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# Combined Loads Test Fixture for Thermal-Structural Testing Aerospace Vehicle Panel Concepts

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**February 2004**

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# ABSTRACT

A structural test requirement of the National Aero-Space Plane (NASP) program has resulted in the design, fabrication, and implementation of a combined loads test fixture. Principal requirements for the fixture are testing a 4- by 4-ft hat-stiffened panel with combined axial (either tension or compression) and shear load at temperatures ranging from room temperature to 915 °F, keeping the test panel stresses caused by the mechanical loads uniform, and thermal stresses caused by non-uniform panel temperatures minimized. The panel represents the side fuselage skin of an experimental aerospace vehicle, and was produced for the NASP program. A comprehensive mechanical loads test program using the new test fixture has been conducted on this panel from room temperature to 500 °F. Measured data have been compared with finite-element analyses predictions, verifying that uniform load distributions were achieved by the fixture. The overall correlation of test data with analysis is excellent. The panel stress distributions and temperature distributions are very uniform and fulfill program requirements. This report provides details of an analytical and experimental validation of the combined loads test fixture. Because of its simple design, this unique test fixture can accommodate panels from a variety of aerospace vehicle designs.

# NOMENCLATURE

| | |
|---|---|
| CTE | coefficient of thermal expansion |
| FLL | Flight Loads Laboratory |
| TMC | titanium matrix composite |

# INTRODUCTION

The National Aero-Space Program (NASP) Joint Project Office (JPO) sponsored the design, fabrication, and flight test of the X-30 experimental hypersonic aircraft. Powered by an airbreathing propulsion system, the X-30 vehicle was intended to horizontally take off from conventional runways and achieve single-stage-to-orbit (SSTO) flight. The technical challenges proved insurmountable, and the X-30 vehicle was never built. Many technological advances, however, have been accomplished by attempting to achieve the goal of the X-30 vehicle. To accomplish the X-30 vehicle, a vehicle structural concept utilizing low-weight, high-strength materials and capable of operating at high temperatures (1000–3000 °F), had to be designed and demonstrated. After a promising material was identified and appropriate material tests were conducted, many test articles representing various locations on the vehicle, structural configurations, and loads and thermal conditions were fabricated for laboratory testing at the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center (DFRC), Edwards, California, Flight Loads Laboratory (FLL). Many of the test programs had objectives to validate the methods of fabrication, the design concepts, and the analytical tools. Additionally, the test programs were intended to demonstrate the structural performance of the many components subjected to their unique load and temperature conditions.

One test article fabricated for the X-30 concept vehicle is a hat-stiffened panel called the side shear panel. This panel represents an external fuselage skin section on the side of the X-30 vehicle in the location of the highest shear loading. This panel location also experiences high axial loads, both tension and compression, and high temperatures. Figure 1 shows the location of the side shear panel on the X-30 concept vehicle and illustrates a positive shear load combined with a compression axial load. To simulate these load and temperature conditions in a ground test, a test concept had to be generated. This concept then would define the requirements for the design and fabrication of a test fixture capable of imposing the combined loads and temperatures. In particular, the most difficult problems to be encountered in the design of this concept would be to achieve appropriate thermal and mechanical boundary conditions. References 1–6, spanning 25 years, provide insight into the difficulties associated with this problem. The latest of these references (ref. 6) dwells entirely on the significance of this issue and documents numerous test configurations.

This report describes the side shear panel test requirements, the test article, and how the boundary condition problems are solved. The test fixture design, fabrication and test capabilities, and the data used to evaluate the performance of both the fixture and the X-30 test article are also detailed.

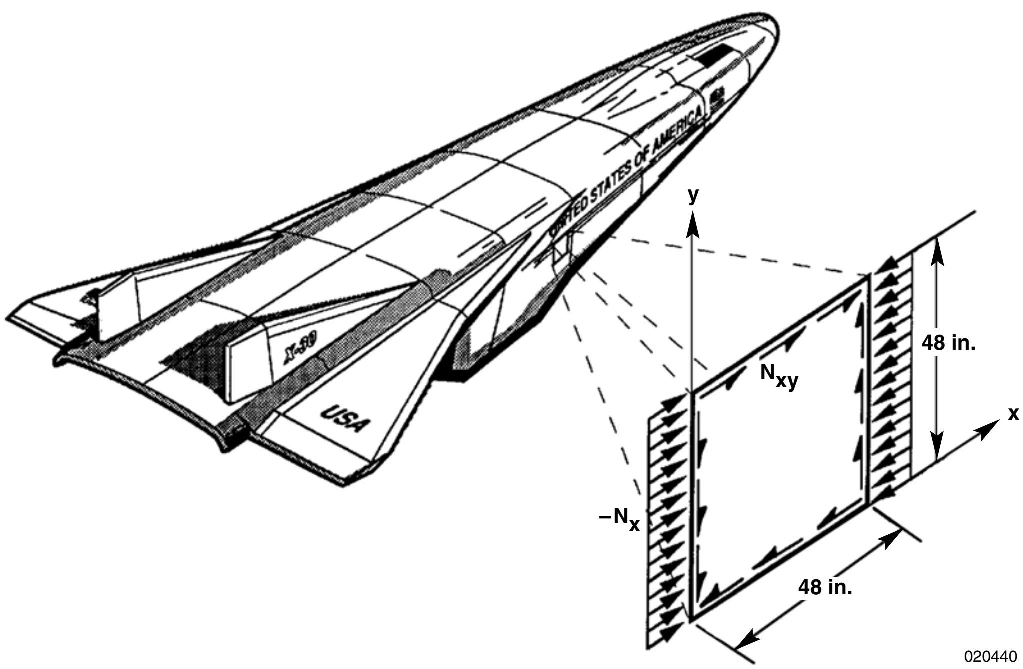


Figure 1. Side shear panel location on the X-30 concept vehicle illustrating a positive shear load ($N_{xy}$) combined with a comprehensive axial load ($–N_x$) relative to the x-y coordinate system.

## SIDE SHEAR PANEL TEST REQUIREMENTS

The test requirements for the side shear panel test program are to:

- Test a 4- by 4-ft panel.
- Apply maximum axial loads of 240,000 lbf compression and 300,000 lbf tension that result in maximum test panel loads of 3,400 lbf/in compression and 4,260 lbf/in tension, respectively.
- Apply maximum longitudinal and lateral loads of 30,000 lbf and 50,000 lbf, respectively, in both directions, at four points that result in maximum test panel shear loads of 1,060 lbf/in.
- Maintain structural stability during application of compressive loads.
- Achieve uniform stresses over the entire test panel for all load conditions.
- Achieve uniform test panel and boundary frame temperatures from room temperature to 915 °F to minimize in-plane thermal stresses.
- Provide a capability to apply moderate temperature gradients (50–100 °F) from lower to upper test panel surfaces and from test panel to boundary frames.
- Maintain all load attachment points (axial and shear) in the same plane for all test conditions.
- Ensure the test panel attachment and loading system achieve a stress-free (that is, freely expanding) system during thermal tests.
- Isolate test panel thermal stresses from axial load introduction–fixture parts, which are not heated.
- Design test fixture components to a safety factor of 3.0 on ultimate load.

## SIDE SHEAR PANEL TEST ARTICLE

Figure 2 shows an exploded view of the side shear panel test article assembly. The test article is a 48- by 48-in. hat-stiffened panel fabricated from Beta 21S/SCS-6 titanium matrix composite (TMC) that incorporates a smooth, flat skin and 10 hat stiffeners. The TMC transition panels, consisting of three hats each, are bolted to the panel using TMC splice plates to help isolate the test panel from the test fixture boundary conditions. With the addition of the transition panels, the overall dimensions of the test article are 48 in. by 96 in.

The TMC side shear panel assembly is attached to an Incoloy 909 (Huntington Alloys Corporation, Huntington, West Virginia) frame, and corrugated panels with steel load blocks are attached to each end for load introduction. Figure 3 shows a sketch of the test article assembly as viewed from the hat-stiffened side. The Incoloy 909 material was selected to match, as closely as possible, the TMC coefficient of thermal expansion (CTE) while still providing the required strength properties at the test temperatures. The Incoloy 909 frame that surrounds the TMC side shear panel is representative of the X-30 frame attachment concept. For the corrugated axial load transition structure, A286 steel was selected because of its high-temperature strength properties. The A286 corrugated structure provides good longitudinal stiffness for load introduction while minimizing transverse stiffness, thus preventing excessive thermal stresses at those boundaries during combined heating and loading tests. Because the end fittings are outside the heated area, low-carbon steel was selected because of its availability, ease in machining, and relatively low cost. Figure 4 shows the test article assembly delivered to the NASA DFRC.

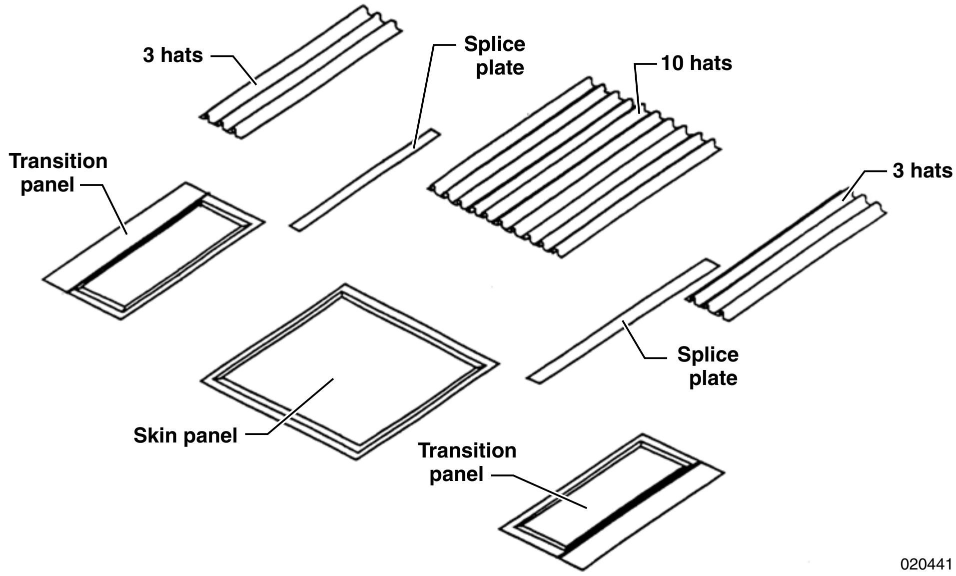


Figure 2. Exploded view of the titanium matrix composite (TMC) side shear panel assembly.

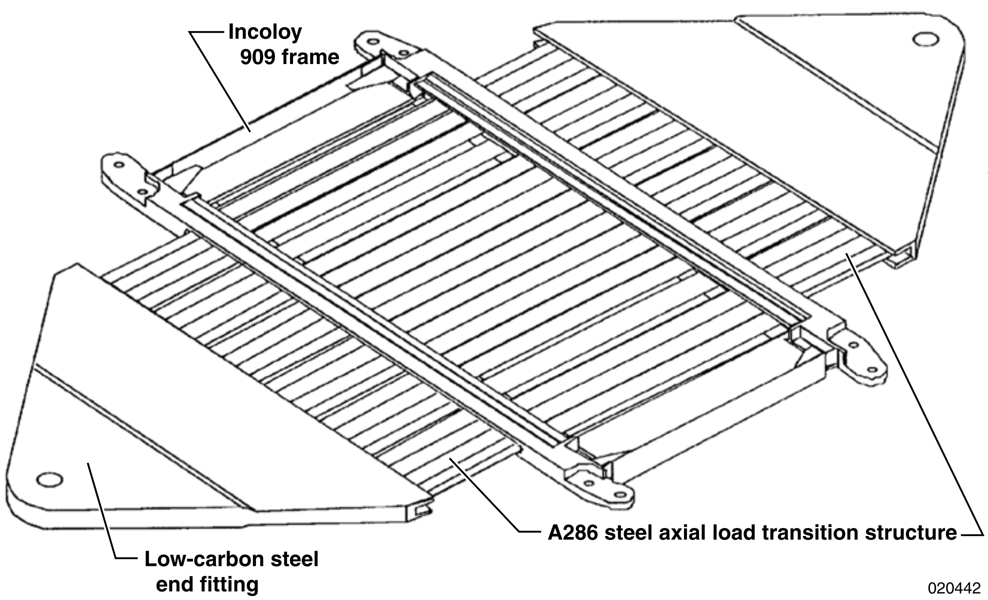


Figure 3. Sketch of the side shear panel test article assembly, viewed from the hat-stiffened side.

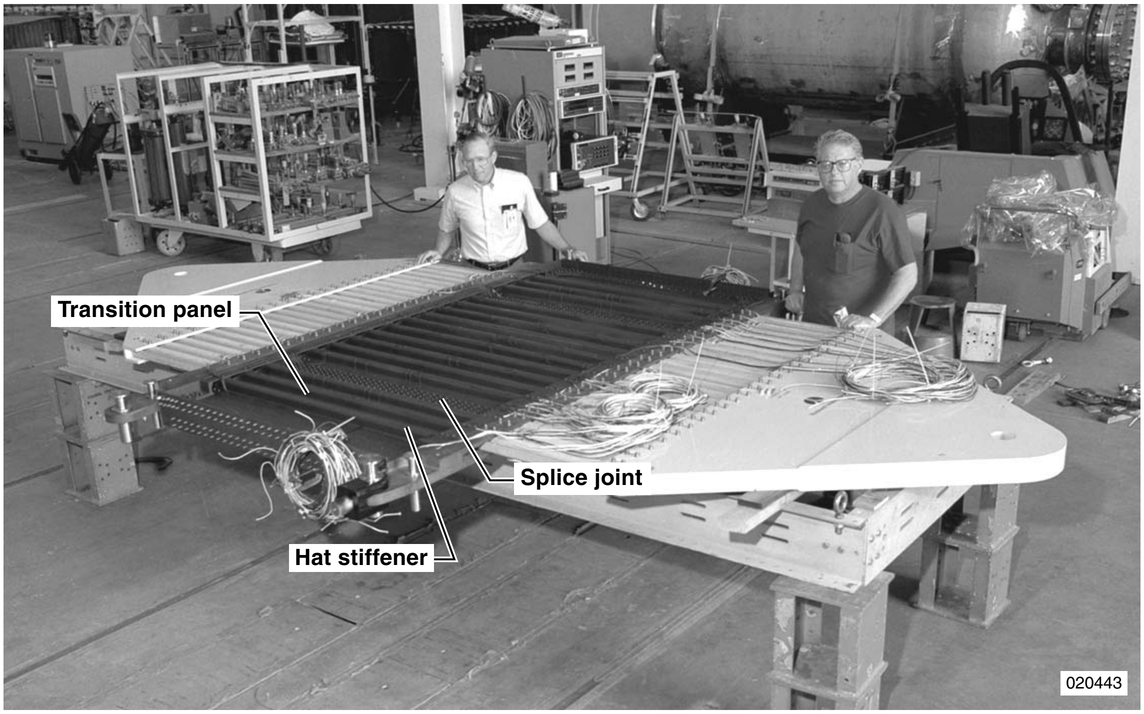


Figure 4. Side shear panel test article assembly, viewed from the hat-stiffened side.

## DETAILED TEST FIXTURE DESIGN

Figure 5 shows a sketch of the test article assembly including the test panel as viewed from the hat-stiffened side, the various components of the test article assembly, its overall size, and the load introduction and load reaction points. The *x*-*y* coordinate axes (fig. 1) are shown for clarity. The side shear panel test fixture is required to provide the means to mechanically load the test article at both room temperature and elevated temperatures with and without temperature gradients. The following sections present the detailed test fixture design as two distinct systems: the system that applies and reacts the mechanical axial and shear loads, and the system that provides the capability to mechanically load-test at elevated temperatures and to induce thermal loads into the test article.

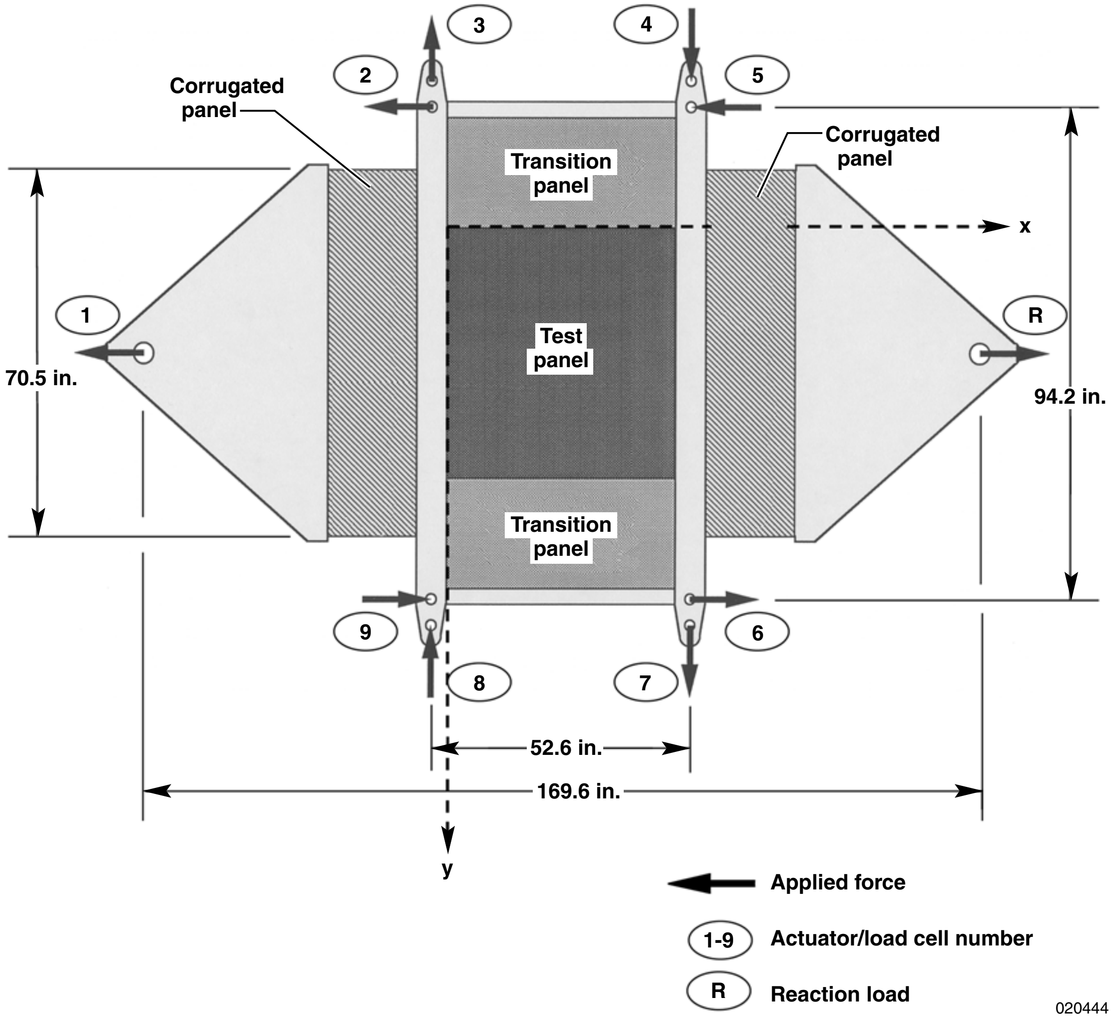


Figure 5. Test article assembly, viewed from the hat-stiffened side, with combined positive shear and positive axial loads illustrated.

## Mechanical Loading

Mechanical loading is achieved with a system composed of three major subsystems: the test article, which is designed to meet the unique requirements of the 4- by 4-ft test panel; the vertical links, which are critical to maintain a coplanar test article; and the self-reacting load frame. The following subsections detail these three subsystems.

## Test Article

Figure 6 shows the final test fixture design concept with the test article (fig. 5) positioned within it. Axial load, either tension or compression, can be applied to the test article at connection point K with actuator 1. The resulting axial load is reacted at pinned joint F.

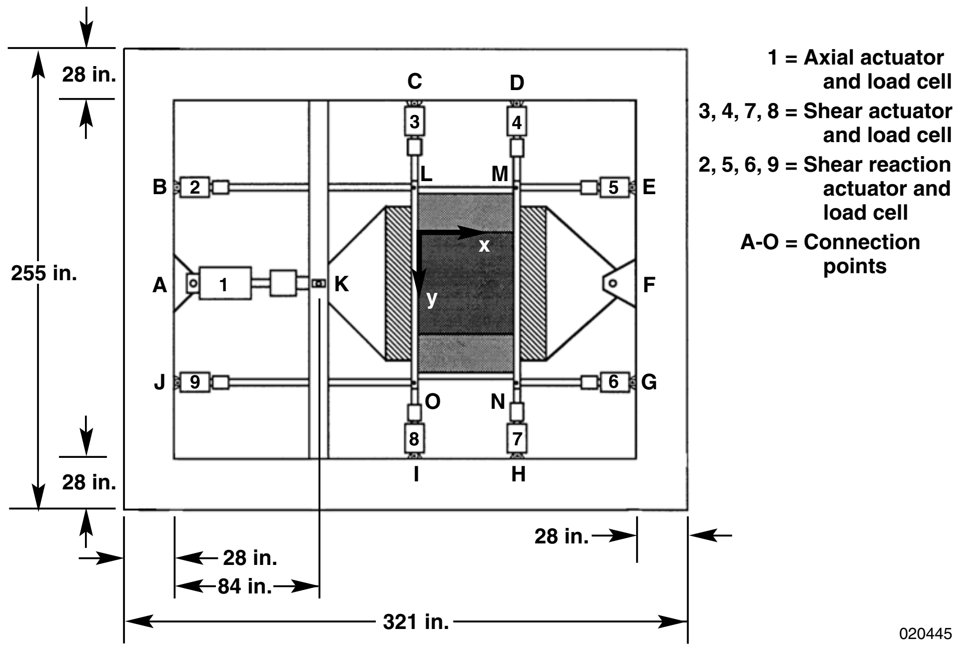


Figure 6. Test article assembly mounted in the test fixture, viewed from the hat-stiffened side (drawing not to scale).

Shear load is applied with actuators 3, 4, 7, and 8 (fig. 6). For shear load in the direction defined as positive (+shear), actuators 3 and 7 apply equal tensile loads, and actuators 4 and 8 apply equal compressive loads that are also equal in magnitude to the tensile loads of actuators 3 and 7. To achieve static equilibrium, this set of forces must be reacted with a set of forces applied with actuators 2, 5, 6, and 9 (fig. 6). For the case stated above, actuators 2 and 6 apply equal tensile loads and actuators 5 and 9 apply equal compressive loads, which are also equal in magnitude to the tensile loads of actuators 2 and 6. The magnitude of the equilibrating loads $P_{2,5,6,9}$ applied by actuators 2, 5, 6, and 9 is related to the shear loads applied by actuators 3, 4, 7, and 8, $P_{3,4,7,8}$, by the ratio of their respective distances, or

$$P_{2,\,5,\,6,\,9} = \left(\frac{52.6 \text{ in.}}{94.2 \text{ in.}}\right)(P_{3,\,4,\,7,\,8}) \tag{1}$$

Application of the shear loads requires a precision load control system in which each of the eight loads is applied proportionally to the others at all times. For example, to apply 10-percent shear load, each actuator should be commanded to apply 10 percent of the predetermined 100-percent load value with appropriate tension or compression direction. Use of actuators 1 and 2–9, therefore, can provide independent axial and shear loads or any combination to the maximum design capabilities as given in the "Detailed Test Fixture Design" section.

