Structural Engineering

Technical Report

Hemo Gorge Sculpture
As Built Inner Tube Connection Test

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Issue and Amendments

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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. Observations of dry fibres in one of the inner tubes lead to additional coupon testing of key laminate properties using the as built tube laminate. This testing indicated an interlaminar shear strength below the design value.

Upon review of this result it was determined that further testing should be carried out at full scale to verify whether the tube connections were still capable of withstanding the design loads. This testing was carried out on the same section of inner tube that was used for the coupon tests.

The full-scale testing was carried out at a mechanical testing laboratory at SCION in Rotorua. The connection was loaded to a proof load and held, then loaded to destruction. The connection performed well, holding the proof load with no damage and then continuing to a failure load above that predicted by analysis.

Based on the results of the full-scale testing Gurit is satisfied that the low interlaminar strength observed in the coupon testing has not compromised the ability of the sculpture to perform as intended.

TABLE OF CONTENTS

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.

During installation it was observed that one of the tubes appeared to have dry areas within the laminate. Test coupons were cut from the tube in question and strength tests were performed at Gurit's mechanical testing laboratory. The testing produced a low interlaminar shear strength (ILSS), below the design strength used in the analysis of the sculpture. Additional analysis incorporating the test result showed areas of the sculpture, primarily around the connections, with strength margins below the target reserve factors.

As the coupon testing does not capture the influence of the geometrical shape of the sculpture it was decided to conduct full scale testing on the connection that was part of the tube from which the test coupons were cut. The results of this testing would determine if the as built connection strength was acceptable for the design.

2 Influence of low interlaminar shear strength

A review of the reserve factors on interlaminar shear strength was undertaken to understand the effects of the low value returned by the coupon testing. Interlaminar shear strength was not a property that was tested during the design phase of the project, thus Gurit's typical strength property was used in the analysis and factored accordingly.

The structural design phase showed that there was no issue with interlaminar shear with the analysis model showing all elements being below the target failure index of 0.4630. The highest element had a failure index of 0.4382, meaning there was a reserve factor of 0.4630/0.4382 = 1.06. This is shown in Figure 1, below.

