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STRUCTURAL ATTACHMENTS FOR LARGE SPACE STRUCTURES

CONTRACT NAS8–33599

OCTOBER 15, 1980

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HUNTSVILLE FACILITY • 3322 Memorial Parkway South, Huntsville, Alabama 35801 •

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FOR
LARGE SPACE STRUCTURES

Contract NAS8-33599

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Marshall Space Flight Center, Alabama 35812

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FOREWORD

This final report presents the results of a 13 month study performed by Essex Corporation for NASA's George C. Marshall Space Flight Center (MSFC) under contract NAS8-33599. The original contract required the design and fabrication of several crew-installed joints for use with beams fabricated by the automated beam builder (ABB). The contract was modified to include the design and fabrication of more joints and additional test support hardware, including a beam builder mockup, crew restraints, and a beam support structure.

The support and guidance provided by Mr. Eric Engler (EP13), the contract COR, Mr. Jack Stokes (EL15), and Mr. Steve Hall (PD24) are gratefully acknowledged. Their interest in the project resulted in a healthy and frequent exchange of ideas and a thorough evaluation of proposed designs throughout the project. Their contributions are greatly appreciated as are those of the neutral buoyancy test personnel, including test subjects and utility divers.

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1.0 INTRODUCTION

1.1 BACKGROUND

The identification of payloads that require large mounting surfaces or longer on-orbit times than can be provided by the shuttle have prompted NASA to investigate several concepts for large space structures (LSSs). These structures have been generally classified as erectables and deployables with the erectable structures assembled on-orbit with individual columns or beams, and the deployable structures deployed like an umbrella or folding cot. A third type of structure could be assembled using beams fabricated for very large structures where the high packing density of the beam raw materials could reduce the number (and cost) of shuttle flights from that required for erectable and deployable structures of the same size.

To investigate the feasibility of fabricating beams in space and using these beams as components of a large, crew-assembled structure, MSFC funded two efforts as briefly described below:

- Contract with Grumman: To design and develop a ground version of an automated beam builder (ABB) capable of producing triangular cross-section aluminum beams approximately 1 m on each side.
- Contract with Martin Marietta: To design and fabricate lap joints for connecting the beams orthogonally and centroidal end caps for connecting the beams end-to-end at any desired angle.

The first contract produced a beam building machine capable of fabricating aluminum beams suitable for neutral buoyancy evaluation in whatever length and quantity needed for testing. The Martin Marietta contract resulted in concepts for the lap joint and end cap. However, neither of these joint concepts was suitable for use by a pressure-suited crew member in a zero-gravity environment. Therefore, before the beams could be evaluated in the MSFC Neutral Buoyancy Simulator, the joint designs needed to be completed and sufficient joints produced to allow assembly of a complex structure.

1.2 SCOPE

The purpose of Essex' original contract was to (1) design a lap joint and end cap suitable for one hand operation by a crew member, (2) fabricate five lap joints and nine end caps, and (3) make design changes as a result of 1-G and N/B evaluations of the joints.

The contract was later modified to include a requirement for one additional lap joint and two additional end caps, a mockup of the ABB, beam supports and crew restraints including foot restraints and hand rails.

2.0 TASK DESCRIPTIONS

The following paragraphs describe the tasks performed by Essex during the original contract and the two modifications.

2.1 ORIGINAL CONTRACT

Three tasks were performed to develop the two types of beam joints. These tasks are briefly described below in terms of the major task activities and task outputs. Figure 2-1 illustrates the contract tasks and the review and testing activities.

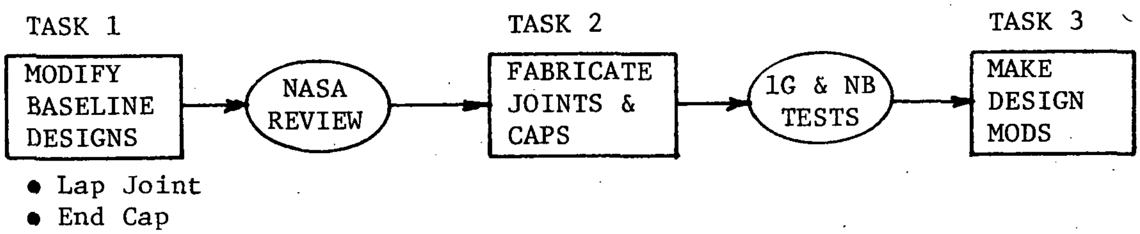

Figure 2-1: Task Flow Diagram

During Task 1 the Martin report, Structural Attachments for Large Space Structures, was reviewed to determine the preliminary concept design for the lap joints and end caps. The fabricated beams were also examined to identify the potential interfaces for new joint concepts. Based on the beam design, existing joint designs, and design goals of installation by one crew member, several concepts for the two types of joints were developed. These concepts were then presented to the COR for review. When the designs for the end cap and lap joints were selected, the detailed designs were completed, and fabrication drawings were prepared.

During Task 2, several local fabrication shops were selected to fabricate the components for the lap joints and end caps.

In Task 3, after a neutral buoyancy evaluation by NASA, Essex modified the design for the lap joints. The end cap design was acceptable without modification.

2.2 MODIFICATION S/A 2

In this contract modification, one additional lap joint and two additional end caps were required. This change occurred early enough in the effort that all joints were fabricated at the same time.

2.3 MODIFICATION CO #3

This modification required the design and fabrication of a low fidelity mockup of the ABB, crew restraints, and beam support equipment for the NB-19 test series. This equipment is described in Sections 4.0, 5.0 and 6.0.

3.0 JOINT DESIGNS

The two major outputs of this effort are the lap joints and end caps. These are described in the following paragraphs. The other hardware items were developed to support the neutral buoyancy tests and are described in later sections.

3.1 LAP JOINTS

3.1.1 Design Description

The lap joints were designed to orthogonally connect two triangular cross section beams as shown in Figure 3-1. This joint can be used to join two beams at the beam ends (as shown) or toward the center of the beams.

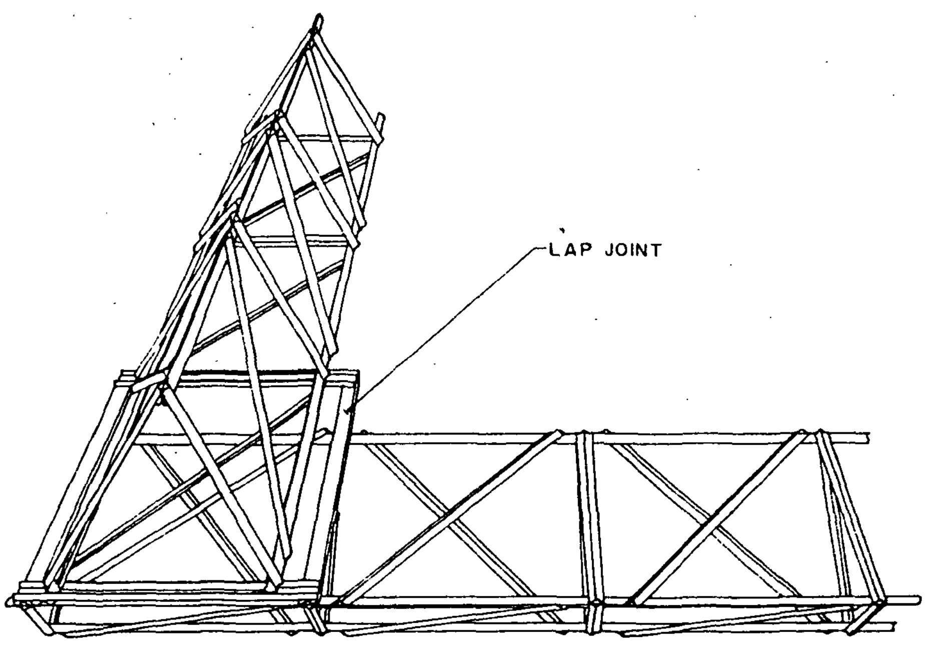

Figure 3-1: Lap Joint and Beam Configuration

The basic lap joint structure consists of four U-shaped channels welded into a box frame. Two stainless steel springs are located near the center of each U-channel to initially capture the beam cross member. Alignment/indexing guides are located near the ends of the U-channel to position the beam within the channel. Eight crew operated, over-center latches (two per side) are located within the channel to secure the beams' cross members. The lap joint and its various components are shown in Figures 3-2 and 3-3. Figures 3-4 and 3-5 show the lap joint latch during a pre-test demonstration and during testing.

Essex drawing 796401 shows the final configuration of the six lap joints.

3.1.2 Test Results

The NB-19 test series which started August 11, 1980 was performed in two phases. Phase 1 provided an evaluation of the hardware and crew operations associated with installation of end caps and lap joints onto a beam as it exits the beam machine. Phase 2 provided an evaluation of crew assembly of a nine-element structure after installation of the beam joints. The tests indicated the need for several design changes to the lap joint components that would produce a stronger, more reliable and more easily installed joint. These changes are minor in nature and do not affect the basic joint design or crew operations. The problems prompting these design changes are briefly described below.

