Swage Panel Analysis and Verification

Ship Design and Material Technology Panel

National Steel and Shipbuilding Company

Initial Design & Naval Architecture

Issued: MARCH 2011 – Revision (-)

Contents

Project Overview

The goal of all U.S. shipyards, as they push to meet world class standards, is to reduce the overall cost of ship design, construction, and life cycle maintenance for all customers. In order to reach this goal, they must continuously research and employ cost cutting concepts and practices used in modern ship design and construction across the world.

One such cost cutting practice is the application of swaged bulkheads (also called swedged, pilaster or crimped bulkheads), which are widely used in Japan, Korea and Europe. In the United States, their application is limited in large part due to the lack of data proving the structural characteristics of the concept.

Swaged bulkheads, similar in design to corrugated bulkheads, use a single steel plate that is pressed or swaged to form “bumps” at spacing similar to that of normal stiffeners. The swage geometry can be adjusted to increase rigidity and overall strength. A typical swaged section is shown in Figure 1.

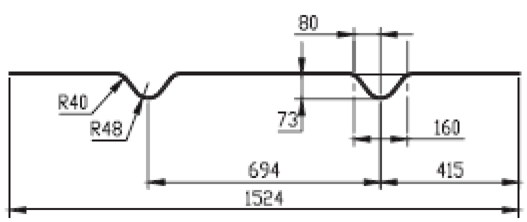


Figure 1. Typical Swaged Bulkhead Geometry

Swaged bulkheads have been demonstrated to provide significant cost benefits when compared to traditional stiffened bulkheads, due to decreased welding, reduced part count, and improved paint application. In addition, they have less total bulkhead depth, and in some applications use lighter plate, which makes them particularly attractive for applications in thin scantling structures typical for naval surface ships.

The goal of this project was to provide a body of useful data comparing the calculated and actual strength characteristics of swage bulkheads to assist design engineers in selecting these configurations for reduced cost construction alternatives.

In this project, swaged panels and stiffened panels were designed and analyzed using finite elements and then tested under compressive and shear load profiles at the University of California, San Diego’s Charles Lee Powell Structural Laboratory. Strain gages were used to collect data, which provided a comparison between the strength of both panels and a comparison between measured and calculated values.

During the course of this project, a deeper understanding of the possible applications of this technology has created the realization that further research and testing should be done to maximize benefits returned to the industry.

Technical Overview

Design Concept

The shapes and dimensions of the two panels were chosen based on literature research. The selected swage panel configuration has characteristics reflecting swage panels approved by ABS and in use on an existing NASSCO-built vessel. Additionally, the necessary fixtures to create the swaged panel were available, which greatly simplified the panel's construction. The stiffened panel was designed to match the swaged panel's section modulus, which was considered most important for comparing relative strength characteristics of the two sections. The swaged section is shown in Figure 2.

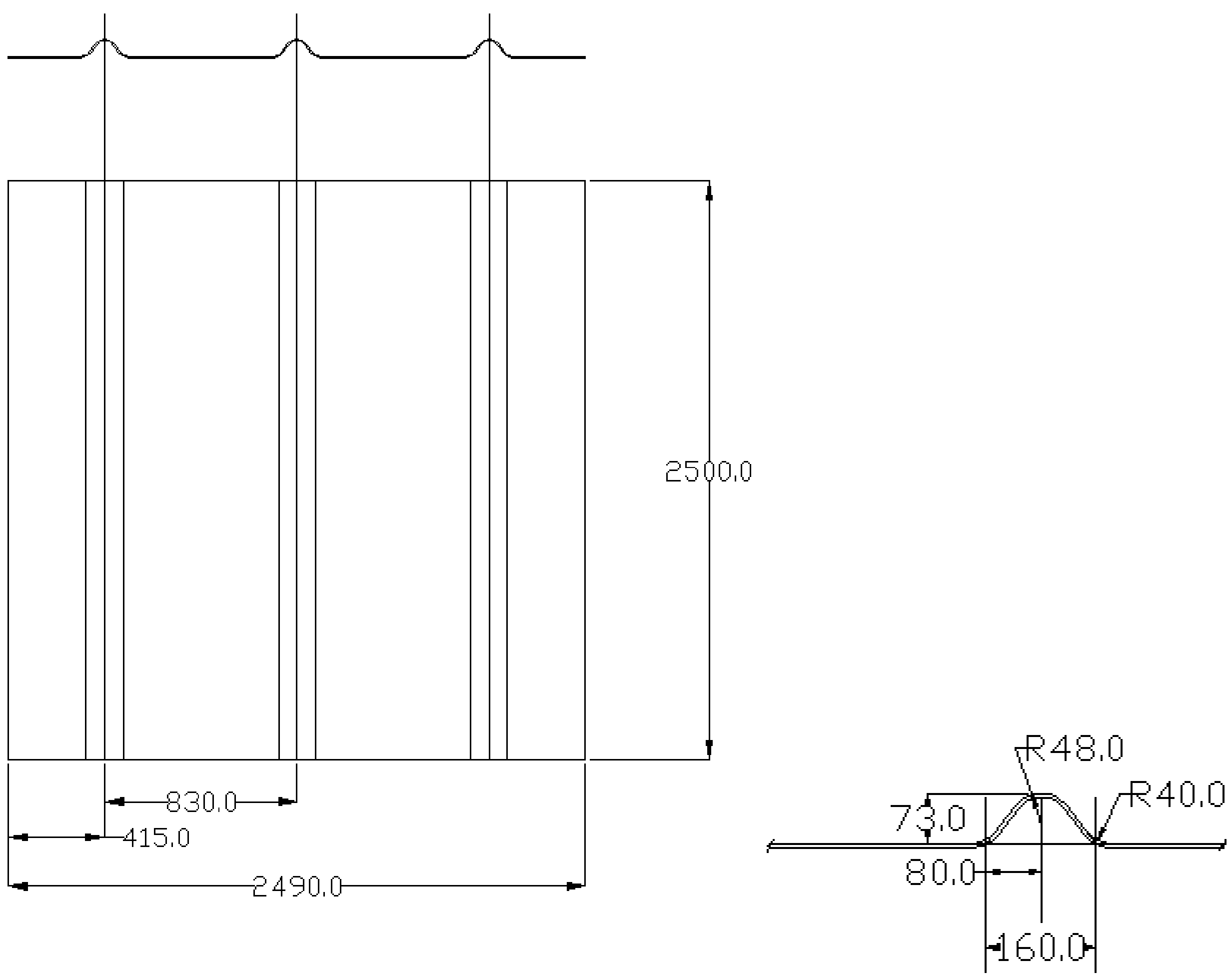


Figure 2. Swaged Panel Concept Dimensions (mm, 6 mm thick plate)

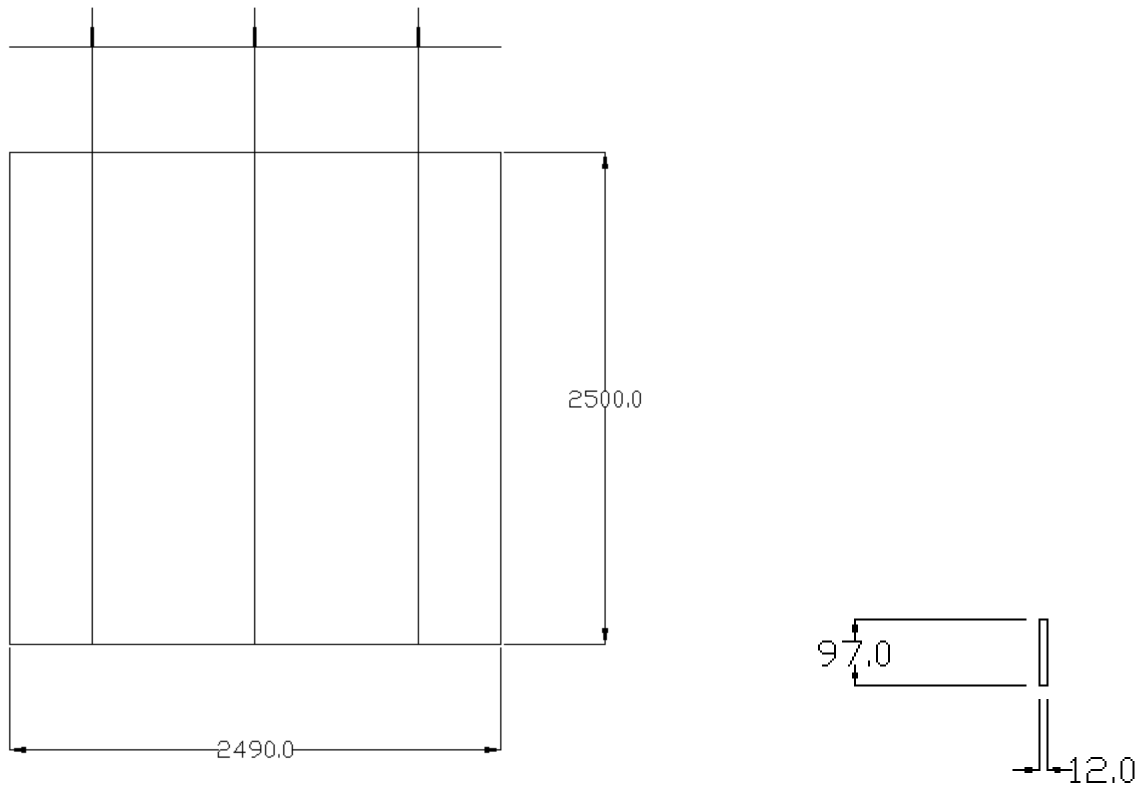


Figure 3. Stiffened Panel Concept Dimensions (mm, 6 mm thick plate)

Figures 4 and 5 give the section properties of the swaged and stiffened panels, respectively.

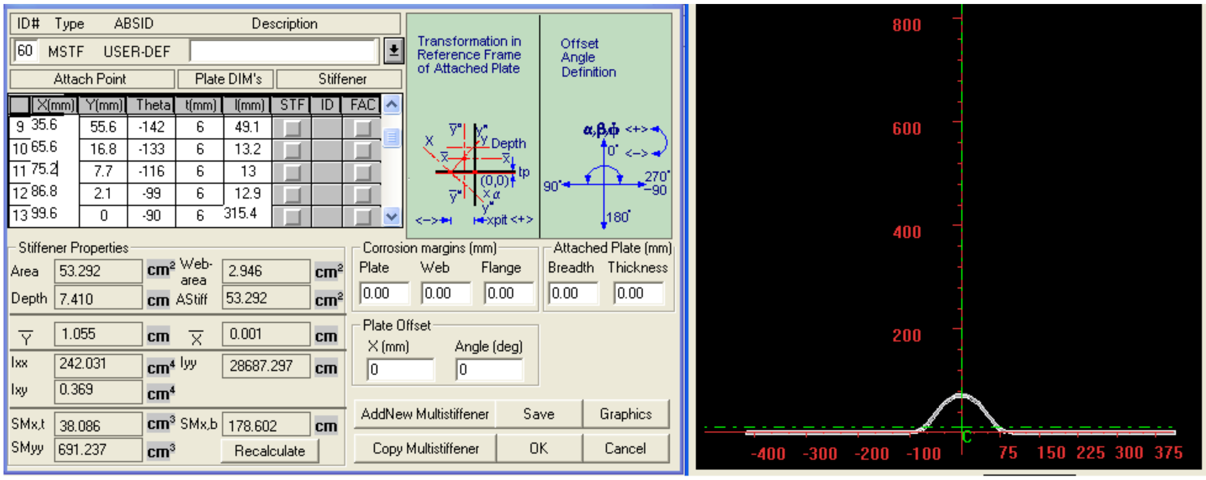


Figure 4. Swage Panel Section Properties

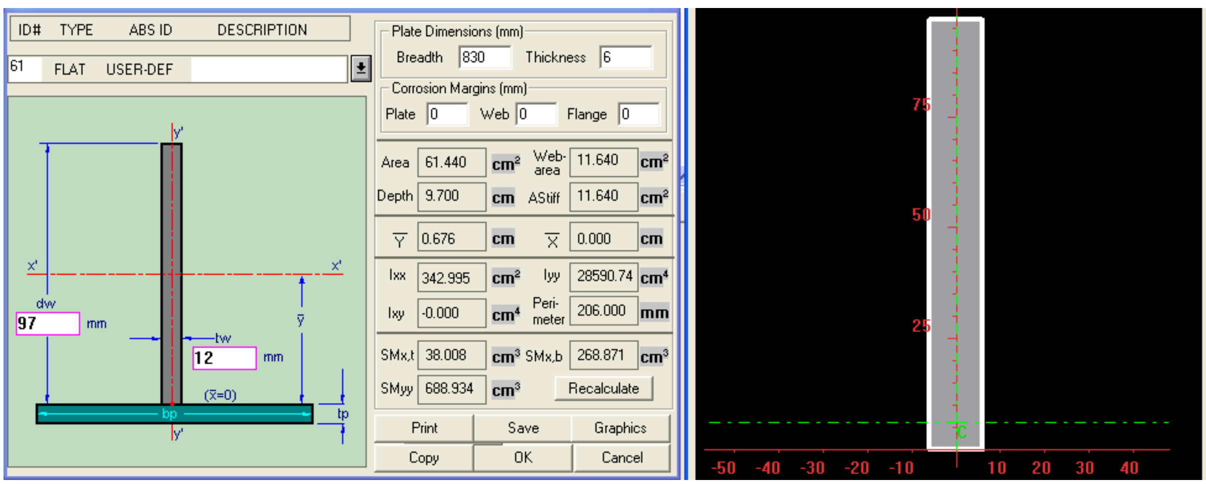


Figure 5. Stiffened Panel Section Properties

Table 1. Section Properties Summary

	Stiffened	Swaged Panel
$SM_{x,t}$	38.008 cm^3	38.086 cm^3
SM_{yy}	688.934 cm^3	691.237 cm^3
Area	61.440 cm^2	53.292 cm^2
I_{xx}	342.995 cm^4	242.031 cm^4
I_{yy}	28590.74 cm^4	28687.297 cm^4

Configuration Design

The initial concept design was modified through an iterative process to achieve the desired boundary conditions and testing configuration. GD NASSCO worked with the Structural Engineering Department at the UC San Diego to perform the tests of the swaged and stiffened panels.

Utilization of UC San Diego's testing facility offered a well-controlled environment, providing the best results possible. The shear and compression load profiles were each tested in specially designed configurations.

Shear Load Arrangement

For the application of shear loads, two identical panels were tested simultaneously in order to create the appropriate boundary conditions. Square tubes were utilized to simulate the stiffness that would be provided on an actual ship by decks above and below a bulkhead. The two panels were connected by a steel square tube with the load applied at one end. The outside edges were also attached to square tube members, which were rigidly fixed. The load was applied to the center square tube, imposing a shear load across both panels.

Both the stiffened and swaged panels were specifically designed to meet the requirements of this style of shear testing, which was selected by the NASSCO team after discussion with the testing team at UC San Diego Powell Labs.

A. Shear Loading – Stiffened Panel

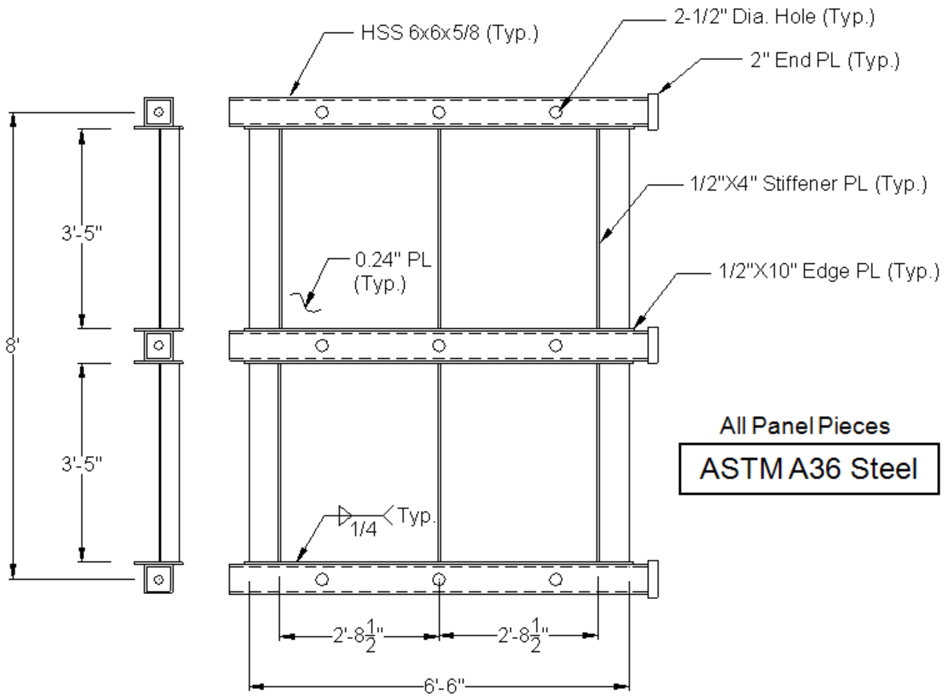


Figure 6. Shear Load Arrangement for Stiffened Panel.

B. Shear Loading – Swaged Panel

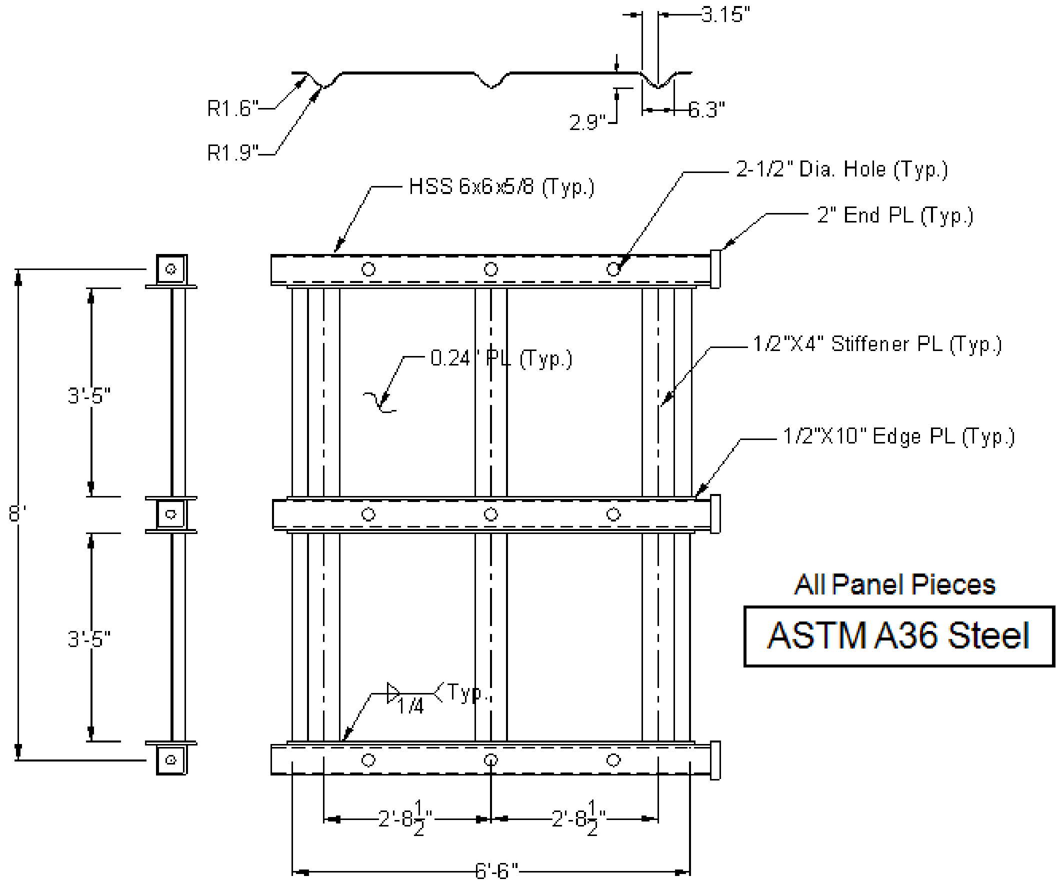


Figure 7. Shear Load Arrangement for Swaged Panel.

Compressive Load Arrangement

For the compressive load profile, the specimens were designed to fit within the SATEC Universal Testing Machine at UC San Diego Powell Labs. This provided a large financial savings in combination with controlled load application.

Both the stiffened and swaged panels were designed with a specialized I-Beam to distribute a compressive load from the Testing Machine.