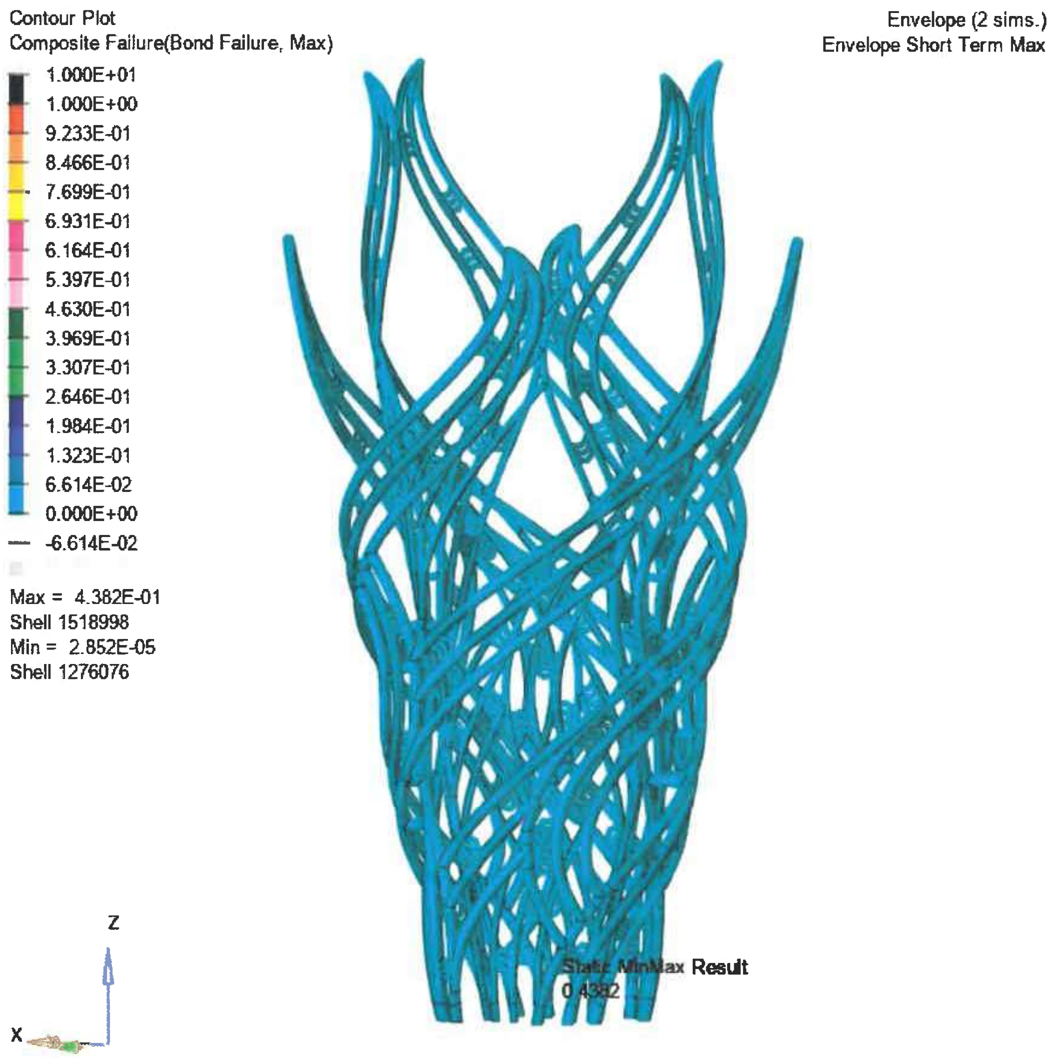

Figure 1. Bond failure index, as designed, prior to test result

To see the effects of the low interlaminar shear strength from the coupon testing, the model results were factored up by the ratio between the design strength and the tested strength:

$$\text{ILSS Factor} = 36.6/11.7 = 3.13$$

When this is applied to the analysis model there are 861 elements that exceed the target failure index (non-compliant), and 43 of these elements have a failure index greater than 1.0, meaning the model considers that the elements have failed (physical failure). Refer to Figure 2, on the following page.