Latch Hook - The lap joint latch locking lever was designed to be lifted 90° from the latch position to locate the latch hook in the fully open position. During the test, the subjects had difficulty determining the position of the locking lever and occasionally rotated the lever 180° which would bend or break the hook. Lack of friction between the latch hook, lever, locking arm, and hinge also made the task more difficult. The proposed solutions to these problems are to use thicker stock for the latch hook and to mount friction producing washers on the dowel pins holding the latch parts together.

Alignment Guide - The alignment guides were difficult for the subjects to see and were occasionally damaged by the beam cross piece during beam insertion. The proposed solution to this problem is to provide two guides for each cross piece that simultaneously align the beam from both sides and are more visible to the crew.

After the N/B tests, the fabricated beam structure was assembled in a 1-g setting in preparation for a demonstration at Langley Research Center (LaRC). It was then discovered that the lap joints and end caps, when assembled into the nine-element structure, caused several of the beams to warp and several of the beam cross pieces to buckle. The stresses in the cell were thought to be caused by the end cap tripods being too long. However, on review of the Essex lap joint and end cap drawings, and the configuration drawings provided by EP13, it was determined that the end caps and lap joints were fabricated correctly but that the lap joint cross piece alignment guides were located improperly. The alignment guides were positioned such that the outside edge of the lap joint was even with the end of the cross piece. This made crew installation of the lap joint easier than if the lap joint had been offset as indicated by the EP13 configuration drawing.

