Effects of Variable Pretension on the Behavior of Bolted Connections with Prying

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Some time ago, Thomas Murray, Ph.D., suggested that full pretension of tension bolts might not be necessary in bolted connections to resist environmental loads such as wind (Murray, Kline, and Rojiani, 1992). Discussions following this suggestion led to concern that during assembly of bolted connections an iron worker may inadvertently tighten some of the bolts in a connection while leaving others untightened. This situation could lead to an unzipping type of failure due to a fracture of the tightened bolts before the untightened bolts achieve their full expected capacity. To investigate this possibility D.L. Johnson from Butler Manufacturing conducted a research study in which two-bolt T-stub specimens were tested under a tensile load in a back-to-back configuration (Johnson, 1996).

The results of Johnson's test program are presented in Table 1. The pretension levels in the bolts were varied so that different combinations of pretension could be investigated. "F" denotes a bolt that was finger tight, "S" denotes a bolt that was snug tight, and "T" denotes a bolt that was fully tensioned. "F-T," for example, indicates a test that was conducted with one bolt finger tight and the other fully tensioned. ASTM A325 bolts were used for all of the tests. Two lengths were selected—2¾ in. and 3¼ in.—to investigate the effect of varying the number of threads in the grip of the bolt. It was speculated that reducing the number of threads in the bolt's grip could lead to an earlier fracture of that bolt and make the connection more susceptible to the unzipping type of failure mentioned earlier. The exact dimensions of the tees used in Johnson's tests, such as flange thickness, bolt gage, etc., are not known. While Johnson noted differing strains in bolts with different levels of pretension in the same connections, the overall load carrying capacity of the connection was not greatly affected.

The current investigation was conducted to verify Johnson's results and to provide additional data. While duplicating some of Johnson's work, the current investigation extends the range of data to include tests of T-stubs using four bolts in tension and T-stubs connected with ASTM A490 bolts in tension with varying levels of pretension. This paper presents a summary of the current investigation. Those interested in additional detail are encouraged to request a copy of the final report from the authors (Swanson, 2002).

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EXPERIMENTAL PROGRAM

The T-stub specimens that were tested at the University of Cincinnati are outlined in Table 2. The program included three lengths of A325 bolts, one length of A490 bolts, and two T-stub specimens not included in Table 2. These last two specimens were connected by four A325 bolts—one fully tensioned with the remaining three finger tight. All of the bolts were ¾ in. in diameter. While it is not expected that finger tight bolts will be used in practice, this condition was used as a lower bound in the test program. To achieve a level of prying in the connection of approximately 20 to 25 percent, the T-stub specimens were cut from a W18×106 section made of ASTM A992/A572 Grade 50 steel. The gage of the tension bolts was held constant at 6 in. for all tests.

After the first six specimens with A490 bolts (the series identified as A490-A) were tested, tensile testing of the bolts showed that these fasteners were of questionable strength. As a result, this series of six tests was repeated using bolts from a different lot and is identified in this report as series A490-B.

Material Characterization

A section of the W18×106 was selected and machined into six sheet-type tension specimens (ASTM E8) for testing at the University of Cincinnati Material Characterization Laboratory. Two coupons were cut from each flange and the web of the section transverse to the direction of rolling. The coupons were tested to failure in an MTS universal load frame using hydraulic wedge grips. A 2-in. gage length extensometer was used to measure strain. The coupons were loaded in displacement control at a rate of 0.010 in. per min. in the elastic range and throughout initial yielding. This displacement rate corresponded to an elastic loading rate of approximately 20 ksi per minute. After the onset of strain hardening, the displacement rate was increased to 0.100 in. per min. until failure.

Table 1. Results of D.L. Johnson's Test Program (kip).

	A325 3/4" x 2-3/4"	A325 3/4" x 3-1/4"
F-F	92.0, 92.9	95.7, 97.6
F-S	92.5	95.4
F-T	90.8	95.2
S-S	92.5, 93.3	93.5, 93.5
S-T	92	96
T-T	95.6, 95.7	98.4, 100.5

Table 2. University of Cincinnati 2-Bolt T-stub Test Program (Number of Specimens).

