strength, and the compressive strength achieved a corrected value 192% of the target strength.

Due to the low interlaminar result, Gurit cannot say that the sculpture has been built to the specifications provided.

A review of the analysis model incorporating the low interlaminar shear strength highlighted several areas where the ILSS is above the tested allowable strength, with reserve factors less than 1.0 and elements that have physically failed. However, there are some uncertainties around the model validity in these areas due to the absence of modelling the secondary cove and taping.

There are other mechanical properties that may also be affected by the observations of dry laminate, but these have not yet been tested.

Further investigation is required to verify the structural integrity of the structure, and/or define remedial actions as required.

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1 Overview and Introduction

The Hemo Gorge Sculpture is a 12m tall spiral art installation located at the Hemo Gorge roundabout in Rotorua. The sculpture was commissioned by Rotorua Lakes Council (RLC) and constructed by Kilwell Fibretube out of carbon fibre and e-glass fibre laminated over a 3D printed former. The structural engineering of the sculpture was done by Gurit, who issued a PS1 in respect of this work.

As a result of miscommunication, the requirement for issuing a PS4 in respect of the manufacturing process was not made clear by RLC until after manufacture was complete. Gurit were subsequently contracted by the council to review, where possible, that the sculpture had been constructed to the specifications in the design documentation issued to accompany the PS1.

2 Construction Monitoring and Quality Assurance

As Gurit had been contracted to the level of PS1 only, and not PS4, no structured construction monitoring program was in place. However, some visits to Kilwell Fibretube were made by Gurit during the manufacture of the sculpture as a result of professional interest and to provide clarification/interpretation of the construction documents.

During the visits to Kilwell Fibretube several of the individual tubes were able to be inspected between lamination stages. Where observed defects were pointed out and remedial action was requested and supported with laminate repair specifications. The e-glass sock layers observed (outer tubes, final e-glass layer) did not show any significant dryness, see below.

No completed quality assurance (QA) documentation was able to be provided by Kilwell Fibretube for Gurit to review as of the date of issuing of this report.

Figure 1. Example of outer tube final e-glass sock layer during manufacture

3 Pre-installation Inspection

A visual review of the as built sculpture was carried out by Gurit prior to the sculpture being installed at the Hemo roundabout location.

The aim of this inspection was to verify that:

- Taping laminate extents at chevrons and tube joins appeared consistent with specifications
- Through chevron components had been located and installed correctly
- Joiner tubes were in place as specified
- Visual inspection of laminate quality was consistent with expectations
- Metal base plates had been cut according to drawing dimensions.

Access to the sculpture was available via scaffolding up to approximately 5m (access could have been gained to higher levels but was not considered necessary as the upper portions of the sculpture are less critically loaded).

Spot checks of the taping extents for both the chevrons and tube joins measured as per the specifications. All other visually inspected taping extents appeared consistent with the specifications.

All the through chevrons were located correctly for both the inner and outer tubes and the additional taping required on the opposite side of the tube was present.

The connecting tubes between the main curved tubes were all in place as specified.

Overall, the visual quality of the taping at the tube connections was lower than expected with a high level of wrinkling in many of the taping laminates. Inspection of the wrinkles indicated that they appeared and sounded solid. i.e. they are full of resin, rather than being an air gap/void.
It is difficult to quantify the effect on the taping strength that wrinkling such as this may have. It is noted that expectation often exceeds requirement, particularly in cases such as this, where it is a sculpture not a critical piece of infrastructure. When compared to the tested samples, as per **Error! Reference source not found.**, the level of wrinkling appears similar and the connection testing produced satisfactory strength results.

