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TESTS ON STEEL T-STUB CONEECTIONS

Roberto T LEON[1] And James A SWANSON[2]

SUMMARY

In the aftermath of the 1994 Northridge and 1995 Kobe earthquakes, during which welded steel moment connections exhibited unexpected brittle fractures, there has been a resurgence of interest in the performance of bolted connections under seismic loading. As part of the SAC Program, a series of 58 component and 8 full-scale tests have been carried out (1) to better understand failure modes in bolted connections subjected to seismic loads, and (2) to develop simplified models capable of predicting the initial stiffness, ultimate strength, and rotational capacity of bolted connections. The results of the tests show that it is possible to detail bolted connections to perform well under large cyclic load reversals, but that careful attention must be paid to the different deformation mechanisms possible in T-stubs. The tests indicate that it is possible to extrapolate from component tests to full-scale tests when careful instrumentation and material characterisation are carried out. The tests have also shown that the most favourable design is one in which yielding of the T-stub flanges is followed by yielding of the stem of the T-stub. In these cases, it is difficult to prevent a net section failure at ultimate, but careful detailing results in connections capable of achieving large rotations before the net section fracture occurs. The component tests also indicate that current formulas for predicting prying forces in bolts are quite accurate.

INTRODUCTION

The numerous failures of fully welded moment connections during the 1994 Northridge and 1995 Kobe earthquakes were unexpected and troubling, as these connections had been assumed to provide the optimum combination of strength, stiffness and ductility in special moment-resisting frames (SMRFs). The failures have led researchers and engineers to seek alternative connections capable of providing the required stiffness, strength and rotational capacity demanded by SMRFs. Among the alternatives under consideration both for new construction and retrofit of existing buildings, bolted connections are a particularly attractive choice as they have been used for decades and have performed well in past earthquakes [Roeder et al., 1996, Leon, 1997]. Bolted connections circumvent some of the major problems associated with welded connections, particularly those related to large stress concentrations in the joint region and quality control/quality assurance in the field.

When selecting bolted connection alternatives, T-stubs and thick end plates appear to be ideal candidates as they are the bolted connections with the largest initial stiffness. However, end plate and T-stub connections are typically less stiff than welded ones, and thus drift control would appear to be a problem. Therefore, it is likely that a larger number of bolted connections will need to be used in the lateral load-resisting system than current practice prescribes when using welded ones. Field experience with bolted and riveted connections indicate that T-stubs can provide the strength and rotational capacity required for use in SMRFs [Leon, 1997]. In reviewing previous literature, however, it is clear that there is a dearth of experimental and modeling information on the cyclic performance of strong and stiff bolted connections in general, and in particular with reference to T-stub connections with eight tension bolts. The latter is important because a large number of tension bolts will be required if large girders are used, as is typical in modern moment-resisting frames. To address these issues this research program, sponsored by SAC, intends (1) to develop new design models for bolted connections under seismic loading, and (2) to calibrate the models against a large, controlled database. This paper presents an

[1] *Georgia Institute of Technology,Atlanta, GA 30332-0355, USA, email: rleon@mail.ce.gatech.edu*
[2] *University of Cincinnati, Cincinnati, OH 45221-0071, USA, email: jswanson@uceng.uc.edu*

overview of the component tests and some preliminary conclusions related to the design of T-stub connections for seismic loads. Extensive documentation of these tests, as well as of the full-scale ones, can be found at http://www.ce.gatech.edu/~sac.