	A325-A 3/4" x 3-1/2"	A325-B 3/4" x 3-1/4"	A325-C 3/4" x 3-3/4"	A490-A 3/4" x 3-1/2"	A490-B 3/4" x 3-1/2"
F-F	1	1	1	1	1
F-S	3	---	---	1	1
F-T	3	---	---	1	1
S-S	2	1	1	1	1
S-T	3	---	---	1	1
T-T	1	1	1	1	1

The W18×106 section was rolled from ASTM A992/A572 Grade 50 material. The average mill certified yield and ultimate strengths of the material were 52.5 ksi and 71.4 ksi, respectively, with a 29.4 percent elongation at fracture. Coupon tests of the flange transverse to the direction of rolling that were conducted at the University of Cincinnati indicated averages of 48.1 ksi and 67.6 ksi for the yield and ultimate strengths, respectively, with a 29.8 percent elongation at fracture. Coupon tests of the web transverse to the direction of rolling that were conducted at the University of Cincinnati indicated averages of 57.4 ksi and 70.7 ksi for the yield and ultimate strengths, respectively, with a 30.4 percent elongation at fracture.

Fastener Testing

The fasteners that were used in the experiments were tested for strength and load-deformation characteristics at the University of Cincinnati Material Characterization Laboratory. A photo of the bolt test set up is shown in Figure 1. An extensometer was used to measure the displacement of the bolt head while the displacement at the nut was taken as the average of two linear variable differential transformers (LVDT). The A325 fasteners were obtained in lengths of 3½ in., 3¼ in., and 3¾ in. in order to investigate the effects

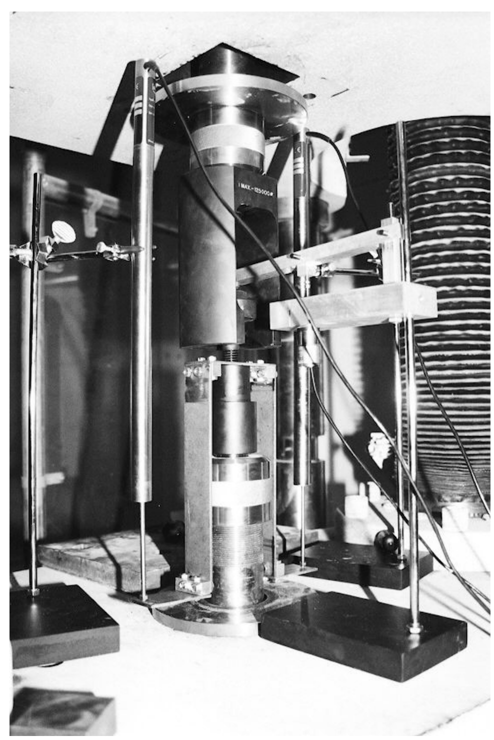

Fig. 1. Bolt Testing Set-Up.

Table 3. UC Fastener Test Results.

Fastener	Average F_u	Standard Deviation	# Samples
	(ksi)	(ksi)	
A325-A 3/4” x 3-1/2”	142	2.11	10
A325-B 3/4” x 3-1/4”	139	2.88	6
A325-C 3/4” x 3-3/4”	143	2.54	5
A490-A 3/4” x 3-1/2”	148	1.77	5
A490-B 3/4” x 3-1/2”	164	1.55	5

of including a moderate number of threads, a maximum number of threads, and a minimum number of threads, respectively, in the bolts’ grips. To replicate the T-stub experiments, the 3½-in. long bolts were tested with 5 to 6 threads in the grip, the 3¼-in. long bolts were tested with 8 to 9 threads in the grip, and the 3¾-in. long bolts were tested with 1 to 2 threads in the grip. The A490 fasteners that were used in the program were all 3½ in. in length. All fasteners were ¾ in. in diameter.

The test results are summarized in Table 3 and the load-deformation curves are shown in Figures 2 through 5. The number of threads in the grip of the bolt affected the deformation capacity of the bolt greatly but only slightly affected its strength. Figure 6 shows a fractured A325 ¾ in. × 3¼ in. bolt on top, a fractured A325 ¾ in. × 3½ in. bolt in the middle, and a fractured A325 ¾ in. × 3¾ in. bolt on the bottom. This visual comparison verifies that when more threads are included in the grip of a bolt, the plastic deformation is distributed over a longer length and leads to a more ductile fastener behavior. The affect on T-stub behavior that was noted when varying the bolt length is discussed in a later section.