Figure 2. Example of inner tube connection taping checks

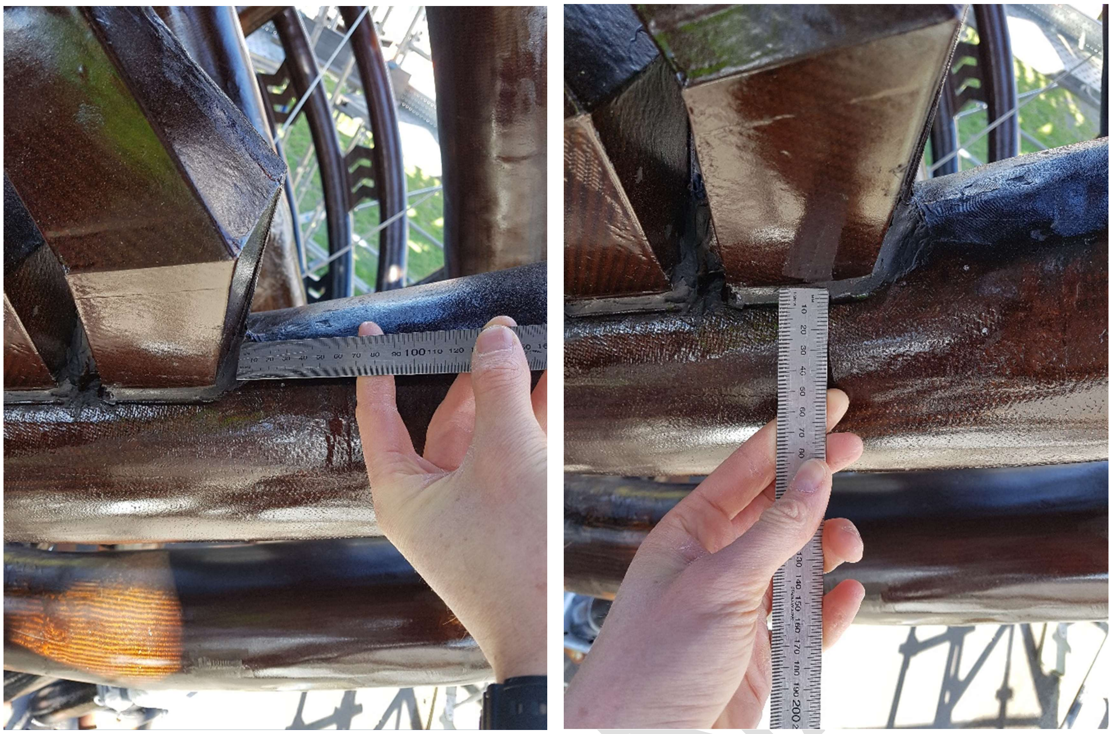

Figure 3. Example of outer tube chevron taping check

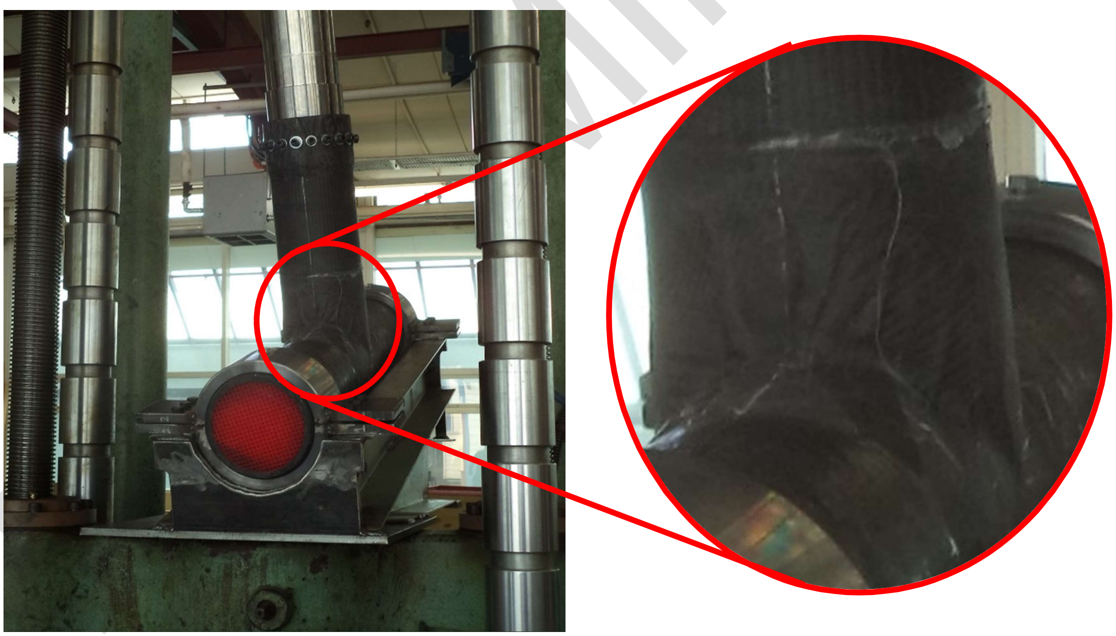

Figure 4. Example of taping seen in tube joint testing

The metal base plates of both the inner and outer tubes were measured and were correct with respect to the issued construction drawings and the cut-outs did not intrude into the minimum area around the individual tubes as specified by the designer.

Prior to the on-site inspection on the 7th August Kilwell Fibretube reported on the complete ‘ready to lift’ weights of the sculpture as provided by their crane contractor when a test lift was done. The weights for the outer and inner tubes were 3100kg and 2500kg respectively.

During installation the crane used to lift the sculpture from the Te Puia carpark into the roundabout reported that the outer tube weight was approximately 2000kg. As this stage it is unsure what the inner tubes weighed when lifted from the carpark, or what the weights measured by the helicopter were, if any.

