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DESIGN CONSIDERATIONS FOR JOINTS IN DEPLOYABLE SPACE TRUSS STRUCTURES

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INTRODUCTION

All of the structures considered for the Control of Flexible Structures (COFS) flight experiments are deployable truss structures and their response will be dominated by the structural response of the joints. To prepare for these experiments some fundamental research work is being conducted in the Structures and Dynamics Division at LaRC which will provide insight into structurally efficient and predictable deployable truss joints. This work involves generic studies of the static and dynamic response of joints as well as the development of analytical models which can be used to predict the response of a large multijointed truss. Some of this work has been documented in references 1 and 2, and additional publications are planned. In addition to the generic joint studies, the research effort encompasses the design and fabrication of a 20-meter long deployable truss beam for laboratory evaluation of its structural characteristics and correlation with developed prediction methods.

The purpose of the present paper is to present a snapshot of a limited part of this research activity and discuss some design considerations in the static behavior of joints for deployable space truss structures.

STATIC TEST EVALUATION OF TWO JOINT TYPES

The work presented in the current paper covers some recent experimental studies to evaluate the static stiffness of two joint types commonly incorporated in most deployable truss structures. These joints are a pin-clevis type and a folding linkage system described herein as a near-center latch joint. The pin-clevis joint is used in a wide range of industrial and commercial applications and there is considerable information in the open literature regarding factors that affect its static strength. However, very little information is available on the design aspects that affect the structural stiffness. The present experimental study was a limited parametric evaluation of some factors that affect the stiffness of pin-clevis joints.

The tests on the near-center latch described herein are a part of the total experimental evaluation for the 20-meter long deployable truss beam mentioned previously. This joint incorporates a spring-loaded linkage-mechanism to obtain mechanical advantage and lock the hinge in the deployed position. It has a long history of successful applications (reference 3) and has also been called an "almost-over-center latch" and a "suitcase latch". The studies conducted in this experimental program will be presented in the order shown on the figure.

- Parametric study of pin-clevis joints

- Representative tests on near-center latch joint

Figure 1

Shown on figure 2 are some structural aspects of pin-clevis joints that can affect stiffness. It is obvious that the elastic moduli of the joint components will be important. However, due to the availability of standard parts or other considerations such as cold welding, it can be expected that the pin and the joint body would be fabricated from different materials. The shear and bending deformations of the pin will directly influence joint stiffness; however,analytical characterization of their effects is difficult due to the uncertainty of the loading and support conditions on the pin. Bearing and seating conditions are also difficult to characterize for the same reasons.

All of the aspects noted above affect joint stiffness in varying degrees. The experimental study was conducted to provide quantitative information that would assist in the practical design of joints for deployable truss structures with high axial and torsional stiffness.

Design aspects that affect stiffness

- Pin and parent joint material properties
- Pin response in shear, bending and bearing
- Load path
- Pin-diameter to joint-width relation

Figure 2

TEST SETUP AND PARAMETERS

The test setup and parameters evaluated are shown in figure 3. Three plates were bolted to fixtures attached to the loading heads of a hydraulic test machine. The plates were all 1-inch wide; the center plate was 0.5-inch thick and each side plate was 0.25-inch thick. The plates had a single hole in the center of the width and the hole was reamed to fit a steel gage pin of the desired diameter. The plates were assembled and bolted lightly to the test fixture. A close fitting pin was placed in the hole and the plate set was loaded in tension to aline all of the components in the load chain. The bolts were then tightened to firmly clamp the plates to the fixture to preclude slippage during the test. The displacement across the pin connection was measured with two commercial extensometers, one on each side of the plate, while load was applied. The load was cycled slowly through tension into compression. Data from the extensometers were taken frequently during the test.

Three materials were evaluated during the test: 7075 aluminum, 416 corrosion resistant steel, and TI-6AL-4V titanium. They were selected to be representative of materials with applications in space structures and they have a wide modulus range. The specimens were all tested as sets of a given material and several sets of each material were evaluated in selective tests to determine repeatability of results. All sets were drilled and tested with a nominal 0.25-inch diameter pin. Following this test series, one set of each material was drilled and reamed to fit the next larger test pin. This process was continued with the same plate set until the width of the load-bearing section adjacent to the hole was reduced enough to cause a significant loss in the tensile stiffness of the plate. At several of the test pin diameters, the plates were fitted with pins that were slightly undersized in increments of .0010 inch to evaluate the effect of pin fit on the test results.

After varying the nominal pin diameter and determining the diameter which would yield the highest value of stiffness, the length of the plate "e" was reduced to determine the minimum plate length beyond the hole center required to give a high value of stiffness.