It is interesting to note that the strength of the first lot of A490 fasteners—the A490-A fasteners—as tested at the University of Cincinnati was determined to be less than the ASTM minimum specified strength and that these bolts demonstrated more ductility than some A325 bolts. Because of this behavior, bolts from a second lot of A490 fasteners were obtained—the A490-B fasteners—and the associated bolt and T-stub testing was repeated. The difference in behavior of the bolts from the two lots is illustrated in Figure 5. It should be noted that the loading rate used in the fastener tests was relatively slow. The authors used the same loading rate for fastener testing as was used for T-stub testing. The authors speculate that had a faster loading rate

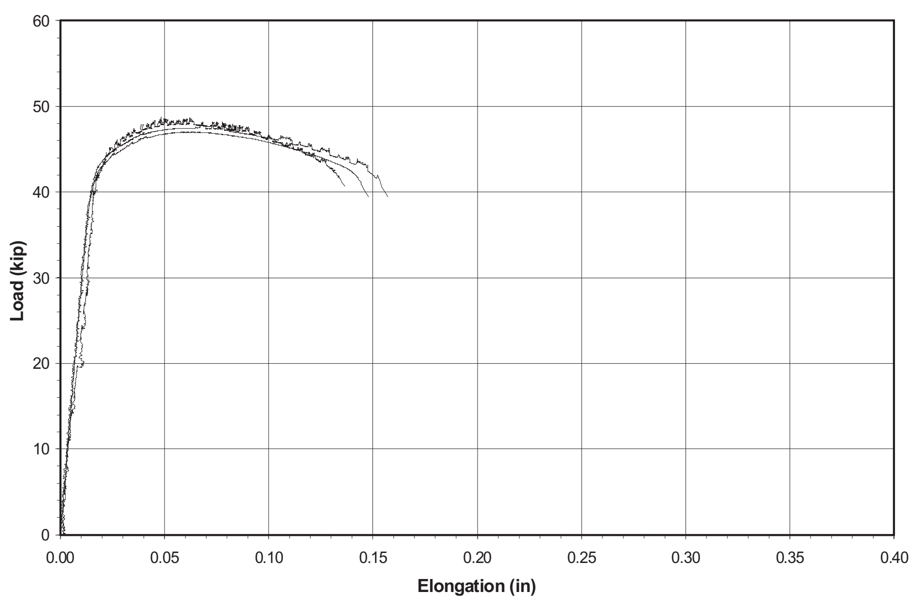

Fig. 2. Load-Deformation Curves for A325-A ¾” × 3½” Bolts.

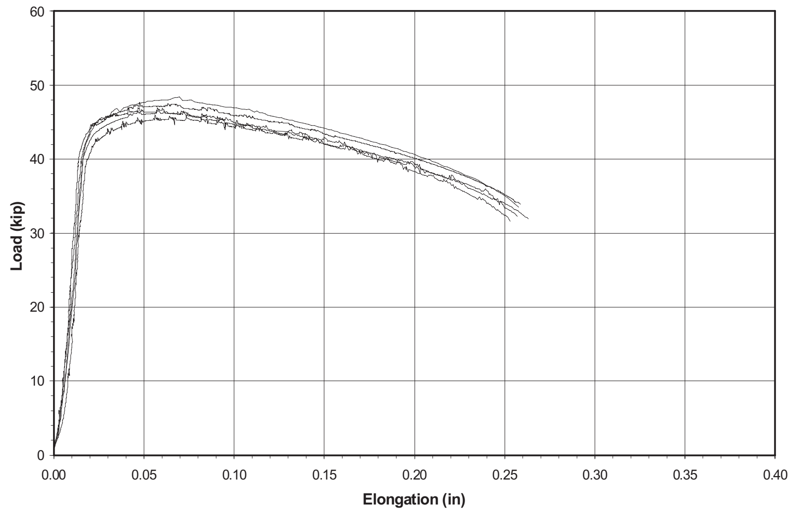

Fig. 3. Load-Deformation Curves for A325-B ¾" × 3¼" Bolts.

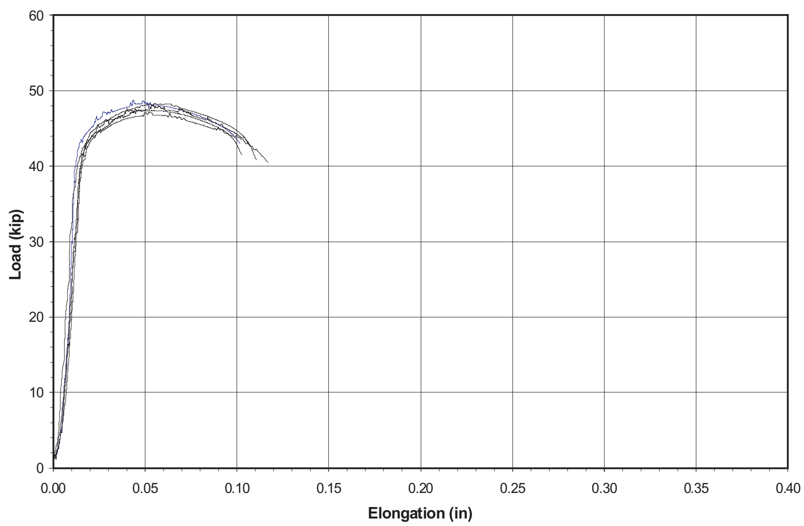

Fig. 4. Load-Deformation Curves for A325-C ¾" × 3¾" Bolts.