The estimated weights of the sculpture are 1757kg and 1536kg for the outer and inner tubes respectively. These estimated weights are based on a weight study by Gurit using per metre weights from several individual as built tubes provided by Kilwell Fibretube. An internal peer review by Gurit engineers found no significant errors in the weight estimate.

It is not certain which assembled weights are correct but based on the as built weights of the individual tubes it is likely that the 2000kg number for the outer tubes is correct.

While on site for the inspection the weight of two outer tube offcuts was measured and compared to previous weights that had been provided. The offcuts weighed an average of 6.85kg/m compared to the earlier tubes that were measured at an average of 6.0kg/m, indicating that there was some variation in the tube weights during construction, tending towards the tubes being slightly heavier than expected, in the order of 15%.

This structure is not self-weight critical and added weight is not likely to have a structural significance.

4 Installation and On-site Observations

Installation of the sculpture took place on 12th September. The outer tubes were successfully installed and bolted to the foundation. Inner tube assembly was installed second and lowered inside the outer tube assembly. However, it stuck approximately 1m above the foundation due to an interference between the inner and outer tubes. This interference was likely due to a combination of:

- not enough tolerance in the original geometry
- variations in the tube geometry from the as designed geometry during construction.

Several attempts were made to adjust the position and rotation of the inner tubes to remove the interference, but a solution that allowed the inner tubes to sit correctly on the base was not found on the day.

Retuning on the 14th September a solution was found whereby several sections of inner tubes were cut and removed to allow the assembly to locate correctly on the foundation. The sections that were removed would be rebuilt and reinstalled to pass around the outer tubes.

Cutting of the inner tubes was done with an electric grinder. Several attempts had to be made due to the weight of the remaining portion of tube above the cuts closing the cut and grabbing the blade of the grinder. This also necessitated hammering the section out of the way once it had been cut through.

Figure 5, on the following page, shows the inner tube assembly installed correctly on the foundation and the location of two of the tubes that were cut. A third inner tube, not shown in the image, was also cut. The cuts to the tubes were approximately mirrored on the opposite side of the sculpture. (A total of six inner tubes were cut)

Figure 6, also overleaf, shows two of the ends from the cut tubes. There are clear lines of fracture/delamination that predominantly follow the e-glass sock (white) layers, and sometimes transitioning into the unidirectional layers. Observation of these fractures highlighted:

- The presence of dry, or resin starved, areas particularly in the e-glass sock layers in the middle of the laminate

- Interlaminar fractures. Note that it is possible that the interlaminar fractures could have resulted from cutting and hammering the tubes, or as a result of poor interlaminar strength, itself due to the dryness and poor resin impregnation.

The structural concerns associated with these observations are that there is no support for the load carrying fibres (in this case the unidirectional carbon plies) and when compressed they will fail at a load much less than expected. It was therefore decided to have samples from the cut sections tested to determine whether the defects observed were localised or systematic through the tube(s).

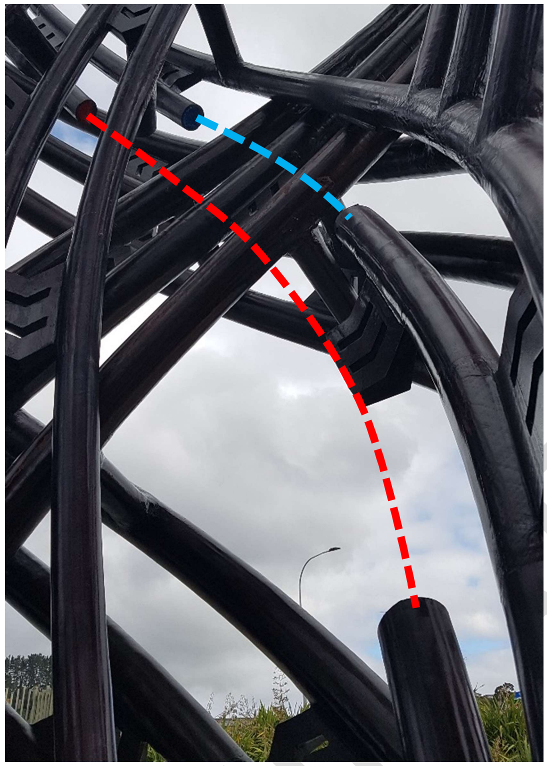

Figure 5. Inner tubes after installation showing locations of cut tubes

Figure 6. Inner tube sections removed during installation showing dry layers and interlaminar fractures/delamination

5 Non-destructive Testing

Prior to carrying out any mechanical testing, an ultrasound scan was performed on the inner tube sections that were removed from the sculpture. Ultrasound testing is often used with composite components as a non-destructive test method capable of establishing the presence of voids/porosity and delamination within the laminate. It was hoped that by ultrasounding the cut section a baseline level of laminate quality could be established and then linked with the planned mechanical testing results. Subsequent tubes could then be ultrasounded on site, if required, and compared back to the baseline.

