2018

BOLTED STRUCTURAL CONNECTIONS IN FIBERGLASS MATERIALS

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ABSTRACT:

This paper compares several methods of connecting fiberglass reinforced pultruded plastic (FRP) structural members to tubular sections using bolted designs that are commonly used in the cooling tower industry. The study compares theoretically predicted values with full-scale actual laboratory test results.

The geometry of the structural members studied herein are representative of the diagonal bracing typically found in cooling towers, but the results are not limited to just those members, nor only to the FRP structures found in cooling towers.

INTRODUCTION AND BACKGROUND:

Typical FRP diagonal bracing geometry used in cooling towers was chosen for this study. Diagonal bracing is responsible for preventing lateral movement of the structure under loading. These loads result from winds, seismic activity, and vibrations from the equipment (e.g. pumps, fans, flowing water, etc.). They carry the accumulative static and dynamic lateral loads, fluctuating widely in magnitude between tension and compression, cyclically fatiguing the members and connections. These forces result in bearing shear stress in the connections of structural members. Reliable connection performance under this cyclic loading is essential for long-term mechanical stability over the expected life of the structure.

FRP materials, as well as both bolted and adhesive connection methods, have been very well characterized by both industry and academia. FRP manufacturers frequently endorse making combination connections by using an epoxy-type adhesive in combination with fastening screws to apply pressure to the connection while the adhesive cures. The screws also contribute to the peel strength of the joint. Properly executed, these adhesive combination connections have been proven over long periods of time to effectively carry required loading, distribute stress uniformly, and increase joint stiffness – all resulting in superior fatigue and impact resistance.(1)

The quality of these adhesive connections is highly dependent on proper preparation of the glued surfaces, as well as the ambient temperature and humidity conditions at the time the connection is made. Unfortunately, this has proven to be challenging for cooling tower construction or reconstruction, since field conditions and operator skill levels vary widely. The amount of time needed to make the connections is also significantly longer than simple bolted connections. The time-windows for tower maintenance are frequently limited by site down-time constraints. Also, verification of the connection integrity is virtually impossible after-the-fact. Finally, removing or replacing a structural member for any reason at a later date is problematic.(1,2)

As a result, bolt-only connections are the preferred connecting methodology in the cooling tower industry. Several factors are generally known to affect bolted-joint bearing strength. For example, fastener threads in the bearing areas are known to reduce bearing load capacity and accelerate hole deformation under fatigue loading.(3,4) Plastic bushings and stainless-steel bearing sleeves have been added to both increase the shear bearing area and protect the FRP from the fastener's threads.(5,6) Clamping pressure and washer diameter are known to have a significant impact on connection strength. Increasing fastener torque (clamping pressure) and washer diameter and thickness can significantly increase the static strength capacity by increasing the friction in the joint and distributing it over a larger area.(7,8,9) Loose bolts should always be avoided, particularly under reversed cyclic loading conditions.

However, the cooling tower industry is not unified when it comes to the specifics of bolting structural members to hollow tubular FRP structural members. FRP manufacturers caution against applying clamping/compression on unsupported cross-sections of tubular structural members.(3,10) When compression is required for maximum joint strength and stiffness, FRP manufacturers recommend using spacer blocks to prevent bolt tension from damaging the column profile.(10,11) This adds material cost and installation labor time, but compression in the connection creates what may be referred to as a strong "friction-type or slip-critical joint."(12)

Without internal support in the tube, applying even relatively low levels of tension in the connections (e.g., only 13-16 N-m (10-12 ft-lbs) of fastener torque on a Ø12.7 mm (Ø½") fastener) results in cracking of the tube (inelastic failure) in the fastener location, as well as at the tube's corners, as shown in Figure 1. This failure mode ensures there is little-to-no tension in the connecting bolt and the connections will loosen over time due to creep.(13) Unfortunately, Figure 1 is a very common field observation throughout the cooling tower industry.(14)

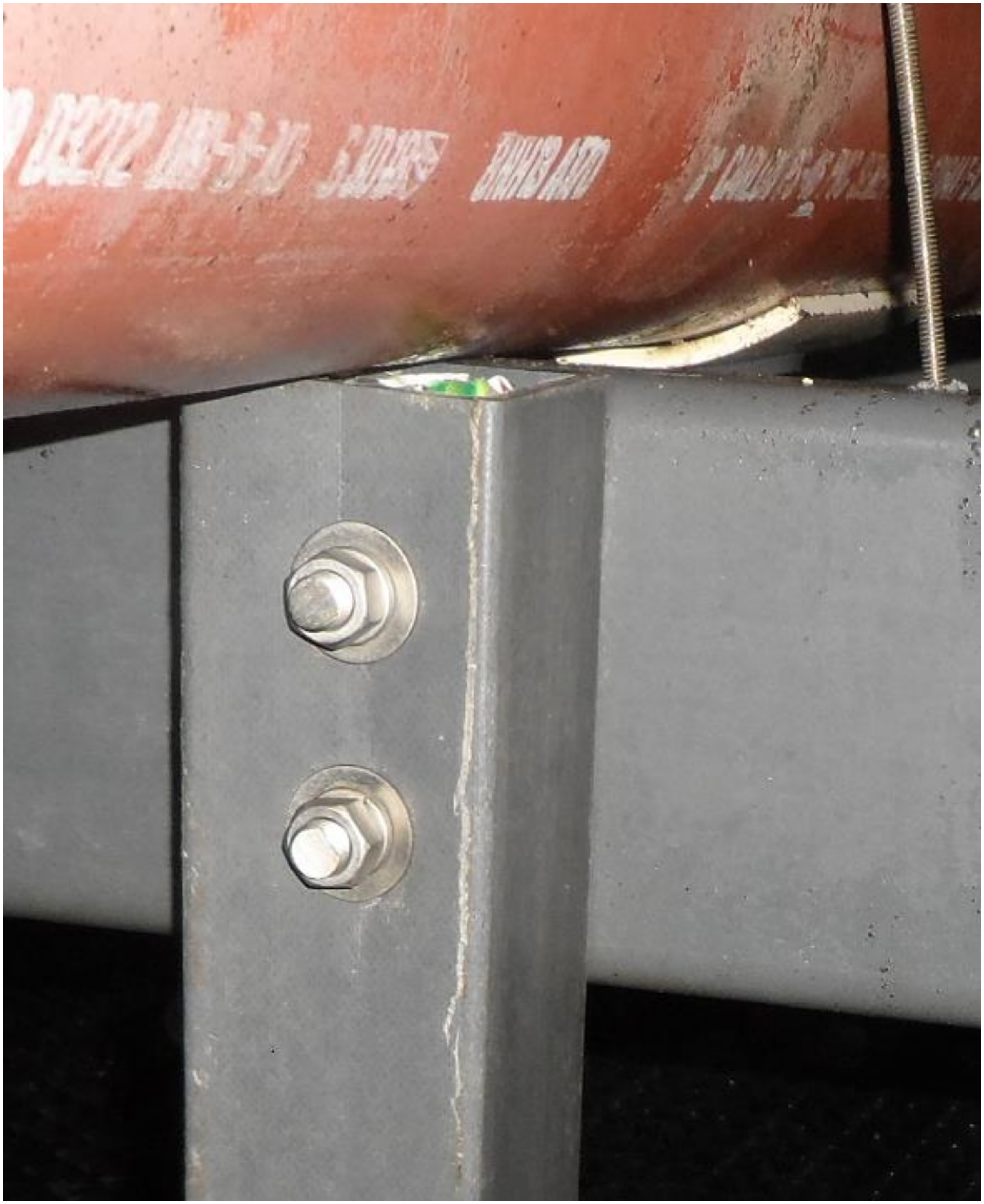


FIGURE 1
EXCESSIVE COMPRESSION ON UNSUPPORTED FRP STRUCTURAL TUBING

A compromise solution used in the industry to the problem of not significantly compressing the tube while avoiding the added cost of inserting spacer blocks or full-width support tubes is to treat bolted connections to tubular columns as bearing-only or "pinned" joints, idealized by a clevis pin and hairpin cotter retainer. One practical implementation is making connections by using self-locking nuts and only lightly tightening the nuts. These nuts are about 3 times the cost of standard nuts and limits installation to hand tools and proper operator training and technique.

Another approach suggests applying an anaerobic locking compound to the nut and "finger-tightening" standard nuts to secure assemblies.(6) It is common practice to use stainless steel fasteners in cooling towers for corrosion resistance since they generate an oxide film for corrosion protection. However, during assembly the oxides are broken, possibly even wiped off. This reduces corrosion protection and can result in galling, leading to thread seizure. To protect against this occurring, CTI recommends applying a thread lubricant when using stainless-steel fasteners.(15) Some anaerobic locking compounds do offer some degree of lubrication before curing.(16) Careful adhesive selection and proper application is critical. Again, installation is limited to hand tools and proper operator training and technique.