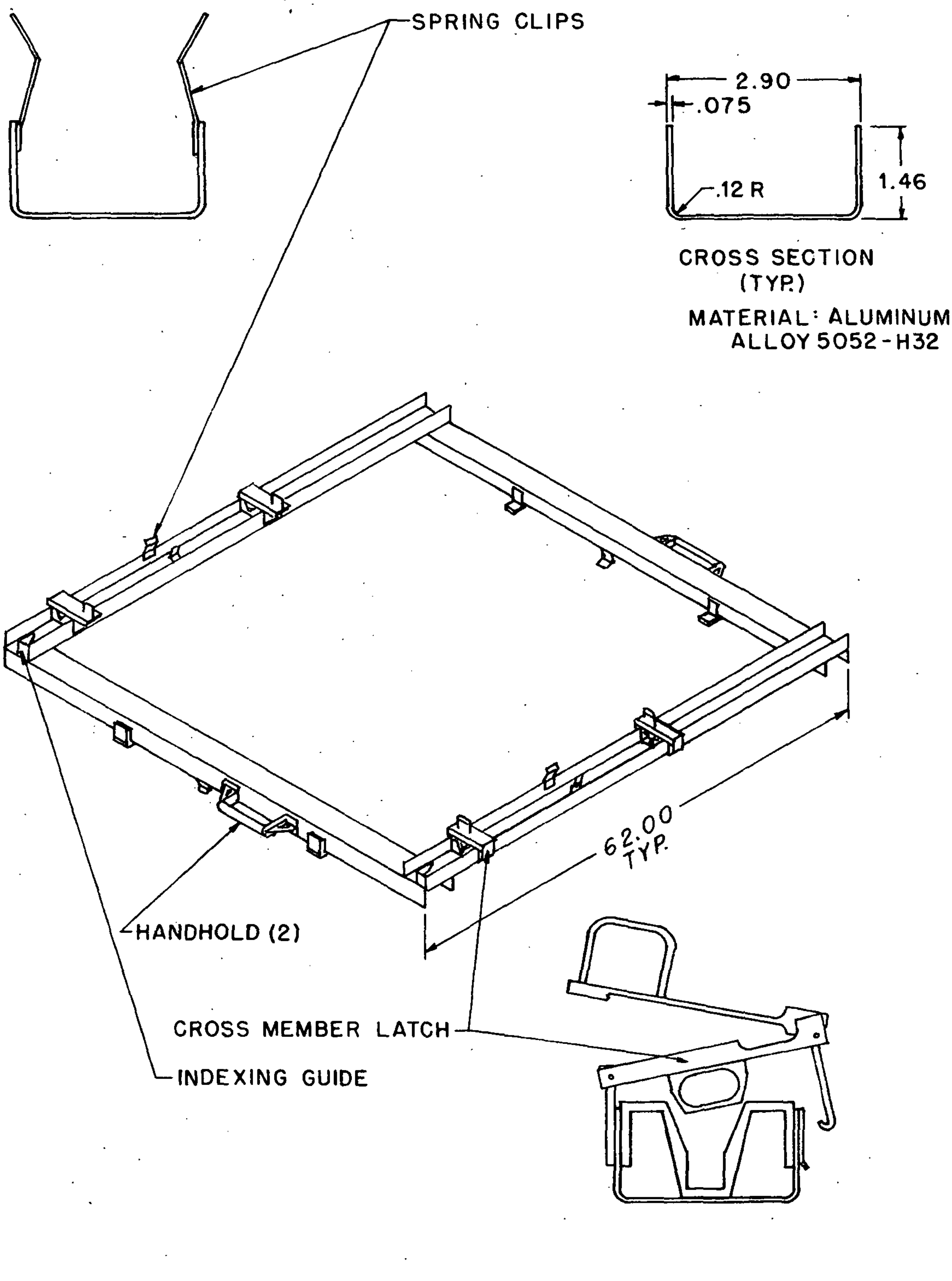

Figure 3-2: Lap Joint and Components

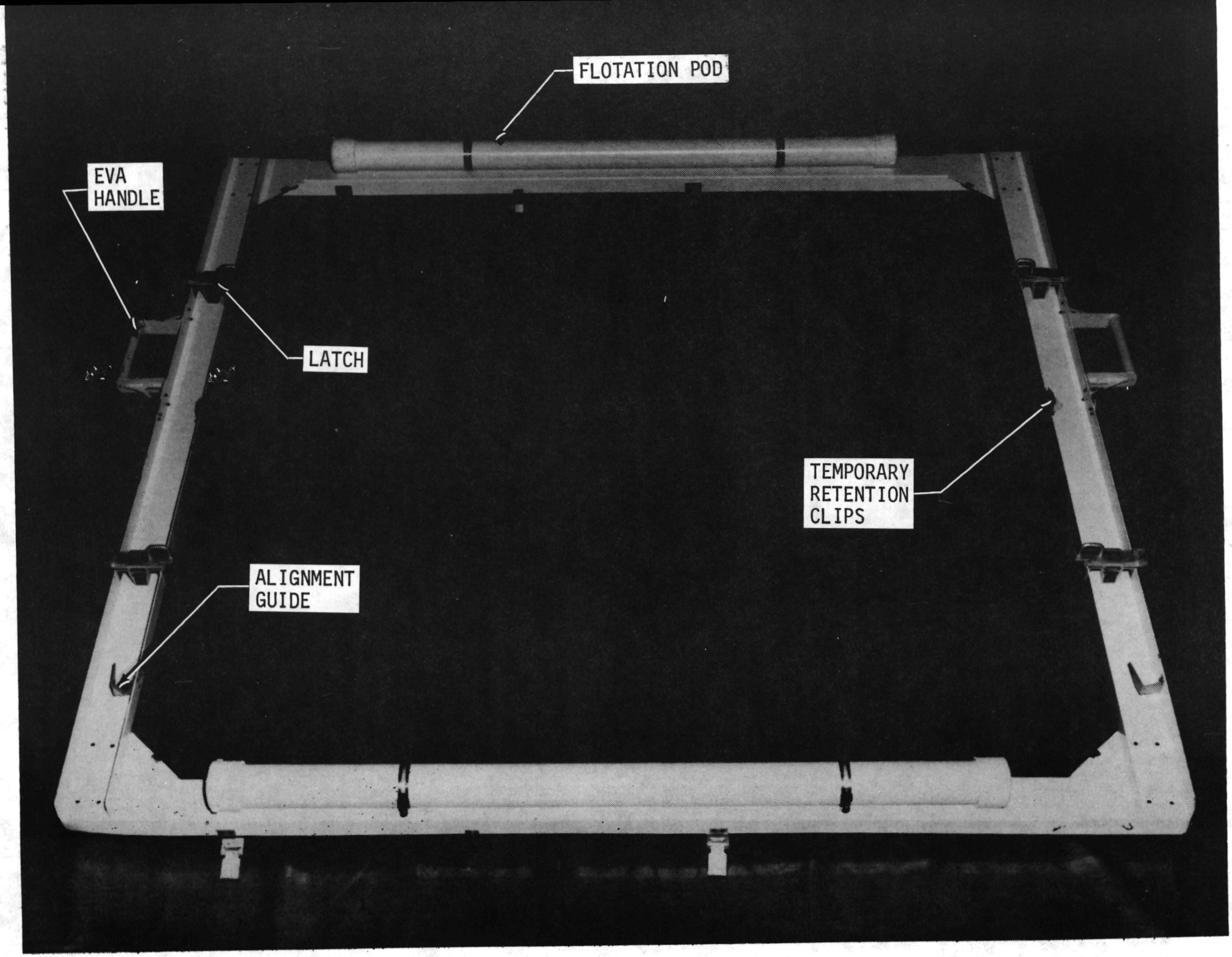

Figure 3-3: Lap Joint Photograph

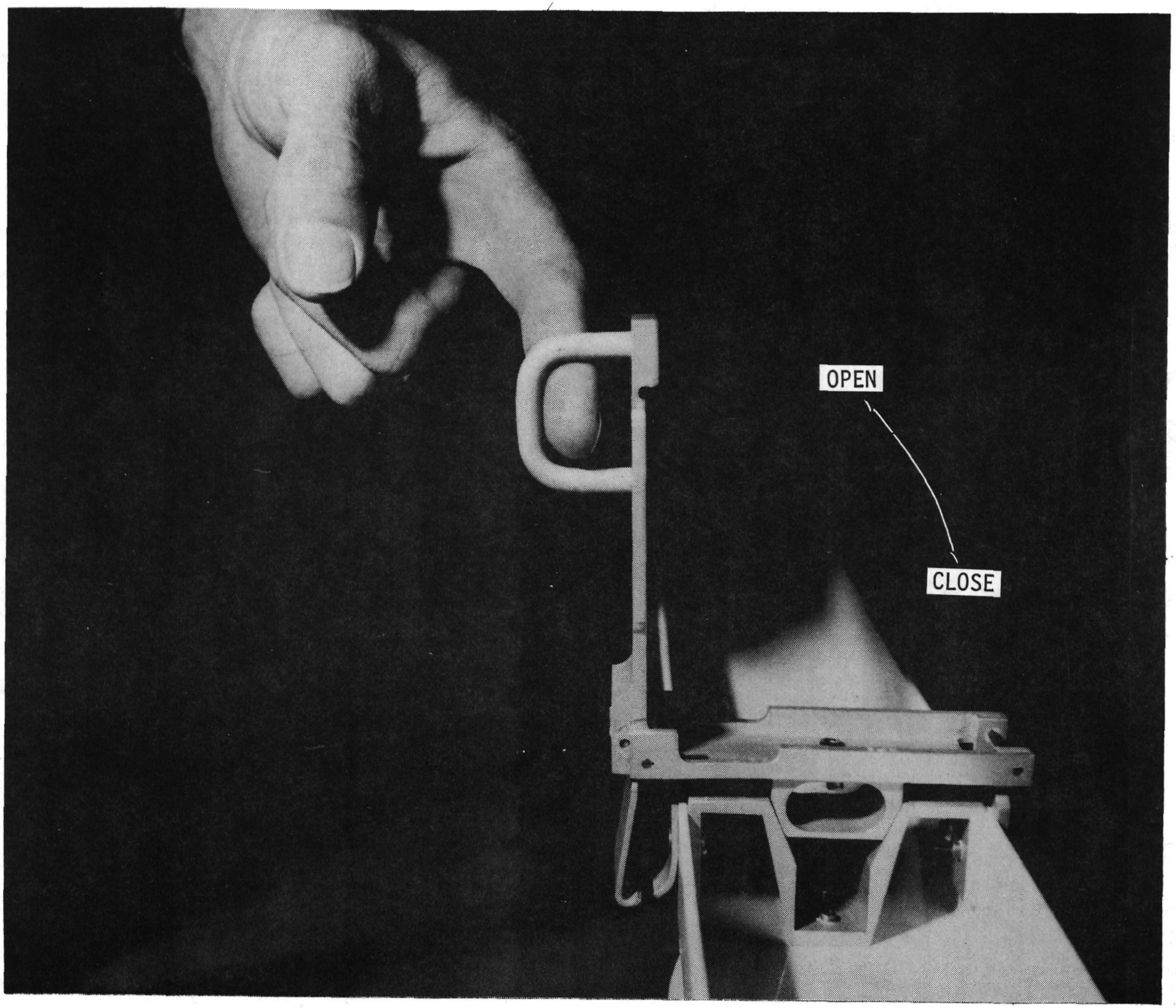

Figure 3-4: Lap Joint During Demonstration

Figure 3-5: Lap Joint During Test

To correct this problem, the outside alignment guide should be removed or offset approximately 4.0 in. and the inside guide should be moved approximately 4.0 in. towards the outer end of the lap joint.

3.1.3 Proposed Modifications

The lap joint drawings have been red-lined and presented to the COR to illustrate the proposed design changes. These changes are briefly described below.

Latch Design - Belleville washers (.093 in. ID, .187 in. OD stainless steel) should be inserted on the latch dowel pins to add friction to all moving parts. Additionally, the latch hook should be modified per Figure 3-6.

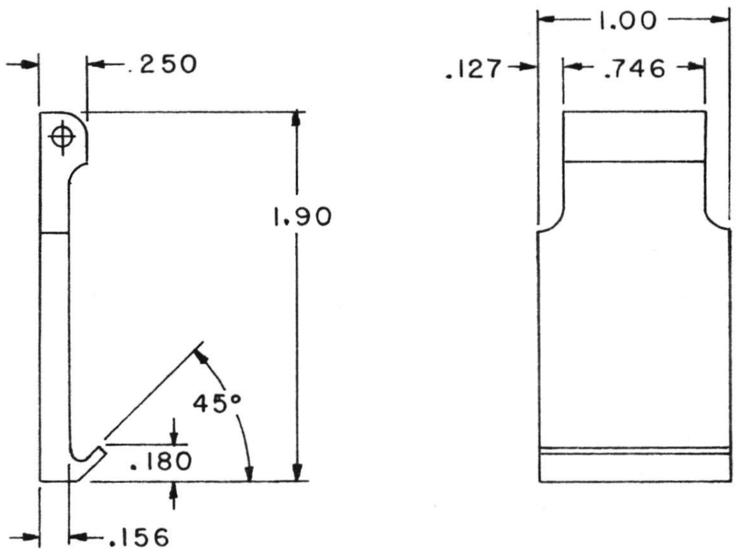

Figure 3-6: Proposed Latch Hook Design

Alignment Guides - Two alignment guides should be used for the outer cross piece only. The proposed new design is illustrated in Figure 3-7.

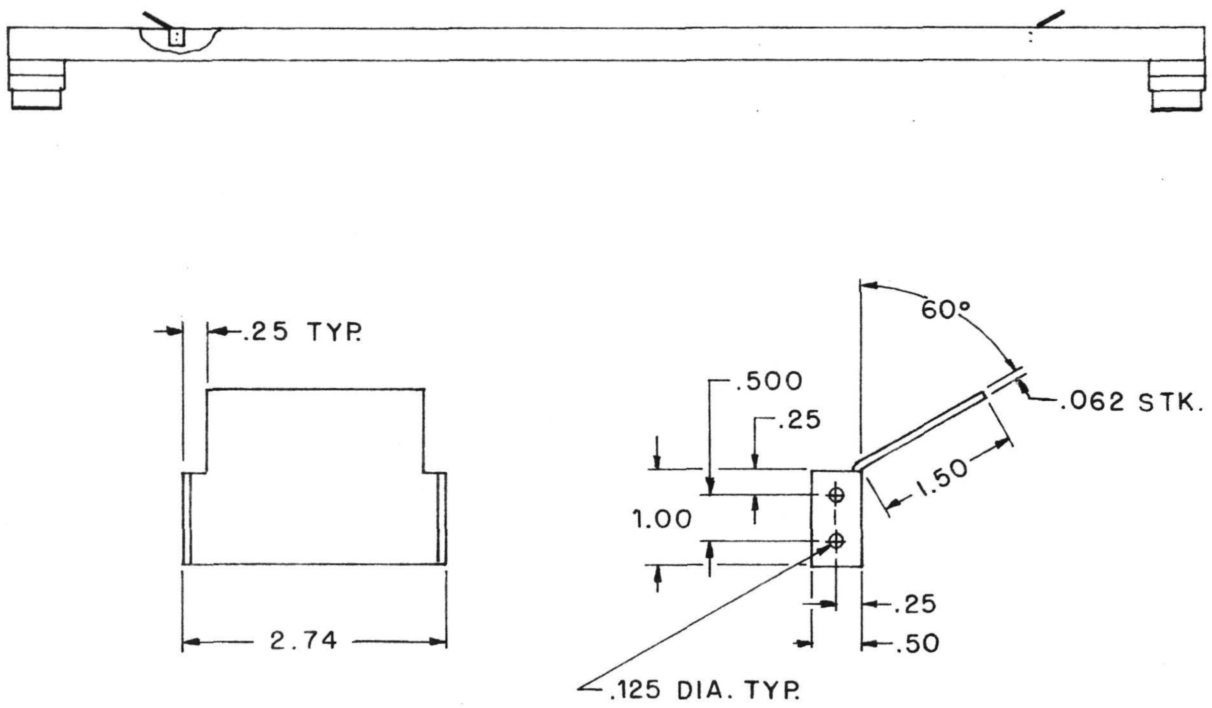

Figure 3-7: Proposed Alignment Guide Design

3.2 END CAPS

3.2.1 Design Description

The end caps were designed to attach to the end of the beam and to permit attachment of several beams using a Rockwell ball and socket joint. Figure 3-8 shows the final end cap design. Figure 3-9 shows a typical use of the end caps in connecting three beams at a central socket joint.

The end cap is stowed in a folded configuration (Figure 3-10) to conserve space and increase packing density. The crewman extends the slide down the center slider bar to extend the three tripod legs with the three spreader bars. Friction between the slide and slider bar holds the tripod in the deployed position until it is inserted in the beam end. Once the tripod is deployed, the end fitting inserts are slid into the beam longeron ends and the over-center latches are secured (Figure 3-11). Each latch has a beryllium-copper spring which holds the locking lever in the locked position to provide a positive latch in addition to the over-center feature. Figure 3-12 shows the end fitting inserted in the beam during the neutral buoyancy test. Essex drawing number 796402 presents the complete as-built design.