Actuator connection points A–E and G–J (fig. 6) are pinned so that each actuator can only rotate within the plane of the test article. Connection points L–O are also pinned; however, each of these points has a vertical link attached to it, as shown in figure 7, to maintain a coplanar load frame.

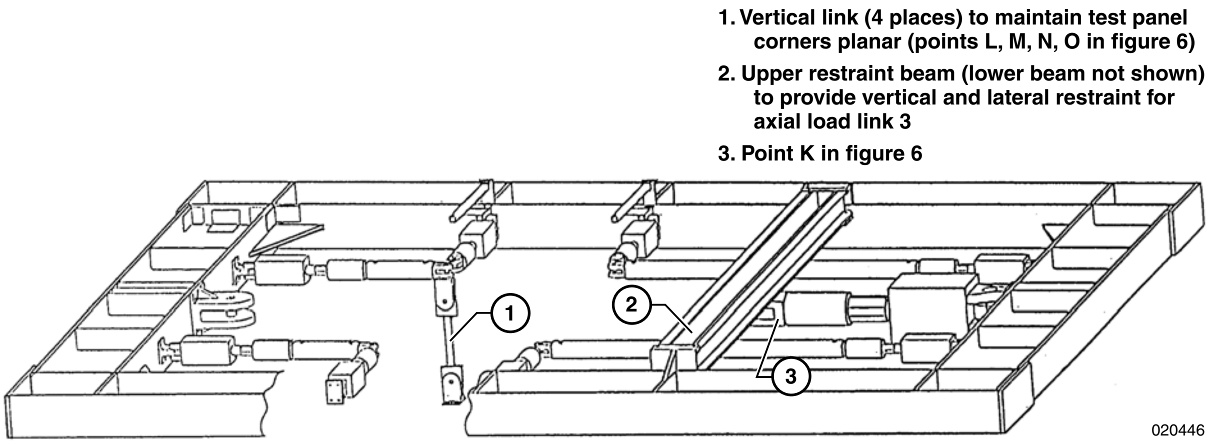


Figure 7. Combined loads test fixture details of the out-of-plane motion constraints (with the test fixture removed for clarity).

Connection point F (fig. 6) is pinned and will allow rotation only in the plane of the test article. This point also provides the reaction force for axial loads applied at point K. The number 1 actuator and load cell are pinned to the test article at point K.

Because points A, K, and F must remain coplanar and in axial alignment for compressive loading to prevent instability, connection point K can be allowed to move only in the plane of the test article and along the line between points A and F. To accomplish this, the axial load link is sandwiched between two restraint beams (fig. 7) that also permit it to slide. As shown in figure 8, the pin that attaches the axial load link to the test article passes through slots in the restraint beams. The restraint beams allow the pin and the test article to move only in the direction of the slot and the axial force. The upper and lower restraint beams, therefore, restrict both vertical and lateral movement of point K (fig. 6).

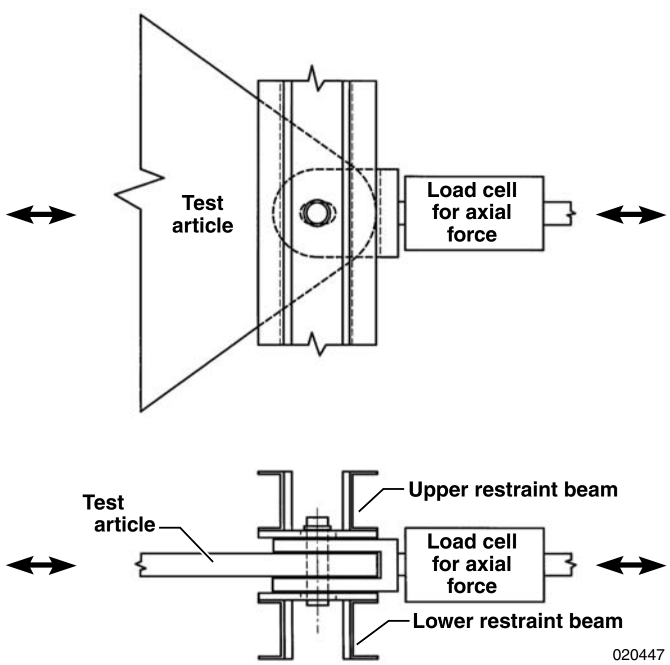


Figure 8. Attachment point K (fig. 6) detail for axial force application to the test article.

## Vertical Links

The fabrication plan required defining the size of the fastener holes for the vertical link attachments before the finite-element analysis models were fully functional. Consequently, an estimation of the vertical link load was necessary. Theoretically, if the test article remains aligned or in the same plane with the compressive load, then the force in the vertical links is zero. If the test article moves out of plane, an eccentricity develops with a resulting moment that causes the out-of-plane forces to rapidly increase. Holes were drilled to accept 3/4-in. fasteners with an ultimate load capability of 44,500 lbf. The vertical links were designed accordingly for stress in tension and buckling in compression. As a check during testing, the links were instrumented with strain gages to measure the tension and compression loads in real time. An additional design requirement for the vertical links is to allow a 2-deg rotation of the link in any direction, which is equivalent to an in-plane translation of approximately 1 in. at the test article attachment. Hemispherical rod ends at each end of the vertical links were used to meet this requirement.

## Self-Reacting Load Frame

The outer frame (fig. 7) for the side shear panel test is self-reacting for all in-plane loads. In other words, all applied loads are reacted by the frame in such a manner that no external loads or tie-downs are required. Only the weight of the structure needs to be considered. Consequently, the frame is supported by six tripod hydraulic jacks, which offer a convenient means of accurately adjusting the height of the test setup. Figure 9 shows the outer frame resting on the six supports, without the test article and the hydraulic actuators. Each of the support points employs a hemispherical seat, so that any rotational movement at any point would not be restrained. The only loads the frame is unable to react are the out-of-plane vertical link loads discussed above, and they are reacted by tie-downs to the floor.

Specific outer frame design requirements are as follows:

- Design limit loads in lbf shall be as shown in figure 10.
- All parts shall have a minimum safety factor of 3.0 on ultimate stress.
- Maximum frame deformation caused by loads shall be less than 0.1 in.
- The horizontal centerline of the frame shall be approximately 4 ft above the floor and the height shall be easily adjustable.
- The frame shall be large enough to accommodate the test article, hydraulic actuators positioned at midstroke, load cells, and attachment fittings.

A finite-element model of the outer frame was used for overall stress analysis and deflection calculations. Hand analyses were also made for all individual components and connections.

Figure 11 shows a photograph of the completed setup for the room-temperature test. An independent frame is also shown spanning the load frame immediately above the test panel and transition panels. This frame is used to support transducers for measurement of out-of-plane test article deformations.

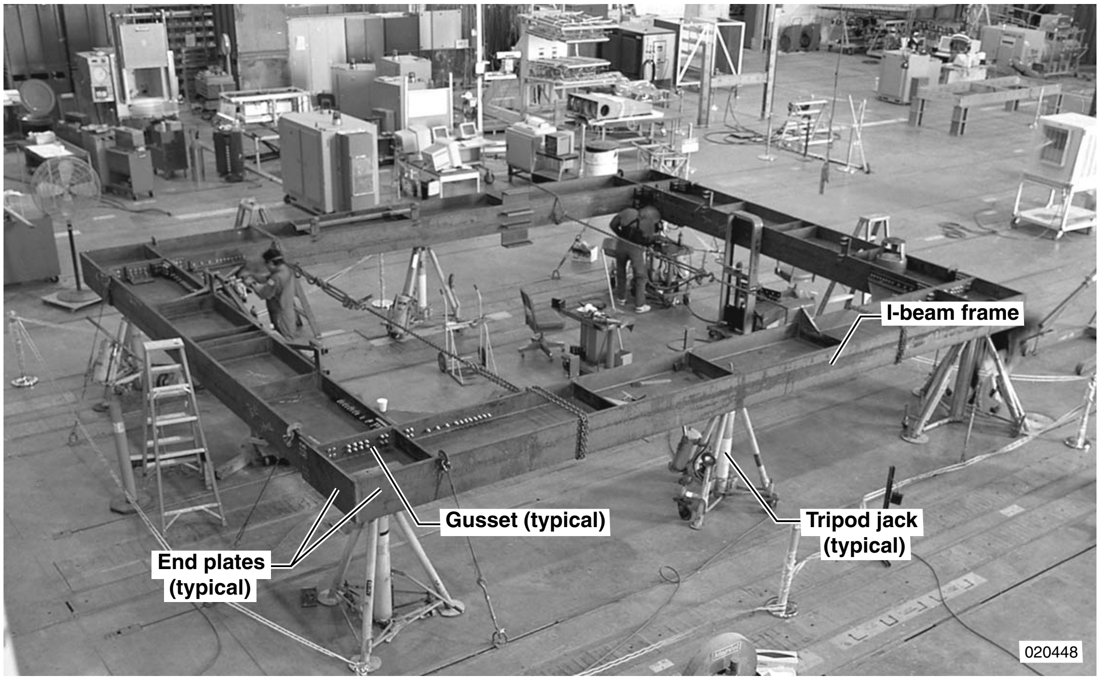


Figure 9. Assembly of the self-reacting load frame.

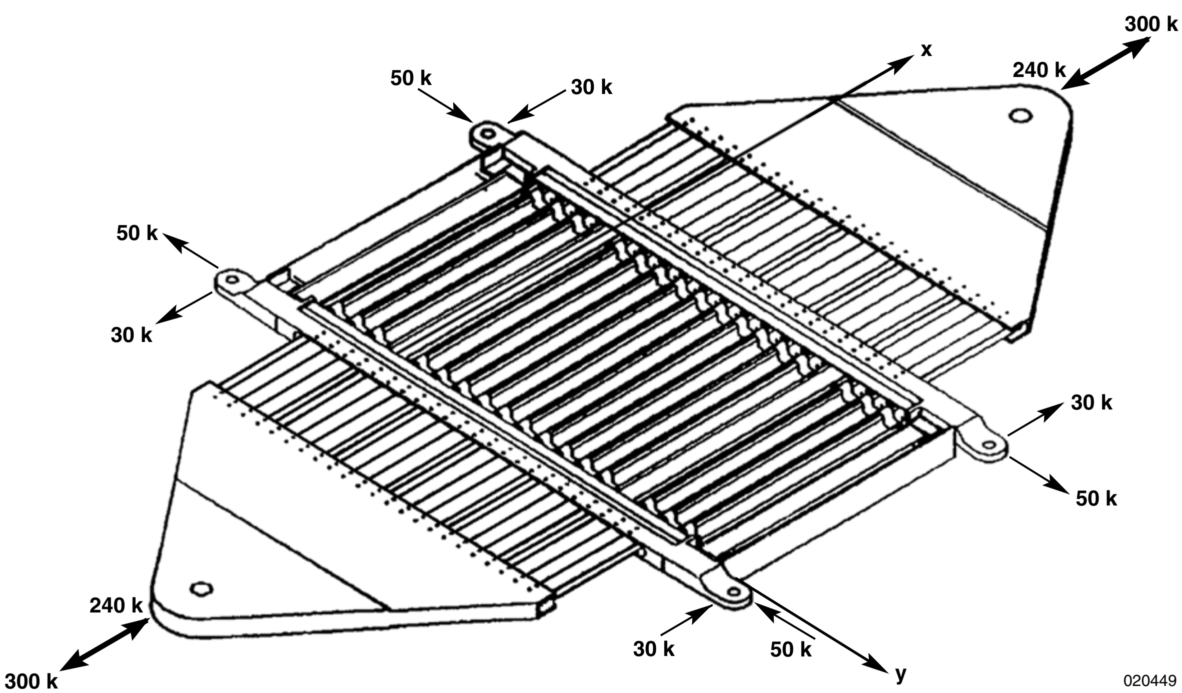


Figure 10. Design limit loads for the self-reacting load frame shown applied to the test article assembly.

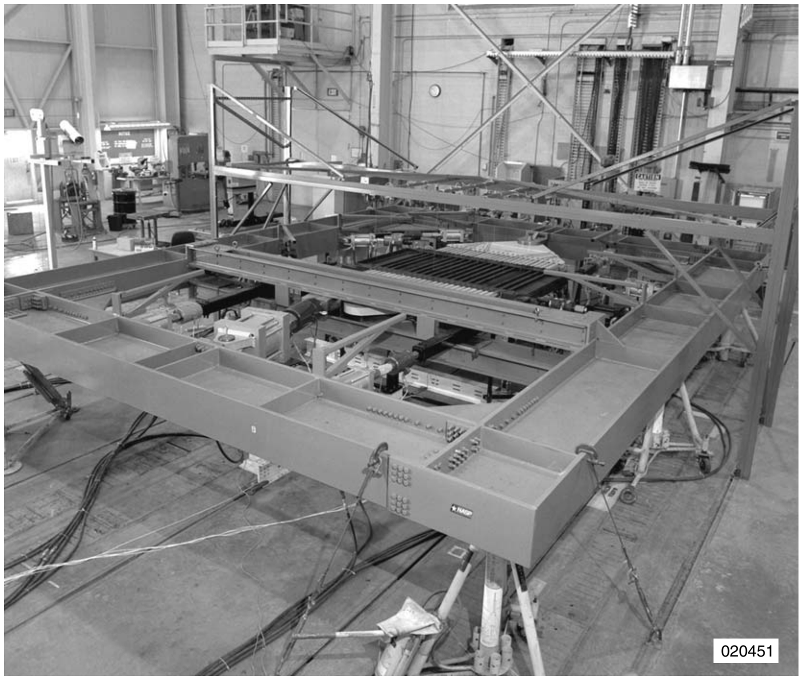


Figure 11. Side shear panel room-temperature test setup.

## Thermal Loading

Thermal loading is achieved with a heater system that uses infrared quartz lamps. Many important considerations exist in designing a system that must not only ensure thermal gradients, and thus, thermal stresses, are minimized for certain test conditions, but also must provide appropriate thermal gradients when required for other test conditions. The unique requirements of the thermal loading system are described, followed by a detailed description of the heater system.

### Requirement and Approach

The primary thermal requirement for the side shear panel test is to maintain a uniform temperature of 915 °F on the test panel and boundary frame during the application of the mechanical loads. To adequately address this requirement, recognizing that all thermal-structural tests demand special attention to boundary conditions is important. As noted in references 1–6, both thermal and mechanical boundary conditions must be addressed because of their inherent interaction with the test panel and attendant structure. Blosser (ref. 6) specifically summarizes this problem and references the approach taken in many test programs.

Since the side shear panel boundary frame is of different material than that of the test panel and the transition panels, it is important that the CTE of each of the materials be similar. Consequently, the frame material was carefully chosen for that reason. If the CTEs did not closely match, then the temperatures could be adjusted to provide a match of overall thermal expansion.That situation, however, would make it much more difficult to achieve uniform temperatures on the test panel.

The structural interfaces to the panel boundary frame are high-temperature corrugated steel panels (figs. 3 and 5). These corrugated panels tend to respond in an “accordion” fashion to the differential thermal expansion of the heated area on one side and the room-temperature triangular steel blocks of the other side. Although this response does not completely eliminate thermal stress from being introduced into the test panel, the overall thermal displacements and the resulting thermal stresses are small. The corrugated panels, therefore, serve to minimize thermal stresses and also provide a stable and effective means of applying axial load into the test panel.

A secondary thermal requirement is to provide a moderate temperature gradient (50–100 °F) between the lower and upper panel surfaces. This requirement is accomplished by simply programming the computer-controlled temperatures for the desired areas to the necessary values. The system then adjusts the heat flux distribution as required.

## Heater System

The mechanical loading concept described above and shown in figure 6 provides an unobstructed area above and below the test article for positioning a heater system capable of applying the thermal load. The test panel, transition panels, and surrounding rectangular framework are the only portions of the test fixture that are heated. The heating is applied to both sides of the test panel by an infrared quartz lamp heater system with 36 independent temperature control zones (18 upper and 18 lower) as shown in figure 12.

Because the outer test article frame has much more heat sink capacity than the test panel and transition panels, the density of quartz lamps in zones 1–4 and 19–22 is much greater than in the rest of the zones. This design provides the necessary higher heat flux for those areas and also provides a buffer around the test panel from the boundary conditions, which makes producing uniform surface temperatures on the panel easier.

At the interface between zones 1–4 and 19–22, a radiation barrier, or fence, is required to shield the less massive material from being heated by the interior zones from the comparatively higher heat flux of the exterior zones (ref. 1). The outside boundaries of zones 1–4 and 19–22 also had radiation barriers for the following reasons:

- to minimize heat flux losses
- to reduce the maximum temperatures on corrugated panels
- to restrict undesirable convection currents
- to enclose those zones for post-test cooling
- to restrict visible light for test personnel safety

Each of the 36 zones can be independently programmed for temperature rise rate and maximum temperature. The required temperature rise rate and maximum temperature for the side shear panel test are 1 °F/sec and 915 °F, respectively. The actual heater system performance maximums are dependent upon the material and test article. For example, a less massive structure with a high-emissivity surface can be tested to both high rates and high temperatures.

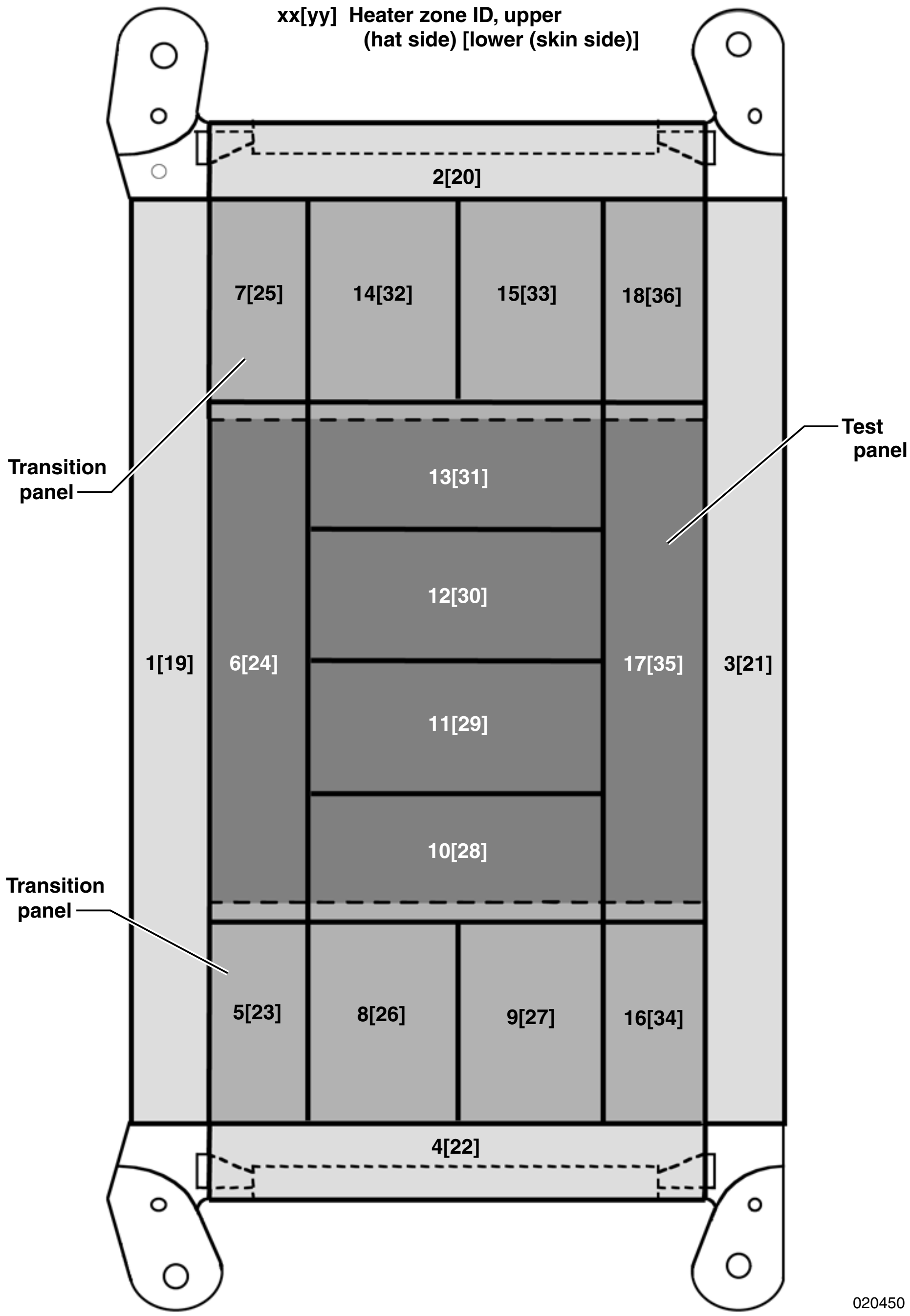


Figure 12. Quartz lamp heater zone layout relative to the test article.

The lower heater is supported from the floor by a hydraulic lift table. The upper heater is lowered into place with an overhead crane and then attached to the lower heater. This simple design allows for easy accessibility to the test panel. Figure 13 shows a sketch of both upper and lower heaters in place surrounding the heated portion of the test article. As can be seen, the attachment locations for the shear load actuators are not in heated areas (except by conduction). Likewise, the vertical load links are not heated. The test article movement during loading and heating tests is relatively small; therefore, the heater assembly was not designed to move.

The quartz lamps are positioned approximately 6 in. from the heated surfaces; the thermal barriers, which serve as heater zone dividers, are positioned far enough from the surface of the test article to accommodate test article movement. Flexible insulating curtains are used on the remaining gaps and holes in the test setup to enclose it as much as possible. Figure 14 shows a photograph of the actual test setup with the heaters and curtains in place. The flexible insulating curtains shown on the corners of the heater also serve to prevent radiation from heating the load cells when the load cells are connected for a combined heating and loading test. The load cells are otherwise sufficiently isolated from the test article so as not to be subjected to significant heating.

During the cool-down phase of the heating tests, cooling the heavy test article frame at the same rate as the panel is difficult, and the heater system cannot be moved to provide external forced convection. A system, therefore, was designed into both the upper and lower heaters that injects cold nitrogen gas into the cavities that are heated by zones 1–4 and 19–22 (fig. 12). The system forces gas through lines in the heaters to cool the ends of the quartz lamps for extremely high-temperature testing. Nitrogen gas is directed to the cavities with additional tubing. The cold nitrogen gas is provided by a FLL system that pumps vaporized liquid nitrogen at a controlled pressure and temperature.

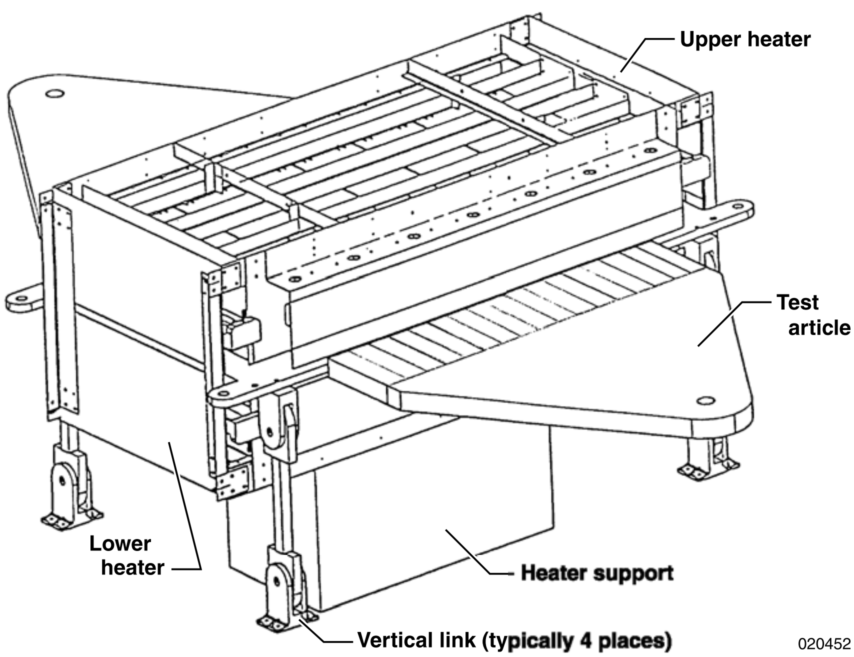


Figure 13. Side shear panel heater assembly shown fitted to the test article.