An alternative method commonly employed is to use a helical-spring split locking washer under the nut and only tightening the fastener until the spring washer is compressed – essentially using the washer as a "torque gage". Compressing a typical Ø12.7 mm (Ø½") stainless-steel split locking washer only requires about 1.4 to 2.7 N-m (1 to 2 ft-lbs) of torque on the fastener, producing little-to-no tension on the connection and results in no damage to the FRP tube(13) This is commonly referred to as a "snug-tight" connection.(12) This makes the use of power tools possible but dangerous. Many installers in the industry limit operators to using only hand tools to avoid the condition shown in Figure 1. This requires additional installation labor and quality monitoring. But more importantly, bolts installed with this limited-tension method are frequently found to be completely loose and even missing entirely due to tower vibrations and thermal cycling (creep) over time. A helical-spring lock washer is effective only when one of the materials being fastened (e.g. lumber) are soft enough for an edge of the spring washer to dig into one of the surfaces. Since neither the nut nor the FRP are soft enough, by the time the washer is flattened, helical-spring washers are effectively useless for locking in this application.(16)

Figure 2 shows examples of such disorders at one recently-inspected site. Alarmingly, this follow-up inspection was done less than six months after its initial installation. The photos shown in Figure 2 are not isolated cases within this large installation. More disturbingly, this condition is commonly the case found during many tower inspections. (14)

FIGURE 2
LOOSE AND MISSING BOLTS FOUND DURING SITE INSPECTION

Regardless of the implementation method, pinned connections have been shown to be inferior to properly executed combination adhesive-mechanical connections in terms of ultimate tensile and compression strength. Pinned connections produce ultimate yield strengths that are only about 60 percent as strong as classical theory would predict or as comparable adhesive/fastener combination connections. Adhesive connections have been demonstrated to be as strong as the polyester-to-polyester shear strength of the connected substrates.(2,17)

Even more importantly, however, pinned connections cannot, by definition, contribute any torsional moment resistance needed for structural stiffness against the fatigue loading from the shifting cyclical compressive and tensile forces existing in the diagonal members. Practical joints are rarely loaded in pure shear or tension. Indeed, field inspections of FRP towers that have been in service for several years with pinned connections shows clear indication that the clearance holes of pinned FRP connections have elongated from cyclic wear, particularly near the top of the tower where deflections are greatest.(14) Figure 3 shows two such examples. Note that the bolt thread pattern is worn into the hole in the picture on the left. The hole on the right had been dramatically elongated before the bolt fell out.

FIGURE 3
DAMAGED BOLT HOLES OF PINNED CONNECTIONS

An adhesive connection or a properly-designed and installed bolted connection with sufficient clamping pressure supplies resistance to bending and cyclic forces.(18) The purpose of this study is to compare the performance of various versions of bolted pinned connections to FRP tubes with bolted connections that are design for compression and tightly clamped.

TEST METHODOLOGY:

This study is limited to the more severe tensile rather than compression loading in composite joints. Composite joints subjected to compression loading are less sensitive to joint geometry and are generally stronger than joints subjected to tensile forces. Members are loaded in the lengthwise orientation according to the direction of the pultrusion to utilize the maximum tensile strength available from the FRP. All edge distances exceed the minimum recommendations relative to bolt diameter. As such, the predicted failure mode is bearing failure, rather than failure by tension or shear out. Bearing failure is caused by the bearing pressure forces from the bolt applied to the hole boundary producing delamination of the composite.(7,9,18,19) Historically, bearing failure has been defined as 4% elongation of the bolt-hole diameter. No appreciable load capacity can be expected after the 4% diameter elongation is met. Any further elongation of the holes only allows the structure to become loose and unstable.(4,17,18,19)

The FRP materials used for this test are fire retardant polyester, compliant with CTI industry standards.(20,21) Cross-sectional dimensions of the tubes are 88.9 mm square x 6.4 mm thick (3.5” square x 0.25” thick). Cross-sectional dimensions of the straps are 76.2 mm wide x 9.6 mm thick (3.0” wide x 0.38” thick). Fastener materials are all of S30400-grade stainless steel, Ø12.7 mm-13 (Ø½”-13) UNC. One flat washer is placed below the head of the bolt. One flat washer and one helical locking washer is placed under the nut. All threads are lubricated with a graphite-petrolatum anti-seize compound.

Five different bolted-joint configurations are examined as described in Table 1.

TABLE 1
TEST CONFIGURATIONS

CONF. NO.	SHEAR BUSHING INSERT	TUBE CLEARANCE HOLE	STRAP CLEARANCE HOLE	TIGHTENING CONDITION/JOINT TYPE
№ 1	**NONE**	**Ø14.3 mm (Ø0.56”)**	**Ø14.3 mm (Ø0.56”)**	**SPLIT WASHER FLATTENED (SNUG-TIGHT/PINNED)**
№ 2	**STANDARD PLASTIC PARTIAL-LENGTH SHEAR BUSHINGS(a)**	**Ø26.4 mm (Ø1.04”)**		**SPLIT WASHER FLATTENED (SNUG-TIGHT/PINNED)**
№ 3	**FULL-LENGTH S.S. SHEAR TUBE(b)**	**Ø20.3 mm (Ø0.79”)**		**38-41 N-m (28-30 ft-lbs) TORQUE(d) (TIGHTLY CLAMPED)**
№ 4	**MATING FULL-LENGTH PLASTIC SHEAR BUSHINGS(c)**	**Ø26.4 mm) (Ø1.04”)**		**SPLIT WASHER FLATTENED (SNUG-TIGHT/PINNED)**
№ 5	**MATING FULL-LENGTH PLASTIC SHEAR BUSHINGS(c)**	**Ø26.4 mm (Ø1.04”)**		**38-41 N-m (28-30 ft-lbs) TORQUE(d) (TIGHTLY CLAMPED)**

(a) Standard Partial-Length Bushings: 25.4 mm O.D. x 14.3 mm I.D. x 12.7 mm long (Ø1.00” O.D. x Ø0.56” I.D x 0.50” long). Polycarbonate plastic material.

(b) Stainless-Steel Tube: 304 ASTM A269 Seamless Round 19 mm O.D. x 14.2 mm I.D. x 88.9 mm long (Ø0.75” O.D. x Ø0.58” I.D. x 3.50” long).

(c) Mating Full-Length Shear Bushings: 25.4 mm O.D. x 14.3 mm I.D. x 44.5 mm long (Ø1.00" O.D. x Ø0.56" I.D x 1.75" long). Polycarbonate-blend plastic material. These are similar to the standard shear bushings described in (a) above that are also commercially available in 44.5 mm (1.75") lengths.(5) But, this is a newly-designed, custom-molded component. It has been designed with the added feature of a larger, thicker integral washer/flange to better distribute compression stress and increase friction in the connection. It also adds self-retention features to snap into the clearance hole, facilitating more efficient field assembly (patent pending).

(d) 39 N-m (29 ft-lbs) of applied torque results in approximately 20.5 kN (4600 pounds) of clamping tension in a lubricated bolted connection ($K_{EST} = 0.15$). 20.5 kN (4600 pound is about 75% of the stainless-steel's bolt proof strength.(22,23) This is generally recommended best practice to achieve tightly-clamped bolted connections.(18,23)

The five configurations described in Table 1 are illustrated in Figures 4A-4D:

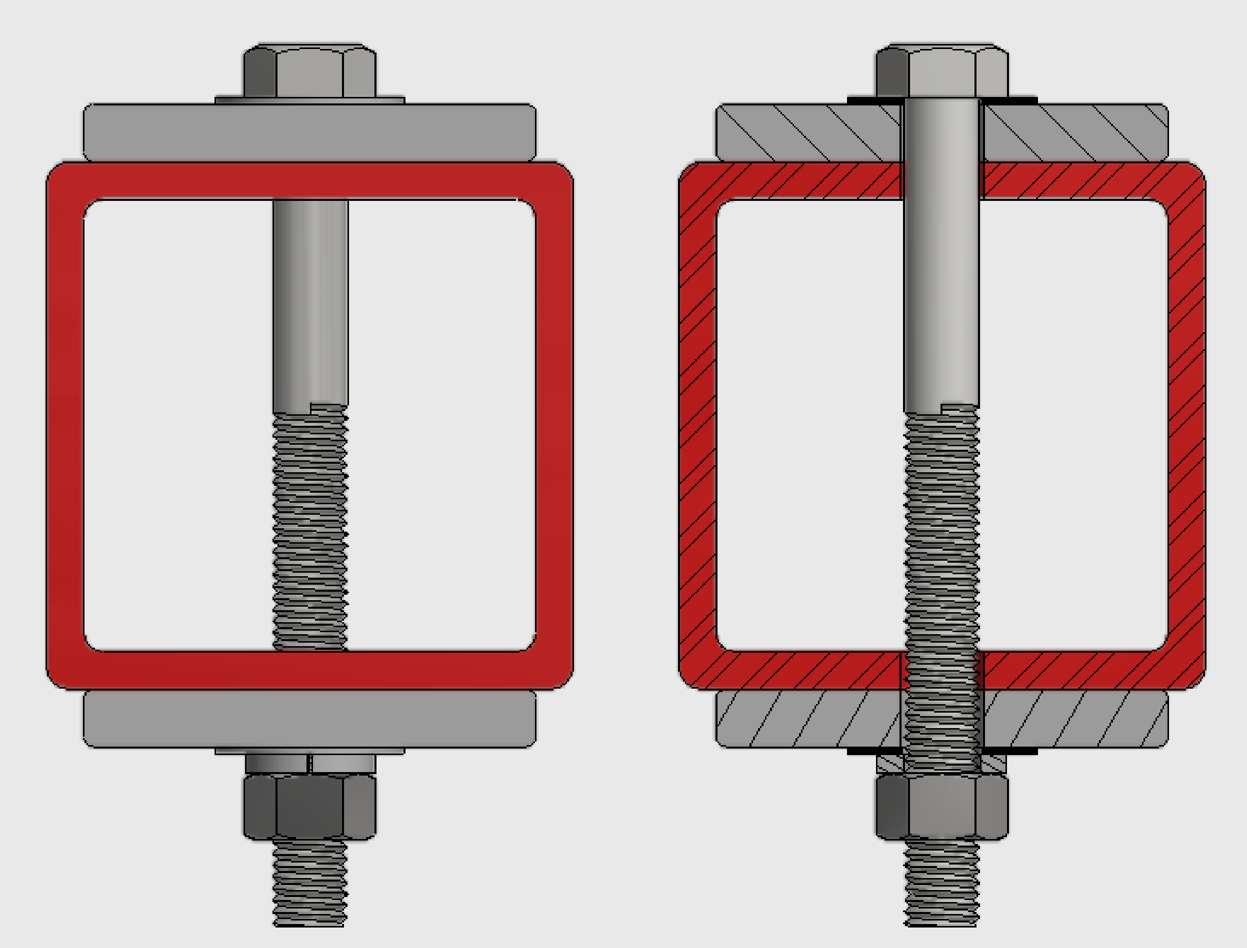


FIGURE 4A – CONFIGURATION *№ 1*
NO SHEAR BUSHINGS: SNUG-TIGHT TENSION (PINNED CONNECTION)