EXPERIMENTAL PROGRAM

The experimental portion of the research program was intended to fill gaps in the existing bolted connection database. As a first step in this research, information from a comprehensive literature review was compiled into a database containing 771 bolted connection tests. Careful examination of this database revealed that there were few well-documented test series that could be used to calibrate mechanistic models. In addition, almost all the tests for T-stubs were on specimens with four bolts, and little information was available on the performance of T-stubs with eight or more bolts. To supplement this database, a series of 48 T-stubs and 10 clip angles were tested individually under cyclic tensile and compressive loads as part of this program. The T-stubs were designed to be full strength for smaller W18 to W27 sections, but would also be suitable as partial strength connections for larger W30 to W36 sections. Table 1 summarizes the dimensions for the specimens tested. The T-stubs were cut from W-sections, with the length of the stem adjusted to accommodate the required number of shear bolts. The stems were tapered from the assumed width of the beam flange (labeled stem width in Table 1) to the width of the column flange (15.5 in.). The size, grade, number, gage, and spacing of the bolts were varied to study the effects of prying on the tension flange and bearing on the stem. Various configurations of 7/8” and 1" diameter A325 and A490 bolts were used. The four series of T-stubs and the single series of clip angles were further divided into groups based on bolt diameter.

Most of the specimens were subjected to cyclic load histories applied axially. Four duplicate T-stubs were tested monotonically to provide reference points for comparing the cyclic data to the existing monotonic data found in the literature search. The cyclic load history specified in the SAC (1997) testing protocol was used. Because of the different stiffnesses of the components in tension and compression, a system of force and displacement limits was used for the cyclic tests. During the tension portion of the first cycle of a given load step, the T-stub was pulled to a target displacement and the load was recorded. The specimen was then pushed in compression until a load equal to the tensile load was reached. This system of force and displacement limits, while in stroke control, was used for all of the cyclic tests.

Figure 1 shows the instrumentation employed in the component tests. Displacement transducers (LVDTs) monitored a large number of displacements that were to be used to isolate the different components of the overall deformations. In Figure 1, LVDT A monitored the connection slip, B measured the uplift of the T-stub flange from the face of the column at the level of the T-stem, C measured the uplift of the T-stub flange at the bolt line, D measured the elongation of the tee stem, E measured the overall tee deformation, and G indicated the use of bolts instrumented with strain gages to obtain the bolt forces, including the effects of prying. Strain gages were also used on the T-stub to help calibrate three-dimensional advanced finite element models.

EXPERIMENTAL RESULTS

The test results for the 48 T-stub and 10 cleat angle component tests are summarized in Table 2 and a typical load-deformation curve is shown in Fig. 2. The quantities shown in Table 2 were defined as follows:

Failure Mode: The failures are classified as tension bolts / prying (T-Bolt), net section failures (Net-Sec); shear failure of the bolts (S-Bolt), and block shear (Block-Shr).

Max Load: This is the maximum tensile force experienced during the test. The maximum load is not necessarily the load at failure.

Max Deformation: This is the maximum axial tensile deformation experienced during the test before or at failure. For some tests, the deformation at the failure point is less than the maximum deformation because of the cyclic nature of the load histories.

Min Deformation: This is the minimum axial deformation (or maximum compressive deformation) recorded during the test before or at failure.

Initial Stiffness: The component service load stiffness is defined as the axial stiffness of the component during the first load step.

Energy Dissipated: This is the total cumulative energy dissipated during the test, and represents the area inside the load-deformation curves obtained.

The performance of the different groups can be summarized as follows:

Group 1: The objective of this group was to investigate the prying mechanism of T-stubs with 4 tension bolts in the column flange. The primary variable within this group is the gage (g_t) of the tension bolts, which varied from 4" to 7". Grade A490 bolts 7/8" in diameter were used in all T-stubs of this group. The maximum loads shown in Table 2 clearly illustrate the large effect that prying action had on the behavior of the specimens. The capacity of TA-17 (g_t = 4"), for which prying action was small, was almost 35% larger than that of TA-20 (g_t = 7") for which the prying effect was large. The effect of prying action on the bolt force is shown in Fig. 3. The bolt force decreased substantially when the pretension was exceeded.