The ultrasound test found that it was very difficult to get any meaningful backwall reading from the tube laminate when measuring directly from the finished surface. It was possible that the paint finish may have been preventing a good signal transmission. However, an excellent signal was able to be obtained through the painted finish on the connecting tubes (that were manufactured using a different process, specifically a high quality pre-preg process). It was therefore likely that the laminate porosity was very high, or that there was delamination between the layers, preventing the ultrasound signal from penetrating into the laminate thickness of the main tube.

In an attempt to gain a better reading, the outermost layers of carbon and e-glass woven sock were removed in two local areas of the tube. The signal was slightly better when measured in these areas, and a broken backwall was observed at a depth of 1.1mm. This depth roughly corresponds to the thickness of the group of four unidirectional layers that make up the next portion of the laminate, prior to another woven e-glass layer.

Figure 7 shows a comparison of the scan results from the main tube section compared with that of a connecting tube. The main inner tube section was produced using a combination of wet-vac hand lamination and infusion, over the 3D printed former. The connecting tube, being straight, was able to be manufactured using pre-preg material over a steel mandrel. This is a higher quality process and results in more compaction of the layers and lower voiding/porosity.

From the image on the right we observe, for the connecting tube, a clear laminate with minimal echo through the thickness, then a solid backwall echo at 5.1mm corresponding to the measured thickness.
The left-hand image, of the main tube, shows a partial backwall at 1.1mm and then a very faint echo beyond, showing the ultrasound is unable to penetrate the laminate to the measured thickness of 8.9mm

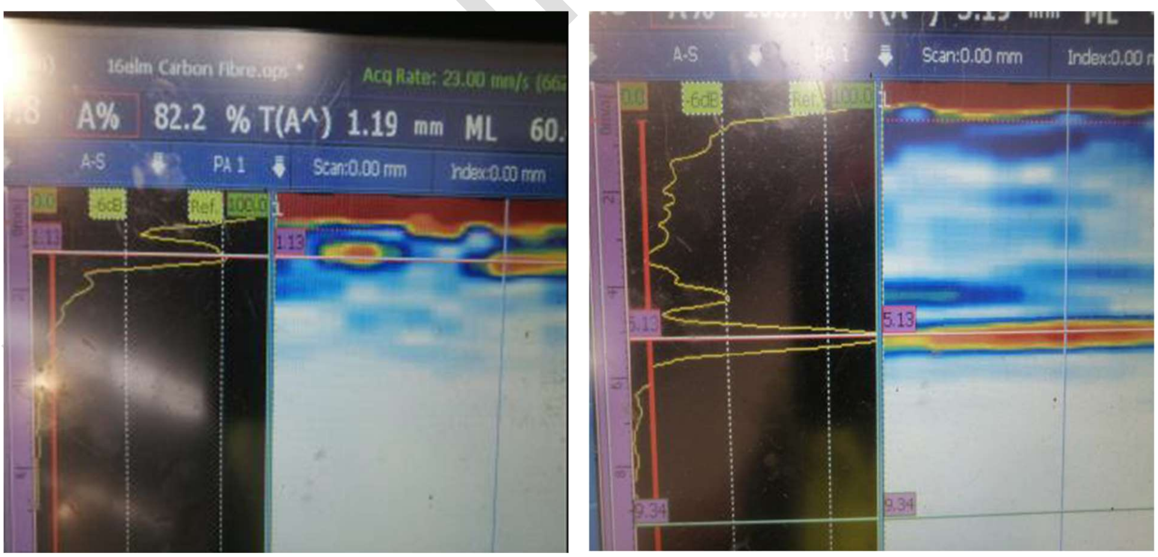

Figure 7. Ultrasound results. L - main tube, poor response with variable backwall at 1.1mm depth. R – connecting tube, excellent response with solid backwall at 5.1mm depth

If the main inner tube had produced a reading of similar quality to the joiner tube, the laminate would have been considered of high quality, and the observed defects of the previous section judged to be isolated/caused by removing the tube.

Instead the ultrasound readings obtained indicate that the defects observed are likely to be spread throughout the tube(s). Such a reading in the aerospace industry would not pass a QA check and the part would be rejected. As there is no definitive standard for composite quality measurement by NDT/ultrasound in the civil industry it leads us to destructive testing as a means of verifying whether the observed defects compromise the structural integrity of the sculpture.

For the full NDT report refer to the following report attached at the end of this report:

- *J57785.1 - PO.402754 - 20.09.17 - Sculpture Tubes.pdf*

6 Mechanical Testing

Mechanical testing was carried out on specimens cut from a 250mm long section of one of the inner tubes removed from the sculpture. The purpose of this testing was to verify the as built strength properties of the laminate.