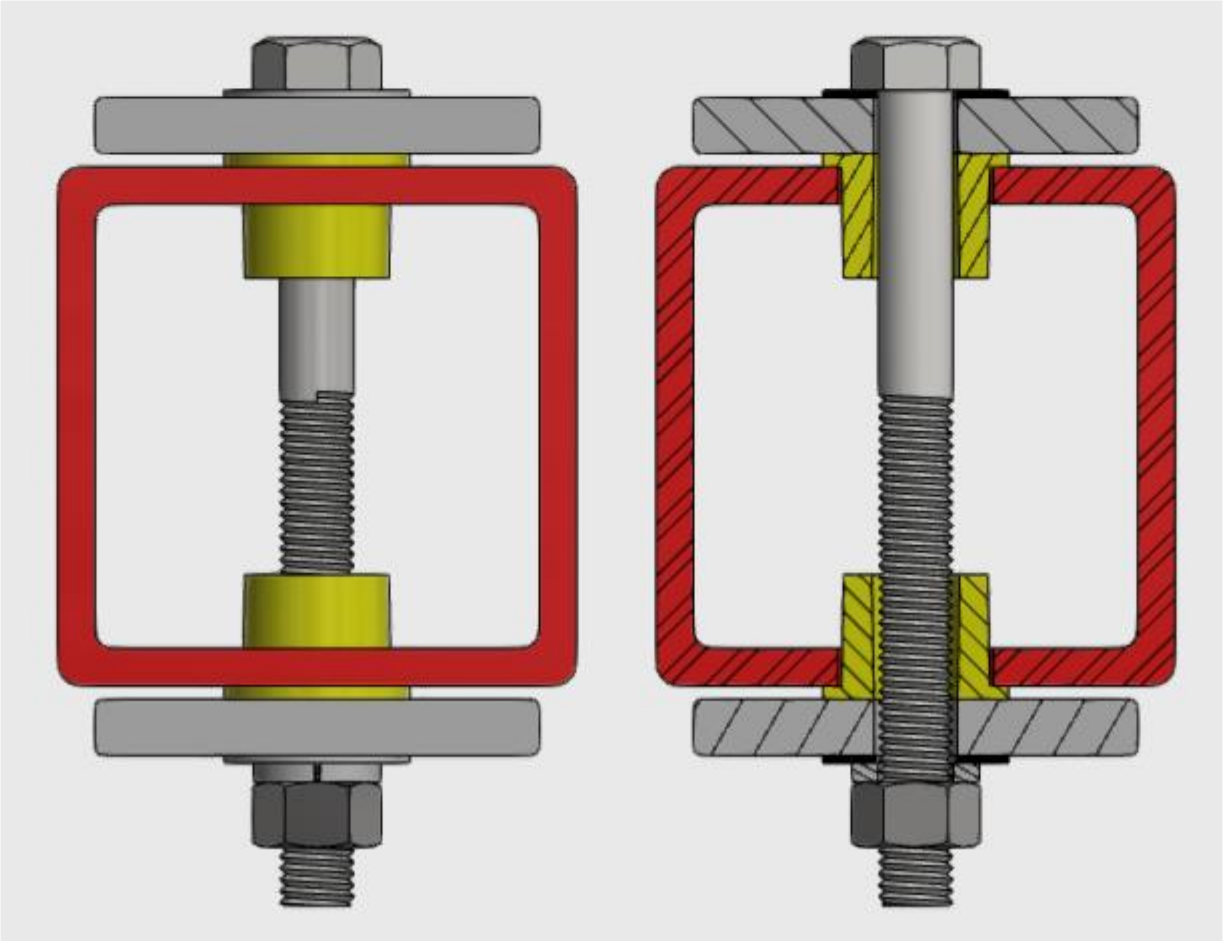


FIGURE 4B – CONFIGURATION *№ 2*
STANDARD FLANGED PLASTIC PARTIAL-LENGTH SHEAR BUSHINGS:
SNUG-TIGHT TENSION (PINNED CONNECTION)

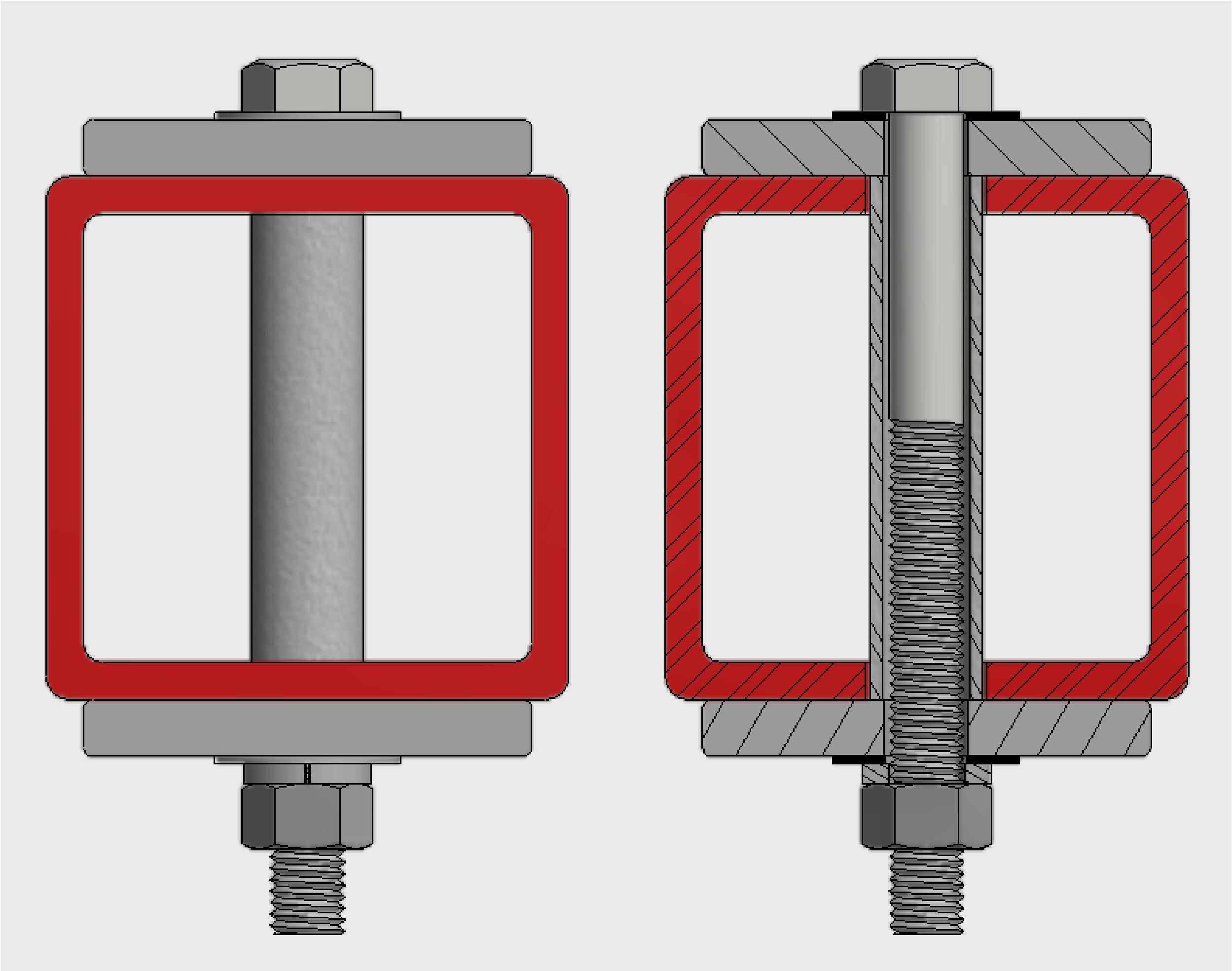


FIGURE 4C – CONFIGURATION *№ 3*
STAINLESS STEEL FULL-LENGTH SUPPOT TUBE/SHEAR BEARING:
39 N-m (29 FT-LBS) TORQUE (TIGHTLY CLAMPED CONNECTION)