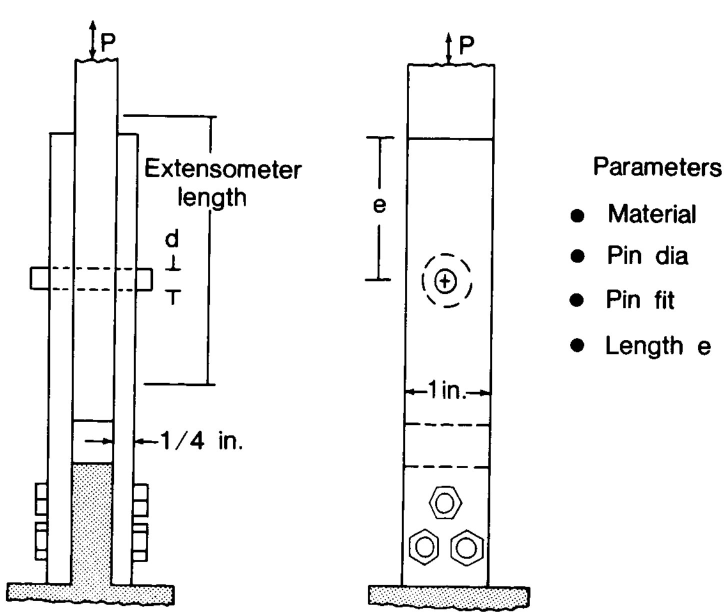


Figure 3

TESTS FOR PIN FIT

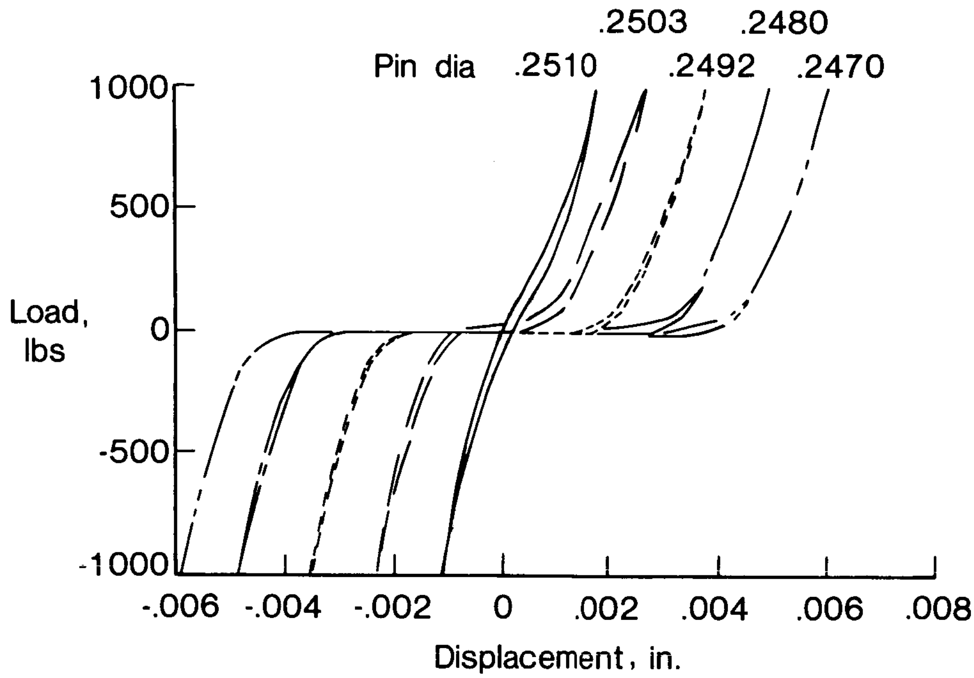
TITANIUM AND STEEL PLATES

Typical load deflection test results for a nominal 0.250-inch diameter steel pin in a titanium and a steel plate are shown in figures 4a and 4b respectively. Several test pins were used to examine the effect of pin fit on joint stiffness. It was anticipated that the effect of small changes in pin diameter and subsequent bearing area and stress distribution might affect the stiffness of the joint. However, the curves for each material are effectively parallel throughout the load range for all the diameters shown. The largest pin diameter tested (0.2510-inch diameter in figure 4a) provided a line fit with the hole (i.e., light pressure was required to insert the pin but when the pin was removed there was no evidence of substantial interference or marking of the surface around the hole or on the pin). The test results show that there was no free play between the plate and the pin. All other test results have a region of free play of approximately twice the value of the pin clearance. Therefore, hole to pin clearance should be eliminated for deployable pin-clevis joints if possible. This is especially true for truss beams and platforms that are only lightly loaded. Free play and nonlinearity in large multijointed trusses can accumulate, making accurate pointing and control very difficult to achieve. However, if the joints have interference or line fit pins, the level of interference must not be high enough to require large moments to deploy the truss. To accomplish a close hole-to-pin fit in the joint of a member that can be deployed with a reasonable moment, the diameter of the hole and pin must be accurately controlled with tolerances in the range of 0.0001 inch.

