Co-axial joint technology applied to antenna backup structures

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ABSTRACT

The increasing demand to improve focusing accuracy and to accommodate higher frequencies in space communications and radio astronomy has created significant challenges for improving the capability of the constituent systems in radio antennas and telescopes. One important system is the radio antenna/telescope backup structure connections. The backup structure is a key element in providing a stable, precise and rigid support for the reflective surface. The ideal connection for these types of structures is rigid and concentric resulting in minimal deformation with stress/strain curves that are linear, repeatable and exhibiting no hysteresis over the entire service load range. Conceivably such a connection could be designed so that the stress/strain curve mimics the stress/strain characteristics of the connecting member in both tension and compression. When this is achieved then such joints can be said to be "invisible" in the global behavior of the backup structure. At that point, overall reflector deflection becomes more linear and highly predictable. In conjunction with this advantage, optimized backup structure geometries, adaptive reflectors and compensating algorithms can best be applied in producing an instrument of unparalleled performance. This paper introduces Co-Axial Joint (CAJ) technology as the practical and economical means to produce an invisible connection.

Keywords: backup structures, joint connections, trusses, co-axial joints, structure erection, structure assembly

1. INTRODUCTION

1.1 The Co-Axial Joint (CAJ)

The CAJ connection is a non-welded, non-bolted mechanical attachment used to rigidly join multiple round tubular elements to a node in a structure. As shown in figure 1, the mechanical attachment between the pipe and the node is effected by 3 couplings 1) tension sleeve, 2) end cap, and 3) compression sleeve. All components, including the tubular member and block connector (node), are machine threaded. The size and shape of the block connector is determined by the diameter, number and attitude of the pipe elements framing into the joint. This attachment transmits shear and moment as well as axial tension and compression. From a structural analysis point of view, the joint is considered to be locally fixed or rigid.

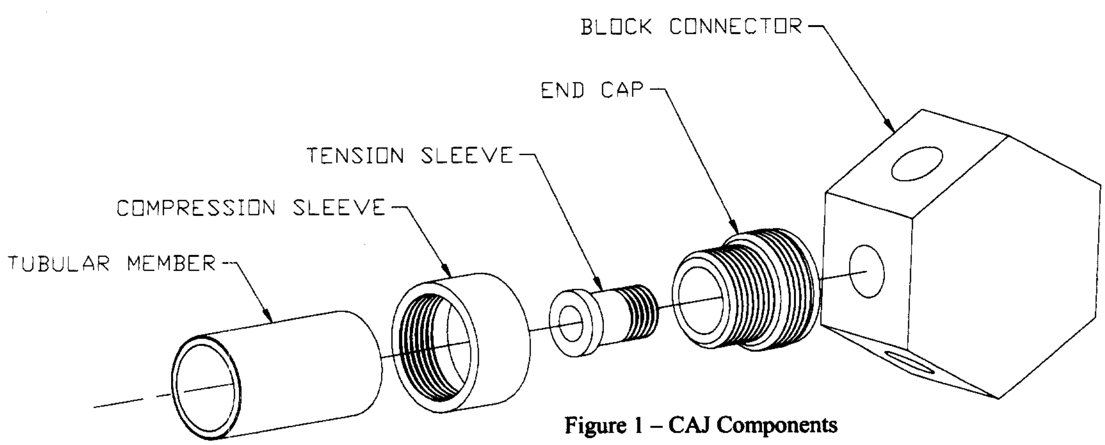

Figure 1 – CAJ Components

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1.2 CAJ development and theory

When considering general structural efficiency, optimum strength-to-weight ratios and minimized deformation the ideal and most efficient compressive element has a round cross-section. However, current technologies do not facilitate the attachment of round pipes to a joint without serious compromises. Two types of connections commonly used to connect pipes are "fish-mouth" welded joints and "ball-node" bolted connections. Welding has the following disadvantages:

- Intricate and costly pattern cutting at the pipe ends
- Lack of precision in shop built-up subassemblies and final field assembly due to distortion from welding
- The need for weld patterns, jigs and fixtures
- Exaggerated transportation costs due to shipping low-weight, high-volume shop weldments
- Field welding, shoring and inspection costs
- Field painting of welded field connections/assemblies
- Elimination of the use of advanced, weld sensitive materials
- The need to employ other technologies to compensate for the lack of precision of welded up structures

Similarly, ball-node connections have their own set of drawbacks:

- The connection is secured via a sleeved bolt from the ball-node to a cone welded to the end of the pipe
- Elimination of the use of advanced, weld-sensitive materials
- The relative stiffness of the ball-node and the pipe are much larger than the intermediate bolt
- The connection cannot transfer moment or shear forces and must be analyzed as a "hinged" joint
- The buckling ratio (kL/r) increases, which reduces the natural efficiency of the pipe as a compressive element
- The lack of joint stiffness allows minor eccentricities to induce rotational flexibility in the connection

Thus, clearly a major improvement in the connection of round elements to a node needed to be developed. The CAJ connection was conceived and developed upon this basis.