C. Compressive Loading – Stiffened Panel

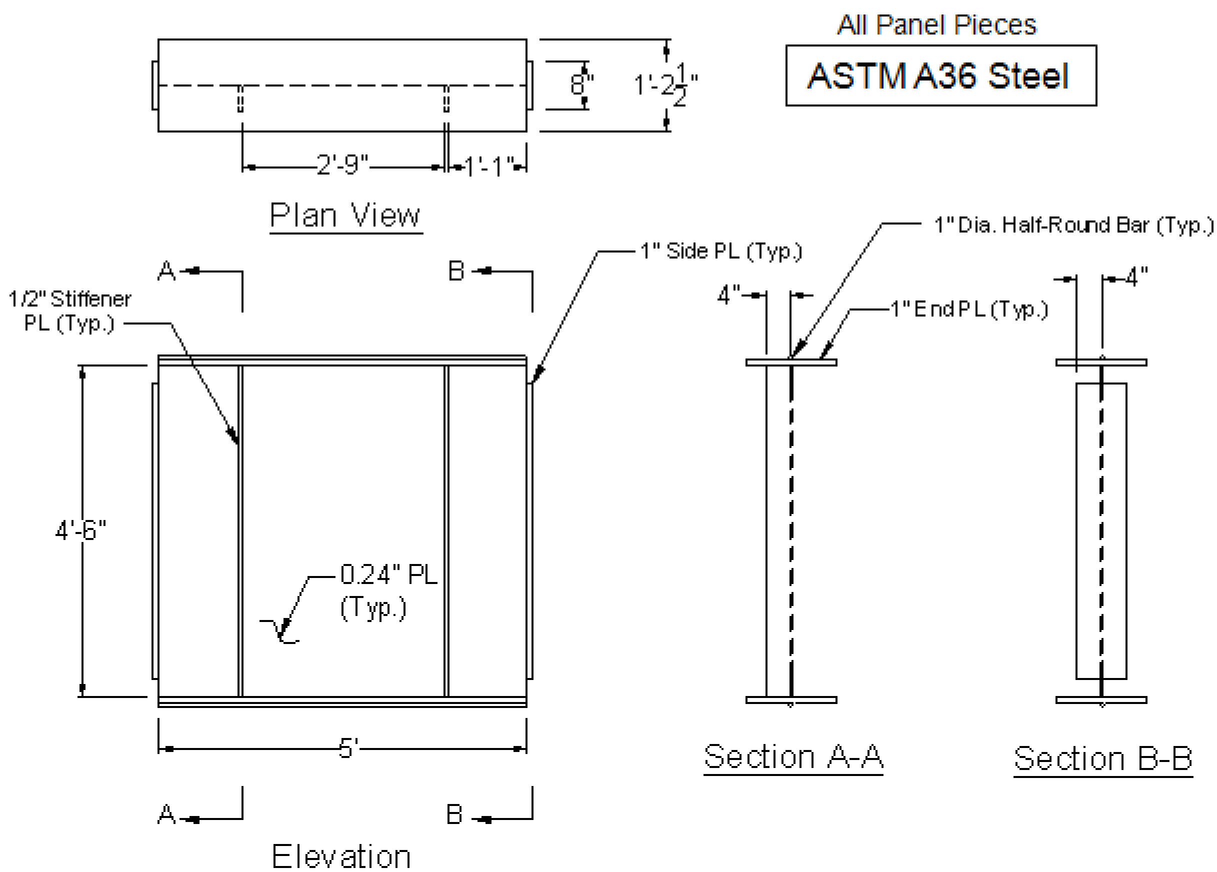


Figure 8. Compressive Load Arrangement for Stiffened Panel.

D. Compressive Loading – Swaged Panel

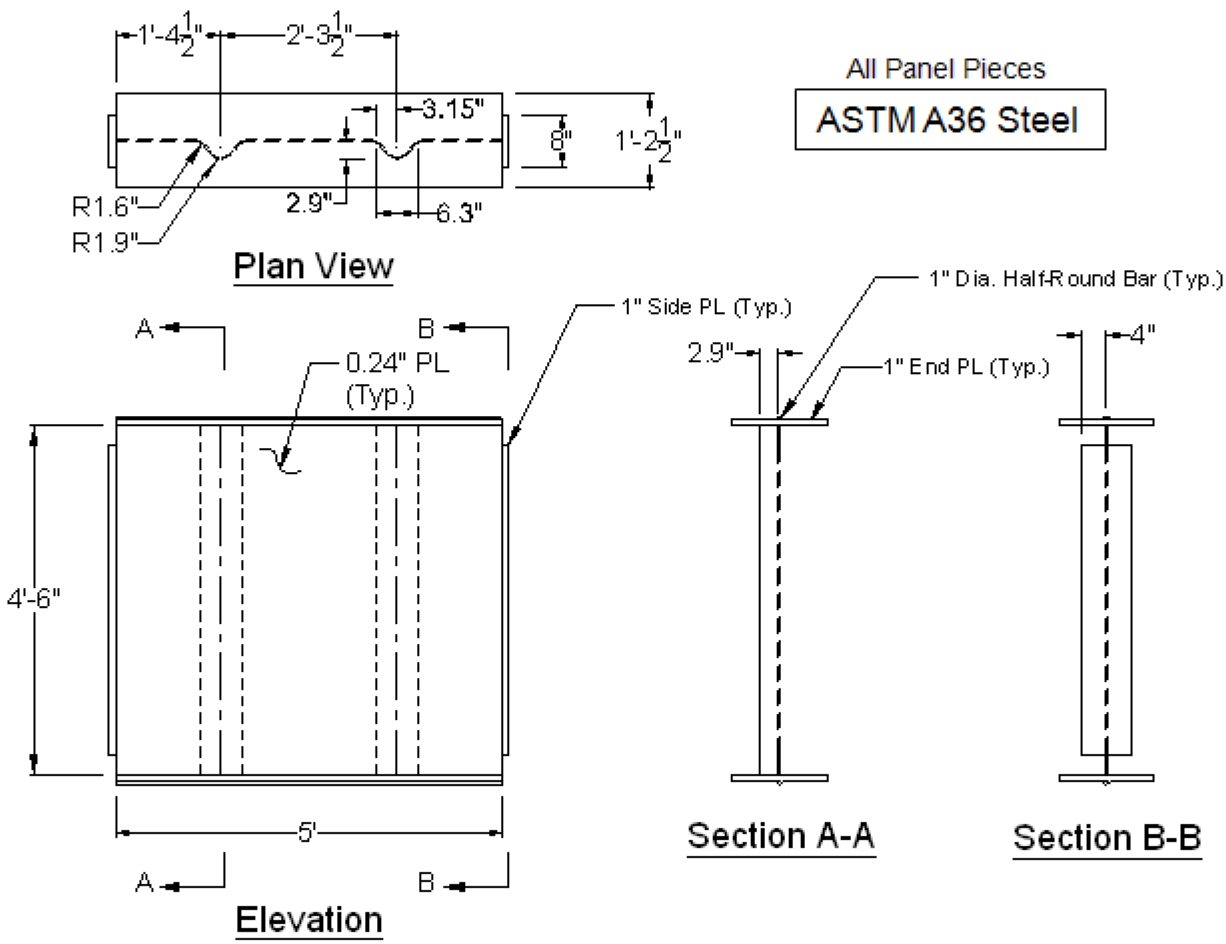


Figure 9. Compressive Load Arrangement for Swaged Panel.

Fabrication

Construction drawings of the four test specimens was completed by the NASSCO team, and the completed pieces were then taken to the Charles Lee Powell Structural Labs at UC San Diego. Following are several graphics depicting example construction drawings and photos of the completed pieces upon delivery to the testing facility at UC San Diego.

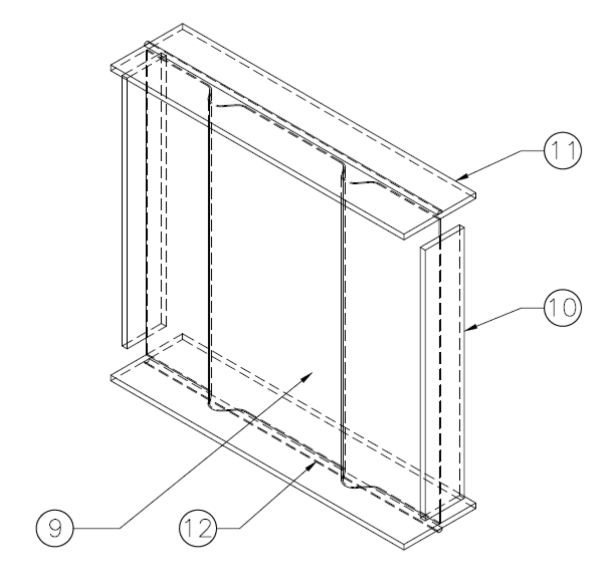


Figure 10. Example of Swaged Panel Construction Drawing

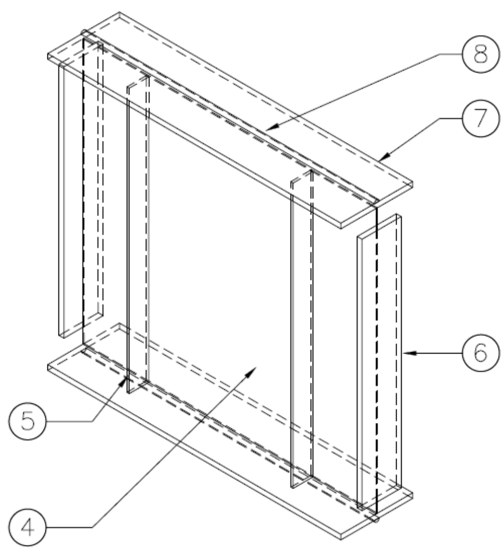


Figure 11. Example of Stiffened Panel Construction Drawing

Figure 12. Swaged Panels Unloaded by Crane at UC San Diego

Geometric Imperfections

Fabrication imperfections were present in the test specimens. These defects were measured and documented as follows. It is likely that the strain gage readings were affected by the geometric imperfections because the strain distribution within the panel is influenced by out of plane geometry. The strains measured are correct for the panel, but may not compare well with the idealized FEA.

Interestingly, the geometric imperfections on the panels with stiffeners were greater in magnitude of those imperfections found on panels with swages. This can be correlated to the simple fact that stiffeners must be welded in place, which causes heat distortion, as opposed to swages, which require no welding.

A. Shear Loading – Stiffened Panel

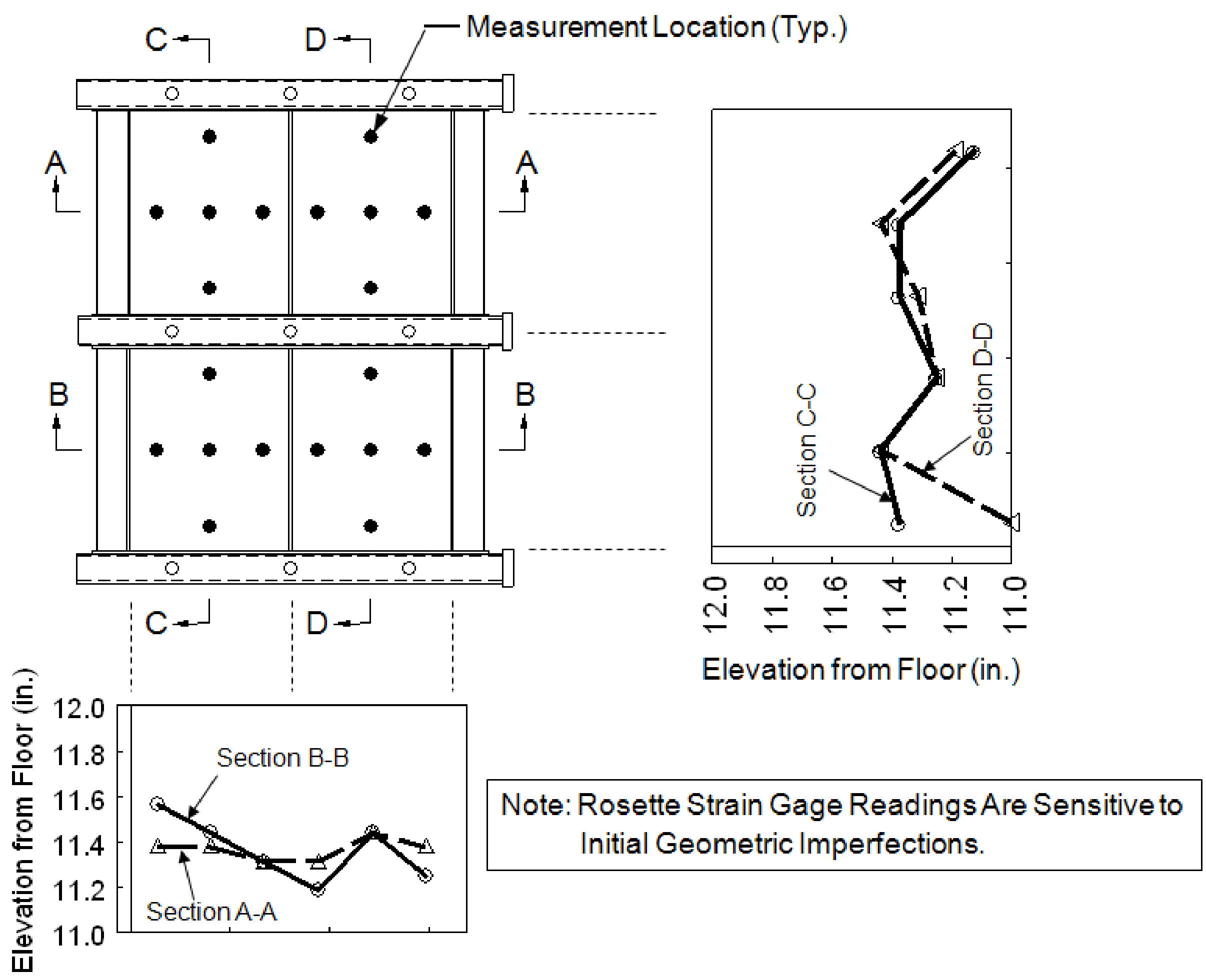
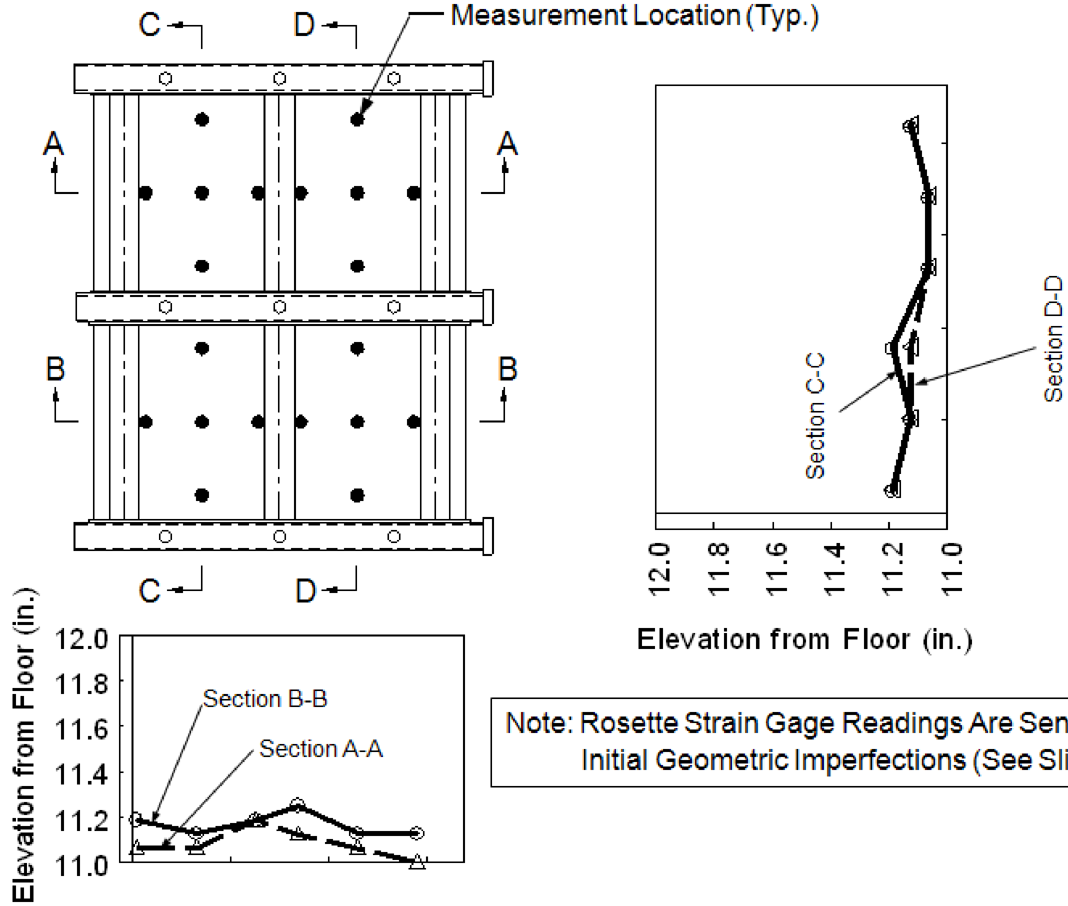


Figure 13. Stiffened Panel Geometric Imperfections

B. Shear Loading – Swaged Panel



Note: Rosette Strain Gage Readings Are Sensitive to Initial Geometric Imperfections (See Slide No. 10)

Figure 14. Swaged Panel Geometric Imperfections

C. Compressive Loading – Stiffened Panel

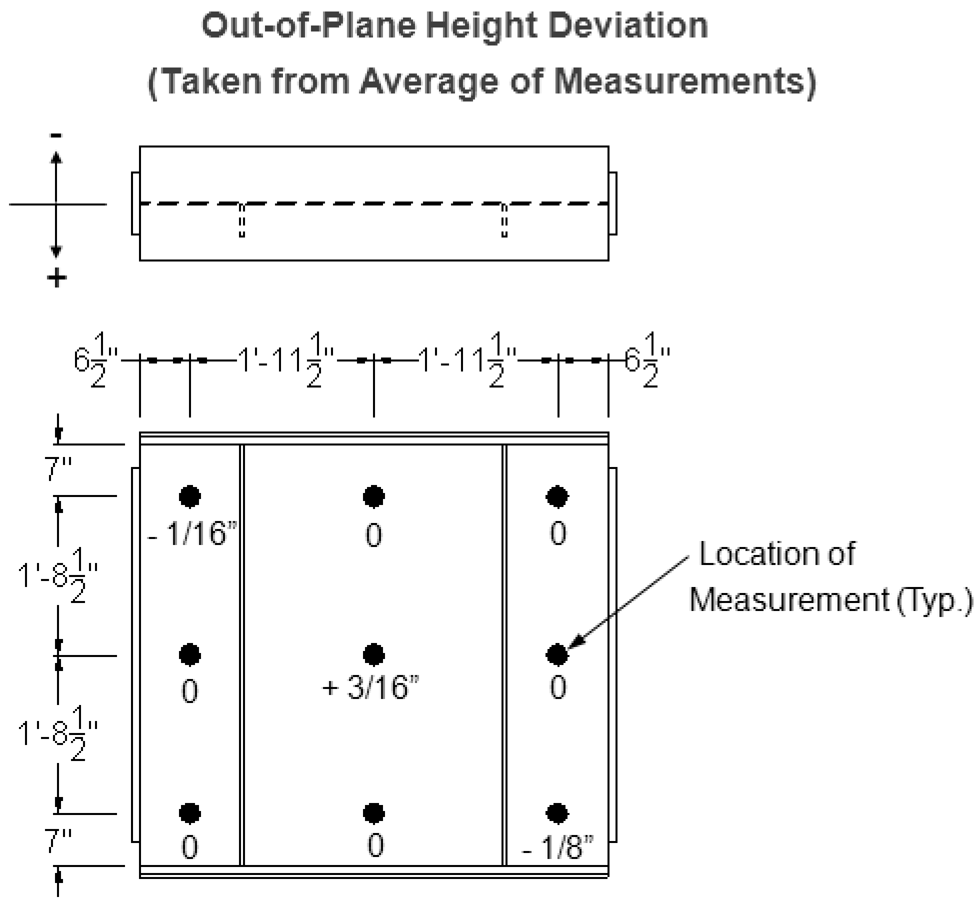


Figure 15. Stiffened Panel Geometric Imperfections

D. Compressive Loading – Shear Panel

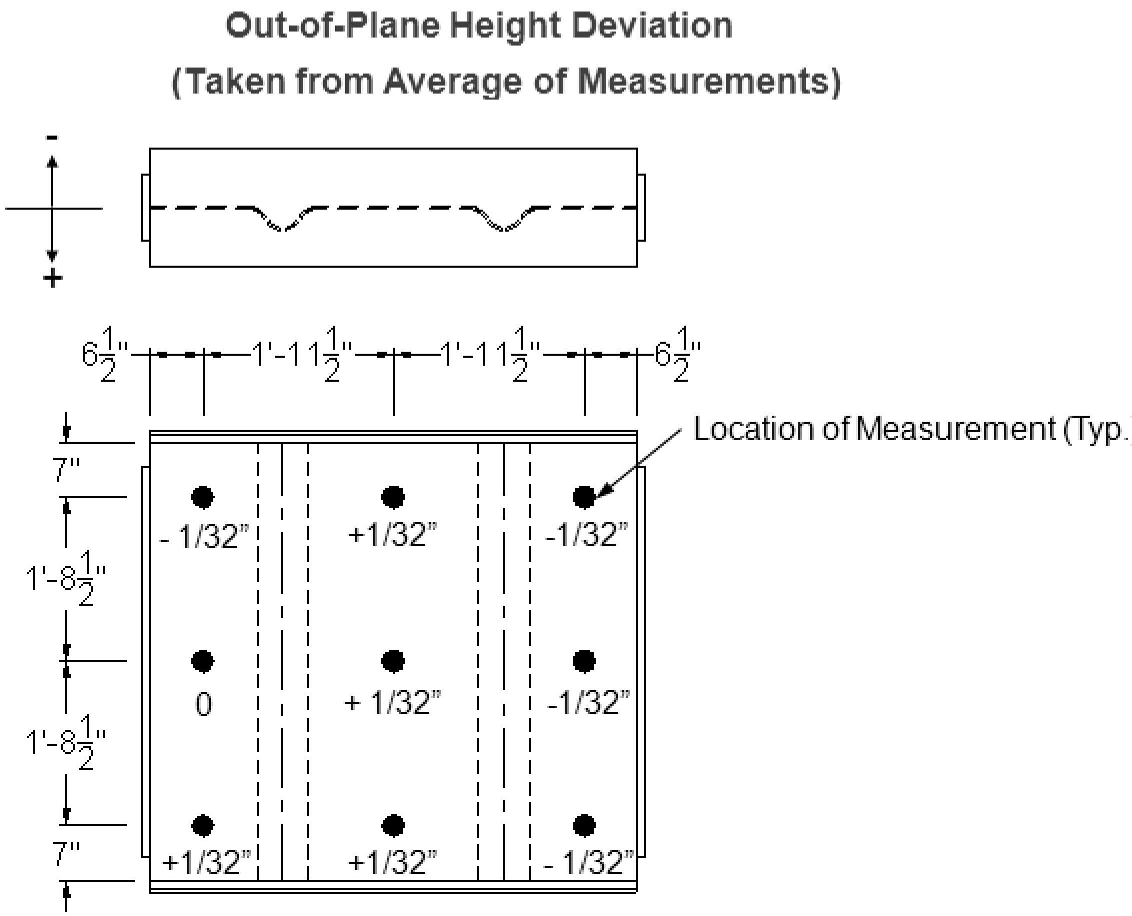


Figure 16. Swaged Panel Geometric Imperfections

Finite Element Analysis

Preliminary Analysis Concept

A preliminary analysis was performed to determine the expected loads as shown below. For the calculations, see Appendix A.