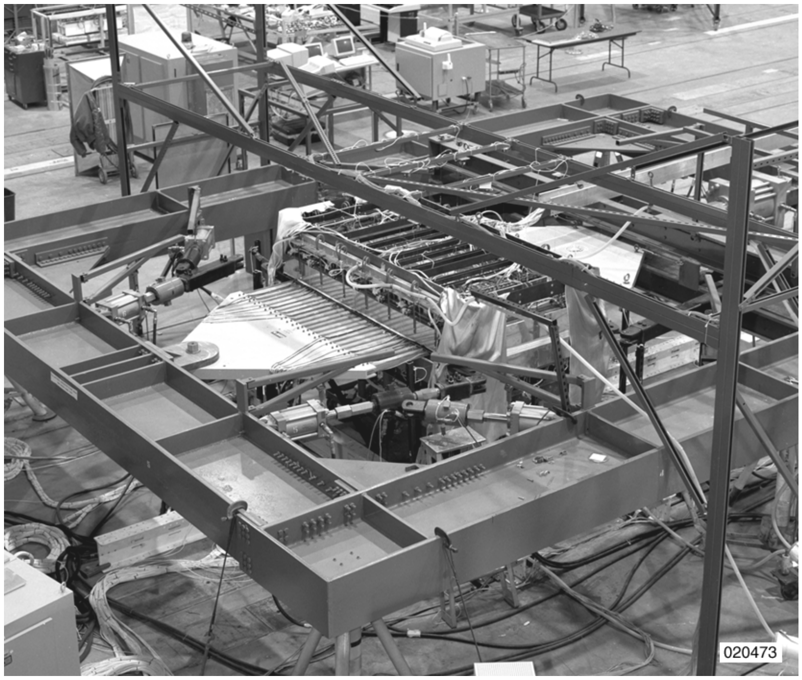

Figure 14. Side shear panel elevated temperature test setup.

## TEST FIXTURE FABRICATION AND ASSEMBLY

The fabrication and assembly of the test fixture required considerable planning to ensure test requirements were met. Important elements of the self-reacting frame, the axial load restraints, and the vertical links are presented.

### Outer Frame

Because the outer frame for the test fixture is so massive, the decision was made to bolt the I-beams together at the corners instead of welding them (figs. 9 and 11). This decision allows the individual beams to be handled with the laboratory 5-ton overhead crane; collectively, the fixture components exceed the lift capability of the crane. The bolted joints also provide the potential to more easily relocate the fixture to another location, if needed.

Before the I-beams were bolted together, one or more gusset plates were welded to the webs and caps at each concentrated load location, and end plates were welded to the end of the I-beams (fig. 9). Considerable care was taken to not warp the beams during the welding process. After all web gussets and end plates had been welded to the I-beams, each beam was supported precisely horizontal and positioned at right angles at the corners to be connected. The beams were rigidly clamped together while all corner connection components were match-drilled and bolted. Corner gussets then were added for reinforcement of the joints. After this huge frame was bolted together, the two diagonal measurements of nearly 333 in. differed by only 1/8 in.

With the outer frame supported horizontally on the six tripod jacks (figs. 9 and 11), a surveyor's level was used to accurately position the fittings for all attachment points of the test article. The shear- and shear-reaction load actuators (fig. 6) are required to apply load in the same plane as the centerline of the test panel skin, which carries the shear load. The axial load actuator and opposite attachment point are required to apply load through the neutral axis of the test panel, which is slightly closer to the hat-stiffened side of the skin. This requirement prevents an induced bending moment from being induced into the panel as a result of eccentric loading.

### Axial Load Alignment Restraints

The restraint beams for the axial load link were discussed earlier and shown in figures 6, 7, and 8. The upper and lower restraint beams (fig. 7) must be carefully aligned both vertically and horizontally to ensure that the axial load link is accurately positioned directly between the two axial load connections on the outer frame. Because the axial load is the largest load in the system, any misalignment at these points could produce major bending moments on the test article. The two restraint beams also must be precisely parallel with each other, and the slots for the connection pin perfectly aligned. The slots were originally simultaneously machined with the beams clamped back-to-back.

The vertical distance between the two restraint beams (fig. 8) must be such that the clevis, which attaches to the test article, can move freely for horizontal loading but is vertically restricted with nearly zero free play.

The original plan was to bolt the restraint beams to the outer frame. After considerable time and effort to accurately shim and align the beams, however, the decision was made to weld the beams in place. This approach ensures that the alignment will be maintained during subsequent testing. Conversely, if disassembly of the test setup is required at a later date, then the welds will have to be cut.

### Vertical Links

When the vertical links are attached to the test article, the surveyor's level is again used to ensure that the test article is in a horizontal plane and the shear and axial load attachments are at the correct height for accurate alignment. The vertical links are adjustable (similar to a turnbuckle) so that precise positioning of the test article can be accomplished. The vertical height of each point is measured to within ±0.003 in. After the links are adjusted, they are locked in place.

## TEST FIXTURE DESIGN VALIDATION

The essence of validating a test fixture design lies in assessing its performance during the tests for which it was designed. The main question to be answered with such testing is: did the test fixture meet its requirements? The combined mechanical and thermal loads test requirements of the side shear panel are so complex that the test fixture and test panel were designed as an integrated system, which required two finite-element models. A simple model was used for the conceptual design of the test panel and test fixture, and a complex model to provide analytical strain predictions with sufficient fidelity to correlate with the experimental results.

A thermal analysis was required to design a heater system meeting the test requirements. An instrumentation system capable of providing high-quality experimental data to evaluate the test panel, assess the performance of the test fixture and heater, and correlate with analytical predictions, also was needed. A test procedure that minimizes risk to the test article, yet extracts high-quality experimental data, had to be developed. All of these elements must be factored into the results and discussion of the test program to accomplish a successful test fixture design validation.

## Structural Analyses

Two finite-element structural analysis models were developed and used during the side shear panel test program. The first of these models was a relatively simple model of the entire test article and is shown in figure 15. In this case, the test panel was simplified to an equivalent-thickness flat plate. This simple model proved to be very valuable in the design and pretest phases of the program for assessing the adequacy of the initial test fixture design concept and aiding in methods of improving the design. For example, the test article and this model did not originally have the transition panels on both sides of the test panel, but data from the model showed high strain gradients in the corners of the test panel where the shear loads were introduced. The addition of the transition panels caused the comparatively greater areas of strain in the corners to move outward and produce a relatively uniform strain field throughout the entire test panel. The simple model was also used to ensure that the shear forces were applied correctly.

Originally, the shear reaction forces were planned to be applied using just two actuators, actuators 5 and 6 (fig. 6). Stress data from the simple model, however, showed that reacting the shear at all four corners was necessary. Additionally, the simple model was used as a guide for strain-gage instrumentation placement on the panel and for strain-gage range predictions. The predicted strain range information helped establish the strain ranges required for the data acquisition hardware setup. Thus, the simple model became an integral and indispensable part of the program.

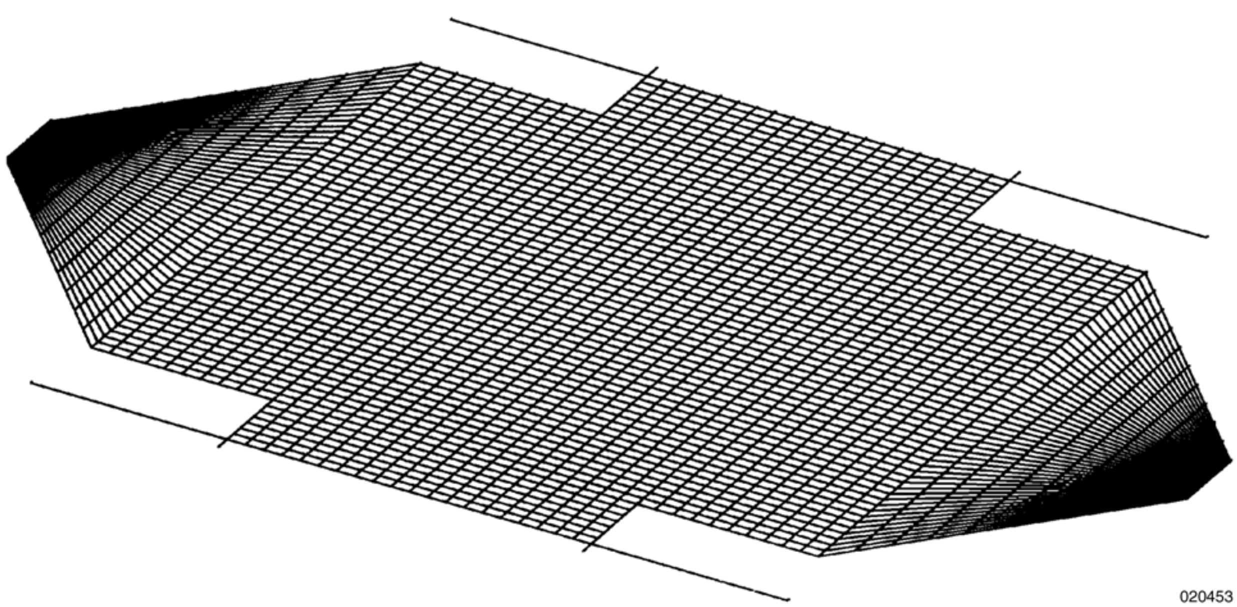


Figure 15. Simple finite-element model of the test article assembly.

In addition to the simple model used in the fixture design, another more detailed model was required in the program. This detailed model was essential to provide analytical data at the strain-gage locations, both on the panel hat stiffeners and on the flat skin, for comparison to test measurements. Additionally, because the panel is buckling-critical, this complex, out-of-plane model is required. The detailed complex model with 27,166 elements was formulated, which included all parts of the test fixture and the corrugations of the test panel and is shown in figure 16.

The detailed model was used to analyze a variety of test conditions. Figures 17–21 show strain contour maps determined by the complex model for the skin side of the test panel and the transition panels. Figure 17 shows shear strain for a positive shear load. Note that the shear is shown in units of microradians. Figures 18 and 19 show axial strain for tension and compression loads, respectively. Figures 20 and 21 show shear strain, also in microradians, for combined tension and positive shear, and combined compression and positive shear, respectively. As can be seen in each of the strain contour maps, the calculated strain distribution over the test panel skin is extremely uniform. These data provided a high degree of confidence in the design of the test fixture.

The complex model also was extensively used to provide strain distributions before each load condition for comparison to strain-gage measurements. Additionally, buckling analyses were performed to identify potentially critical buckling loads and mode shapes.

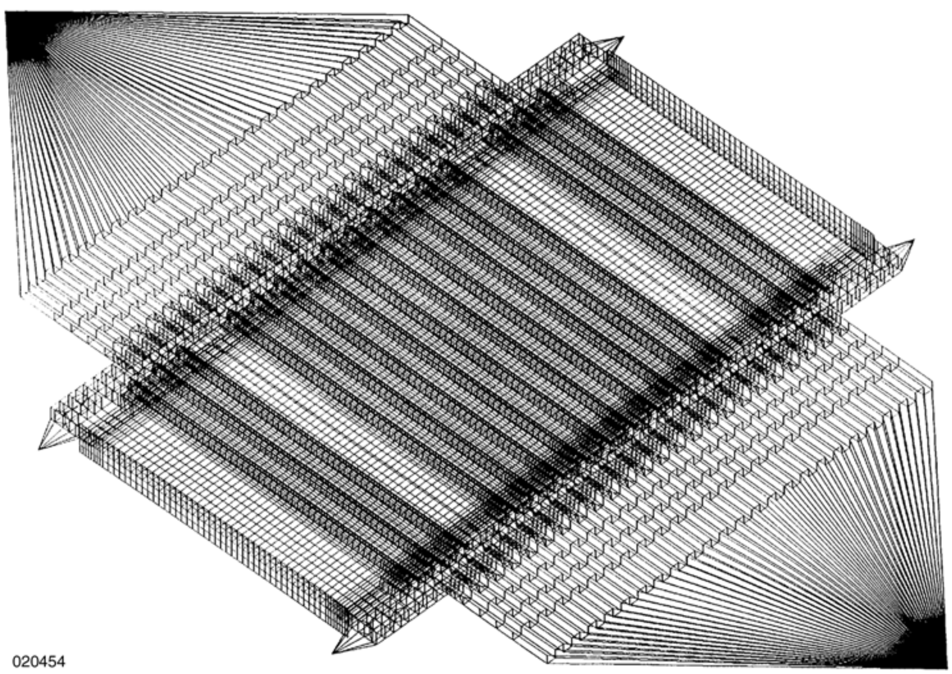


Figure 16. Complex finite-element model of the test article assembly.

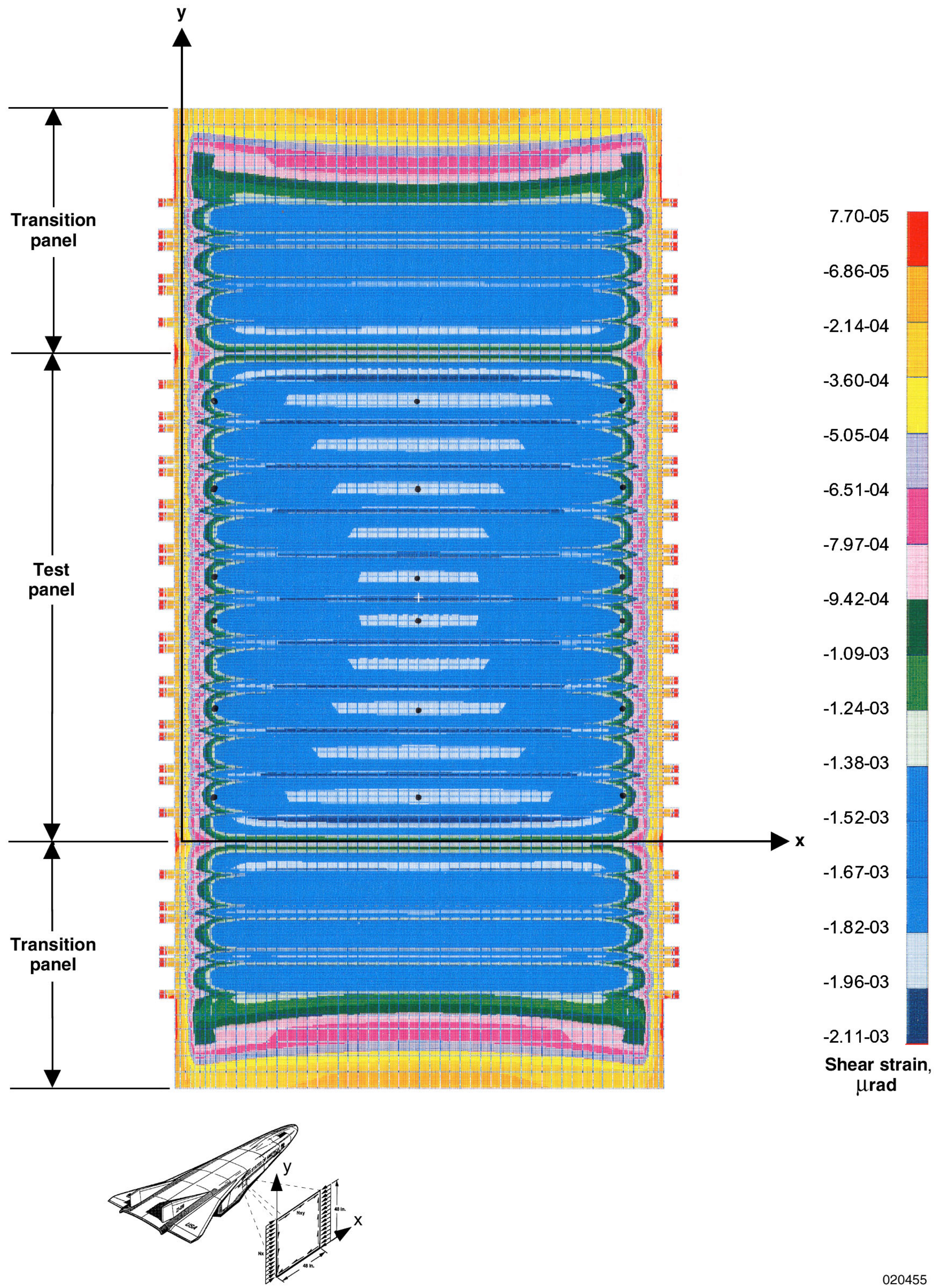


Figure 17. Shear strain contour map for a positive shear load on the side shear panel and the transition panels.

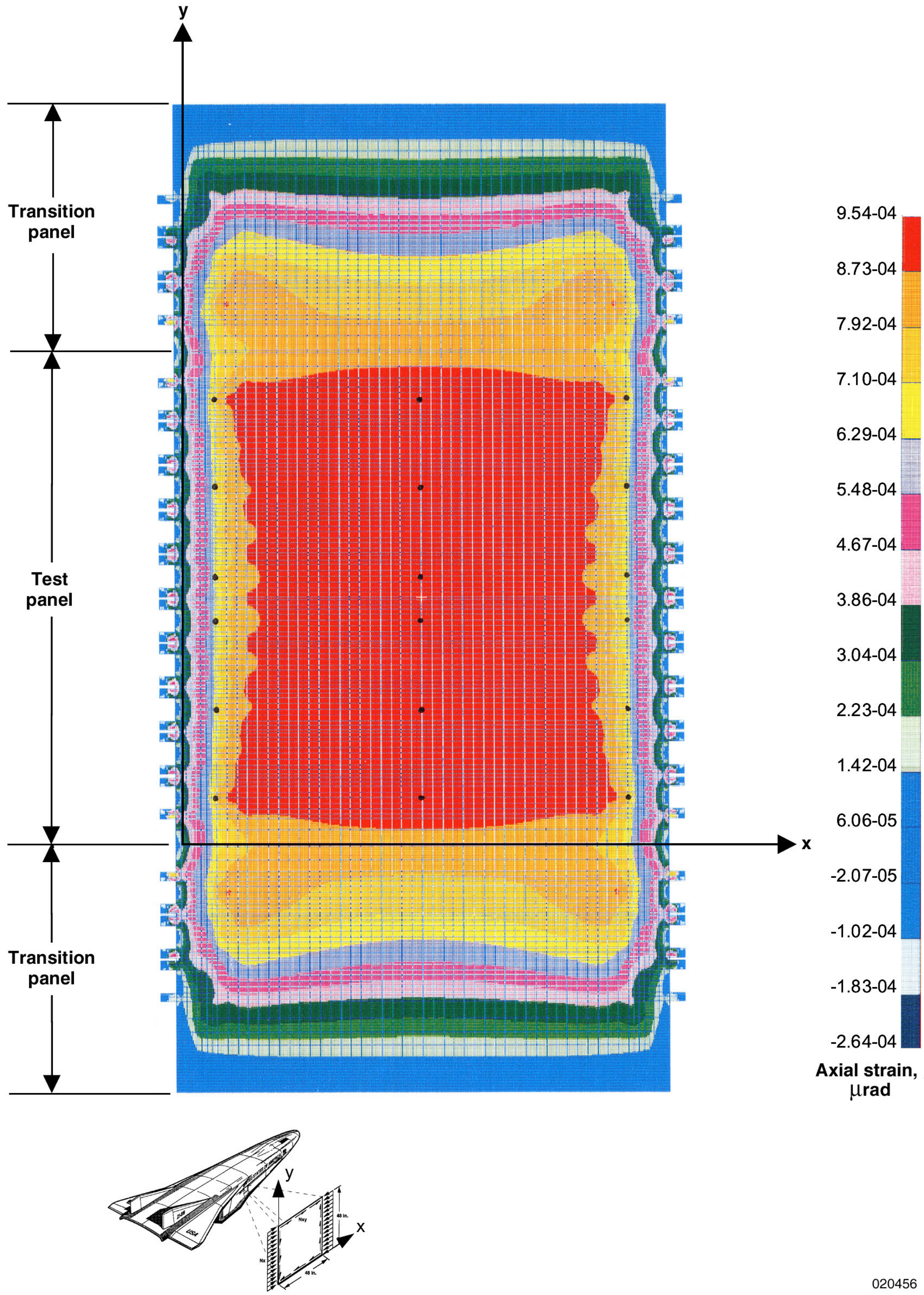


Figure 18. Axial strain contour map for a tension load on the side shear panel and the transition panels.

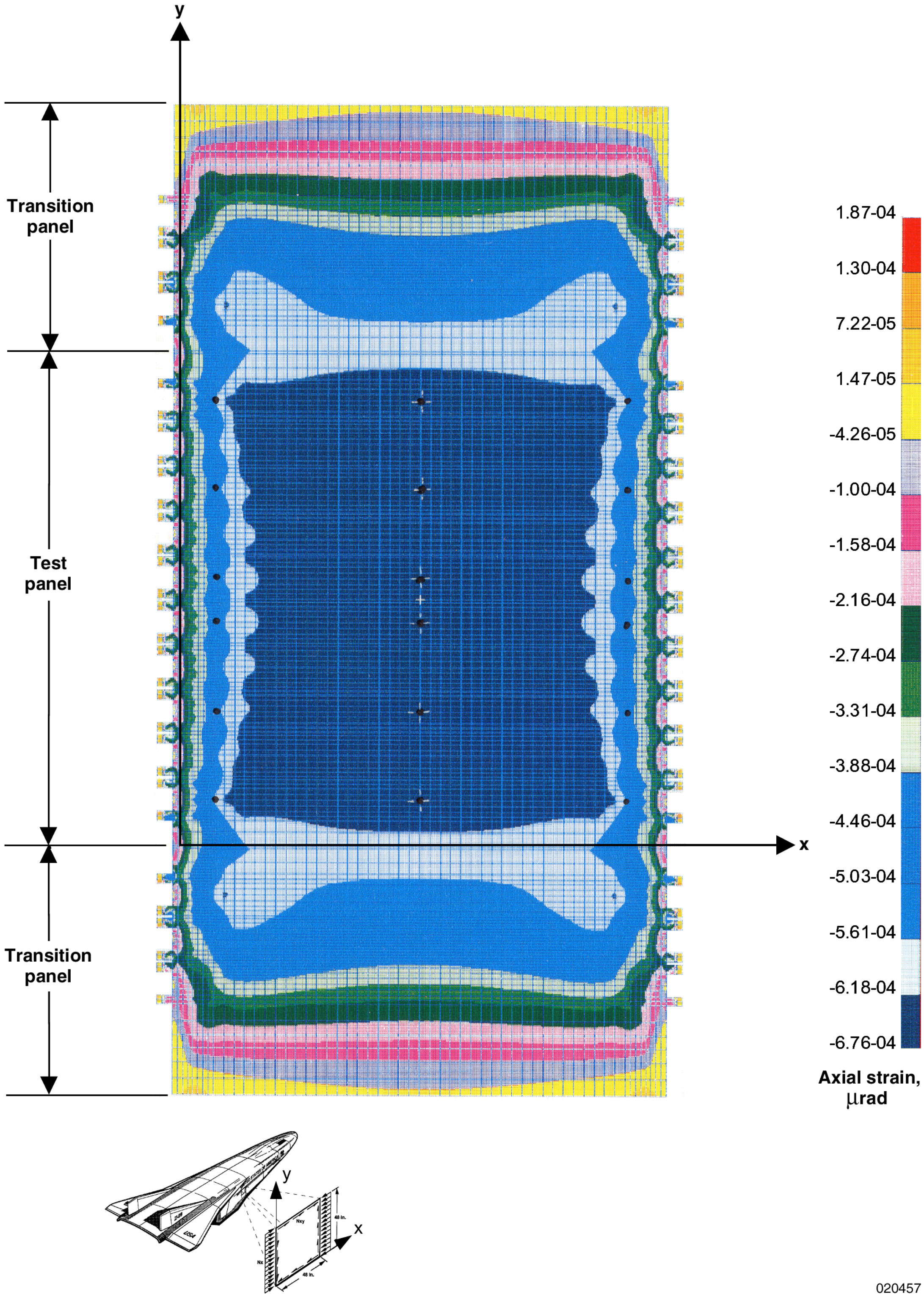


Figure 19. Axial strain contour map for a compression load on the side shear panel and the transition panels.