Two properties, Interlaminar shear strength (ILSS) and compression strength, were chosen to be tested. These two properties were chosen for several reasons: Interlaminar strength is a good indicator of overall laminate quality, measuring how well the individual layers are bonded to each other; compressive strength is a critical property directly effecting the structural stability of the sculpture; and the specimen shape for both of these tests (long rectangular strips) can be easily cut from the available tube section.

The following ASTM test procedures were used to carry out the tests:

- ASTM D2344 Short Beam Strength of Polymer Matrix Composite Materials and Their Laminates
- ASTM D6641 Compressive Properties of Polymer Matrix Composite Materials Using Combined Loading Compression Fixture

Nine specimens were prepared for each test to allow characteristic strength values to be calculated.

During preparation of the samples the end of the remaining cut tube (away from on-site cut/hammered region) was cleaned and inspected. See Figure 8 overleaf. This showed a moderate level of voiding/porosity, predominantly at the interface between the e-glass sock layers and the blocks of unidirectional material. However, the unidirectional layers themselves appeared to be predominantly free from voids and evenly consolidated. Several areas of the e-glass sock layers at the cut surface were visibly fluffy/dry.

Figure 9, pg. 14, shows one of the interlaminar shear test samples where the fracture from the cut end had propagated along the length of the sample and the layers were able to be cleaved apart by hand with minimal force. Inspection of the e-glass layer along the line of separation showed dry or resin deprived areas and areas were there was no resin and the layer was not adhered to the adjacent laminate at all. This sample was not used for testing.

Both tests were conducted in Gurit's IANZ accredited test laboratory.

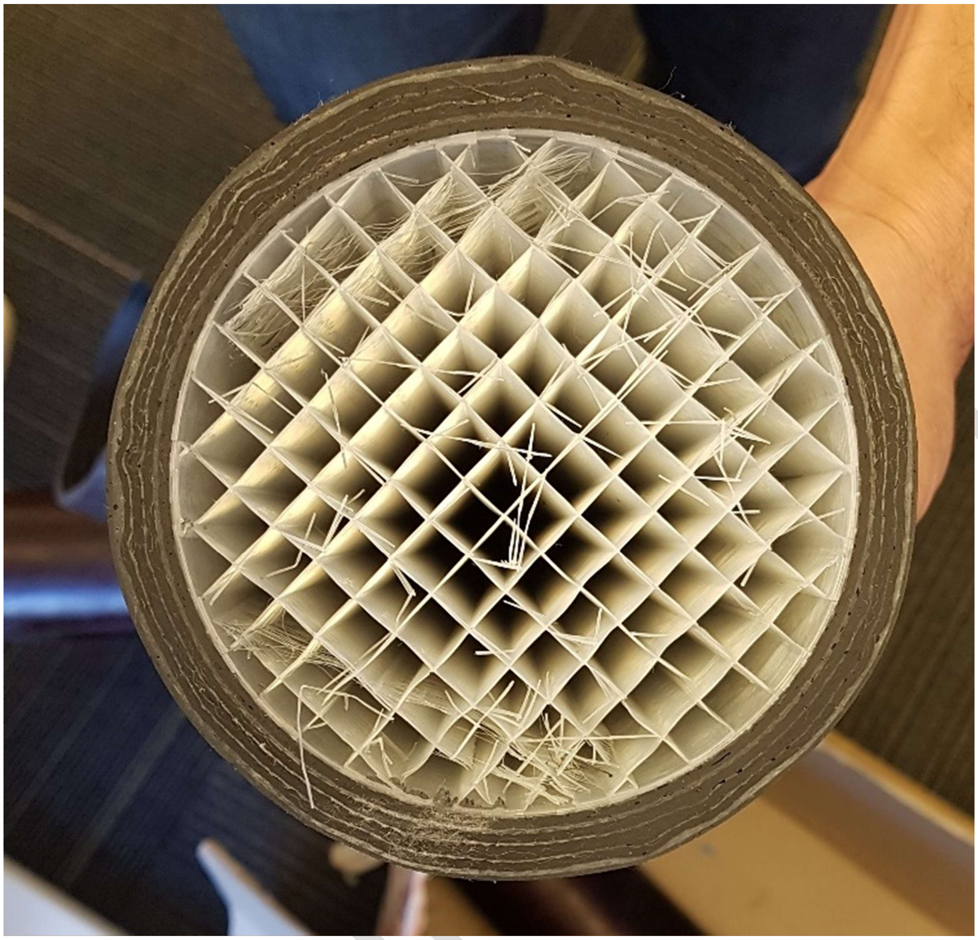

Figure 8. cross section of inner tube used for testing samples

Figure 9. Sample from inner tube section. Top - showing delamination at e-glass layer after first unidirectional stack. (inside of tube facing up), Mid – layers once taken apart, Btm – showing completely dry portion of e-glass layer.