Shear
Based on 60% shear yield: 129.0 Mtons.
Based on 100% shear buckling: 68.1 Mtons.

Compression
Based on 60% yield: 214.8 Mtons.
Based on 100% compressive buckling: 49.1 Mtons.

Bending
Simply supported: 2.63 Mtons (applied on a line load across the plate).
Fixed ends: 5.26 Mtons (applied on a line load across the plate).

A preliminary Finite Element Analysis was performed on both the stiffened and swage panels. For this analysis, the boundary conditions were set as fixed in all six degrees of freedom on the upper and lower edges of each panel, and a symmetric constraint on the sides (which represents the continuation of the panel section for a full-length bulkhead). Constraints in the final model were chosen to best represent the actual test specimens in the testing fixture. The loading condition for this preliminary analysis was a notional distributed pressure load applied to all elements (see Figure 19).

Figures 17 and 18 show the elements used (plate elements with bending), and Figure 20 shows the resulting deflected shapes.

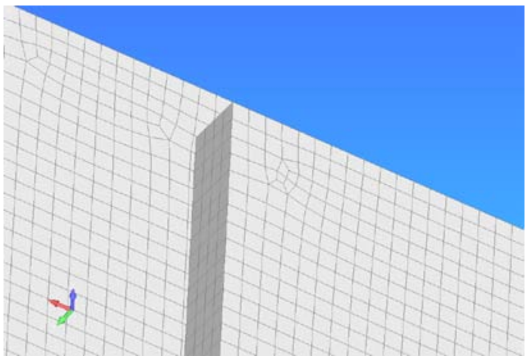


Figure 17. Stiffener Elements

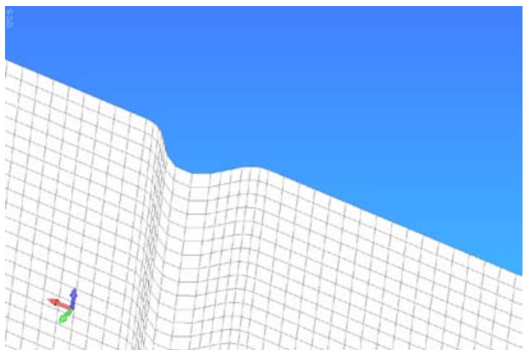


Figure 18. Swage Elements

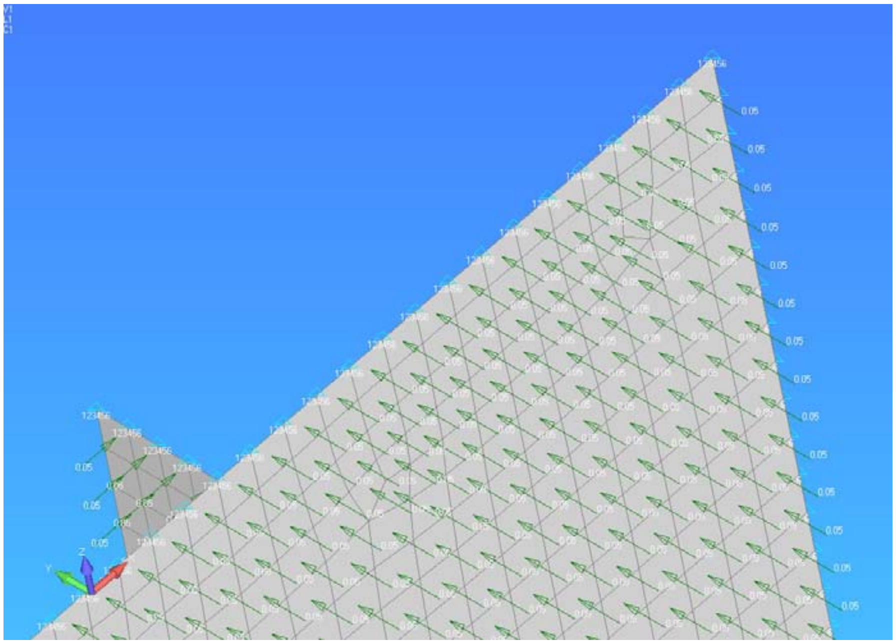


Figure 19. Pressure Load and Boundary Conditions

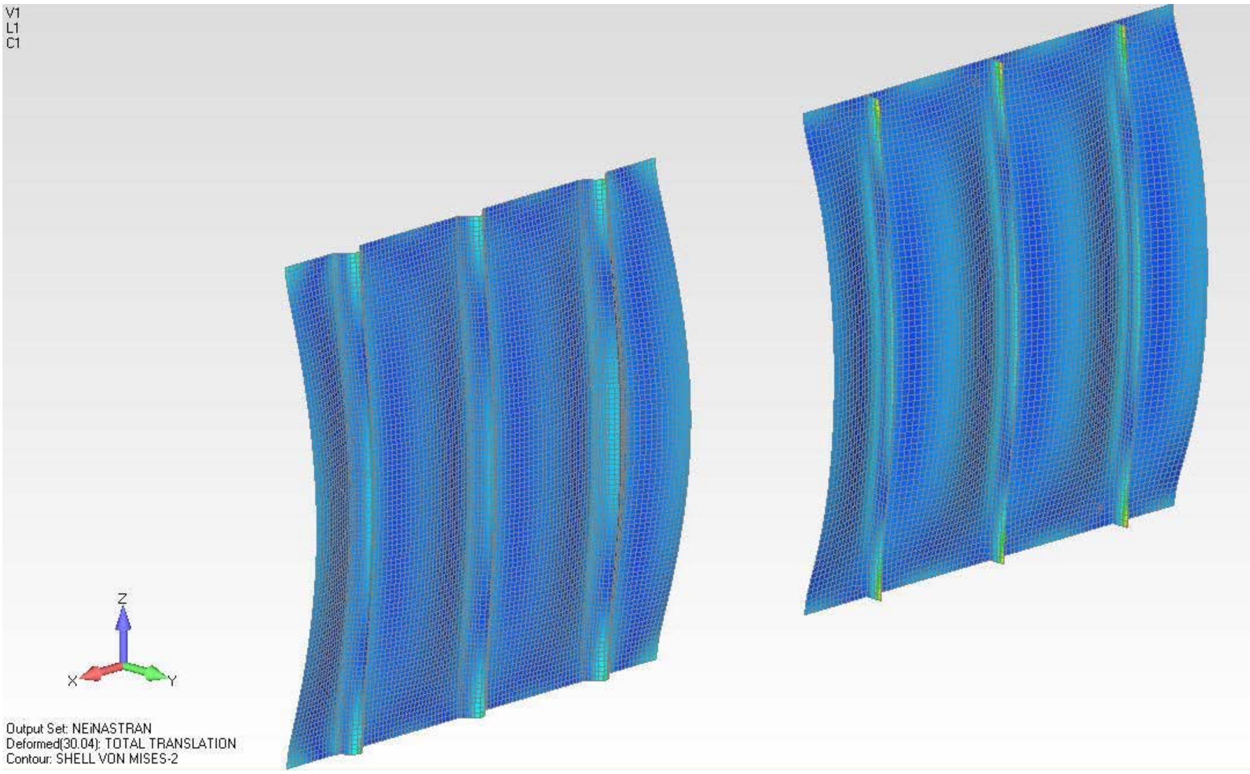


Figure 20. Preliminary Finite Element Analysis

FEMAP Models

The final models were created using plate elements. The average element was approximately 25 mm x 25 mm, using a medium mesh size. The model was made using the material properties described in the Configuration Design Section.

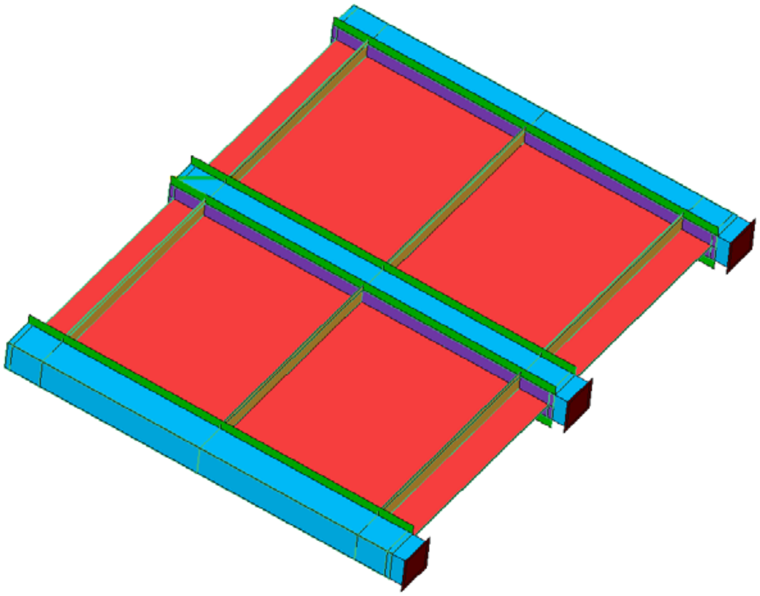


Figure 21. Shear Loading Stiffened Panel Finite Element Model

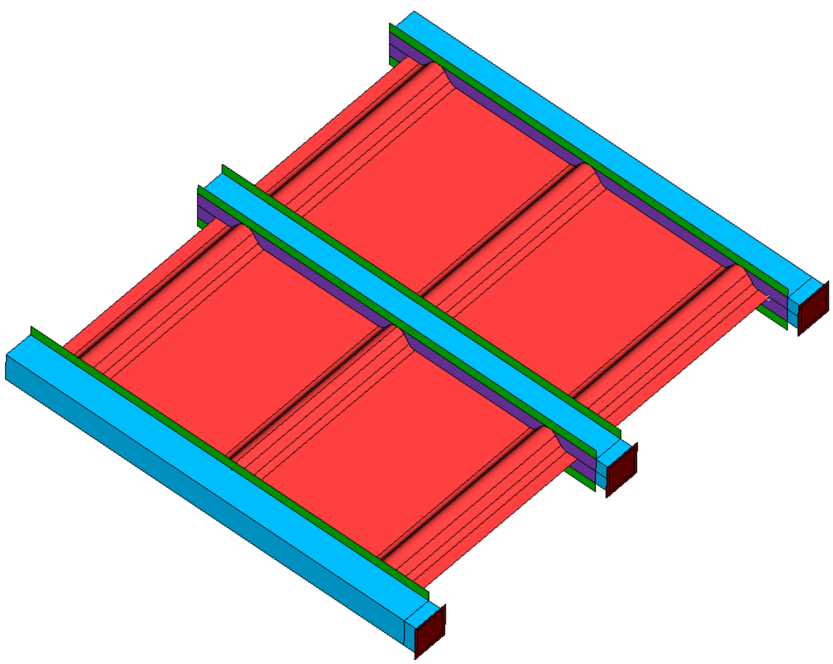


Figure 22. Shear Loading Swaged Panel Finite Element Model

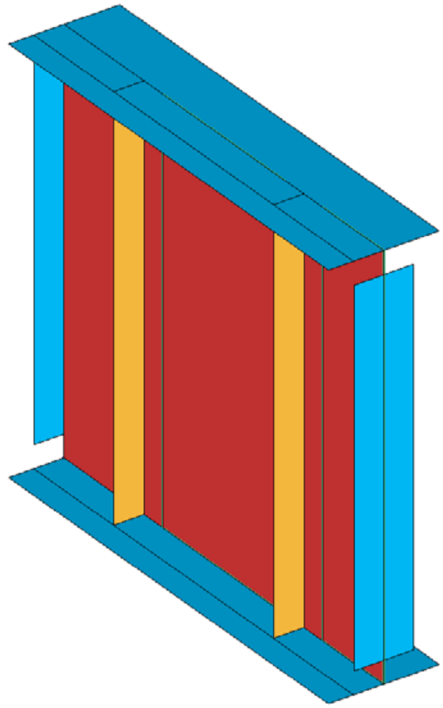


Figure 23. Compression Loading Stiffened Panel Finite Element Model

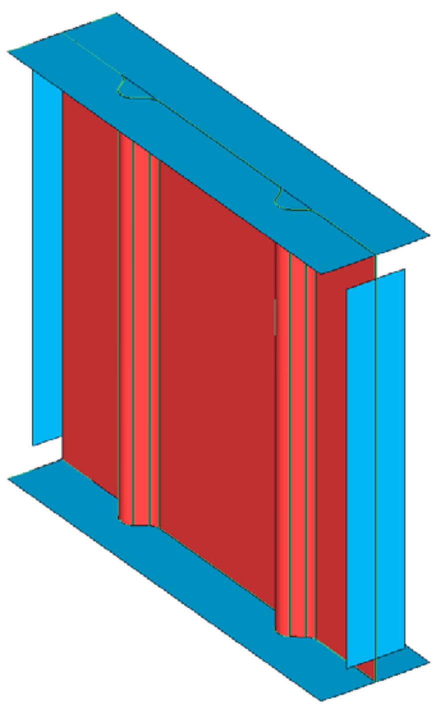


Figure 24. Compression Loading Swaged Panel Finite Element Model

Applied Loads and Boundary Conditions

The Finite Element Analysis was performed using NEi Nastran v. 10.2. Loads and boundary conditions were applied to simulate the actual testing environment.

For the shear load profile, the two outer square tubes were fixed at one end, and the lengths of the outer tubes were constrained against out-of-plane rotation to create a symmetric boundary condition. This was done to simulate the panel's continuation in an actual ship. A load of 300 kips was applied to the center tube.

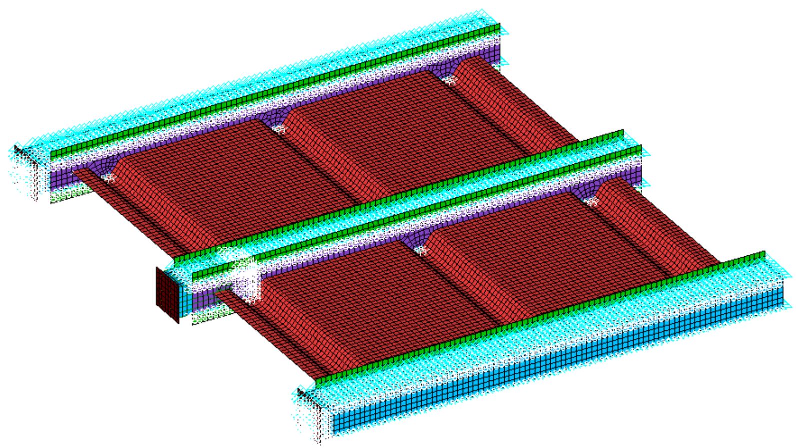


Figure 25. Shear Load and Boundary Conditions

For the compressive load profile, the lower plate was fixed in translation, but allowed to rotate, while the upper plate was fixed in out-of-plane translation, which allowed for deformation in the direction of load application. The load was applied as a line-load along the top of the upper plate. This simulates the application of the compressive load from the Testing Machine to the specialized I-beam, which was used to distribute the load into the specimen. Given that the load cannot be applied directly onto the neutral axis of the specimen, some bending as a result of buckling was expected.

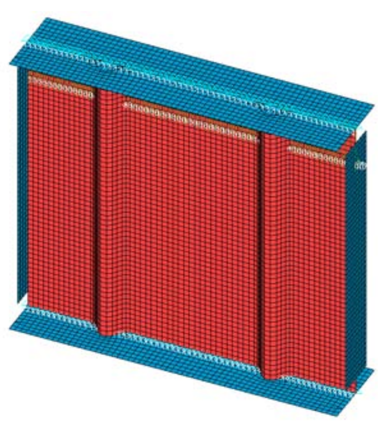


Figure 26. Compression Load and Boundary Conditions

Analysis Results

Stresses shown are in MPa.