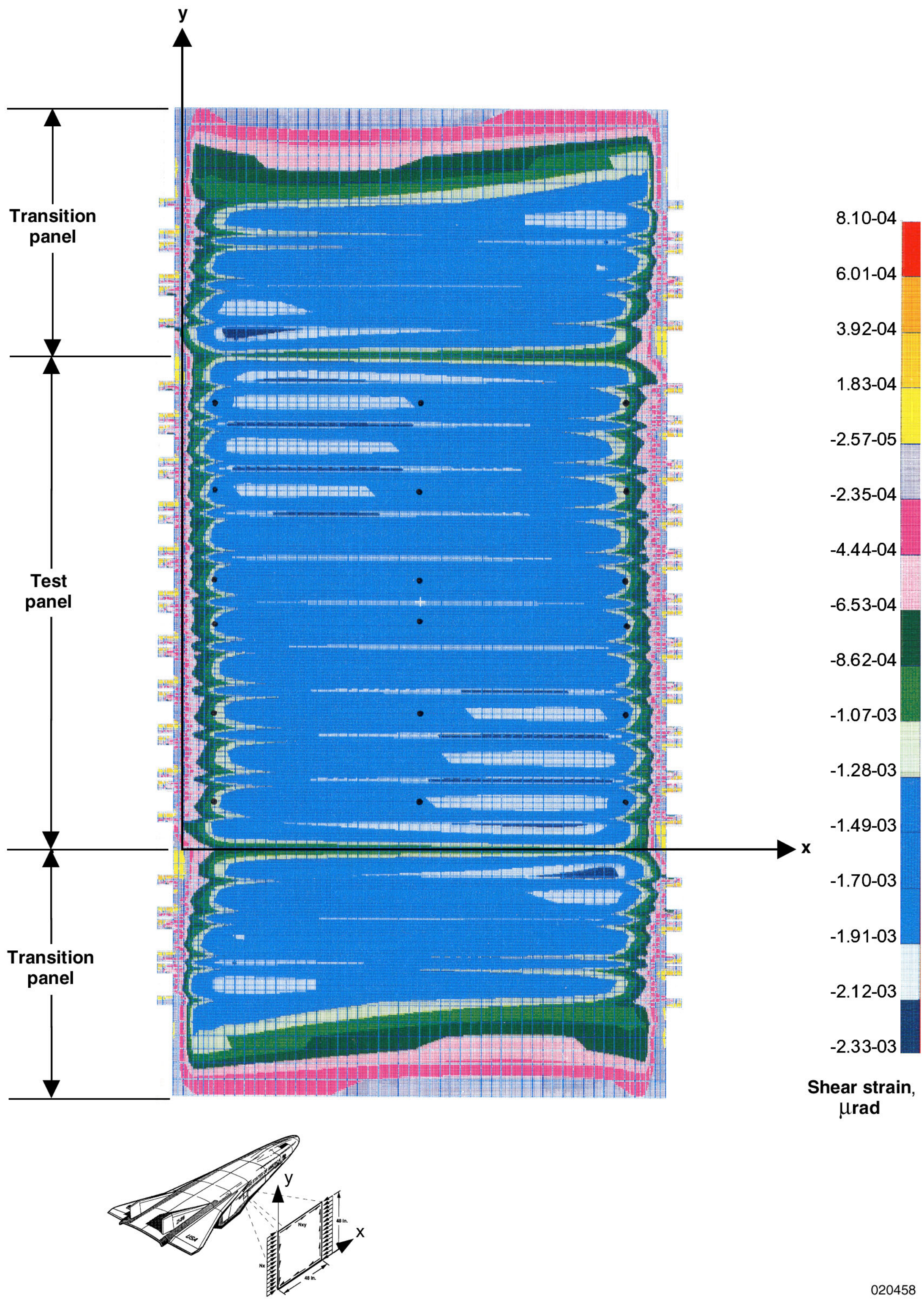


Figure 20. Shear strain contour map for combined tension and positive shear loads on the side shear panel and the transition panels.

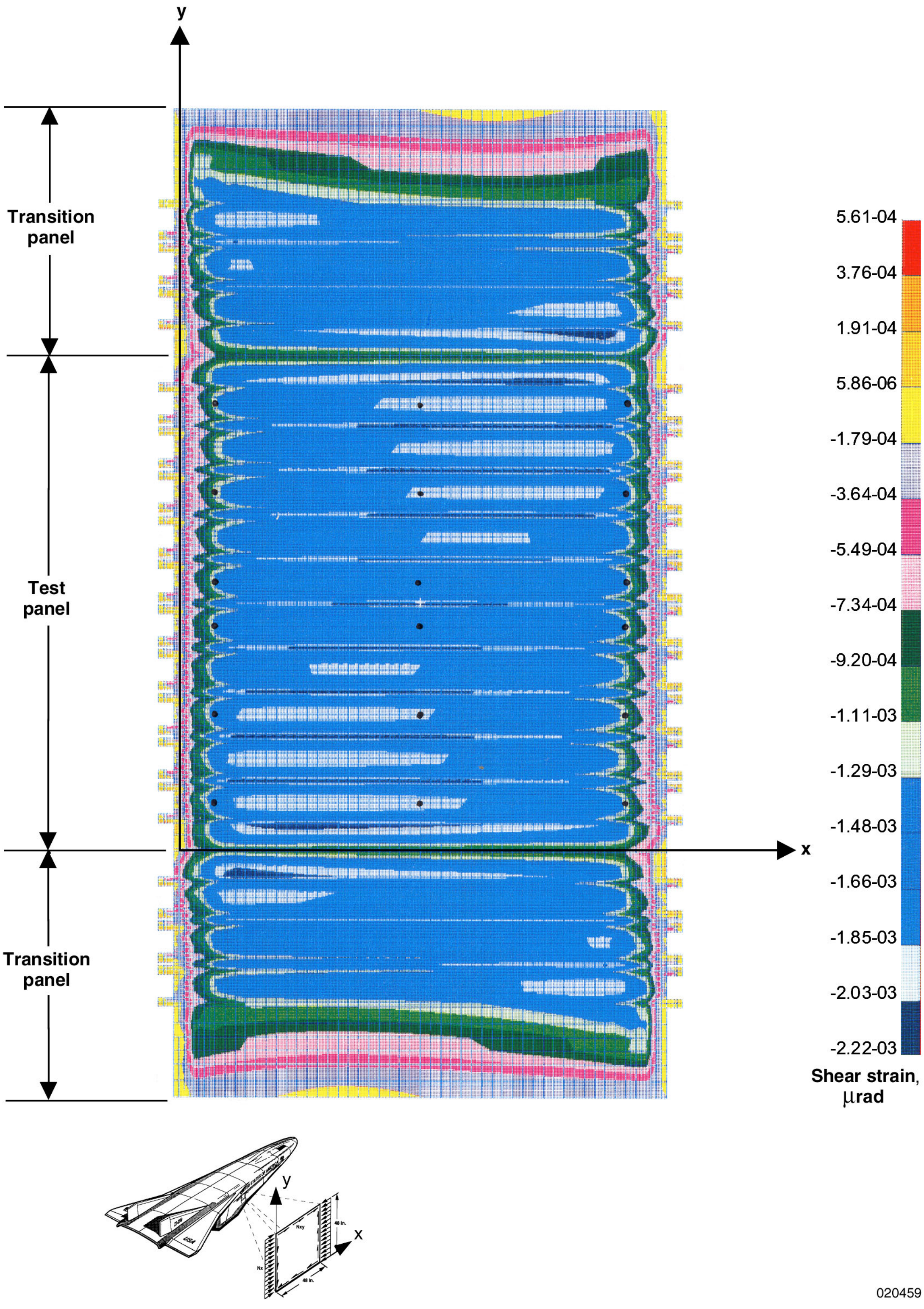


Figure 21. Shear strain contour map for combined compression and positive shear loads on the side shear panel and the transition panels.

## Thermal Analyses

An independent thermal analysis of the test article was performed to establish heating requirements for the quartz lamp heater system design and to generate temperature values for stress analyses using the detailed model. For stress calculations at elevated-temperature test conditions, the calculated temperatures were input to the detailed model so that the thermal stress and material property effects could be included.

Reference 7 was prepared by the contractor for the program and provides more details on both the thermal and structural analyses for the side shear panel. Detailed test and analysis comparisons are presented in the final report for all room-temperature load conditions. Unfortunately, because of program restraints, very little elevated-temperature test and analysis data are presented in the contractor’s report. Selected room-temperature test measurements and analysis comparisons from the final report are presented later in this report, as are results of the elevated-temperature tests conducted at the end of the test program.

## Instrumentation

The side shear panel test instrumentation is comprised of load cells, strain gages, thermocouples, and deflection transducers. Table 1 shows a summary of the instrumentation. Figures 22 and 23 show the locations of the strain-gage instrumentation installed on the test panel. The majority of the strain gages are a foil type (ref. 8) and are known to be highly reliable at temperatures to a maximum of 600 °F. For the planned tests at higher temperatures, two types of high temperature strain gages were installed. These gages can easily function at temperatures greater than the planned maximum test temperatures; however, they are less reliable than the foil gages and more expensive. One of the high temperature strain-gage types has built-in compensation for apparent strain. Several uncompensated high temperature strain-gages are also included to provide experience with both types of gages and to provide a comparison of the two. The foil rosette strain-gages consist of three independent gages (A, B, and C); however, only gages A and C are shown in the figures for clarity. Figures 24 and 25 show the thermocouple locations on the test panel. Glass-braided type-K thermocouples are installed at each strain measurement location and also at other locations where temperature measurement or thermal control are required.

Other instrumentation includes 24 deflection transducers (fig. 23) to measure displacements at specific test article points, 9 load cells to measure the load applied with each hydraulic actuator, and 4 strain-gage bridges on the vertical links to measure out-of-plane reaction forces.

The total number of recorded data channels for each test was 463. The data were recorded at a nominal maximum sampling rate of 12 samples/sec for each channel. During some portions of any particular test, such as when the mechanical load system was inactive or on hold, the data sampling rate was reduced in an effort to conserve system recording space.

Table 1. Instrumentation summary for the side shear panel test.

| | Quantity | Description |
|---|---|---|
| Skin side | | |
| | 30 | WK rosette strain gages (90 data recording channels) |
| | 22 | WK axial strain gages |
| | 24 | Compensated BCL axial strain gages |
| | 6 | Uncompensated BCL axial strain gages |
| | 90 | Thermocouples |
| Hat side | | |
| | 6 | WK rosette strain gages (18 data recording channels) |
| | 54 | WK axial strain gages |
| | 24 | Compensated BCL axial strain gages |
| | 6 | Uncompensated BCL axial strain gages |
| | 92 | Thermocouples |
| Other | | |
| | 24 | Deflection transducers |
| | 9 | Load cells |
| | 4 | Vertical link strain-gage bridges |
| Summary | | |
| | 248 | Strain-gage data recording channels |
| | 182 | Thermocouples |
| | 24 | Deflection transducers |
| | 9 | Load cells |
| Total | | |
| | 463 | Data recording channels |

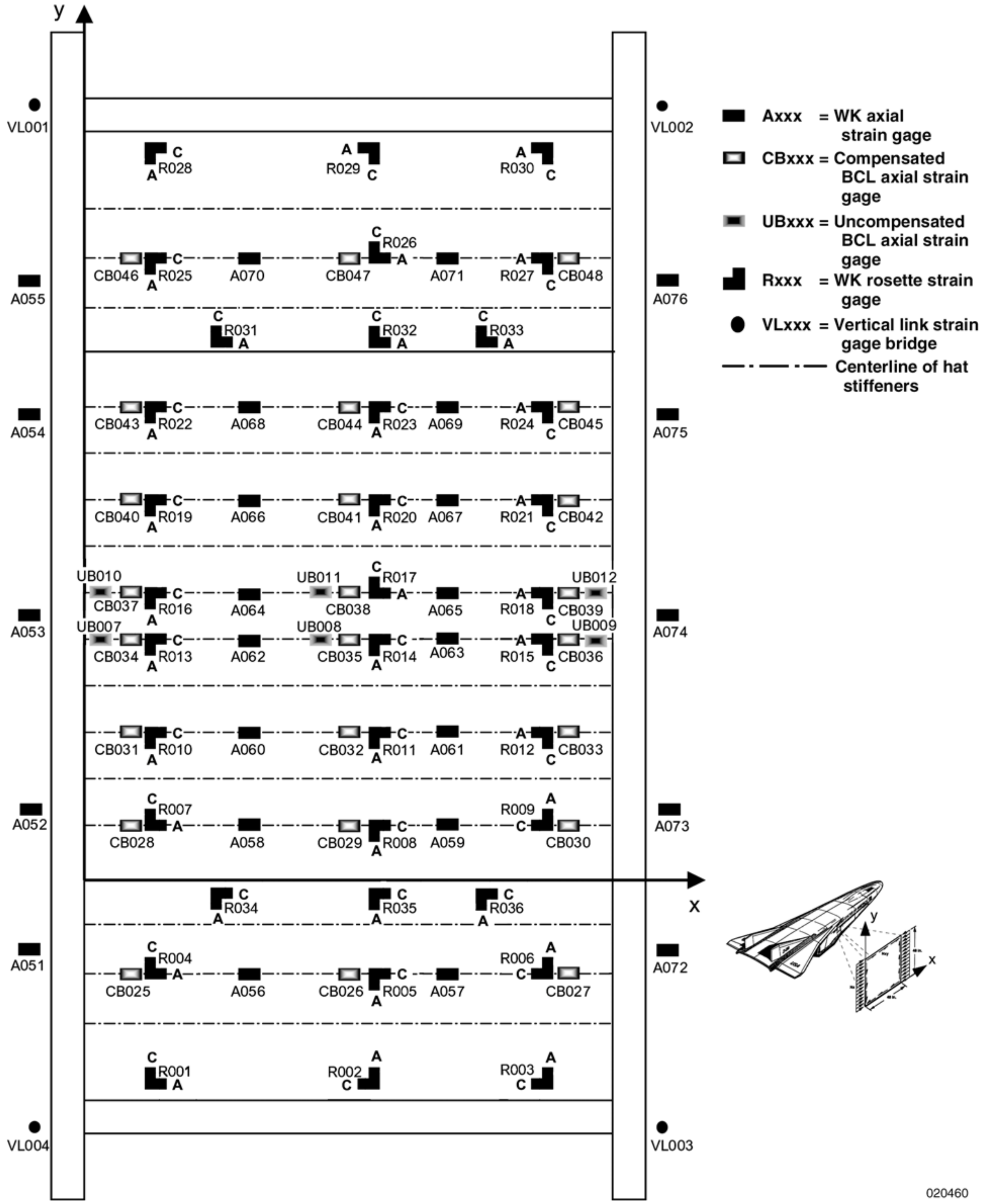


Figure 22. Strain-gage locations on the skin side of the side shear panel test article.

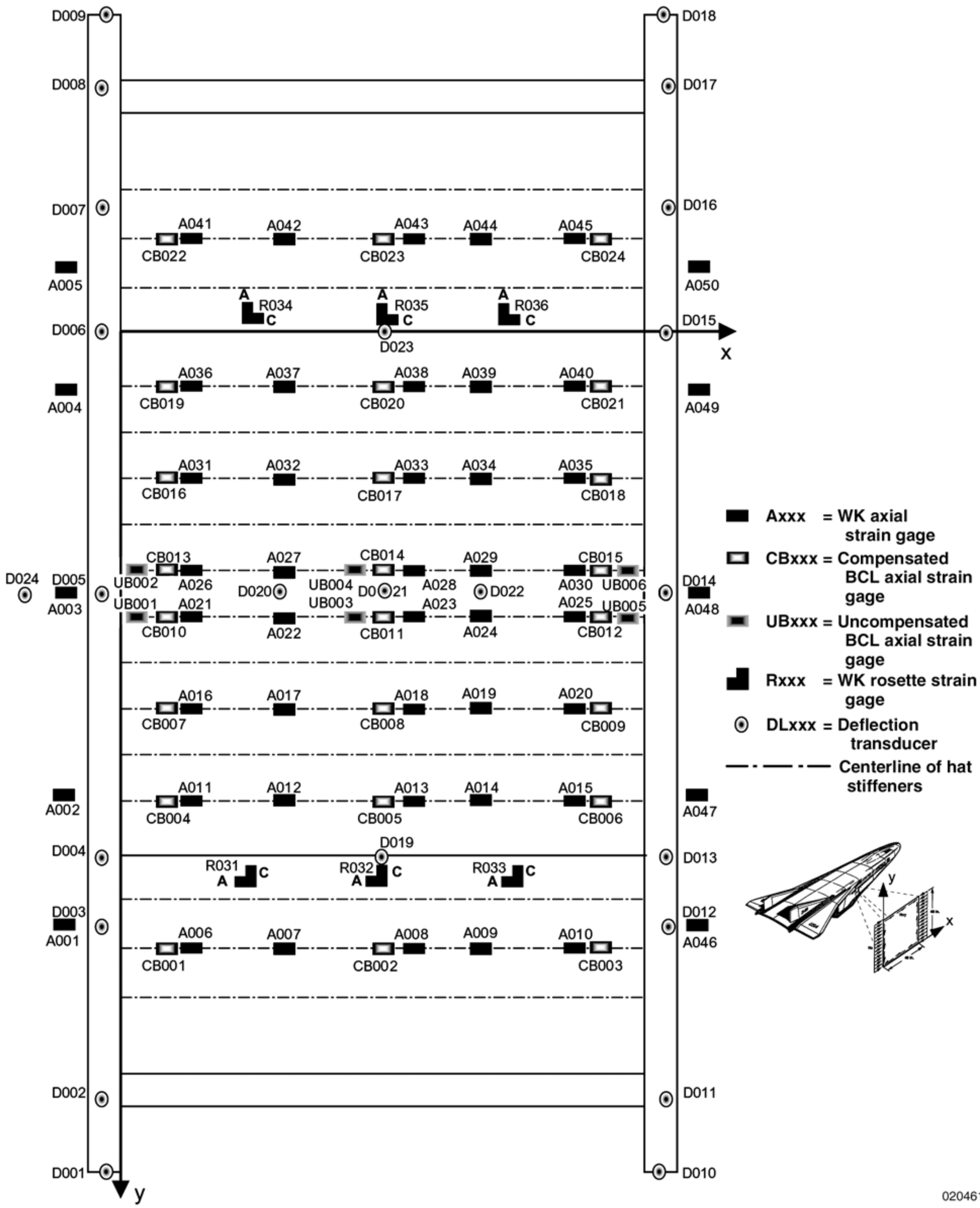


Figure 23. Strain-gage and deflection transducer locations on the hat-stiffened side of the side shear panel test article.

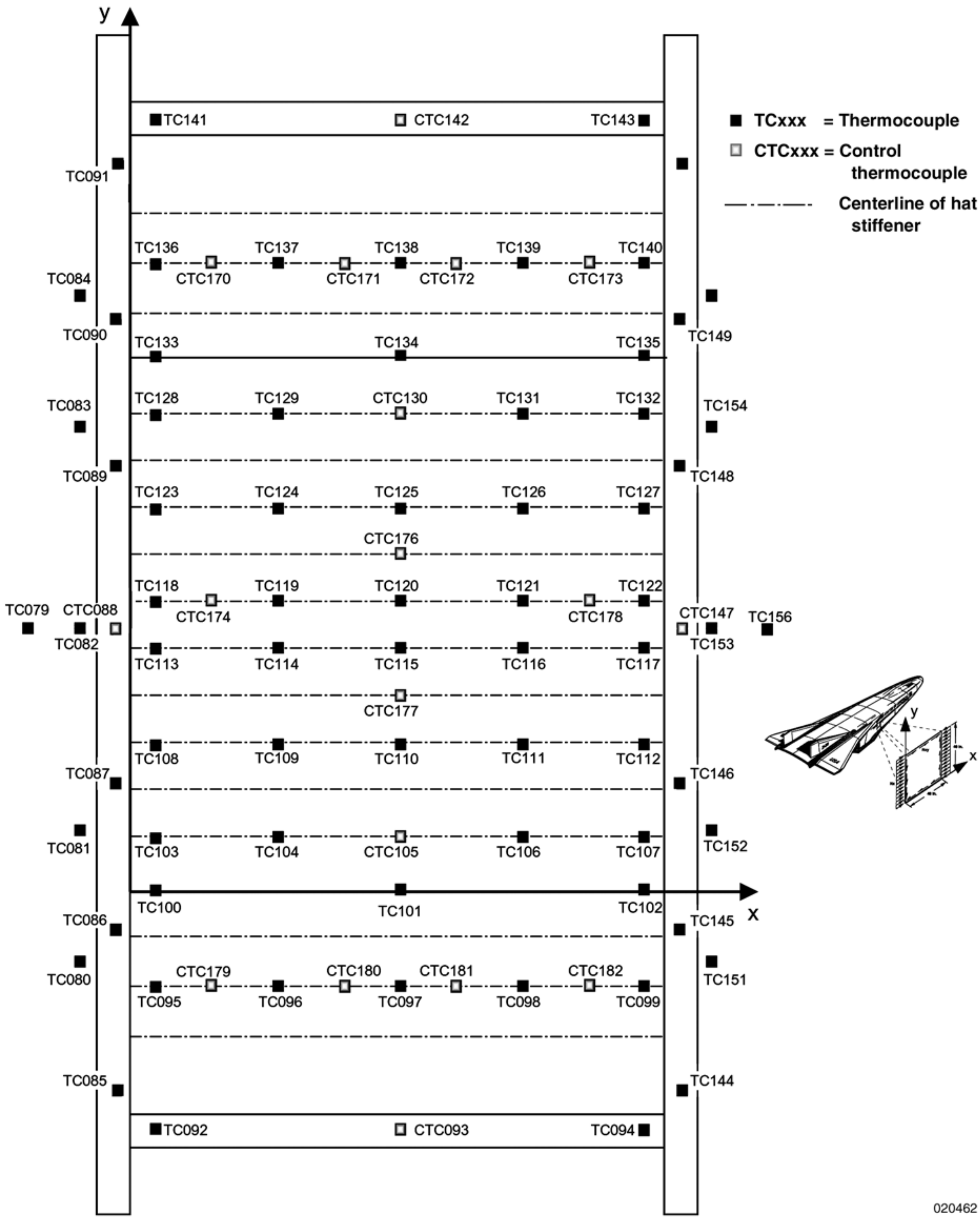


Figure 24. Thermocouple locations on the skin side of the side shear panel test article.