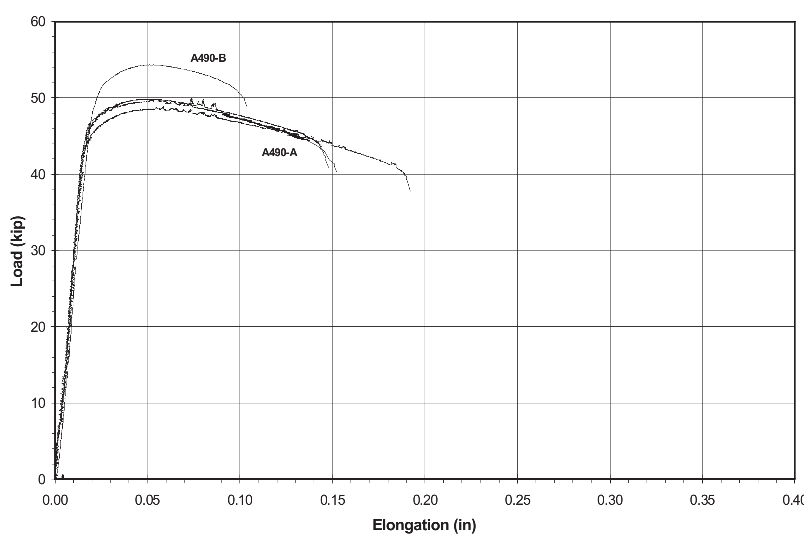

Fig. 5. Load-Deformation Curves for A490 ¾" × 3½" Bolts.

been used—one still within ASTM specifications—the first lot of A490 bolts may have met minimum strength limits.

Instrumented Fastener Calibration

In addition to testing fasteners for strength, all A325 and A490 bolts that were used in T-stub tests were instrumented with internal strain gages and were calibrated to facilitate the measurement of bolt forces during the T-stub experiments. Bolts that were to be used in the T-stub experiments were numbered for identification and subjected to a few cycles of load within their elastic range while load and strain were recorded. A regression analysis was then performed on the resulting data to yield a linear relationship between the measured strain and the load applied to the fastener.

T-stub Test Method

The T-stub specimens were tested in a 400 kip Tinius-Olsen test frame using a set-up similar to that shown in Figure 7. Figures 8 and 9 show actual photos of the T-stub test set-up. The top and bottom crossheads of the test machine were sandwiched between stiffened W12×136 sections that were installed to act as column stubs. The lower flange of the test specimen was selected to act as the test flange and was connected with the prescribed bolts for the given test. The top flange of the specimen was connected with 1-in. diameter A490 bolts so as to force the failure into the bottom flange. All bolts that were installed to the fully- tensioned condition were installed using the turn-of-the-nut method. A Skidmore-Wilhelm torque-tension tester was used to verify the required number of turns and the bolt force was monitored during tightening using the strain output from the bolt strain gages.

Fig. 6. Fractured A325 Bolts with Varying Numbers of Threads in their Grips.

The cyclic load history shown in Figure 10 was used to load all but one of the T-stub specimens. Towards the end of the test program, it was speculated that the cyclic load history was leading to a loss of pretension in the tighter bolt thus lessening or negating the effects of the differing pretension. As a result, test FT-1e was conducted monotonically. No significant difference in behavior from the cyclic tests was noted.

Data was recorded using an Optim Electronics MegaDAC system. Load was monitored by outputting a proportional voltage from the Tinius-Olsen controller to the Optim data system. Relative crosshead displacement was monitored by using an independent LVDT. Two additional LVDTs were arranged to measure the uplift of the bottom T-stub flange. The average of these LVDT outputs was taken as the nominal flange deformation. Finally, the internal bolt strain gages were also connected to the Optim system and used with a calculated channel so that bolt forces could be monitored in real time.