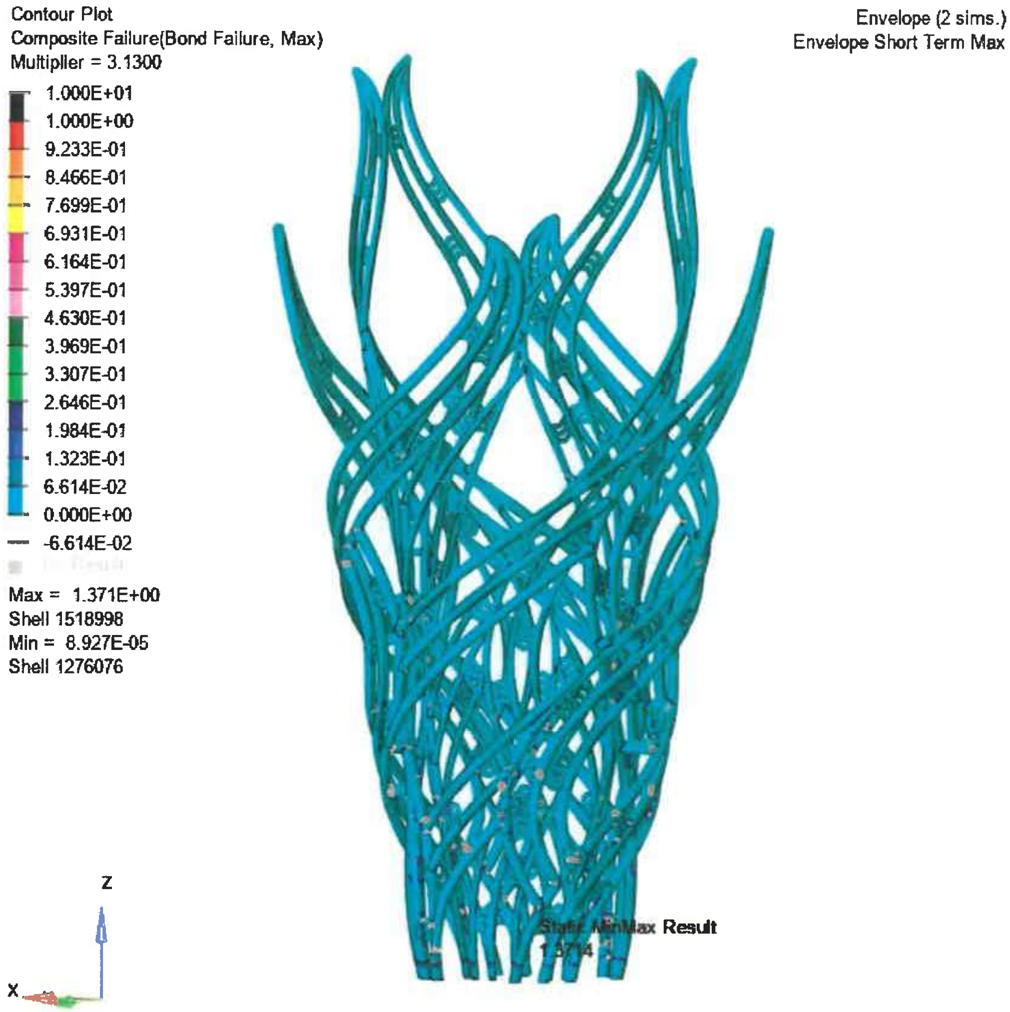

Figure 2. Bond failure index, factored to match test results. Elements exceeding target highlighted in red

In designing the connection test it was found that, due to the difference in geometry of the larger diameter outer tube and the smaller diameter inner tube available for the test, it was not possible to generate the maximum ILSS in the test assembly without risking a failure in the inner tube via the secondary mode of compression in the circumferential direction, due to bending across the tube. Such a failure would invalidate the test. Instead the point of maximum ILSS from the inner tubes was used to design the connection test. See Figure 3. The outer tubes have a 19% higher maximum ILSS than the inner tubes.

The point of maximum interlaminar shear in the inner tube assembly occurs at one of the joiners between the inner and outer tubes. The geometry of this area is similar to that of the inner tube available for testing.