There is evidence in comparing the hysteresis in the curves of pin fit that the amount of hysteresis in the joint decreases with pin diameter. However, no measurements adequate for accurate evaluation of this effect were made.

TESTS FOR PIN FIT IN TITANIUM PLATE

.250 Nominal pin dia



TESTS FOR PIN FIT IN STEEL PLATE

.250 nominal pin dia

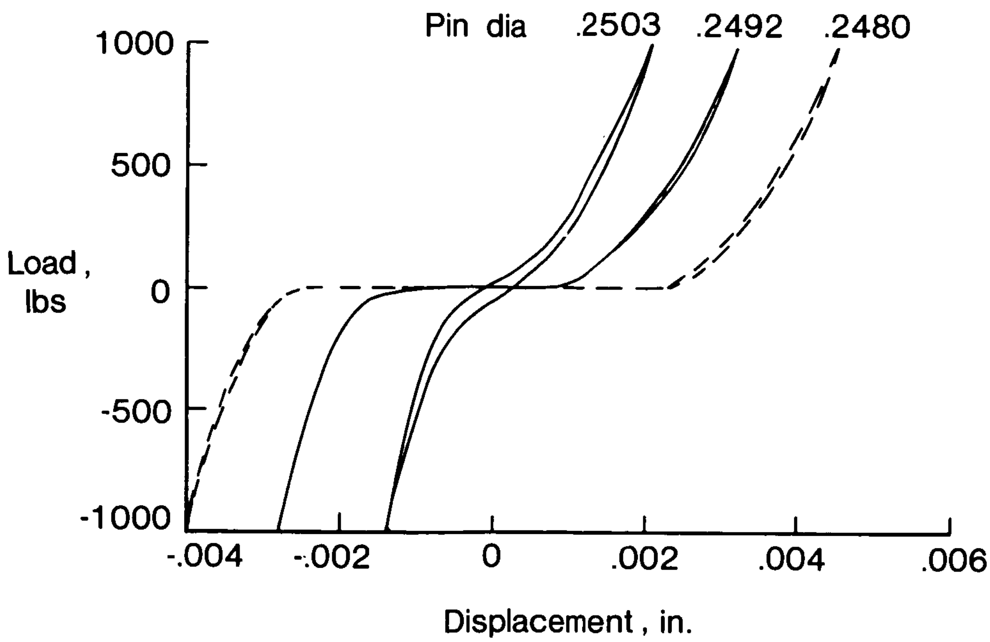


Figure 4

EFFECT OF PIN DIAMETER ON JOINT STIFFNESS

The average stiffness of the joint in the high load region (loads above 300 pounds) was determined from plotted results such as those shown on figure 4 for several nominal pin diameters. Typical stiffness results are shown in figures 5a and 5b for the steel and aluminum plates respectively. The dashed curves were faired through the points to represent the trends in the data. The stiffness for tensile loads increases in a well controlled manner with increase in pin diameter until it reaches a plateau in the range of 45 to 55 percent of the plate width. Then it decreases markedly for the largest diameter (0.63 inch) tested. However, the compression results continue to increase with pin diameter. The area reduction in the section adjacent to the pin is responsible for the loss in tensile stiffness but has no adverse effect on the compression stiffness because it is not in the compression load path. The data also indicate that the structural stiffness of a pin-clevis joint is bilinear and that the stiffness in compression will always be higher than it is in tension. This is because a tensile loaded joint has a longer load path and the net section stress level adjacent to the hole, which is in that load path, can be very high. To minimize this bilinearity, the results indicate that the pin diameter should be about 45 percent of the plate width, regardless of the parent joint material.