T-stub Test Results

The load/deformation response of a typical specimen is shown in Figure 11. All of the specimens failed with a fracture of one or both bolts. In all but one case, when the bolts were tightened to different levels of pretension, the tighter bolt failed first. This was also true for the two T-stubs using

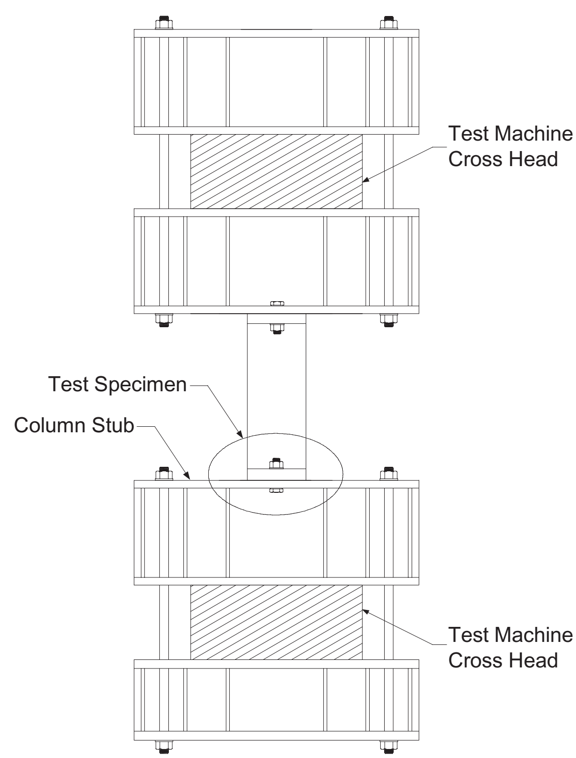

Fig. 7. T-stub Specimen Test Set-Up.

Table 4. Detailed T-stub Specimen Test Results.

Test ID	Bolts	Bolt Pretension Left (kip)	Bolt Pretension Right (kip)	Failure Load (kip)	Failure Def (in)	Level of Prying %
FF-1	A325-A 3-1/2"	0	0	74.1	0.330	27.7%
FS-1A	A325-A 3-1/2"	9.8	0	75.4	0.280	25.4%
FS-1B	A325-A 3-1/2"	9.3	0	73.3	0.380	29.0%
FS-1C	A325-A 3-1/2"	10.5	0	73.7	0.252	28.3%
FT-1B	A325-A 3-1/2"	40.6	0	71.8	0.276	31.8%
FT-1C	A325-A 3-1/2"	31.8	0	72.6	0.348	30.3%
FT-1D	A325-A 3-1/2"	0	34.2	72.2	0.247	31.0%
SS-1B	A325-A 3-1/2"	9.7	10.8	74.3	0.345	27.3%
SS-1C	A325-A 3-1/2"	11.8	13.0	74.1	0.262	27.7%
ST-1B	A325-A 3-1/2"	36.7	9.5	75.1	0.202	25.9%
ST-1C	A325-A 3-1/2"	10.1	36.6	73.7	0.208	28.3%
ST-1D	A325-A 3-1/2"	10.5	34.2	74.6	0.249	26.8%
TT-1A	A325-A 3-1/2"	39.1	35.4	74.3	0.200	27.4%
FF-3	A325-B 3-1/4"	0	0	72.6	0.550	27.8%
SS-3	A325-B 3-1/4"	9.2	11.9	71.4	0.475	29.9%
TT-3	A325-B 3-1/4"	32.5	22.8	70.4	0.404	31.7%
FF-4	A325-C 3-3/4"	0	0	75.3	0.270	26.6%
SS-4	A325-C 3-3/4"	9.4	12.9	74.6	0.229	27.7%
TT-4	A325-C 3-3/4"	29.3	29.2	71.5	0.199	33.4%
FF-2A	A490-A 3-1/2"	0	0	75.6	0.400	30.4%
FS-2A	A490-A 3-1/2"	10.2	0	77.7	0.290	26.8%
FT-2A	A490-A 3-1/2"	40.1	0	76.5	0.214	29.0%
SS-2A	A490-A 3-1/2"	10.5	12.7	75.7	0.291	30.2%
ST-2A	A490-A 3-1/2"	40.0	9.7	77.9	0.214	26.6%
TT-2A	A490-A 3-1/2"	39.2	38.3	76.8	0.272	28.4%
FF-2B	A490-B 3-1/2"	0.0	0.0	83.1	0.325	31.4%
FS-2B	A490-B 3-1/2"	14.0	0.0	82.5	0.227	32.3%
FT-2B	A490-B 3-1/2"	35.6	0.0	82.5	0.220	32.3%
SS-2B	A490-B 3-1/2"	11.5	12.5	82.3	0.224	32.7%
ST-2B	A490-B 3-1/2"	36.1	15.6	84.9	0.215	28.7%
TT-2B	A490-B 3-1/2"	37.8	36.5	82.0	0.167	33.1%
FT-1e	A325-A 3-1/2"	33.7	0	72.8	0.252	29.8%
4 Bolt-A	A325-A 3-1/2"	0	32.3	145.2	0.220	30.3%
4 Bolt-B	A325-A 3-1/2"	0	33.8	146.5	0.228	29.1%

Note: Test FT-1e was conducted monotonically.

four tension bolts. The detailed test results are shown in Table 4. Table 5 shows a summary of the results in a format similar to Table 2; duplicate test results have been averaged in this table. A quick examination shows that all failure loads in a given column are within a few percent of the baseline "T-T" value. Additionally, the failure loads of the four-bolt T-stub specimens were roughly 98 percent of twice the failure load of the corresponding two-bolt T-stubs with both bolts fully tensioned. From this it can be concluded that varying the level of pretension within a connection did not appreciably affect the overall connection strength in the configurations tested.

