

Effects of Variable Pretension on Bolted Connection Behavior

Final Report

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ABSTRACT:

A series of 38 bolted T-stub type connection specimens were tested at the University of Cincinnati as part of an effort to determine if varying levels of pretension within a connection adversely affect the connection's performance. The test program included A325, A490, Grade 5, and Grade 8 fasteners, three different lengths of A325 fasteners, and three different levels of pretension. Bolts used to connect the test specimens were instrumented with strain gages and calibrated to facilitate monitoring of bolt forces during the experiments. Independent testing of the fasteners, which included the monitoring of load/deformation behavior, was performed to verify manufacturer certifications and provide a baseline for comparing connection behavior. It was found that varying the level of pretension in the connection did not appreciably affect the connection strength but did affect the connection stiffness and deformation capacity.

BACKGROUND:

Some time ago, Dr. Thomas Murray suggested that full pretension of tension bolts might not be necessary in bolted connections to resist environmental loads such as wind. Discussions

following this suggestion led to concern that during assembly of bolted connections an iron worker may tighten some of the bolts in a connection while inadvertently 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. Grade A325 bolts were used for all of the tests. Two lengths were selected - 2-3/4" and 3-1/4" - 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. 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, T-stubs connected with A490 bolts in tension with varying levels of pretension, and T-stubs connected with fully threaded fasteners.

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, fully threaded

Grade 5 and Grade 8 bolts (very similar to A325 and A490 bolts)*, and two T-stub specimens not included in Table 2. These last two were connected by four A325 bolts - one fully tensioned with the remaining three finger tight. All of the bolts were 3/4" 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 20-25%, the T-stub specimens were cut from a W18 x 106 made of grade A992/A572-50 steel. The gage of the tension bolts was held constant at 6" 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 x 106 was selected for material testing and was machined into six subsize tension specimens (ASTM E8) as is shown in Figure 1. 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" gage length extensometer was used to measure strain. The coupons were loaded in stroke control at rate of 0.010 inches per minute in the elastic range and throughout initial yielding. This displacement rate corresponded to an elastic loading rate of approximate 20 ksi per minute. After the onset of strain hardening, the displacement rate was increased to 0.100 inches per minute until failure. The results of the coupon tests are presented in Table 3 while the stress-strain curves of the flange and web coupons are shown in Figures 2 and 3, respectively.

The W18 x 106 section was rolled from ASTM Grade A992/A572-50 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% 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% elongation at fracture. Coupon tests of the web transverse to the direction of rolling that were conducted at the University of Cincinnati

* Grade 5 and Grade 8 bolts were used instead of fully threaded A325 and A490 bolts because they were more readily available to the investigators.

indicated averages of 57.4^{ksi} and 70.7^{ksi} for the yield and ultimate strengths, respectively, with a 30.4% elongation at fracture.

The modulus of elasticity of the material was determined by performing a regression analysis of the stress-strain data that appeared to be linear. The upper yield point, F_{yu} , was defined as the data point immediately preceding the first data point demonstrating a drop in load with an increasing strain. The dynamic yield stress, F_{yd} , was determined using the 0.2% offset method. The static yield stress, F_{ys} , was taken as the minimum stress observed while holding the specimen at a constant displacement for approximately three minutes at a strain of approximately 0.3 - 0.6%. The strain at the onset of strain hardening and strain hardening modulus, E_{st} , were determined in accordance with the guidelines of method 2 of ASCE Manual No. 41 - Plastic Design in Steel (ASCE, 1971). The dynamic ultimate strength of the material, F_{ud} , was taken as the maximum stress resisted by the coupon during testing. Finally, the percent elongation at fracture was determined by placing two small indentations approximately 2 inches apart on the front and back of the coupon. The exact distance between the two indentations was measured before and after testing. The final measurement divided by the initial measurement minus one was taken as the 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 4. 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 additional LVDTs. The A325 fasteners were obtained in lengths of 3-1/2", 3-1/4", and 3-3/4" in order to investigate the effects of including a moderate number of threads, a maximum number of threads, and a minimum number of threads in the bolts' grips, respectively. To replicate the T-stub experiments, the 3-1/2" bolts were tested with 5 to 6 threads in the grip, the 3-1/4" bolts were tested with 8 to 9 threads in the grip, and the 3-3/4" bolts were tested with 1 to 2 threads in the grip. The A490, Grade 5, and Grade 8 fasteners that were used in the program were all 3-1/2" in length. All fasteners were 3/4" in diameter.

The test results are summarized in Table 4 and the load-deformation curves are shown in Figures 5-10. 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 11 shows a fractured A325 3/4" x 3-1/4" bolt on top, a fractured A325 3/4" x 3-1/2" bolt in the middle, and a fractured A325 3/4" x 3-3/4" 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 more ductile fastener behavior. The affect on T-stub behavior that was noted when varying the bolt length's discussed in a later section.

A comparison of the Grade 5 results with the results for the same size A325 and the Grade 8 results with the A490 results shows that significant fastener ductility gains can be achieved by using fully threaded fasteners in tension. Figure 12 shows three Grade 8 bolts that have been subjected to increasing loads. The bolt on top is new and has not been stressed, the bolt in the middle has been stressed well past its elastic limit, and the bolt shown on the bottom has been fractured. This comparison substantiates the idea that in fully threaded fasteners; the plastic behavior is distributed over the entire length of the fastener instead of being concentrated in the short threaded region.

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 8. It should be noted that the loading rate used in the fastener tests was relatively slow. The author speculates that had a faster loading rate been used – one still within ASTM specifications – that the first lot of A490 bolts would 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. An example of the load/strain data for a representative bolt is shown in Figure 13 along with the results of a regression analysis.

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 14. Figure 15 shows actual photos of the T-stub test set-up. The top and bottom crossheads of the test machine were sandwiched between stiffened W12 x 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” diameter A490 bolts so as to force the failure into the bottom flange. All bolts that were installed to the fully tensioned conditioned 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.

The cyclic load history shown in Figure 16 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 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 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 17. 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 four tension bolts. The detailed test results are shown in Table 5. Table 6 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 are roughly 98% 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 18, 19, and 20 show the bolt forces plotted vs. 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. 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 7 shows a summary of the deformations of the T-stub specimens with bolts that were tightened uniformly. Referring to Table 7 and using the case with two A325 3/4” x 3-1/2” fully tensioned bolts as the baseline case, the following observations can be made.

- The snug tightened case deforms 52% more before failure and the finger tightened case deforms 65% more before failure than the fully tensioned case for specimens connected with A325 3/4” x 3-1/2”. As Figure 21 illustrates, this gain in deformation capacity is accompanied by a loss of initial stiffness.
- The specimen connected with fully tensioned A325 3/4” x 3-1/4” bolts deformed slightly more than twice as much as the one connected by fully tensioned A325 3/4” x 3-1/2” bolts. The specimen connected with A325 3/4” x 3-3/4” bolts behaved almost identically to the specimen connected with A325 3/4” x 3-1/2” bolts.
- The specimens connected by fully tensioned A490-A bolts deformed 36% more than the specimen connected with the same size fully tensioned A325 bolts.
- The specimens connected by fully tensioned A490-B bolts deformed 37% less than the specimen connected with the same size fully tensioned A325 bolts .

- The specimen connected by fully tensioned Grade 5 bolts deformed 186% more than the specimen connected by the same size fully tensioned A325 bolts. As Figure 22 illustrates, the Grade 5 bolts provide a substantial increase in connection ductility over A325 bolts while minimally affecting strength and stiffness.
- The specimen connected by fully tensioned Grade 8 bolts deformed 62% more and 164% more than the specimens connected by the same size fully tensioned A490-A and A490-B bolts, respectively.

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". Despite this, the results shed some light on the effects of varying the bolt length, grade, and pretension on the behavior of the connection.

CONCLUSIONS:

Several conclusions can be reached by examining the results of the research project documented in this report.

- Varying the pretension of tension bolts within a connection did not appreciably affect the overall connection strength. 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.
- 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 lower initial stiffness but increase the deformation at failure.
- As one may expect, varying the grade of the bolts affected the overall behavior of the connection - significantly in some cases. Using fully threaded Grade 5 and Grade 8 bolts

in place of A325 and A490 bolts, respectively, lead to much greater deformations at failure while minimally affecting the strength and initial stiffness of the specimens.

- 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).

REFERENCES:

ASCE, 1971, "Plastic Design in Steel – A Guide and Commentary, 2nd Ed."

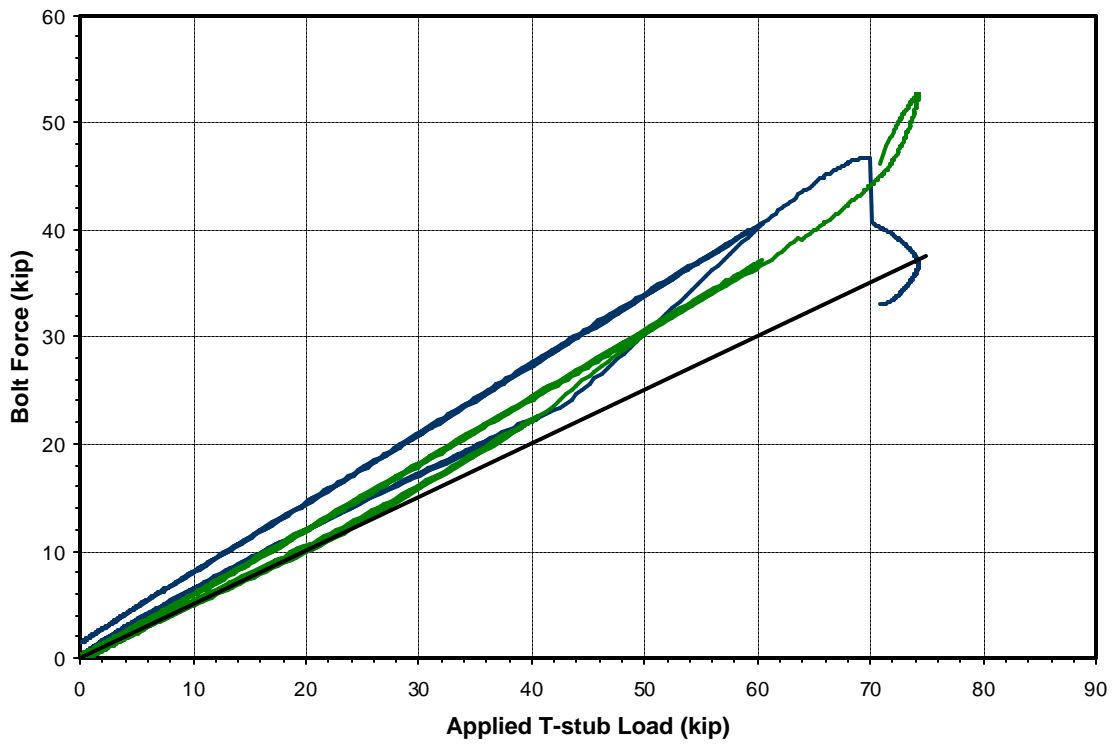
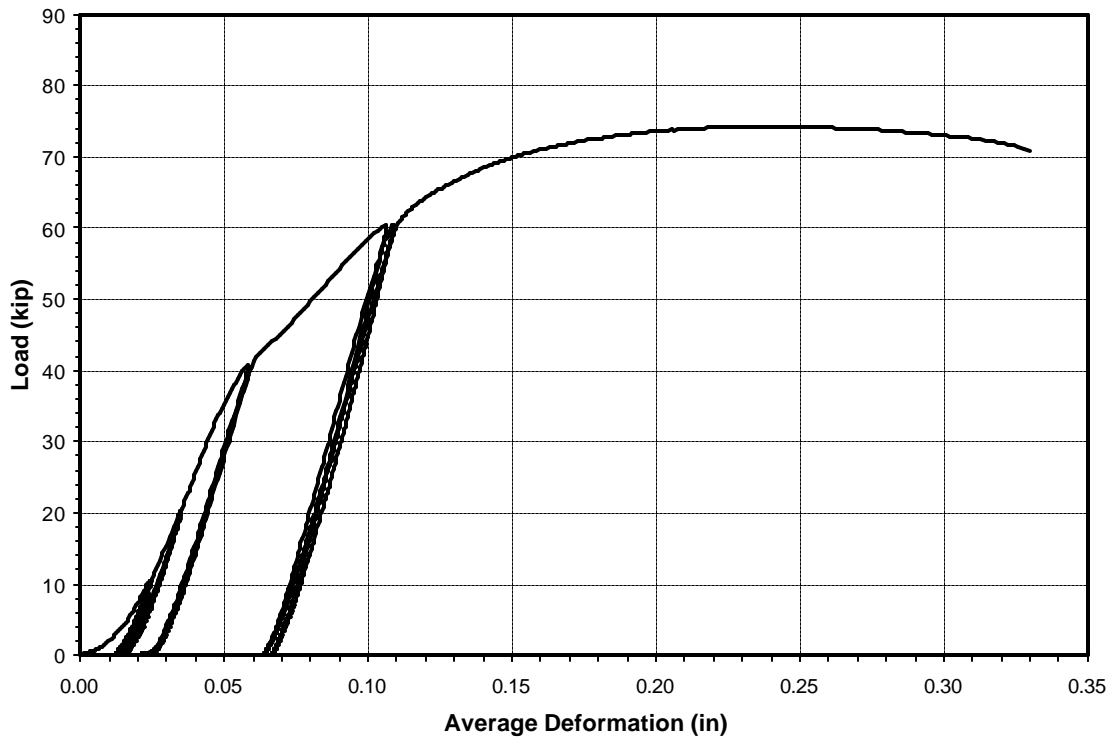
ASTM Specification E8-96a, "Standard Test Methods for Tension Testing of Metallic Materials"

Johnson, Donald L., 1996, "Final Report on 'Tee' Stub Tests, Butler Manufacturing," May