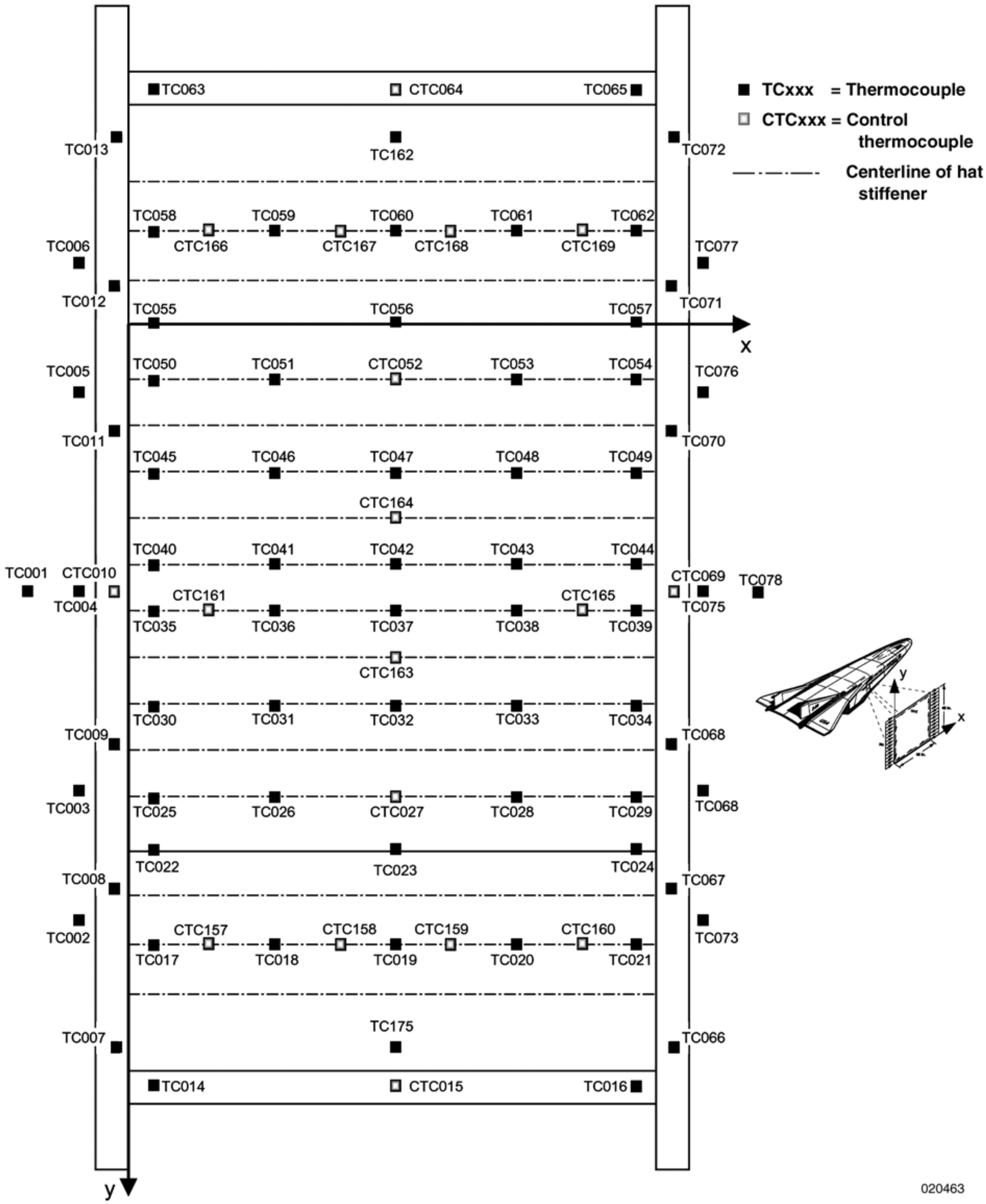


Figure 25. Thermocouple locations on the hat-stiffened side of the side shear panel test article.

## Test Procedure

Table 2 shows the planned testing sequence for the side shear panel program, utilizing the unique features of the combined loads test fixture. The sequence consisted of eight groups of test conditions, with each successive condition more critical than the previous condition, until the projected X-30 design temperature and loads for the panel were achieved. The eight groups of test conditions were:

1. a mechanical load survey (tests 1–5).
2. limit loads at room temperature (tests 6–10).
3. a temperature survey from room temperature to 500 °F (test 11).
4. limit loads at 500 °F (tests 12–16).
5. ultimate mechanical load conditions below 500 °F (tests 17–18).
6. a temperature survey from room temperature to 915 °F (test 19).
7. ultimate load conditions between 500 °F and 915 °F (tests 20–21).
8. a test to failure at room temperature (test 22).

Note that for each test and for each test group, based on experience and safe test management, multiple tests were anticipated to be required. These multiple tests would primarily consist of buildup tests and any repeat tests caused by system problems or anomalies.

During each of the tests, real-time data were monitored and continuously recorded. Measured strain data were also continuously compared to predicted values obtained from finite-element programs. Because the side shear panel is buckling-critical, a real-time force-stiffness technique was used to predict local and general instability loads during all tests at greater than 50 percent of the design-limit load. References 9 and 10 provide additional information about the force-stiffness method.

Mechanical loads were applied with a linear load rate that ranged from 100–200 lbf/sec. The loading rate was paused at approximately 10–20 percent increments to provide a “hold” in the load condition that allowed for review of the test data. Holds at additional times during the loading were implemented as needed to investigate anomalies and as critical loads were approached. The basic test procedure for the combined heating and loading tests was as follows:

1. Start data acquisition.
2. Connect all load actuators to the load fixture and command zero load for each.
3. Heat test article at 1 °F/sec to the planned maximum temperature.
4. Hold at the maximum temperature.
5. After thermal equilibrium is achieved (approximately 15–20 min) apply axial load to the maximum value and hold.
6. Apply shear load in one direction, return to zero, then apply shear load in the reverse direction.
7. Remove shear load.
8. Remove axial load.

9. Start cooling system and simultaneously initiate the thermal control cool-down profile.
10. Shut down cooling system and thermal control after temperature measurements on the test article are less than 200 °F.
11. Disconnect all load actuators.
12. Allow test article to cool to a uniform ambient temperature condition.
13. Stop data acquisition.

Table 2. Test sequence for the side shear panel program.

| Test ID | Test description | Percent limit load | Actuator load, lb shear / axial |
|---|---|---|---|
| 1 | Mechanical load survey at room temperature - shear | 50 | 30000 / 0 |
| 2 | Mechanical load survey at room temperature - axial tension | 50 | 0 / 120000 |
| 3 | Mechanical load survey at room temperature - axial compression | 50 | 0 / 85000 |
| 4 | Mechanical load survey at room temperature - shear + tension | 50 | 30000 / 120000 |
| 5 | Mechanical load survey at room temperature - shear + compression | 50 | 30000 / 85000 |
| 6 | Limit shear load at room temperature | 100 | 60000 / 0 |
| 7 | Limit axial tension load at room temperature | 100 | 0 / 240000 |
| 8 | Limit axial compression load at room temperature | 100 | 0 / 170000 |
| 9 | Limit shear + axial tension load at room temperature | 100 | 60000 / 240000 |
| 10 | Limit shear + axial compression load at room temperature | 100 | 60000 / 170000 |
| 11 | Temperature survey to 500 °F | 0 | |
| 12 | Limit shear load at 500 °F | 100 | 60000 / 0 |
| 13 | Limit axial tension load at 500 °F | 100 | 0 / 240000 |
| 14 | Limit axial compression load at 500 °F | 100 | 0 / 170000 |
| 15 | Limit shear + axial tension load at 500 °F | 100 | 60000 / 240000 |
| 16 | Limit shear + axial compression load at 500 °F | 100 | 60000 / 170000 |
| | | | |
| The following tests were initially planned but were not completed during the side shear panel test program. | | | |
| 17 | Ultimate load-taxi condition at room temperature | 150 | 65000 / 255000 |
| 18 | Ultimate load Mach 6 condition at 215 °F | 150 | 32000 / 360000 |
| 19 | Temperature survey to 915 °F | 0 | |
| 20 | Ultimate load Mach 13 condition at 850 °F | 150 | 90000 / 240000 |
| 21 | Ultimate load Mach 15 condition at 915 °F | 150 | 6000 / 63000 |
| 22 | Load test to failure at room temperature | Failure | 90000 / Failure |

# RESULTS AND DISCUSSION

The real proof of any test concept lies in the actual measured performance and the comparison of measured experimental data to the analytical predictions. Figures 17–21 show finite-element predictions to which the combined loads test fixture was expected to perform. In each case, the strain distributions over the test panel surface, except for relatively small areas at the panel boundaries, were exceptionally uniform. Figures 26–36 show typical test data that were measured at room temperature and reported in the contractor's test report. As noted on figures 26–33, the strain-gage identification boxes are oriented in the principal strain direction and the arrows attached to the identification box represent a positive strain (tension). Figures 34–36 show the three legs of the rosette strain-gage with the corresponding strain measured for the stated condition. Table 3 summarizes the percentage differences between the finite-element predictions and test data. The average differences range from approximately 6–14 percent for the various test combinations. Given that:

- computer models are not perfect representations of actual structure;
- “as-built" structures can be significantly different from the design drawings;
- the test panel composite material properties are not well established;
- strain-gage measurements on the test panel material need further development;
- experience has shown that repeatable strain measurements of ±100 microstrain on any complex structural test concept is considered very good;

the percentage differences of table 3 are considered excellent.

Table 3. Average percent differences between finite-element analyses and test data.

| Test ID | Load description | Axial strain difference, percent | Shear strain difference, percent |
|---|---|---|---|
| 6 | Positive shear | - | 6.98 |
| 6 | Negative shear | - | 6.14 |
| 7 | Tension | 11.14 | - |
| 8 | Compression | 11.19 | - |
| 9 | Tension + shear | 13.48 | 12.64 |
| 9 | Tension – shear | 13.42 | 12.8 |
| 10 | Compression + shear | 13.77 | 10.26 |
| 10 | Compression – shear | 14.44 | 10.24 |

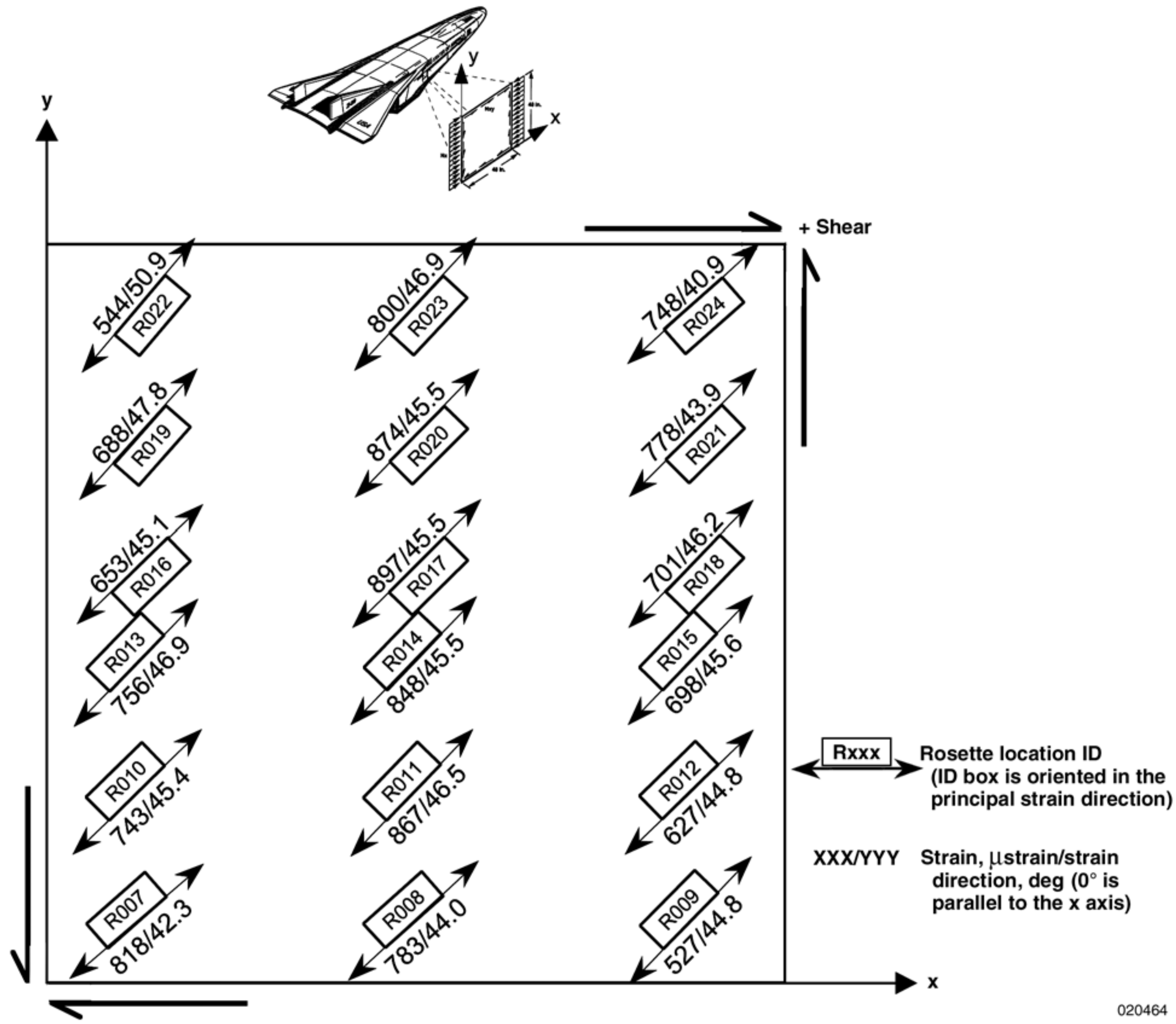


Figure 26. Maximum measured principal strains for a test load of 100-percent design-limit positive shear.

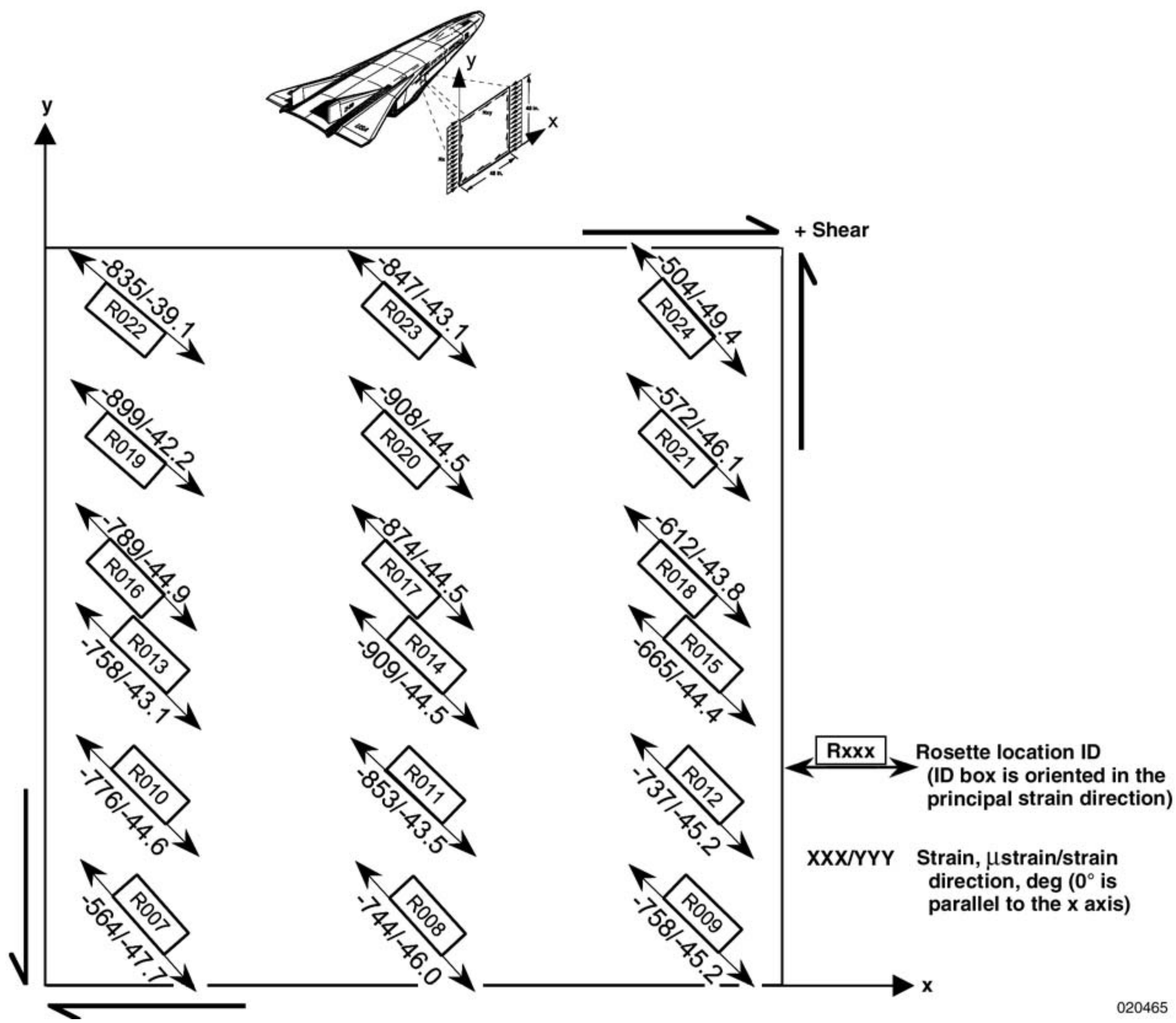


Figure 27. Minimum measured principal strains for a test load of 100-percent design-limit positive shear.

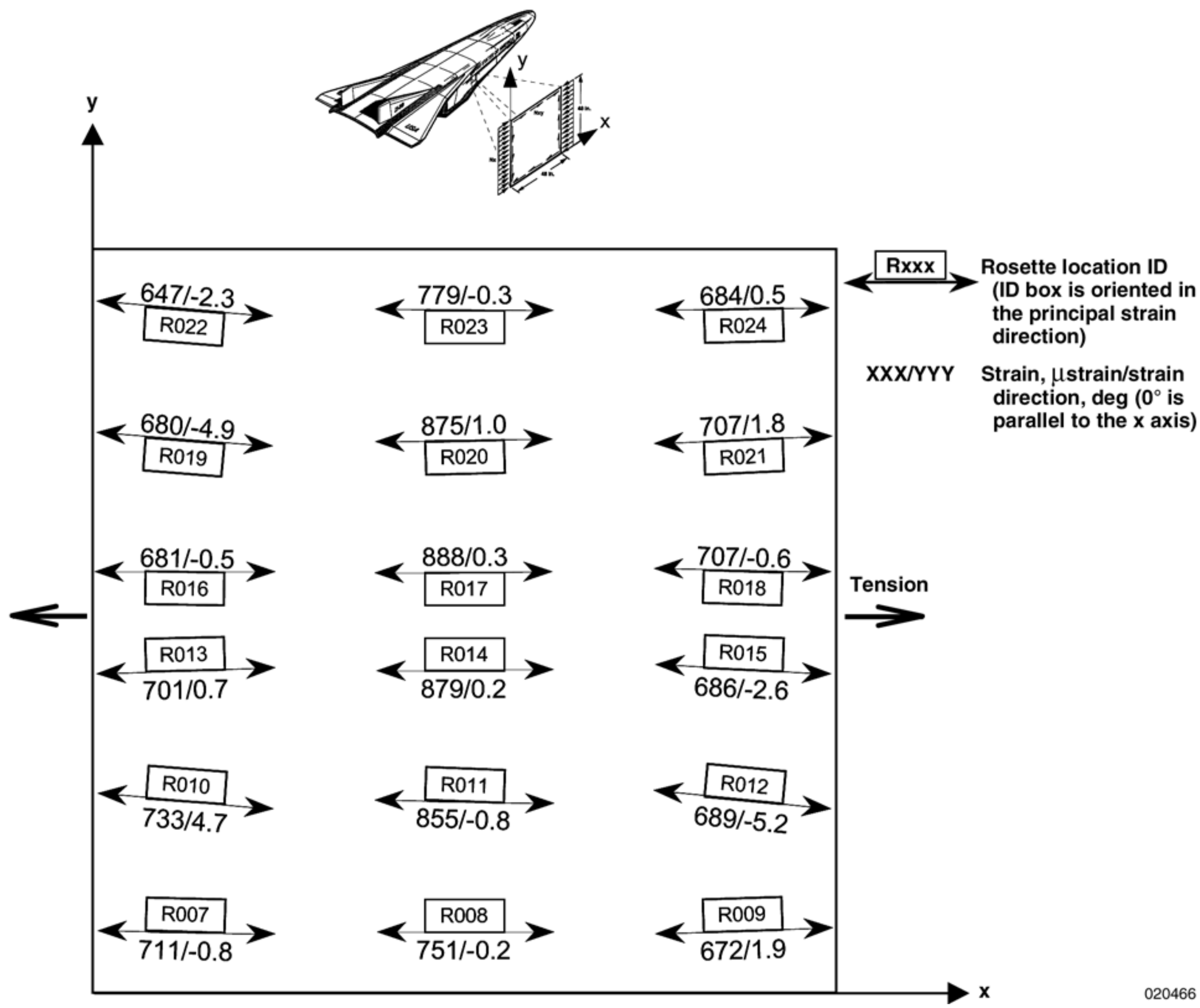


Figure 28. Maximum measured principal strains for a test load of 100-percent design-limit tension.

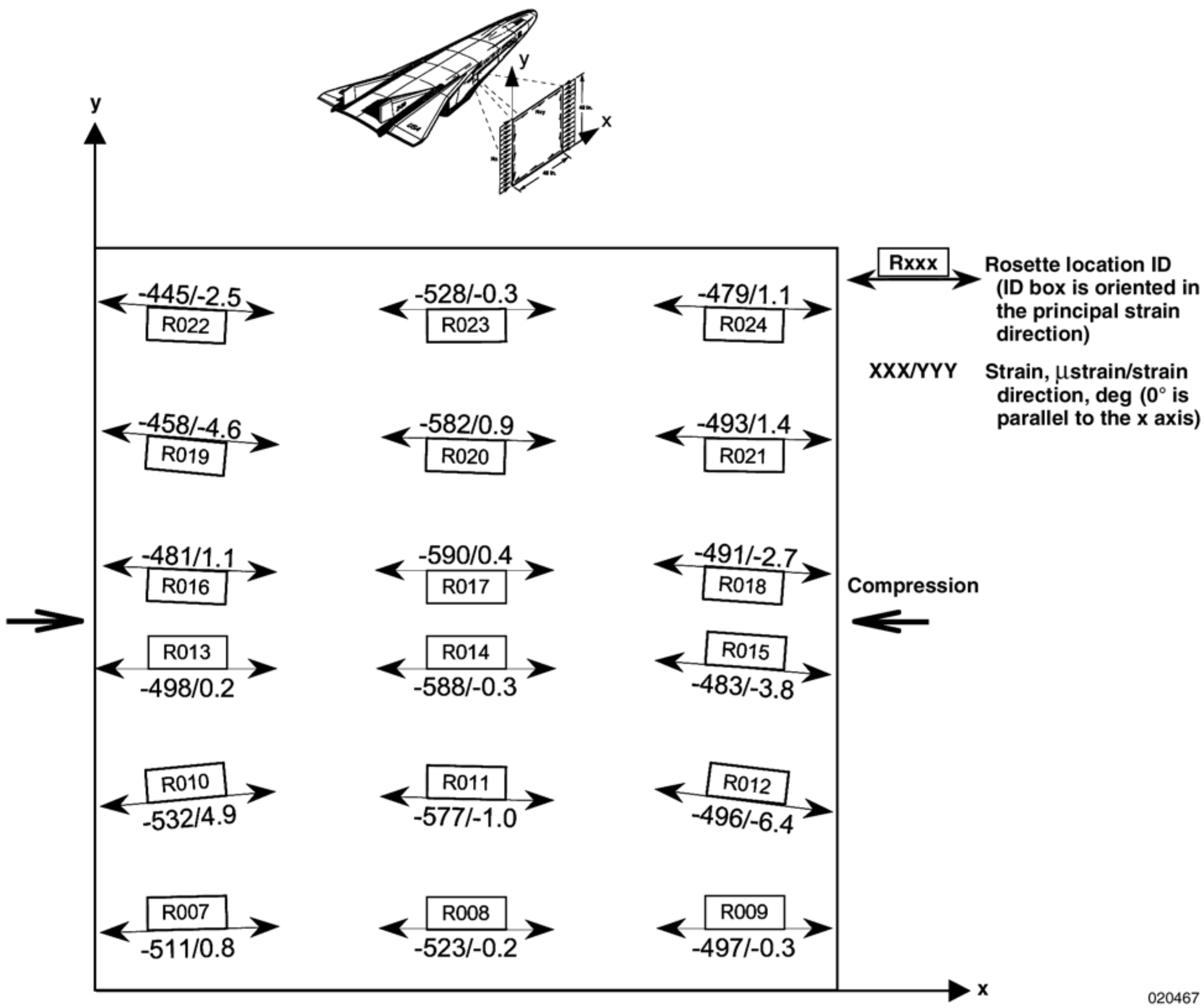


Figure 29. Minimum measured principal strains for a test load of 100-percent design-limit compression.