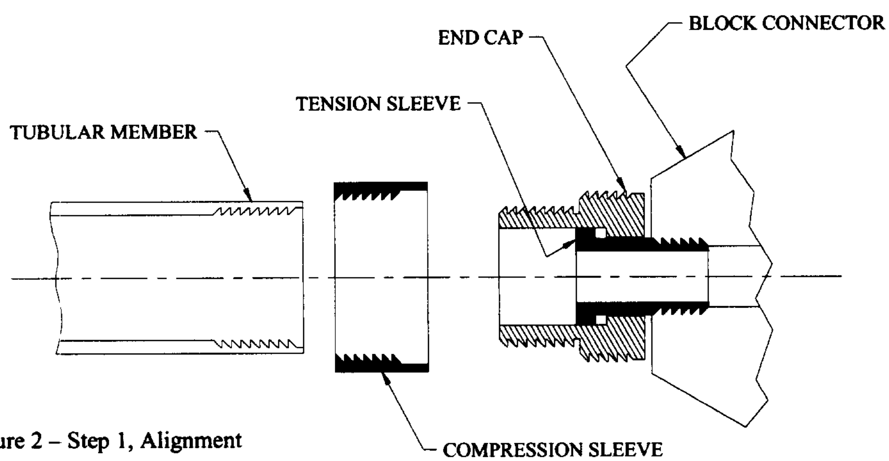


Figure 2 – Step 1, Alignment

The block connector, end caps and tension sleeves are pre-assembled in the shop and shipped to the field as one unit. The connection is field assembled in three steps. Figure 2 illustrates the first step - alignment. The tension sleeve and end cap are configured to allow travel of the end cap along the shoulder of the tension sleeve. When the end cap is fully retracted towards the block connector there is a set clearance between the end of the pipe and the retracted end cap. Thus, the pipe is actually shorter than the clear distance between the joints at either end. This feature allows for any order of assembly. Furthermore, hard fit-up conditions are eliminated. At this point, the compression sleeves are slid on each end of the pipe and are left in position for installation later in the process.

Figure 3 illustrates the second step – the completed coupling between the end cap and pipe. During this operation, the end cap is threaded on while the pipe is held steady. Tolerance between the end cap and the tension sleeve facilitates ease of assembly even when there is minor misalignment. When the end caps are fully seated on both ends of the pipe the travel between the end caps and the respective tension sleeves are fully extended. Final tightening of the end caps is accomplished with a spanner wrench. The hand-application of the spanner wrench is capable of exerting 2,000 pounds of axial force in making the connection.

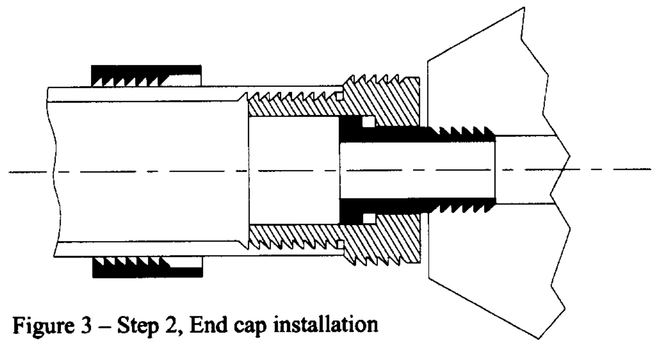


Figure 3 – Step 2, End cap installation

Figure 4 illustrates step 3 – a fully seated compression sleeve. The compression sleeve is threaded down over the end cap. As the compression sleeve is fully tightened, again with the spanner wrench, any remaining gap between the end cap and tension sleeve is eliminated. From this hand tightening, there is a minor pre-load built into the joint. As the compression sleeve is forced against the block connector, it pushes the end cap away from the block connector. In turn, the end cap pulls against the tension sleeve.

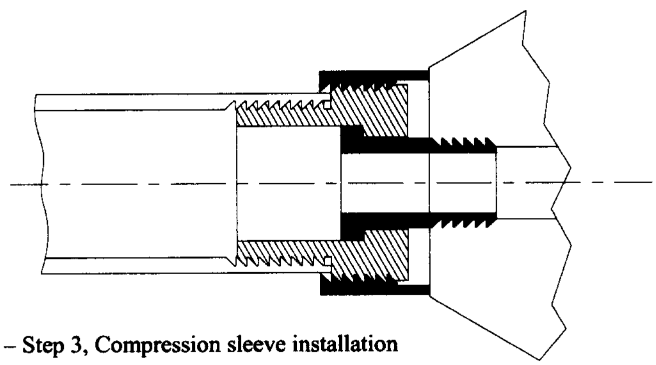


Figure 4 – Step 3, Compression sleeve installation

When tension is applied to the joint through the pipe, the force path is through the end cap into the tension sleeve. When compression is transmitted to the joint from the pipe, the force path is through the end cap into the compression sleeve. Because there are two different force paths for compression and tension along a common centerline, the connection is called the Co-Axial Joint (CAJ). Therefore, the joint is capable of not only transmitting axial tension and compression, but moment and shear forces as well. In summary, the CAJ connection is a non-welded, non-bolted moment (rigid) connection.

1.3 Advantages

CAJ technology possesses advantages over other methods of joining pipes at a node such as fish-mouth welding and ball-node connections. These advantages fall into the areas of design, manufacturing and field assembly. In design CAJ supports centerline geometries; increased strength-to-weight ratios; the use of different building materials including weld-sensitive and/or exotic materials; hollow connections for routing power conduit, communication and data lines, cooling/heating air; and improved kL/r ratios. In the area of manufacturing, CAJ components are easily machined in a standard CNC (computer numerically controlled) machine shop; part tolerances produced are inherently superior to conventional construction materials, and no welding is required. Field assembly advantages are the members are shorter than the clear distance between the joints resulting in no hard fit up conditions; any variety of erection techniques may be used; all components can be shop painted before delivery; no field welding; minimal shoring; hand tool assembly; skilled trades not required; ease of assembly at austere/remote sites, and expedient assembly. The CAJ structural system impacts every phase of design and construction with cost saving features.

1.4 Demonstrated technology

Before a concept is suitable for field applications there are three requirements that must be satisfied. First, the concept must be available from an intellectual property point of view. There should be no restrictions on acquiring the product. Second, the technology must be feasible from a rational engineering analysis aspect. The technology must be capable of embodying frame designs based on the application of standard engineering principles and practices. Third, the product should be economically producible. Categorically speaking, the patented CAJ system meets all of these requirements. The patented technology is available to the general scientific community for use on projects. The technology has been tested at an independent lab and applied to three different projects resulting in successfully completed structures. Shown below in figure 5 is the "Roller Coaster" Pedestrian Bridge at the Pike Development in Long Beach, California. This is the first large scale application of CAJ technology. Primarily, the economic, aesthetic and practical advantages of CAJ construction of this architectural icon were keys to the construction manager's decision to move forward with this new technology.