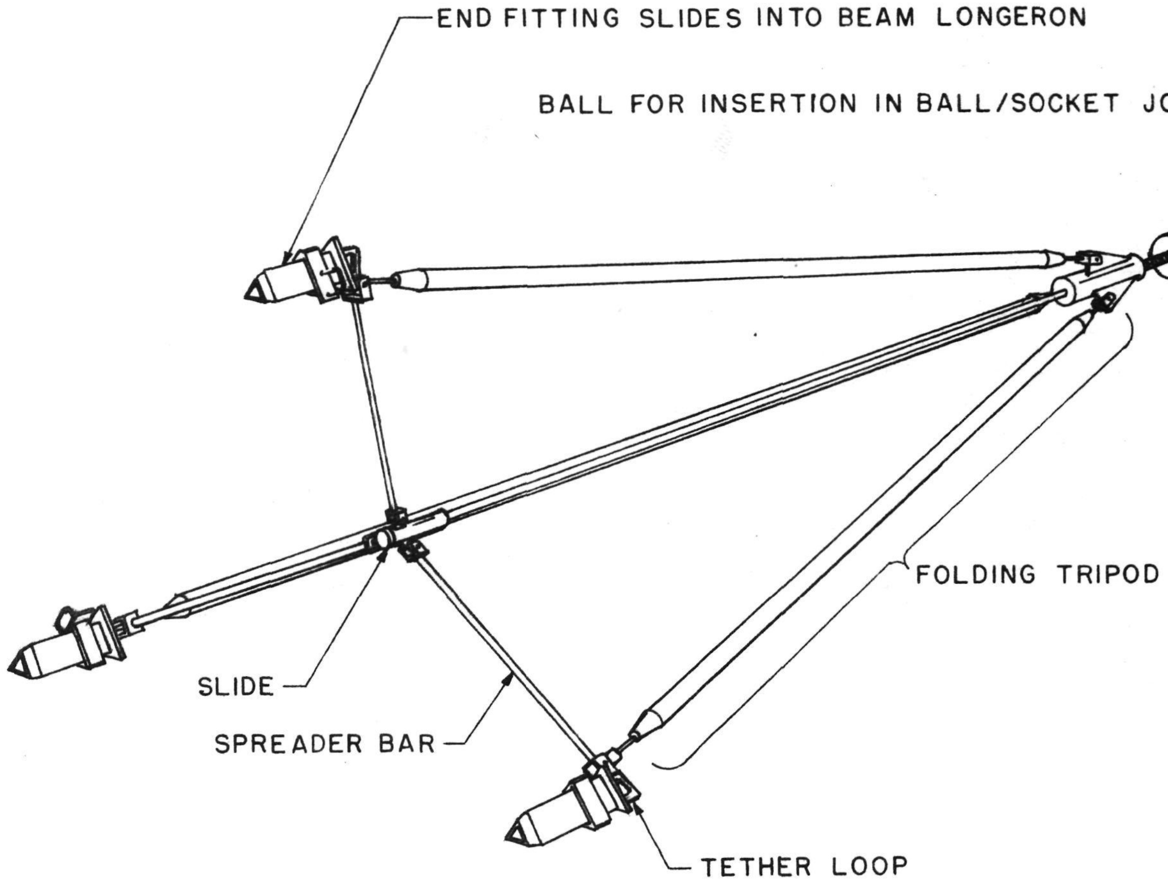

Figure 3-8: End Cap Design

3.2.2 Test Results

The NB-19 test series indicated no major problems with the end cap that required changes to the design. However, before the test started, it was discovered that the tabs on the tripod slide were too short and not sufficiently stong to handle the loads imposed during 1-G handling. These were replaced with longer tabs having more weld surface. This apparently solved the problem. A positive spring lock on the tripod slider bar would have been useful to hold the slide in place during end fitting installation, although no major problem was encountered in tripod deployment and handling.