A. Shear Loading – Stiffened Panel

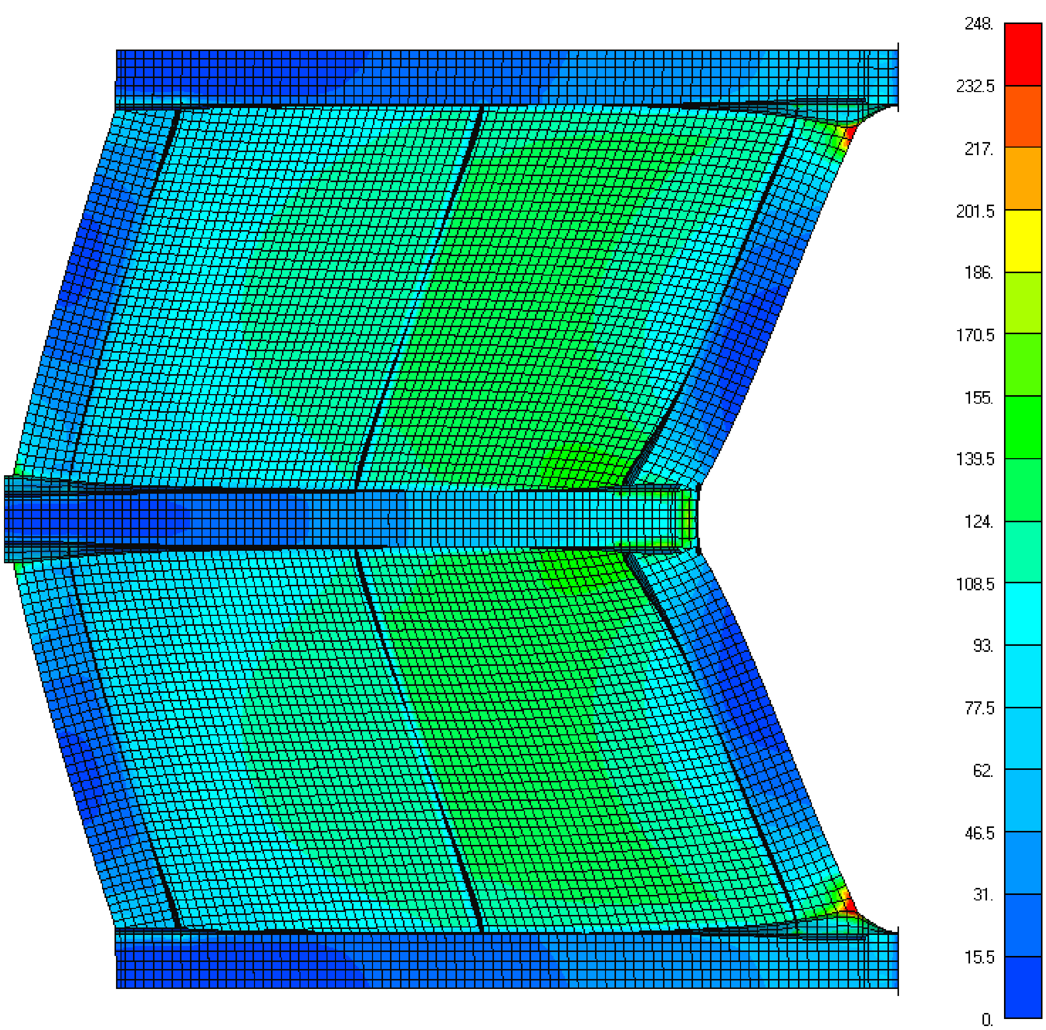


Figure 27. Shear Load – Stiffened Panel FEA Results

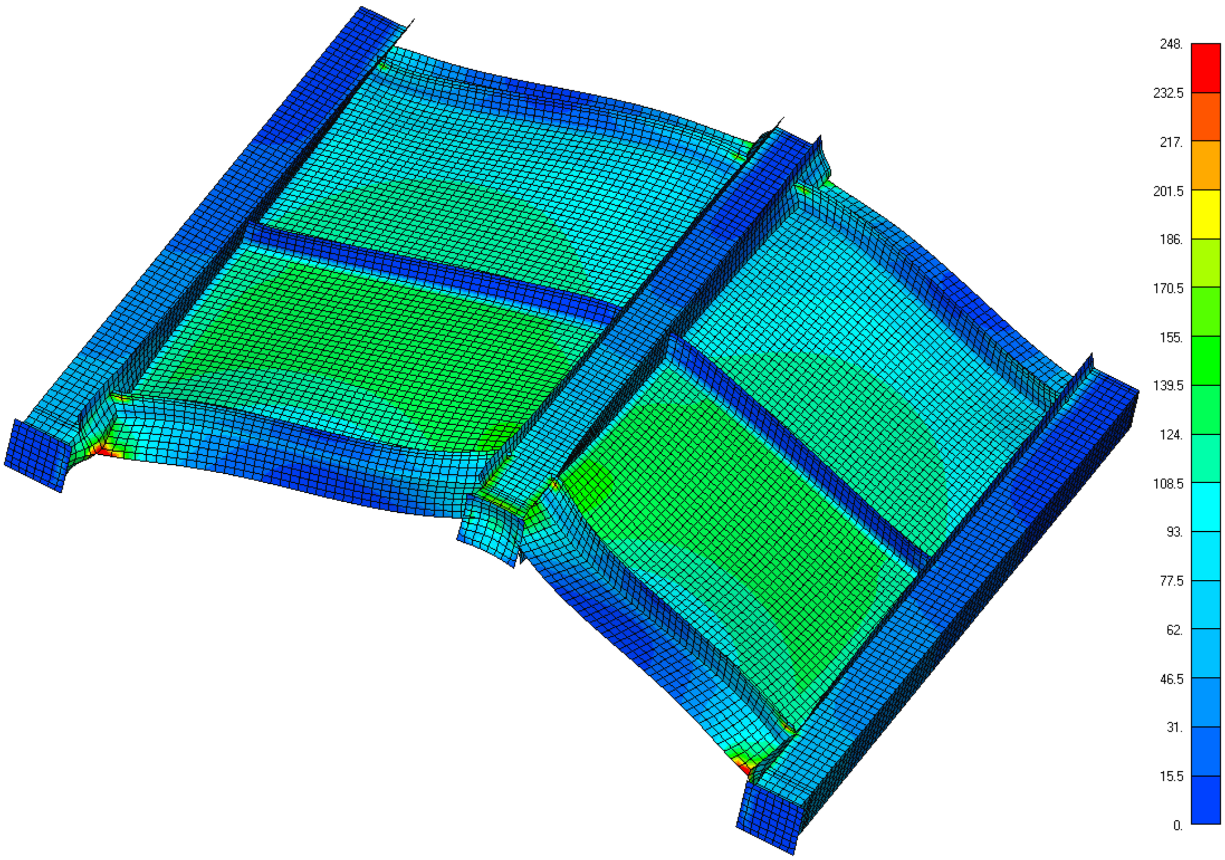


Figure 28. Shear Load – Stiffened Panel FEA Results

B. Shear Loading – Swaged Panel

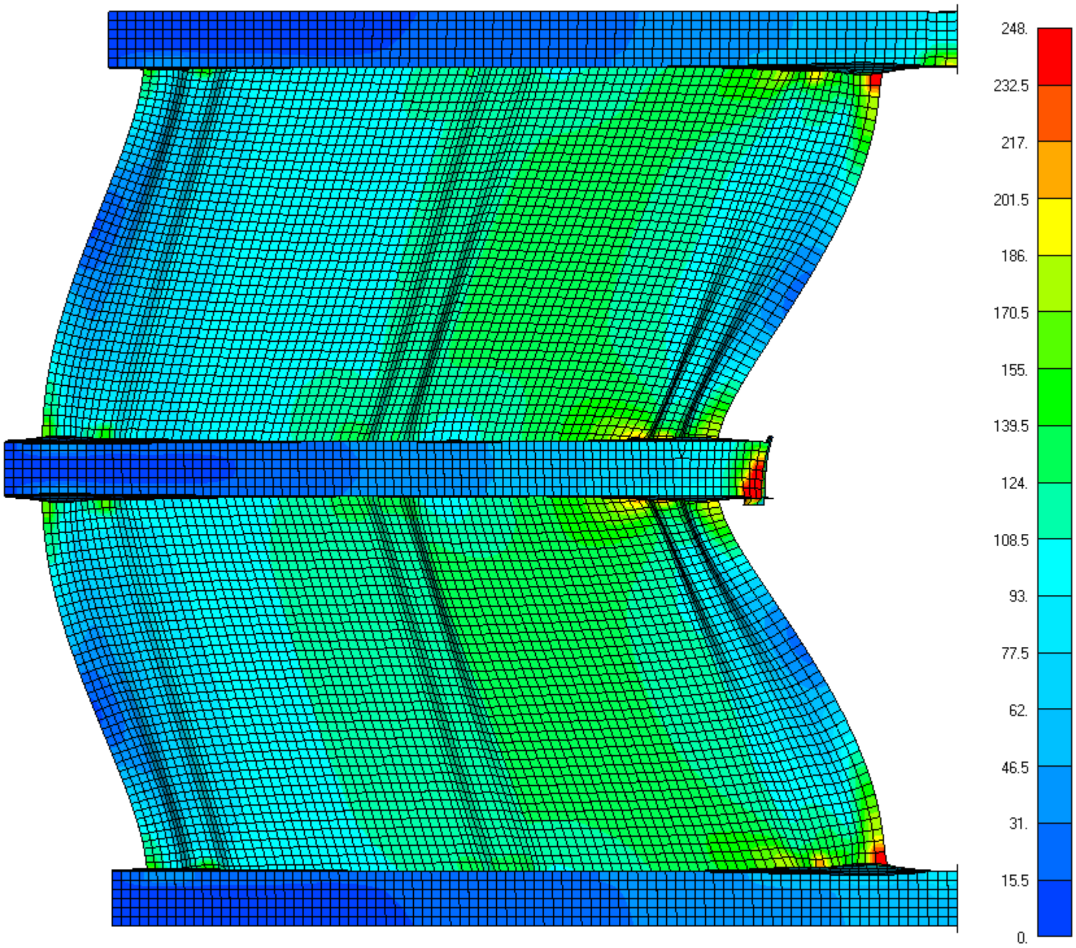


Figure 29. Shear Load – Swaged Panel FEA Results

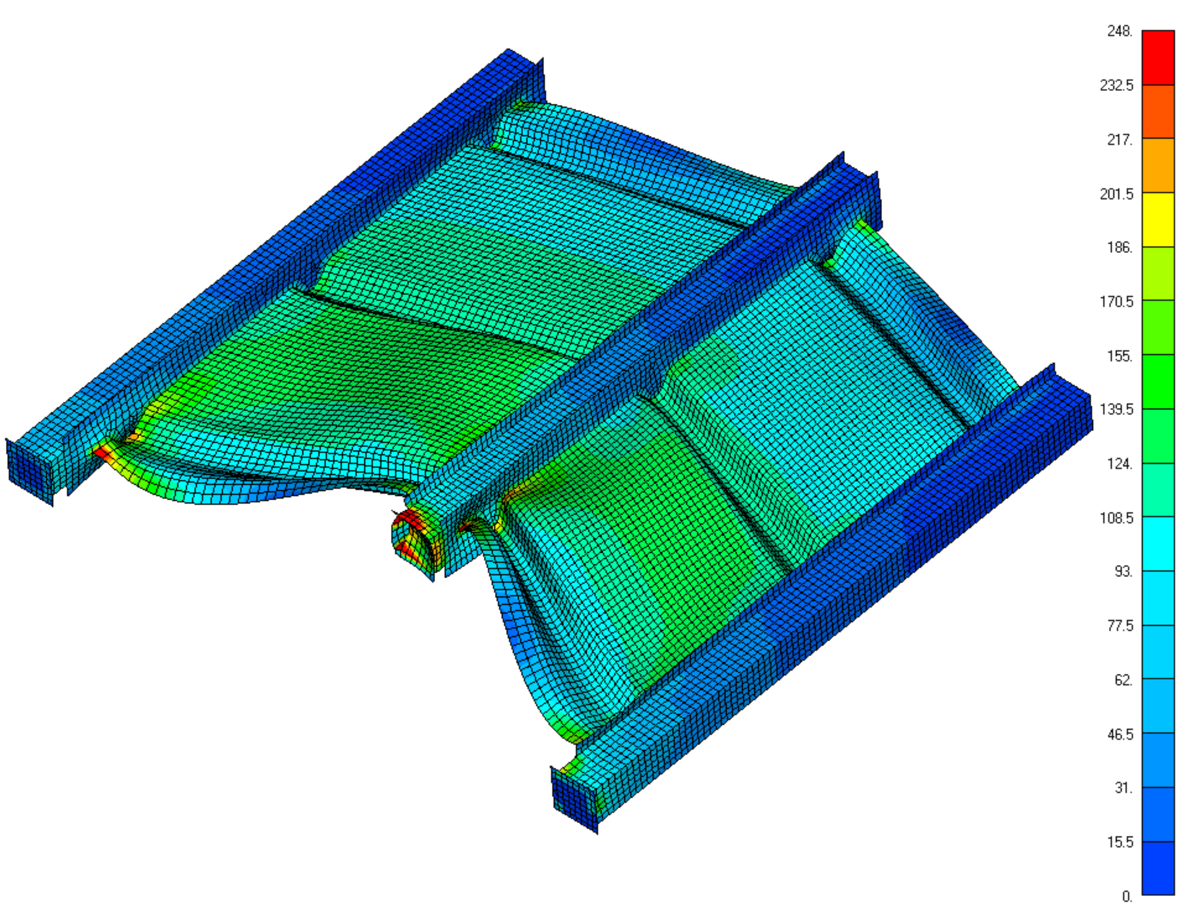


Figure 30. Shear Load – Swaged Panel FEA Results

C. Compressive Loading – Stiffened Panel

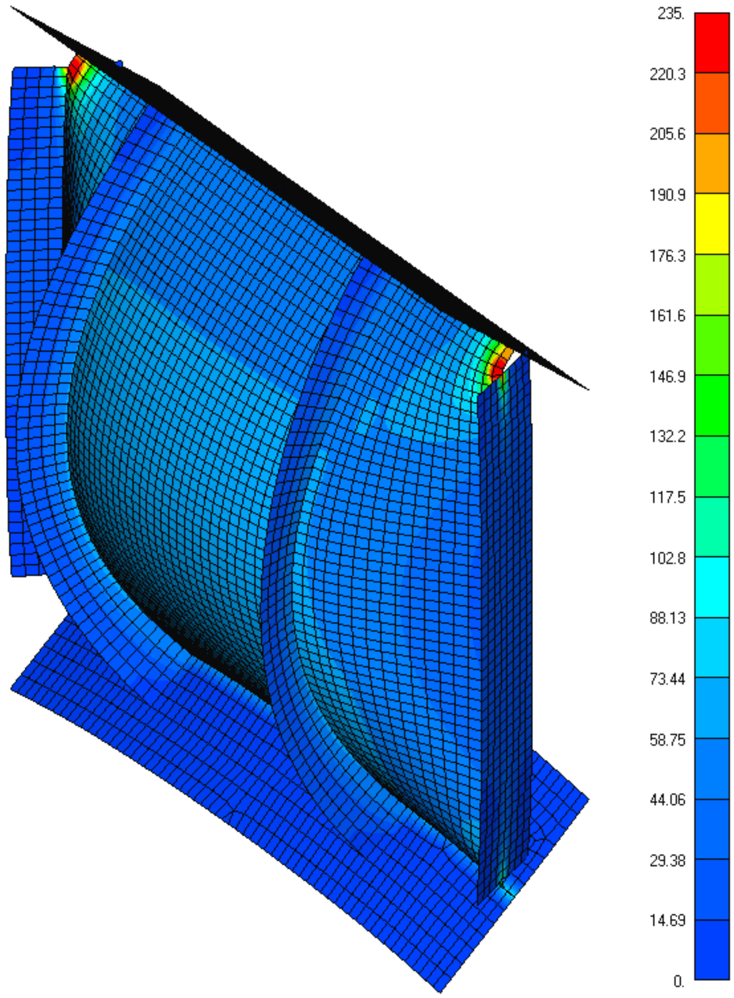


Figure 31. Compression Load – Stiffened Panel FEA Results

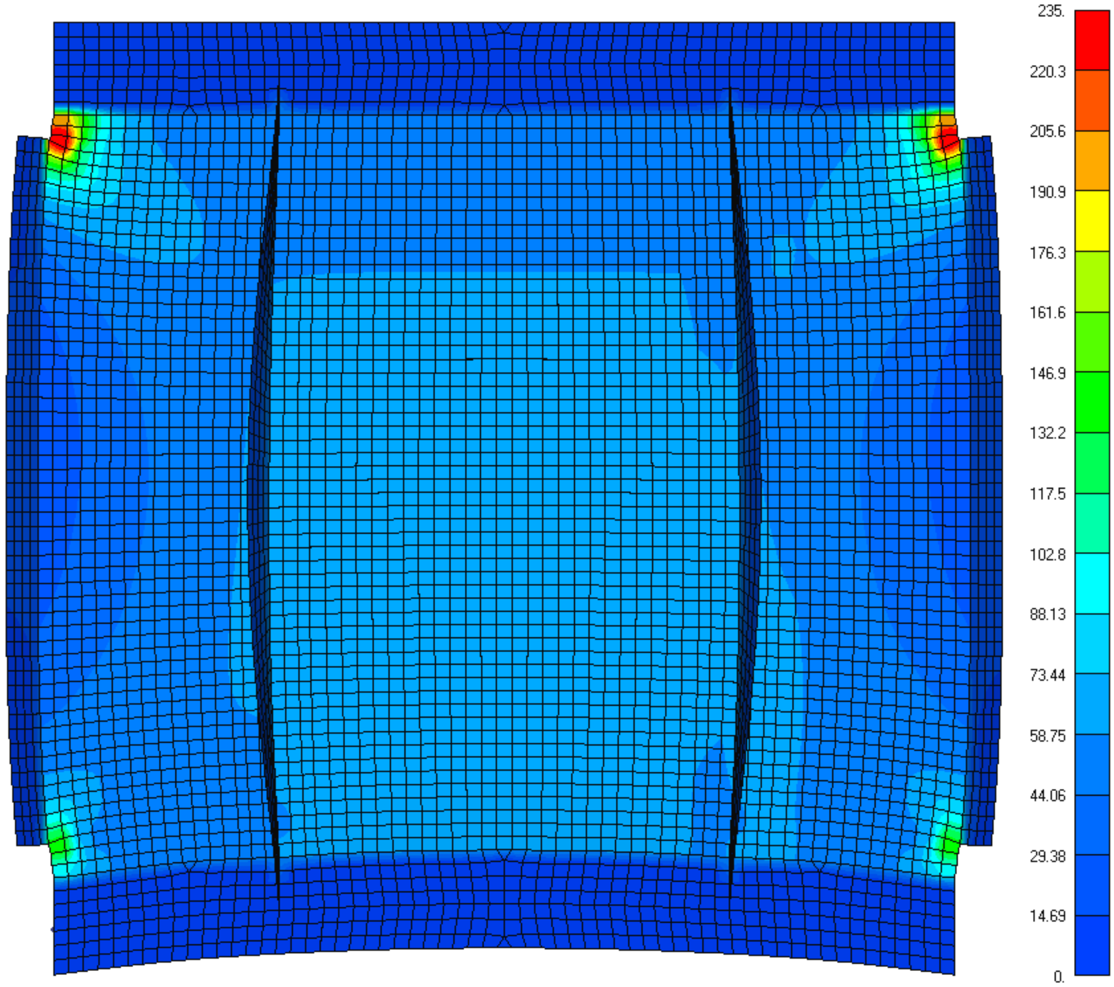


Figure 32. Compression Load – Stiffened Panel FEA Results

D. Compressive Loading – Swaged Panel

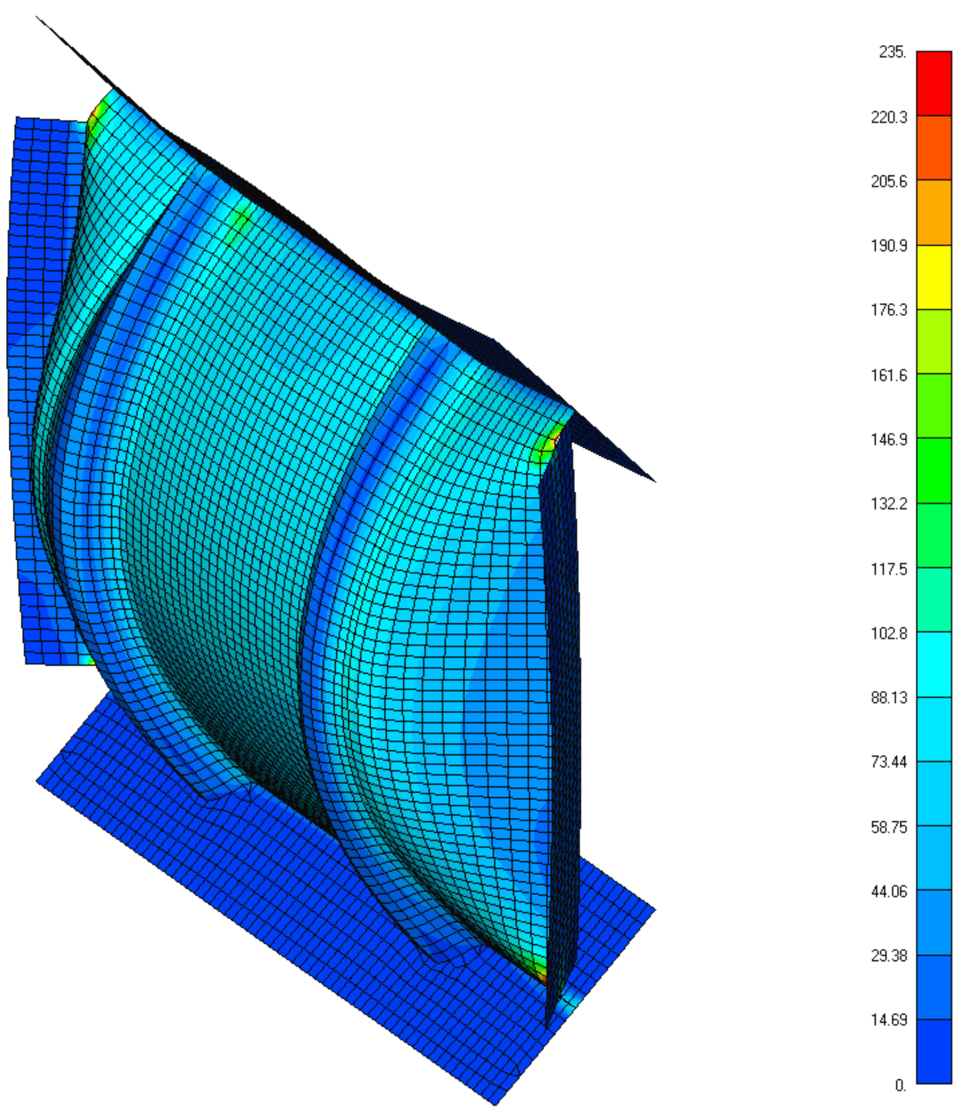


Figure 33. Compression Load – Swaged Panel FEA Results

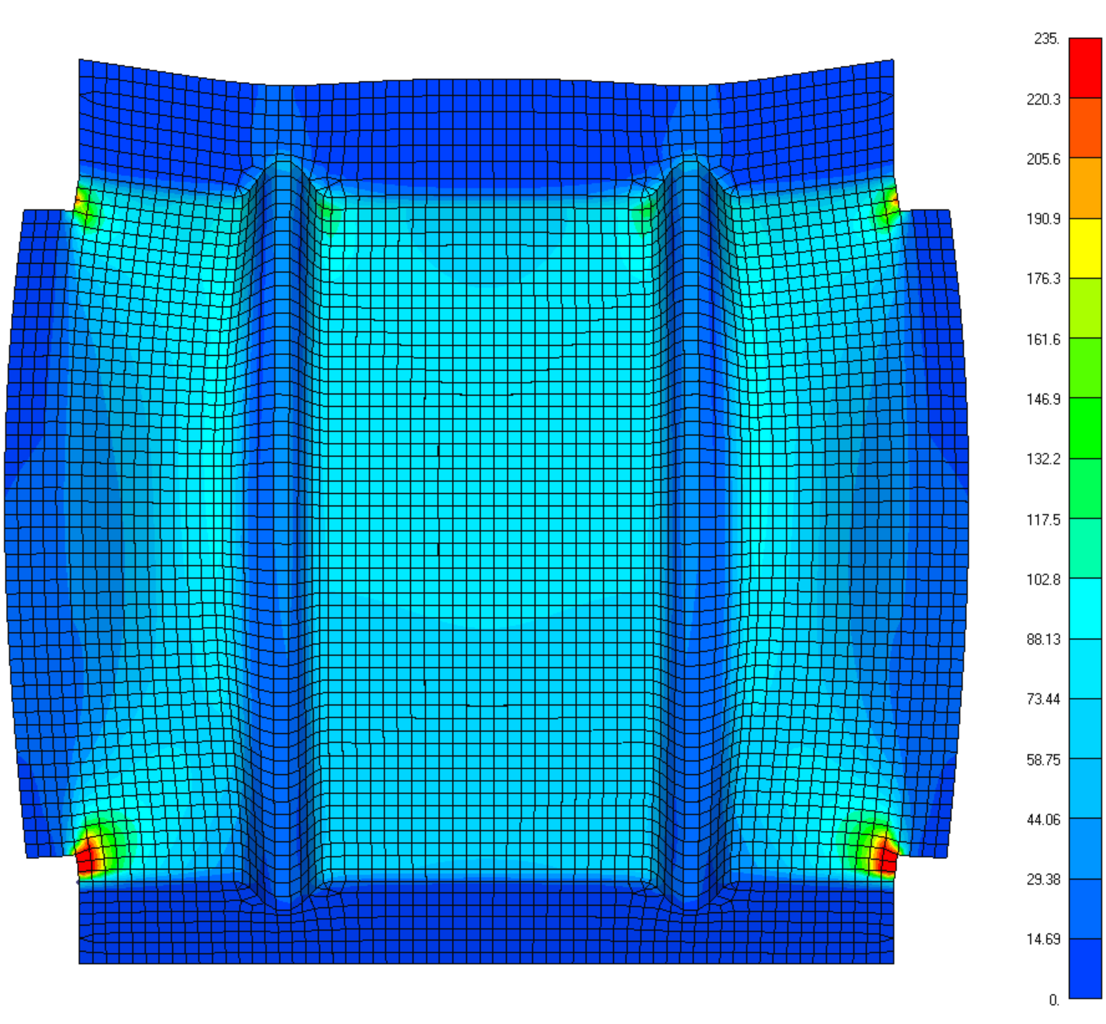


Figure 34. Compression Load – Swaged Panel FEA Results

Laboratory Testing

Testing Configuration

Each load profile was applied to both stiffened and swaged panels for a total of four different tests on four unique specimens.

Compressive loads of approximately 150 kips were applied by a SATEC Universal Testing Machine. In order for the load to be distributed along the width of the panel, two specially-designed I-beams were included in the test configuration for both the stiffened