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DESIGN OF A WELDED JOINT FOR ROBOTIC, ON-ORBIT ASSEMBLY OF SPACE TRUSSES

Prepared By:	William K. Rule
Academic Rank:	Assistant Professor
Institution and Department:	The University of Alabama Department of Engineering Mechanics
NASA/MSFC:	
Office:	Structures and Dynamics Laboratory
Division:	Structures
Branch:	Structural Development
MSFC Colleagues:	Frank P. Thomas Pedro I. Rodriguez

INTRODUCTION

In the future, some spacecraft will be so large that they must be assembled on-orbit (1,2,7,13). These spacecraft will be used for such tasks as manned missions to Mars or used as orbiting plaforms for monitoring the Earth or observing the universe. Some large spacecraft will probably consist of planar truss structures to which will be attached special purpose, self-contained modules. The modules will most likely be taken to orbit fully outfitted and ready for use in heavy-lift launch vehicles. The truss members will also similarly be taken to orbit, but mostly unassembled. The truss structures will need to be assembled robotically because of the high costs and risks of extra-vehicular activities. Some missions will involve very large loads. For instance, the truss structure supporting an aerobrake heat shield will experience up to 6 g's of deceleration during entry into the Martian atmosphere (4). To date, very few structures of any kind have been constructed in space. Two relatively simple trusses were assembled in the Space Shuttle bay in late 1985 (12).

Here the development of a design of a welded joint for on-orbit, robotic truss assembly is described. An expanded version of this document has been written (10). Mechanical joints for this application have been considered previously (9,14). Welded joints have the advantage of allowing the truss members to carry fluids for active cooling or other purposes. In addition, welded joints can be made more efficient structurally than mechanical joints. Also, welded joints require little maintenance (will not shake loose), and have no slop which would cause the structure to shudder under load reversal. The disadvantages of welded joints are that a more sophisticated assembly robot is required, weld flaws may be difficult to detect on-orbit, the welding process is hazardous, and welding introduces contamination to the environment. In addition, welded joints provide less structural damping than do mechanical joints. Welding on-orbit was first investigated aboard a Soyuz-6 mission in 1969 and then during a Skylab electron beam welding experiment in 1973 (5,15). A hand held electron beam welding apparatus is currently being prepared for use on the MIR space station (8). Presently, Marshall Space Flight Center is evaluating processes appropriate for on-orbit welding (11). A low gravity environment has been found to have very minor effects on the welding processes appropriate for this application. This is based on tests run on-orbit as well as low gravity environments achieved by flying aircraft in parabolic trajectories. In fact, low gravity can make welding easier since the flow of the molten metal is dictated by surface tension effects undisturbed by gravitational forces (11). It appears that a modified form of gas tungsten arc welding (GTAW) will be most appropriate for welding together structures on-orbit (11). The process has been modified to work in a vacuum by providing gas to the arc zone by means of a hollow tungsten electrode with special shielding. A commercial tube welding head has been successfully modified for use on-orbit with a gas leakage rate of approximately 2.5 liters/min (11).

To develop as realistic a joint as possible, a specific truss structure was selected on which to base the design. The structure considered was based on the 120 foot diameter aerobrake tetrahedral truss structure (4,6,9,14). The truss members were assumed to consist of graphite/epoxy tubes. Also, it was assumed that the nodes were constructed of 2219-T87 aluminum alloy. The magnitude of the member load assumed for design purposes was 100 kips.

MEMBER FORCES GENERATED BY RANDOM MEMBER MISFITS

The 660 members of the tetrahedral truss were all 12.56 ft long and consisted of identical graphite/epoxy tubes (elasic modulus = 10.5E6 psi, shear modulus = 4.0E6 psi, Poisson's ratio = 0.33, outside diameter = 5 in., wall thickness = 0.375 in.). The truss was 10.25 ft. deep in accordance with the geometric properties of a tetrahedron. No manufacturing or assembly process is absolutely accurate. Thus, after being welded into the truss, the members will tend to be slightly too long or short. These randomly distributed misfits will lock in member forces before service loads are applied and they will also distort the truss to some degree. Before a joint can be designed some measure of an acceptable misfit must be determined which will dictate the accuracy required of the robot and the joint configuration. Member misfits will be randomly distributed so peak member forces can only be determined in a statistical sense. The structure was analyzed 50 times with different randomly generated sets of member misfits, and the mean and standard deviation of the peak member force magnitudes were calculated from these results. The analysis procedure can be summarized as follows. Random member misfits were generated and the associated initial member forces were calculated and stored in a file. Nodal loads due to the initial member forces were calculated and summed up to form a global nodal load vector. The load vector was applied to the structure and the finite element program was run to calculate a set of intermediate member loads. Finally, the initial member loads were added to the intermediate member loads to produce a set of final member loads.