Group 2: The Group 2 T-stubs were similar to the Group 1 T-stubs, except that the flange width, Bf , was decreased from 10-3/8 in. for Group 1 to 8-3/8 in. for Group 2. Because of the smaller width, only 4 and 5 inch tension bolt gages could be used. Table 2 shows that the capacities of TB-09 and TB-10 are comparable to TA-17 and TA-18. Therefore, it does not appear that the distance from the tension bolts to the end of the flange has an appreciable influence on the strength of the connection.

Group 3: Group 3 was intended to investigate prying action in T-stubs with eight tension bolts to the column flange. The specimens of Group 3 are directly comparable with those in Group 1, as the main variable was the gage between the tension bolts, which varied from 4 in. to 7 in. (TA-01 through TA-04, respectively). All bolts were 7/8" diameter Grade A490. In addition, this group looked at differences between monotonic and cyclic loading (TA-01 vs. TA-05 and TA-03 vs. TA-07). The data indicate that there is little difference between the cyclic and monotonic loading insofar as the failure loads and failure modes are concerned. As the gage increased from 5 in. to 6 in., the failure mode shifted from net section to tension bolt fracture with an increase in prying action. It is interesting to note that the increase in capacity from TA-19 to TA-03 is only 75.3% and that the increase in capacity from TA-20 to TA-04 is only 65.7%. One might expect an increase in capacity much closer to 100% as the number of tension bolts is doubled. This observation suggests that the bolts are not stressed uniformly in the T-stubs utilizing eight tension bolts. The increased spacing used to accommodate the web and K-zone of the column may lead to 2D plate effects in the tension flange which shifts more load to the inside bolts than the outside bolts.

Group 4: The objectives Group 4 were to investigate the prying mechanisms and compare the behavior of A490 (TA-09 to TA-12) and A325 bolts (TA-13 and TA-15). Behavior similar to Group 3 was expected from these T-stubs. T-stubs TA-13 and TA-15 are identical to TA-09 and TA-11 except that A325 1" bolts were used instead of the A490 bolts to provide a comparison between the two grades. The results show that the behavior of the T-stubs in this group was very similar to the behavior of T-stubs TA-01, TA-02, and TA-05 in Group 3. Since the 1" diameter bolts reduced the net area of the T-stem, all of the T-stubs failed with net section fractures. T-stubs TA-25 and TA-26 are the same as TA-09 except that the spacing of the shear bolts was decreased to 2.67 d_b and 2.5 d_b, respectively. This reduction in the bolt spacing led to a lower net section capacity for TA-25 than for TA-09 and to a block shear failure for T-stub TA-26 (Fig. 4).

Group 5: This group was designed to investigate the effects of prying and to compare A325 and A490 bolts. TB-01 was identical to TB-03, and TB-02 was identical to TB-04 except that A490 7/8" diameter bolts were used with TB-01 and TB-02 and A325 7/8" diameter bolts were used with TB-03 and TB-04. Decreasing the tension bolt gage (g_t) from 5 in to 4 in shifts the failure mode from a tension bolt fracture to a shear bolt fracture. Referring to the actual bolt strengths, an increase of 17.8% in capacity from TB-04 to TB-02 and an increase in capacity of 20.4% from TB-03 to TB-01 were expected from strength calculations based on simple models.. The actual increases were 14.5% and 6.8%, respectively. Note that the deformation range of TB-01 was 1.008 in while the range of TB-03 was only 0.810 in. It is generally accepted that A325 bolts provide more ductility or deformation capacity than A490 bolts. The increased ductility of TB-01 over TB-03 was realized not because of the ductility characteristics of individual bolts, however, but because the increased strength of the A490 bolts allowed more deformation to take place within the T-stub itself before the bolts finally failed. The same trend is noticed in T-stubs TB-02 and TB-04, which showed deformation ranges of 0.691 in and 0.604 in, respectively.

Group 6: Group 5 and Group 6 were identical except that 1" diameter bolts were used in Group 6 while 7/8” diameter bolts were used in Group 5. The larger holes required for the 1" diameter bolts, and the smaller resulting net section area, shifted the failure modes from shear bolt and tension bolt fractures to net section fractures. As expected, the capacities of all four T-stubs in this group are closely grouped and independent of the bolt material properties.