The mechanical testing established that:

- The characteristic[1] interlaminar shear strength of the inner tube sample, not including material factors (see explanation below), is 11.7MPa, being 34% of the normal design value
- The tested laminate allowable interlaminar shear strength, accounting for the appropriate material factor (MF = 1.66 for tested laminates as per Eurocomp Design Code), is 7.0MPa, being 44% of the design allowable used in the analysis
- The characteristic compressive strength of the inner tube sample is 2205kN/m width, being 74% of the normal design value, but 148% of the result based on ply testing carried out earlier in the project.
- The tested laminate allowable compressive strength, accounting for the appropriate material factors, is 1328kN/m, being 192% of the design allowable used in the analysis.

As per the design basis report (*GU6706-6001 Rev B Hemo Gorge Sculpture Design Basis Report*) and the design report (*GU6706-6002 Rev A Hemo Gorge Sculpture Design Report*) material factors have been applied, as per the Eurocomp Design Code for Composites, to account for the level of uncertainty in the material properties. The level of uncertainty is based on: the level of testing which is performed, the material and processing techniques used in construction, and the environmental conditions of the operating environment. Essentially as you move through the project and testing is done on materials and laminates or parts that more closely represent the final article the material factor reduces.

For the interlaminar strength no testing was done until the laminate testing discussed in this report. The design value used in the analysis was based on Gurit's typical value, believed to be capable of being achieved by competent laminators. There was thus a large material factor applied to account for uncertainties. The characteristic value for ILSS of the as built inner tube came in at 34% of the typical value. Even with a smaller material factor, this tested allowable strength is still below the design allowable strength.

For the compressive strength, testing was done on the individual plies of both the unidirectional material and the carbon woven sock (but not the e-glass sock). The results of these tests, when applied as a laminate, produced a compressive strength approximately 50% of that expected based on our typical values. When accounting for the reduced material factor due to the ply testing this improved to 76%. The material properties used in the analysis of the sculpture were therefore reduced to match this result from the ply testing. Thus, while the as built compressive strength came in lower than Gurit's typical compressive strength value, it is higher than the ply testing value used in the analysis.

The information in the above two paragraphs is illustrated graphically in Figure 10 and Figure 11, overleaf.

The implications of the low interlaminar shear strength are discussed in section 7.

For the full test results refer to the following test reports attached to this report:

- *GU6706 Test Results - Apparent Interlaminar Shear Strength - ASTM D2344 - RevA.pdf*
- *GU7231 Test Results - Compressive Strength and Modulus - ASTM D6641 - Rev A.pdf*

[1] Characteristic values are used to account for variability in the test results. In the case of the testing referred to in this report characteristic values have been calculated such that there is 95% confidence that no more than 5% of any tested samples could be expected to return a value less than the characteristic value.