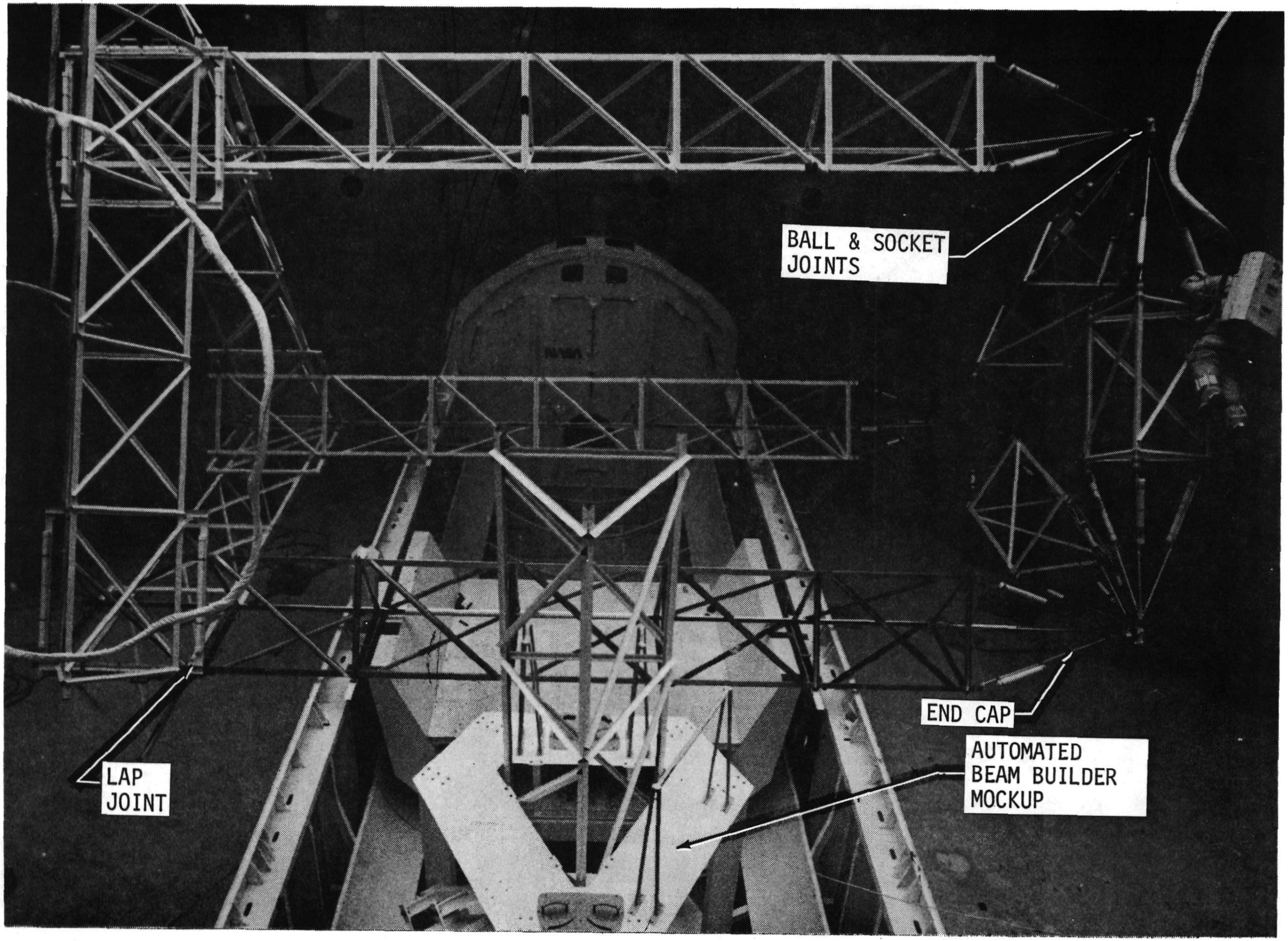

Figure 3-9: Use of End Caps and Lap Joints

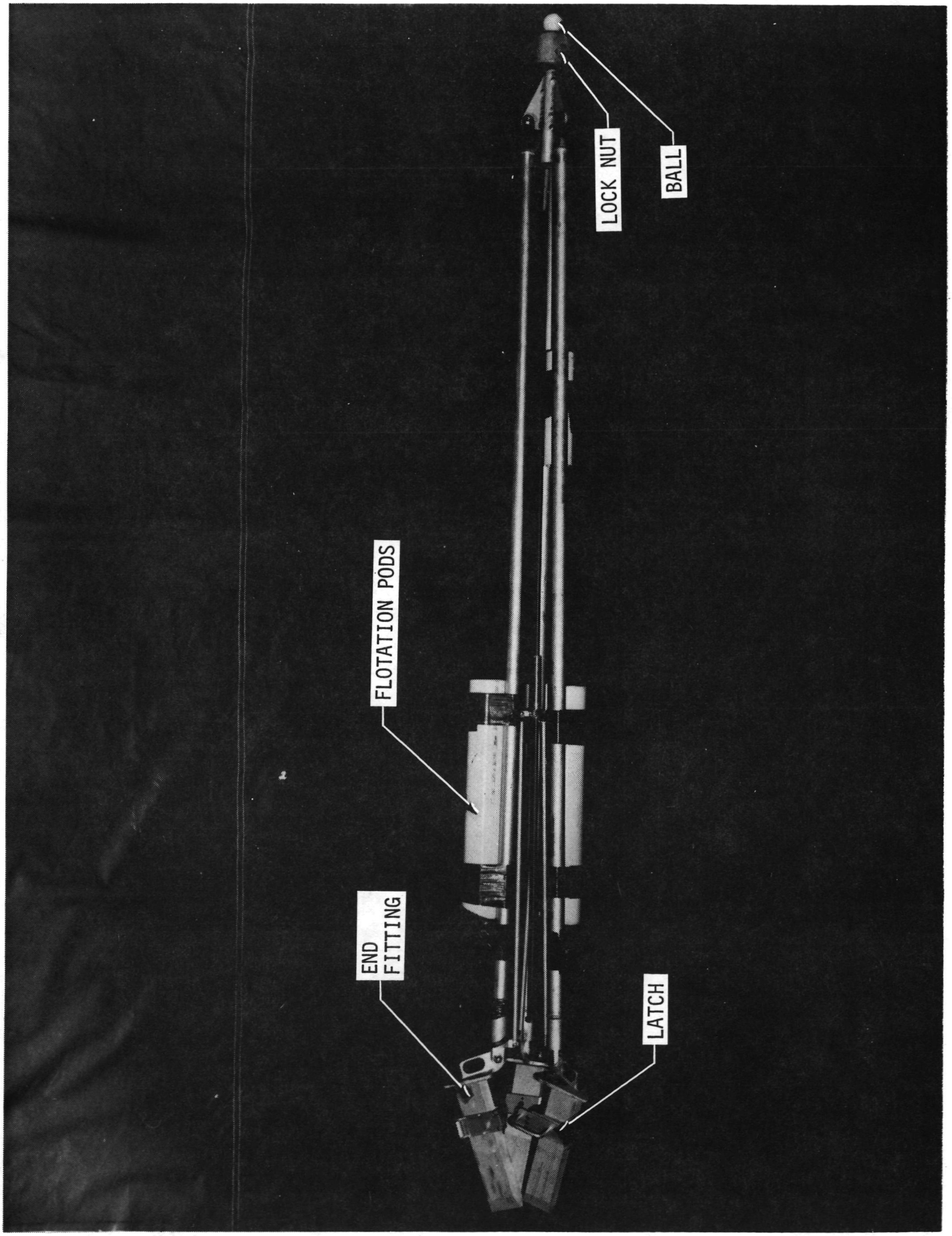

Figure 3-10: End Cap in Folded Configuration

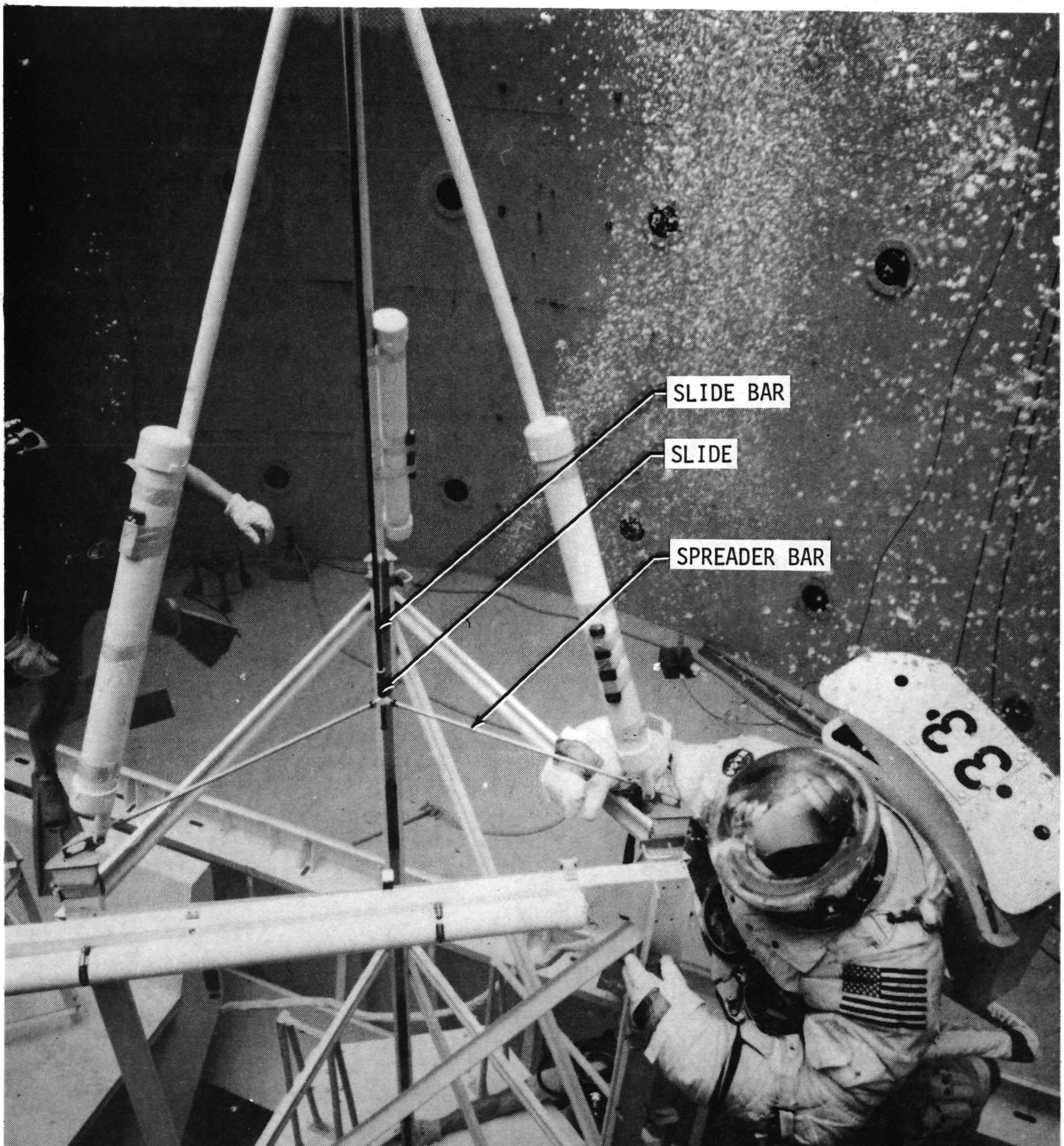

Figure 3-11: End Cap Installed in Beam End

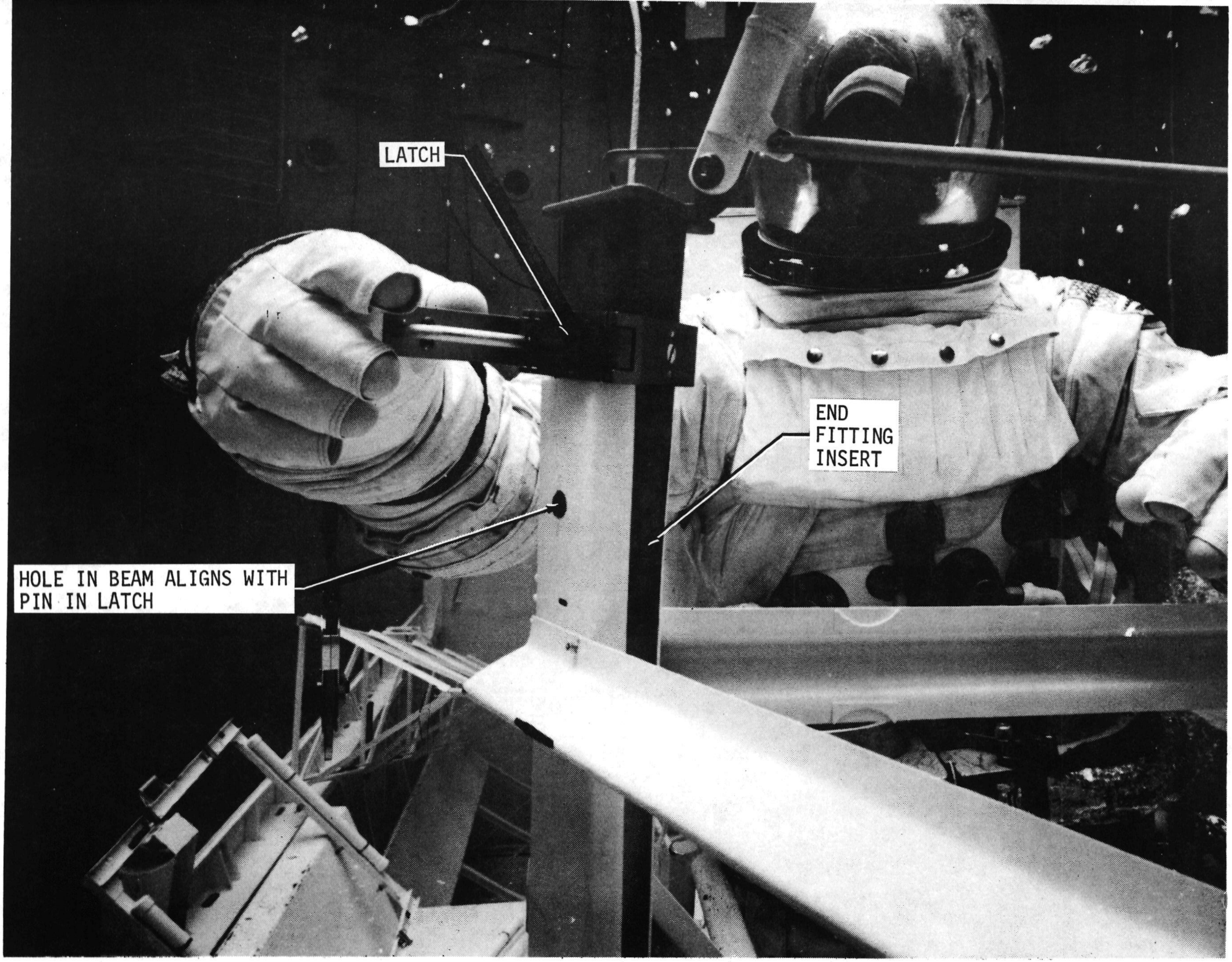

Figure 3-12: End Fitting Attachment to Beam Longeron

3.2.3 Proposed Modifications

No design modifications are proposed other than those described for the slider bar spring mentioned above. However, the 11 end caps fabricated and tested were intended for use in a test situation where minor hardware adjustments might be advantageous to accommodate warped beams, misaligned support fixtures, etc. For this reason, the tripod structure contains several adjustable length members. A flight type tripod design should have fixed length members with little or no adjustment and close tolerance clevis fittings. Also, the ball is attached with a screw with approximately four inches of adjustment capability. For flight hardware, this should be replaced with a more rigid, fixed length member.

4.0 AUTOMATED BEAM BUILDER

The automated beam builder (ABB) was developed to be used during Phase 1 of NB-19. During this exercise, the crewmembers mounted end caps and lap joints on the fabricated beam as it was fabricated by the beam builder. Figure 4-1 shows the ABB mockup. The mockup represents the envlope of the basic ABB with the diagonal brace stowage cartridges and rolls of longeron stock. The smaller ABB protuberances were not included since they were not expected to affect crew operations.

The mockup is fabricated from 6061-T6 aluminum in thicknesses of 1/8, 3/16 and 1/4 inch and consists of small weldments bolted together to facilitate use of the forward part of the mockup on the KC-135 if required for the evaluation of lap joints and end caps.