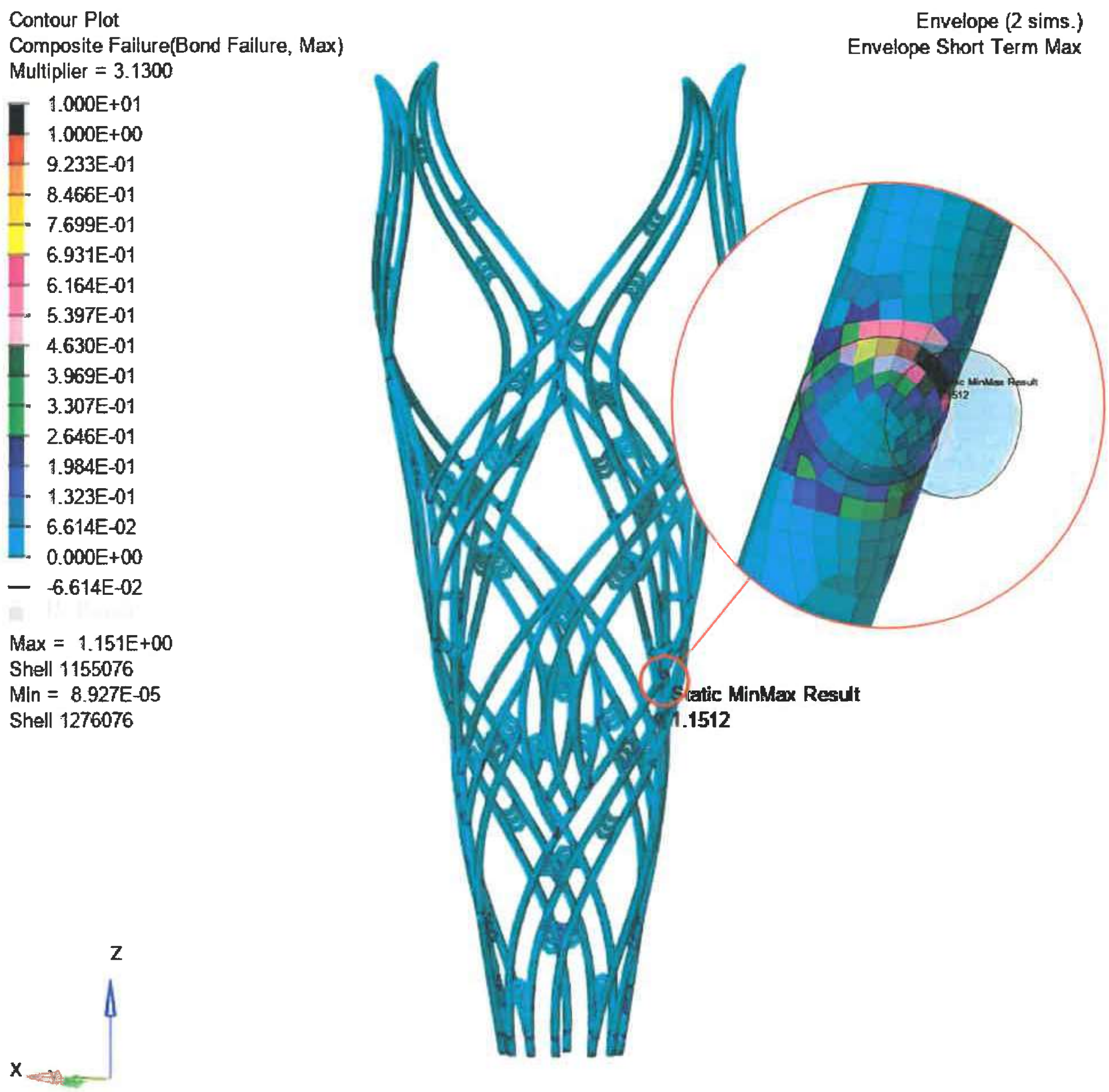

Figure 3. Bond failure index, factored to match test results. Inner tubes only

3 Derivation of testing methodology

The initial steps towards designing the test to validate the interlaminar shear capacity were to extract the loads required to generate the maximum ILSS at the connection and then apply these to a model of the full scale test, so that an equivalent test load could be calculated.

Using the free body tool available in the analysis software the forces and moments were extracted from about the inner tube connection identified above as having the highest ILSS.

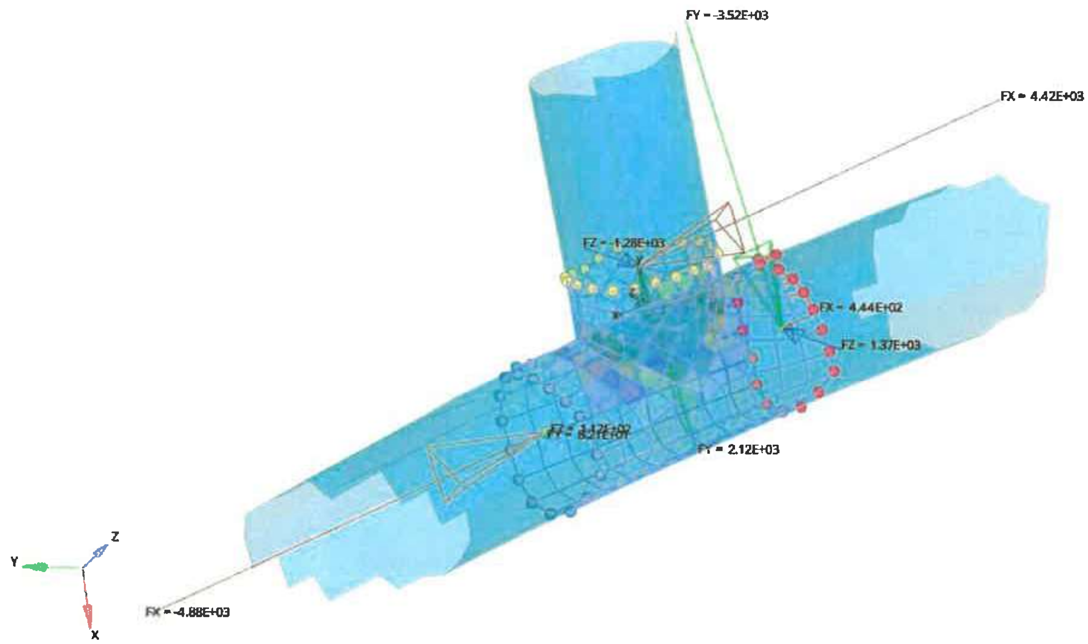

Figure 4. Extraction of free body forces from model (moment vectors not shown for clarity)

The loads were extracted relative to a local co-ordinate system aligned with the axis of the joiner tube and the inner tube. Out of plane loads, relative to this co-ordinate system, were small and were not considered as part of the testing.

By adjusting the geometry of the test model, a compressive force vector was found that produced the same level of interlaminar stress in the inner tube as the full model. See Figure 5 on the following page.

The applied load to generate this stress state was 11,606N, which represents an equivalent to the ULS stress state in the full model.

Taking guidance from *AS/NZS1170.0-2002 Appendix B – Use of Test Data for Design* a successful test will withstand the appropriate limit state, in this case ULS, including any other appropriate factors to be applied depending on the materials used. Thus, the proof load for testing was determined as the ULS state multiplied by the material factor derived from the *Eurocomp Code for Composites.*

Test Proof Load = ULS load x Eurocomp Material Factor
= 11,606N x 1.66
= 19,266N

The test loads along with their equivalent failure index values are summarised in Table 1, on the following page.