Group 7: The Group 7 and 8 T-stubs, cut from W33 x 169 sections, were the largest tested. The increased flange thickness and width were expected to reduce the level of prying and the increased stem thickness was expected to increase the stem's capacity. A490 bolts 7/8” in diameter were used in T-stubs TC-01 though TC-04 and 7/8” diameter A325 bolts were used in TC-05 and TC-07. All of the T-stubs in Group 7 failed by tension bolt fracture. An increase in strength is noticed with reduced tension bolt gage, g t . The capacities of T-stubs TC-05 and TC-07 are lower than those of TC-01 and TC-03, respectively, as expected due to the lower strength of the A325 bolts. In this group, the T-stubs utilizing A325 bolts showed some additional ductility over those using the A490 bolts.

Group 8: Group 8 was the same as Group 7 except that 1" diameter bolts were used instead of 7/8” diameter bolts. The reduction in the net section of the stem from Group 7 to Group 8 caused the failure mode to shift from tension bolt failure to net section fracture for T-stubs TC-09 and TC-10. A comparison of the deformation ranges of TC-12 and TC-15 shows that the A325 bolts provided increased ductility.

Group 9: The D series T-stubs of Groups 9 and 10 were added to the testing program after testing of the series A and B T-stubs was started. It was hoped that the smaller flange thickness of the W16 x 45 section would promote pronounced tension flange yielding. The reduced stem thickness, however, led to net section fractures in all of the T-stubs before significant flange yielding was achieved. The monotonic test, TD-01, again showed that monotonic tests provide an accurate envelope of the cyclic behavior.

Group 10: The Group 10 T-stubs were identical to the Group 9 T-stubs except that 1" diameter bolts were used instead of 7/8” bolts. It is interesting to note that the average capacity of Group 10 is higher than the average capacity of Group 9, even though all of the T-stubs failed by net section fracture and the net area of the Group 10 T-stubs is lower than the Group 9 T-stubs. Because the series D T-stubs were added after the others, they were fabricated in a different shop. The quality of work was significantly lower for the series D T-stubs than for the others, including hand flame cut edges instead of the computer controlled flame cut edges of the other T-stubs. It is believed that the poor workmanship, combined with random variability, are responsible for this anomaly.

CONCLUSIONS

Several observations can be made about the behavior the T-stubs.

- The most desirable behavior was obtained from T-stubs that were proportioned such that a flange mechanism and advanced stem yielding developed simultaneously. T-stubs TA-03, TA-07, TA-12, TB-08, and TC-10 would be considered well proportioned and demonstrated failures that were balanced between the flanges and stems. Groups 1, 2, and 8 would be considered poorly proportioned because the tension bolts did not provide enough resistance to capitalize on deformation contributions from the stubs.

- There is a trade off between strength and deformation capacity in the flanges of the T-stubs and clip angles. Using wide tension bolt gages on the flanges yields larger flange deformations at failure. but the load carrying capacity can be reduced by as much as 20%.

- T-stubs that used only four tension bolts failed with relatively little deformation. A comparison of test results showed that the T-stubs using 4 bolts had 60% of the capacity of the 8 bolt T-stubs, but achieved only 30% of the deformation at failure.

- There appears to be little difference in the behavior of connections fabricated with A325 and A490 bolts. Twelve pairs of identical T-stubs and clip angles were tested with each type of bolt to enable a direct comparison of behavior. On average, connections using A325 bolts achieved 94% of the ultimate load and 106% of the ultimate deformation of connections using A490 bolts. Each type of bolt can have advantages in certain cases, however. In situations where the bolts are subjected to nearly direct tension, a marginal ductility increase can be gained by using A325 bolts

- Increasing the thickness of the T-stub flange dramatically increases its initial stiffness. Comparisons of T-stubs that have similar flange widths and tension bolt gages shows an average increase in stiffness of 138% with an increase in flange thickness of 25%. Increasing the bolt size and reducing the tension bolt gage also increase the initial stiffness but to a much smaller degree.