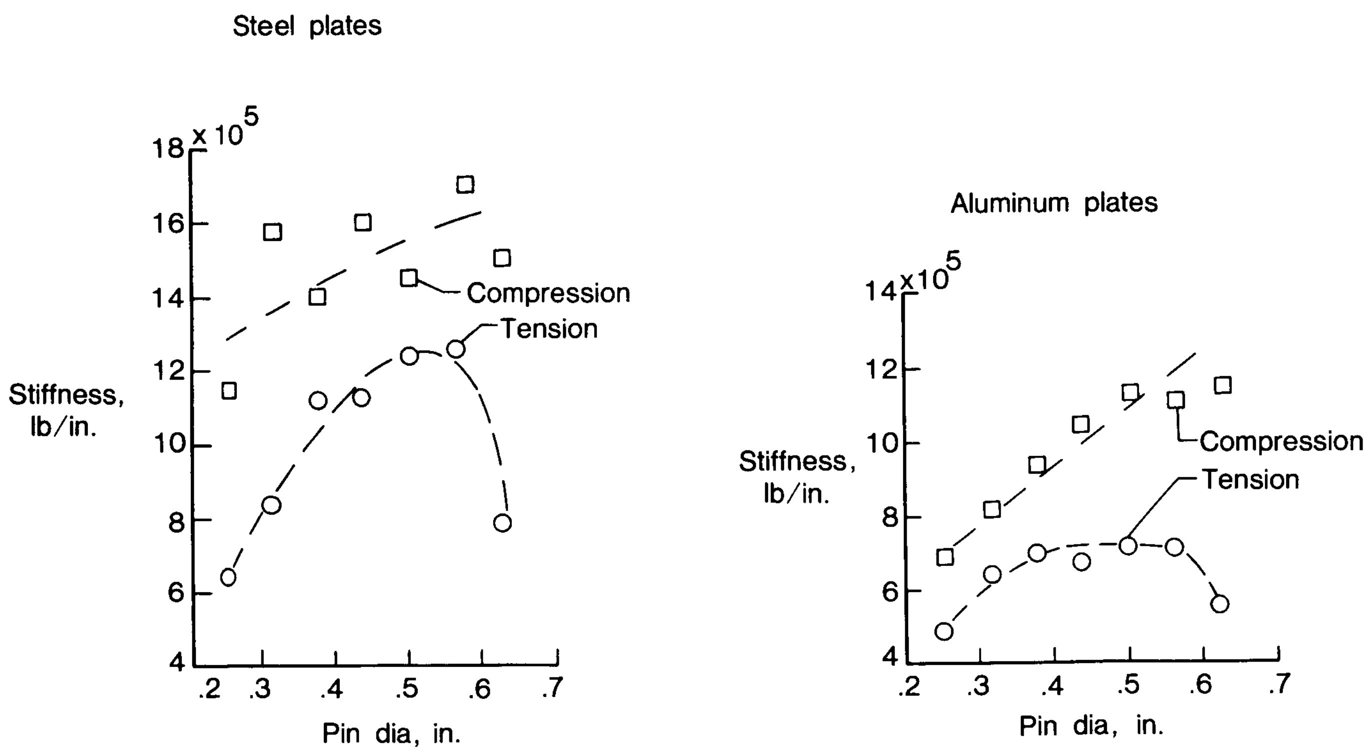


Figure 5

JOINT SECTION EFFICIENCY

Based on results such as those shown in figure 5 for all three materials tested, an estimated maximum joint efficiency was determined that may be useful in calculating the stiffness of deployable truss structures. The efficiency thus determined is shown in figure 6. The values shown are based on the maximum measured stiffness as determined from the test for a pin diameter in the range of 45 percent of the specimen width, with that stiffness normalized by the calculated stiffness of a solid bar of equivalent length. The efficiency noted on the figure for the various materials varies inversely with the elastic modulus of the plate material. Since all plates were connected with steel pins, it is apparent that the modulus of the pin contributes significantly to the efficiency of the joint.

$$\text{Efficiency} = \frac{\text{Max measured stiffness}}{\left(\frac{EA}{L}\right)_{\text{Test section}}}$$

Joint material	Efficiency Tension	Efficiency Compression
Steel	30%	38%
Titanium	43%	59%
Aluminum	50%	76%

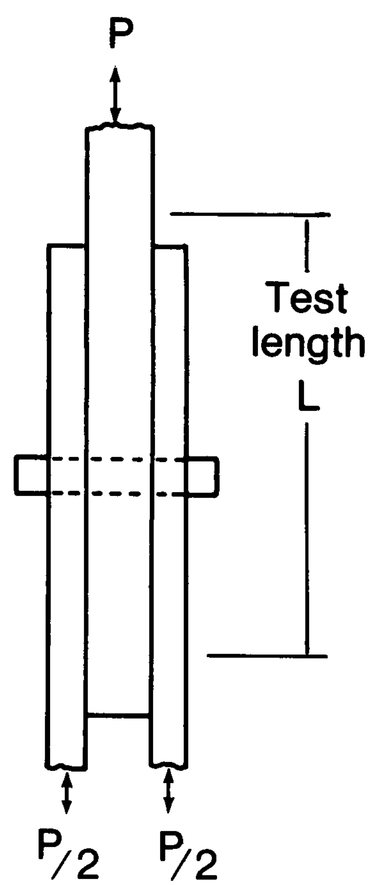


Figure 6

DESIGN RECOMMENDATIONS

Some design recommendations for pin-clevis joints are shown in figure 7. They are based on the results previously discussed and on some observations from similar work performed under the NASA sponsored contract for the 20-meter test beam model. The tests conducted in the present investigation were for only one width and thickness of plates, however, the results should be representative of a typical joint.