Figures 12, 13, and 14 show the bolt forces plotted versus the applied T-stub load for tests TT-1A, ST-1B, and FT-1B, respectively. The straight line shown in the figures represents the "no-prying" response for the bolt forces.

Table 5. Summary of T-stub Specimen Strengths (kips).

	A325-A	A325-B	A325-C	A490-A	A490-B
	3/4" x 3-1/2"	3/4" x 3-1/4"	3/4" x 3-3/4"	3/4" x 3-1/2"	3/4" x 3-1/2"
F-F	74.1	72.6	75.3	75.6	83.1
F-S	74.2	---	---	77.7	82.5
F-T	72.2	---	---	76.5	82.5
S-S	74.2	71.4	74.6	75.7	82.3
S-T	74.5	---	---	77.9	84.9
T-T	74.3	70.4	71.5	76.8	82.0

Table. 6. Summary of T-stub Specimen Deformation at Failure (in.).

	A325-A	A325-B	A325-C	A490-A	A490-B
	3/4" x 3-1/2"	3/4" x 3-1/4"	3/4" x 3-3/4"	3/4" x 3-1/2"	3/4" x 3-1/2"
F-F	0.330	0.550	0.270	0.400	0.325
S-S	0.304	0.475	0.229	0.291	0.224
T-T	0.200	0.404	0.199	0.272	0.167

Fig. 8. T-stub Test Set-Up.

Fig. 9. Test Set-Up for a T-stub Specimen with 4 Tension Bolts.

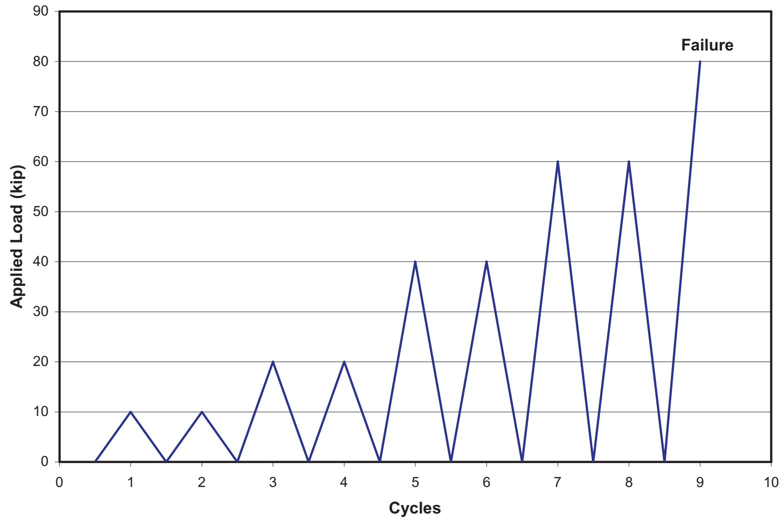

Fig. 10. Cyclic Load History for T-stub Specimen.

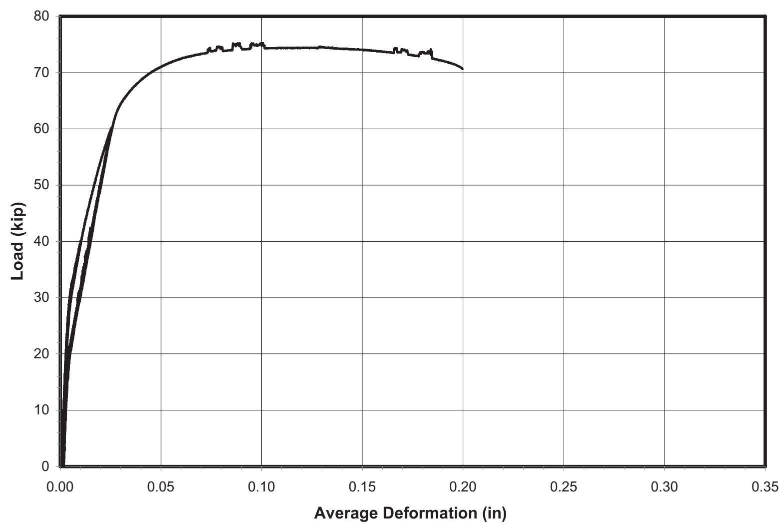

Fig. 11. Load/Deformation Response of T-stub Specimen TT-1A.