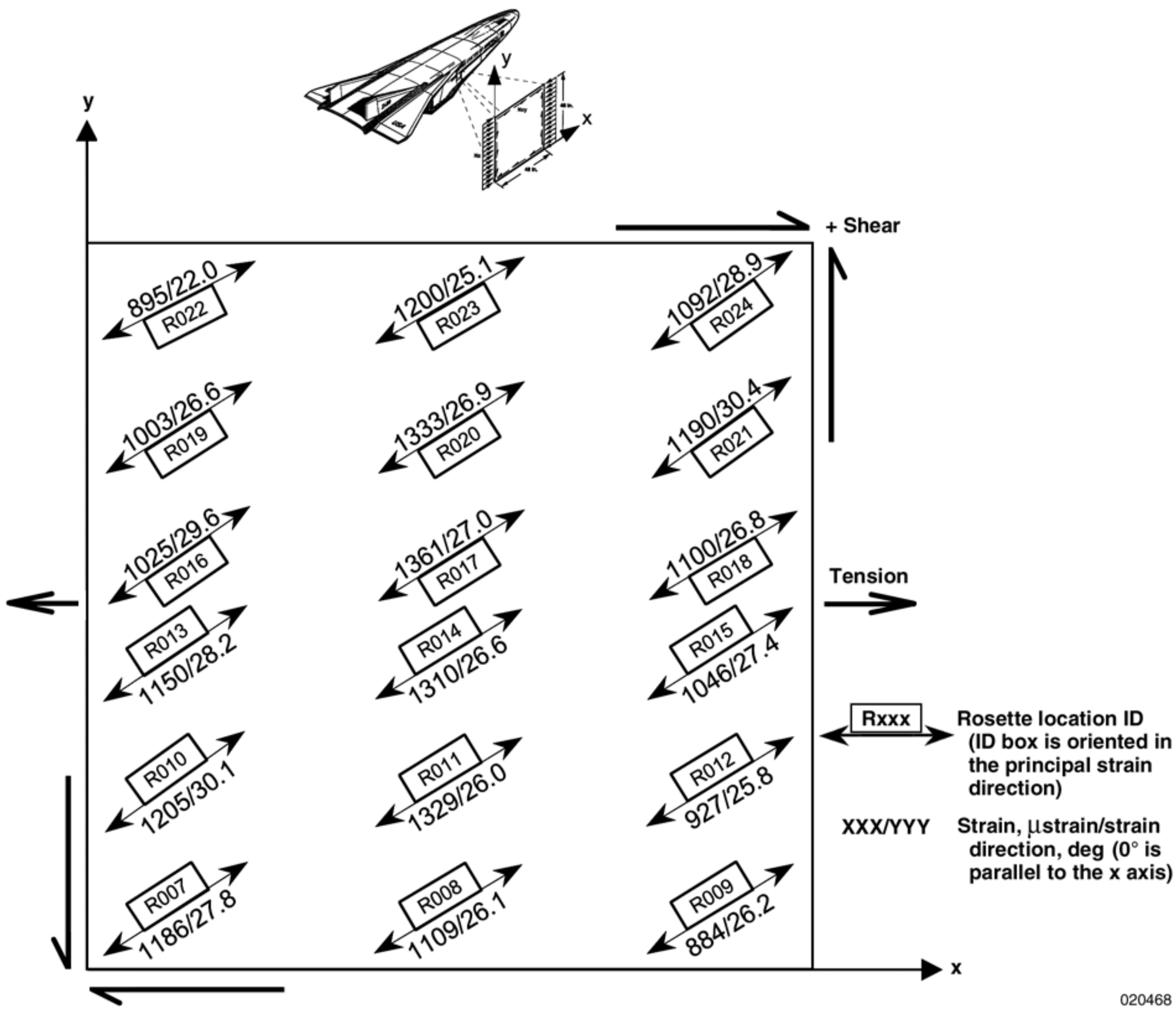


Figure 30. Maximum measured principal strains for a test load of 100-percent design-limit tension plus 100-percent design-limit positive shear.

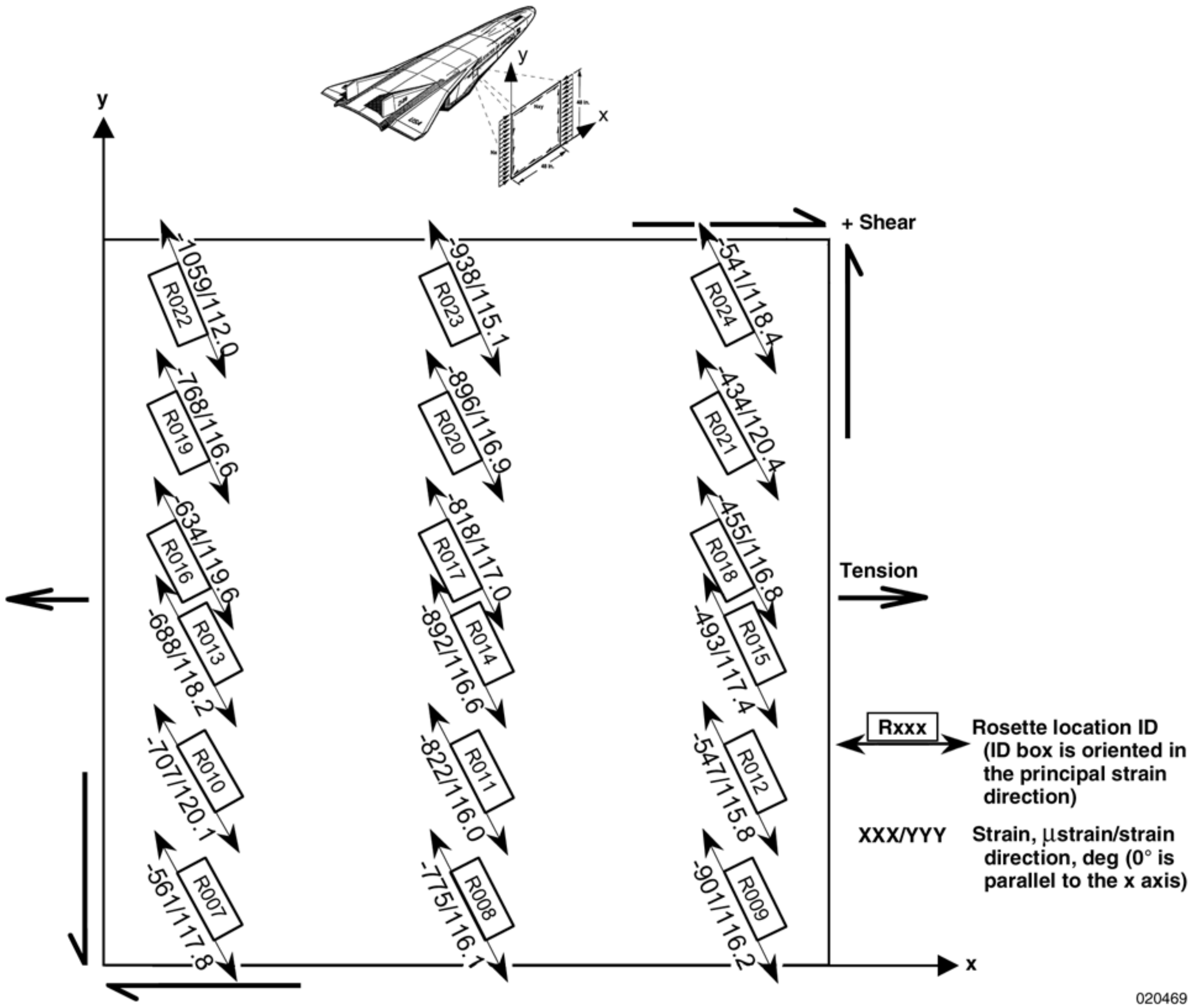


Figure 31. Minimum measured principal strains for a test load of 100-percent design-limit tension plus 100-percent design-limit positive shear.

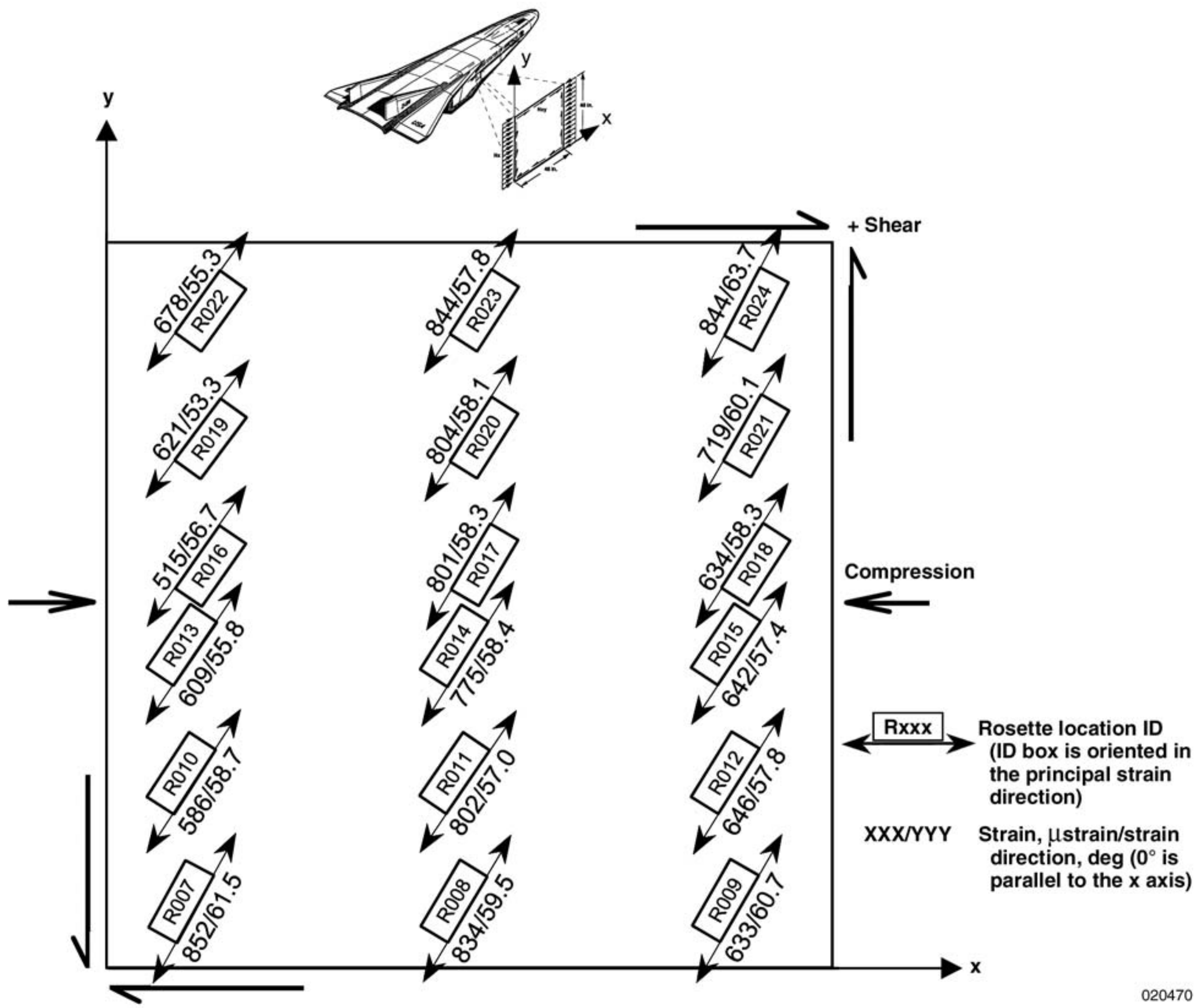


Figure 32. Maximum measured principal strains for a test load of 100-percent design-limit compression plus 100-percent design-limit positive shear.

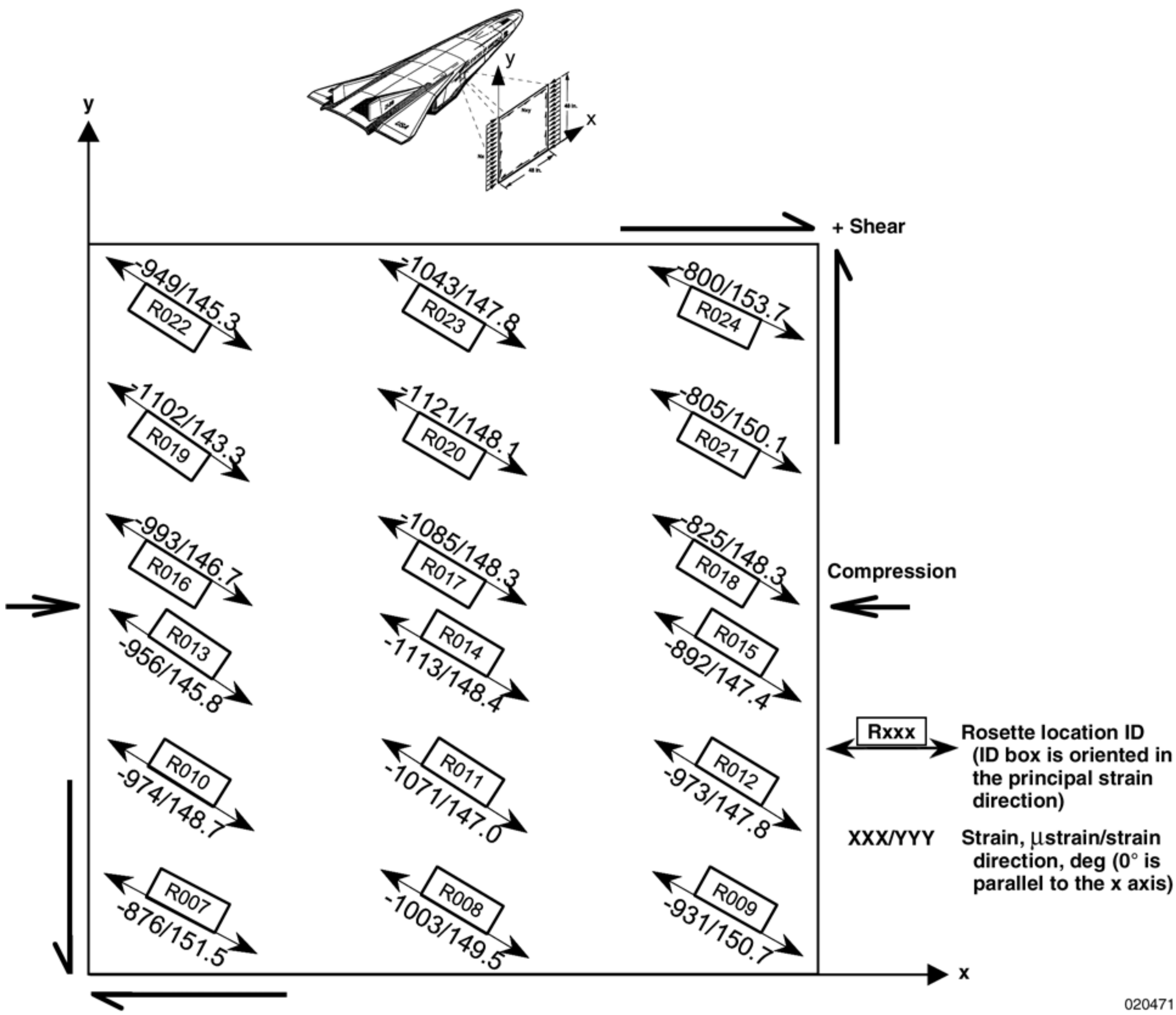


Figure 33. Minimum measured principal strains for a test load of 100-percent design-limit compression plus 100-percent design-limit positive shear.

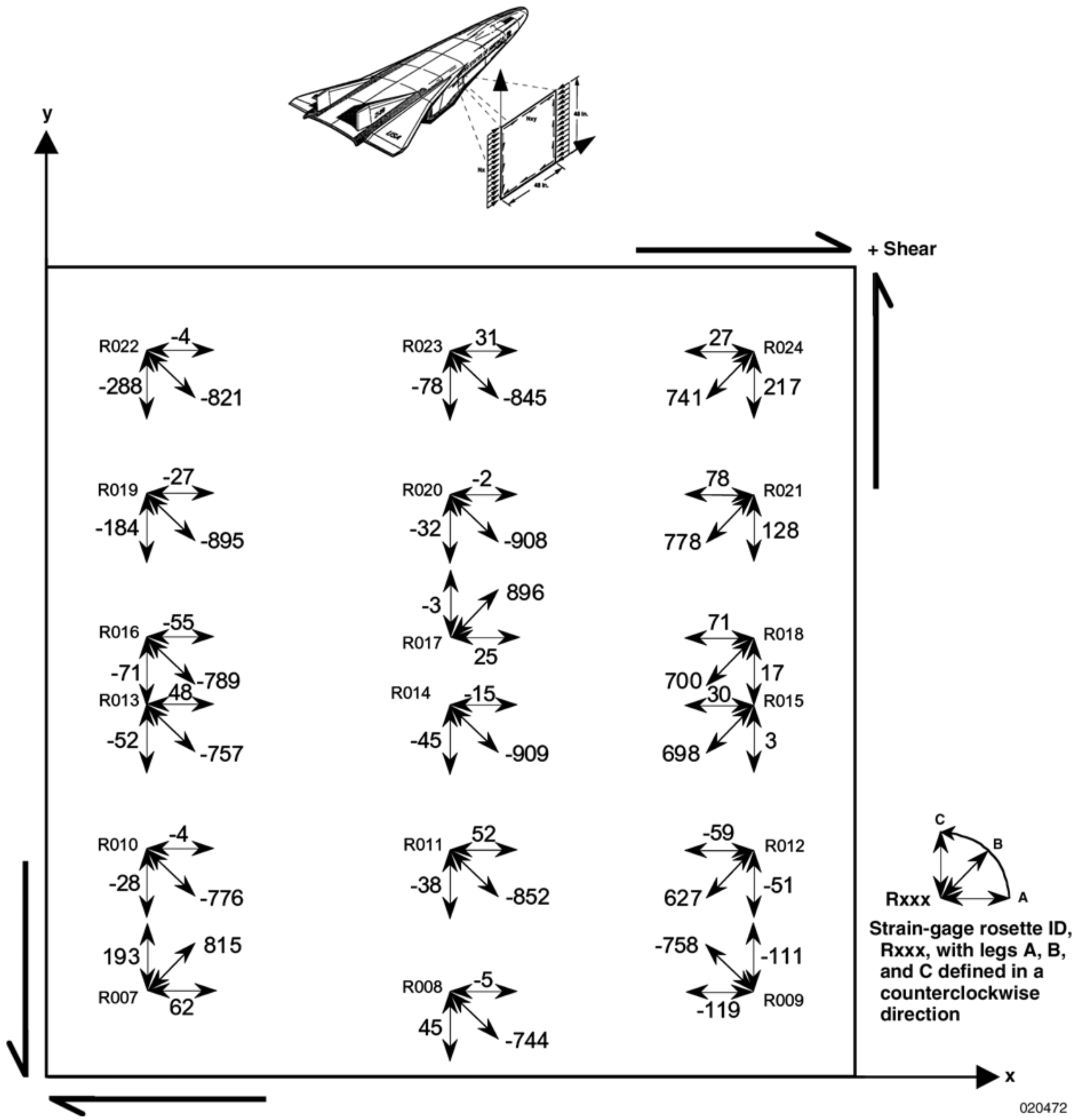


Figure 34. Measured rosette strains for a test load of 100-percent design-limit positive shear.

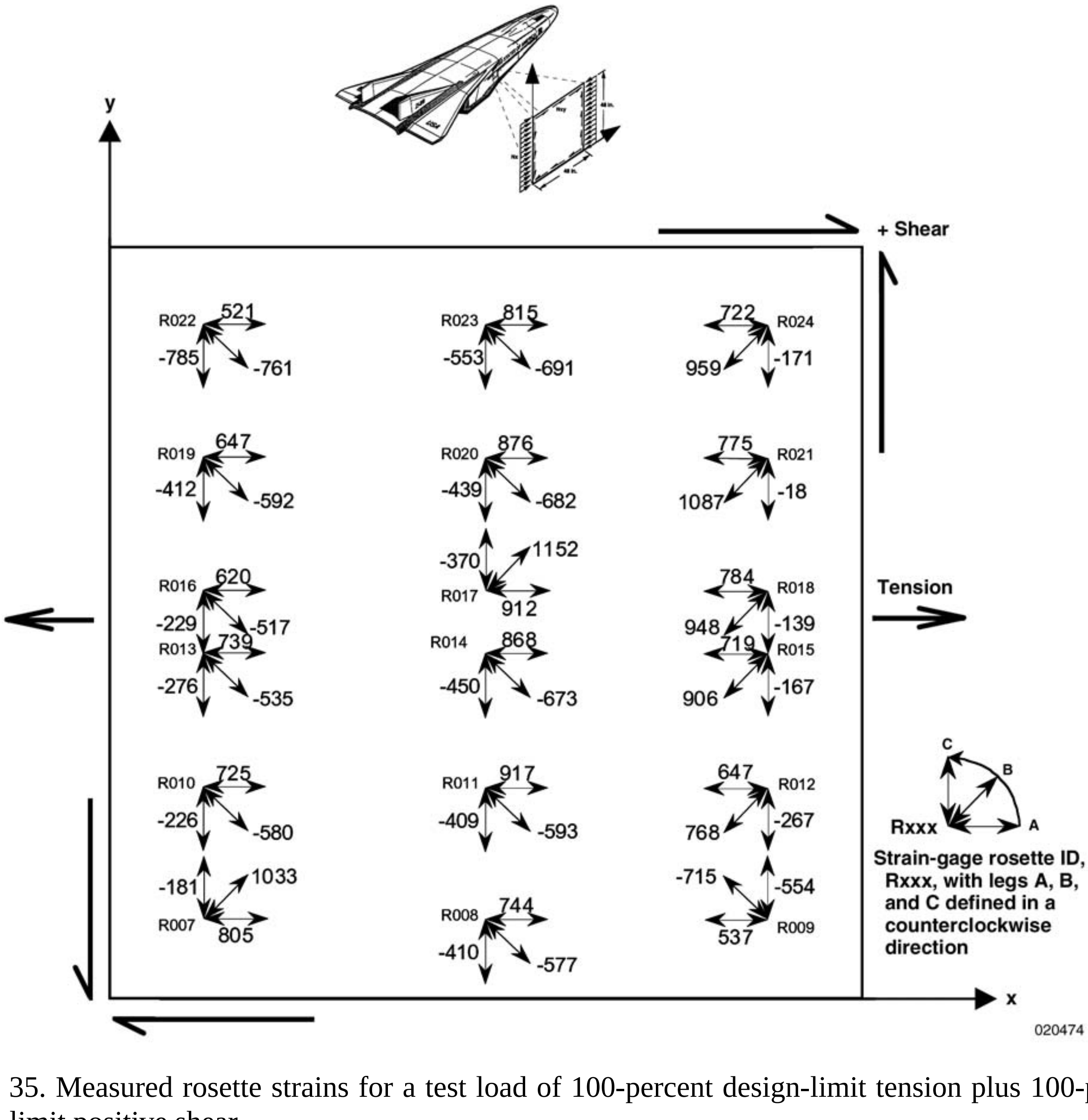


Figure 35. Measured rosette strains for a test load of 100-percent design-limit tension plus 100-percent design-limit positive shear.