Essex drawing number 796403 shows the dimensions, fasteners, and finish specifications in detail.

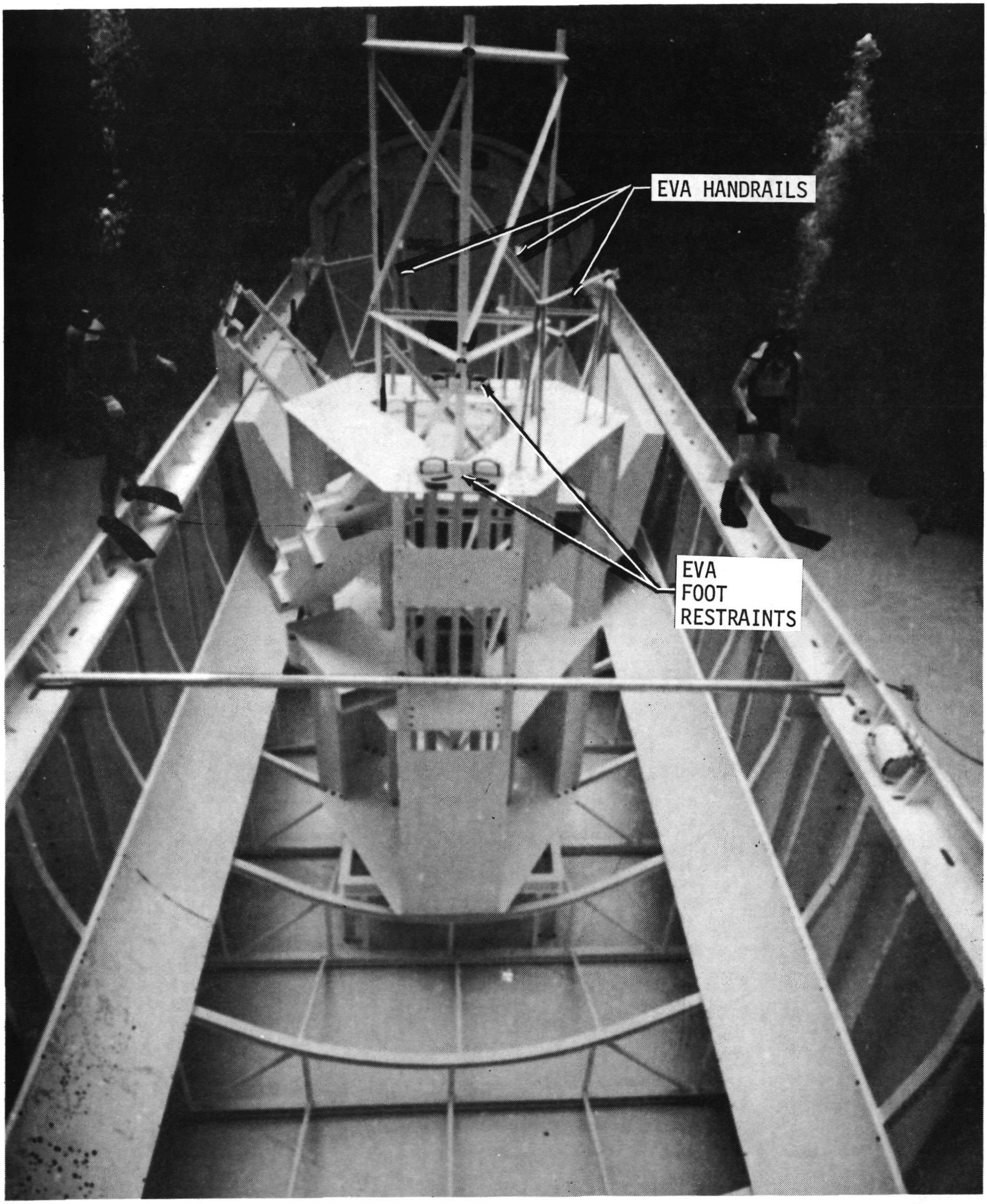

Figure 4-1: Automated Beam Builder Mockup

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5.0 CREW RESTRAINTS

Crew restraints were required for the ABB mockup forward bulkhead to aid the crew in joint installation tasks. To enhance crew mobility and restraint and to prevent damage to the pressure suit by the longeron, Essex provided handrails around the periphery of the mockup at waist height, and foot restraints at two locations on the mockup forward end. These handrails and foot restraints are shown in Figure 4-1. The handrails have the standard EVA cross section specified in MSFC-STD-512A (1.25 x .75 in.). The foot restraints are configured for the A7LB suit but can be modified to be compatible with the new extravehicular mobility unit (EMU) boot when the new suits are available.

The quick-look test report for NB-19 (Appendix B) describes how these crew aids were used during NB-19, Phases A and B.

6.0 BEAM SUPPORT STRUCTURE

A structure was required to hold the fabricated beams to the cargo bay sill during the assembly process in Phases 1 and 2. To accomplish this, Essex developed eight hold down supports, each consisting of a U-channel and a center-mounted latch (Figure 6-1). The U-channel had the same cross section and length as the lap joint frame member. Also, the center-mounted latch had the same configuration as the latches used on the lap joints. During Phase 2, three of the hold down supports were mounted to aluminum channels that extended across the cargo bay (Figure 6-2). These same supports are available for beam support during Phase 3, if needed.

