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Dear Shane,

This letter and accompanying report constitute my and Adam's analysis of the mechanical test specimens, fatigue tested tapestry and information in the document entitled "Eisenhower Memorial Tapestry Engineering and Technical Data Summary Volume 2: Tapestry Technical Data Summary, all provided to NIST by the NCPC.

A summary of the significant points:

1. Nothing in the corrosion tests nor in the fatigue specimen would lead us to believe that the materials are inadequate for the application.
2. The corrosion behavior is consistent with previous tests, and does not change the recommendation that 317L is the best choice of the candidate materials.
3. Significant variation in the strength of the welds was reported, and can be directly traced to variability in the degree of penetration and, in the case of twisted and woven braids, the number of sub-wires participating in the weld.
4. A close examination of the analysis by Najjarine Structures of the thermal loads on the panels found considerable errors, and leads one to suspect possible errors in other analyses. There was insufficient time to check over all of their work but, to whatever extent these results bear on assumptions such as the maximum expected weld load of 1.7 pounds on the tapestry structural welds, the errors found should be kept in mind.
5. The 3' x 3' tapestry sample panel prepared by the design team, a picture of which is attached to this report, appears largely unaffected by the fatigue test, however it is noted that nearly 2% of the structural welds were unsuccessfully formed during fabrication, and aesthetically the resulting panel does not look very much like the CAD drawing presented or the tapestry mockups previously prepared by hand.
6. The proscribed cleaning regimen of a worker scrubbing with a brush while perched 60 feet in the air, or using a power washer, will very likely cause

loads on the structural welds of the tapestry well in excess of the expected 1.7 pounds.

Please feel free to contact me with questions or comments, and also please let us know the schedule and procedure for returning the panel and samples to whomever.

Regards,

Tim Foecke, PhD
Leader, Mechanical Performance Group, Materials Science and Engineering Division

More detailed analysis of issues in the report, and things to consider going forward:

1. Fabrication conditions of the test specimens

Pages 6 through 11 of the Element report in Section 4.4 describe the measured strength of the welded cables under different combinations of wire (structural and artistic) and loading (shear, peel, torque). Note that for each combination of wire, the weld settings reported were slightly different, which is assumed to have been necessary to form welds from the different wire types (twisted and braided), but complicates inter-comparisons. The various weld settings that were used are reported in the matrix included in Section 4.2.

2. Analysis of the strength of welds by other parties

The structural weld analysis on Pages 10 and 11 of the Najjarine structural report in Section 4.4 states that the expected load on the structural wires is 1.66 lbs, and the load on the artistic wires is 0.37 lbs. Intuitively, this seems low even for the self loading of the weight of the multi-layered sections of the tapestry. We've done our best to digest the analysis by Najjarine of the wind, ice, self and thermal loadings on the vertical structural and horizontal non-structural wires within the time we have available, and it appears that some of the analyses are incorrect. We shall describe a singular example of the thermal loads (Section 4.4: Mechanical Strength Analysis, Page 6 of 11).

- In the analysis, the lengths of the spans are given as 36 inches in the horizontal and 24 in the vertical, with areas and moments of inertia calculated for the twisted cables that assume a structure of a solid wire of the same diameter. Coefficients of thermal expansion are specified, as well as temperature changes that are somewhat low but not totally unreasonable of 60 degrees for "mean" and 120 degrees for "total". The change in length and stress are calculated for the "mean" temperature range (cooling from the average temp to the low for the year), and it is found that the increase in stress for the horizontal is 16.6 ksi due to thermal contraction. This stress, with the area of the braid, is used to calculate the change in load to be 51 pounds.

- The next equation attempts to calculate the shear load on the weld using the relation for the bending in a beam fixed at two ends under a point load

$$V_{\Delta,v} = \frac{48\Delta_{ex}E_{ss}I_w}{L^3}$$

where Δ_{ex} is the change in length of the horizontal wire (0.5mm), E is the elastic tensile modulus of stainless steel, L is assumed to be L_v (the vertical wire length) but the subscript is cut off in the text, and I_w is the moment of inertia of the braid. It comes up with a horizontal force of less than 1/40th of an ounce.