and swaged panels. These were attached to the actual test specimen with a pin connection. This connection consisted of a half round steel bar welded to the end-plate of the specimen, and a section of steel pipe welded to the I-beam, as shown.

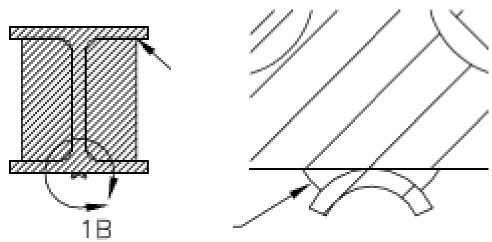
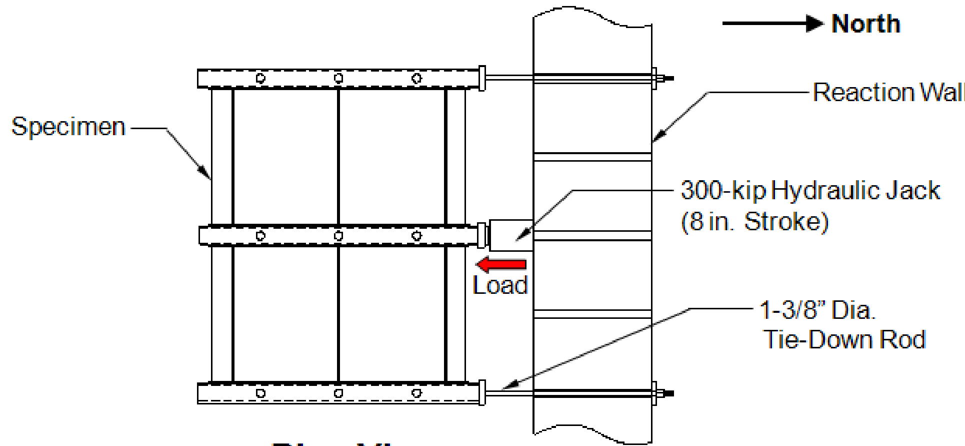


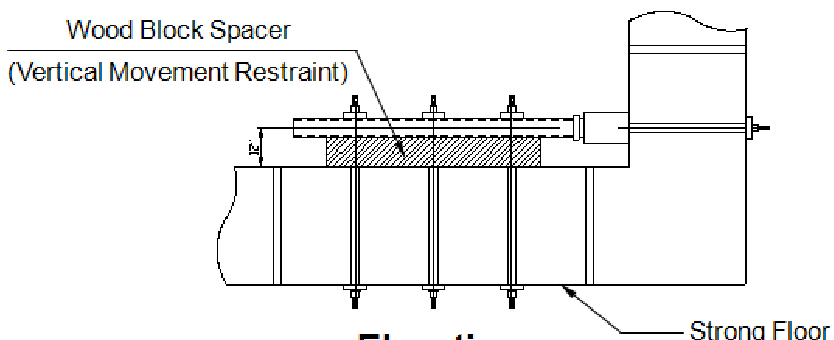
Figure 35. Pin Connection for Compression Test

For the application of shear loads, two identical panels were tested simultaneously in order to create the appropriate boundary conditions. The two panels were connected by a steel square tube with the load applied at one end. The outside edges were also attached to square tube members, which were rigidly fixed. The load was applied to the center square tube by a 300 kip hydraulic jack.

A. Shear Loading – Stiffened Panel

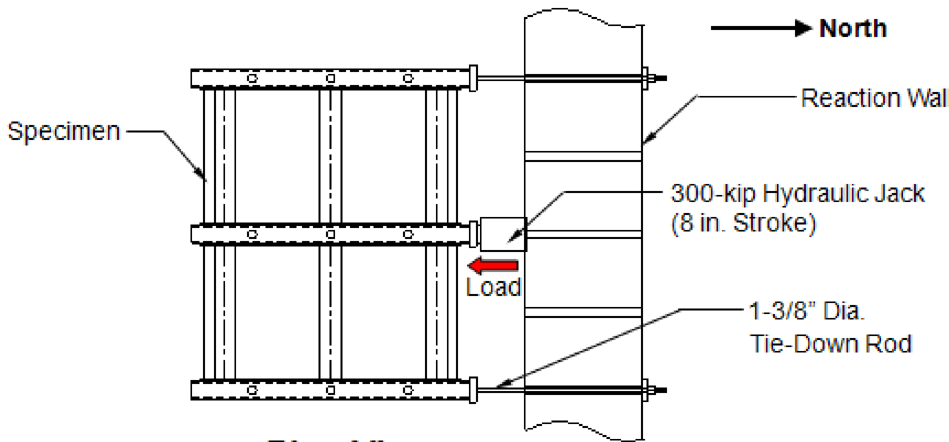


Plan View

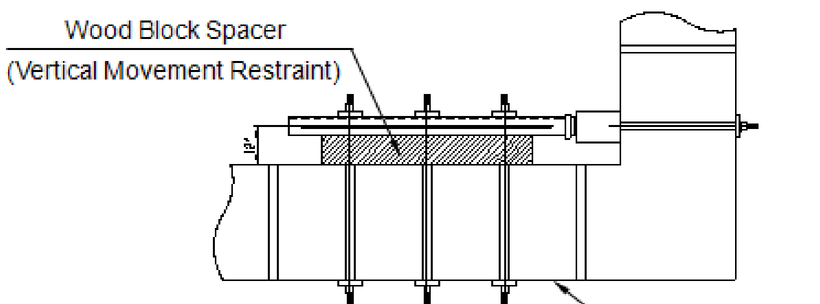


Elevation

B. Shear Loading – Swaged Panel

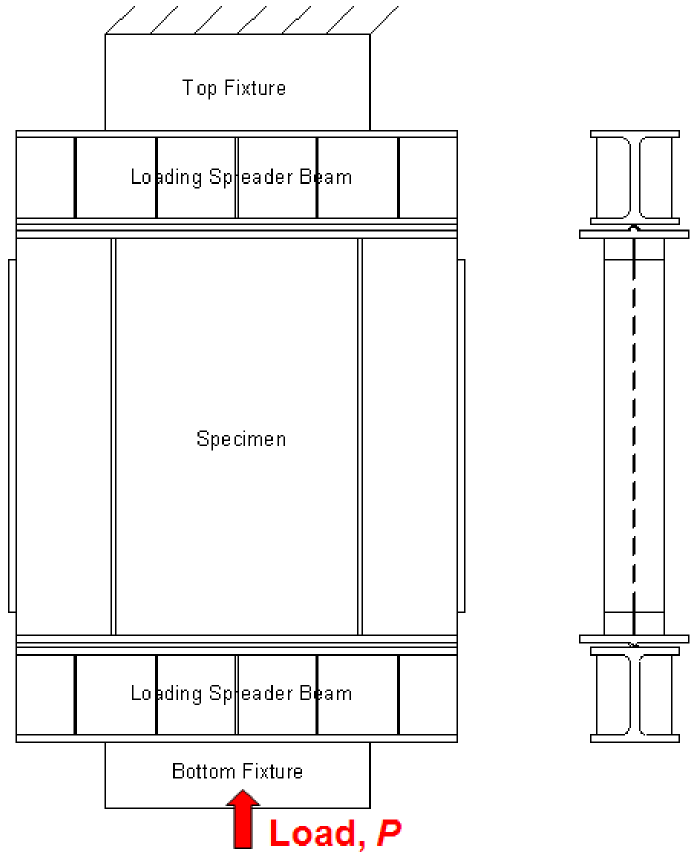


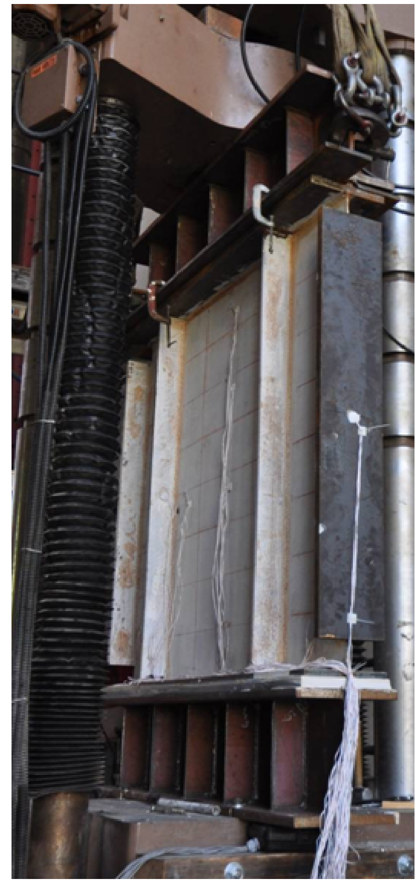
Plan View



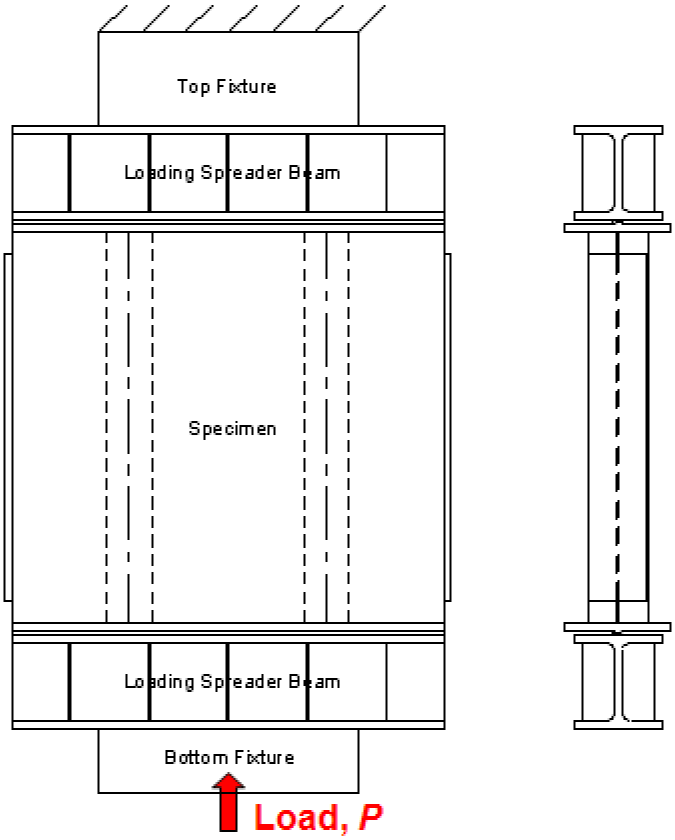
Elevation

C. Compressive Loading – Stiffened Panel





D. Compressive Loading – Swaged Panel



Instrumentation

A. Shear Test – Stiffened Panel

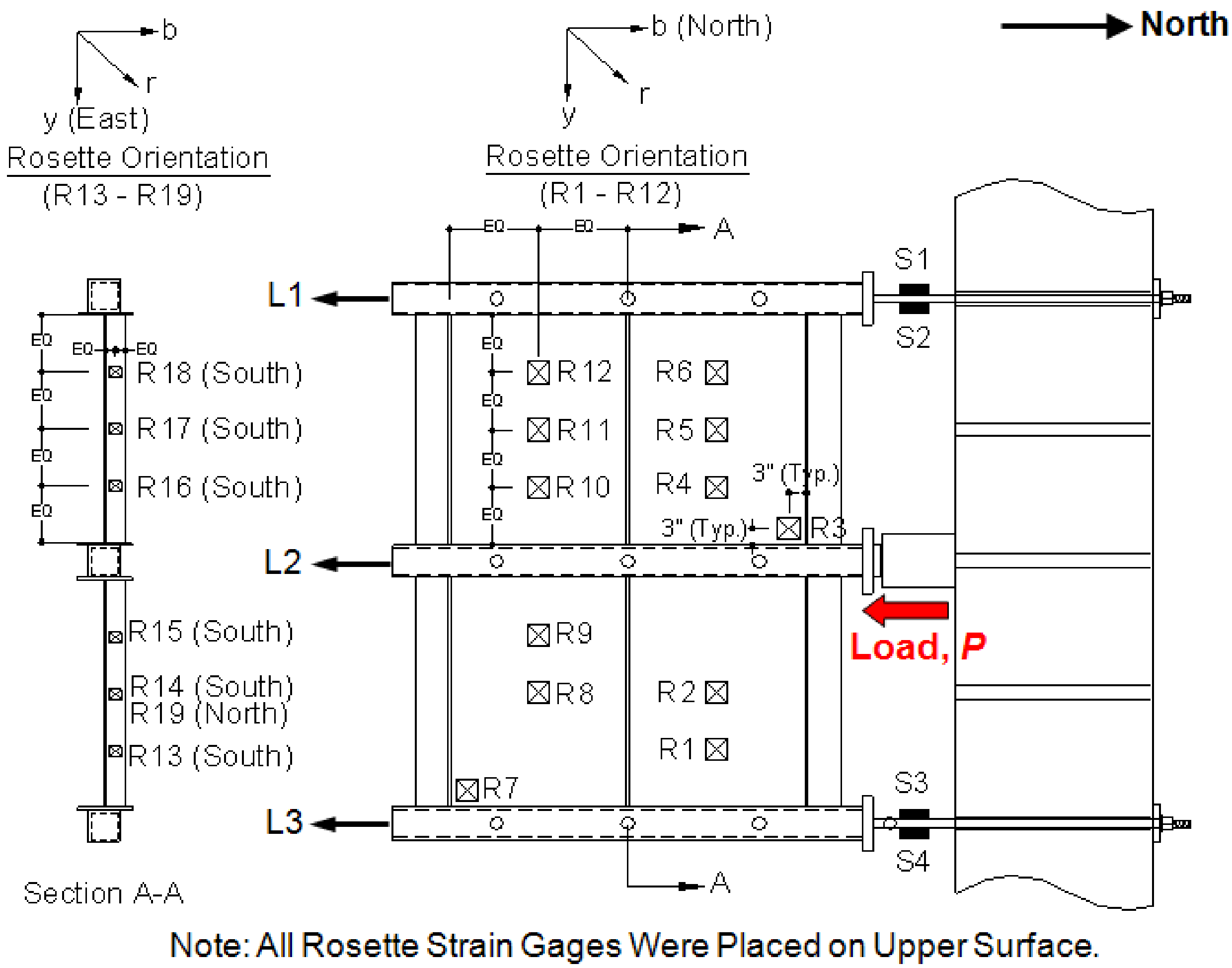
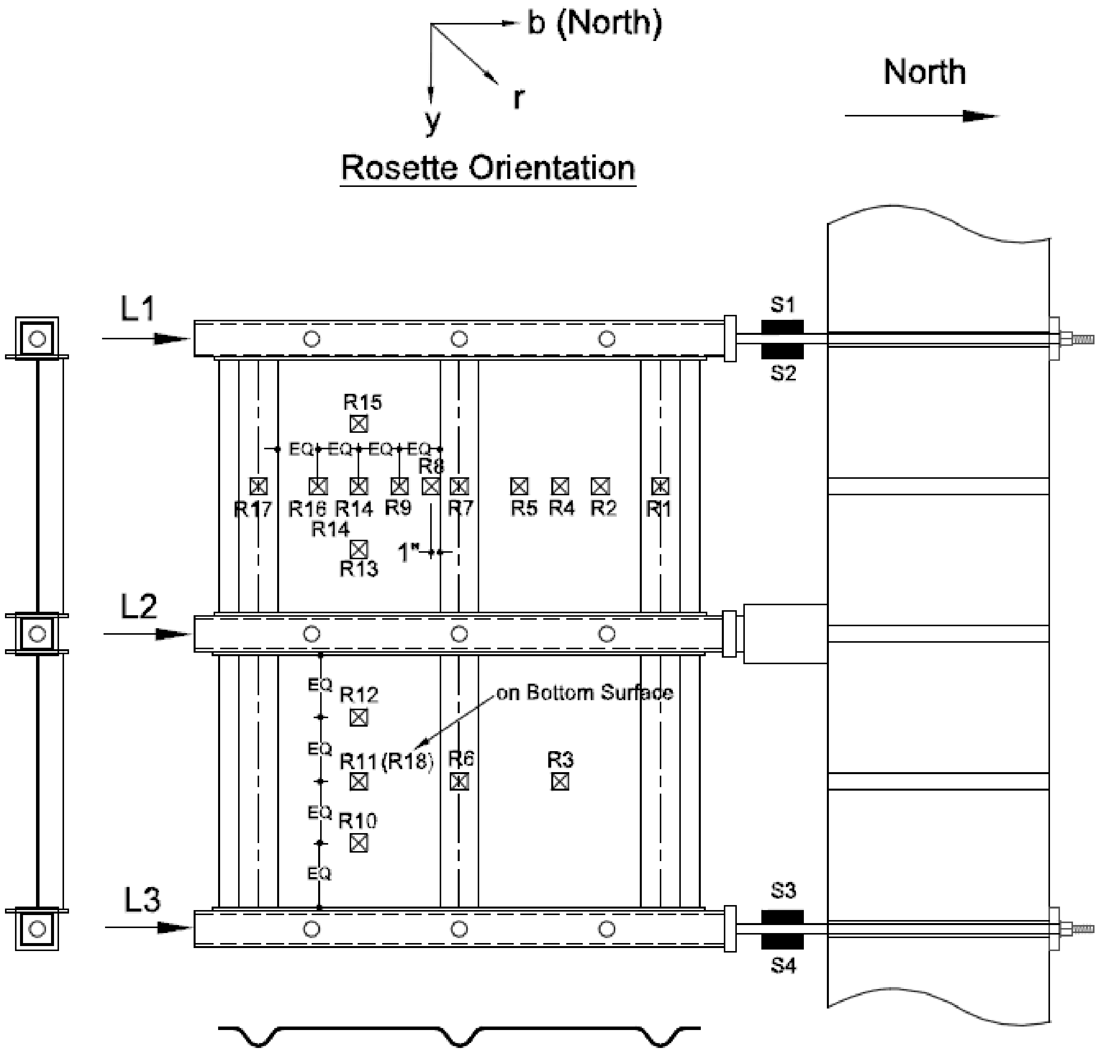