For a maximum member misfit of 0.02 in. (only 0.013% of the member length), the estimated maximum member force (that will not be exceeded with a 97% level of certainty) was 11.4 kips, which is a significant portion of the design load capacity of 100 kips. Besides generating member forces, random member misfits will distort the structure causing problems for truss structures supporting equipment with fine pointing requirements, and for the heat shield associated with aerobrake structures (3).

NODE SEPARATION INDUCED BY RANDOM MEMBER MISFITS

Here, the effect of member misfits on relative node displacement of a partially assembled truss structure is considered. Misfit induced member forces will cause the truss to distort and thus will force pairs of nodes to move closer together or farther apart from each other. These relative nodal displacements will have to be corrected by the robot during the assembly process. As more members are assembled, relative nodal displacements will tend to increase since there are more member misfits to cause distortion. Thus, the robot will have to make the largest relative nodal displacement corrections while assembling the last few members of the truss.

To correct for these misfit induced relative nodal displacements, the robot will be required to push or pull on pairs of nodes. The magnitude of force required to make these corrections must be estimated because it affects the design of both the robot and the joint. The correction force can only be estimated in a statistical sense since the member misfits are randomly distributed. To be conservative, the correction force required while assembling the last member of the structure was considered. It was assumed that the structure will be assembled from one edge through to a far edge, so the last member would be an edge member. Accordingly, for this relative nodal displacement correction force study, an edge member was removed from the structure described in the previous section. Fifty sets of random member misfits were generated and the robotic force required to reposition the nodes for assembly of the last member was calculated. This analysis indicated that the assembly robot must be capable of pulling or pushing with a force of 3.8 kips (that will not be exceeded with a 97% level of certainty) while attempting to correct for member misfit induced relative node displacements. Here, a maximum possible member length error of 0.02 in. was also assumed.

PRELIMINARY DESIGN OF THE WELDED JOINT

The trusses under consideration here will be robotically assembled on-orbit. This makes it imperative that the truss members and joints be *designed for assembly*. The design should be such that the robot can: transport the member from the storage pallet to the appropriate position on the truss; insert the member between the nodes; correct the node positions for member misfit errors; and weld the member into position. The members and joints must also be light and able to be densely packed together for efficient transport to orbit, a major cost driver. A light design is also necessary to control inertial forces while in service. The joint components must be relatively easy to produce so that manufacturing costs will not be excessive. The joint design must provide a seal so that fluids may be pumped throughout the members of the truss. Based on prior studies (14) it was assumed that the joint must be capable of carrying 100 kips and that the members consist of graphite/epoxy tubes of circular cross section (5 in. outside diameter, 0.375 in. wall thickness).

A major difficulty with the joint design was allowing for the member to be inserted into the nozzles of two nodes that had already been welded into position. This could be handled in two ways. A member could be made precisely the correct length so that it could be postioned between the nozzles (without being inserted) and then welded into place. This approach has two major drawbacks: the joint configuration provides no alignment assistance to the robot; and joint gap control will be difficult. Alternatively, one half of the member could be designed to telescope into the other as shown in Fig. 1. This would allow a member to be shortened (telescoped), placed between the nodes, and then extended so that its ends would fit inside the nozzles of the nodes. This provides for very accurate alignment of the joints and complete control of the weld joint gap. When the joint has been fully made up the joint overlap will be snug against the inside surface of the nozzle of the node and the joint will be temporarily held together by the friction provided by a compressed o-ring. The telescoping action allows for very compact shipment to orbit. A disadvantage of the telescoped member approach is that three weld joints will now have to be made (at each end and at the sliding joint in the middle) instead of the two required for the nontelescoped design. However, it appears that the telescoped design will make it easier for the robot to assemble and weld up the structure, and so the telescoped design was selected for further study.