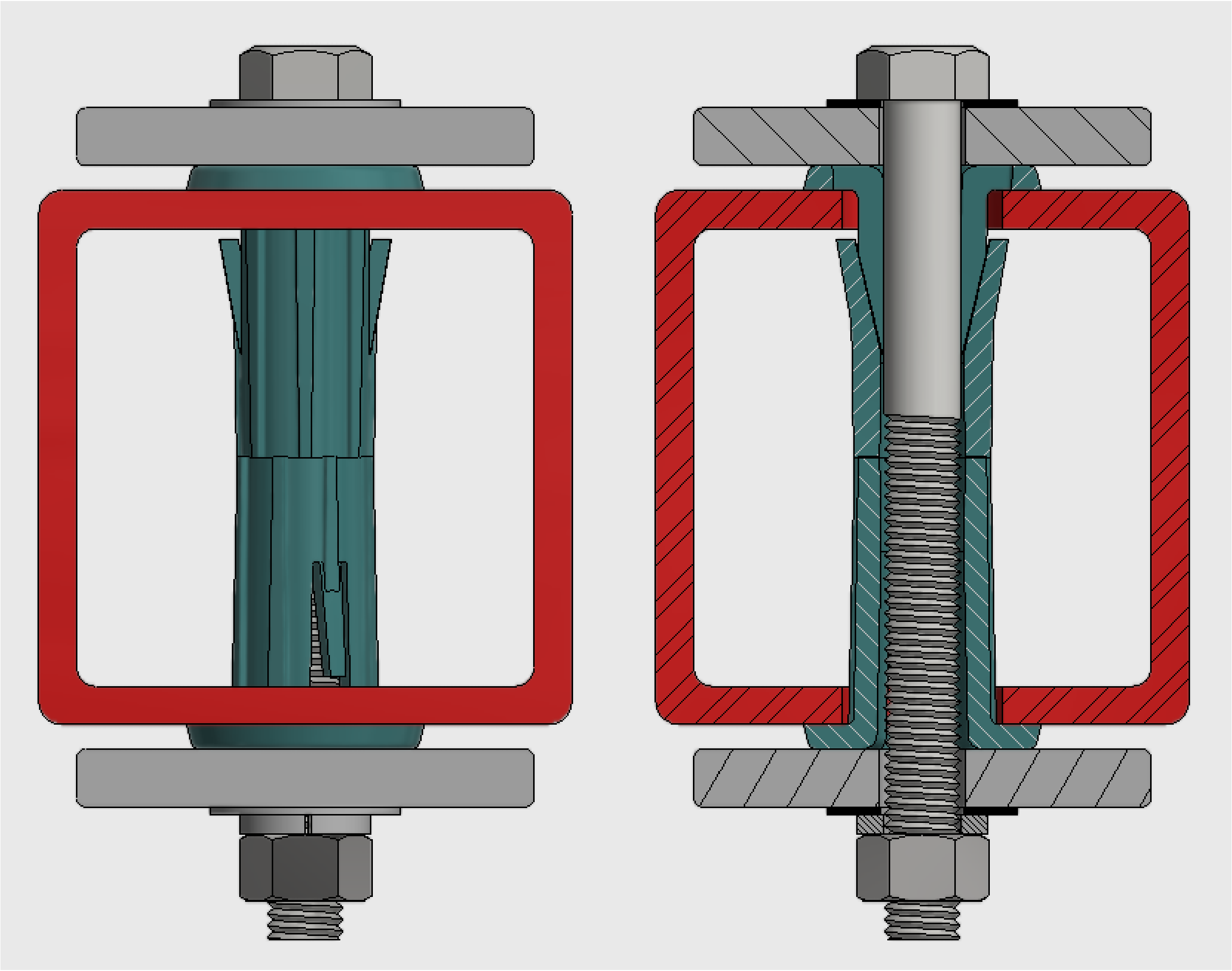


FIGURE 4D – CONFIGURATIONS *№ 4 & № 5*
MATING FULL-LENGTH SHEAR BUSHINGS TESTED UNDER TWO CONDITIONS: SNUG-TIGHT TENSION (PINNED CONNECTION) AND 39 N-m (29 FT-LBS) TORQUE (TIGHTLY CLAMPED CONNECTION)

A test fixture designed to perform this testing is shown in Figure 5. It is comprised of two identical yokes to hold the specimens under test by clamping the tubes and interface them to an Instron® 3384 Tester, as shown in Figure 6. As stated above, the scope here is limited to tensile-only testing, although the fixture is capable of compression testing (and, hence, cyclical testing) as well for future work.

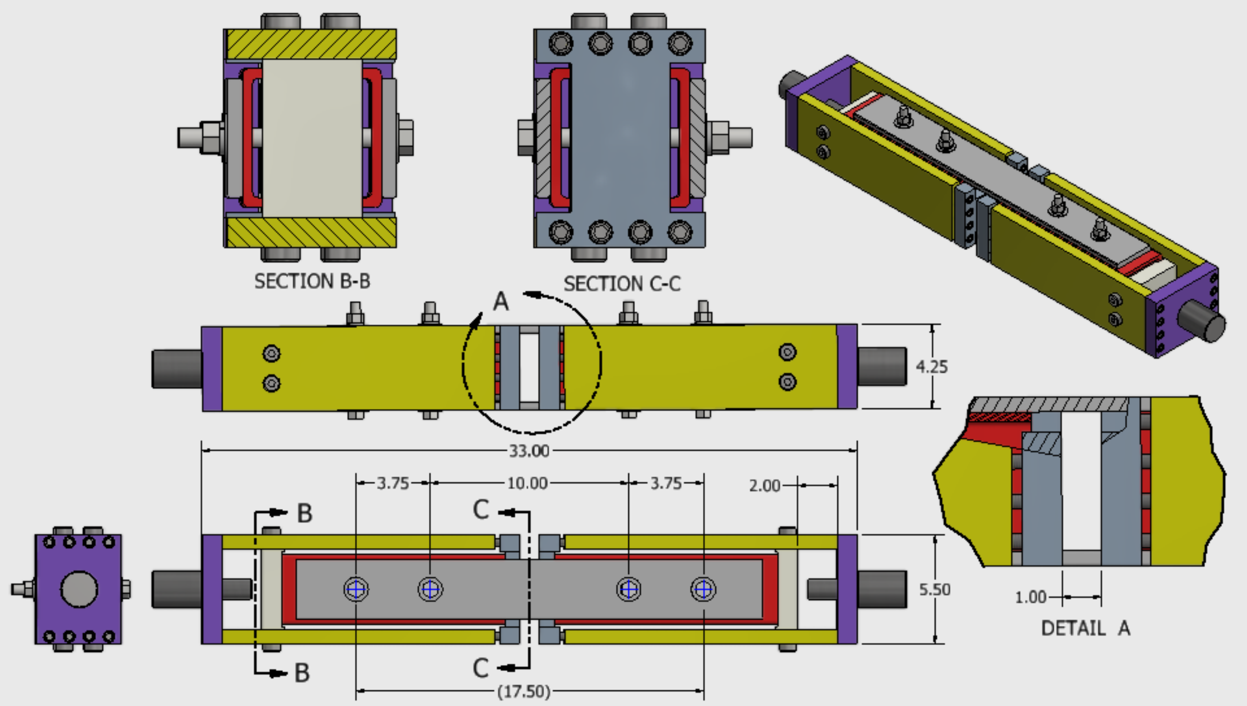


FIGURE 5
TENSILE (OR COMPRESSION/CYCLICAL) TEST FIXTURE

Since this system is more complex than a single bolt/hole configuration, a gage length of 254 mm (10”) is used and a marker set on the output curves at the 10.2 mm (0.4-inch) elongation point (4%) to use as an arbitrary reference point to compare results with those of the references previously cited above.

It is important to note that there is significant “slack” in the pinned test specimens due to the clearance holes in the four connections. A pre-load of 1.3 kN (300 pounds) was placed on all test specimens under test (both pinned and clamped) before the bolts were either snug-tightened or torque-tightened to remove this slack. This is needed to “normalize” the graphical representations of the data. Otherwise, there are long and varying levels of “dead-time” at the base of the curves of the pinned specimens while the slack is taken out of the system.

Three samples of each of the five configurations in Table 1 are tested by increasing tensile force at a rate of 2.54 mm/min (0.10 in/min) to failure. Elongation is recorded in the process. The slopes of the force-strain curves (elastic modulus of the systems) are compared for each configuration. Higher elastic modulus is indicative of the stiffness of the structure and its resistance to cyclic fatigue loading.(24,25,26,27)

FIGURE 6
FIXTURE WITH TEST SPECIMEN MOUNTED TO TENSILE TESTER

Ideally, a more statistically significant number of samples of each configuration would be tested (30 or more), but pragmatic constraints limited the number to only three.

Finally, one new sample is assembled with the mating plastic shear bushings and a structural member attached to one side of the tube only. The purpose of this test is to determine the worst-case safety factor of the bushing's ability to protect the FRP tube under compressive torque loading. This configuration is shown in Figure 7. The bolt is tightened beyond the recommended 39 N-m (29 ft-lbs) of torque until audible cracking in the tube is heard. Audible cracking is indicative of the fibers in the composite breaking and the beginning of degradation of the FRP.(24) The tube will only take a few N-m (ft-lbs) of torque beyond this point before it catastrophically fails as shown in Figure 1.(13)

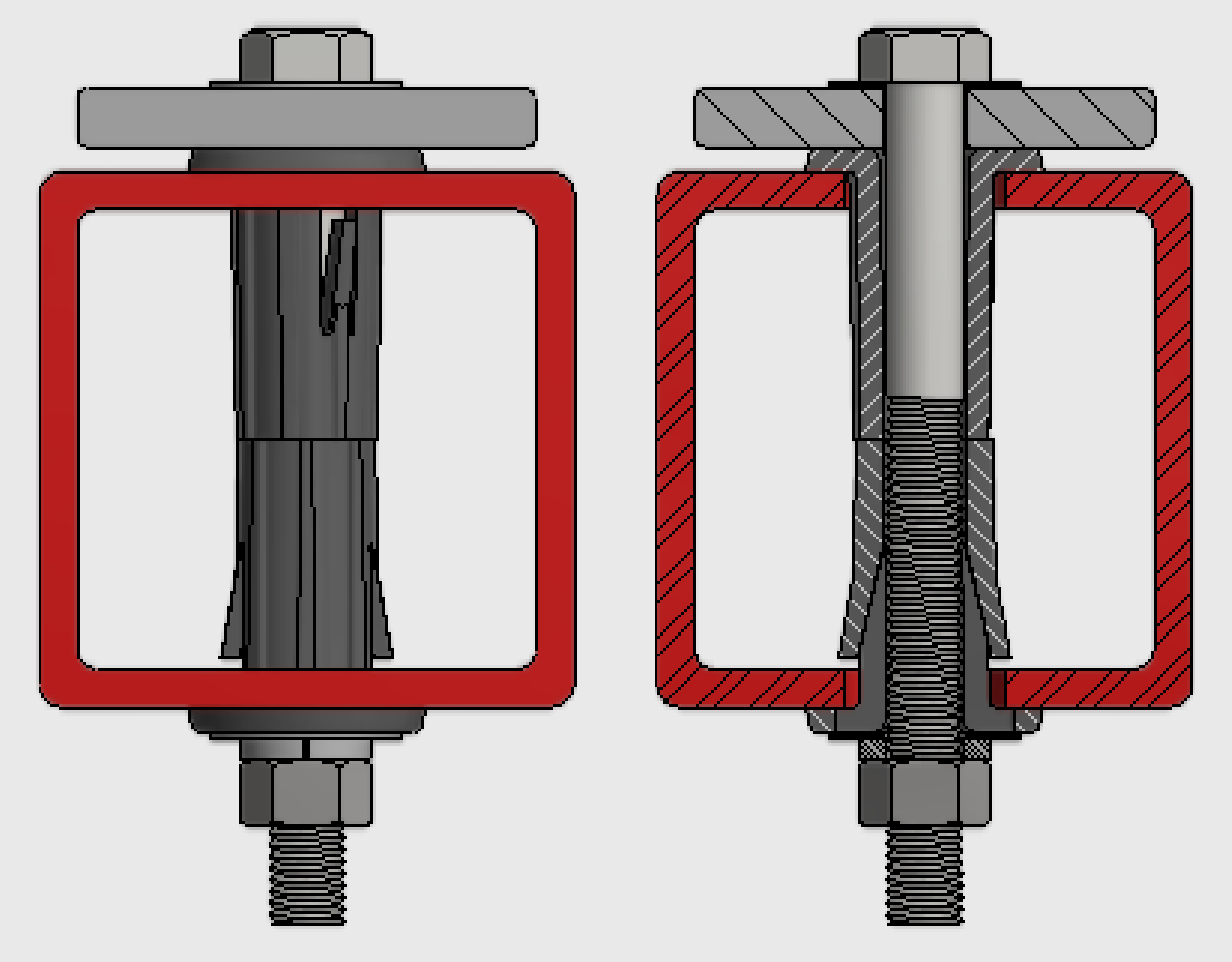


FIGURE 7 – CONFIGURATION *<u>№ 6</u>*
MATING SHEAR BUSHINGS: COMPRESSION SAFETY FACTOR TEST

PREDICTED RESULTS:

TENSILE TESTING

As stated above, the predicted failure mode during the testing is bearing failure. Based on data in the public domain and conventional engineering analysis, the ultimate predicted failure values and modes for the samples being tensile tested are summarized in Table 2.