Figure 36. Shear Test – Stiffened Panel Instrumentation

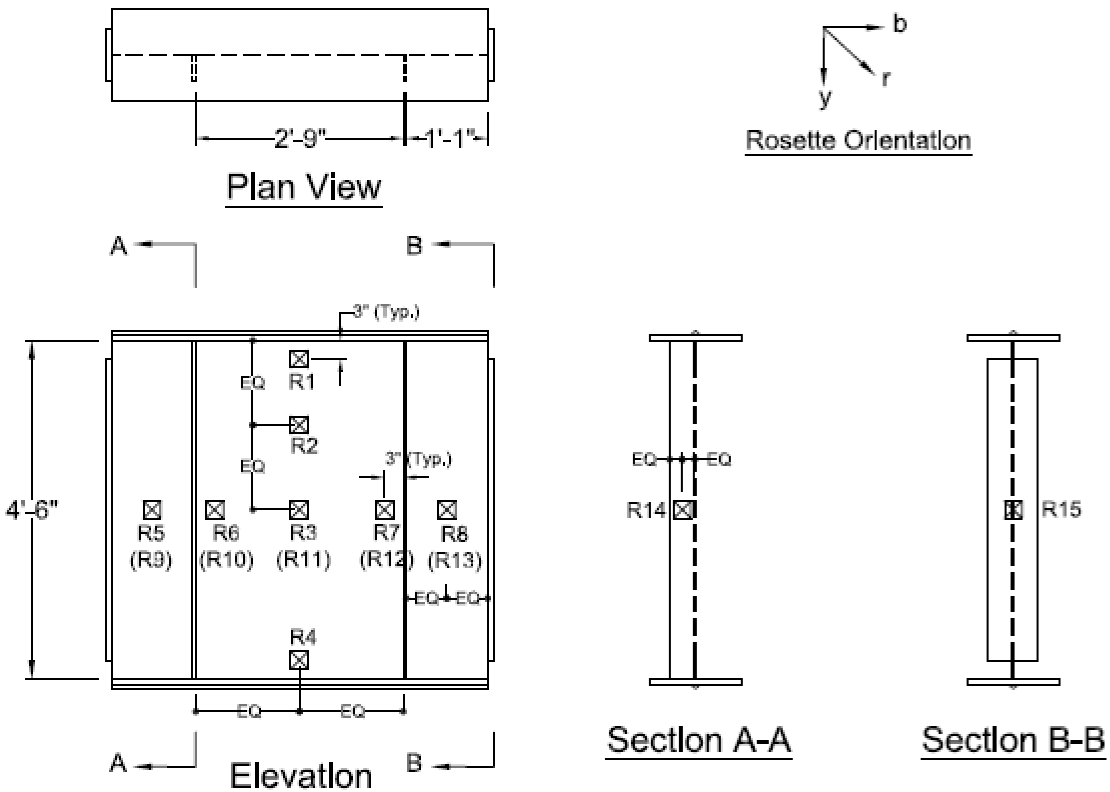
B. Shear Test – Swaged Panel



Note: Rosettes in parentheses are symmetrically located on opposite side.

Figure 37. Shear Test – Swaged Panel Instrumentation

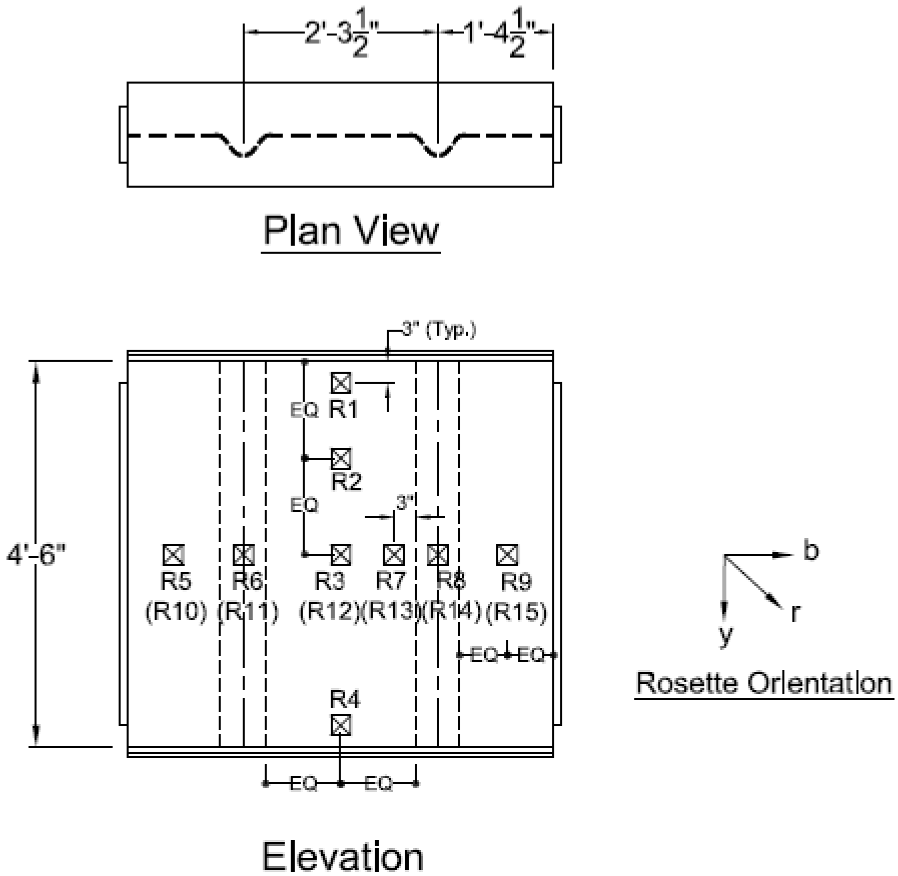
C. Compression Test – Stiffened Panel



Note: Rosettes in parentheses are symmetrically located on opposite side.

Figure 38. Compression Test – Stiffened Panel Instrumentation

D. Compression Test – Swaged Panel



Note: Rosettes in parentheses are symmetrically located on opposite side.

Figure 39. Compression Test – Swaged Panel Instrumentation

Test Results and Discussion

All data reduction was completed by calculating stresses from measured strains using equations 3, 4 and 5 found in Vishay Micro-Measurements Tech Note TN-515.

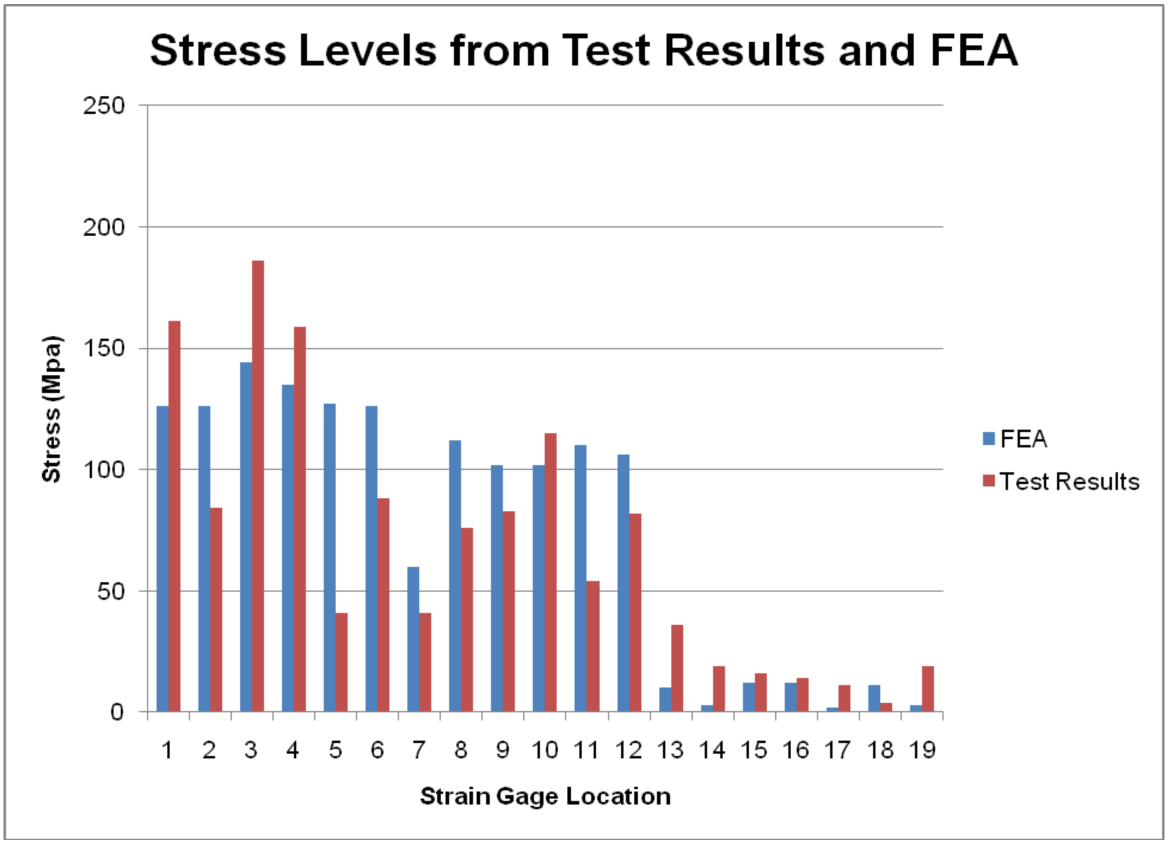
Shear Test

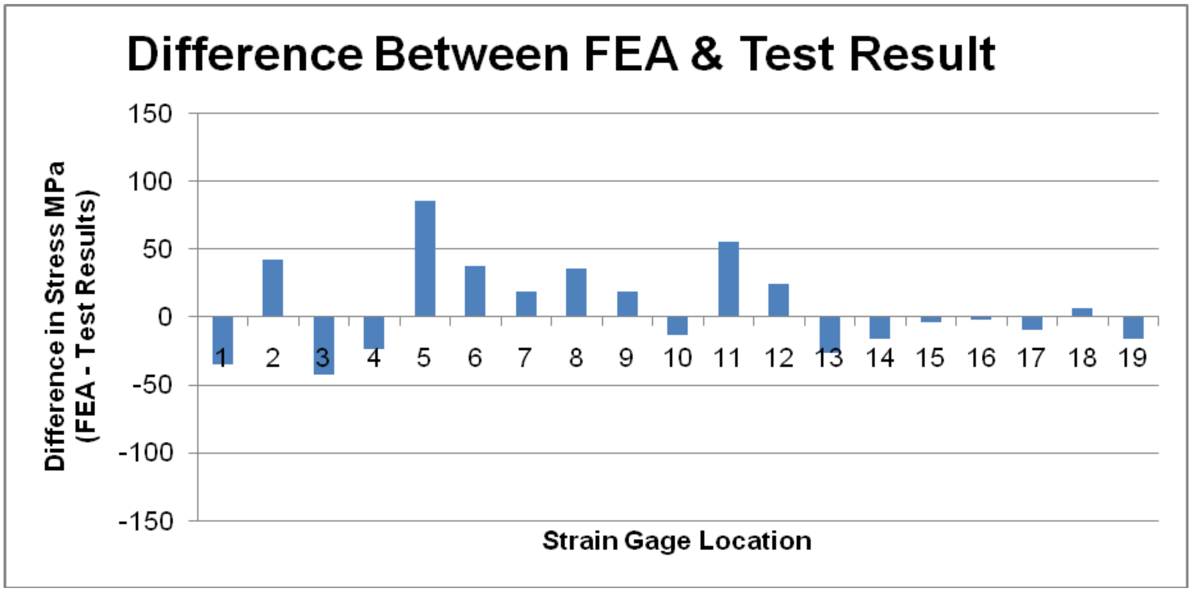
The measured stress values have some variation from the values predicted by the Finite Element Analysis for both the stiffened panel and the swaged panel.

It is believed that a major contributing factor to this variation is the geometric imperfections documented earlier in this report: the FEA model assumes an idealized specimen. In addition, the FEA does not take into account any slight variances in the application of load or initial displacements of the specimen.

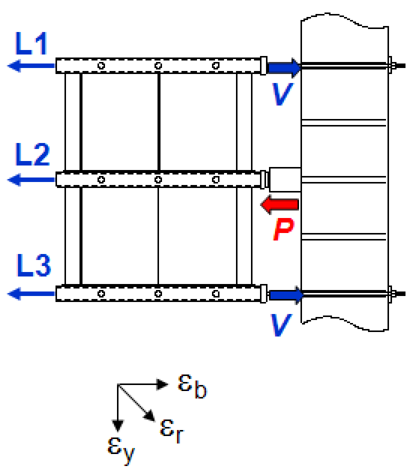
In order to bring the FEA predictions closer to the stresses calculated from the strains collected during actual testing, further study, as outlined in NASSCO NSRP Research Announcement Proposal 0901-04, is necessary.

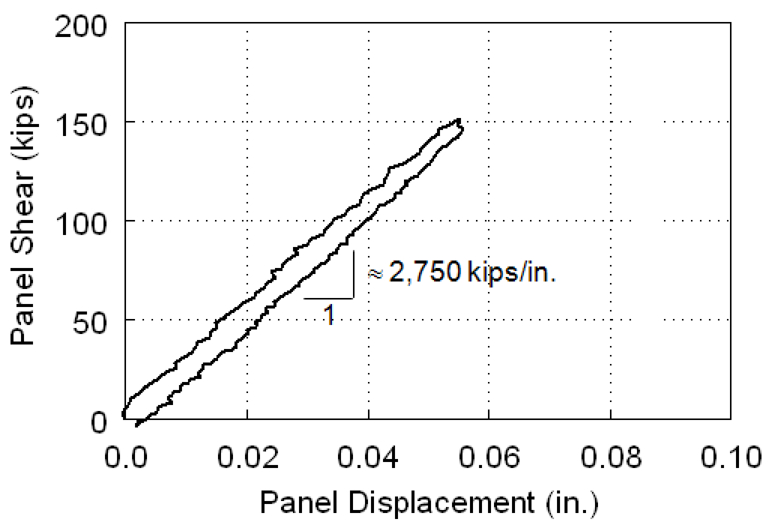
A. Shear Test – Stiffened Panel





Global Response:

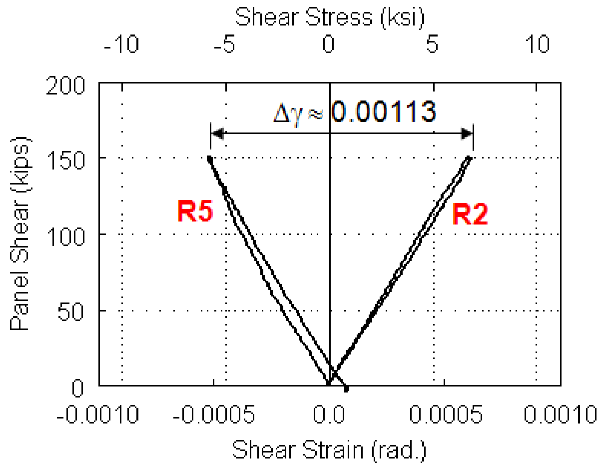


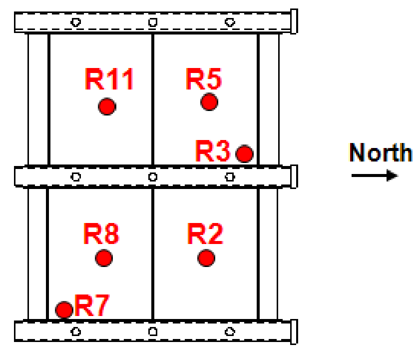


Data Reduction

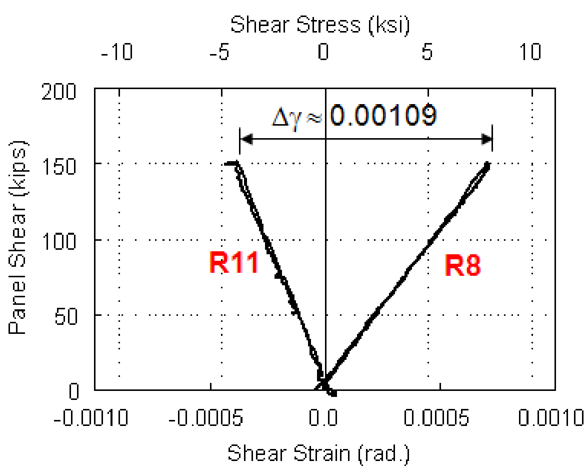
- Panel Shear: $V = P / 2$
- Panel Displacement: $\delta = L2 - (L1+L3) / 2$
- Shear Strain: $\gamma = 2\varepsilon_r - \varepsilon_b - \varepsilon_y$
- Shear Stress: $\tau = G\,\gamma$ (G = 11153 ksi)

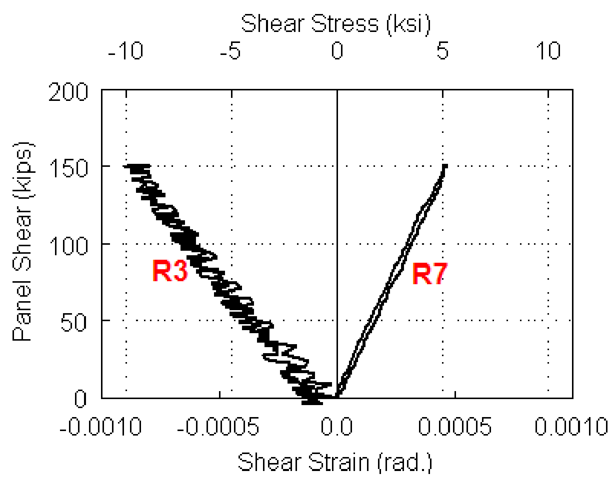
Measured Shear Strain vs. Panel Shear:



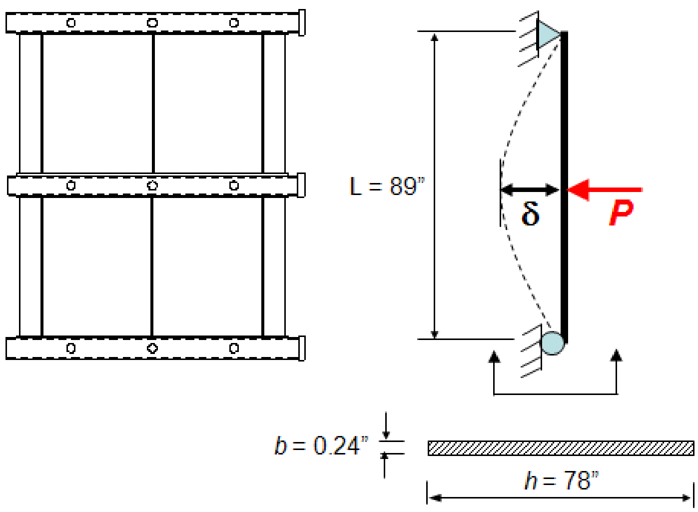


Rosette Locations





Comparison of Global Response (Test vs. Analysis) Simplified Model:



$$I = \frac{bh^3}{12} = 9{,}491\,\text{in}^4$$

due to Shear   due to Bending

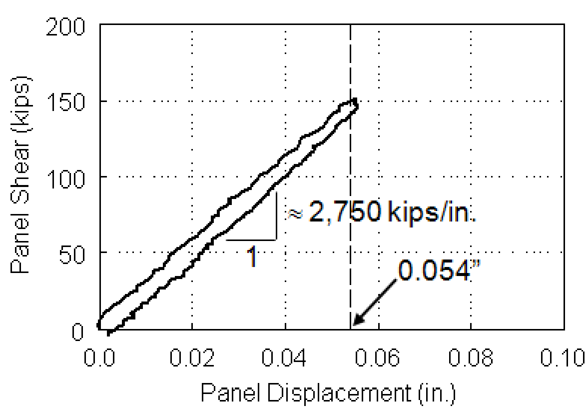
$$\delta \approx \frac{\alpha_S PL}{4GA} + \frac{PL^3}{48EI} = 0.038'' + 0.016'' = 0.054''$$