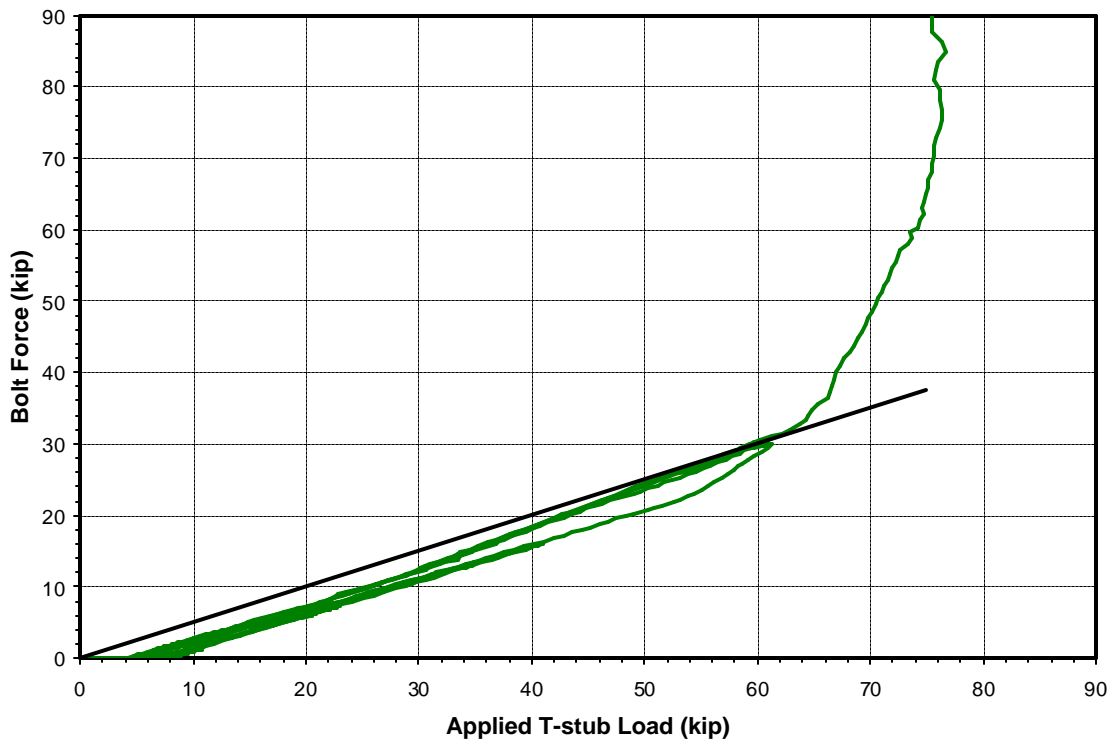
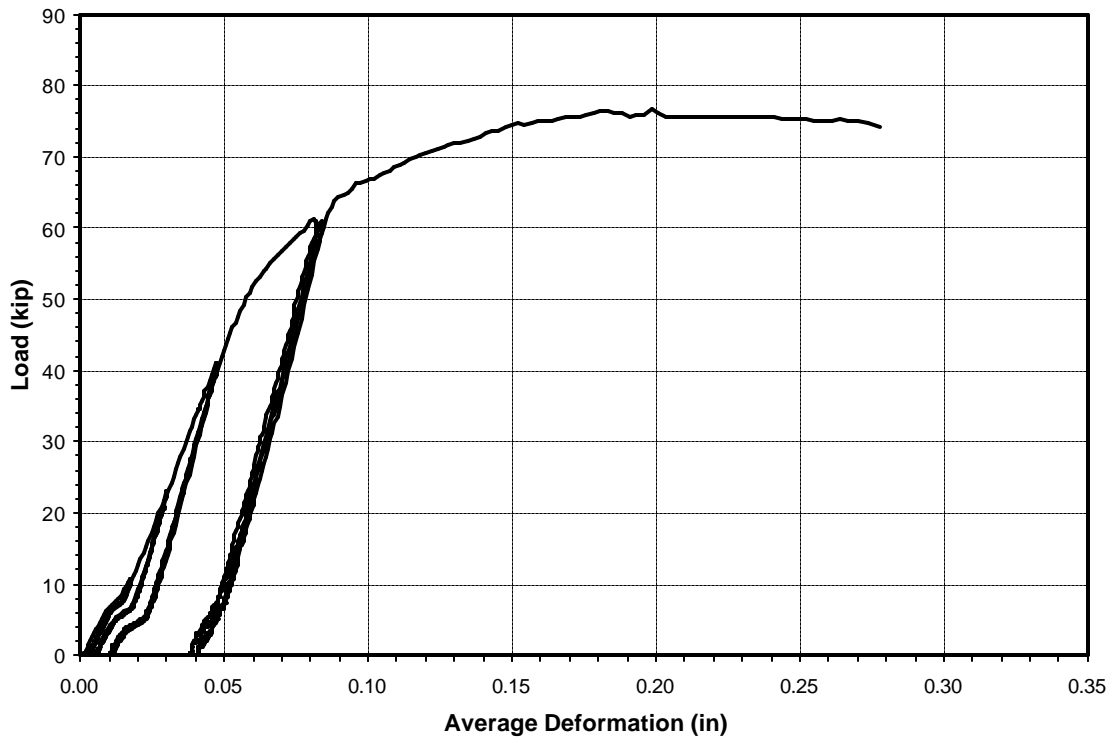
APPENDIX I

This appendix includes the force/deformation response and bolt force/applied T-stub force response for each of the T-stub specimens that were tested.