This is a 137 meter (450 feet) complex comprised of a 61 meter (200 foot) bridge, a 18 meter (60 foot) bridge and 58 meter (190 feet) split between two plaza areas over retail buildings along the waterfront. There are over 10,000 machined components in this structure and 3.7 km (2.3 miles) of 100 mm (4 inch) diameter aluminum pipe. The main clear span is 46 meters (150 feet) long where the aluminum superstructure, configured to look like a roller coaster, does the work of holding up the 9 meters (30 foot) wide steel and concrete deck. The construction manager reportedly saved $500,000 with the CAJ design. Considering aesthetics, the client and the City of Long Beach wanted the roller coaster appearance while maintaining maximum transparency. Finally, the client wanted the superstructure to be made of aluminum for the elimination of the corrosive attack on an alternate steel structure by the salt air.

The "Roller Coaster" Pedestrian Bridge project has demonstrated that CAJ technology is ready for application on large scale, heavy-duty structural frames.

Figure 5 – CAJ Pedestrian "Roller Coaster" Bridge

2. USE OF CAJ TECHNOLOGY IN ANTENNA APPLICATIONS

2.1 The demands of science

The Jet Propulsion Laboratory (JPL) operates the Deep Space Network (DSN) for the National Aeronautics and Space Administration (NASA). The DSN consists of large reflector antennas operating at S, L, X and Ka bands that are subject to an ever-increasing demand for better performance while facing increasingly more stringent budgetary constraints. The design and construction of these large precision scientific instruments is principally dependent on the application of microwave, structural, controls and mechanical engineering. Microwave engineering defines the electronic requirements, components and antenna configuration while controls, structural and mechanical engineering provide a system to precisely support and position the electronic components. Figure 6 shows the main structural components of a typical DSN ground antenna.

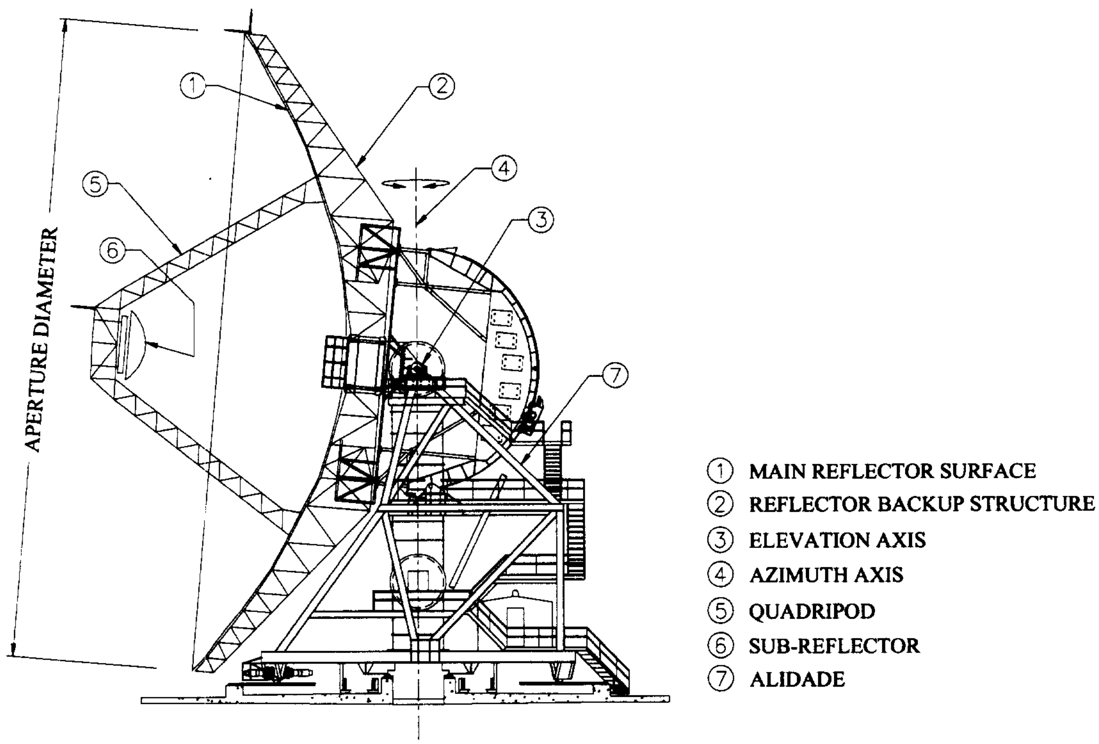


Figure 6 – Antenna Components

The current trend in deep space communications is toward smaller spacecraft operating at higher antenna frequencies and less power, with the ultimate goal being communications at optical frequencies. In order to maintain adequate performance as operating frequencies increase, the required accuracy of the antennas increases, which means that stiffness of the mechanical, structural and reflecting surface components of the DSN ground antennas also increases. For example, the required reflector surface accuracy, estimated by the root-mean-square (rms) of the surface deformations, for a 34-meter antenna operating at Ka-band (~32 GHz) must be better than one twentieth of the wavelegth ($\lambda/20$) or 0.47 mm to obtain adequate performance. The pointing accuracy (rms) required for a 34-meter antenna is approximately $\lambda/(10^*D)$, or a tenth of the beamwidth or 0.0016 degrees. This is almost three times the requirement for operation at X-band (8.4 GHz). Overall antenna efficiency, however, is the product of many loss-contributing factors from both microwave and physical effects. Microwave efficiency factors include illumination, spillover, cross-polarization and leakage. Physical effects include aperture blocking (subreflector, subreflector support structure, feedcones, etc.), reflecting panel manufacturing tolerances, reflecting panel alignment and reflecting surface deformations. Of all of the factors, both microwave and physical, a significant reduction of overall efficiency is due to reflecting surface deformation. Additionally, the efficiency factor due to surface deformations can range from 0.40 to 0.90.