A preliminary analysis of the joint using an isotropic finite element model without thermal loading was conducted. The finite element mesh and joint dimensions are displayed in Fig. 2. Axisymmetric elements were used in the analysis. As shown in Fig. 2, the part of the node that the truss member ferrule was welded to was assumed to consist of a nozzle similar to that found in pressure vessels. A design of this nature allows for the easy passage of fluid along the truss member and into the node. This configuration also provides for a very simple and clean design of both the member ferrule, the weld, and the node. However, the nozzle approach is not very efficient structurally since the load path must change abruptly as axial loads run from the member into the node. This produces large bending stresses in the node fitting. Thus, generous fillets and relatively thick components will be required for the design of the node. A GTAW groove weld 0.5 in. deep is required to keep the Von Mises stress level within the heat affected zone to less than the weld metal yield stress of 26 ksi (16).

For many applications, the ideal design of the graphite/epoxy strut will consist of laying up the fibers such that they are oriented at $^+/_-$ 10^0 with respect to the axis of the member (4). This layup will provide for high stiffness and strength parallel to the axis of the member, along with a slightly negative axial coefficient of thermal expansion. The slightly negative coefficient of thermal expansion of the struts, coupled with the relatively large positive coefficient of thermal expansion of the aluminum fittings can produce members with a net axial coefficient of thermal expansion of zero. This is highly desirable in spacecraft since it prevents temperature changes from causing structural distortions. However, a $^+/_-$ 10^0 layup will create some problems, especially in applications where the composite material must be attached to a metallic component in an environment where there will be large temperature changes, as is the case here. In this study it was assumed that during the mission temperature variations as large as $^+/_-$ 250 F^0 could occur. The primary difficulty with this type of joint is that the coefficient of thermal expansion of the composite material in the circumferential direction is five times that of the aluminum. Fig. 2. shows a double scarf joint for the composite strut - aluminum ferrule connection. This scarf joint was subsequently redesigned due to concerns about manufacturability and thermal loading capacity. The redesigned joint is still under development.

CONCLUSIONS

On the basis of this study the following conclusions were reached:

1. Member length errors should be carefully controlled in large truss structures. Member length errors can lock in large stresses and structural distortions before service loads are applied. Distortions may cause problems for instruments with accurate pointing requirements. Distortions may also disturb the flow of hot gases over an aerobrake heat shield.
2. The assembly robot will need to be designed to exert relatively large forces while building the truss structure. The assembly robot will also require an accurate device for ensuring that the member length is correct before welding.
3. The telescoping member and joint overlap with o-ring approach seems to be a workable technique for positioning the truss members before welding. It is important that the joint system be *designed for assembly*.
4. A modified GTAW process appears to be a feasible technique for the automated welding of aluminum components on-orbit.
5. A 0.5 in. thick groove weld will be required to carry the design loads. This weld will be made in three passes.
6. A good design for the graphite/epoxy strut - aluminum end fitting joint is difficult to obtain because of the differential thermal expansion problem. Temperature changes during the mission should be minimized.

REFERENCES

1. Braun, R. D., and Blersch, D. J. "Propulsive Options for a Manned Mars Transportation System," AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, CA, Paper No. AIAA-89-2950, 1989.

2. Cirillo, W. M., Kaszubowski, M. J., Ayers, J. K., Llewellyn, C. P., Weidman, D. J., and Meredith, B. D. "Manned Mars Mission Accomodation - Sprint Mission," NASA TM-100598, 1988.

3. Dorsey, J. T., and Mikulas, M. M. "Preliminary Design of a Large Tetrahedral Truss/Hexagonal Heatshield Panel Aerobrake," NASA TM 101612, 1989.

4. Dorsey, J. T., and Mikulas, M. M. "Preliminary Design of a Large Tetrahedral Truss/Hexagonal Panel Aerobrake Structural System," 31st Structures, Structural Dynamics, and Materials Conference, Long Beach, CA, AIAA Paper No. 90-1050, 1990.