REFERENCES

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2. Roeder, C. W., Knechtel, B., Thomas, E. , Vaneaton, A., Leon, R. T., and Preece, F. R., 1996, "Seismic Behavior of Older Steel Structures," *ASCE Journal of Structural Engineering,* Vol. 122, No. 4, pp. 365-373.

Series	Designation	Bf	tf	Stem Width	ts	Grade
TA	W16 x 100	10-3/8"	1"	6"	9/16"	A572-50
TB	W21 x 93	8-3/8"	15/16"	7"	9/16"	A572-50
TC	W33 x 169	11-1/2"	1-1/4"	9-1/2"	11/16"	A572-50
TD	W16 x 45	7"	9/16"	6"	3/8"	A572-50
CA	L8 x 4 x 1	4"	1"	8"	1"	A572-50
	L8 x 6 x 1	6"	1"	8"	1"	A572-50

Table 1 – Description of sections used in component tests.

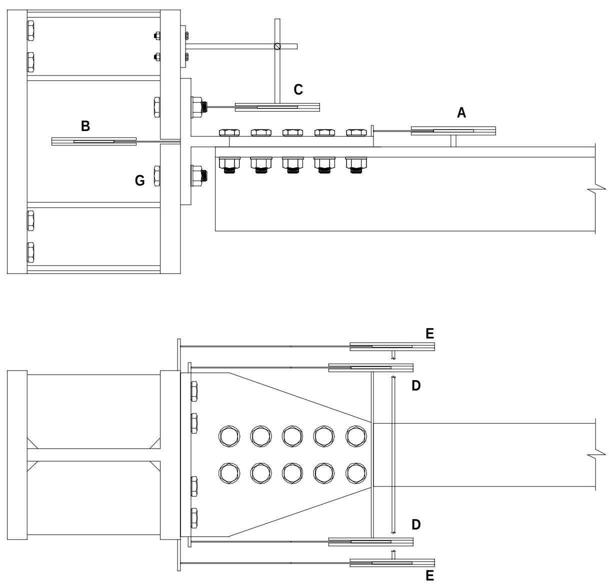

Figure 1 – Instrumentation.