From the data presented in previous figures, it is apparent that a pivot pin of a high modulus material in a joint of the dimensional relations shown will result in a highly efficient joint. To minimize free play and nonlinearity, the pin should have a light interference fit with the plates, and the pin and hole surfaces should be smooth to avoid abrasion and wear. The contact surfaces may require plating or anodizing to prevent galling, particularly if aluminum or titanium materials are used in the fabrication.

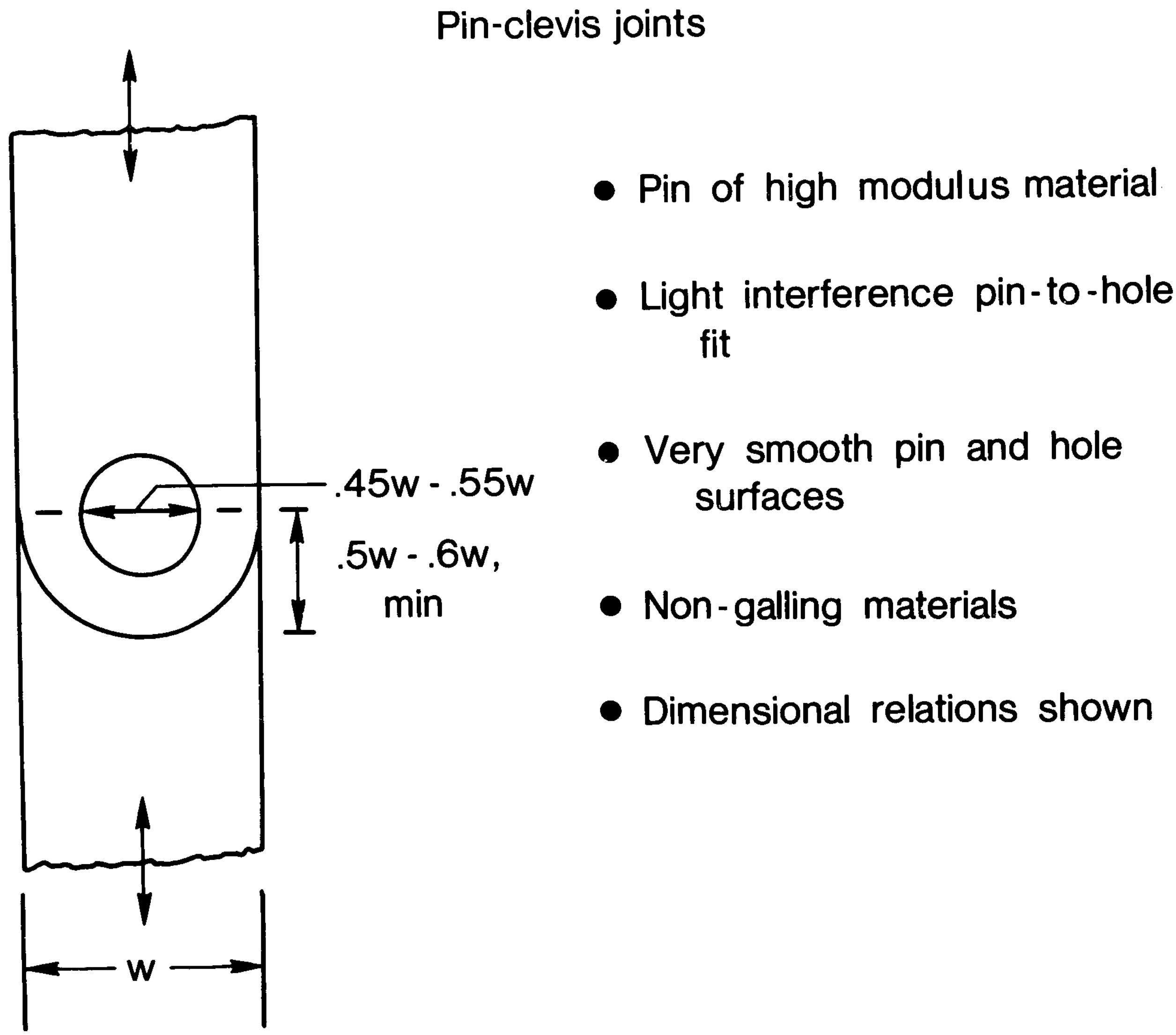


Figure 7

NEAR-CENTER LATCH JOINT

TEST MODEL

A photograph of the near-center latch is shown in figure 8. Joints of this type are very common in deployable trusses because they permit efficient packaging of a member and have a linkage mechanism that can carry significant axial load in both tension and compression in the deployed position. The test joint shown is a mid-length diagonal hinge for the 20-meter deployable beam that is a ground test article for COFS 1. The total test member is representative of the diagonal in that the end fittings are the same as the ones used in the beam. The length of the graphite tube has obviously been reduced to accommodate the test article in a conventional hydraulic test machine. The test joint is fairly large and more massive than would be desired for a flight test beam. This is due to the overall beam design which used the same joint to serve in two diagonal applications with slightly different hinge orientations instead of designing and fabricating a special joint for each location. Also, no significant effort was made to minimize the total joint mass.