TABLE 2
THEORETICALLY PREDECITED RESULTS

CONF. NO.	TUBE STRENGTH kN (POUNDS)	STRAP STRENGTH kN (POUNDS)	PREDICTED FAILURE POINT
№ 1	**67 (15,000)**	**100 (22,500)**	**TUBE**
№ 2	**133 (30,000)**	**100 (22,500)**	**STRAP**
№ 3	**117 (26,250)**	**100 (22,500)**	**STRAP**
№ 4	**133 (30,000)**	**100 (22,500)**	**STRAP**
№ 5	**133 (30,000)**	**100 (22,500)**	**STRAP**

For reference, extrapolating the methodology detailed in Reference 17, the theoretical strength of an 8-screw, 100 mm long (4” long) epoxy adhesive connection to a 76.2 mm wide (3.0” wide) strap is about 98 kN (22,000 pounds).

BUSHING COMPRESSION TESTING

For the one sample being tested for bushing/FRP tube compression failure (Figure 6 – Configuration *№ 6*), based on the mechanical design of the mating shear bushings and the published properties of the plastic polycarbonate-blend material, the failure mode is predicted to be compression/cracking of the bushing’s flange at 31 kN (7,000 pounds). This is slightly higher than the theoretical yield strength of the bolt (about 29 kN (6,500 pounds)), so it is expected that there could be some inelastic deformation of the bolt.(11,22) The torque value at which this would occur is, therefore, unpredictable.

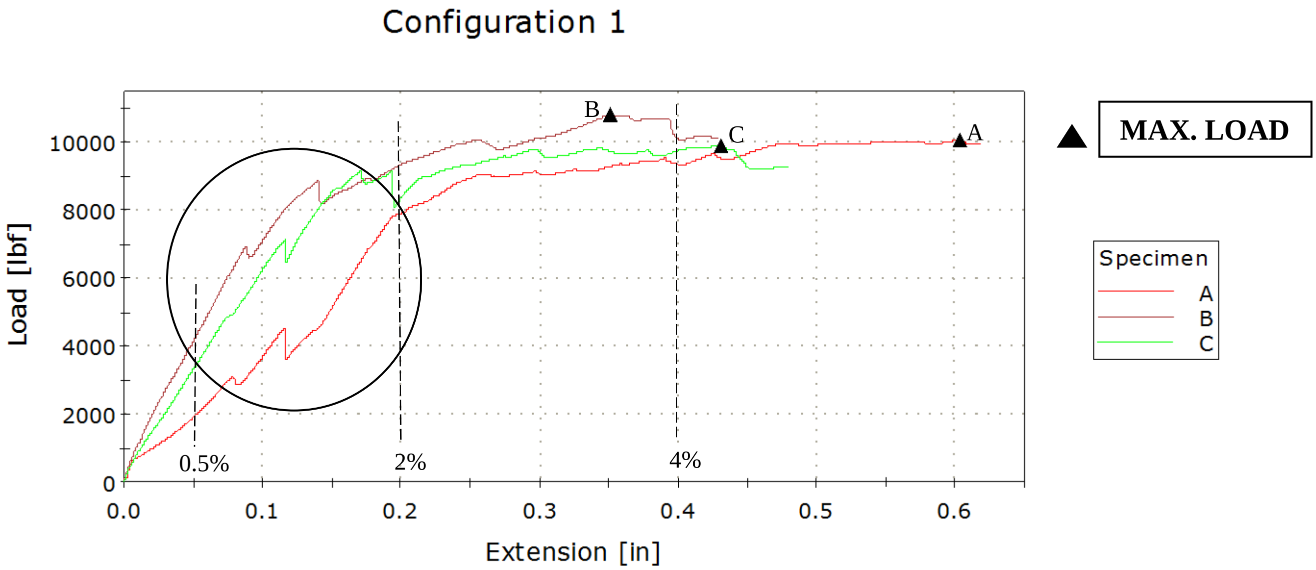
Also, it is expected based on the development history of this component that the bushing without the benefit of the structural member over it to distribute the compressive force is the one that will first show evidence of damage. The washer on the bushing without the benefit of the structural member to distribute the load will be deformed and drawn into the clearance hole.

The full-length stainless-steel bearing tube is not tested in this fashion because its theoretical compressive strength of the steel tube is more than 40kN (9,000 pounds), far exceeding the bolt's limit.(13,22)

ACTUAL RESULTS & INTERPRETATIONS – TENSILE TESTING: (28)

Configuration № *1* (Figure 4A – No Shear Bushing/Pinned Connection)

SPECIMEN	MAX. LOAD: kN (Pounds Force)	LOAD AT 4% STRAIN: kN (Pounds Force)	LOAD AT 0.5% STRAIN kN (Pounds Force)	MODULUS AT 0.5% STRAIN kN/mm (Pounds Force/Inch)
A	**44.80 (10,071)**	**41.59 (9,349)**	**8.54 (1,921)**	**6.72 (38,420)**
B	**48.00 (10,790)**	**44.89 (10,092)**	**18.43 (4,144)**	**14.51 (82,880)**
C	**44.05 (9,902)**	**43.37 (9,751)**	**14.68 (3,301)**	**11.56 (66,020)**
MEAN	**45.61 (10,254)**	**43.29 (9,731)**	**13.88 (3,122)**	**10.93 (50,914)**

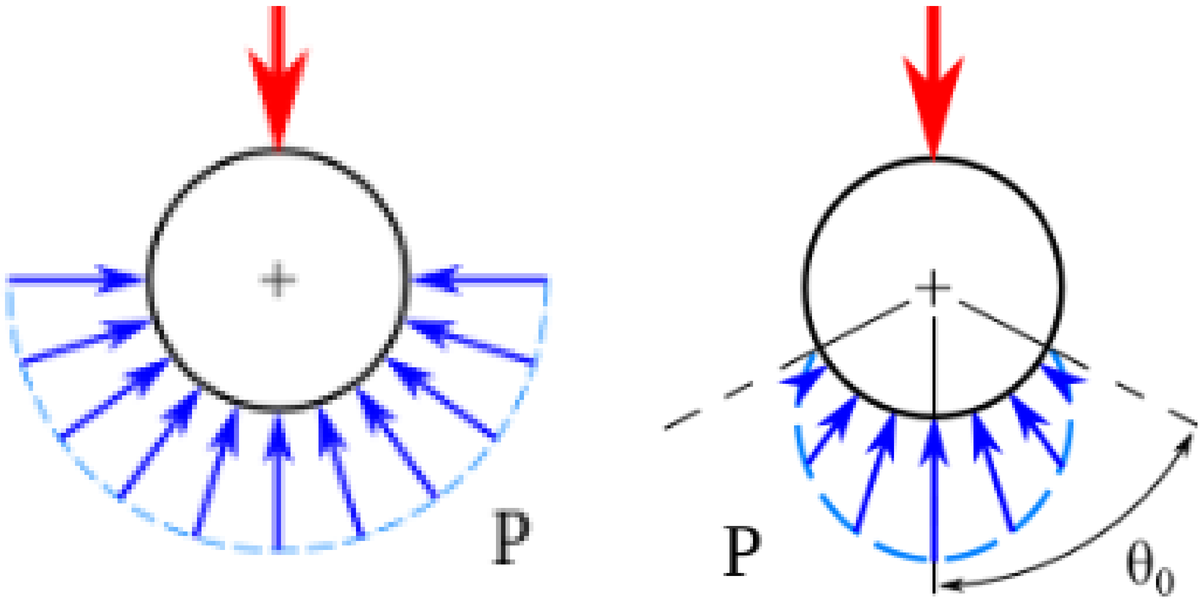


As the pictures in Figure 8 below show, the failure points are the bearing surfaces in the tubes (as predicted). The straps and bolts showed no visible deformation. These results mimic those reported in the prior noted references: Ultimate failure occurs very near the 4% elongation value at loads that are far lower than theoretically predicted. Additional loading simply tares the bearing surfaces out catastrophically. More significantly and surprisingly, however, the curves above show the bearing areas distinctly breaking down along the way to 4% elongation, notably near the 1% and the again at the 2% elongation levels. (These were audible events during the testing.) From this testing, a case could be made that the samples actually failed when the curves began to flatten at 2% at 35.6 kN (8,000 pounds). Were these samples of metal construction (ductile in nature), they would be classified as "yielding" at this point. The modulus calculation for this configuration was done at only 0.5% strain for this reason. These values are highly varied and of questionable significance.