Where,

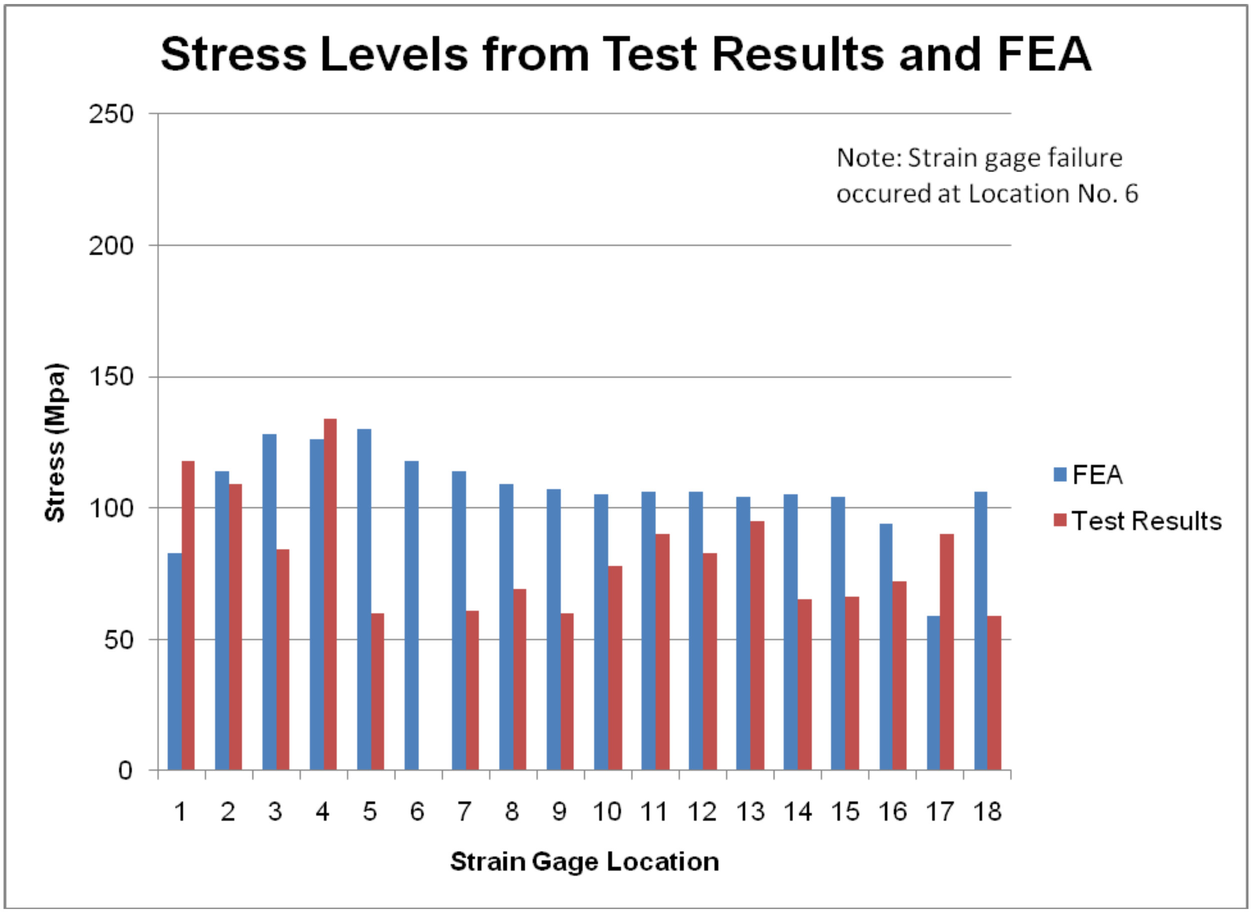
$$\alpha_S\ (\text{Shear Coefficient}) = \frac{12+11\nu}{10(1+\nu)} = 1.18$$

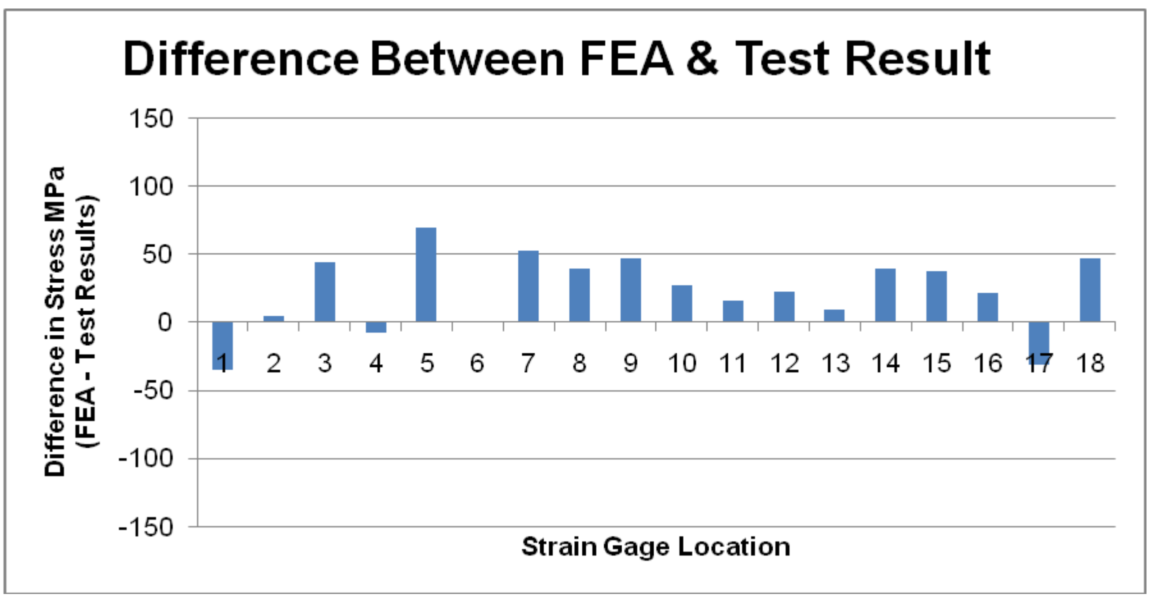
$$\nu\ (\text{Poisson's Ratio}) = 0.3$$

$$\text{Stiffness} = \frac{P/2}{\delta} = \frac{1}{2\left(\frac{\alpha_S L}{4GA} + \frac{L^3}{48EI}\right)} = 2{,}790\ \text{kips/in.}$$

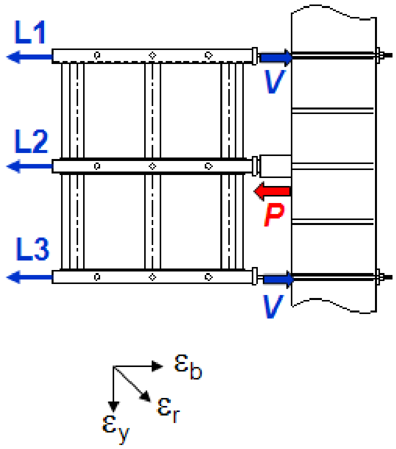


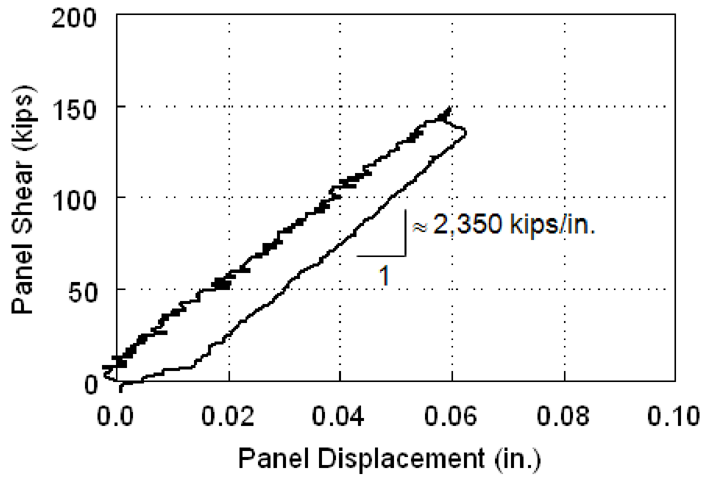
B. Shear Test – Swaged Panel





Global Response:

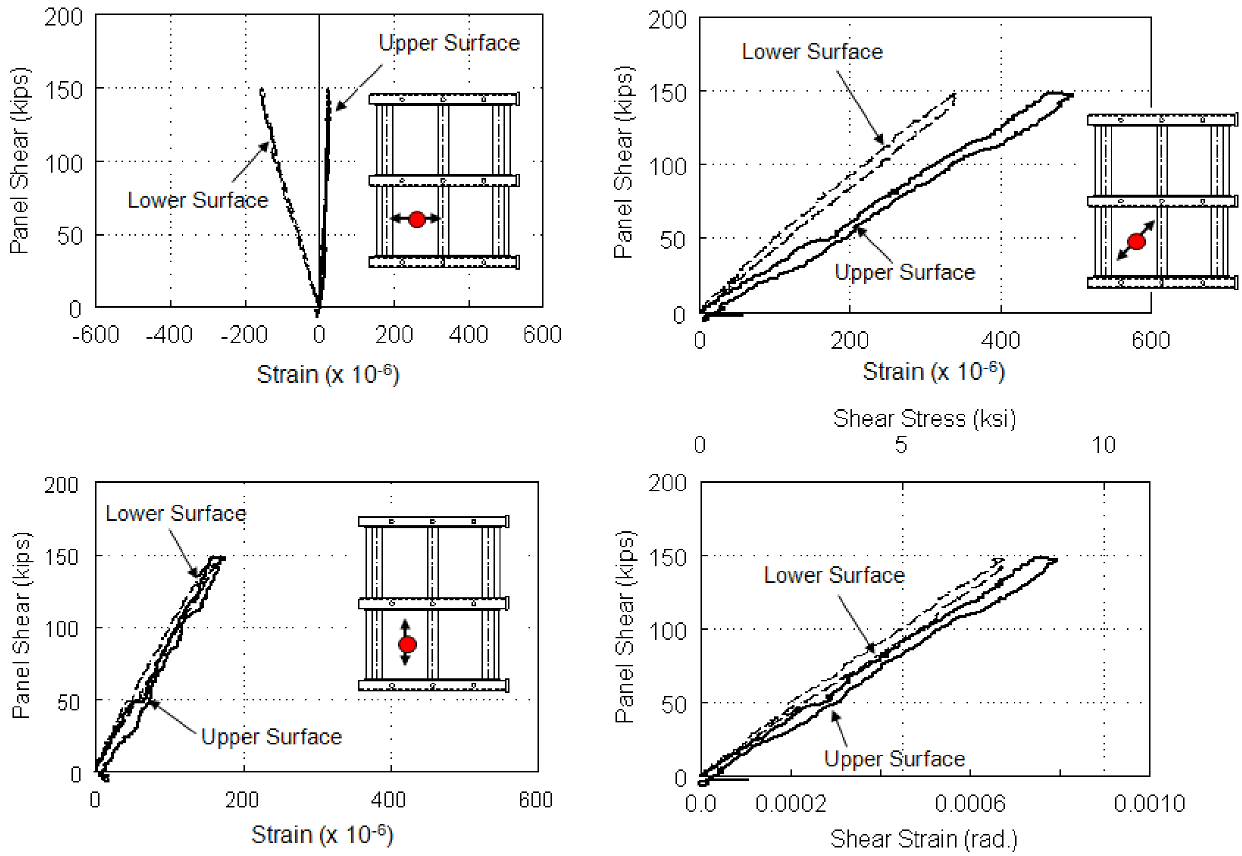




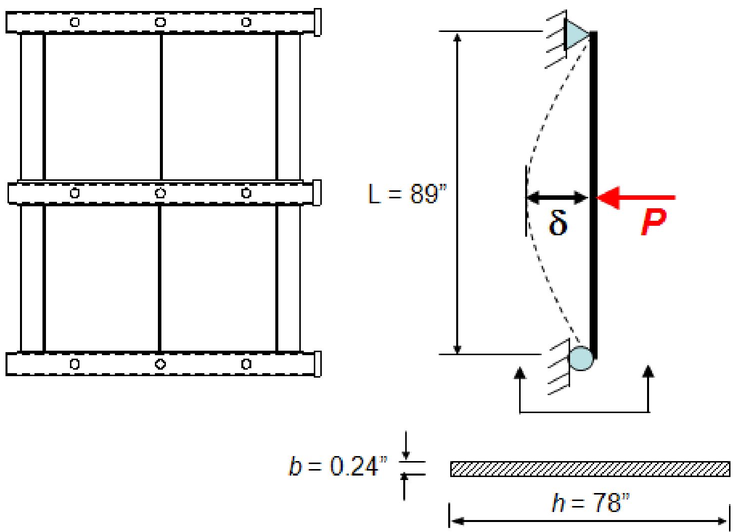
Data Reduction

- Panel Shear: $V = P / 2$
- Panel Displacement: $\delta = L2 - (L1+L3) / 2$
- Shear Strain: $\gamma = 2\varepsilon_r - \varepsilon_b - \varepsilon_y$
- Shear Stress: $\tau = G\,\gamma$ (G = 11153 ksi)

Measured Shear Strain vs. Panel Shear:



Comparison of Global Response (Test vs. Analysis) Simplified Model:



$$I = \frac{bh^3}{12} = 9{,}491\,\text{in}^4$$

due to Shear ↓ due to Bending ↓

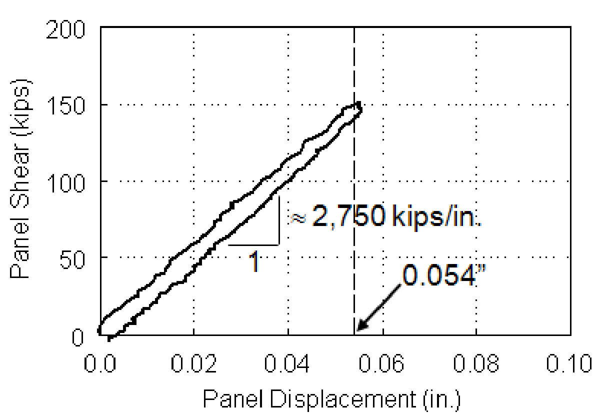
$$\delta \approx \frac{\alpha_S PL}{4GA} + \frac{PL^3}{48EI} = 0.038'' + 0.016'' = 0.054''$$

Where,

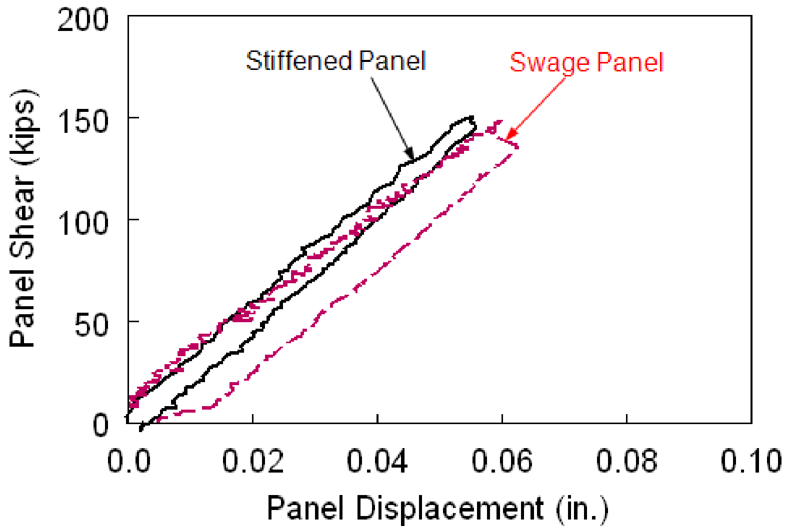
$$\alpha_S\ (\text{Shear Coefficient}) = \frac{12 + 11\nu}{10(1+\nu)} = 1.18$$

$$\nu\ (\text{Poisson's Ratio}) = 0.3$$

$$\text{Stiffness} = \frac{P/2}{\delta} = \frac{1}{2\left(\dfrac{\alpha_S L}{4GA} + \dfrac{L^3}{48EI}\right)} = 2{,}790\ \text{kips/in.}$$



Comparing Stiffened Panel vs. Swage Panel in Shear:



Observation: Stiffened Panel is about 17% Stiffer than Swage Panel

Compression Test

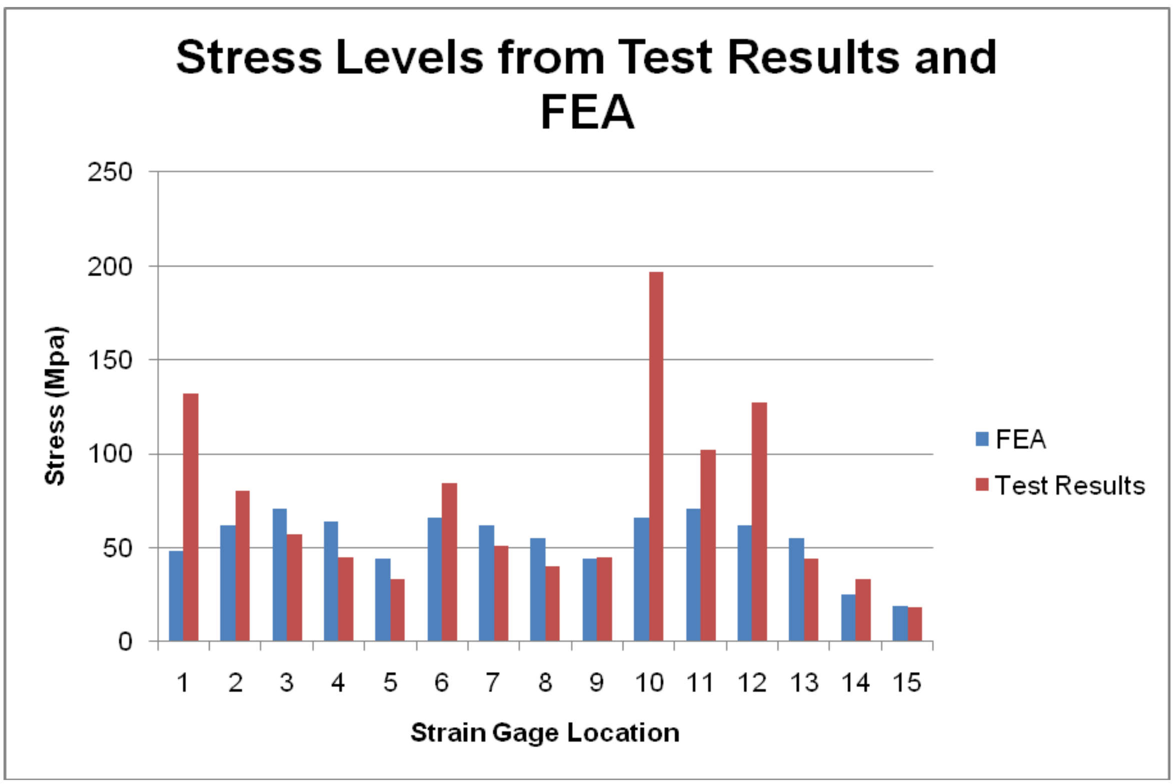
In both compression tests, a specially-designed I-beam was used to distribute the compressive forces from the SATEC Universal Testing Machine to the specimens. The FEA assumes this distribution is even across the width of the top plate.

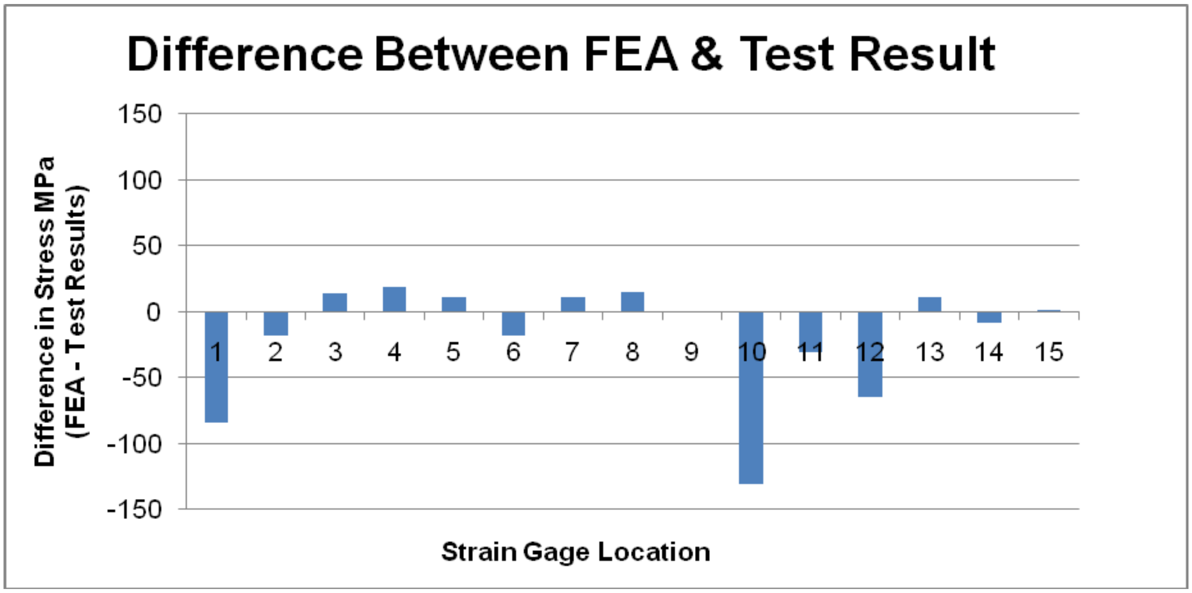
However, the stresses from the compression test results show a fairly consistent pattern of being higher than the FEA prediction for the locations in the center of the panel, and lower than the FEA prediction for the locations on the sides of the panel.