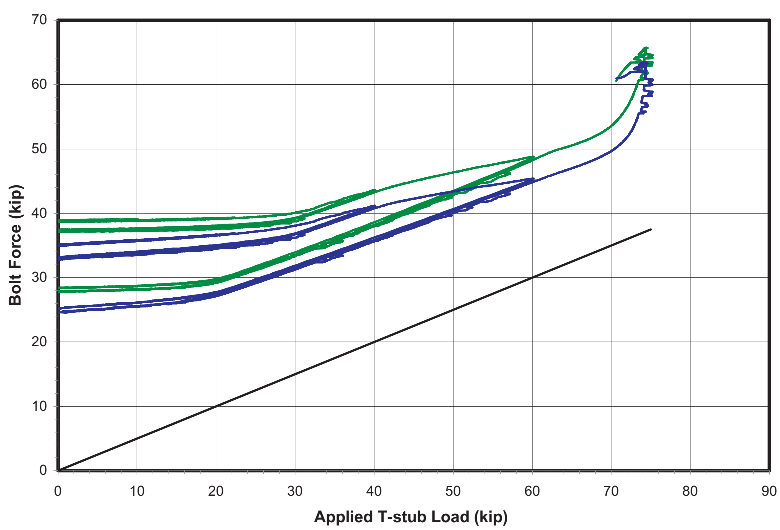

Fig. 12. Bolt Forces for T-stub Test TT-1A (A325-A Fasteners).

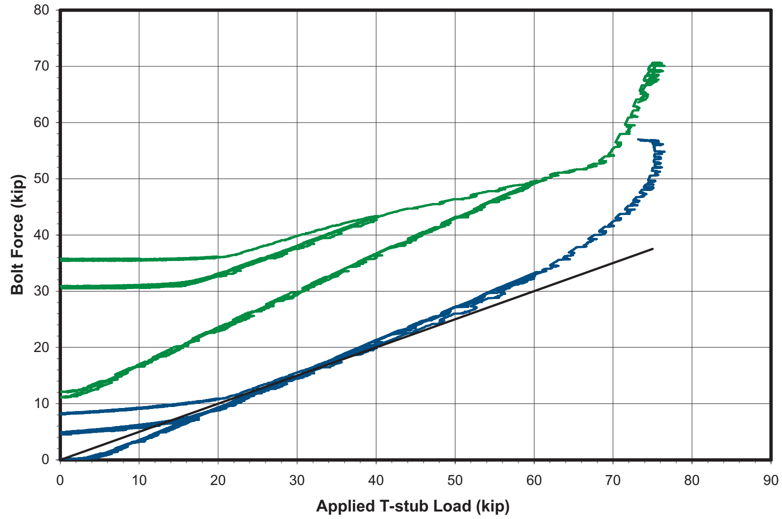

Fig. 13. Bolt Forces for T-stub Test #ST-1B (A325-A Fasteners).

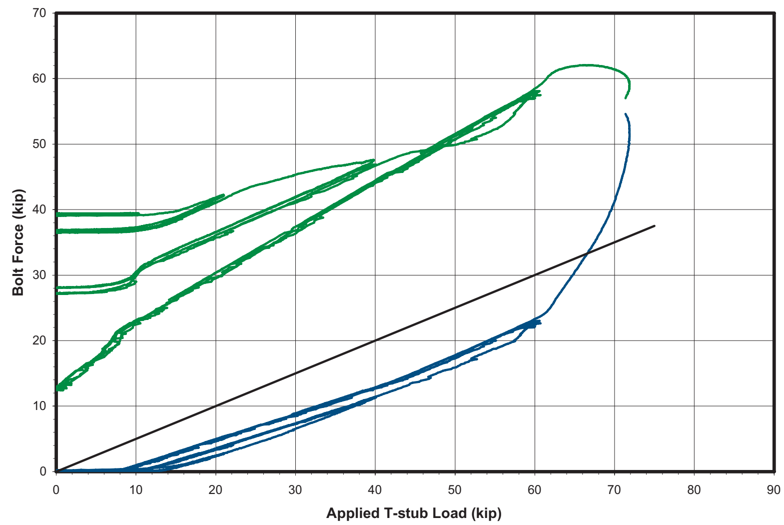

Fig. 14. Bolt Forces for T-stub Test #FT-1B (A325-A Fasteners).