Antenna surface deformations are caused by a number of environmental factors such as wind, temperature gradients and gravity. While the large size of the DSN antennas makes them susceptible to deflections from all factors, the most significant contribution comes from gravity. Since the reflector panels are directly supported by the antenna structure, any deflection in the structure also translates to the reflector panels. As the antenna rotates about the elevation axis, the gravity vector changes with respect to the antenna causing the reflecting surface of the antenna to deform from the ideal shape throughout the entire elevation movement. These deformations cause microwave path-length variations from the affected areas, which has an adverse effect on antenna efficiency.

2.3 Limitations of current technology

The antenna backup structure is the element of the antenna that directly supports the reflecting panels and rotates on the elevation axis. The 34-meter and 70-meter antennas of the DSN have backup structures consisting of very complex welded three-dimensional steel space trusses. The individual members of these three-dimensional trusses consist of both square and round tubes, angles, I-beams, C-channels and plates. These shapes do not always represent the best choice with respect to stiffness-to-weight ratio. The complex three-dimensional geometry of the multi-member connections typical of backup structures sometimes precludes using the best member in favor of one that is adequate but less difficult to design, fabricate and erect. Additionally, techniques used to join multiple members by welding sometimes require compromises in design to achieve the desired geometry.

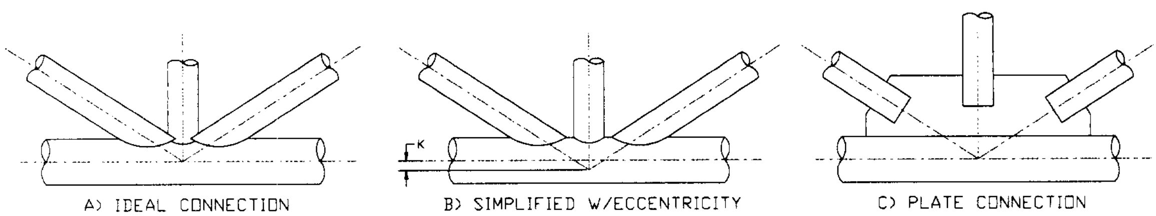


Figure 7 – Typical truss connections

Figure 7 illustrates a few examples of how member connections can be achieved. Figure 7A shows a simple planar welded tube connection using round tube. This type of connection is close to an ideal situation where the joint is as stiff as the members in all directions. It is a very costly joint, in man-hours, to prepare and weld. In the typical backup structure, multiple members (of differing sizes) from all directions and angles in three-dimensional space can come together making this type of joint very difficult and expensive to achieve. Considering the thousands of members and joints in a typical backup structure, joints of this nature become cost and time prohibitive. Figure 7B shows a somewhat less difficult joint to produce although we have now introduced an eccentricity, which can reduce strength and adds difficulty in design analysis. Fig. 7C shows the method utilized most often. In this method a plate is used as an interface between members. This type of joint is relatively easy to produce. It does, however, compromise out-of-plane stiffness, which can reduce the buckling strength of the member. In practice, round tubes, which exhibit the best stiffness-to-weight ratio, are also not used extensively due to added difficulty in joint preparation. Rectangular tube, angles, and C-channel are often utilized instead due to ease of design and fabrication. These structural shapes are not as efficient as round tubes and thus the structure will usually incur a weight penalty. This weight penalty places increased demands on the mechanical components (bearings, gears, tracks, etc.) and control systems, and ultimately reduces antenna performance. Furthermore, additional weight frequently translates to increased construction costs and longer construction schedules. In addition to being a labor-intensive process, the heat produced by welding can cause other undesirable effects such as distortions (warping), residual stresses and metallurgical changes in the parent material. Heat distortion becomes a significant problem when attempting to build a very large precision structure. While major distortion can often be controlled by of the combination of design and skilled welders with proper technique and procedures the final result usually requires more time and is frequently less than ideal. Residual stresses and metallurgical changes in welded joints caused by the heat of welding are generally more difficult to quantify and remedy in the field.

2.4 CAJ enabling technology

Enabling structural technology is required to provide antenna backup structures with greater precision and stiffness while not increasing weight. Additionally, to minimize deformations and make them highly predictable under the structure's loading conditions the joint flexibility must be reduced and hysteresis on the structure that causes non-linearities must be eliminated. Co-Axial Joint (CAJ) technology offers these necessary improvements with a new method of joining tubular members to rigid joints in a primary structural frame.

Some applications that are currently being considered for the use CAJ technology include backup structures for small antennas, on the order of 12 meters in diameter. As a very simplistic example, Figure 8 shows a concept for a 6-meter antenna reflector utilizing CAJ technology. By utilizing this design, the manufacturing and assembly time of this reflector is reduced significantly, thus reducing the cost. Also, the stiffer joints provided by the CAJ will allow for better performance at increased frequencies. In this concept, the idea is to utilize a single piece dish and a backup structure to support it. The dish contributes to the stiffness of the entire reflector and the CAJ structure would be used to transfer the loads to the antenna pedestal.