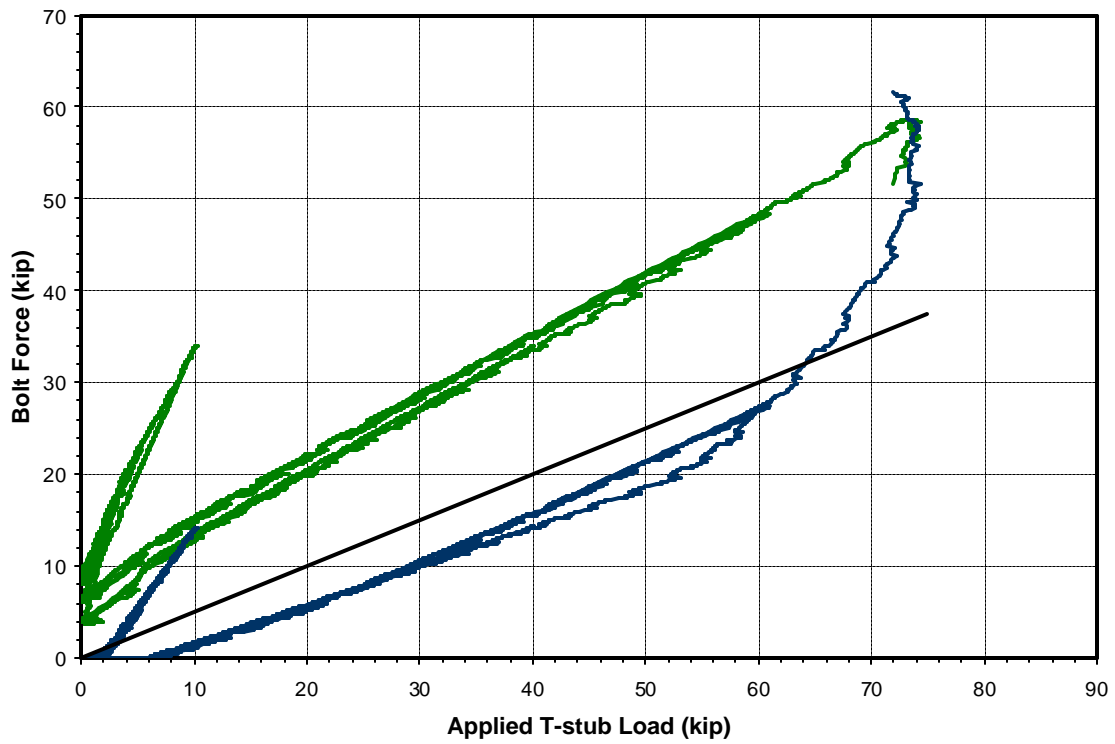
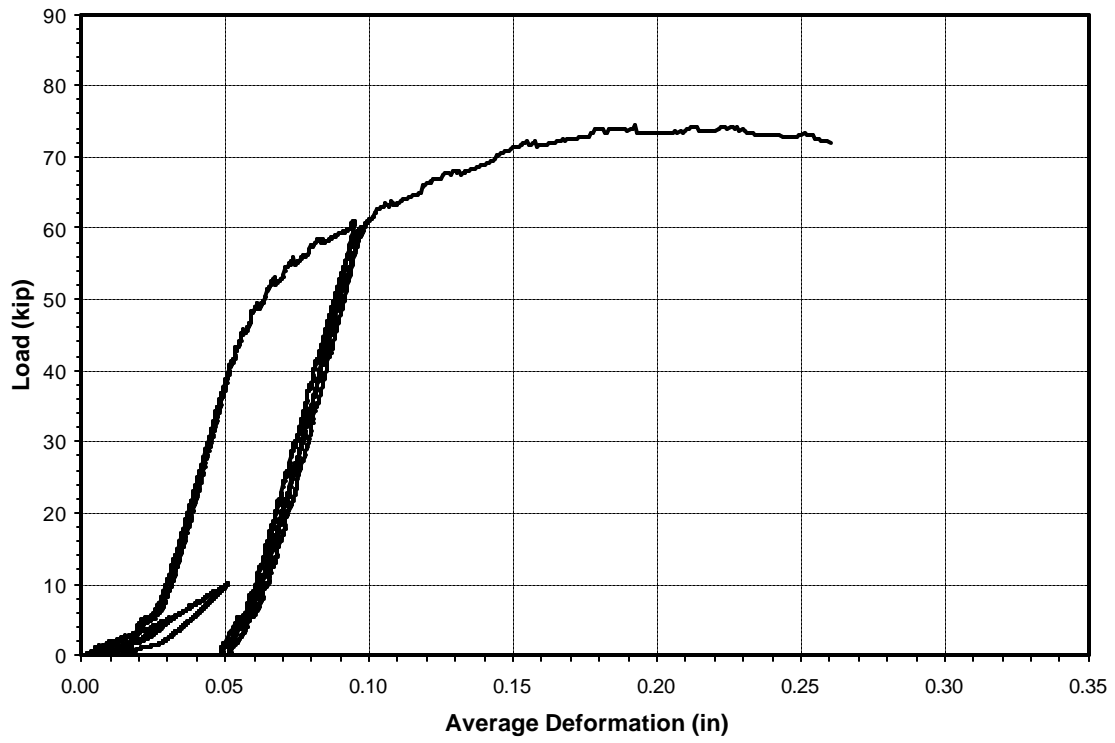
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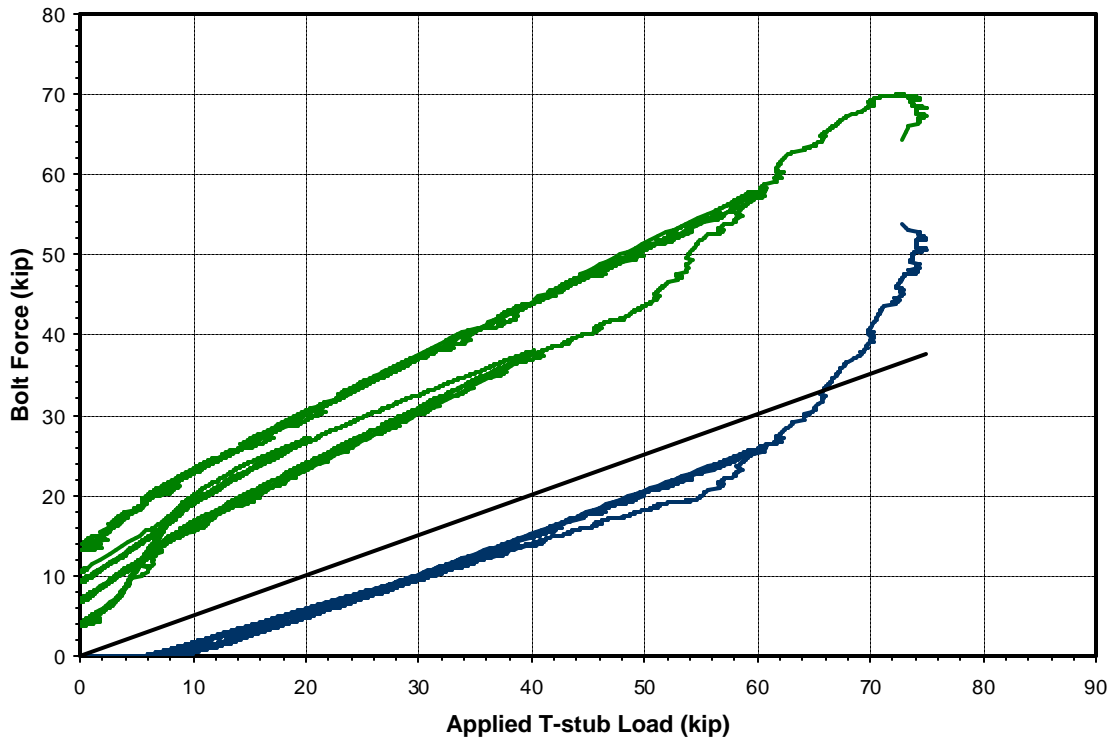
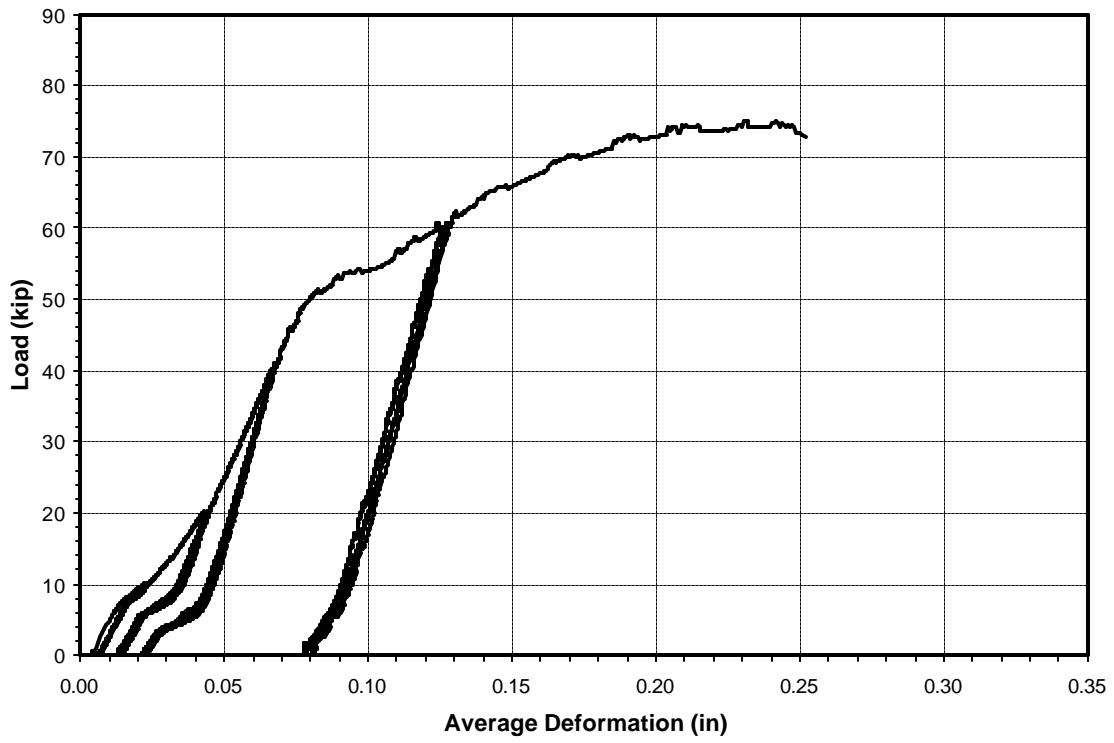
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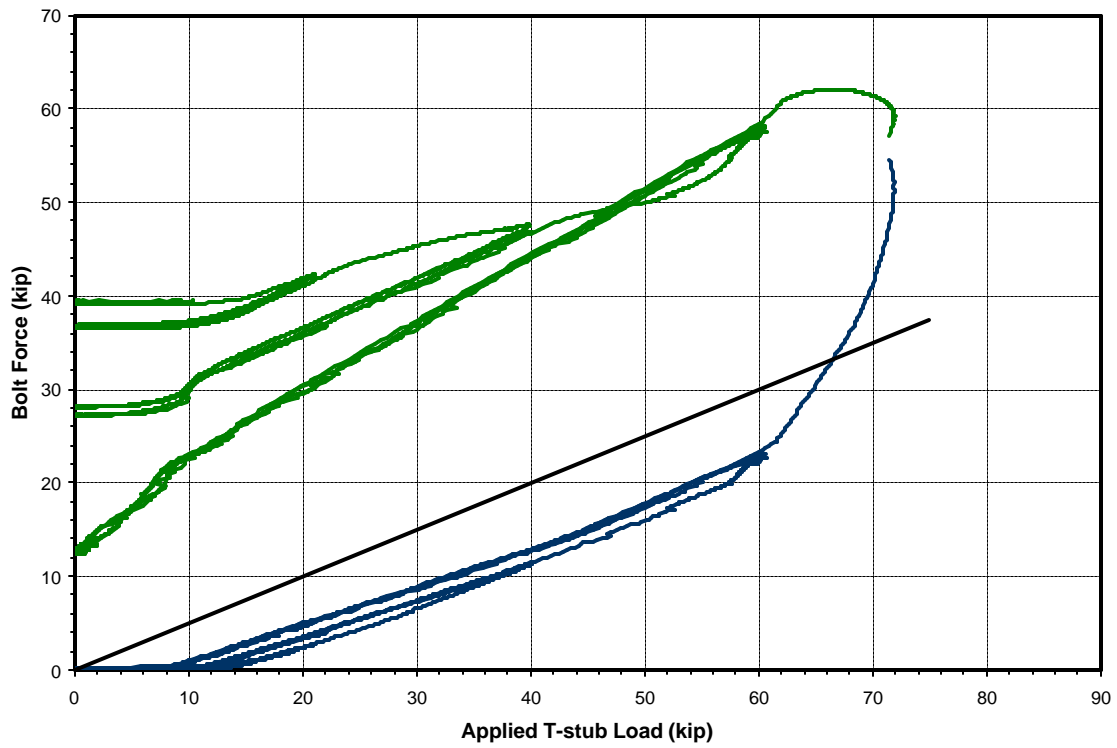
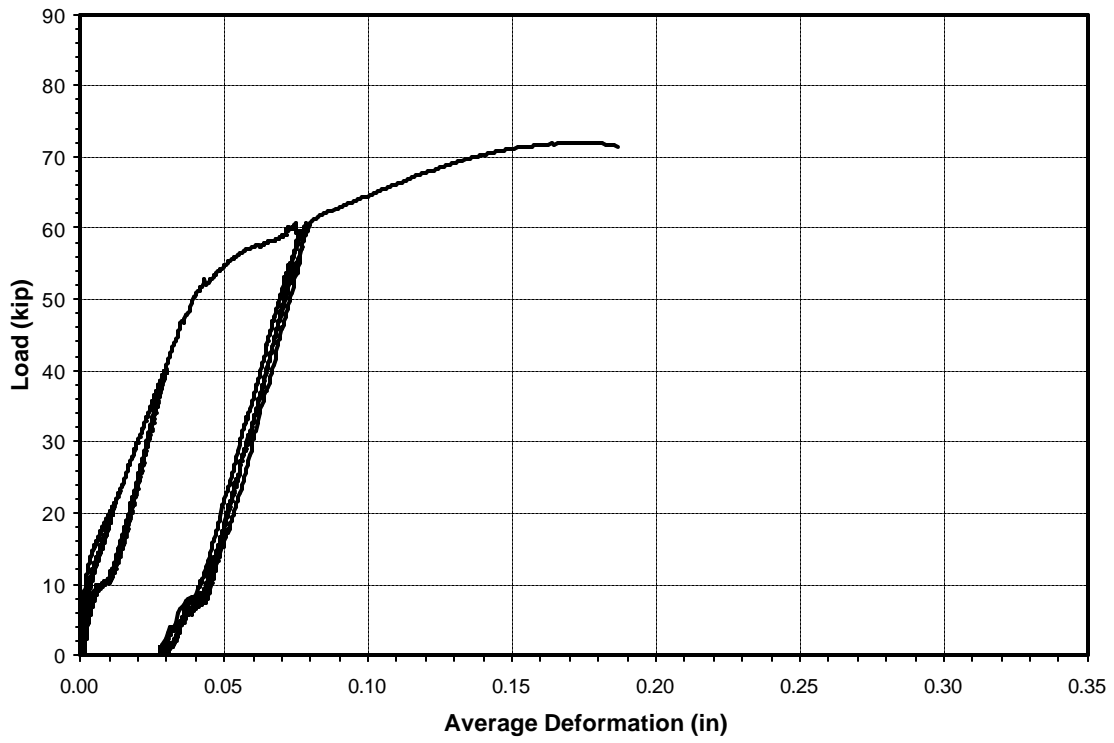
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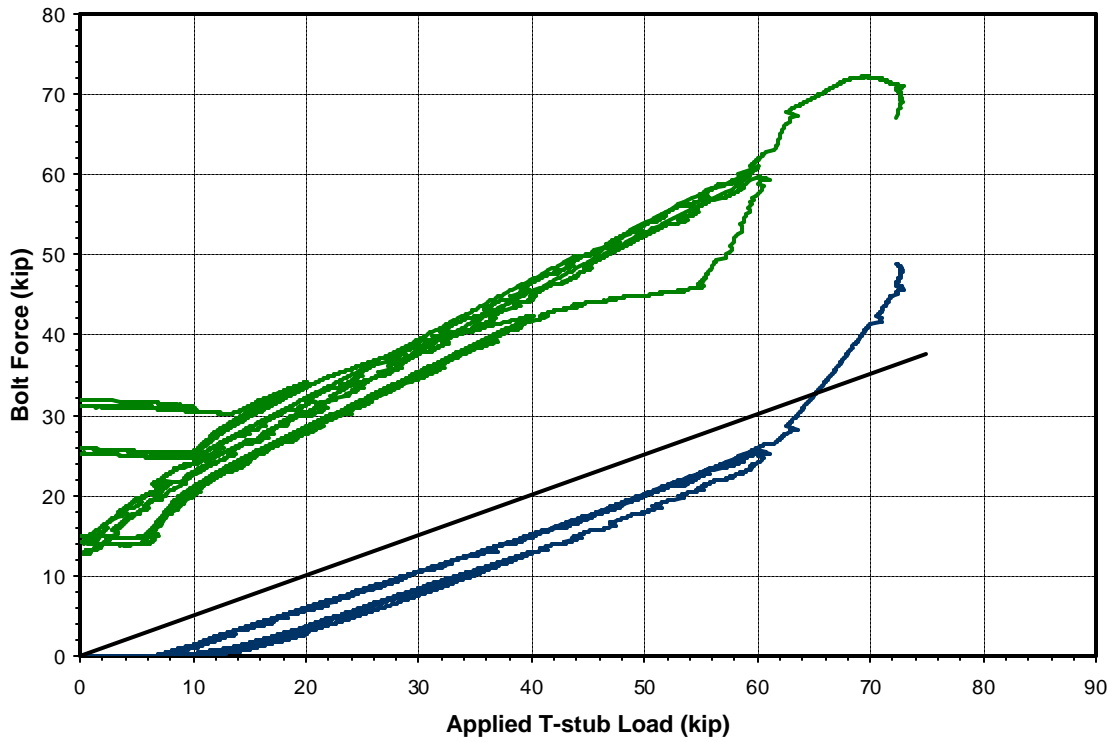