This shows that even with the I-beam in place to distribute the load from the test machine's application to the specimen, the distribution was not even. Thus, more load was applied to the center of the panel than the sides, resulting in higher than expected stresses in the center and lower than expected stresses in the sides.

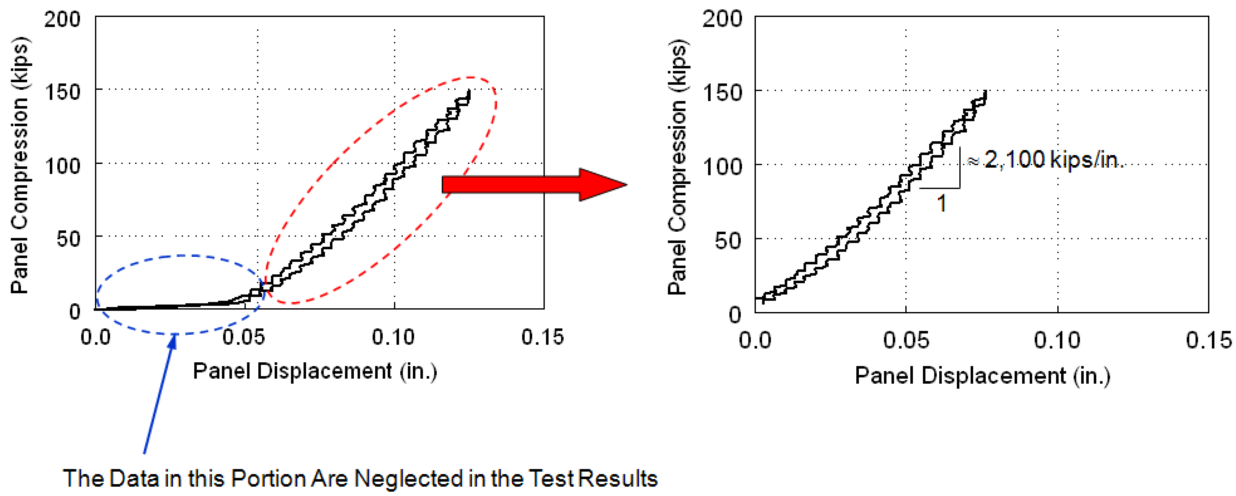
Additionally, in the locations where there were strain gages on both sides of the test specimen, significantly different strains were recorded. Some bending was expected, as the load cannot be applied onto the exact neutral axis of the panel. However, these significant differences indicate that more bending in the panel occurred than was anticipated based on FEA predictions.

C. Compression Test – Stiffened Panel

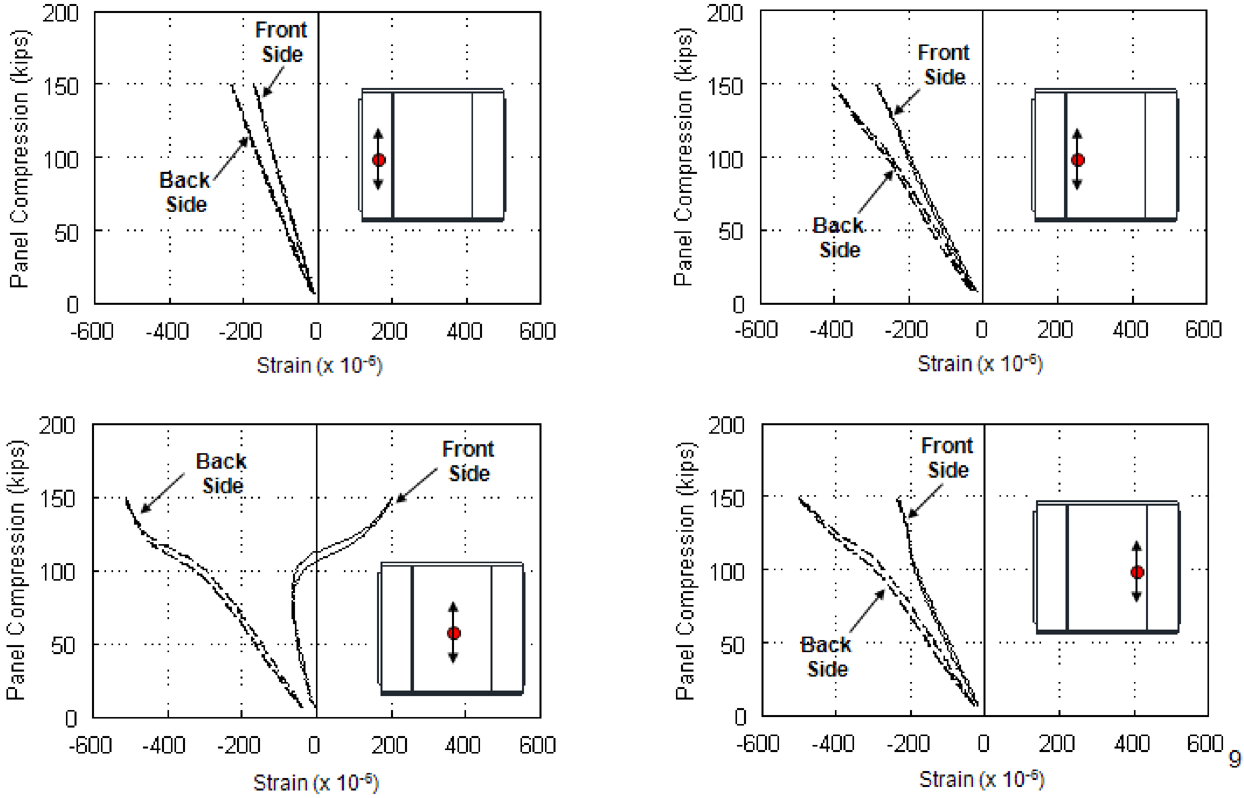




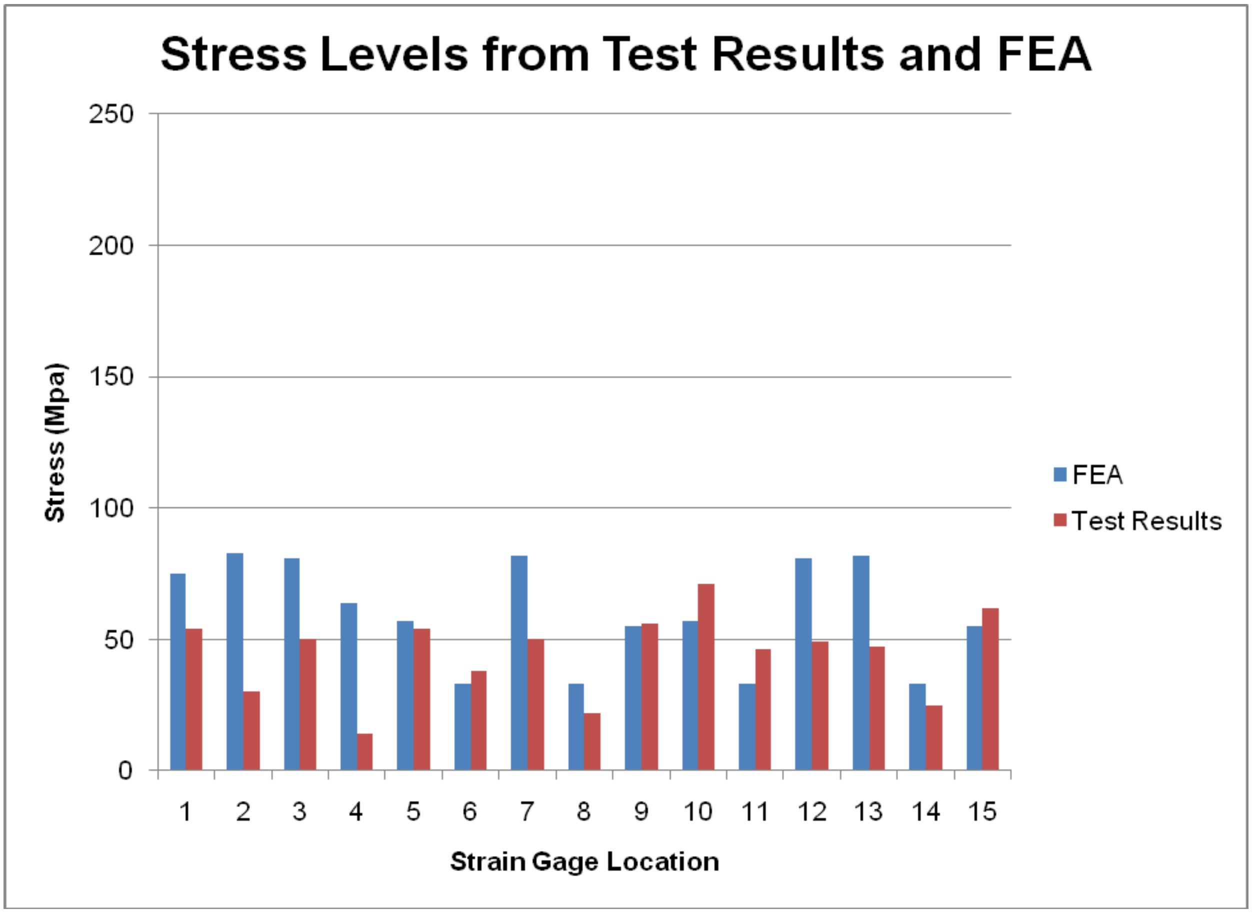
Global Response

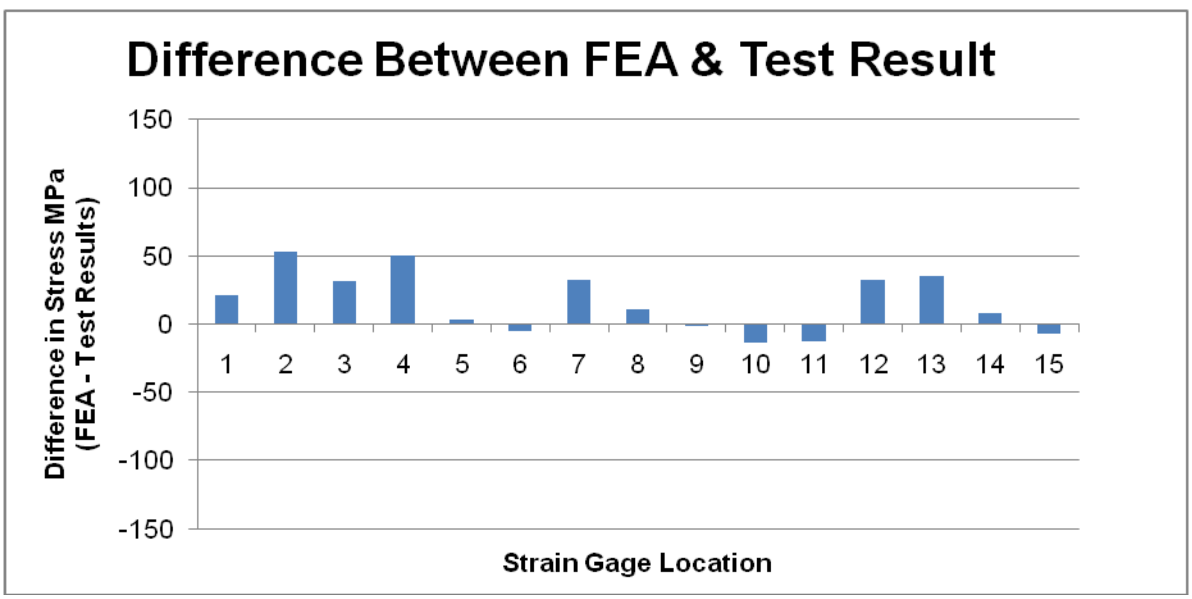


Measured Strain

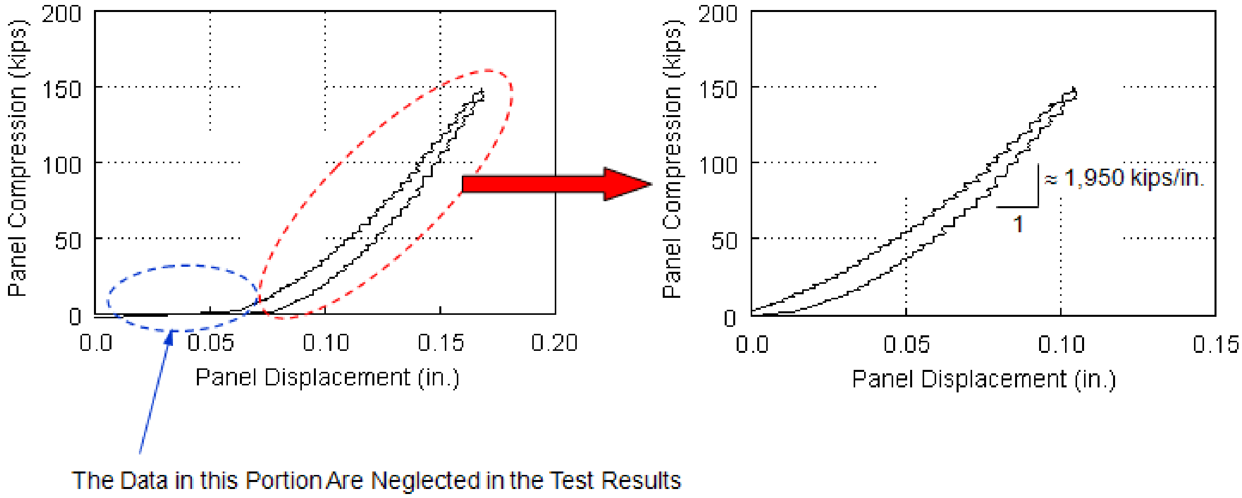


D. Compression Test – Swaged Panel

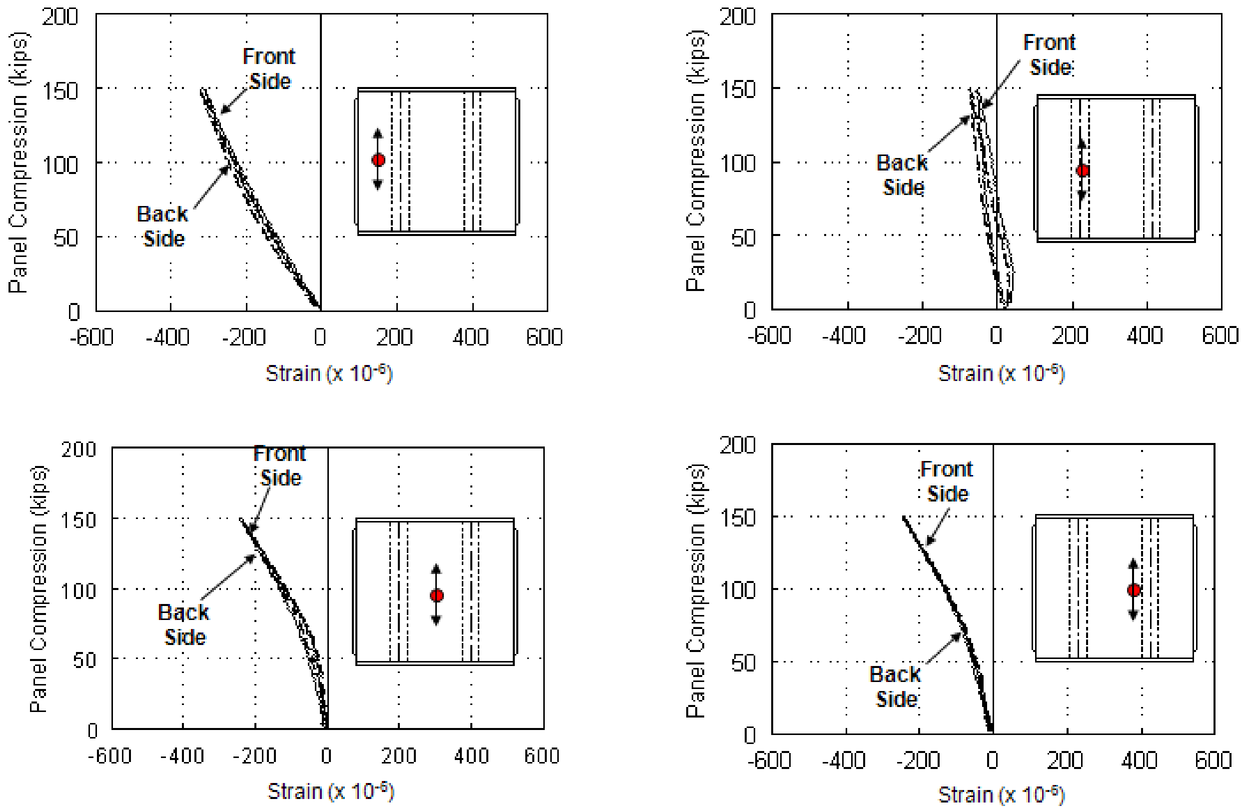




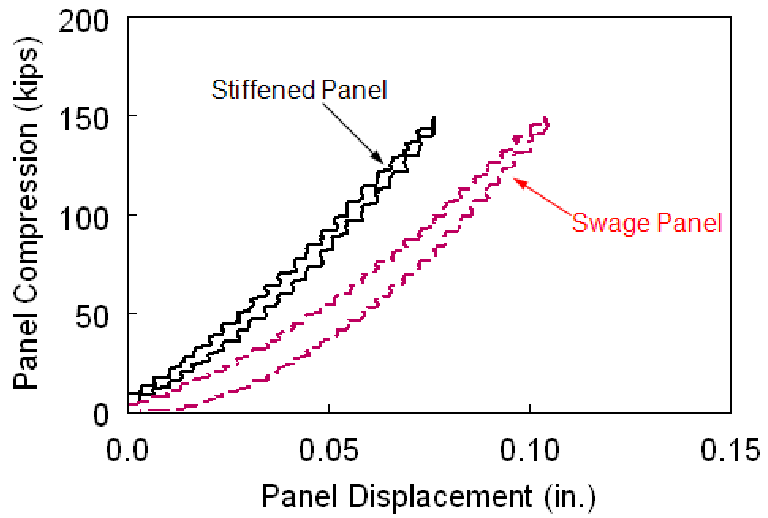
Global Response



Measured Strains



Comparing Stiffened Panel vs. Swage Panel in Compression:



Observation: Stiffened Panel is about 11% Stiffer than Swage Panel

.

Conclusions

It is quite possible that the strain gage readings were affected by the geometric imperfections because the strain distribution within the panel is influenced by out of plane geometry. The strains measured are correct for the panel, but may not compare well with the idealized FEA.

The geometric imperfections on the panels with stiffeners were greater (in some cases, double) the magnitude of those imperfections found on panels with swages. This can be correlated to the simple fact that stiffeners must be welded in place, which causes heat distortion.

In both of the stiffened panels, the FEA over-predicted and under-predicted the stresses indicated in the test results, depending upon the strain gage location. However, in the swaged panels, the FEA almost always over-predicted, and rarely under-predicted the stresses. The overall stress levels in the swage panels were lower than expected relative to the difference noted for the stiffened panels. This indicates that the distortion caused by welding stiffeners to plate may actually increase stress levels.

In order to bring the FEA predictions closer to the stresses calculated from the strains collected during actual testing, further study, as outlined in NASSCO NSRP Research Announcement Proposal 0901-04, is necessary.

References

Beam and Column Strength of Stiffened Plates. A. O. Bell, A. C. Viner and W. S. Richardson.

Transition Design Information Guide: Swage Bulkheads. NASSCO Hull Engineering (Rev -).

ABS Steel Vessel Rules Part 5C Chapter 1 Appendix 2 (2010).

Tech Note TN-515. Vishay Micro-Measurements. <www.vishaymg.com>.