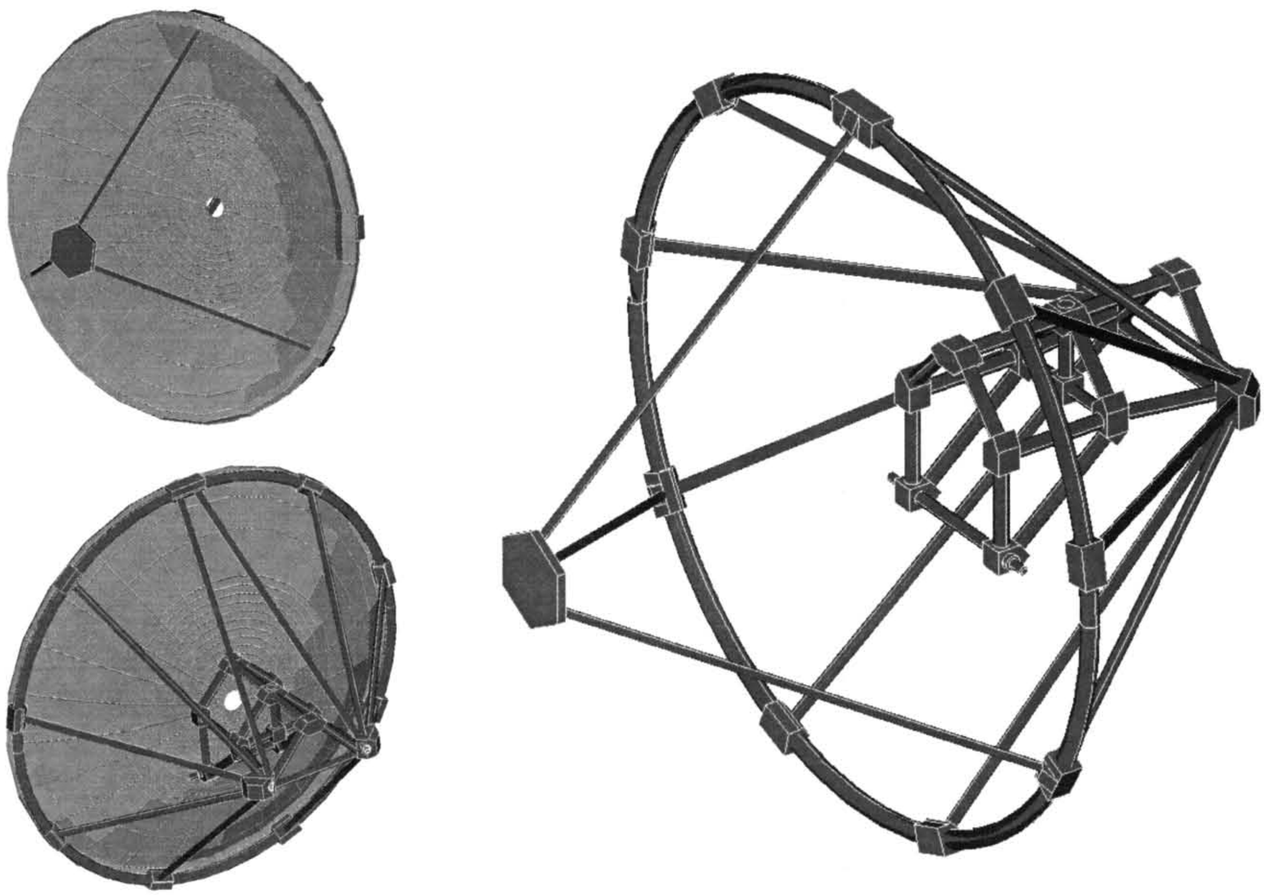


Figure 8 – Antenna Reflector Backup Structure Concept Using CAJ Technology

Because of the high stiffness and repeatability of structures utilizing CAJ technology, the effort could easily be extended to antennas that operate at higher frequencies, for example antennas used in astronomy that operate in the submillimeter range (~300 GHz), and even antennas used in optical communications.

Furthermore, due to the inherited ease of assembly, it is evident that this technology can also be utilized in other space frame applications like space trusses, space habitats and other types of space structures. Simple tools can be devised so that astronauts may be able to assemble the structures in space environments.

3. DESIGN APPROACH, PERFORMANCE AND TESTING

3.1 Dual force path

The patented Co-Axial Joint technology utilizes two separate load paths through the connection assembly; one path carries tension forces and the other carries compression forces. When bending forces are applied, one side of the joint carries the tension component of the bending moment while the other side carries the compression component. This is enhanced by the use of buttress threads where the loads are transferred perpendicular to the nearly flat surfaces of the thread. Hysteresis is theoretically eliminated because there is no slip plane as there is in conventional bolted structural connections. The force paths through the connection follow directly across machined bearing surfaces for both tension and compression forces. The only possibility for hysteresis to take place is through the deformation of the threads and also the sleeve collars, but because of the high stiffness at these locations, it is almost negligible. Figure 9 shows a cross section of the CAJ.