Group	Test ID	Loading	Failure Mode	Max Load (kip)	Max Def (in)	Min Def (in)	Initial Stiffness (kip/in)	Energy Dissipated (kip-in)
Group 1	TA-17	Cyclic	T-Bolt	315.4	0.202	-0.061	12106.4	431.4
	TA-18	Cyclic	T-Bolt	291.7	0.197	-0.092	54984.8	517.5
	TA-19	Cyclic	T-Bolt	257.4	0.173	-0.017	28046.3	199.9
	TA-20	Cyclic	T-Bolt	234.7	0.229	-0.031	32718.5	350.9
Group 2	TB-09	Cyclic	T-Bolt	315.1	0.258	-0.073	13033.5	564.5
	TB-10	Cyclic	T-Bolt	277.1	0.208	-0.018	11638.5	188.3
Group 3	TA-01	Cyclic	Net Sec	468.7	0.615	-0.169	13916.0	1531.4
	TA-02	Cyclic	Net Sec	456.4	0.623	-0.159	12256.9	1622.6
	TA-03	Cyclic	T-Bolt	451.1	0.809	-0.180	7446.1	1852.2
	TA-04	Cyclic	T-Bolt	388.9	0.660	-0.121	8491.7	1291.0
	TA-05	Mono	Net Sec	473.3	0.767	---	---	---
	TA-07	Mono	T-Bolt	434.0	0.665	---	---	---
Group 4	TA-09	Cyclic	Net Sec	432.5	0.608	-0.206	15118.0	1243.5
	TA-10	Cyclic	Net Sec	426.5	0.620	-0.138	14568.1	1345.5
	TA-11	Cyclic	Net Sec	424.9	0.759	-0.108	12780.8	1264.5
	TA-12	Cyclic	Net Sec	424.3	0.974	-0.183	11857.6	2118.7
	TA-13	Cyclic	Net Sec	428.0	0.670	-0.143	14721.9	1256.6
	TA-15	Cyclic	Net Sec	425.3	0.767	-0.156	13829.2	1368.3
	TA-25	Cyclic	Net Sec	414.0	0.649	-0.090	13802.8	1231.1
	TA-26	Cyclic	Block Shr	399.2	0.619	-0.094	13591.5	1083.2
Group 5	TB-01	Cyclic	S-Bolt	506.3	0.876	-0.132	0.0	0.0
	TB-02	Cyclic	T-Bolt	464.8	0.558	-0.133	0.0	0.0
	TB-03	Cyclic	S-Bolt	474.0	0.663	-0.147	0.0	0.0
	TB-04	Cyclic	T-Bolt	405.7	0.497	-0.107	10447.3	923.1
Group 6	TB-05	Cyclic	Net Sec	502.8	0.739	-0.134	16798.1	1751.5
	TB-06	Cyclic	Net Sec	496.8	0.782	-0.121	12507.2	2322.1
	TB-07	Cyclic	Net Sec	496.9	0.683	-0.152	21119.4	1728.1
	TB-08	Cyclic	Net Sec	493.8	0.936	-0.102	15073.1	2157.7
Group 7	TC-01	Cyclic	T-Bolt	584.7	0.383	-0.084	36485.9	1061.6
	TC-02	Cyclic	T-Bolt	525.4	0.290	-0.116	24126.0	856.8
	TC-03	Cyclic	T-Bolt	468.2	0.263	-0.143	22816.9	863.1
	TC-04	Cyclic	T-Bolt	417.0	0.381	-0.065	16459.7	772.8
	TC-05	Cyclic	T-Bolt	543.4	0.440	-0.116	32152.5	960.7
	TC-07	Cyclic	T-Bolt	446.3	0.383	-0.125	26110.8	900.5
Group 8	TC-09	Cyclic	Net Sec	663.0	0.656	-0.118	36747.1	2101.5
	TC-10	Cyclic	Net Sec	651.7	0.777	-0.149	19864.0	2549.9
	TC-11	Cyclic	T-Bolt	580.7	0.449	-0.138	20747.0	1306.5
	TC-12	Cyclic	T-Bolt	512.6	0.560	-0.079	38685.7	1228.4
	TC-13	Cyclic	T-Bolt	633.2	0.619	-0.178	27993.8	1855.1
	TC-15	Cyclic	T-Bolt	516.4	0.565	-0.099	17185.2	1193.0

Table 2 – Results of component tests

	Test ID	Loading	Failure Mode	Max Load (kip)	Max Def (in)	Min Def (in)	Initial Stiffness (kip/in)	Energy Dissipated (kip-in)
Group 9	TD-01	Mono	Net Sec	246.0	0.313	---	---	---
	TD-02	Cyclic	Net Sec	247.2	0.356	-0.126	6977.1	652.8
	TD-03	Cyclic	Net Sec	253.8	0.397	-0.101	10952.0	664.1
	TD-04	Cyclic	Net Sec	246.5	0.334	-0.152	13154.6	738.7
Group 10	TD-05	Mono	Net Sec	256.2	0.332	---	---	---
	TD-06	Cyclic	Net Sec	259.5	0.313	-0.113	5474.7	603.7
	TD-07	Cyclic	Net Sec	259.0	0.269	-0.130	10117.3	693.8
	TD-08	Cyclic	Net Sec	254.5	0.242	-0.101	12631.7	675.5
Group 11	CA-01	Cyclic	T-Bolt	108.3	0.384	-0.143	2138.6	392.3
	CA-02	Cyclic	T-Bolt	125.3	0.359	-0.135	2369.5	354.0
	CA-04	Cyclic	T-Bolt	84.3	0.645	-0.078	1320.8	258.5
	CA-17	Cyclic	T-Bolt	120.9	0.387	-0.088	2033.2	281.1
	CA-18	Cyclic	T-Bolt	119.2	0.354	-0.110	2564.4	345.6
Group 12	CA-09	Cyclic	T-Bolt	125.2	0.448	-0.071	4626.5	350.4
	CA-10	Cyclic	T-Bolt	159.3	0.499	-0.045	4249.7	386.5
	CA-12	Cyclic	T-Bolt	109.2	0.896	-0.112	2207.8	521.1
	CA-14	Cyclic	T-Bolt	136.8	0.543	-0.083	3978.3	407.6
	CA-16	Cyclic	T-Bolt	95.2	0.823	-0.052	2179.9	390.8