This analysis is incorrect. The calculation essentially finds the force applied to a vertical wire by a horizontal wire IF the horizontal wire is, for some reason, disconnected from the frame on one end, and is able to apply the full contraction of 0.5 mm of the horizontal wire to the vertical one. If the horizontal wire were disconnected, that would constitute a much greater structural problem than worrying about the loads on the weld. The correct answer is that if the frame and wires were heated or cooled, as it is made of essentially all the same material, it would shrink and expand uniformly, and the lateral pull of the welded joints would be zero, and thus the stresses on the welds due to thermal effects would be zero. An important caveat is that this analysis is for a single pair of wires, and applies to any uniform distribution of wires on the frame. This would be imbalanced if the art wire were non-uniformly distributed on the panel, but the effect is small. The analysis also assumes that the frame is not absolutely secured such that it cannot freely expand and contract, which appears consistent with the design.

It is possible that this was intended to be some sort of worst-case analysis of the maximum pull of a horizontal wire on a welded connection to a vertical one. However, no narrative of this was provided and it is purely speculation on our part. If so, the conditions for this scenario (horizontal wire with 1 functional weld at the extreme end to one vertical wire with the end of the horizontal wire detached) are extremely unlikely.

Other assumptions that are in error in this analysis are:

- That the bending moment of inertia for a wire and a braid of the same diameter are equal. Braids are MUCH less resistant to bending then wires - by design.
- That the welded joint is the full diameter of the wire. However, based on the samples prepared a maximum of 20% was observed.
- That failure will be in tension when in reality it will be in shear, which is weaker in metals than tension.

This is the only part of the Najjarine Structures report that we were able to analyze in detail, and the errors in this part would cause us to be concerned about errors in other analyses. This is an important point, as other tapestry design and performance parameters such as the minimum weld strength may come from these other analyses.

3. An analysis of the failure load data

Based on the measured strengths in the Element Report of Section 4.4, the Najjarine structural report in Section 4.4 uses the following values to compare the expected load on the cables:

- For the structural cables, values were taken from 2B Joint Type 1 (316L Structural 7x7 Twisted Wire to 316L Structural 7x7 Twisted Wire), showing an average breaking load of 36.4 lbs under torque loading, and 42.2 lbs under peel loading.
- For the artistic wire, combination values were taken from 3B Joint Type 2 (316L Art 1-16 Braided Wire to 317L Structural 7x7 Twisted Wire) showing an average breaking load of 12.4 lbs under torque loading and 11.8 lbs under peel loading.

Based on these mean values and the expected loads on the wires re-stated above, the structure seems very robust. However, these are the average values and there is significant variation in the weld strengths from sample to sample. Inspecting the data for 2B Joint Type 1, the minimum tested values are 26 lbs torque and 36 lbs peel for the structural wire, a decrease of 10 lbs and 8 lbs respectively. For the artistic wire 3B Joint Type 2, the minimum tested values were 0 lbs under torque loading and 6 lbs under peel loading, a decrease of 12 lbs and 6 lbs respectively.

It is worth noting that two of the welds failed before testing (#117 and #173) with a stated strength of 0 lbs. A microscopic examination of these welds revealed that the welding procedure created no joint and only heat tinting (Sample #117) and a joint that consisted of a single wire from each braid that was half burned through (Sample #173).

The mechanical property data for Samples #1 to #5 gave a mean shear strength value of 50.4 lbs. Page 4 of the Element report in Section 4.4 refers to the variation in the weld regions but performs no calculations to account for or quantify the variability, however it is possible to make an attempt. Assuming the welds to vary as a bell curve, the standard deviation is 9.8 lbs. Despite a limited sample set size (5) to work with, we can estimate a confidence interval of 95% (that is, 95% of all welds would have strengths within this range plus and minus from the mean) of ±27.1 lbs. For a confidence interval of 99%, the range is ±44.95 lbs. In this case, 1% of the welds would be outside of this distribution, or 0.5% of all welds would have a strength less than 5.45 lbs and 0.5% of the welds would have a strength greater than 95.35 lbs.

The initial guess that five samples would adequately quantify the variability of the welds strengths seems to have been underestimated, and given our experience with mechanical testing of many different materials systems and geometries, was contrary to our expectations. The observed degree of variability, which is likely due to variability in the bond area and degree of penetration of the welds (see below), is unexpectedly large. As with all investigations of mechanical strengths of structures, an initial estimate is made based on experience, and adjustments are made as the data begins to be generated. In this case, the initial estimate was low due to the unforseeably large variation in weld geometries.