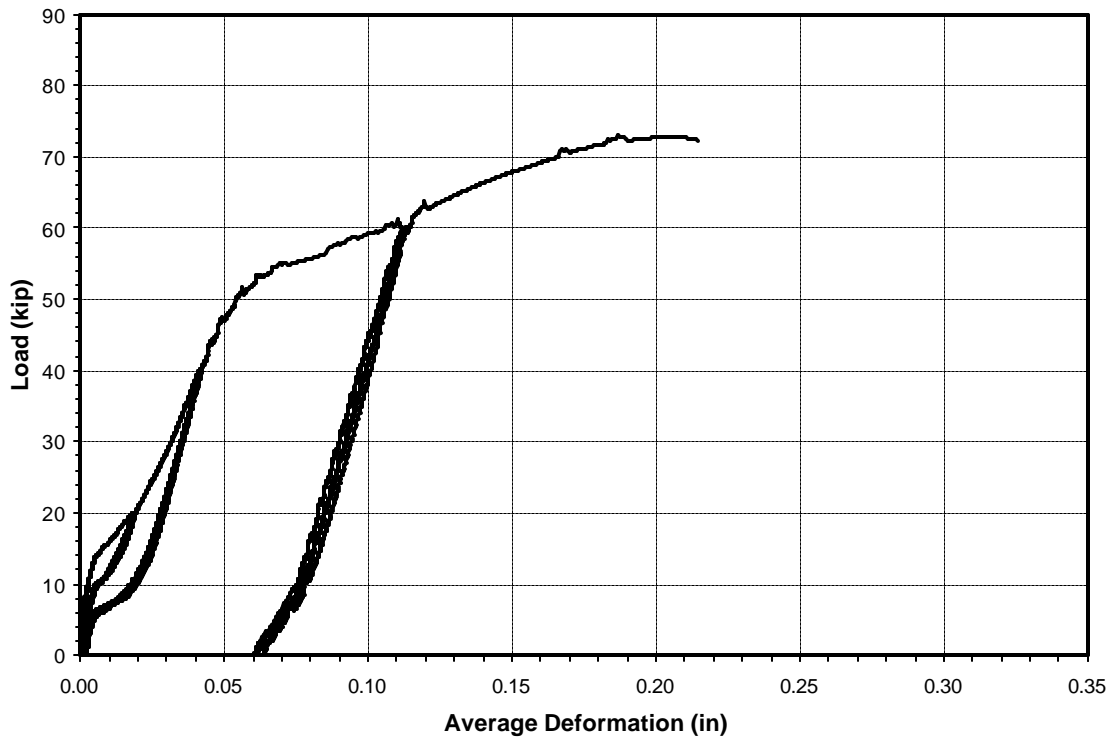
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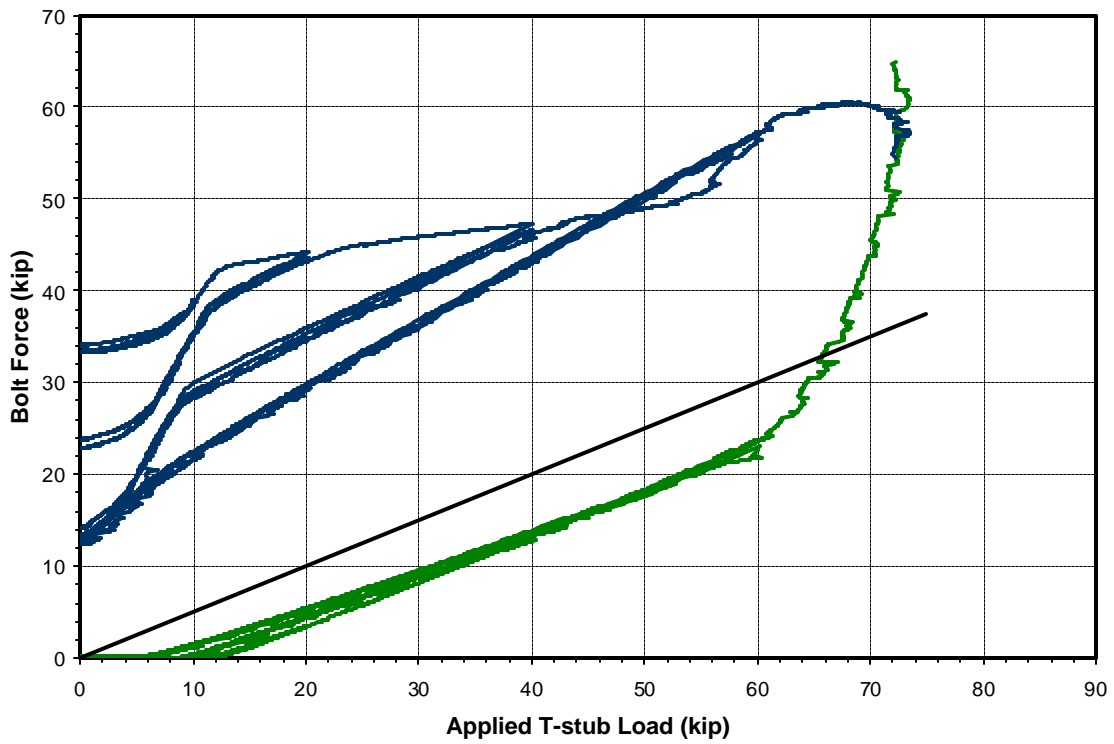
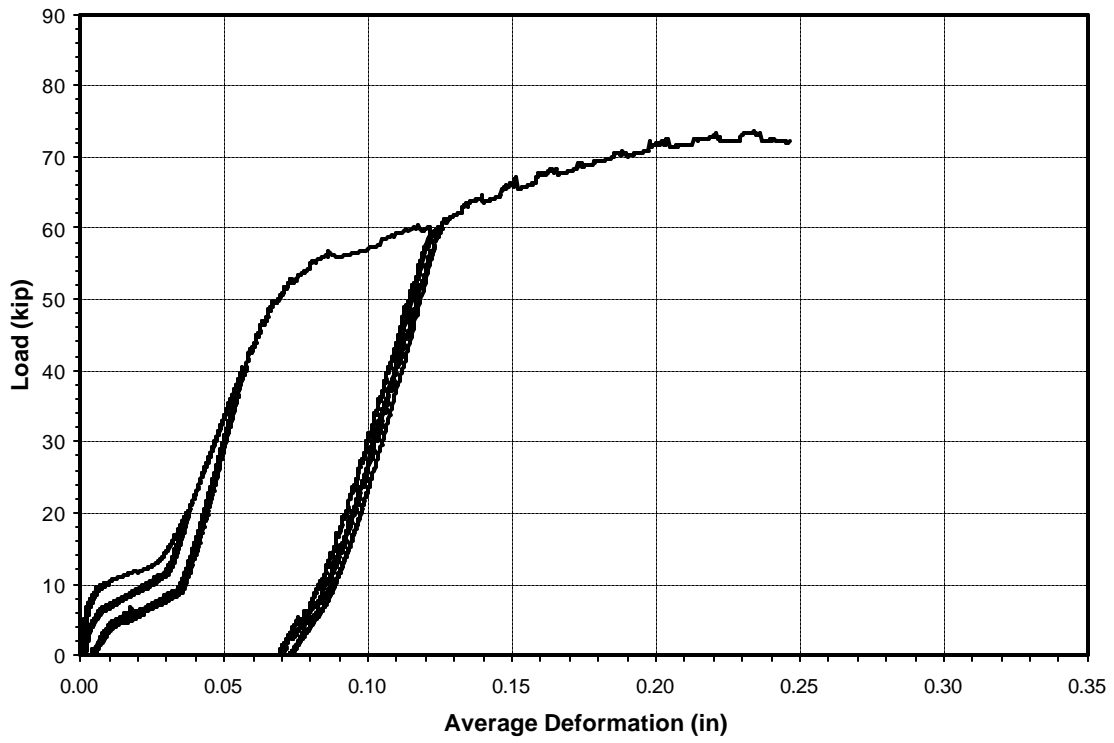
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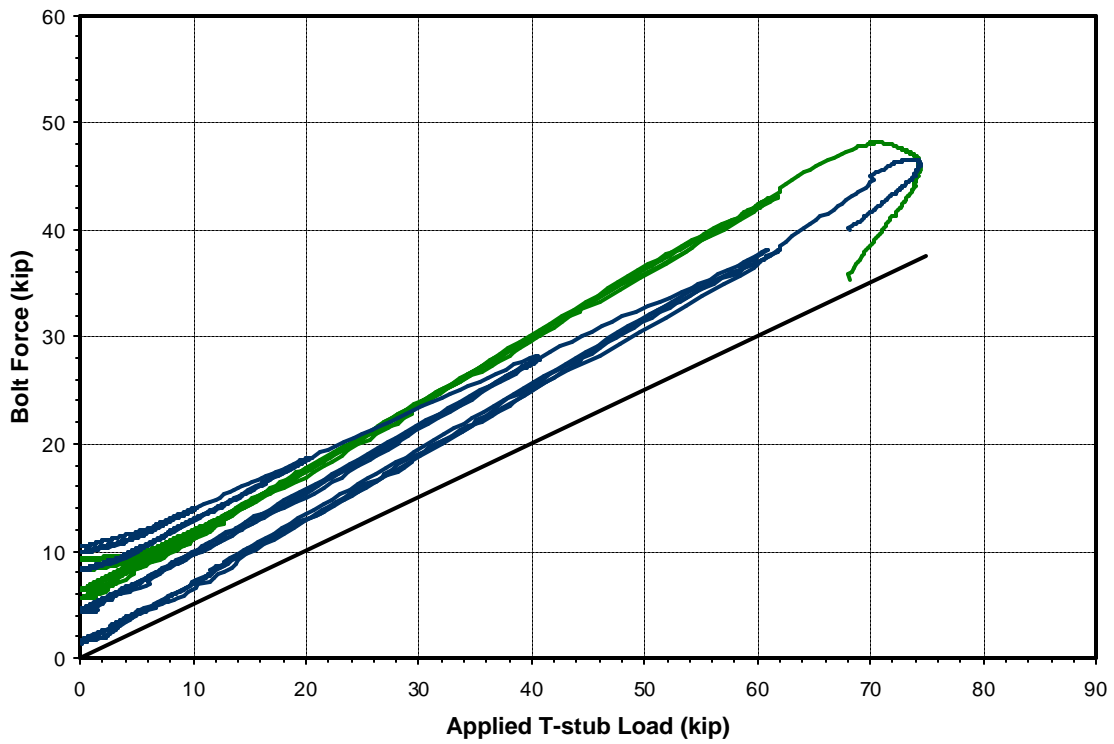
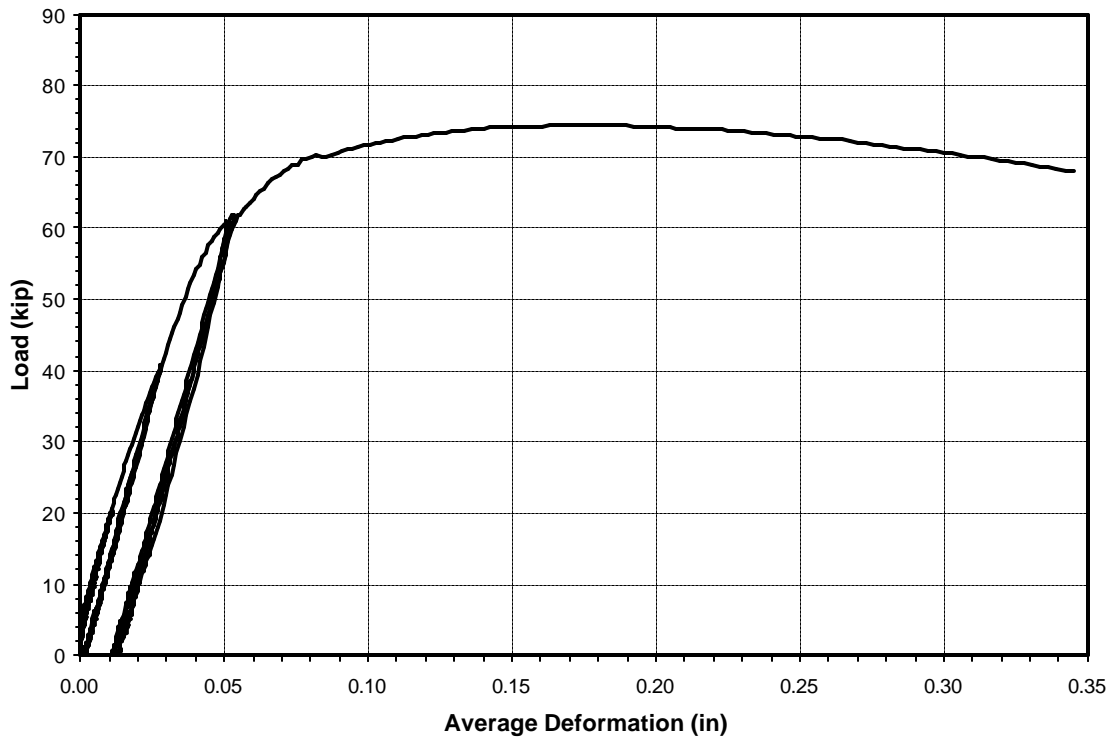
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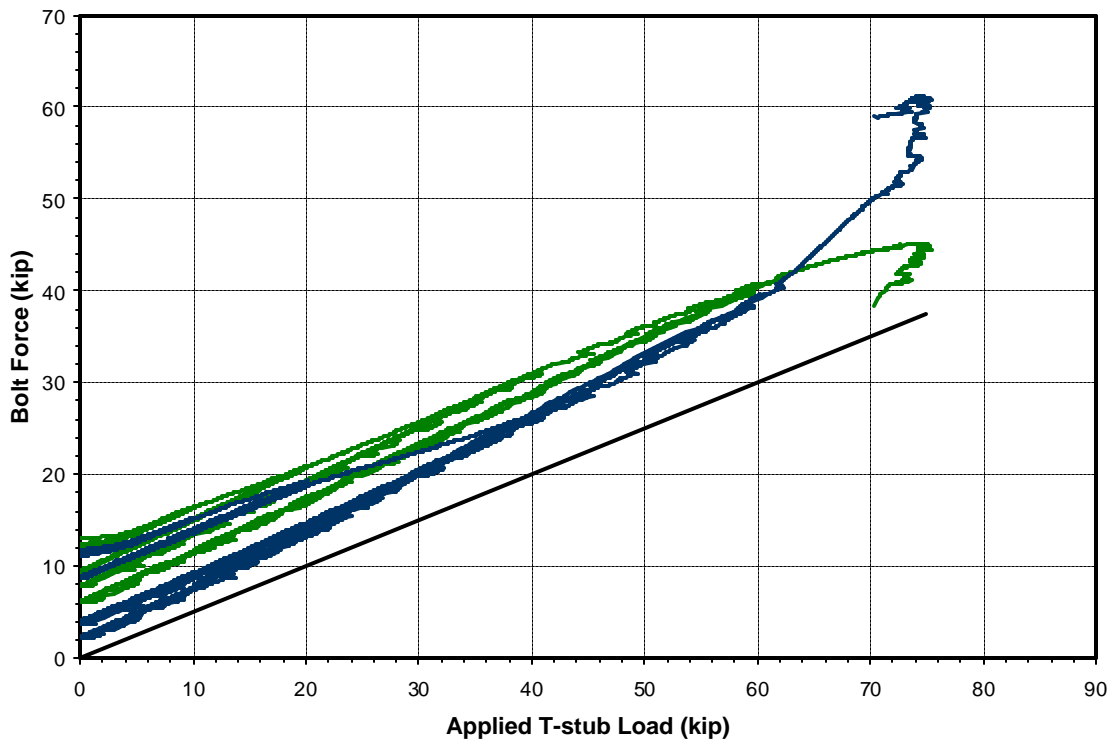