Figure 5. Test model bond failure index

	Test Load (N)	Factor to ULS load	Bond Failure Index Tested	Bond Failure Index Designed	Ply Failure Index
SLS	9,262	0.80	0.92	0.30	0.58
ULS	11,606	1.00	1.16	0.37	0.72
Proof Load	19,266	1.66	1.92	0.61	1.20
Expected Failure [1]	31,379	2.70	3.13	1.00	1.96

1. Assuming as designed ILSS property

Table 1. Test load table showing corresponding bond failure index

4 Test setup

Figure 6, below, shows the tube assembly installed in the mechanical testing rig. The inner tube and attached joiner tube were cut to length to produce the correct load ratio and additional laminate was added in way of the fasteners to prevent bearing failure in the composite laminate. Machined steel end fittings were then bolted and bonded into the ends of the tubes. Steel adaptors were constructed to attach the tube assembly to the testing rig.

Figure 6. tube assembly installed in mechanical testing rig

5 Results

The results of the connection test are presented graphically in Figure 7 to Figure 9 below, and overleaf.

The proof load test shows the two initial load steps to SLS load, where the load was held for 5 minutes then released, before loading to the ULS load and again holding for 5 minutes, and finally increasing the load again to the proof load and holding for 15 minutes (note: an error in the data recording cut short the trace after 5 minutes, so the full 15 minute hold is not shown)

The increase in displacement at approximately 7,500N was attributed to settling of the fixtures. This feature was observed each time the load passed through this range.

The max load graph shows a relatively linear increase in load to around 55,000N, after which it starts to taper off. There was an audible crack at 63,000N, which corresponded to the slight drop in load seen at this point on the graph. The connection continued to hold load up to a maximum of 72,357N at which point explosive cracking was heard and the main tube was visibly seen to have failed in compression just outside the extents of the joiner tube taping, as shown in Figure 10 on page 14.