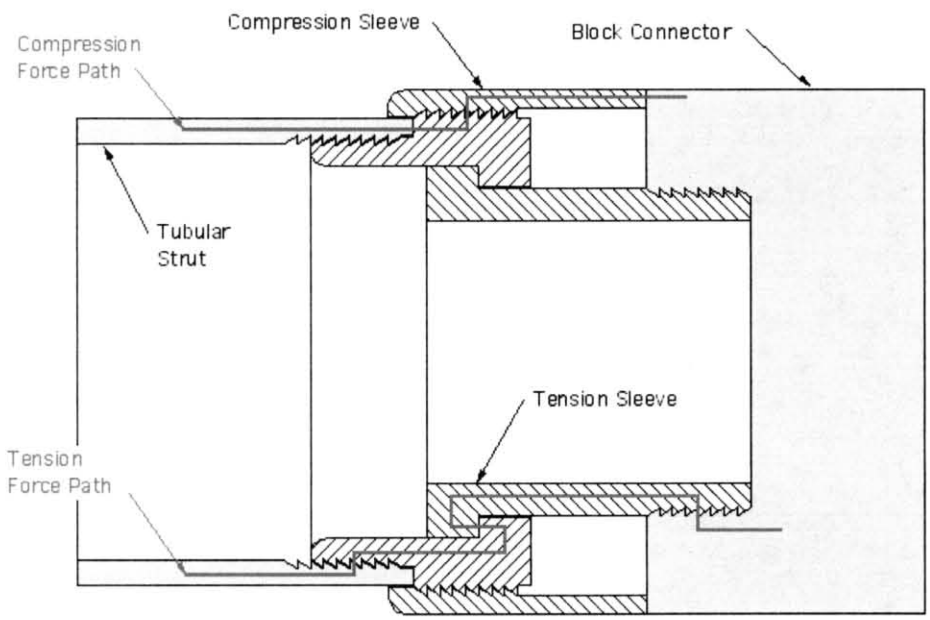


Figure 9 – Cross Section of Co-Axial Joint Elements

The design approach has been to optimize the cross sectional areas and surface bearing areas in the threads, sleeves and couplings for allowable stresses in tension, shear and bearing for the specific material used to minimize the material in the couplings. Thus, the net cross sectional area of a strut after threading will determine the required length of thread and shoulder overlap in the sleeves along the tension path while the buckling capacity of the strut will determine the thread length and compression sleeve wall thickness along the compression path.

The block connector is a solid element, which obviously has much greater stiffness in compression, tension or bending than the tubular struts that it connects. If optimized for stress, the coaxial joint components are less stiff than the struts. However, the coaxial joint components with the lower stiffness are much shorter than the block connector, so the net effect could be theoretically neutral.

Because of the high bending stiffness of the coaxial joint we have performed the structural analysis assuming rigid joints rather than pinned connections. This results in greater efficiencies for the strut sizes by allowing consideration of a higher k in column buckling ratios (kL/r). Since the joint has no torsional resistance pins were added through the sleeves where torsion resistance was required.

3.2 Test Results

As described in Section 1.4, the first major project using the coaxial joint was the "Roller Coaster" Pedestrian Bridge in Long Beach, California. The 9 meter (30 foot) wide bridge has a clear span of 46 meters (150 feet) with a composite concrete and metal deck-walking surface. Predicted dead load deflections were on the order of 38 mm (1.5 inches). Although anecdotal, it is of interest that when the shoring was removed, the measured deflection was approximately 25 mm (1 inch). This did not include the initial deflection between shoring towers, which may have accounted for the 13 mm (0.5 inch) difference.

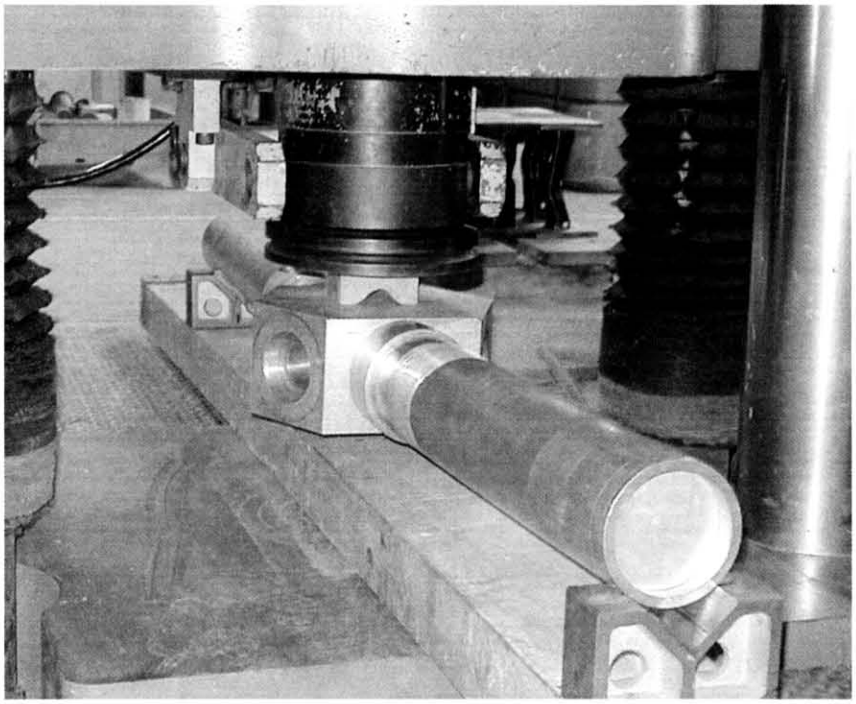


Figure 10 – Bending Test Assembly

A testing program (see figures 10 and 11) was conducted to prove the structural behavior of the aluminum coaxial joint system that was used for the "Roller Coaster" bridge. The results (see Table 1) demonstrated that the fabricated components exceeded the theoretical capacities that had been calculated. All tests were carried to destruction so that the behavior of the joint could be studied for ultimate load and failure mechanisms.

Table 1 – Test Results for CAJ Members

	Predicted Load in kips		Actual Load in kips		Percent Excess	
	Yield	Ultimate	Yield	Ultimate	Yield	Ultimate
Tension	67	79	80	96	20%	21%
Compression	79	94	82	95	4%	1%
Bending	6.4	7.6	7.5	10.5	17%	38%

It should be noted that the purpose of this test was not intended to verify the hysteresis behavior. Measurements of strain were made based on the travel of the test apparatus rather than extensometers bracketing only the joint. However, parallel tests were made on struts without joints to develop an understanding of the elastic behavior of the joint. Comparing the elastic curves for test assembly samples with joints to those without joints produced the following spring constants shown in Table 2.