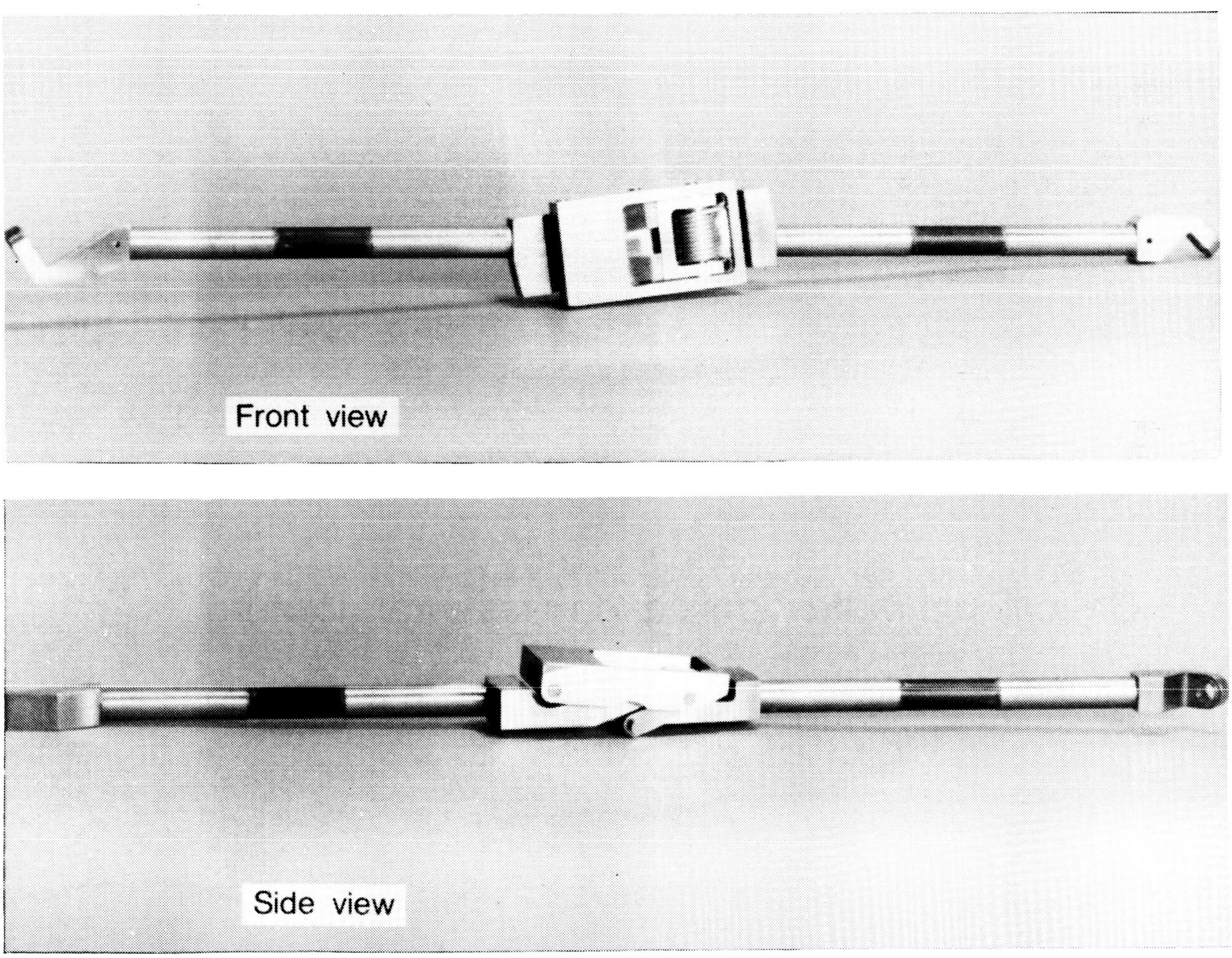


Figure 8

NEAR-CENTER LATCH JOINT

DESIGN ASPECTS

The primary design considerations for the near-center latch joint are outlined in figure 9. The parent metallic material is titanium with four hardened steel pins being used at the linkage and body hinge points. All pin holes were accurately positioned and the critical pin holes (i.e., the ones that control the closure position of the linkage mechanism) and the hinge pin hole were drilled with the parts assembled. All holes and pin diameters were sized to an accuracy of 0.0001 inch, and the assembled parts had between 0 and 0.0002 inches of interference fit. The linkage system was designed so that no member was in bending. The preload in the joint is controlled by the position of the linkage and the torsion load applied by the closure spring. The configuration was designed to have a preload in excess of 80 pounds, however, the response is very nonlinear in the closed position and the actual preload value has not been determined. Considerable effort went into the design of the joint so that a predictable and repeatable response could be obtained for a large number of units.