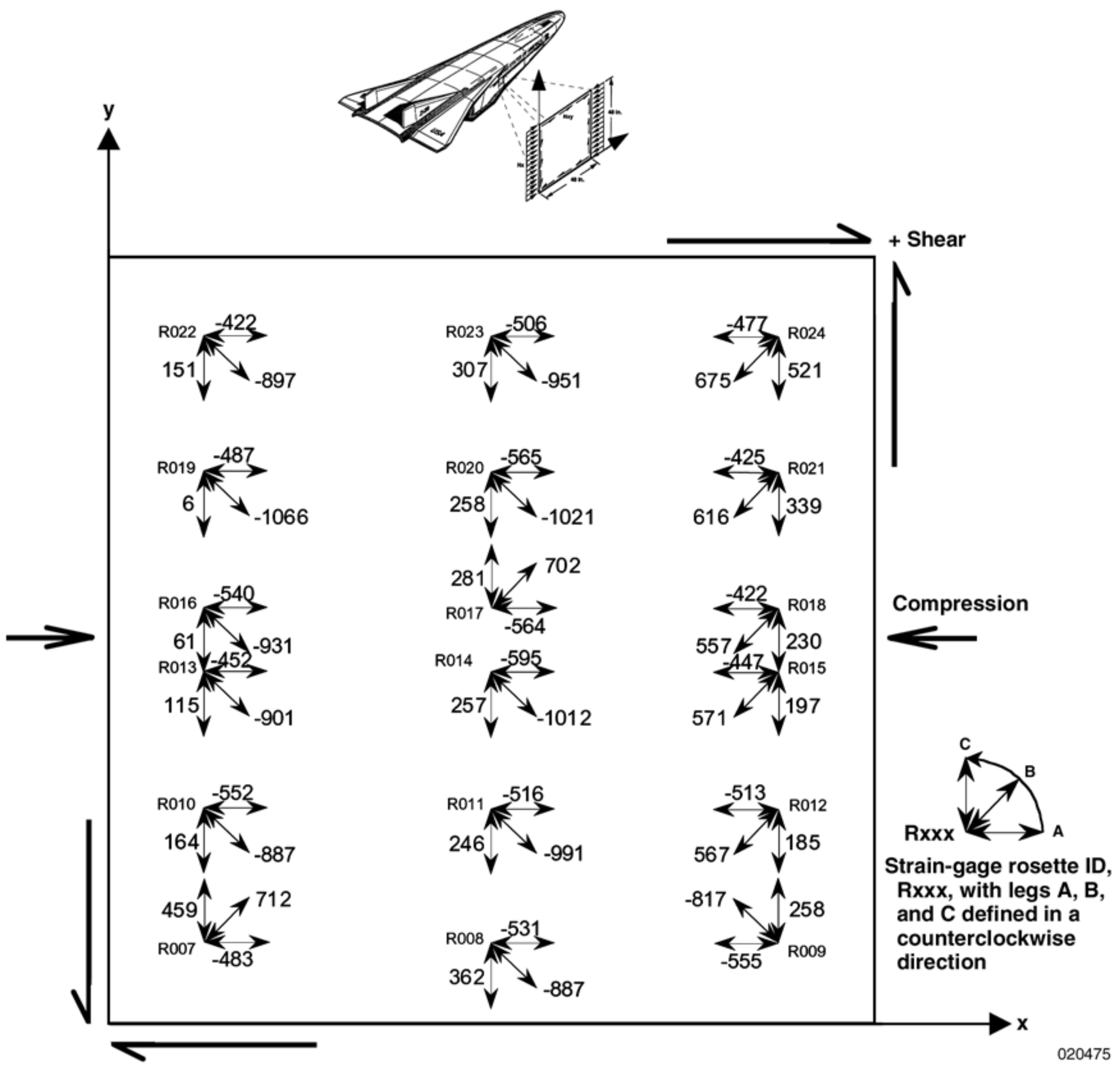


Figure 36. Measured rosette strains for a test load of 100-percent design-limit compression plus 100-percent design-limit positive shear.

The next step in the validation of the test concept and test fixture was to consider the performance and data analysis resulting from elevated temperature testing. Figures 37 and 38 show measured temperatures on the test panel after thermal equilibrium at 500 °F. On the skin side, all measured temperatures were within ±4 percent, and on the hat-stiffened side, all temperatures but three were within ±4 percent. Thus, the temperature distribution is considered uniform; as a result, any anomalous thermal stresses produced by temperature gradients were virtually eliminated.

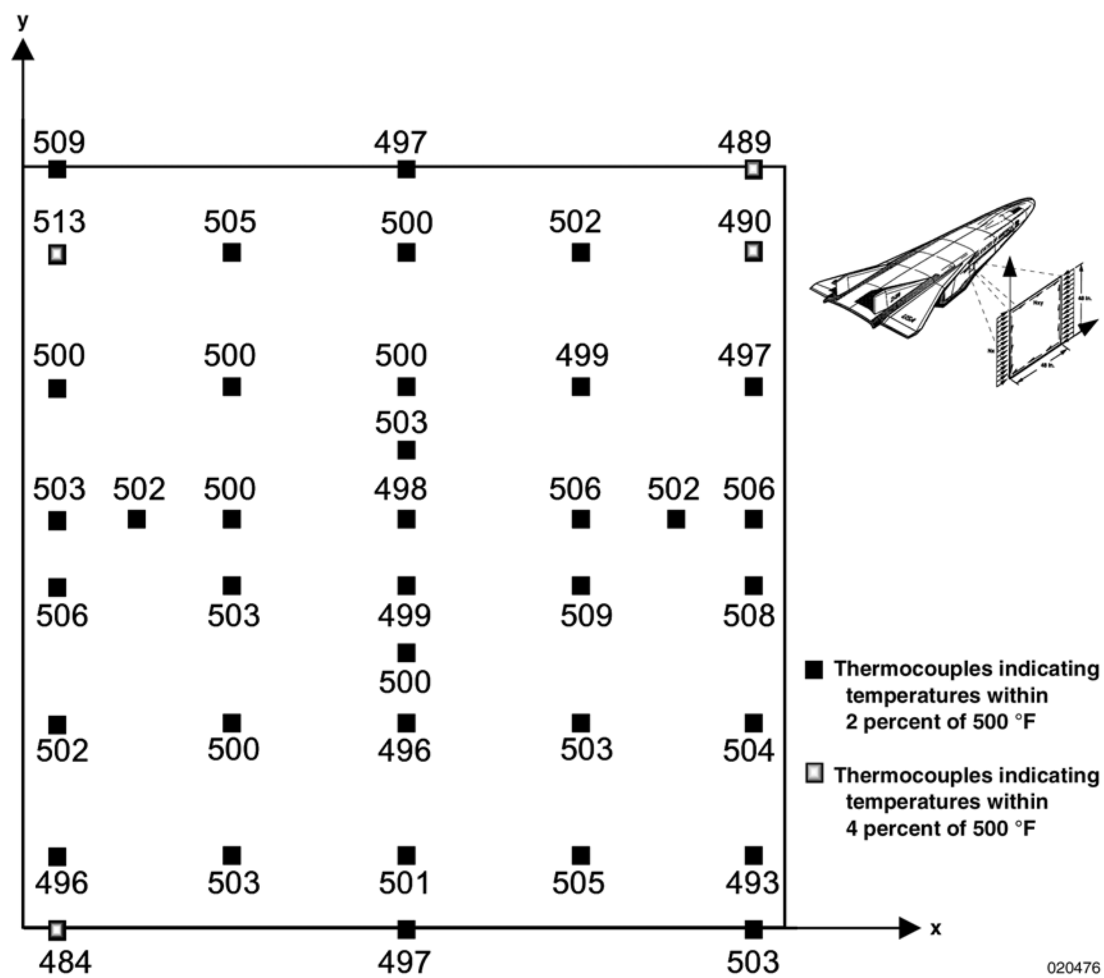


Figure 37. Typical side shear panel skin side temperatures at the 500-°F test condition.

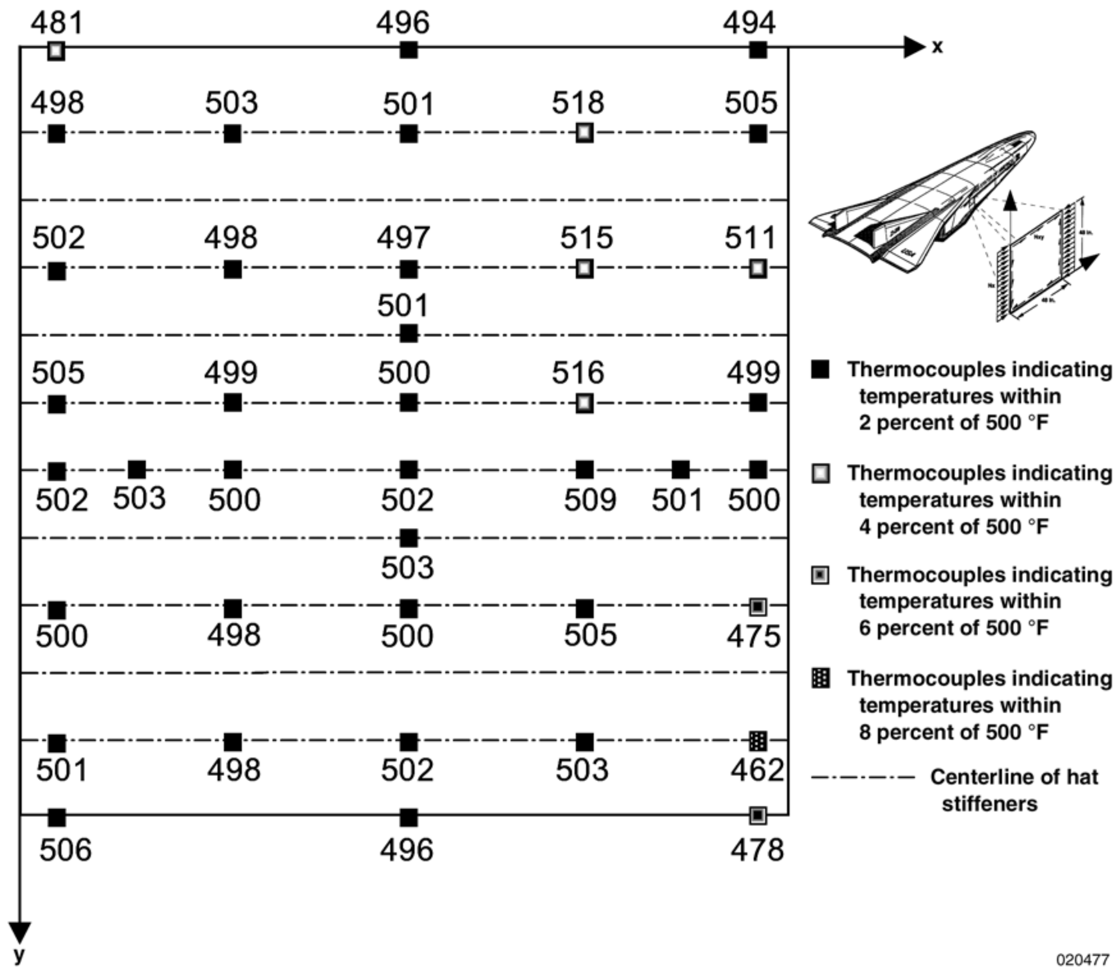


Figure 38. Typical side shear panel hat-stiffened side temperatures at the 500-°F test condition.

Figures 39–42 show a comparison between axial strain measurements in tension and compression for tests at both room temperature and at 500 °F. Because of the hat stiffeners on one side, the test panel was not symmetrical through the thickness, and a uniform temperature imposed on it produced out-of-plane deformations. These deformations cause eccentricities when an in-plane load is applied. The tensile load on the panel tends to reduce the eccentricities. Conversely, the compressive panel load tends to increase the eccentricities and, therefore, decrease the critical panel buckling load. Consequently, in both cases, no reason exists to expect the data of figures 39–42 to be the same for the two temperature conditions.

The thermally induced eccentricities mentioned above do not significantly affect shear strain measurements; therefore, comparisons between room-temperature and 500 °F data are expected to be in close agreement. Table 4 lists minimum and maximum principal strains, determined from rosette strain-gage data, for shear at room temperature and at 500 °F and shear plus tension at room temperature and at 500 °F. Table 4 also lists the calculated angle, where 0° is parallel to the line of axial force, for the direction of the maximum principal strain. As can be seen, the difference between the room-temperature and 500-°F data sets is very small, which demonstrates remarkable test repeatability, even with the added variable of a 500-°F temperature.

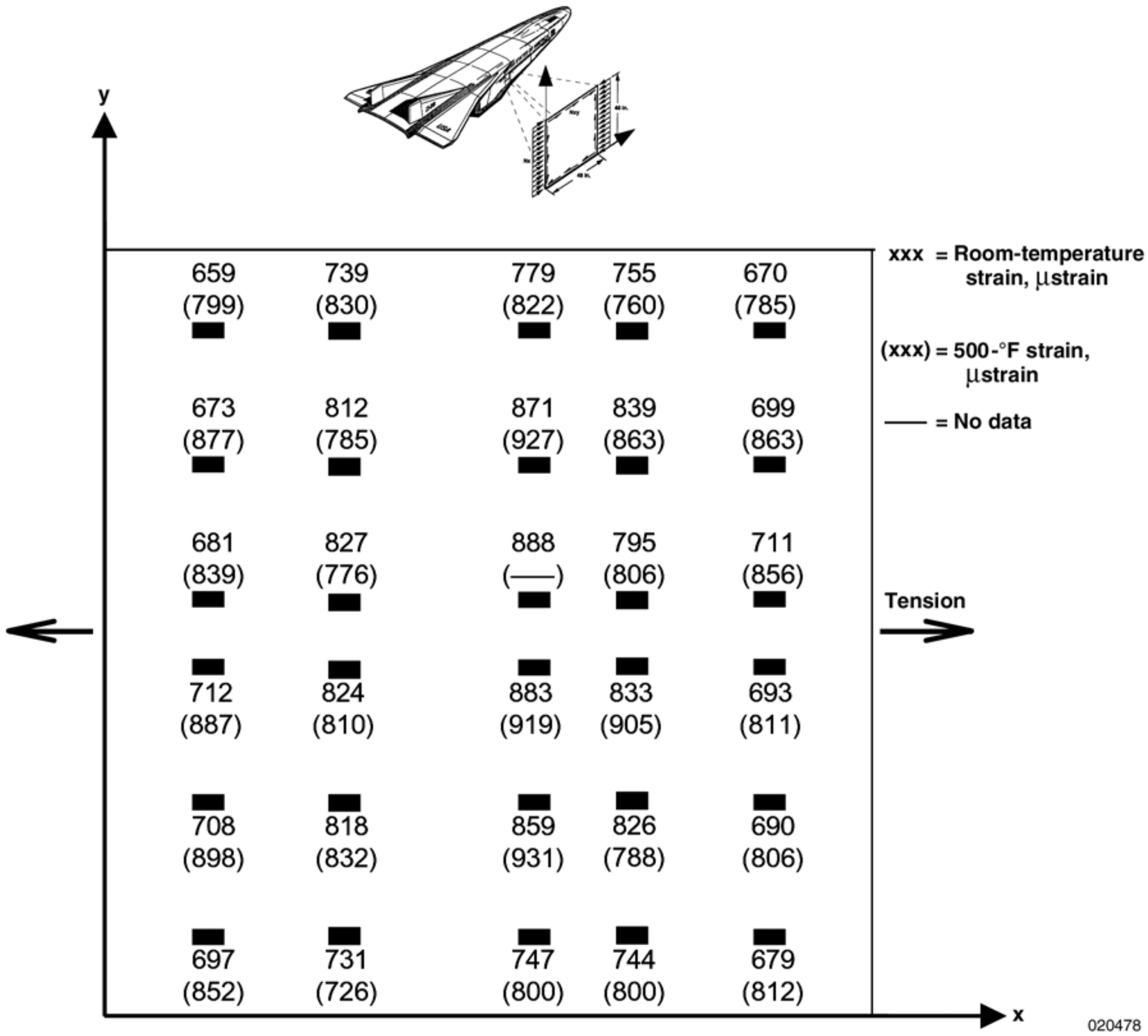


Figure 39. Measured axial strains on the side shear panel skin for 100-percent design-limit tension at room temperature and 500 °F.

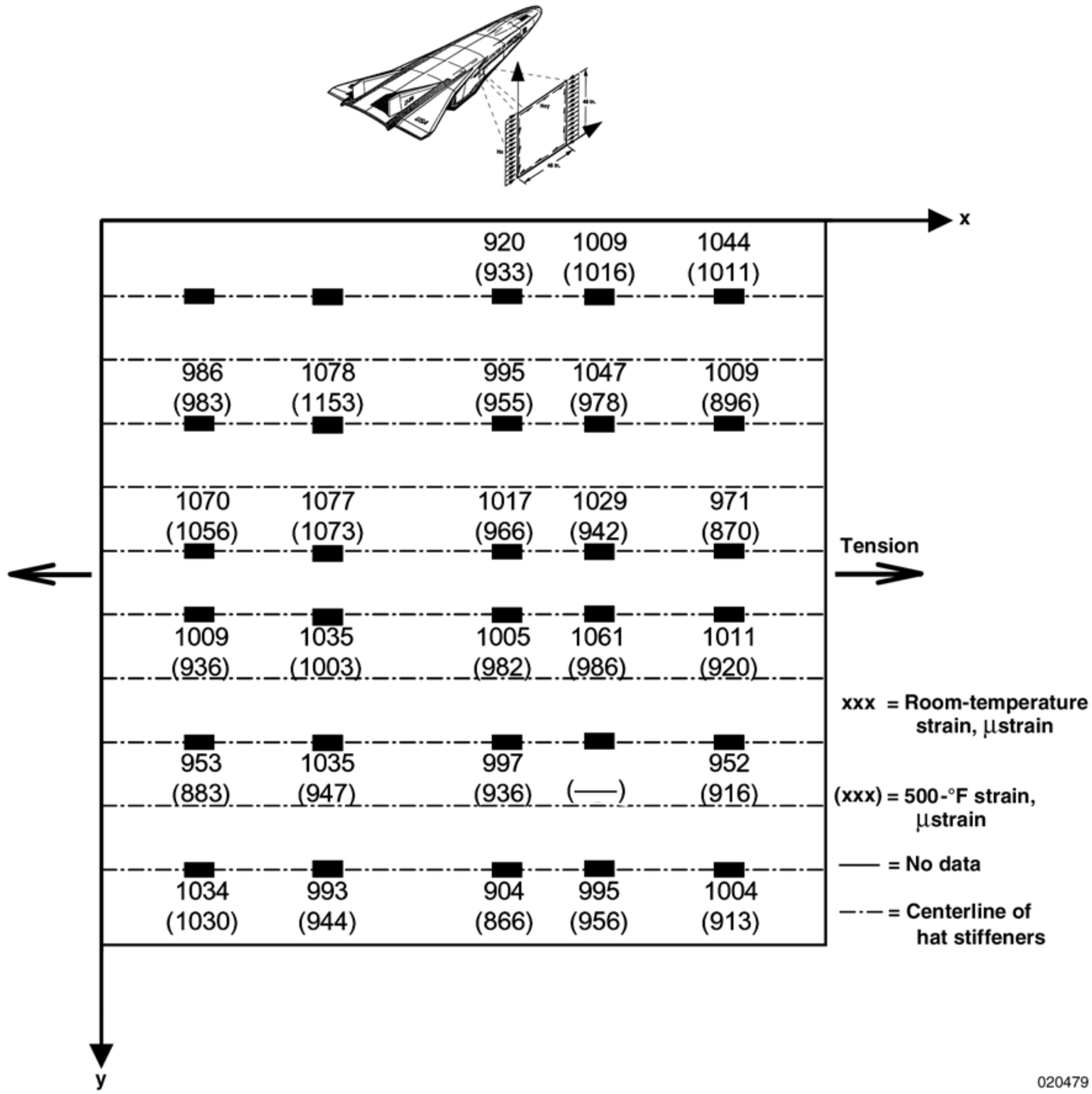


Figure 40. Measured axial strains on the side shear panel hats for 100-percent design-limit tension at room temperature and 500 °F.

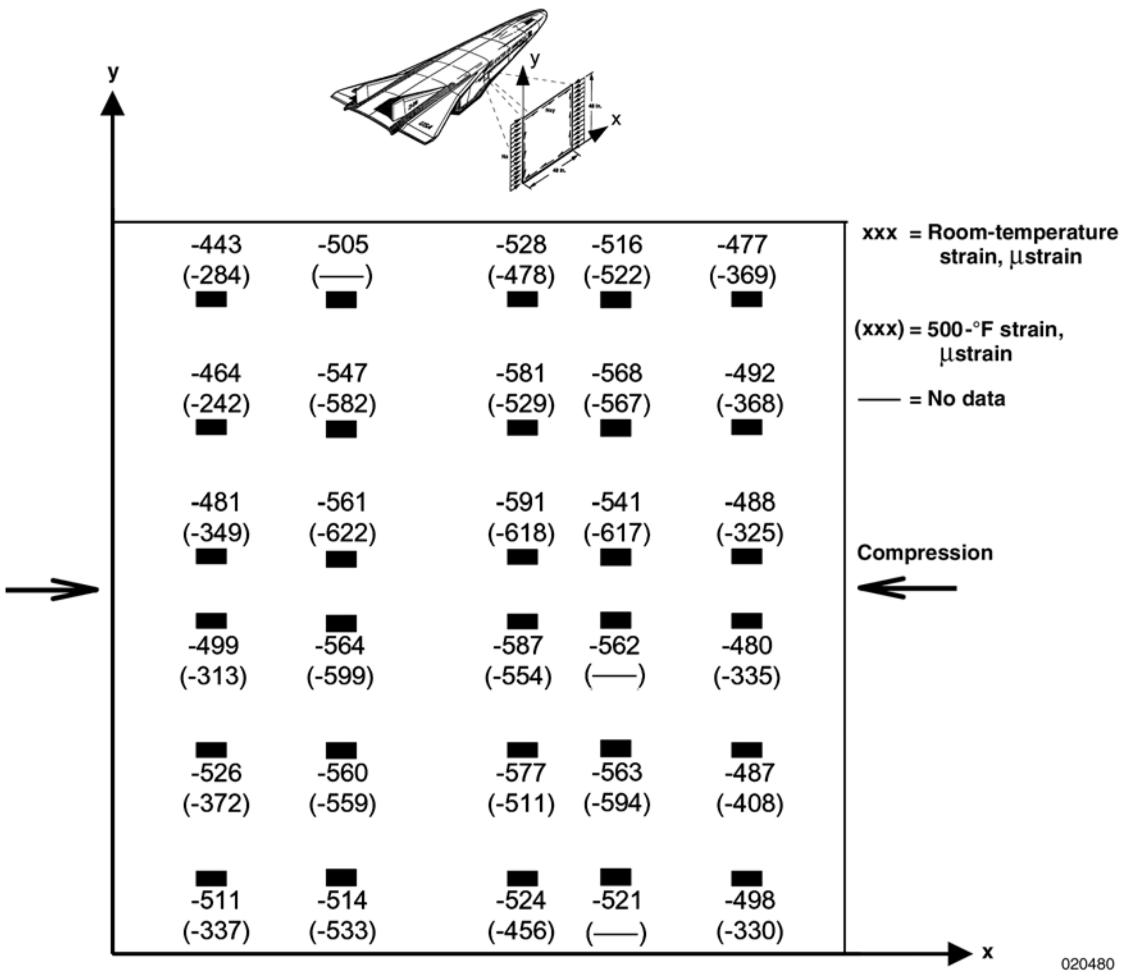


Figure 41. Measured axial strains on the side shear panel skin for 100-percent design-limit compression at room temperature and 500 °F.