4% ELONGATION POINT   FAILURE AT >4% LOAD

FIGURE 8 – CONFIGURATION *№ 1 /* SAMPLE A: 44.8kN (10.0 K-POUNDS)

The pictures in Figure 8 point to the reason that the bearings failed at less than two-thirds of the theoretically predicted levels. The predicted values assume negligible clearance and inelastic bodies, i.e., it assumes the bearing pressure is uniformly distributed. The reality, as shown in Figure 9, is that the bearing pressure is concentrated over a much smaller effective area due to the hole clearance needed for practical assembly.(29)



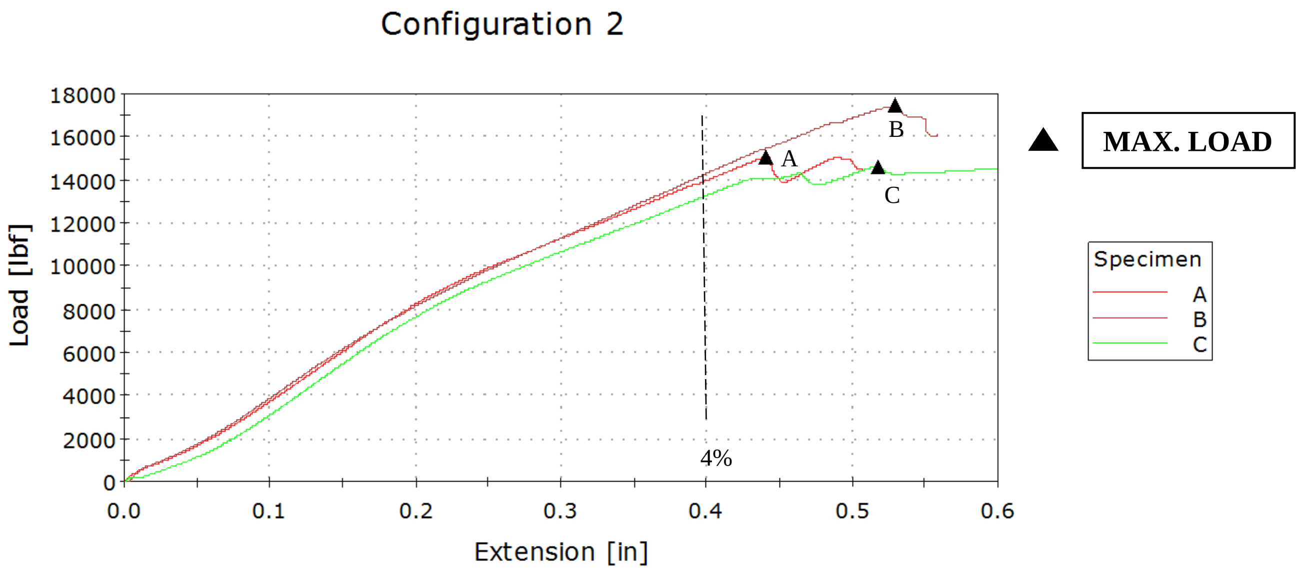
IDEALIZED LOADING **ACTUAL LOADING**

BEARING PRESSURE CONCENTRATION

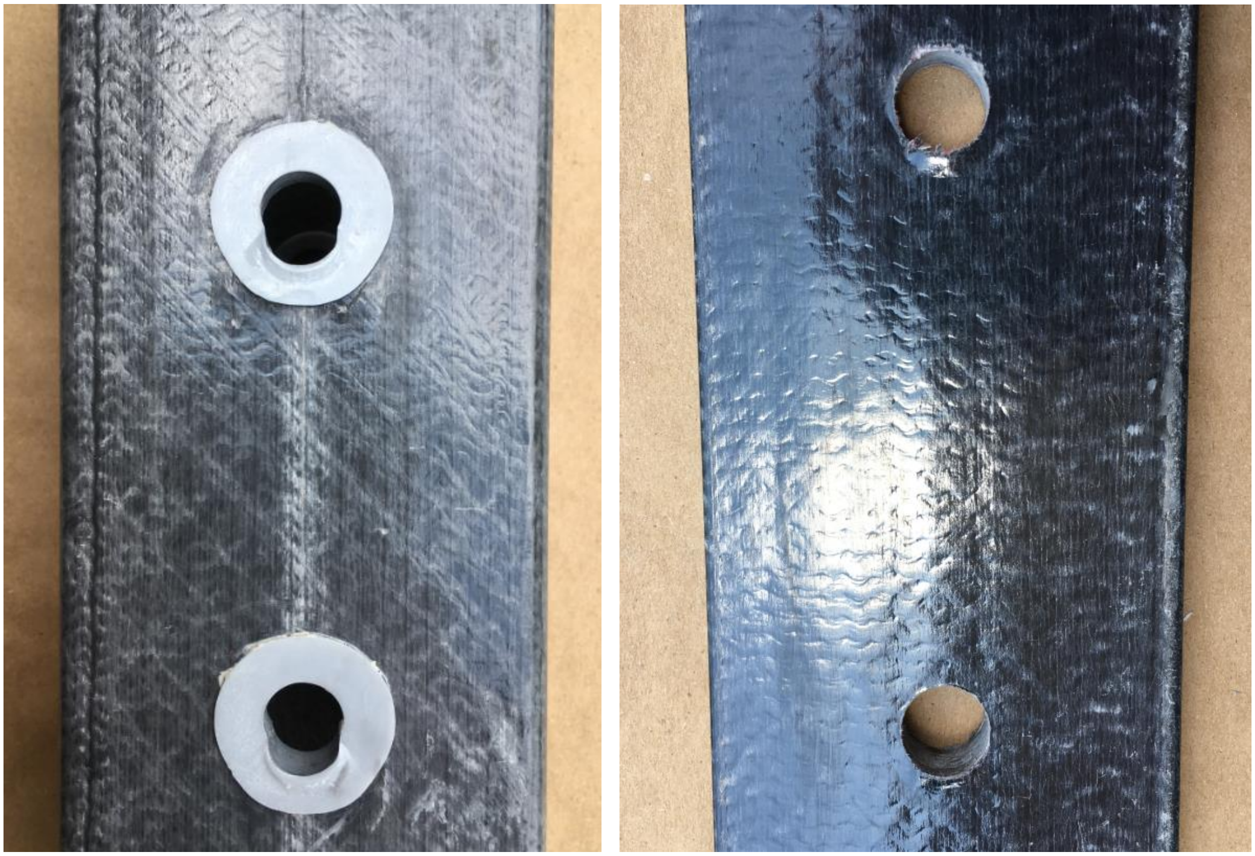
FIGURE 9

Configuration № 2
(Figure 4B – Standard Partial-Length Shear Bushing/Pinned Connection)

SPECIMEN	MAX. LOAD: kN (Pounds Force)	LOAD AT 4% STRAIN: kN (Pounds Force)	MODULUS AT 4% STRAIN kN/mm (Pounds Force/In)
A	**67.00 (15,062)**	**62.11 (13,962)**	**6.34 (34,905)**
B	**77.63 (17,453)**	**63.57 (14,291)**	**6.47 (35,728)**
C	**65.03 (14,620)**	**59.02 (13,268)**	**6.02 (33,170)**
MEAN	**69.89 (15,712)**	**61.56 (13,840)**	**6.28 (34,600)**



These curves show the samples behaving much more consistently and predictably with the addition of shear bushings. The bushings double the shear-bearing area and distribute the pressure more uniformly. Catastrophic tear out of the tubes was not observed. This can be seen in the pictures in Figure 10. Theory predicted the failure mode would shift to the strap and should have held to 100 kN (22,500 pounds). The mean was 70 kN (15.7 k-pounds) – 70% of the predicted value. The straps did not have the benefit of a bushing and the effect of bearing-pressure concentration in the straps (as shown in Figure 9) is the likely explanation of the deficit. The bolts also deformed inelastically, indicating that system failure is fairly uniformly distributed across all the components at this point.