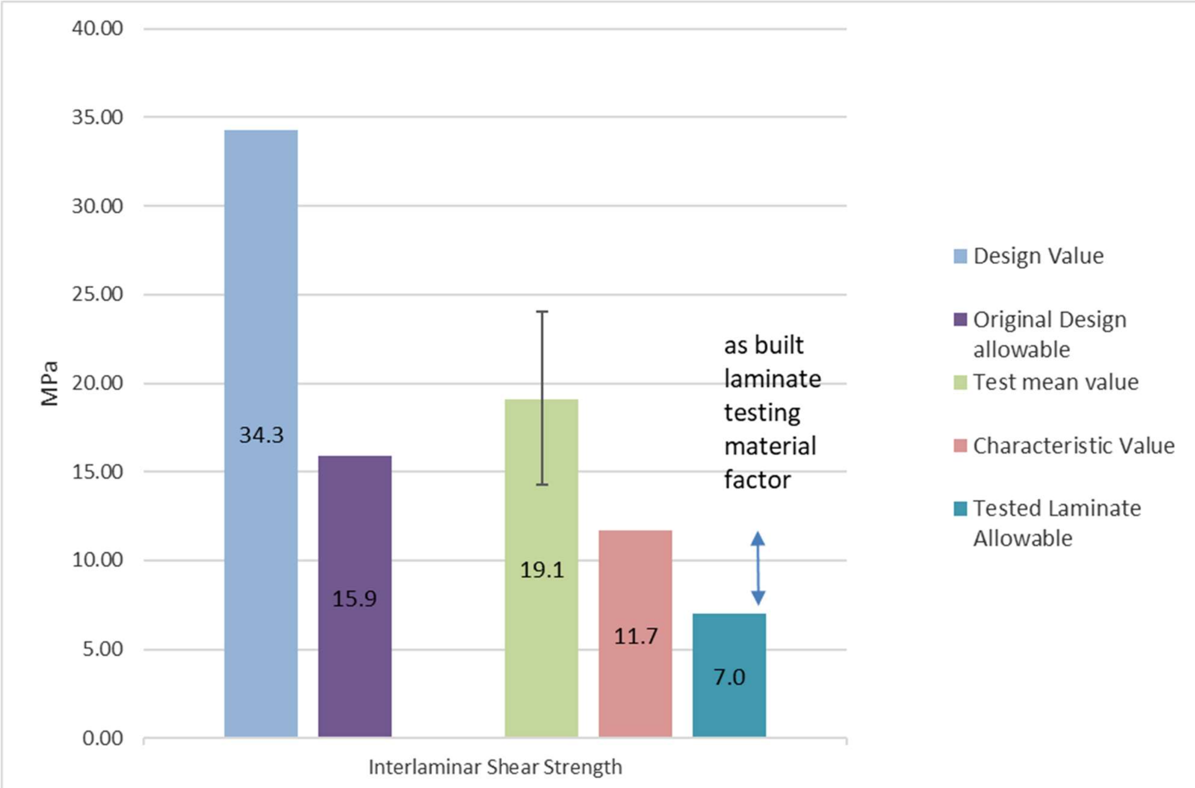

Figure 10. Interlaminar shear strengths

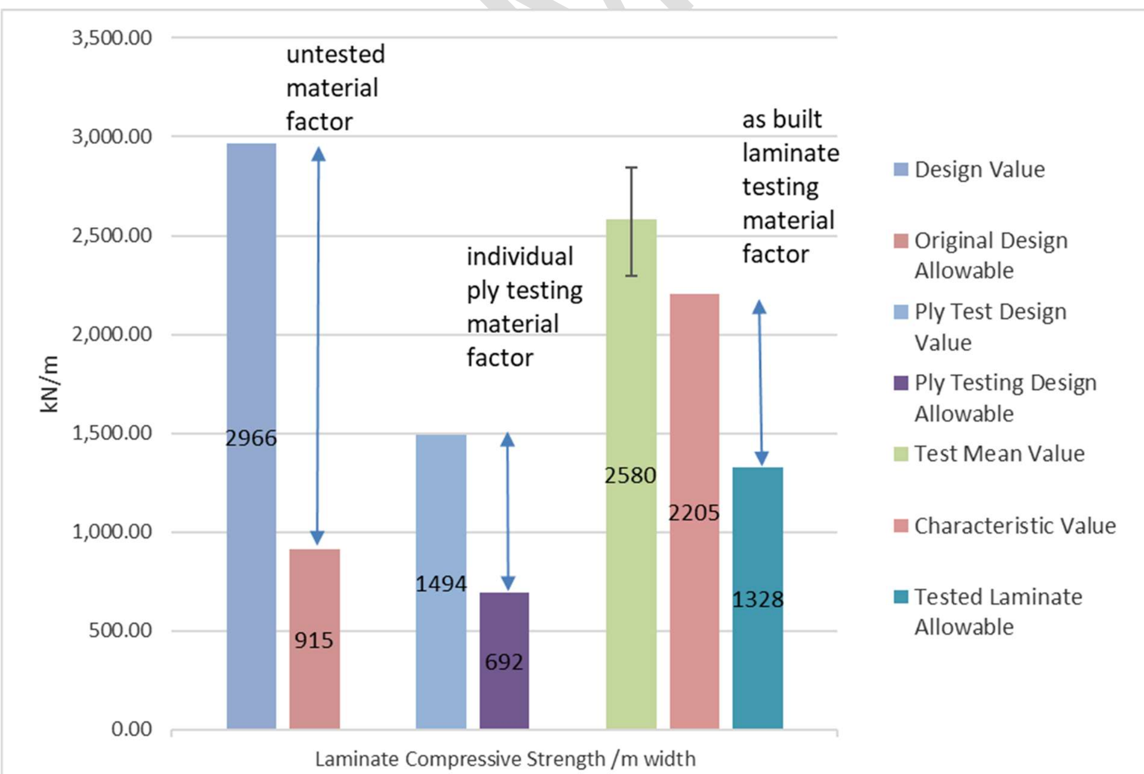

Figure 11. Compressive strengths

7 Structural Review

A brief review of the analysis model used in the design of the sculpture has been carried out using the lower ILSS property from the as built testing. Results from the original analysis were factored to account for the reduction in ILSS and the change in the material factor. Looking at the short-term load cases (the most onerous), this showed that the reserve factor on ILSS reduced from 1.03 to 0.45. The areas that have reserve factors less than 1.0 are predominantly in the outer tubes at the tube connections and at the connecting tubes between the inner and outer tubes. This is shown in Figure 12 below.