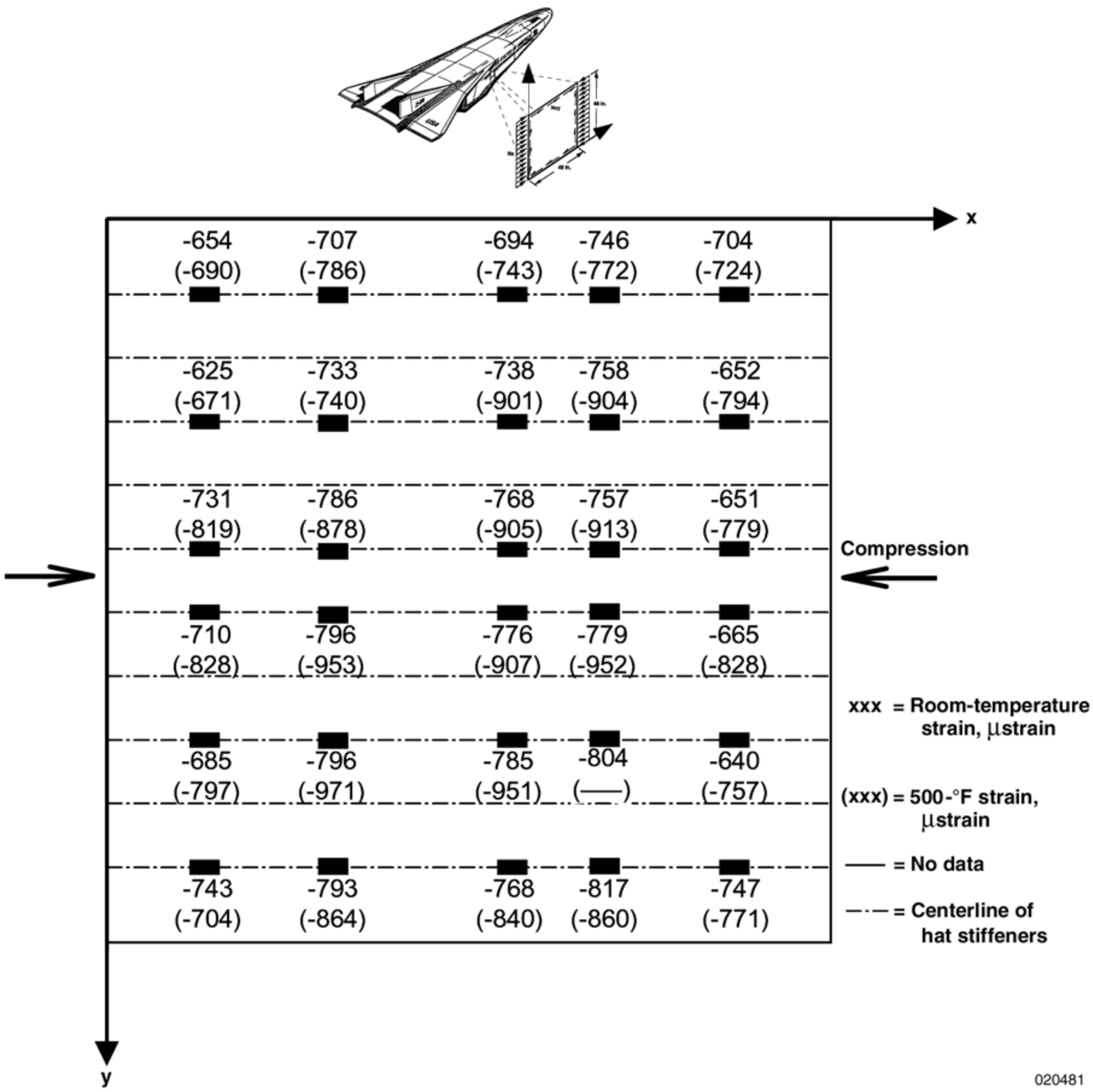


Figure 42. Measured axial strains on the side shear panel hats for 100-percent design-limit compression at room temperature and 500 °F.

Table 4. Minimum (min) and maximum (max) principal strains (p-strain) and directions (angle) for four test conditions.

| Strain gage | Test 6: Plus shear at room temperature | | | Test 12: Plus shear at 500 °F | | |
|---|---|---|---|---|---|---|
| | Min p-strain microstrain | Max p-strain microstrain | Angle degrees | Min p-strain microstrain | Max p-strain microstrain | Angle degrees |
| R007 | -564 | 818 | 47.7 | -571 | 883 | 48.1 |
| R008 | -744 | 783 | 46.1 | -734 | 825 | 46.7 |
| R009 | -758 | 527 | 45.2 | -717 | 554 | 46.1 |
| R010 | -776 | 743 | 44.6 | -765 | 769 | 45.5 |
| R011 | -853 | 867 | 43.5 | -806 | 915 | 45.1 |
| R012 | -737 | 627 | 45.2 | -676 | 664 | 48.5 |
| R013 | -758 | 756 | 43.1 | -740 | 768 | 44.5 |
| R014 | -909 | 848 | 44.5 | -847 | 866 | 46.1 |
| R015 | -665 | 698 | 44.4 | -636 | 757 | 47.2 |
| R016 | -789 | 653 | 44.9 | -761 | 682 | 46.3 |
| R017 | -874 | 897 | 44.5 | -897 | 911 | 44.8 |
| R018 | -612 | 701 | 43.8 | -576 | 760 | 46.3 |
| R019 | -899 | 688 | 42.2 | -834 | 725 | 43.6 |
| R020 | -908 | 874 | 44.5 | -869 | 905 | 45.3 |
| R021 | -572 | 778 | 46.1 | -543 | 852 | 48.4 |
| R022 | -835 | 544 | 39.1 | -835 | 601 | 41.5 |
| R023 | -847 | 800 | 43.1 | -845 | 846 | 43.2 |
| R024 | -504 | 748 | 49.4 | -575 | 863 | 51.4 |
| **Strain gage** | **Test 9: Plus shear and tension at room temperature** | | | **Test 15: Plus shear and tension at 500 °F** | | |
| | Min p-strain microstrain | Max p-strain microstrain | Angle degrees | Min p-strain microstrain | Max p-strain microstrain | Angle degrees |
| R007 | -561 | 1186 | 27.8 | -567 | 1193 | 27.6 |
| R008 | -775 | 1109 | 26.1 | -697 | 1118 | 27.3 |
| R009 | -901 | 884 | 26.2 | -816 | 835 | 26.9 |
| R010 | -707 | 1205 | 30.1 | -729 | 1216 | 30.9 |
| R011 | -822 | 1329 | 26.1 | -729 | 1307 | 27.6 |
| R012 | -547 | 927 | 25.8 | -457 | 889 | 28.2 |
| R013 | -688 | 1150 | 28.2 | -671 | 1126 | 30.4 |
| R014 | -892 | 1310 | 26.6 | -799 | 1311 | 28.6 |
| R015 | -493 | 1046 | 27.4 | -464 | 1041 | 31.3 |
| R016 | -634 | 1025 | 29.6 | -603 | 1010 | 30.6 |
| R017 | -818 | 1361 | 26.9 | | | |
| R018 | -455 | 1100 | 26.8 | -396 | 1142 | 29.7 |
| R019 | -768 | 1003 | 26.6 | -704 | 979 | 27.5 |
| R020 | -896 | 1333 | 26.9 | -821 | 1358 | 28.4 |
| R021 | -434 | 1190 | 30.4 | -427 | 1236 | 31.7 |
| R022 | -1059 | 895 | 22.1 | -981 | 841 | 22.8 |
| R023 | -938 | 1200 | 25.1 | -853 | 1221 | 26.5 |
| R024 | -541 | 1092 | 28.4 | -522 | 1155 | 29.8 |

Table 5 shows a comparison of measured shear strain, in units of microradians, at room temperature and 500 °F. Values were calculated at room temperature using the detailed model. The experimental room-temperature data are for the same tests shown in table 4. The average difference between all of the test data and the calculated data is slightly less than 11 percent. The individual differences, however, range to a maximum of 52 percent (for strain-gage R010, test 15, compared with analysis). In this case, the analysis shows a much lower shear load value, –1129, compared with the measured value of –1717. Because several locations with similar situations exist, further investigation is warranted. Figure 43 shows the distribution of finite-element-calculated, room-temperature shear strains at all rosette strain-gage locations. Data for three load conditions are shown. The load case with finite-element-derived positive shear combined with compression* is shown to demonstrate the effects of both tension and compression on the shear strain. The most obvious observation from figure 43 is that the calculated shear strains across the center of the panel are invariant to the applied axial loads, either tension or compression. Additionally, the shear strains are shown to increase slightly from the center of the panel (R014, R017) laterally to the edges (R008, R023). Combined shear and tension loads result in large decreases in shear strain at the R010 and R017 locations with large increases in shear strain at the R012 and R019 locations. Combined shear and compression loads have an opposite effect at the corresponding locations.

Table 5. Measured shear strain for four test conditions compared to data from room temperature analyses.

| **Strain Gage** | **Shear Strain Due To Plus Shear Load** | | | **Shear Strain Due To Plus Shear Load** | | |
|---|---|---|---|---|---|---|
| | Room Temperature | | 500 °F | Room Temperature | | 500 °F |
| | Test 6 microradians | Analysis microradians | Test 12 microradians | Test 9 microradians | Analysis microradians | Test 15 microradians |
| R007 | -1379 | -1374 | -1446 | -1443 | -1237 | -1444 |
| R008 | -1527 | -1948 | -1557 | -1486 | -1948 | -1479 |
| R009 | -1283 | -1370 | -1269 | -1412 | -1490 | -1333 |
| R010 | -1521 | -1354 | -1534 | -1658 | -1129 | -1717 |
| R011 | -1717 | -1825 | -1721 | -1693 | -1825 | -1674 |
| R012 | -1363 | -1350 | -1330 | -1156 | -1556 | -1122 |
| R013 | -1510 | -1330 | -1508 | -1533 | -1274 | -1567 |
| R014 | -1757 | -1772 | -1711 | -1766 | -1772 | -1774 |
| R015 | -1366 | -1330 | -1389 | -1258 | -1367 | -1335 |
| R016 | -1444 | -1331 | -1441 | -1423 | -1369 | -1413 |
| R017 | -1770 | -1772 | -1808 | -1761 | -1772 | |
| R018 | -1311 | -1330 | -1334 | -1252 | -1273 | -1324 |
| R019 | -1581 | -1351 | -1557 | -1420 | -1557 | -1377 |
| R020 | -1779 | -1826 | -1774 | -1800 | -1826 | -1823 |
| R021 | -1349 | -1350 | -1385 | -1417 | -1126 | -1487 |
| R022 | -1352 | -1368 | -1426 | -1359 | -1491 | -1300 |
| R023 | -1645 | -1951 | -1687 | -1643 | -1951 | -1656 |
| R024 | -1236 | -1402 | -1402 | -1369 | -1230 | -1445 |

*Although analytical data are shown for this load case, similar measured data for shear strain with this load case were not available.

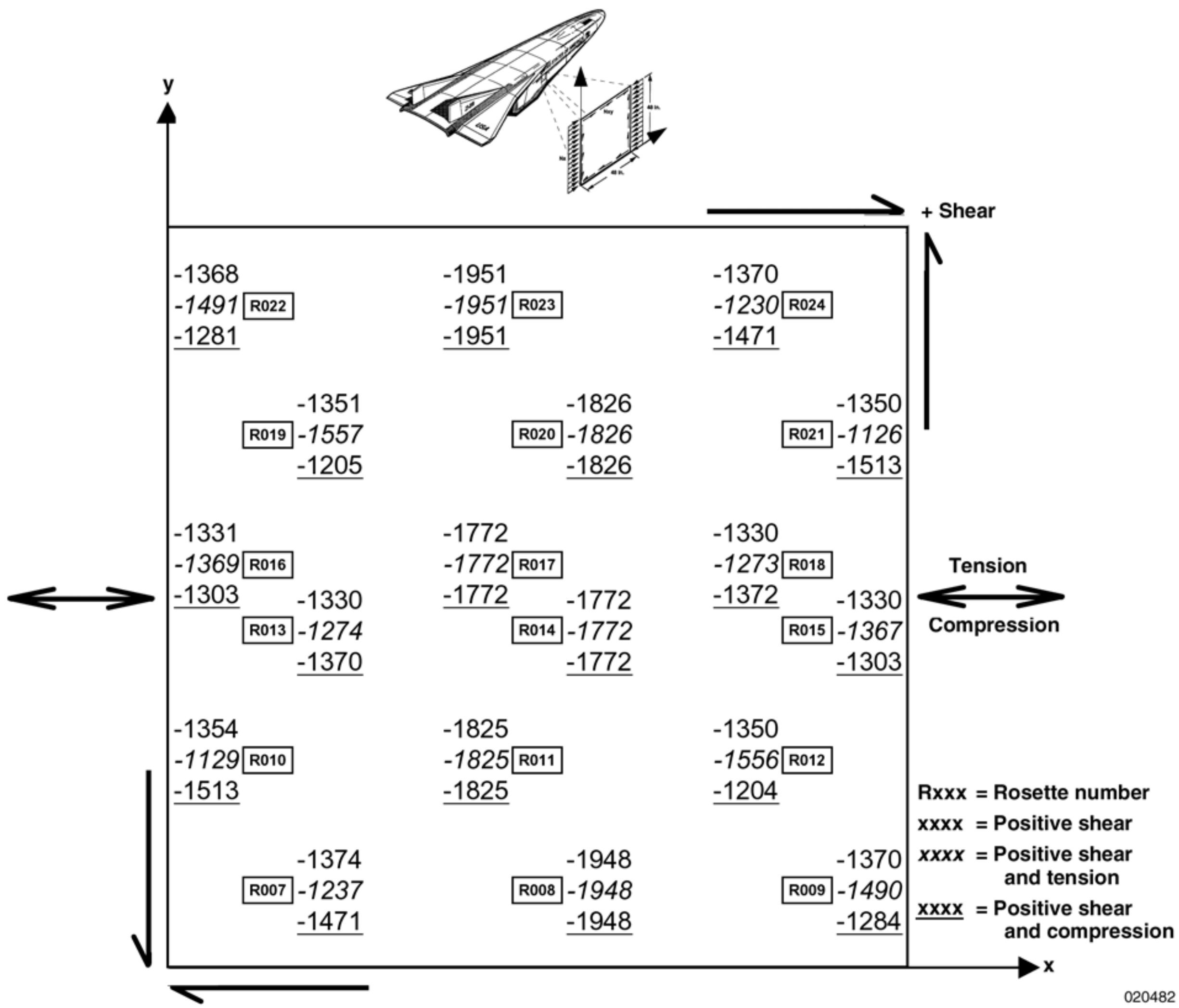


Figure 43. Calculated room-temperature shear strains for the side shear panel at 100-percent design-limit loads.

Figure 44 shows measured shear strain data for positive shear load and combined positive shear and axial tension loads at both room temperature and 500 °F. The data are from room-temperature tests 6 and 9, and 500-°F tests 12 and 15. The consistency of the data from room-temperature and 500-°F tests is again excellent. The most interesting and important fact that can be learned from comparing figure 44 with figure 43 is that the measured data are much more uniform over the panel than the predicted data. Therefore, although a few relatively large errors exist between the analysis and test results comparison of table 5, the actual measured data show the test fixture to be better able to evenly distribute the loads than the complex finite-element model predicted.

The combined loads test fixture has been shown to be very effective in meeting the side shear panel program test requirements at room temperature and at 500 °F. The correlation between the measured test data and the finite-element analyses is extremely good, and tests to higher temperatures are expected to be equally successful. Also, use of the test fixture for tests of other comparable size components from other vehicle programs at room temperature and at elevated temperature should prove to be advantageous.

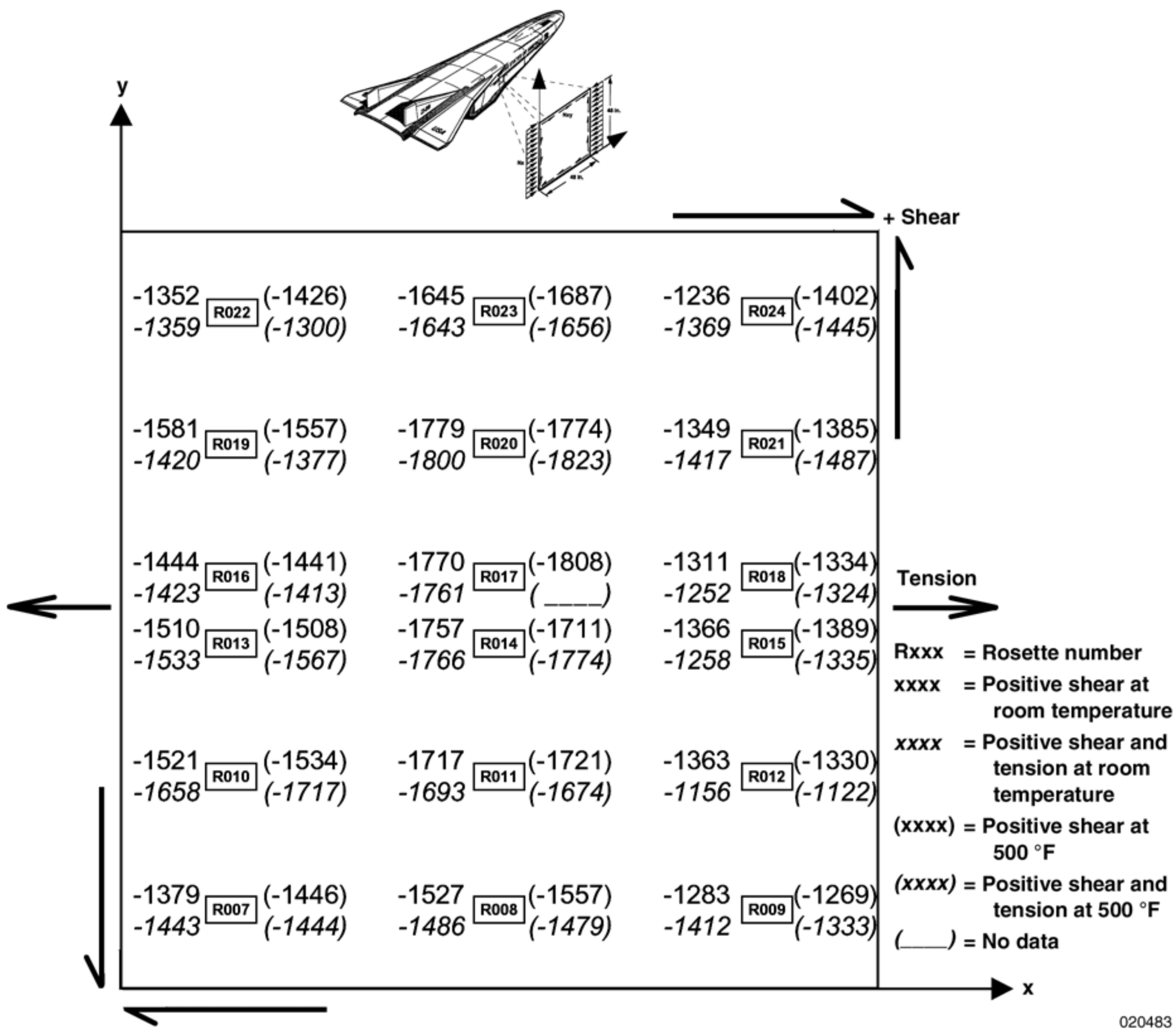


Figure 44. Measured shear strains for the side shear panel at 100-percent design-limit loads.

# CONCLUDING REMARKS

The combined loads test fixture originally was designed to satisfy the requirements of the side shear panel test program. The principal requirements were to test a 4- by 4-ft panel under combined axial (either tension or compression) and shear load, at temperatures ranging from room temperature to 915 °F. The stress field over the test panel surface was to be uniform. Thermal stresses caused by temperature gradients and dissimilar materials were to be minimized. Specific details were given as to how the test fixture design met all of the program requirements for both mechanical loading and thermal loading. The design was shown to be simple and flexible, and to provide easy accessibility to the test panel.

Extensive finite-element structural analyses of the test panel and its boundary structure (buffer panels, load introduction panels, shear load framework, and so forth), for all planned load conditions showed the panel stress distributions to be very uniform and to meet program requirements.

Following a comprehensive test program at temperatures to a maximum of 500 °F, measured data from strain-gages were compared to analytical predictions. The overall correlation of data was outstanding. In a few cases, where significant differences existed between test and analysis, the test panel strain distributions were shown to be more uniform than those of the analysis.

The side shear panel program proved, both analytically and experimentally, that the combined loads test fixture can effectively apply axial load, both tension and compression, shear load in either direction, and thermal load at either uniform temperature or moderate through-the-panel gradients. The above loads can be applied independently or in combination. Finally, because of the simple design of the test fixture, it can easily accommodate similar panels from a wide variety of aerospace vehicle designs.

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*Edwards, California*
*April 23, 2002*

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**13. ABSTRACT (Maximum 200 words)**

A structural test requirement of the National Aero-Space Plane (NASP) program has resulted in the design, fabrication, and implementation of a combined loads test fixture. Principal requirements for the fixture are testing a 4- by 4-ft hat-stiffened panel with combined axial (either tension or compression) and shear load at temperatures ranging from room temperature to 915 °F, keeping the test panel stresses caused by the mechanical loads uniform, and thermal stresses caused by non-uniform panel temperatures minimized. The panel represents the side fuselage skin of an experimental aerospace vehicle, and was produced for the NASP program. A comprehensive mechanical loads test program using the new test fixture has been conducted on this panel from room temperature to 500 °F. Measured data have been compared with finite-element analyses predictions, verifying that uniform load distributions were achieved by the fixture. The overall correlation of test data with analysis is excellent. The panel stress distributions and temperature distributions are very uniform and fulfill program requirements. This report provides details of an analytical and experimental validation of the combined loads test fixture. Because of its simple design, this unique test fixture can accommodate panels from a variety of aerospace vehicle designs.

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