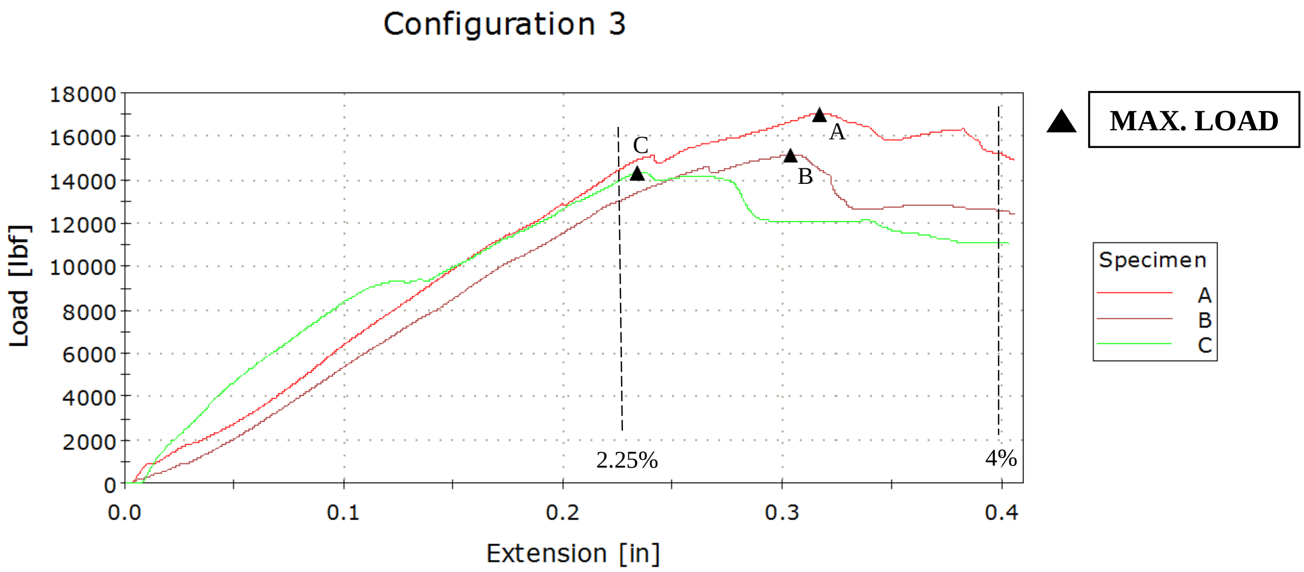
TUBE **STRAP**

BOLT

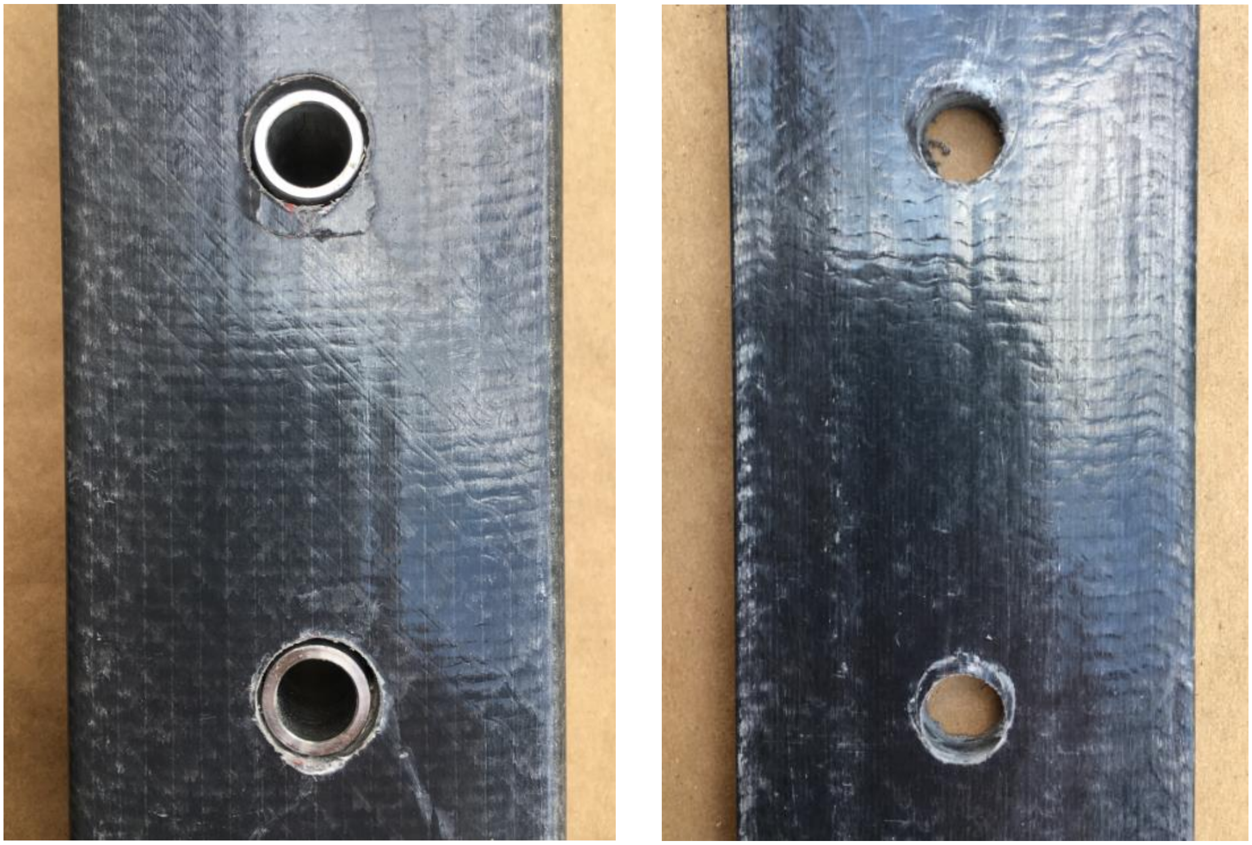
FIGURE 10 – CONFIGURATION *№ 2* / SAMPLE B
17.4 K-POUNDS (77.6 kN)

Configuration *№ 3* (Figure 4C – S.S. Full-Length Tube/Torqued Connection)

SPECIMEN	MAX. LOAD: kN (Pounds Force)	LOAD AT 4% STRAIN: kN (Pounds Force)	LOAD AT 2.25% STRAIN kN (Pounds Force)	MODULUS AT 2.25% STRAIN kN/mm (Pounds Force/Inch)
A	**75.76 (17,035)**	**67.54 (15,183)**	**64.16 (14,423)**	**11.23 (64,102)**
B	**67.51 (15,176)**	**55.85 (12,556)**	**61.89 (13,913)**	**10.84 (61,835)**
C	**63.65 (14,309)**	**49.29 (11,082)**	**57.70 (12,971)**	**10.00 (57,649)**
MEAN	**68.98 (15,507)**	**57.56 (12,941)**	**61.25 (13,769)**	**10.69 (61,195)**



The pictures in Figure 11 again show the system uniformly failing at the tube bearing surfaces, the strap bearing surfaces, and the bolt itself. The combination of the full-length stainless-steel shear bearing and the clamped connection produced a much stiffer system – about twice that of the plastic bushing in a pinned connection. This is reflected by the system's higher modulus. Failure occurred at approximately the same level of loading, but only at half the elongation due to the increase in system stiffness.



TUBE

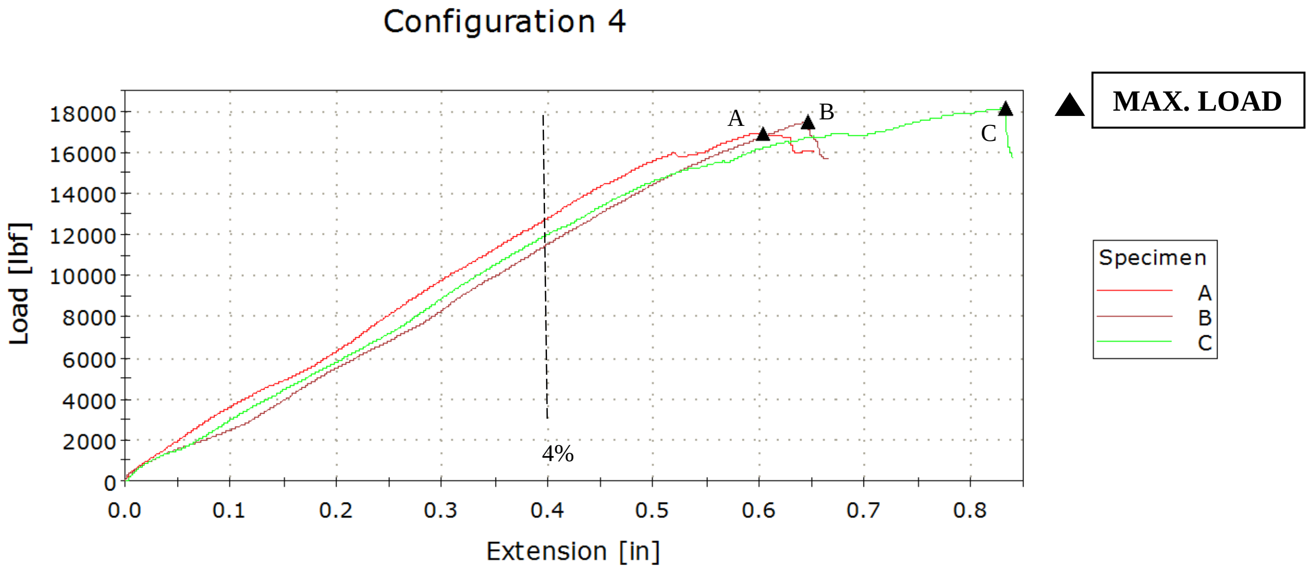
STRAP

BOLT

FIGURE 11 – CONFIGURATION № 3 / SAMPLE A
75.8 kN (17.0 K-POUNDS)

Configuration № *4* (Figure 4D – Mating Full-Length Mating Bushings/Pinned Connection):

SPECIMEN	MAX. LOAD: kN (Pounds Force)	LOAD AT 4% STRAIN: kN (Pounds Force)	MODULUS AT 4% STRAIN kN/mm (Pounds Force/Inch)
A	**75.26 (16,918)**	**57.01 (12,817)**	**5.82 (32,043)**
B	**77.99 (17,533)**	**51.22 (11,515)**	**5.23 (28,786)**
C	**80.67 (18,136)**	**53.42 (12,009)**	**5.45 (30,023)**
MEAN	**77.97 (17,529)**	**54.01 (12,114)**	**5.52 (30,285)**



Theoretically, there should not be a significant performance difference between Configuration № *2* and № *4*: Both are Ø25.4 mm (Ø1”) shear bushings treated as pinned connections. However, these test results show № *4* produces about 12% higher ultimate strength than № *2* and elongates about 20% further before ultimate failure. This is likely due to the advantage of the larger diameter and thickness of the flanges to distribute the loading, as previously predicted in References 7 and 8.