Table 2 (cont.) – Results of component tests.

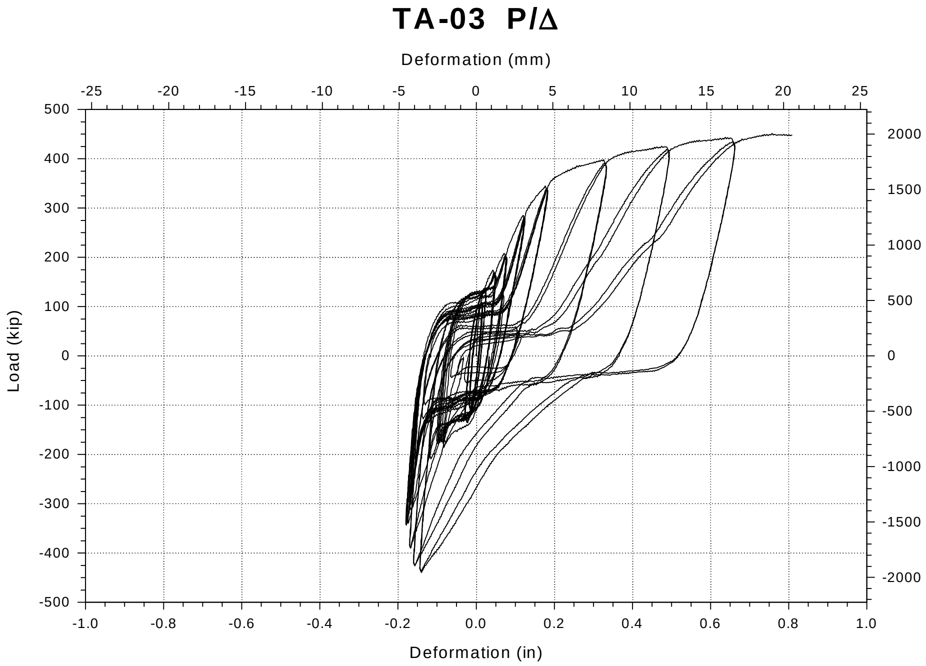

Figure 2 – Load-deformation curve for T-stub failing due to prying action.