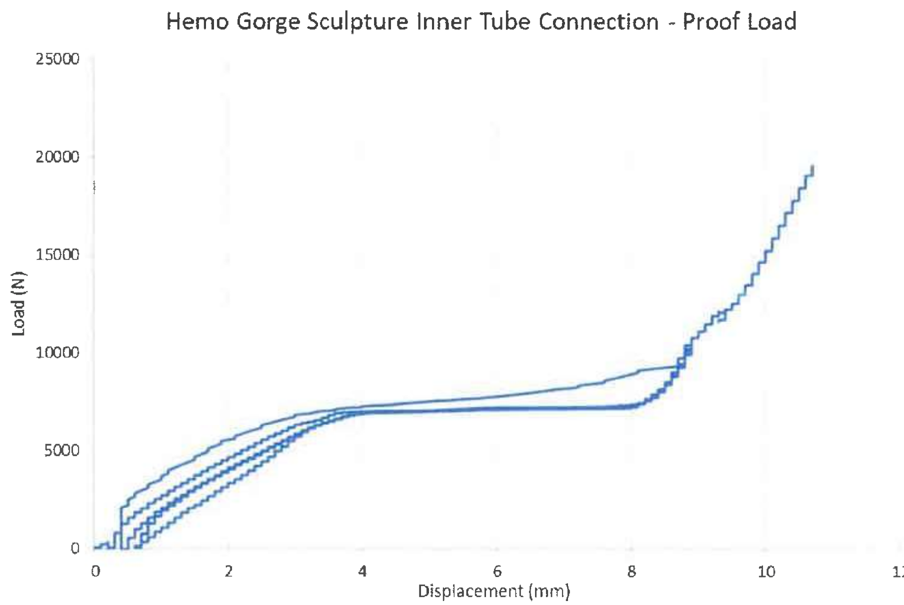

Figure 7. Proof load test, load vs displacement

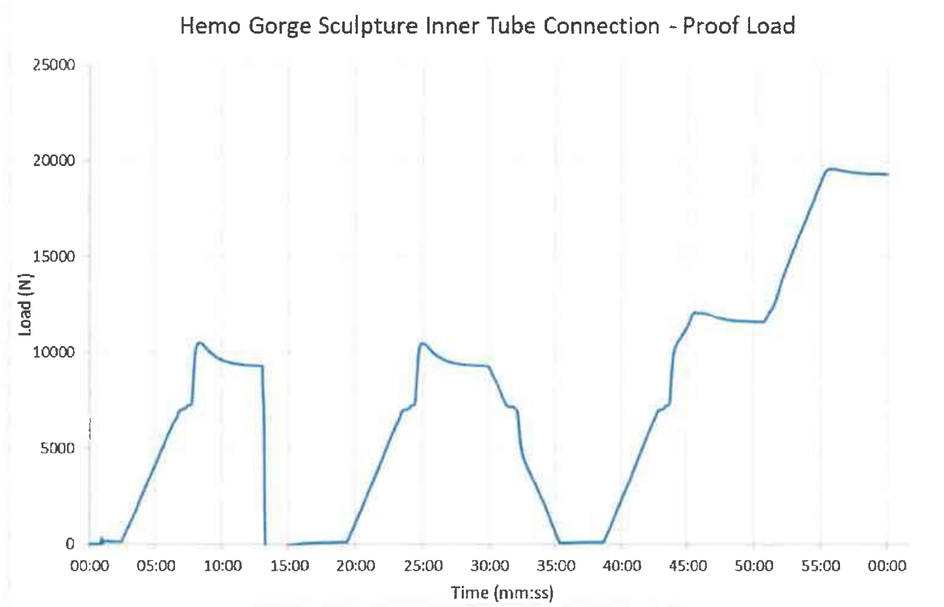

Figure 8. Proof load test, load vs time

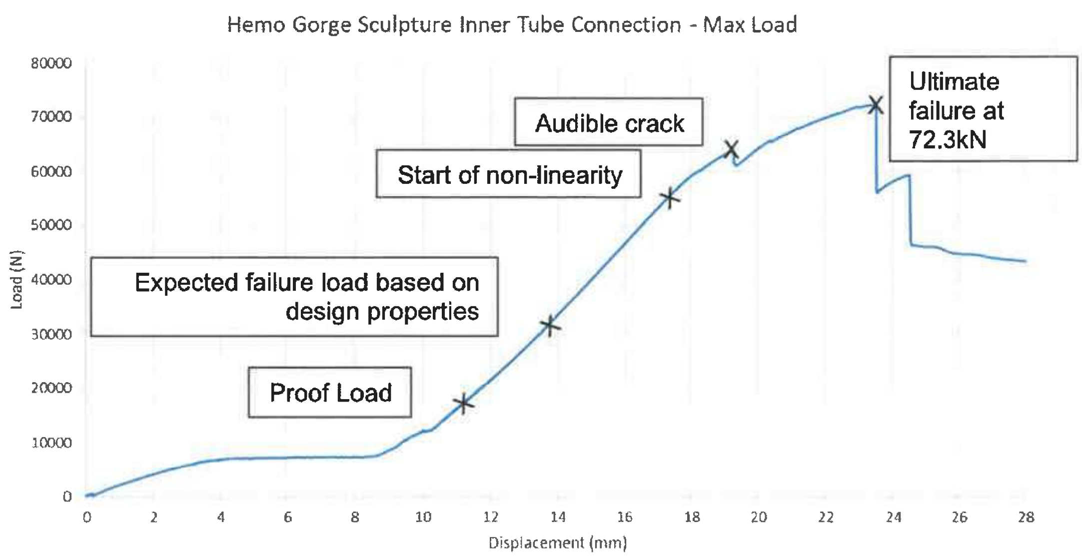

Figure 9. Max load test, load vs displacement

Figure 10. Post max load test, showing compressive failure in inner tube

6 Conclusions

A successful test was carried out on the inner tube connection. The test assembly withstood the calculated proof load with no visual or audible damage and was subsequently loaded past the expected failure load to a final compressive failure at 72,357N. This load is 6.2 times the load at which the analysis predicted interlaminar shear failure due to the low interlaminar strength from the coupon tests. From this perspective we can consider that the inner tubes in the sculpture have the capacity to withstand, and likely exceed, the design loads.

This margin also gives comfort that the maximum interlaminar shear stress in the outer tubes, which is only 19% higher than that in the inner tubes, will be well within the capacity of the as built laminate (620% higher).

Based on the results of this testing Gurit is satisfied that the low interlaminar strength observed in the coupon testing has not compromised the ability of the sculpture to perform as intended.

Appendix A – Connection test construction details and methodology

Refer: *GU7231-802 A Hemo Gorge Sculpture As Built Inner Tube Connection Test Appendix A.pdf*