- Parent joint material-titanium, pin material-steel
- Linkage members in load path take only axial load
- All pins and holes have light interference fits
- Critical pin holes drilled on assembly fixture
- Interior preload of 80 + lbs

Figure 9

RESPONSE OF NEAR-CENTER LATCH JOINT

The load deflection response for the near-center latch joint is shown in figure 10. The deflections indicated in the figure were measured along an 8-inch section which included the latch only. As indicated by the symbols, data were taken at discrete values of applied load rather than continuously during the load cycle. The data points are shown connected by a faired dashed line. The response is linear over the entire 160 pound load range, indicating a preload in excess of 80 pounds. The joint has a stiffness of approximately 3.3×10^5 lbs/in. This is about the same stiffness as an 8-inch length of the graphite-epoxy tube to which the joint is attached. Although the joint is massive, its efficiency is still high in comparison with the results presented earlier for the pin-clevis joint.

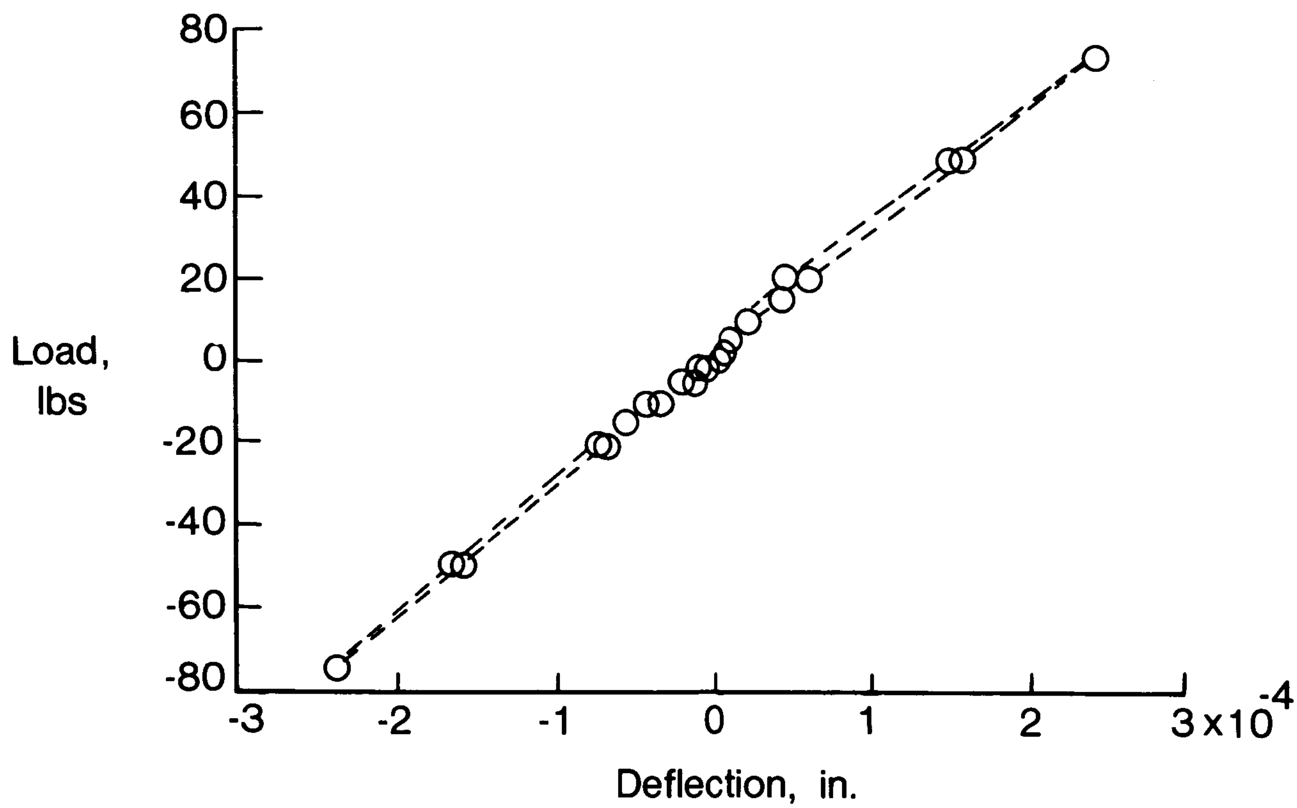


Figure 10

RESPONSE OF MEMBER WITH NEAR-CENTER LATCH JOINT

The member with the near-center latch was instrumented to evaluate the total displacement as well as the displacement across the latch shown in the previous figure. The total displacement, including that of the end attachment, is shown in figure 11. The data points on the plot were taken at the same discrete loads as those in figure 10. Also shown on figure 11, for comparison, is the curve for the latch only from the previous figure. The data shown in figure 11 are for one tension-compression cycle from the results of a three-cycle test and the data do not pass through the origin. The tension load cycle indicates a decrease in slope at a load around 20 pounds. It is suspected that this decrease in slope is due to