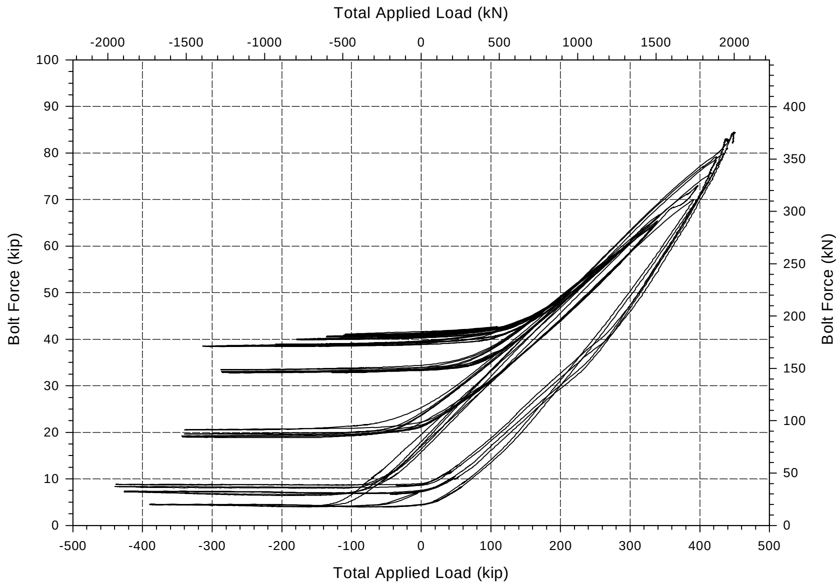

Figure 3 – Loss of bolt force with cycling

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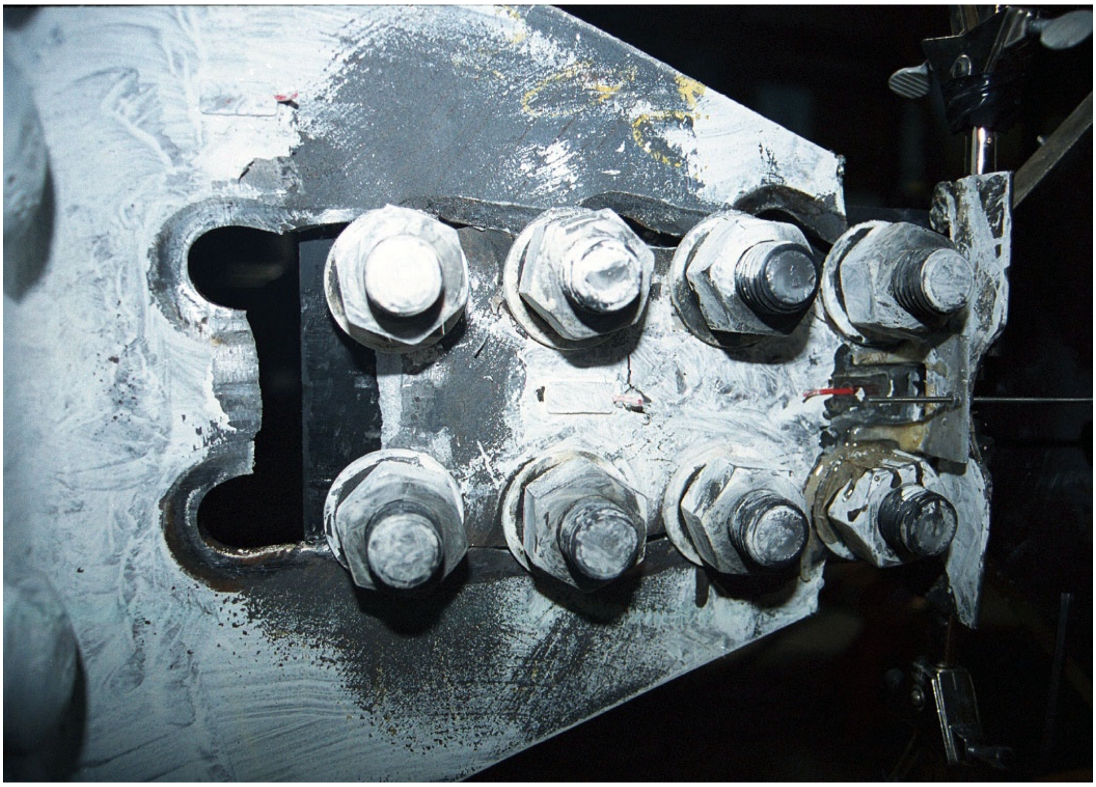

Figure 4 – Block shear failure for TA-26.