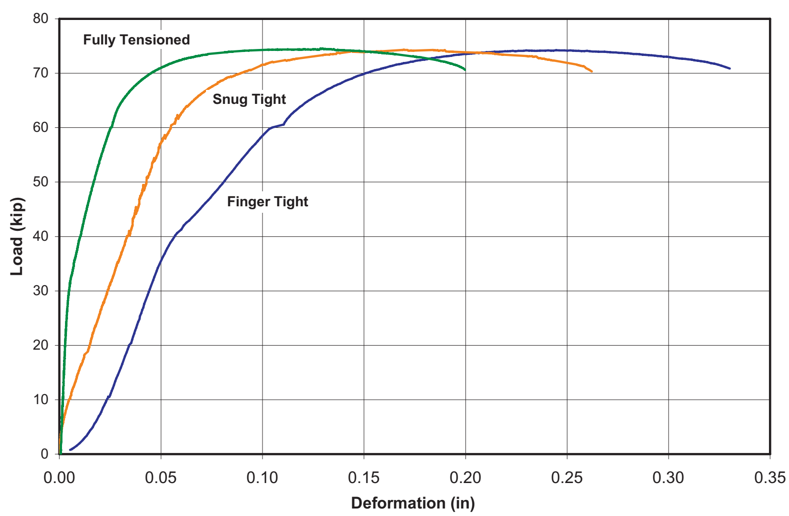

Fig. 15. Monotonic Envelopes of Load/Deformation curve Response for Representative TT, SS, and FF T-stub Specimens Using A325-A ¾” × 3½” Bolts.

Note that the linear relationship between strain and bolt force becomes invalid for bolt forces above the elastic load. As a result, bolt forces above approximately 40 kips in these figures are inaccurate.

Table 6 shows a summary of the deformations of the T-stub specimens with bolts that were tightened uniformly. Referring to Table 6 and using the case with two A325 ¾ in. × 3½ in. fully tensioned bolts as the baseline case, the following observations can be made.

- The snug-tightened case deforms 52 percent more before failure and the finger-tightened case deforms 65 percent more before failure than the fully-tensioned case for specimens connected with A325 ¾ in. × 3½ in. As Figure 15 illustrates, this gain in deformation capacity is accompanied by a reduction in initial stiffness.

- The specimen connected with fully-tensioned A325 ¾ in. × 3¼ in. bolts deformed slightly more than twice as much as the one connected by fully-tensioned A325 ¾ in. × 3½ in. bolts. The specimen connected with A325 ¾ in. × 3¾ in. bolts behaved almost identically to the specimen connected with A325 ¾ in. × 3½ in. bolts.

- The specimens connected by fully-tensioned A490-A bolts deformed 36 percent more than the specimen connected with the same size fully-tensioned A325 bolts.

- The specimens connected by fully-tensioned A490-B bolts deformed 37 percent less than the specimen connected with the same size fully-tensioned A325 bolts.

It should be noted that most of these observations are based on the results of single experiments and that in cases where experiments were duplicated, the deformation at failure varied by as much as 1/8 in. A second limitation of the study is that the distribution of load between the fasteners as function of their position in the connection was not investigated. Since all of the specimens were doubly symmetric with regard to bolt placement in the flange, the possibility of one or a few of the bolts "hogging" more than a proportional share of the total load as a result of bolt position was not a consideration in the investigation. Despite these points, the results shed some light on the effects of varying the bolt length, grade, and pretension on the behavior of the connection.

CONCLUSIONS

Varying the pretension of tension bolts within a connection did not appreciably affect the overall connection strength. Specimens with one fully-tensioned fastener and one finger-tight fastener were able to carry the same loads as specimens with both fasteners tightened to the same level. This leads to the conclusion that engineers need not worry about a premature failure due to uneven tightening in connections with snug-tight tension bolts. The bolt pretension did, however, affect the stiffness and deformation capacity of the specimens. Reducing the bolt pretension lowered the initial stiffness of the connections but increased the deformation capacity. Based on this observation, using snug-tight bolts in tension may be desirable when connection ductility is more critical than initial stiffness.

Varying the length of bolts—and thus the number of threads included within the grips of the bolts—did not appreciably affect connection strength but did affect the stiffness and deformation capacity of the specimens. Using shorter bolts in a given connection tended to slightly lower initial stiffness but increases the deformation capacity.

Differences in fastener properties from lot to lot can affect the behavior of connections significantly. A comparison of the results from the two series of A490 T-stub tests shows that while the T-stub capacities were consistent within each group, the second group of specimens (A490-B) demonstrated a strength that was noticeable higher and a deformation at failure that was substantially lower than the first group of specimens (A490-A).

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