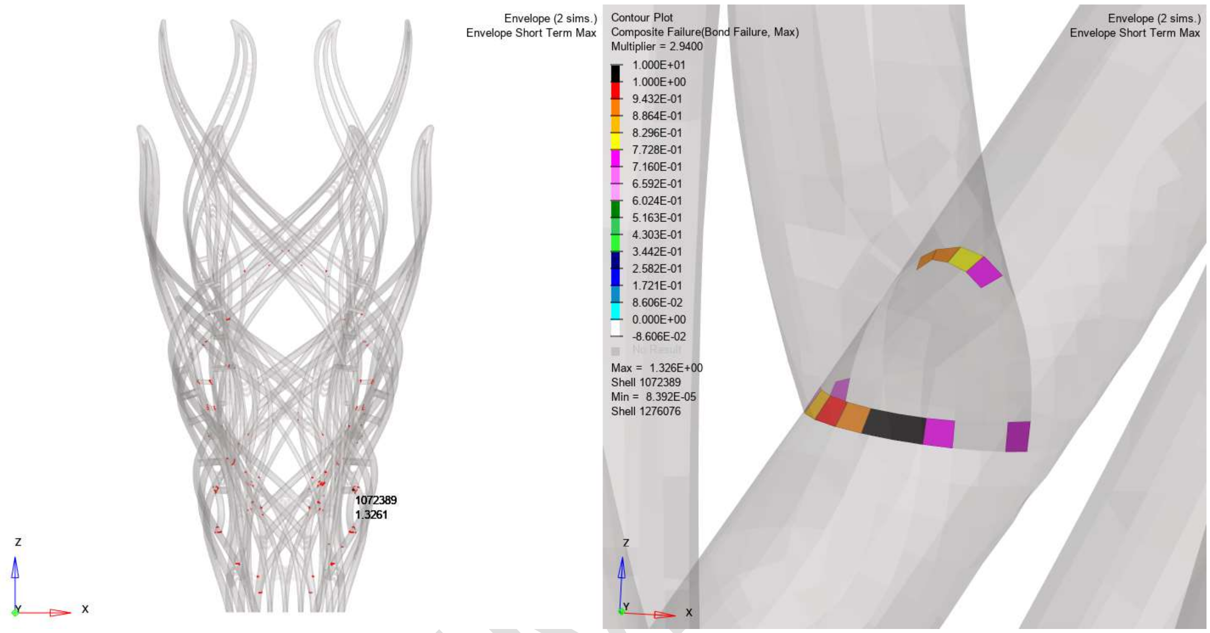

Figure 12. Short term load cases. Bond failure index factored to represent tested ILSS. L – elements with RF <1.0 highlighted in red, R - tube connection showing elements with RF <1.0

The model shows that some elements not only above the requirement but are physically failing.
However, the locations of these elements all fall within areas where there is some question around the model validity as items such as the glue coving and secondary taping are not modelled, and the stresses shown may be exaggerated as a result.

Proof testing was also carried out during the project on a representative ‘T’ connection. This was constructed at full-scale using straight sections of tube matching the outer tube geometry and laminate. The connection was loaded such that it applied the maximum stresses expected in the connection, which were derived from the analysis. The connections tested achieved the target test load without failure.

However, there is no assurance that the quality of the as built structure matches the quality of the tubes used in the testing.

8 Discussion

Visually, the laminate from the tube cut-out appeared to be very dry, particularly in the hand laminated e-glass sock layers. It was possible to clearly see gaps within the weave. The unidirectional layers also did not appear to be wet out correctly in some areas, again identified by gaps between tow bundles.

Given the time and cost constraints directly after installation, the mechanical testing was focused on only 2 mechanical properties, ILSS and compression, being the most practical and critical to test.

The compression strength being OK, means that the bulk of the structure is fit for purpose. In that sense it is not likely to fail catastrophically in the short term.
The ILSS shortfall indicates that laminate is defective and the review of the model indicates that this is likely to be an issue at the connections. This could result in progressive damage to the connection over time and reduce the expected lifespan of the sculpture.

There are other mechanical properties that are likely to be affected by the defects observed and are also important in way of the connections, such as:

- In plane shear
- Circumferential bending
- Interlaminar tension
- Peel

These are more difficult to test, and further discussion is required to determine if testing is appropriate.

We cannot prove whether the defects observed are isolated or systematic throughout the inner and/or outer tubes. It is therefore necessary to discuss the level of confidence which is required and how much more testing may be required to achieve this.

There are a number of potential solutions that could be investigated to ensure the structural integrity of the sculpture:

- Change to the expected lifespan to reduce the design loads. Extension of lifespan could be achieved by regular inspection.
- Refinement of the analysis method to validate the areas of concern in the modelling.
- Updated analysis to include progressive failure effects, as opposed to pass/fail criteria.
- Remedial lamination to areas of concern.
- Remedial work via means of additional members/structure.

Further review and discussion is required to evaluate the potential solutions in order to determine which is the best course of action.

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