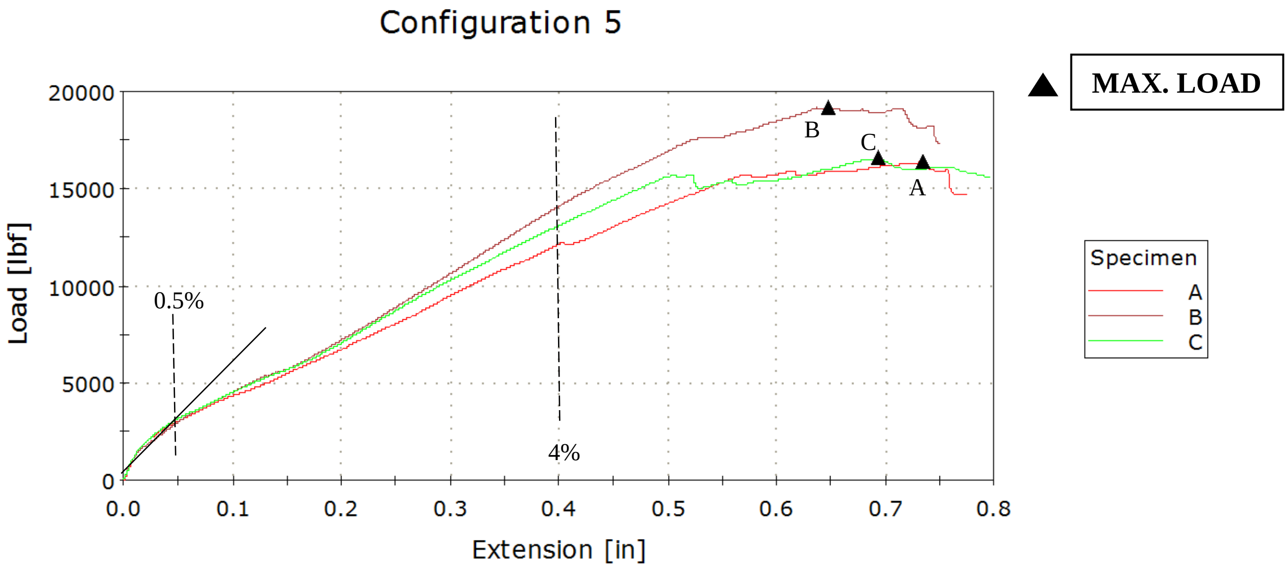
TUBE **STRAP**

BOLT

FIGURE 12 – CONFIGURATION № *4* / SAMPLE C
80kN (17.5 K-POUNDS)

Configuration № 5 (Figure 4D – Mating Full-Length Bushings/Torqued Connection)

SPECIMEN	MAX. LOAD: kN (Pounds Force)	LOAD AT 0.5% STRAIN kN (Pounds Force)	MODULUS AT 0.5% STRAIN kN/mm (Pounds Force/Inch)	LOAD AT 4% STRAIN kN (Pounds Force)	MODULUS AT 4% STRAIN kN/mm (Pounds Force/Inch)
A	72.91 (16,391)	13.32 (2,995)	10.49 (59,900)	53.98 (12,136)	5.01 (30,340)
B	85.27 (19,169)	13.21 (2,970)	10.40 (59,400)	62.71 (14,098)	6.40 (35,245)
C	73.86 (16,605)	14.00 (3,148)	11.02 (62,960)	58.22 (13,089)	5.94 (32,723)
MEAN	77.35 (17,388)	13.51 (3,038)	10.63 (60,753)	58.30 (13,107)	5.95 (32,768)



TUBE **STRAP**

BOLT

FIGURE 13 – CONFIGURATION *№ 5* / SAMPLE B
85.3kN (19.1 K-POUNDS)

Just in terms of ultimate tensile strength, as theory expected, there was not a significant difference between the pinned of Configuration *№ 4* and the tightly bolted connection shown here. The failure modes uniformly included the bearing surfaces in the strap and the bolts. The difference between Configuration *№ 4* and *№ 5* was expected in joint stiffness, as evidenced by overall system modulus. The tightly-bolted connection did show about an 8% increase in system modulus at 4% strain.

It was noted earlier that 1.3 kN (300 pounds) of pre-load was placed on each specimen before bolts were snug- or torque-tightened to take the slack out before actually performing load testing. This pre-load is not present in field installations. Unfortunately, this tended to mute the effectiveness of using the slope of the force-displacement curves as a proxy for system stiffness. That said, however, comparing the curves of configuration *№ 4* (snug-tight) and *№ 5* (torque-tight), there is a distinctly steeper slope of the curves in *№ 5* at the start of the test and a knee transition point at 0.5% elongation. This corresponded to a system load of 13.3 kN (3000 pounds). The modulus at this point is very similar to the stiffness performance of the solid stainless-steel tube in a torqued condition.

ACUTUAL RESULTS -- BUSHING COMPRESSION TESTING:

Finally, as stated above, one new test configuration (Figure 6 – Configuration *№ 6*) was built to test the mating, full-length shear bushings' safety factor under connection torque compression. The bolt was tightened beyond the recommended 39N-m (29 ft-lbs) until audible stress could be heard from the tube, indicating that the fiberglass strands in the FRP were beginning to crack.(24) This started at about 79 N-m (58 ft-lbs), although only minor deformation of the FRP tube was evident based on visual inspection. The test was stopped at 84 N-m (62 ft-lbs) when the flange on the shear bushing without the benefit of a structural member over it to distribute the load developed a crack. The components were disassembled for inspection. No permanent (inelastic) deformation or visible physical cracking was apparent in the FRP tube. The tubular areas of the shear bushings did show some signs of the beginning of inelastic buckling as show in Figures 14A & B below. Some compression/deformation was also noted at the bushing's interfaces. As expected and stated above, the flange crack developed in the bushing without the benefit of the structural strap above it to distribute loading: The flat washer was inelastically deformed after being drawn into the hole of the bushing, creating a wedge-effect to crack the flange.

MINOR BUCKLING BEGINNING IN THE CENTER SECTION.

MINOR EDGE DEFORMATION/COMPRESSION

NEW CONDITION **OVER-STRESSED CONDITION**

FIGURE 14A
COMPRESSION OVER-STRESS TEST
84 N-M (62 FT-LBS) TORQUE

FLAT WASHER IS DRAWN INTO BUSHING, CAUSING CRACK TO DEVELOP IN FLANGE

NEW CONDITION **OVER-STRESSED CONDITION**

FIGURE 14B
COMPRESSION OVER-STRESS TEST
84 N-M (62 FT-LBS) TORQUE

SUMMARY:

With no shear bushings or with only partial-length shear bushings, bolts cannot be adequately tightened without cracking the FRP tube, so only pinned connections can be attained. This work demonstrates that pinned joints do perform comparably to tightly-bolted connections when considering only their ultimate tensile strength performance.

Various methods have been used to realize pinned connection in the field. Field experience has demonstrated that using a “snug-tight” method as defined by a flattened helical lock washer is inadequate to ensure that the fasteners stay in place for the expected life of the structure. A self-locking nut of some type (Nylok®, Nyloc®, Durlok®, Flexloc®, locking collar, castellated nut, etc.) or an anaerobic adhesive should always be specified for bolted pinned connections. Of course, using clevis pins with hairpin cotter retainers are also a viable option.

Ideally, the shear bushings should run the full-length of the tube and be made of an engineering-grade polymer or stainless steel to protect the tube. This allows standard, lubricated stainless-steel fastener hardware to be used without the addition of adhesives, and the fasteners can be fully tightened to the recommended 75% of their proof load. This will ensure that the fasteners stay tight and a stiff, friction-type clamped connections achieved. Tight connections results in a higher structural stiffness as shown in the higher system modulus numbers.

Using properly designed rigid full-length tubing or mating sheer bushings offers a torque-compression safety factor of at least twice the recommended torque value for the fastener. This torque value far exceeds what common commercially available 9.6 mm (3/8”) square-drive Li-Ion impact wrenches are capable of producing with a 19 mm (3/4”) socket.(13) So battery-powered impact wrenches can safely be used. The integrity of the FRP tube will not be compromised. The decrease in assembly time and the quality guarantee this offers can offset the added cost of the full-length bushings.

It’s clear from the results summarized in Table 3 below that addition of shear bushings of any type dramatically improves the ultimate performance of bolted connections made to FRP tubes under tensile-loading conditions. With shear bushings, bolt threads are kept out of contact with the FRP tube. Bearing stresses are more uniformly distributed in the clearance holes and the forces in the overall structural system will be better distributed between the tube, strap, and bolt: The bearing surfaces in the FRP tubes won’t be the “weak link”. A much stronger, more consistent, and more durable structure can be expected. It’s not unusual for the diagonal members of typical cooling towers to routinely withstand cyclic loads of more than 27.6 kN

(6,200 pounds).(30) Peak loading can exceed 37.8 kN (8,500 pounds) during severe hurricane conditions or seismic events(13,24).

TABLE 3

CONFIGURATION	CONNECTION TYPE	AVG. MAX LOAD kN (POUNDS)	FAILURE MODE
№ 1 – NO SHEAR BUSHING/BEARING	**PINNED**	**45.6 (10,254)**	**TUBE**
№ 2 – Ø25.4 mm (Ø1”) PARTIAL PLASTIC SHEAR BUSHING	**PINNED**	**69.9 (15,712)**	**UNIFORMLY DISTRIBUTED**
№ 3 – Ø19 mm (Ø¾”) FULL-LENGTH S.S. SHEAR BEARING	**CLAMPED**	**69.0 (15,507)**	**UNIFORMLY DISTRIBUTED**
№ 4 – Ø25.4 mm (Ø1”) CUSTOM FULL-LENGTH MATING PLASTIC SHEAR BUSHING	**PINNED**	**78.0 (17,529)**	**UNIFORMLY DISTRIBUTED**
№ 5 – Ø25.4 mm (Ø1”) CUSTOM FULL-LENGTH MATING PLASTIC SHEAR BUSHING	**CLAMPED**	**77.4 (17,388)**	**UNIFORMLY DISTRIBUTED**

It should be noted when reviewing the actual test data included here that these results were obtained under typical, ideal laboratory conditions: Room temperature and dry. Both CTI and FRP manufacturers recommend derating published material properties for higher temperatures and wet conditions.(20) It also must be emphasized again that this work is limited to tensile-only ultimate load testing (see “Future Work” below for additional comments). It’s critical that thorough structural analysis be performed and connections properly designed and tested with adequate safety factors in place to withstand both cyclical and worst-case peak loading.

FUTURE WORK:

As noted earlier, this testing was limited to tensile-only loading, primarily to compare bearing joint strength of different bolted connection configurations. In real-world application, the stresses in the connections fluctuate widely between tension and compression (cyclic-fatigue loading). Very limited reference work is available on the fatigue behavior of bolted joints for pultruded composites.(31, 32) From the initial work presented here, there is a reasonable expectation that the performance of tightly-bolted connections using either full-length plastic or metal bushings would far exceed the performance of a pinned connection without the benefit of shear bushings. But, there is clearly an opportunity for valuable future technical contributions to the body of knowledge surrounding these FRP structures: Comparing pinned to tightly bolted connections under cyclic fatigue loading conditions.

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