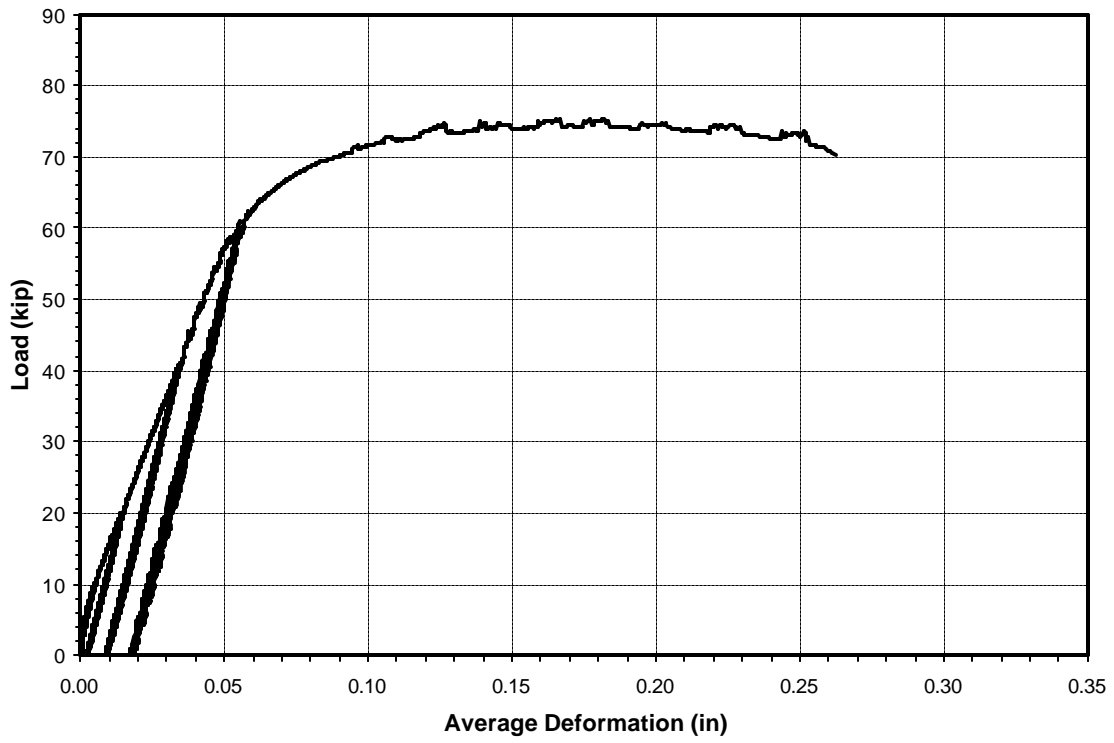
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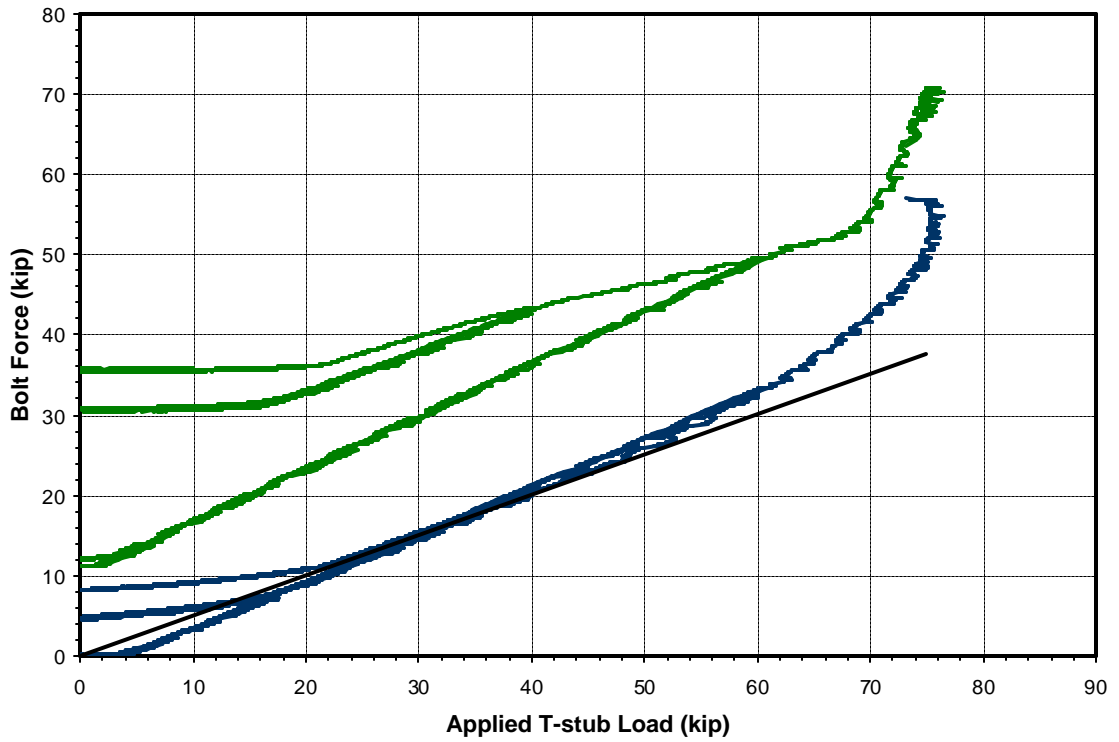
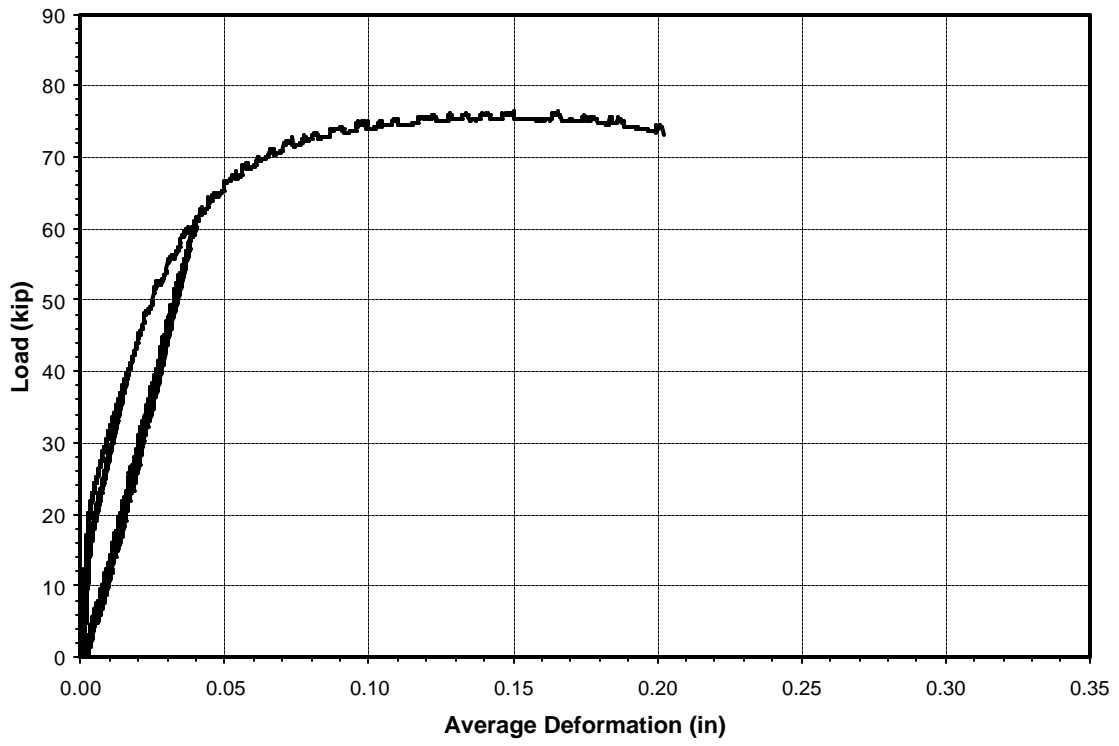
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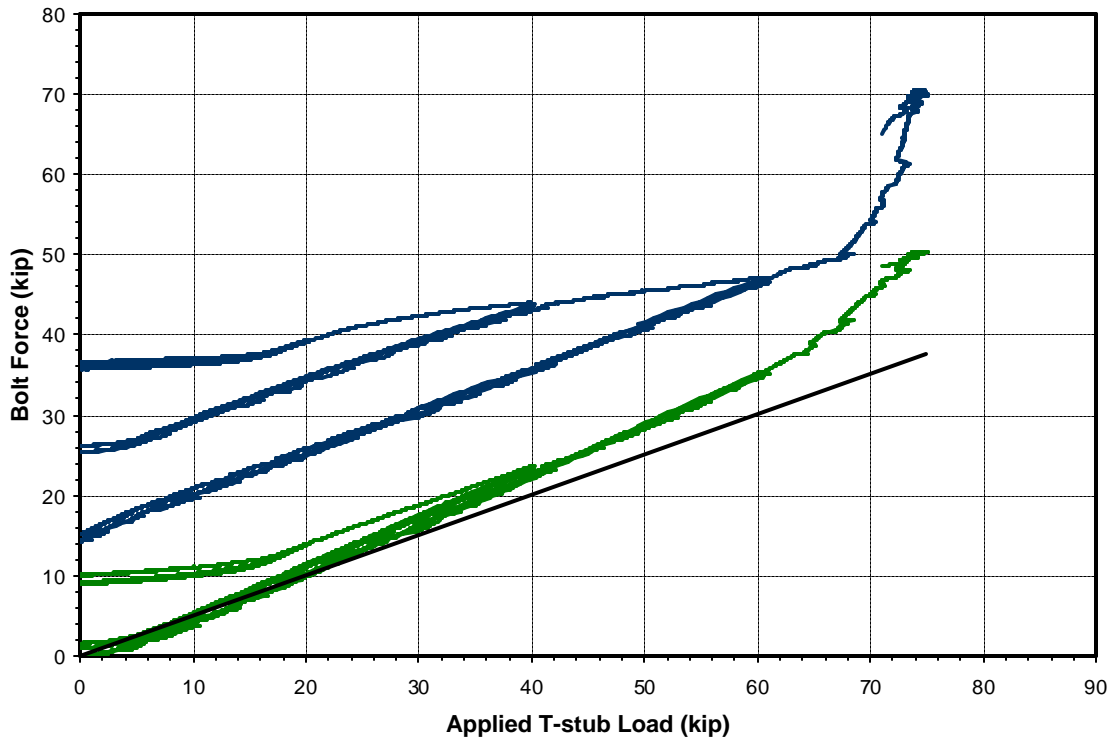
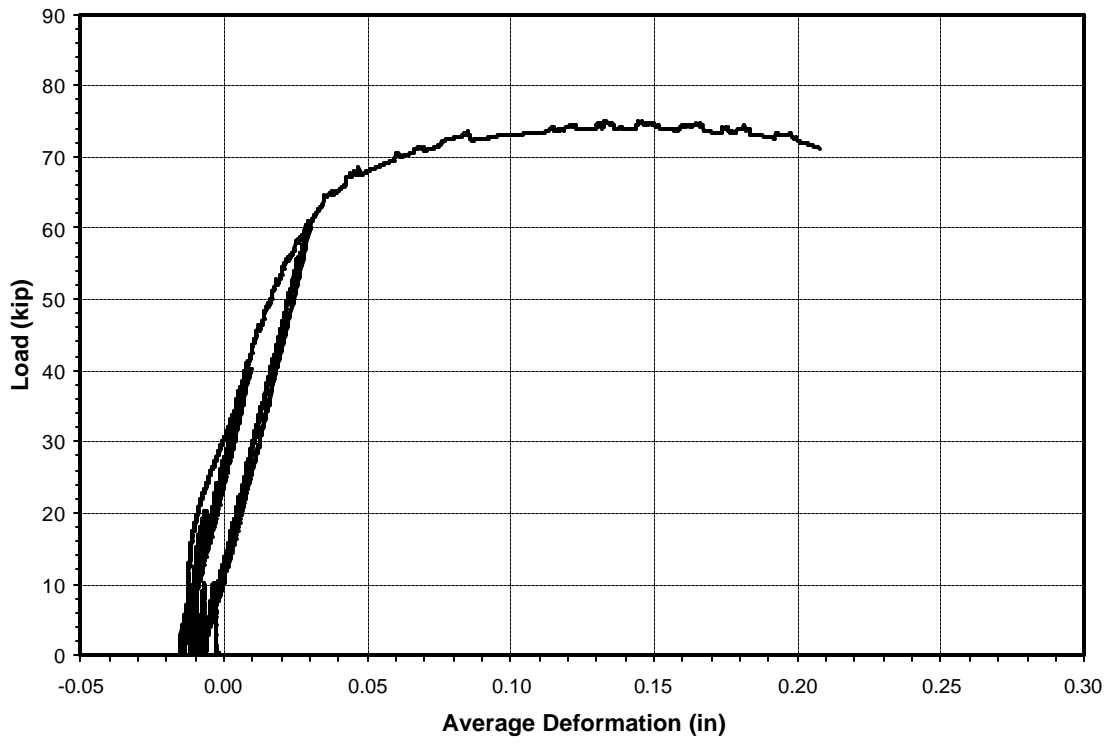
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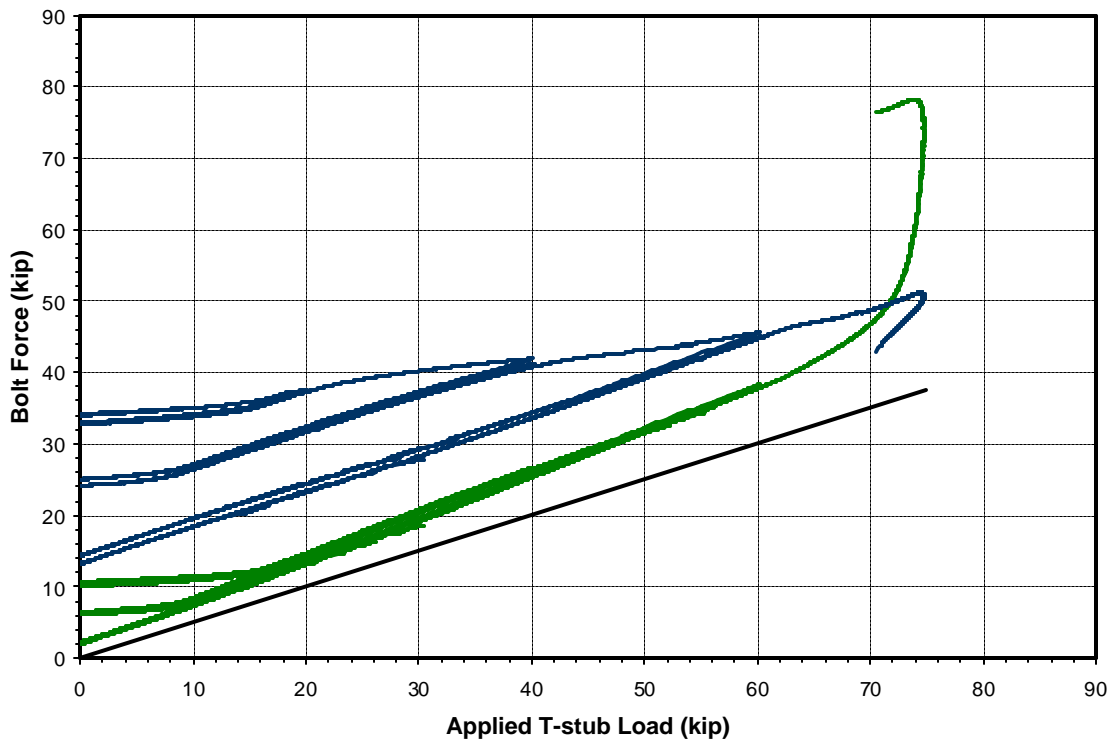