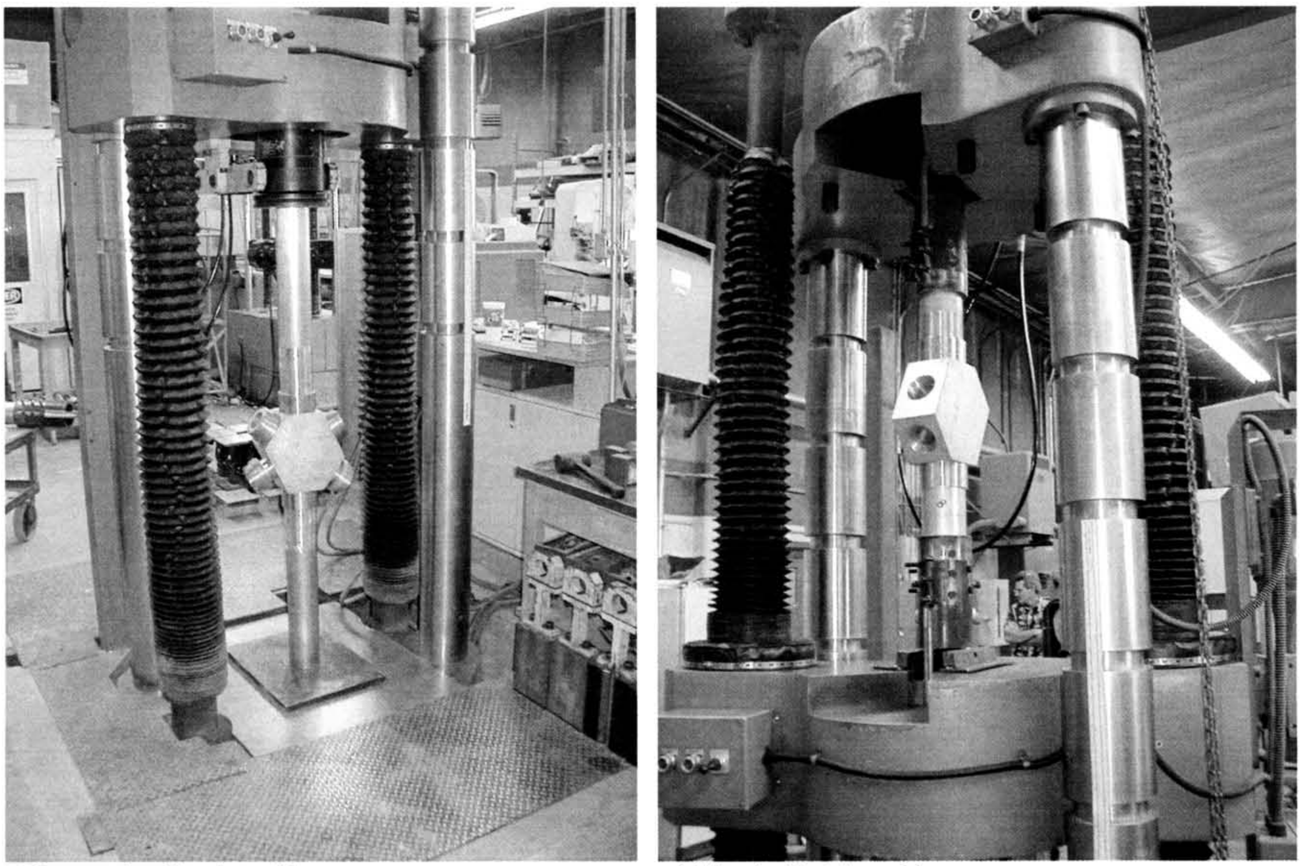
Table 2 – Spring Constants Based on Physical Testing Program

	Sample with Joint [kips/in]	Sample without Joint [kips/in]
Tension	265	333
Compression	510	512
Bending	17.5	16

3.3 Invisible connections

The testing demonstrates that this particular coaxial joint configuration resulted in a joint that was nearly "invisible" for compression loading. That is, the strut had the same elastic behavior with or without the joint. In bending, the strut with a joint was 10% stiffer than one without a joint. In tension the strut with a joint had 80% the stiffness of a strut with no joint. The lesser stiffness for the tension condition is attributable to the longer and more complex force path that the tensile forces travel through the connection. Since the connection was designed for optimizing the components for stress conditions it is apparent that the connection could have been optimized for stiffness considerations so that the joint could be "invisible" for tension as well as compression. It should be noted that the test strut lengths were on the order of 1.5 m (5 feet) while in the actual bridge structure the strut lengths were 3 m (10 feet) or more. Thus, the percentage effects described above for joint stiffness would be less for the longer members. As noted above, the actual deflections of the bridge were less than estimated which satisfied the requirements for this project.

Antenna back up structures will introduce a requirement for a higher level of predictability, which would certainly be achievable with design optimization and testing focused on more stringent criteria (see Section 2, "Use of CAJ Technology in Antenna Applications").



a) Compression Test Assembly b) Tension Test Assembly

Figure 11 – CAJ Test Assembly

Based on the work performed in the development of the coaxial joint for the bridge project it has been demonstrated that a coaxial joint system can be designed and proved by testing to meet the requirements of an idealized frame where the joints behave as if the struts were fused with "invisible" rigid joints. This creates the opportunity for efficient strut size selection, which is not true in the case of pinned connections. The nature of the thread and component assembly for the coaxial joint prevents the occurrence of hysteresis and provides a predictable and repeatable elastic deflection behavior. This is true even where eccentric joints may be considered in order to resolve small angle detailing difficulties in the framing system.

4. MANUFACTURING & ERECTION CHARACTERISTICS

4.1 Machine shop production

CAJ production utilizes standard CNC machining for the fabrication of its components. CAD models of parts and mill fixtures (figure 12) are generated through a 3-D parametric solids program with the resulting data being sent to machine shops using common .dxf or .iges file formats. Then part model data is converted to machine code that drives the milling machine operation (figure 13). Standard machine shop tolerance is usually +/- 0.127 mm (+/- 0.005 inches). As a result, all of the joint components used on the pedestrian bridge inherently had the same tolerance. Furthermore, the structural pipe was given a minimum tolerance of +/- 0.79 mm (+/- 1/32 inch) over an average length of 9 meters (10 feet).