Figure 6-1: Beam Hold Down Support Latch

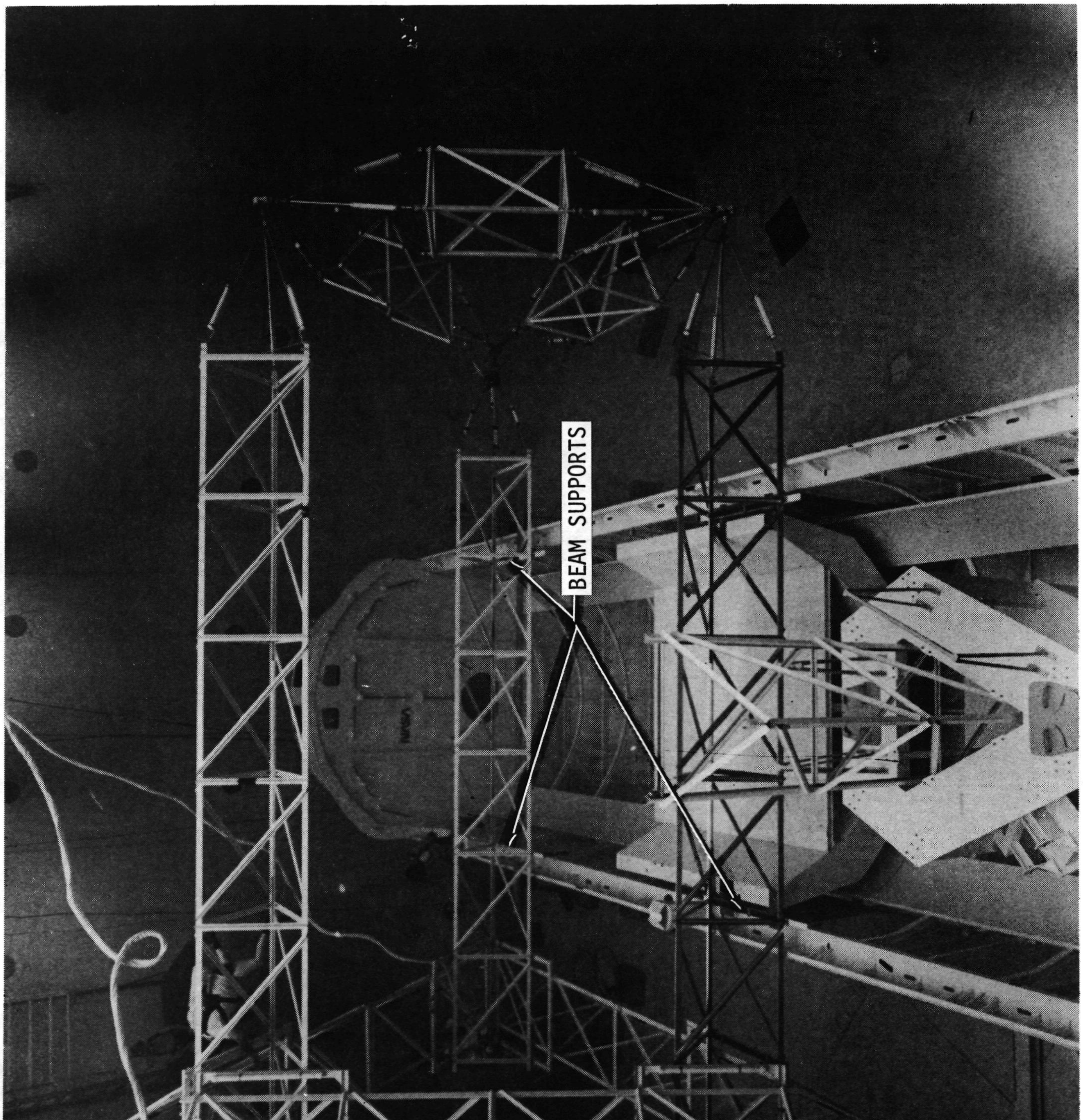

Figure 6-2: Beam Hold Down Supports

7.0 SUMMARY

The NB-19 Fabricated Beam Assembly Tests performed thus far have resulted in the following major contributions:

- The lap joints and end caps can be installed on the beams by a crew member at the ABB work station.
- The remote manipulator system (RMS) is required to support the beam after removal from the ABB for installation of the second end cap.
- Foot restraints and handrails at the ABB work station are adequate, but minor improvements could be made in their location.
- Minor design changes are needed for the lap joint latches and beam alignment guides.
- End cap adjustable length members should be fixed and tolerances on all clevis attachments should be tightened to reduce flex throughout the end cap.
- MMUs (2) and the RMS are essential for the assembly operations.

More lap joint and end cap design changes may result from the additional neutral buoyancy tests scheduled for November, 1980 and from any KC-135 zero-gravity tests performed later. However, based on these initial tests, it appears that the beam assembly task can be performed by two EVA crew members using MMUs and the RMS.

The test procedures and results are more thoroughly described in the Quick Look Test Report, NB-19: Fabricated Beam Assembly, available through MSFC/EL15 (Appendix B).

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APPENDIX A

A CURSORY ANALYSIS OF END CAP AND LAP JOINT STRENGTH CHARACTERISTICS

ANALYSIS OF STRENGTH CHARACTERISTICS

1.0 INTRODUCTION

A detailed analysis of the desired and actual strengths of the end caps and lap joints and their components was not required by the contract statement of work; nor was a strength analysis mentioned in the Essex proposal. However, several cursory calculations of the joints' components were performed to assure the designers that the joints would be sufficiently strong to withstand (1) normal handling, (2) latching operations, and (3) loads imposed by the structure after installation. These calculations are presented below along with various assumptions and engineering assessments.

2.0 END CAP STRESS CALCULATIONS

KNOWNS:

- BEAM MATERIAL: 2024-T3 Aluminum, Thickness = .016 inch
- PIN MATERIAL: 6061-T6 Aluminum, Diameter = .50 inch
- Two 0.50 in. holes with matching pins per beam longeron (6 holes/pins total per beam end)
- Friction pad surrounding pins reduces buckling.

ASSUMPTIONS:

- Tension and compression loads on the tripod ball end are shared equally by the six pins in the three beam longeron ends.
- A tension or compression load on the ball end results in only tension or compression at the pin interfaces. Lateral loads are not produced at the pins because of the rigidity of the deployed tripod and the fact that the end fittings are fixed on the tripod legs.
- The pin/beam hole interfaces are the system's weak point. Strength calculations for the end cap are not provided.
- Stress calculations for multiple rivet joints do not apply because of distance between pins.
- Force provided by friction pads is negligible.

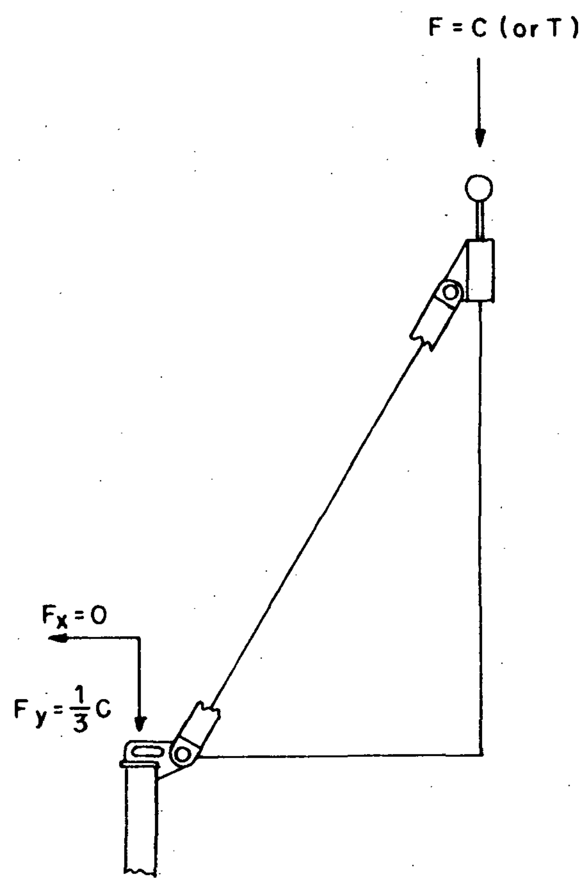

Figure 1: End Cap Compression Force Diagram

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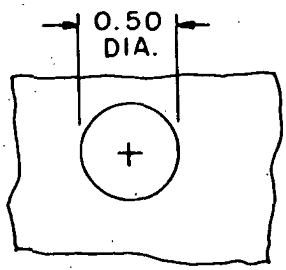
SHEAR STRENGTH OF BEAM MATERIAL



2024-T3:

$Y = 50{,}000 \text{ lbs/in}^2$

$t = .016 \text{ in.}$

$$\text{Projected X-Section Area } (A_P) = .50\ (.016) = .008 \text{ in}^2$$

$$YS_{(1\ \text{Hole})} = A_P\ (Y)$$

$$= .008 \text{ in}^2\ (50{,}000\ \frac{\text{lbs}}{\text{in}^2})$$

$$= 400 \text{ lbs} \quad \text{(per hole)}$$

$$YS_{(2\ \text{holes})} = 2\ (YS_1)$$

$$= 400\ (2)$$

$$= 800 \text{ lbs} \quad \text{(per end fitting)}$$

$$YS_{(6\ \text{holes})} = 3\ (YS_2)$$

$$= 3\ (800)$$

$$= 2400 \text{ lbs (per end cap)}$$

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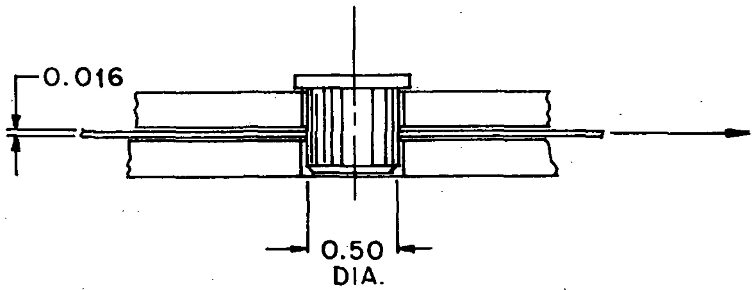
SHEAR STRENGTH OF PIN