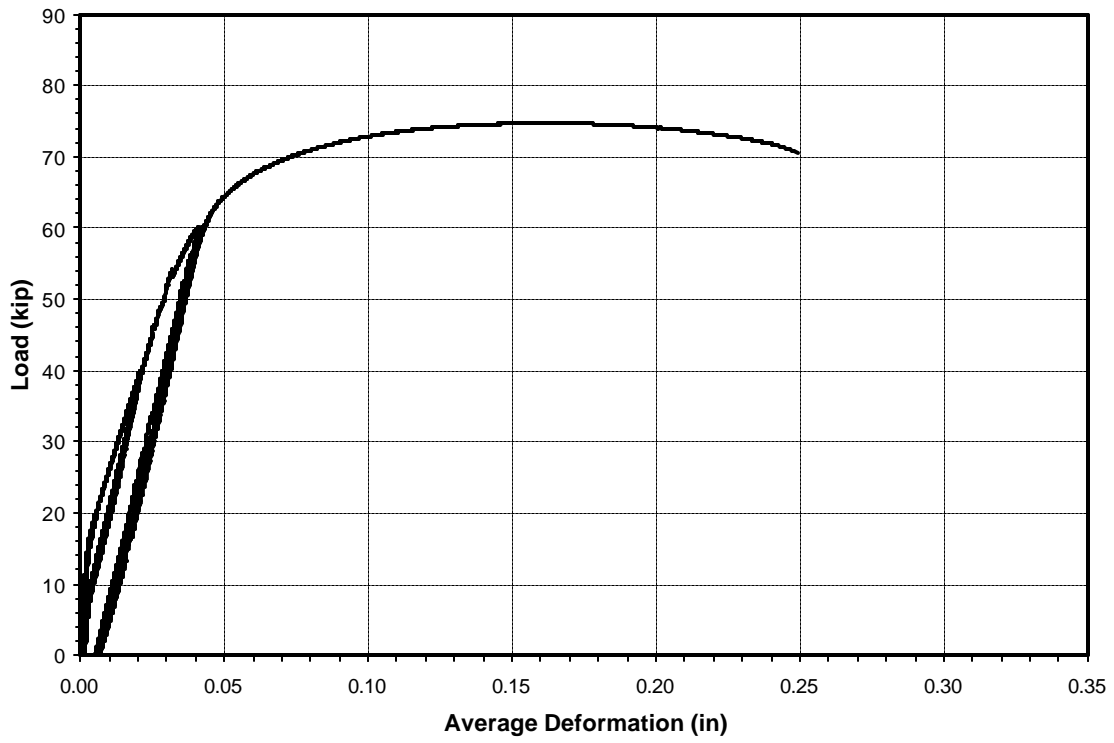
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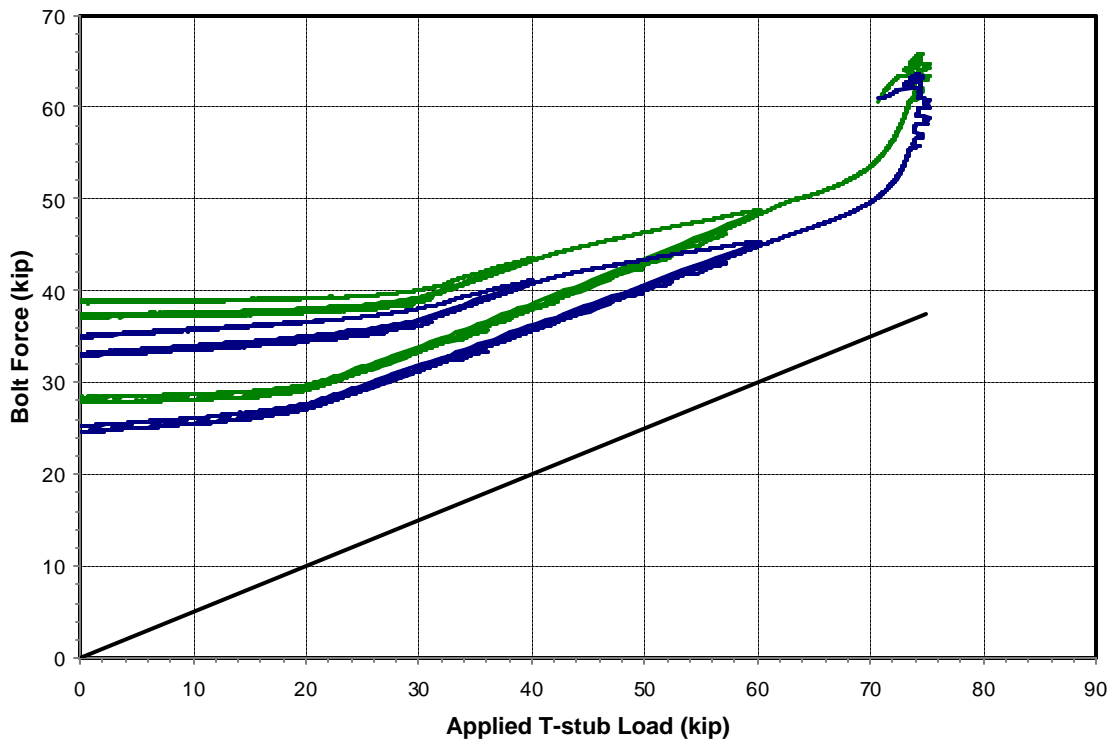
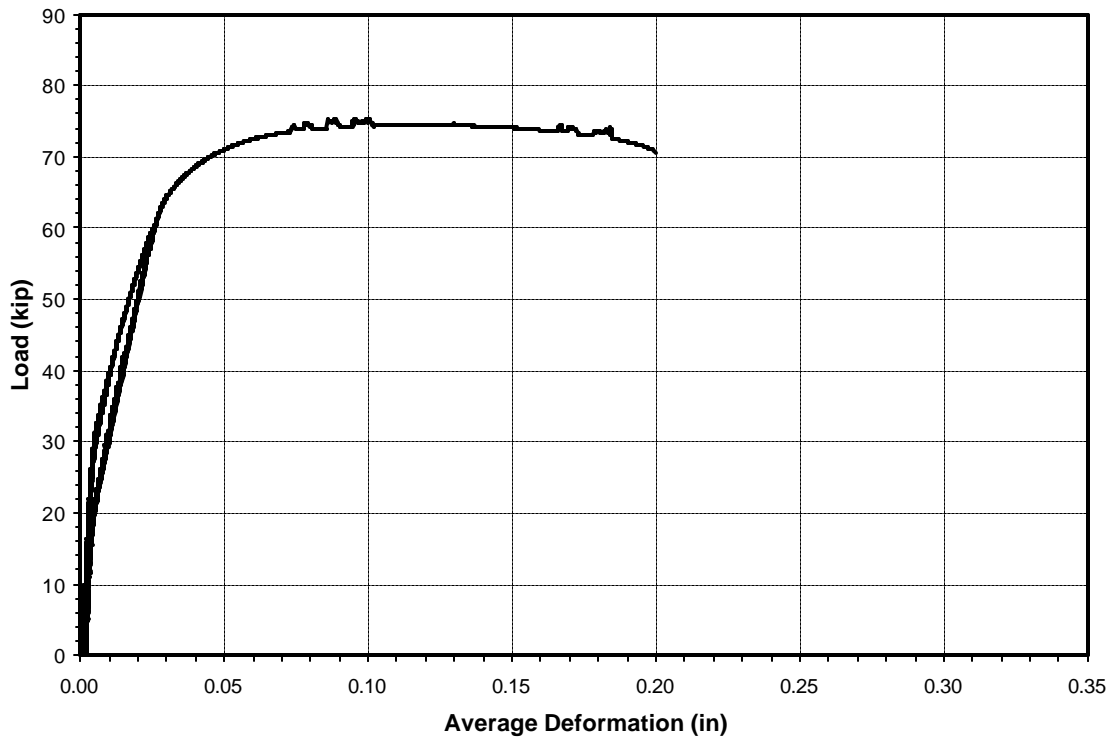
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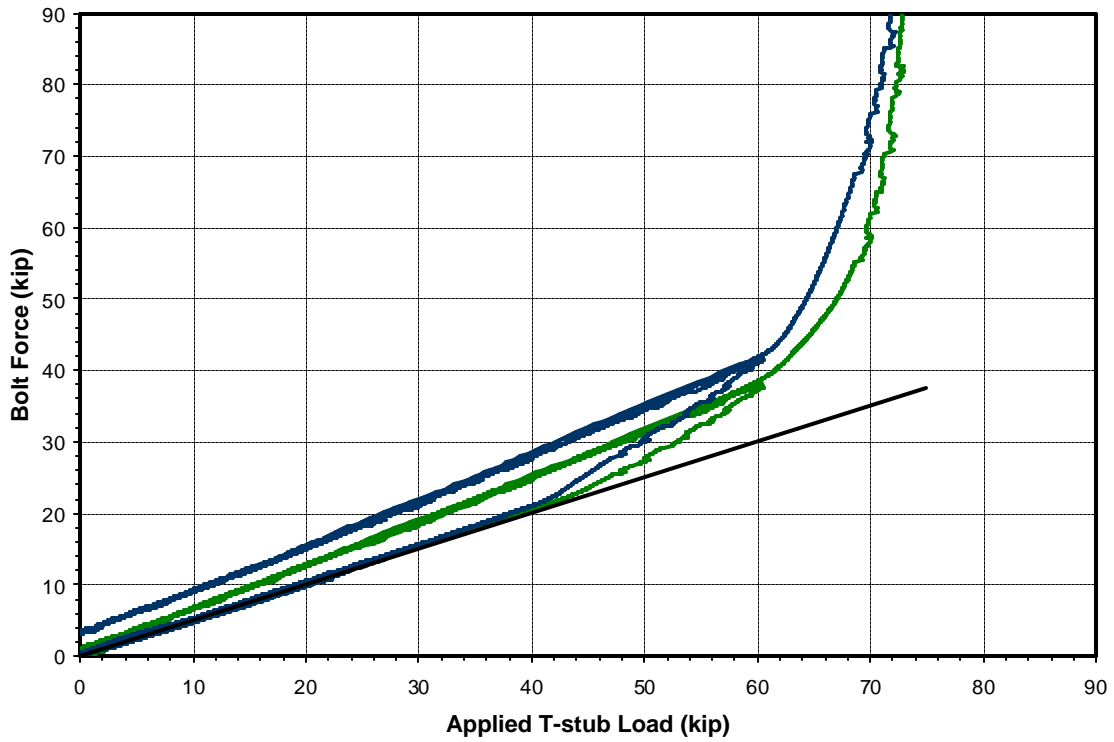
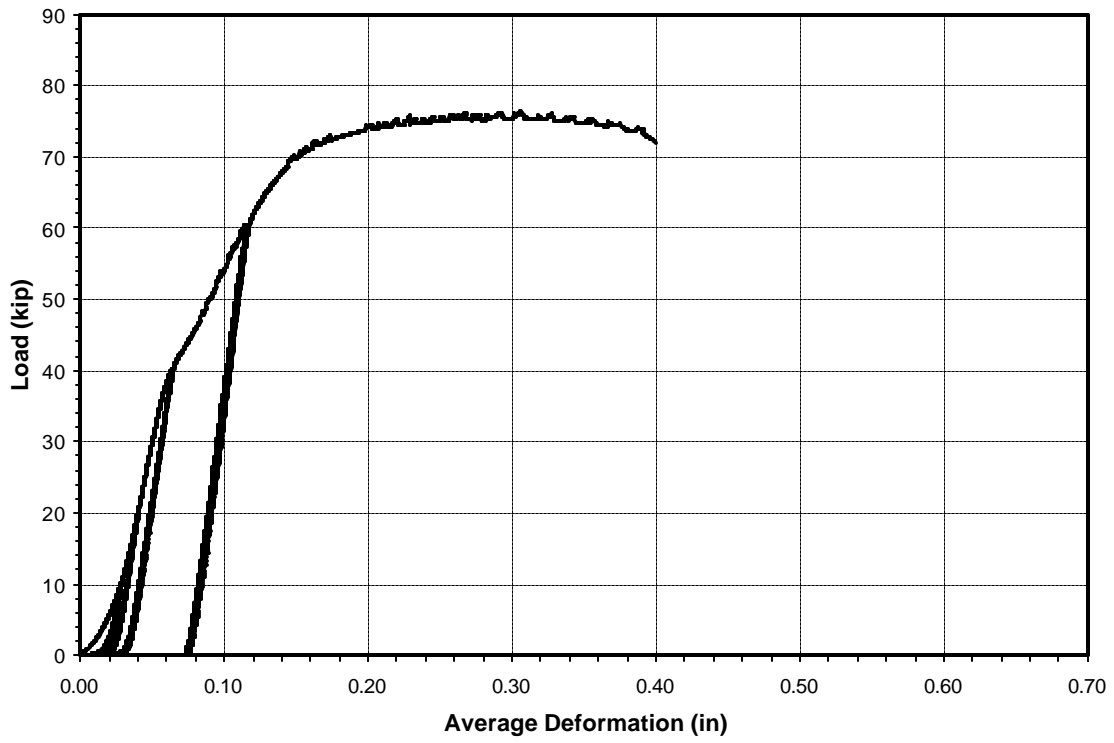
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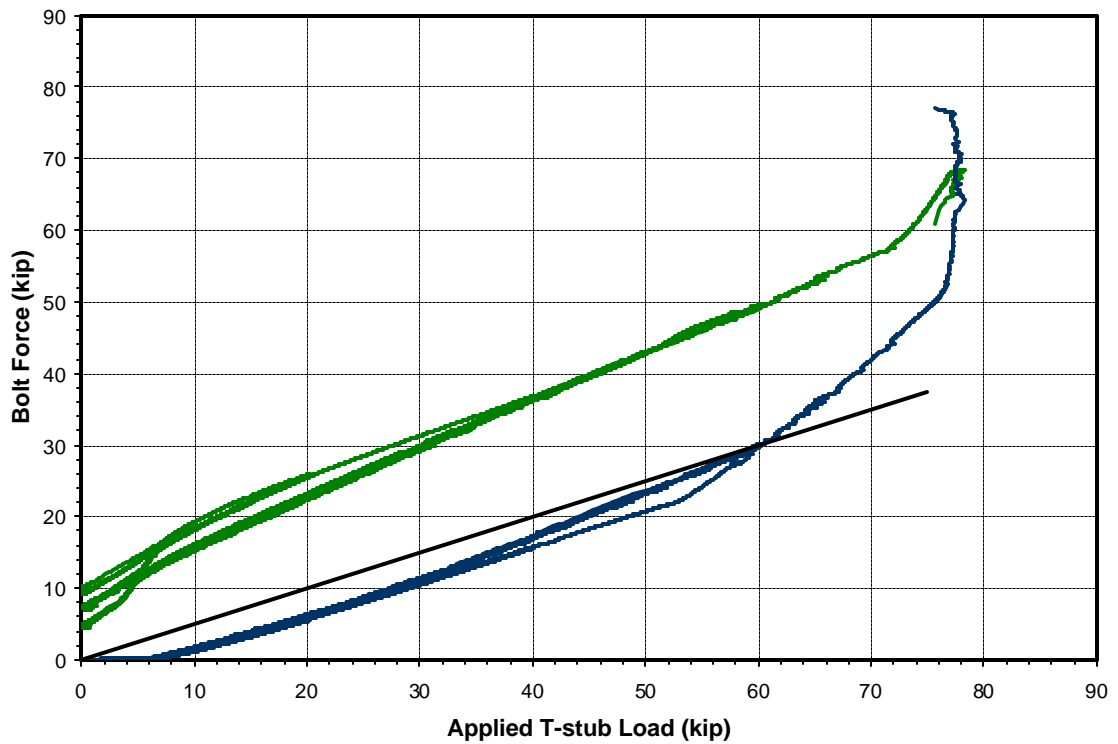