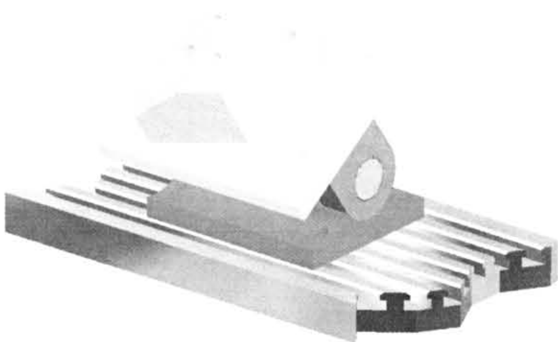


Figure 12 – 3D Computer Model

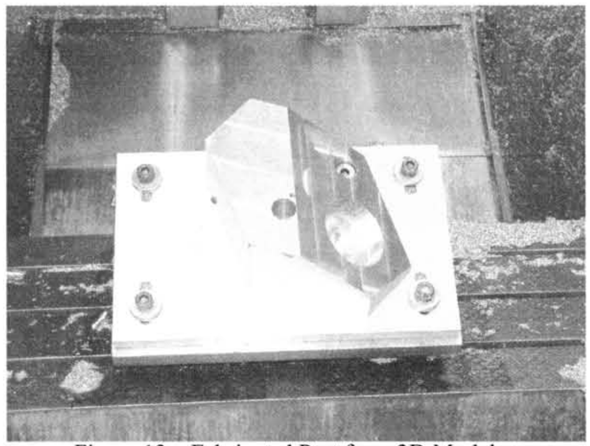


Figure 13 – Fabricated Part from 3D Model

Three different machine shops were responsible for machining mating components for the pedestrian bridge. Each shop had an in-house quality assurance program equipped with a master set of "go/no go" thread gages to perform in-process inspection on the parts.

4.2 Assembly and installation

Field assembly of CAJ components of the pedestrian bridge established three important production characteristics:

1) Mating parts from different suppliers assembled exactly as designed in the 3-D solids model. There was no mismatch between components.
2) Machine shop precision and accuracy was observed in the structure when measurements were taken of large assembled sections. The bay spacing of the bridge was set up at 3 meter (10 foot) increments. Tape measurements from joint-to-joint over 6 meter (20 foot), 9 meter (30 foot) and 12 meter (40 foot) distances revealed no visible deviations. This indicates that the system of components achieved a tolerance of +/- 0.79 mm (+/- 1/32 inch) over larger distances than a single pipe span.
3) Field assembly and erection proceeded quickly and without any part modifications. There were no parts that needed any field modifications for proper fit-up.

The erector chose to preassemble panels in a "lay down" position thereby performing most of the work at ground level, see figure 14. This approach excelled at reducing the field labor and equipment time as opposed to piecemeal erection in place. The erector then crane lifted each preassembled section into place and made the connections to the adjacent panels via man-lifts, see figure 15.

4.3 Shop and field performance

The erector employed local ironworkers to perform the installation. None of the ironworkers had seen the CAJ connection prior to this project. Nevertheless, after a minimal on-site introduction, the work proceeded correctly and quickly. At the end of the installation, the erector had completed the work ahead of schedule and within budget.

Likewise, the machine shops producing the CAJ parts completed their scopes of work on time and within budget. After all, the project demonstrated that conventional means of design, estimating, production and installation can result in the successful application of CAJ technology.

Figure 14 – Lay Down Sections of Structure

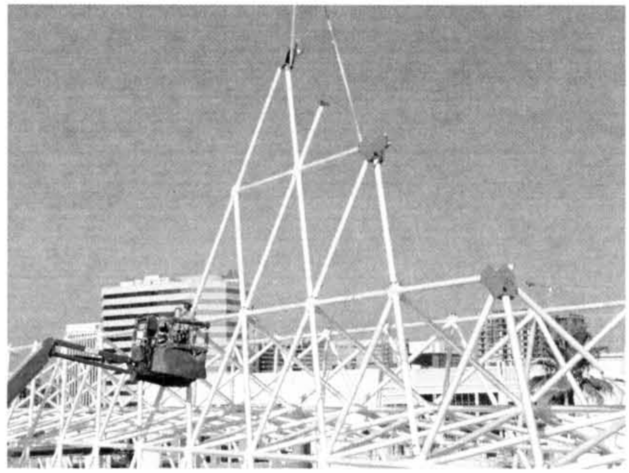


Figure 15 – Lifting Sections into Place

5. CONCLUSION

CAJ was developed because there was no suitable technology for joining round pipes to multiple-member connections with respect to the higher requirements that scientific applications impose on structures. Furthermore, this needed to be accomplished while reducing project costs. CAJ technology provides a rigid connection similar in properties to a fully-welded, fish-mouth joint but without the actual welding and associated high costs. Machine-threaded sleeves and couplings effect the connection of the round pipe to the joint resulting in a rigid joint with inherent properties that reduce and/or eliminate unwanted flexibilities and structure hysteresis. As applied to the backup structure of a radio antenna/telescope, the CAJ connection would become virtually invisible in contributing to global deformations while providing a precise and accurate platform for mounting reflective panels. This new technology has been successfully demonstrated on the construction of a large pedestrian bridge. On this project, the CAJ design was chosen over conventional systems mainly because project costs were significantly reduced.

CAJ technology comes to the scientific community via the private sector. The technology has already undergone significant development and testing with private funding. Unlike many new technologies that result from the investment of research and development resources from scientific organizations and are then disseminated to the private sector, the CAJ system has reached a high level of readiness in the private sector and is now ready for scientific applications.