5. McKannan, E. C., and Poorman, R. M. "Skylab M551 Metal Melting Experiment," Proceedings of the 3rd Space Processing Symposium on Skylab Results, Vol. 1., 1976, pp. 85-100.

6. Mikulas, M. M., Bush, H. G., and Card, M. F. "Structural Stiffness, Strength, and Dynamic Characteristics of Large Tetrahedral Space Truss Structures," NASA TM X-74001, 1977.

7. Mikulas, M. M., and Dorsey, J. T. "An Integrated In-Space Construction Facility for the 21st Century," NASA TM-101515, 1988.

8. Paton, B. "State-of-Art and Prospects of Development of Aerospace Engineering in the USSR," Conference on Welding in Space and the Construction of Space Vehicles, American Welding Society, 1991, pp. 1-11.

9. Rhodes, M. D., Will, R. W., Wise, M. A. "A Telerobotic System for Automated Assembly of Large Space Structures," NASA TM-101518, 1989.

10. Rule, W. K., and Thomas, F. P. "Design of a Welded Joint for Robotic, On-Orbit Assembly of Space Trusses," to be submitted for publication as a NASA Technical Memorandum.

11. Russel, C., Poorman, R., Jones, C., Nunes, A., and Hoffman, D. "Considerations of Metal Joining Processes for Space Fabrication, Construction, and Repair," Proceedings of the 23rd International SAMPE Technical Conference, Kiamesha Lake, NY, 1991.

12. Thomson, M. "Orbital Construction Design Data Book," Astro Aerospace Corporation, Carpinteria, CA, AAC-TN-1160, 1991.

13. Walberg, G. D. "A Review of Aerobraking for Mars Missions," 39th Congress of the International Astronautical Federation, Bangalore, India, Paper No. IAF-88-196, 1988.

14. Williamsen, J., Thomas, F., Finckenor, J., and Spiegel, B. "Definition of Large Components Assembled On-Orbit and Robot Compatable Joints," NASA TM-100395, 1990.

15. "MSFC Skylab Corollary Experiment System, Mission Evaluation," NASA TM x-64820, 1974.

16. Saunders, H. L. "Welding Aluminum: Theory and Practice," the Aluminum Association, 1989, pp. 8.1-8.11.

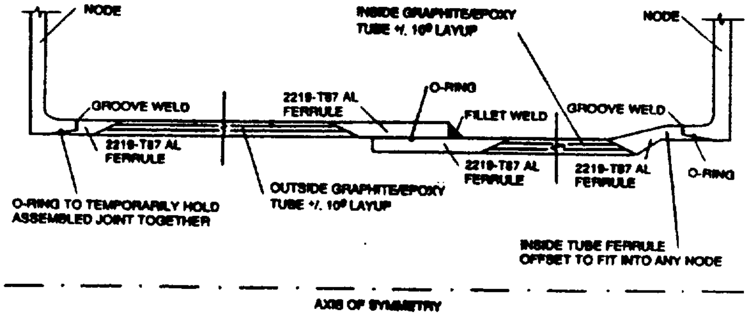

Fig. 1 Truss Member Telescoping Design Concept

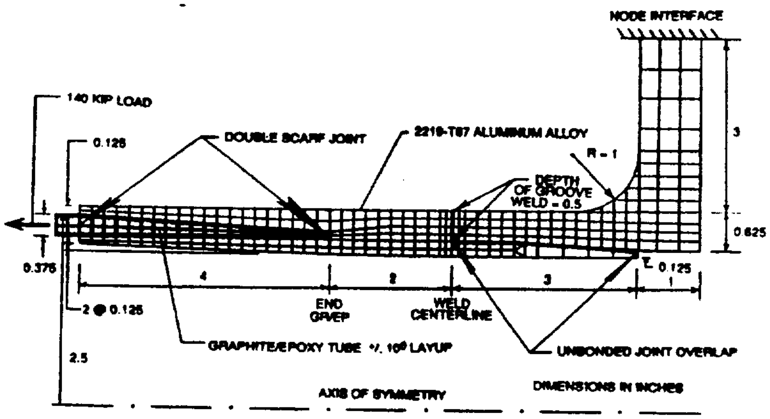

Fig. 2 Finite Element Model of Preliminary Joint Design