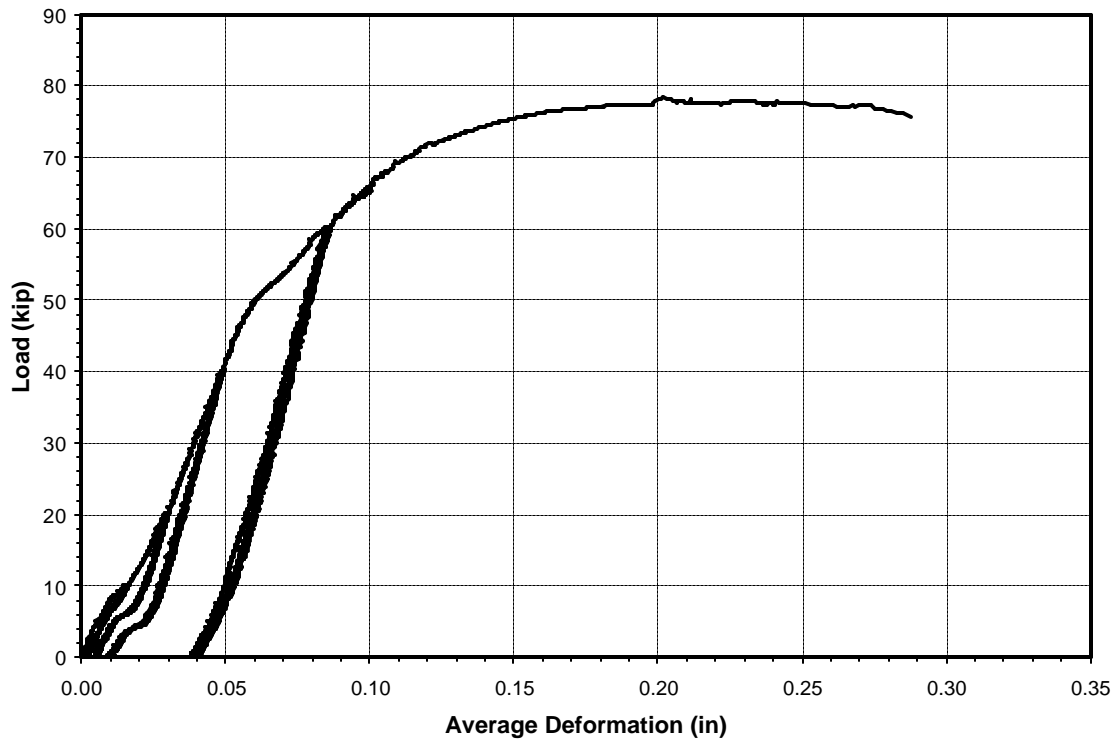
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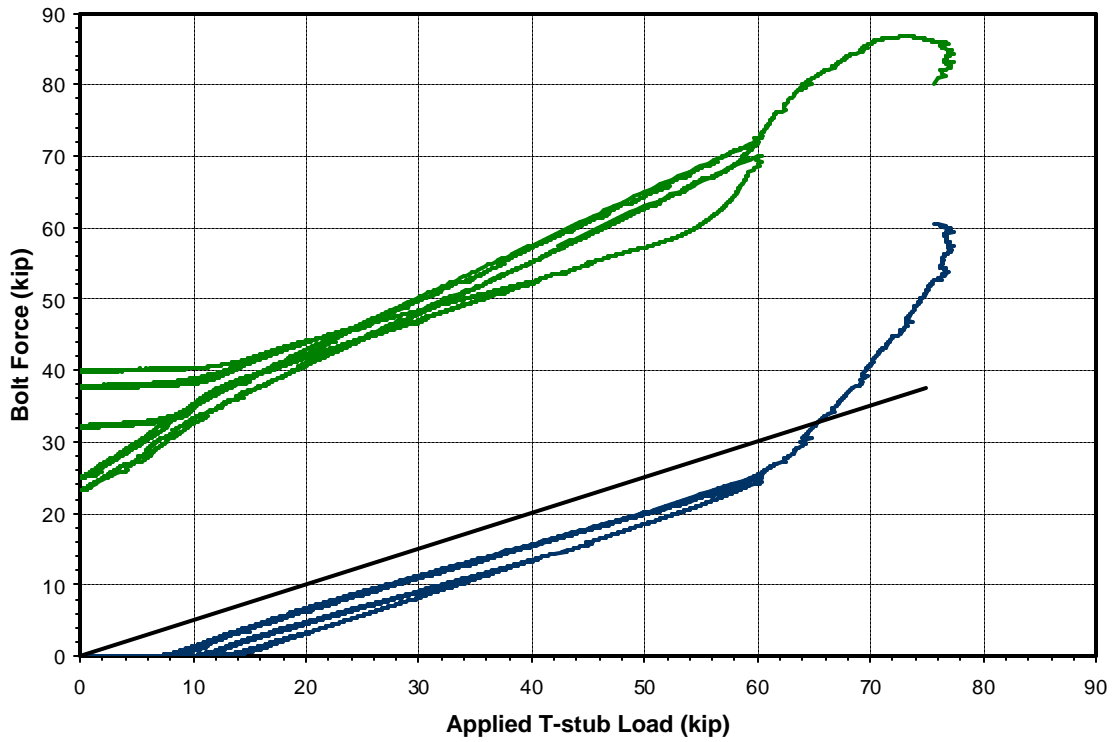
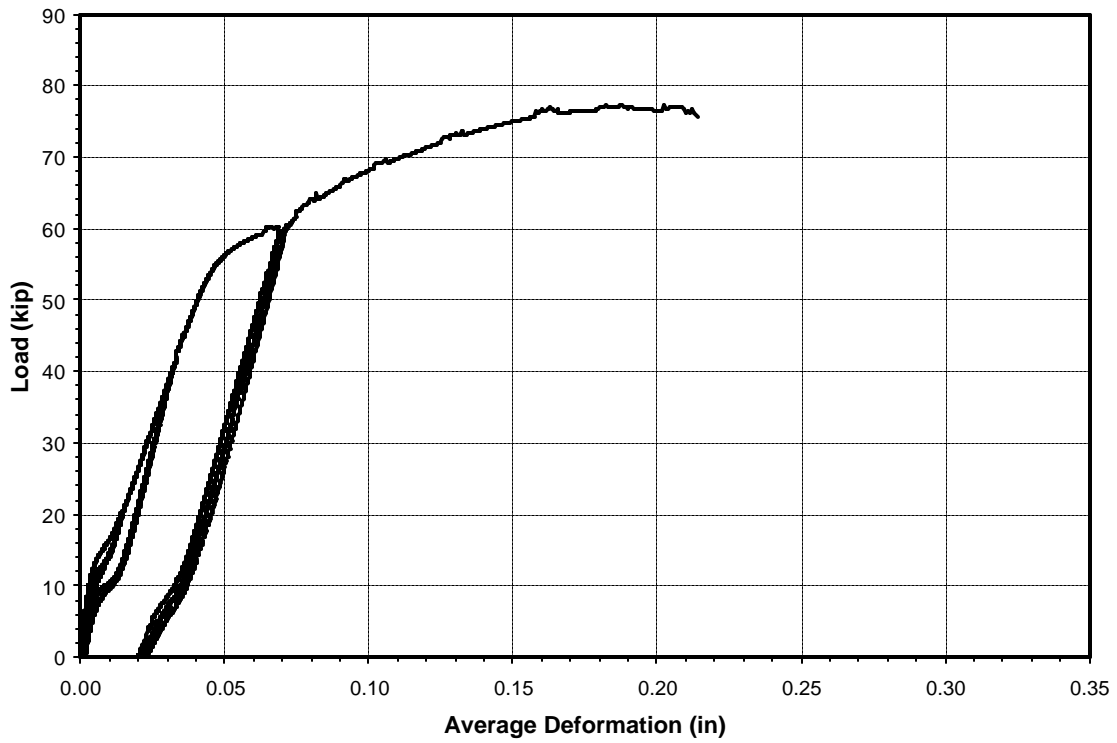
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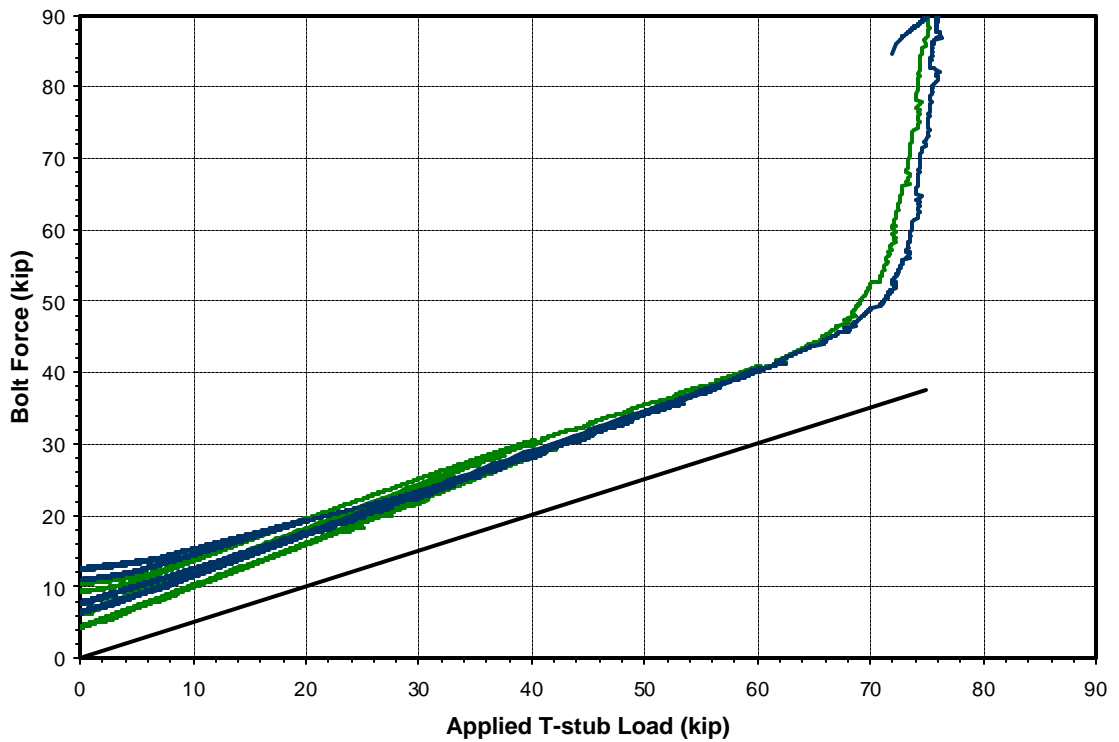
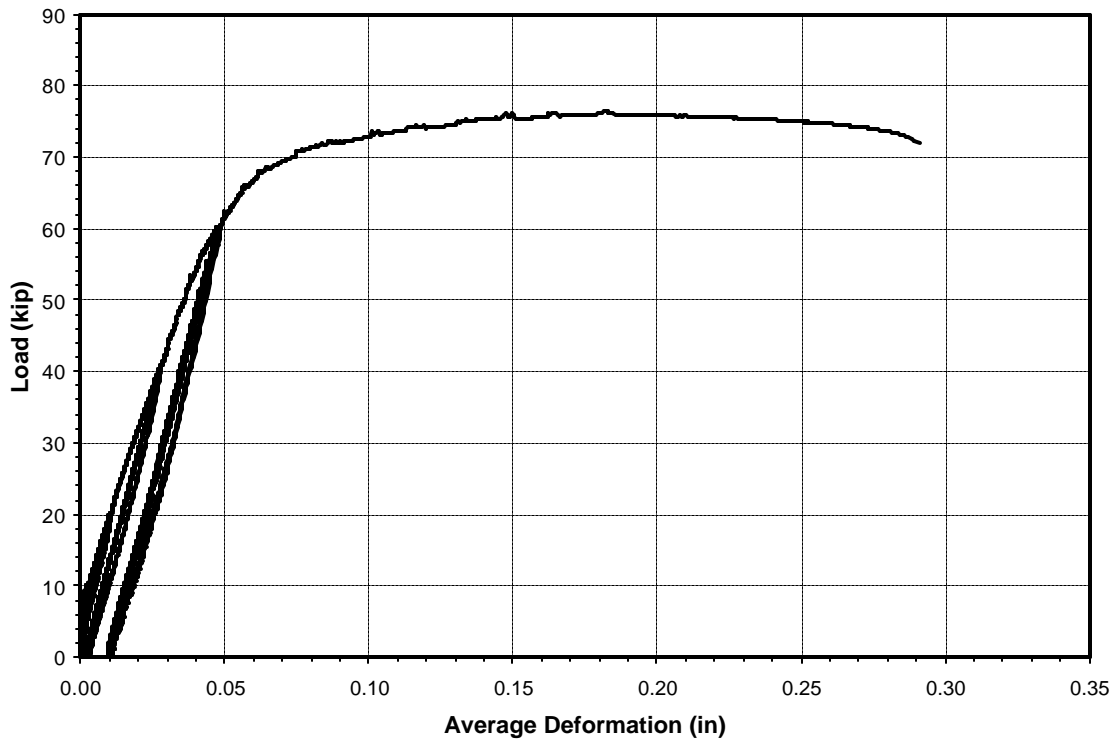
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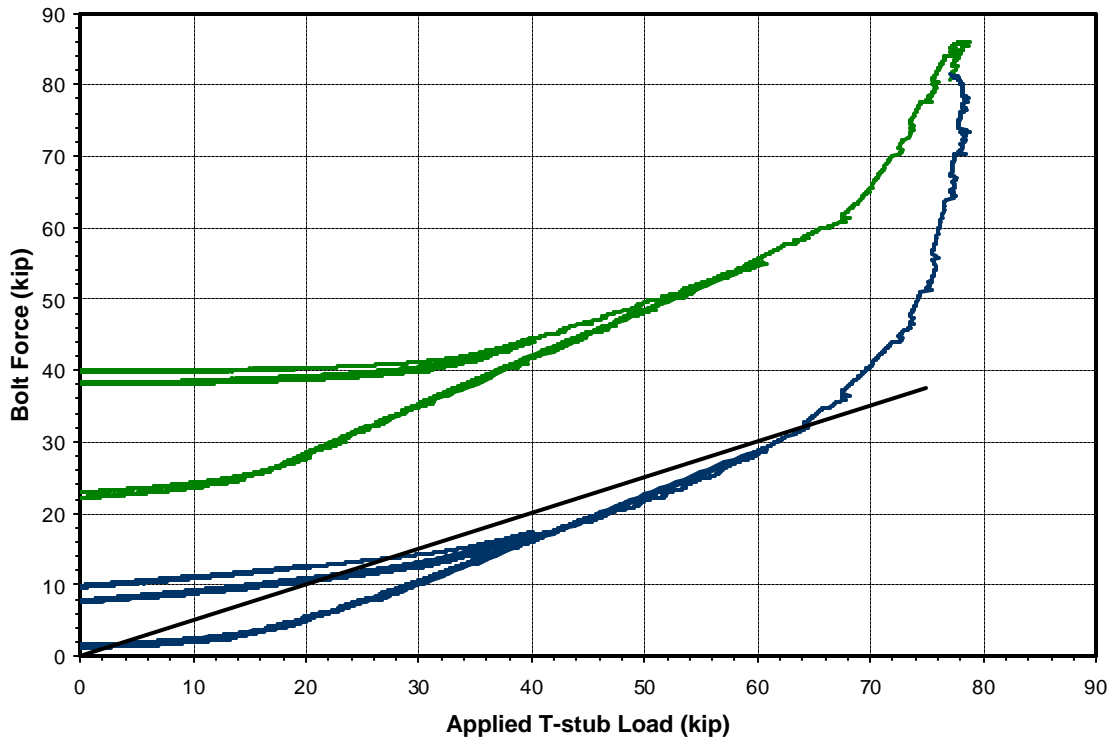