Summing all of the tests together for both as-welded samples and corrosion tested samples (235 tests), two (2) samples failed at "0" (0 structural, 2 artistic), which is a failure rate of 0.8%. This value is fairly close to the assumed confidence interval predicting 0.5% of welds to fail at loads less than 5.45 lbs, shown previously. Ten (10) samples failed at loads less than 10 lbs (0 structural, 10 artistic) which is 4.2% of the population of samples. Combining both sets, there are 12 total tests below 10 lbs, which is 5.1% of the population of the tests.

The variation in weld strengths is attributable to the differing number of wires participating in the welds of the different samples. When welding cables, the number of wires participating in the weld is not going to be a constant, despite the application of consistent weld settings, and it affects the character or geometry of the joint. If there are too many wires, the power from the spot weld is distributed with too little power per wire, causing incomplete heating of the weld zone. If too few wires are participating in the weld, the power is distributed with too much power per wire, and the wires may completely melt rather than weld together.

An example providing evidence of this is shown on pages 25 to 28 of Section 4.3. Sample #19 failed at 68 lbs, and it appears that 13 wires participated in the weld. Sample #23 failed at 36 lbs, and only 5 wires participated in the weld. Page 10 of the structural engineering section of Section 4.4 assumes a total contact area of 20%, which in the structural cable would be approximately 10 wires in each cable. An example on Page 23 of the Element report in Section 4.4 shows a weld with a single strand participating in the weld failing at a load of 5 lbf. The example shown on Page 14 of Section 4.3 indicates that only two to three wire strands participated in the weld, and that the artistic wire and structural wire may participate differently in the weld. Further confirmation of this conjecture would be gained through examination of all the wires, however, this is made difficult by the weld interaction zones being masked by lighting, or the wires themselves, in the Scanning Electron Microscope and optical images shown in Section 4.3.

4. Observations from the fatigue specimen:

Little damage attributable to the fatigue test could be seen.

It was noted that the tension in the horizontal structural cables was many times that of the vertical structural cables, which were nearly slack. Reason unknown.

It was noted on the plastic overlay that came attached to the fatigue specimen that 18-19 welds had failed before fatigue testing. Of these, we determined that 8 were welds of the horizontal-to-vertical structural cables. We further estimate that the art obscured approximately 60% of these structural connections from observation. Thus, of the 1,000 main structural welds, 400 were visible (unobscured by art), and eight (or 2%) were unsuccessfully formed during fabrication. As these were the welds that presumably were the most consistent in terms of weld equipment power settings, tip access, geometry, etc, perhaps it could be assumed that this is a lower bound for an estimate of the non-completion rate of welds during fabrication of the panels.

It is noted that the few structural welds that failed during the fatigue test were located adjacent to welds that were not formed during fabrication of the panel. It is possible that the loads on these welds were increased during the fatigue test by having to bear the loads from the un-welded joints. It is also possible that the insufficient power settings applied to the incomplete welds corrected itself after making a few bad welds, but in the transition made a weak weld that eventually failed in fatigue. It is not possible to make an unambiguous determination of cause and effect.

The imagery of the fatigue sample appears quite different than what is depicted in the CAD file, and particularly when compared to the artistic tapestry mockup previously prepared by hand. This potentially could have an effect on the results of the weld strength testing, and actual performance of the tapestry, if the designer's ultimate intention is to bring the imagery of the mechanically fabricated tapestries closer to what the artistic mockup looks like.

5. Cleaning regimen

It was stated in the document that the tapestry could be cleaned once a year by a worker in a lift using a soft brush with soap and water. In other documents, funding for and mentions of a power washer are made. The forces on the welds due to either cleaning procedure are not explored, but it is our contention that either technique would produce loads well in excess of the expected 1.7 pounds of load per weld. For example, for a 900 psi pressure washer hitting a 1/16th inch diameter braid, (assuming an impact pressure of the full 900 psi and a very conservative estimated square impact area of the diameter of the braid), the load on the wire is approximately 4 pounds. If the water fan hits the braid in the long direction of the fan, the load can be several times this.

6. Combined loading scenarios

The report details the maximum expected loadings due to wind, ice, seismic, etc loadings individually, but does not consider them in combination, nor as mentioned above does the report detail the loadings expected under the proposed cleaning regimen.


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