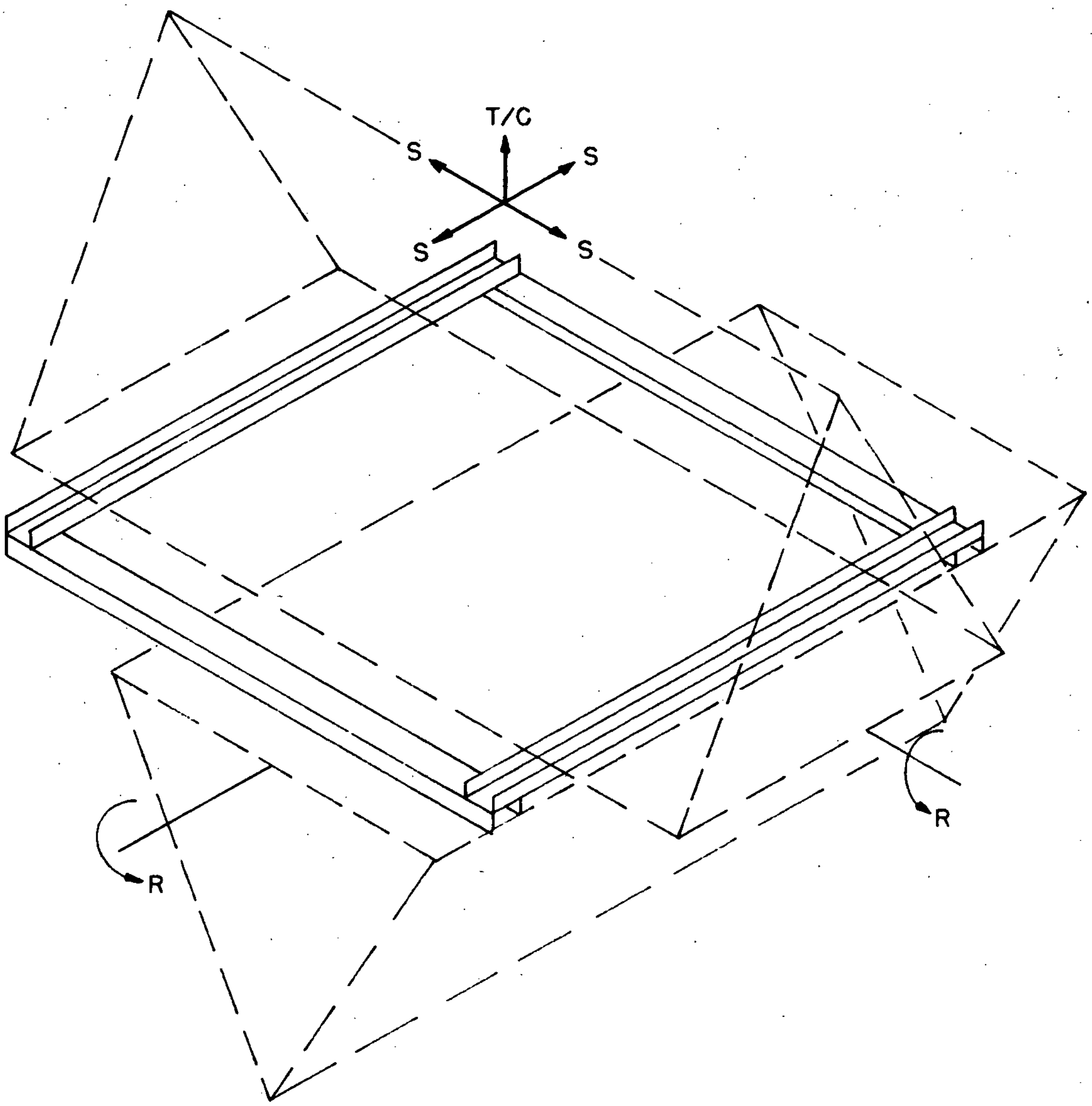


$R = \text{Area}\ (S_s) = \pi R^2\ (S_s) = \frac{\pi d^2}{4} S_s$

$R = \frac{\pi(.50\ \text{in})^2}{4}\ 40{,}000\ \text{lbs/in}^2$

R = 7857 lbs (Each pin will take this load before shearing!)

3.0 LAP JOINT STRESS CALCULATIONS



KNOWNS:

- Latch Material: 6061-T6 Aluminum
- Rivet Material: Stainless Steel

ASSUMPTIONS:

- Assume one beam stable and the other provides tension, compression, shear and torque to the lap joint latches (4).

ASSUMPTIONS (Continued):

- Assume all forces are resolved through the four latches.
- Assume basic frame is strong enough to support all loads w/o deflection or damage.
- Assume weakest parts of latch are the (1) hasp, (2) hasp dowel pin, and (3) rivets.

1. TENSION

- Assume T resolved equally by 4 latches.
- L = safe tensile load = nA_xS

A_x = cross section area of material

n = number of units (rivets, hasps, etc.) sharing load

S = allowable stress (shear or tensile)

(a) HASP

$n = 4$

$A_x = .746$ in (.062 in)

$S_T = 37{,}000$ (Yield)

$L = nA_xS_T$

$L = 4\ (.046252\ in^2)\ (37{,}000\ lbs/in^2)$

$L = 6845$ lbs

(b) HASP DOWEL PIN

$D = .09375$ in

QTY = 4 (1 per patch)

MAT'L = 303 Stainless Steel

$S_T = 90{,}000\ lbs/in^2$

$S_S = 50{,}000\ lbs/in^2$ (assumed)

$L = nA_xS_S = 4\pi R^2S_S = \pi D^2S_S = \pi\ (.09374\ in)^2\ [50{,}000\ lbs/in^2]$

$L = 1381$ lbs

(c) RIVETS (2 per hasp plus 2 per latch = 4 = 16 per 4 latches)

$$L = nA_xS$$
$$= 16\left(\frac{\pi(.161)^2}{4}\right)(50{,}000)$$
$$= 16{,}293$$

2. COMPRESSION

- Not considered a problem.

3. SHEAR (LONGITUDINAL)

- The lap joint latches are sufficiently strong to withstand loads in this direction. The expected failure modes would be (a) shear of the beam cross pieces (2 at 4 latch/beam interfaces) or, more likely (b) destruction of the beam spot welds or pierce and fold points.

4. SHEAR (TRANSVERSE)

- Joint is also sufficiently strong to withstand loads in this direction. The expected failure modes would be (a) tearing of the beam cross piece (in tension) at the two forward latches or (b) destruction of the beam spot welds or pierce and fold points.

5. ROTATION (IN-PLANE)

- This would result in (1) compression of the beam material into the latch insert for two latches at no damage to the latch and (2) tension on the other two latches. In the second case, the beam would fail before the latch dowel pins (weakest part of latch) would shear at approximately 1380 pounds.

APPENDIX B

NB-19 QUICK LOOK TEST REPORT

QUICK LOOK TEST REPORT

NB-19

FABRICATED BEAM ASSEMBLY

TEST PERIOD: August 11-27, 1980

PERSONNEL:

Subjects - Croomes, Elrod, Hall, Sanders (MSFC)
Shields, VanValkenburgh (Essex)

Conductors/Observers - Loughead, Neal, Pruett (Essex)
Stokes (MSFC)

OBJECTIVES:

1) Evaluation of lap joints, centroidal end caps, and ball-and-socket unions for assembly of beams fabricated by Automated Beam Builder (ABB)

2) Evaluation of Large Space Structure (LSS) assembly techniques via EVA

3) Compilation of task and subtask times for EVA assembly techniques.

APPARATUS:

Phase A	Phase B
1 1-bay beam	3 1-bay beams
1 3-bay beam	3 4-bay beams
2 lap joints	3 6-bay beams
2 centroidal end caps	6 lap joints
	9 centroidal end caps
	3 ball-and-socket unions

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NB-19 TEST PROCEDURES

PHASE A (5 Trials)

Installation of two lap joints and two centroidal end caps on 3-bay beam emerging from ABB

Single subject

Two foot restraint work stations on ABB forward bulkhead

Simulated RMS positioning of beam during installation of second centroidal end cap

Final trial: assembly of 1-bay beam and 3-bay beam via lap joint

PHASE B (5 Trials)

Assembly of 9 beam complex structure

Preinstalled lap joints, centroidal end caps and ball-and-socket unions

Two subjects

No work station fixtures

Simulated RMS delivery of beams from ABB to subjects

Simulated MMU translation of subjects about structure

Final trial: end-to-end installation (Phase A) and assembly (Phase B)

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NB-19 TEST RESULTS

Design of lap joints (Essex), centroidal end caps (Essex), and ball-and-socket unions (Rockwell International) proved feasible for assembly of ABB-fabricated beams into Large Space Structures.

Test revealed several hardware problems to be resolved by design modification before test Phase C begins:

- Fragility of lap joint latch hasps
- Fragility of lap joint alignment tabs
- Location of lap joint alignment tabs
- Insufficient friction in lap joint latches
- Lack of detent on shaft of centroidal end cap.

Beams and lap joints suffered minor damage and deterioration as a result of handling and cycling by test personnel.

Component configuration changes made during test included:

- Lengthening slide tube tabs on centroidal end caps
- During Phase B final trial, preinstalling lap joints on 4-bay beams rather than on 6-bay beams as in previous trials.

Phase A joint installation was accomplished with equal facility from either work station. Minor modifications of hand rail placement and tether attach points might enhance performance of installation tasks. Typical task time for installation of two lap joints and two end caps: 35 minutes.

Phase B assembly was accomplished by two work patterns:

- Cooperation of both subjects at one site
- Simultaneous effort of subjects positioned at opposite sides of the cargo bay.

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NB-19 TEST RESULTS (Continued)

The 6-bay apex beam was attached to the two 4-bay diagonal beams more easily by two subjects working in concert than by a single subject. Typical task time: 43 minutes.

Additional data available from this test sequence:

- Videotape recordings of Phase A installation and Phase B assembly
- Voice recordings of subjects and test conductors
- Time and motion data on discrete assembly subtasks.

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