sliding of the end tangs along their support mounting pins. Therefore, the truss member stiffness is represented by the unloading parts of the cycle. It is also apparent from the figure 12 results that the stiffness of the latch is significantly higher than the stiffness of the total member. The lower member stiffness must therefore result from bending of the end tangs. This demonstrates the significance of bending deformations in the design of high stiffness structures and the need to eliminate bending in members and connections in the load path whenever possible. However, this cannot always be accomplished. For example, the angle of the end tangs and orientation of the pivot angles for this beam were determined from a kinematic and structural analysis to minimize the internal member loads during deployment and retraction.

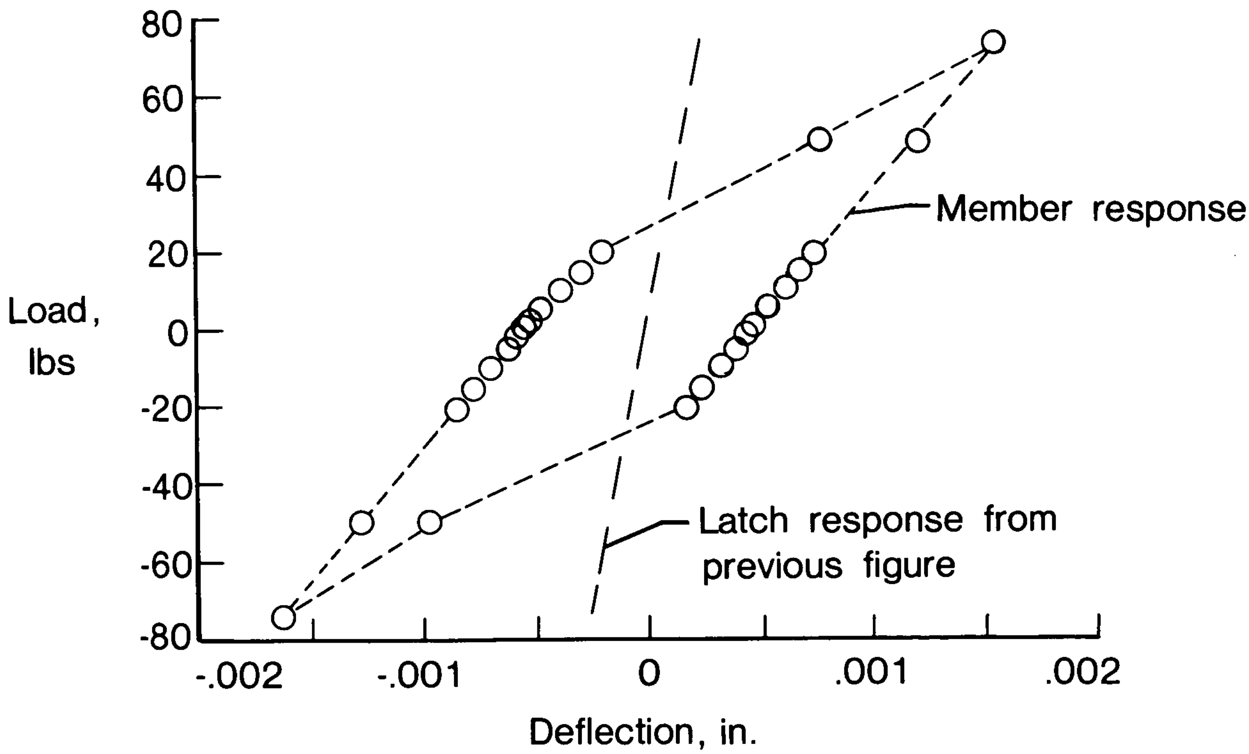


Figure 11

SUMMARY

The experimental results presented have indicated the importance of attention to detail in the design and fabrication of joints for deployable truss structures. The dimensional relations and material considerations for efficient pin-clevis joints have been outlined. The results of tests on the near-center latch indicate that joint complexity does not necessarily sacrifice stiffness. However, the test joint was fairly massive. This is undesirable for dynamic considerations, especially if the joint is in the center of a long member. Bending causes low axial stiffness and must be eliminated in the member and connecting joint if at all possible for the high axial and torsional stiffness of the truss structure to be realized.

Design recommendations formulated for pin-clevis joints

Linear load-displacement can be obtained in complex joints

Bending must be eliminated to realize attributes of well designed and fabricated joint

Figure 12

REFERENCES

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