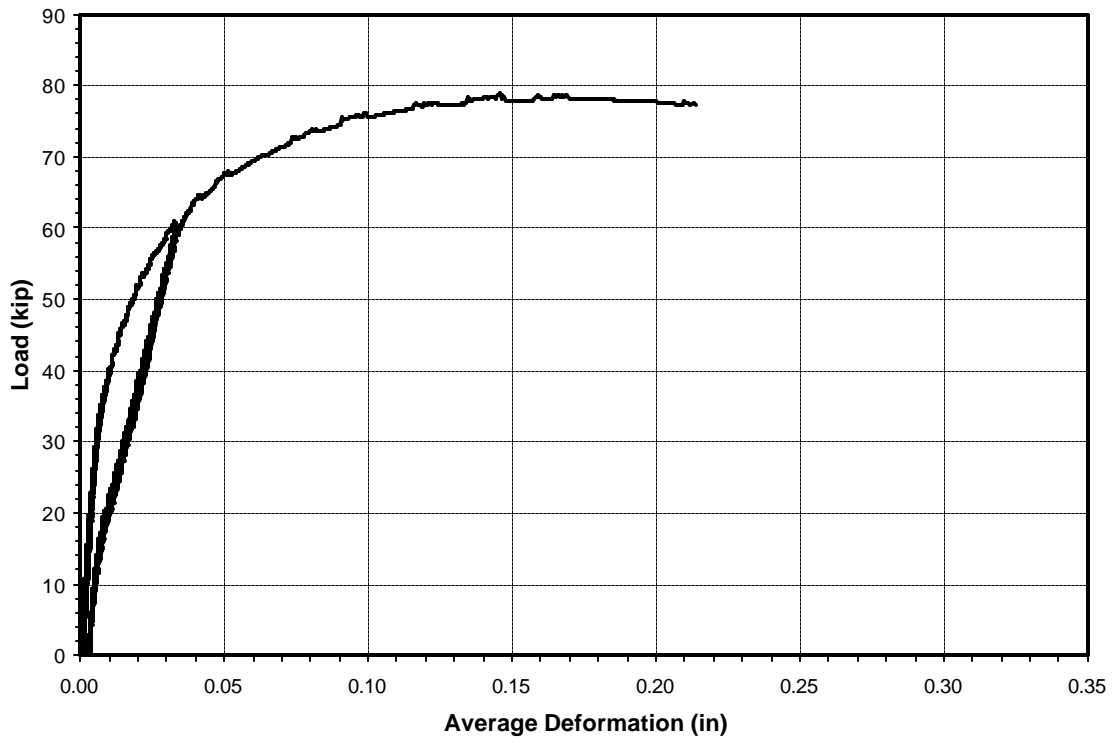
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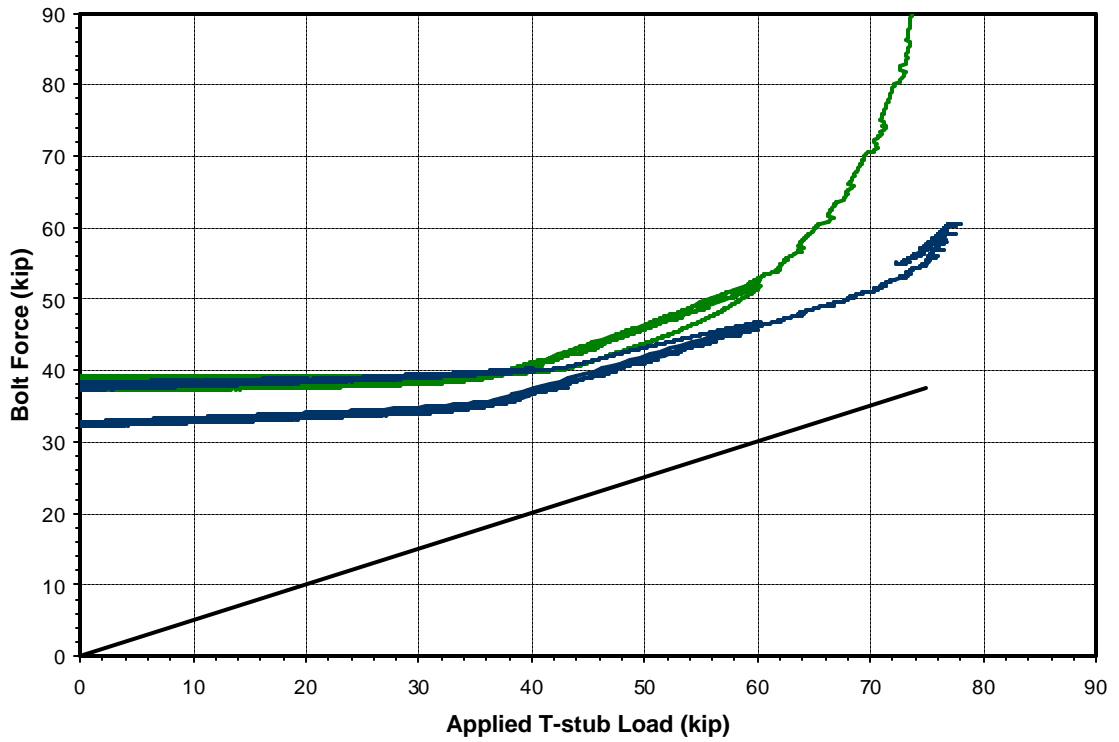
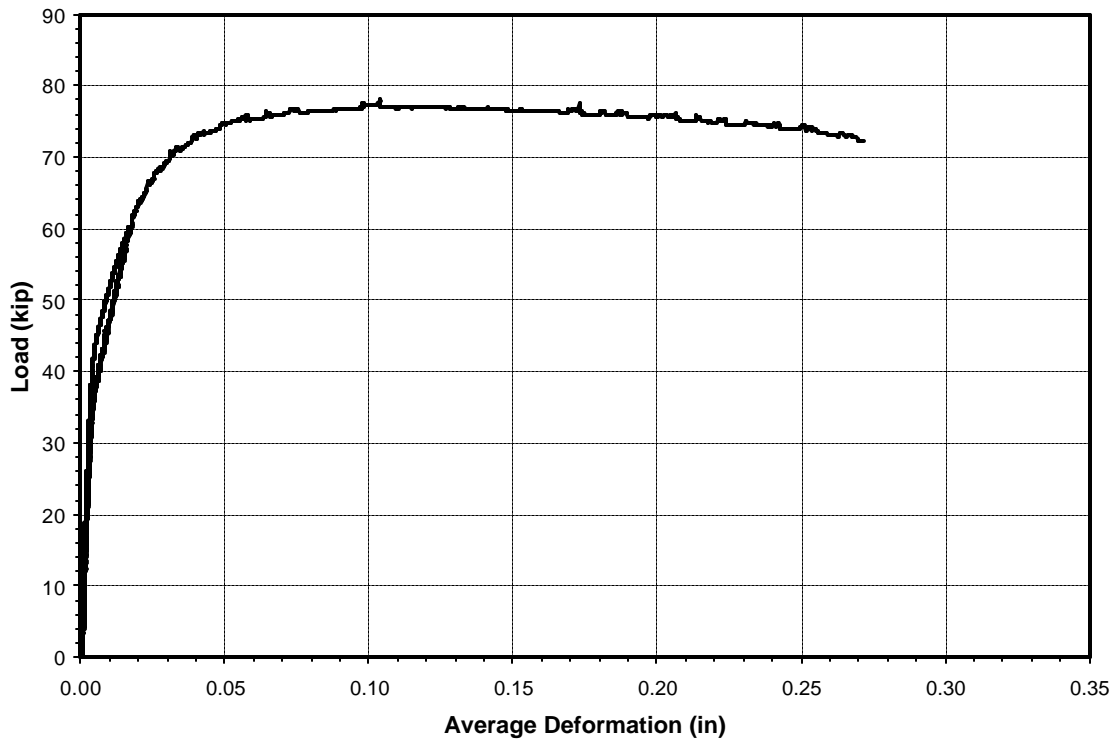
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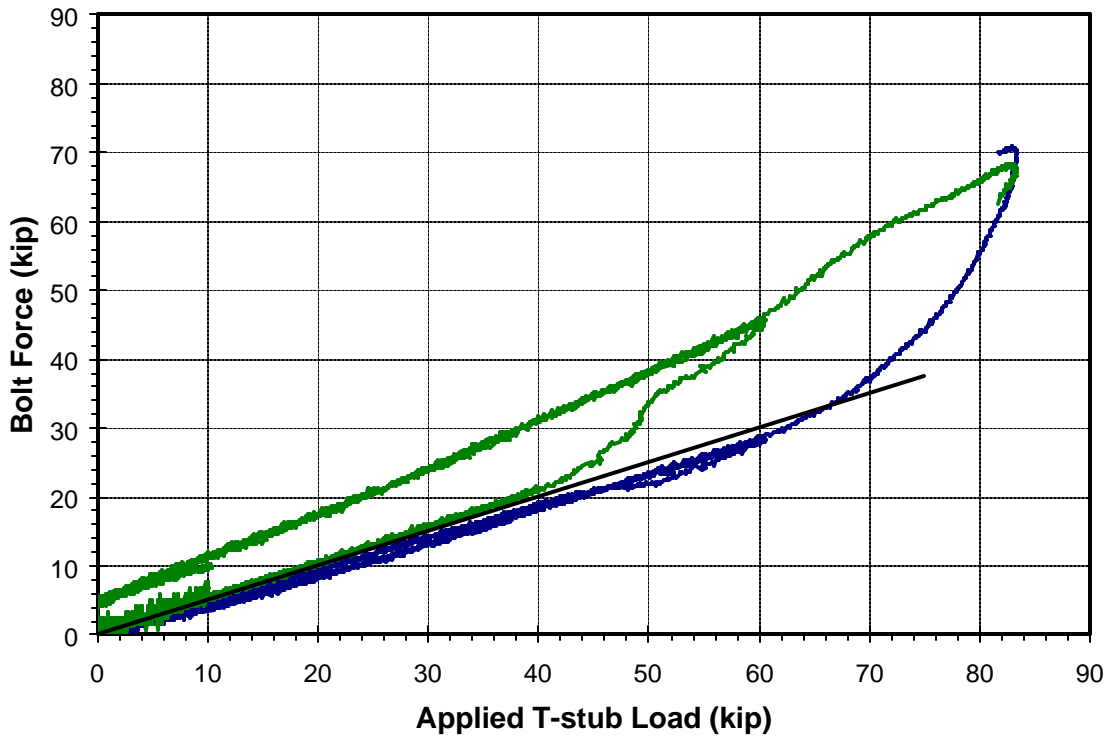
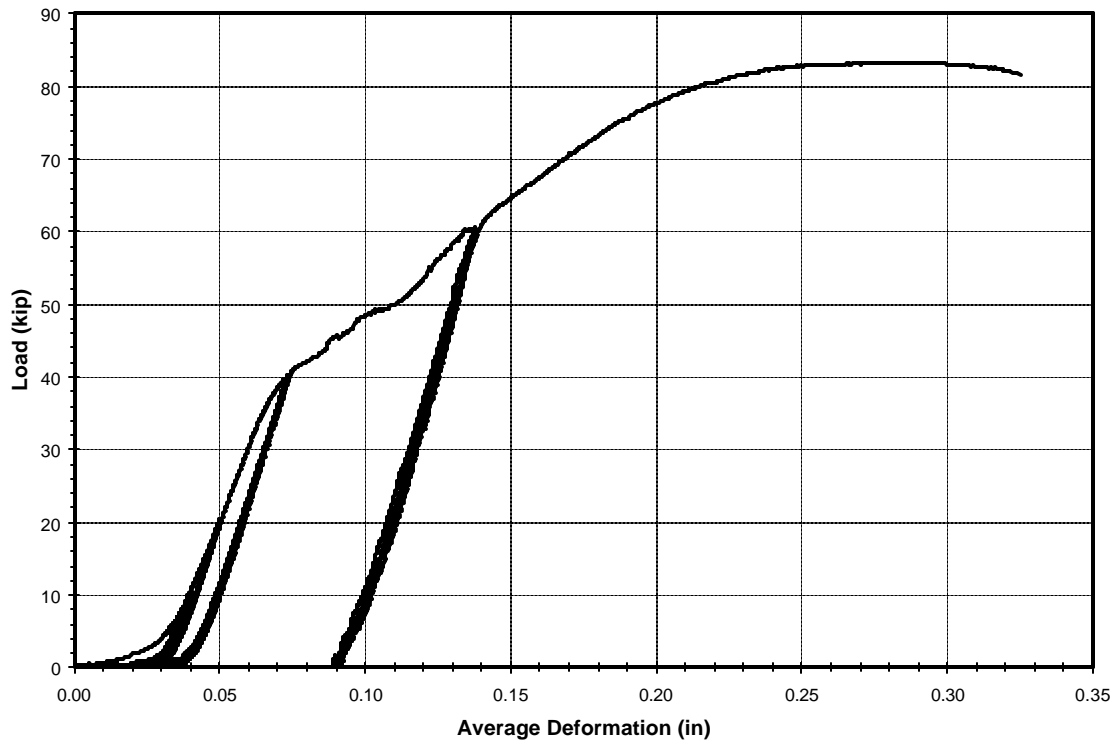
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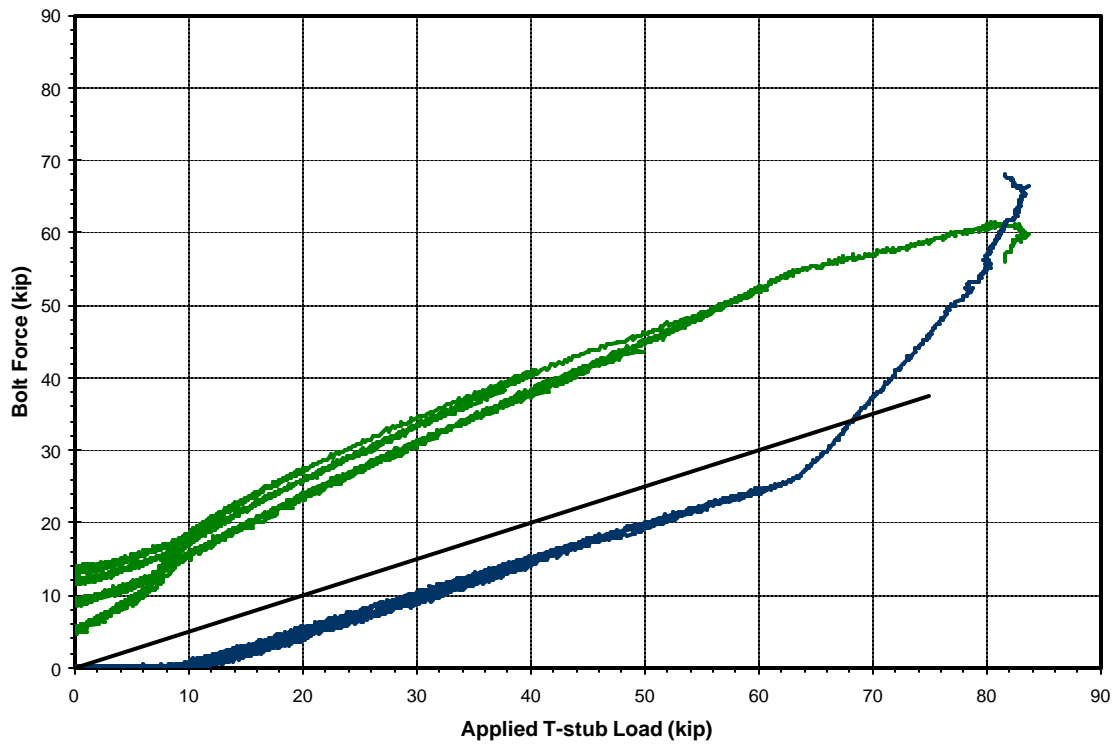
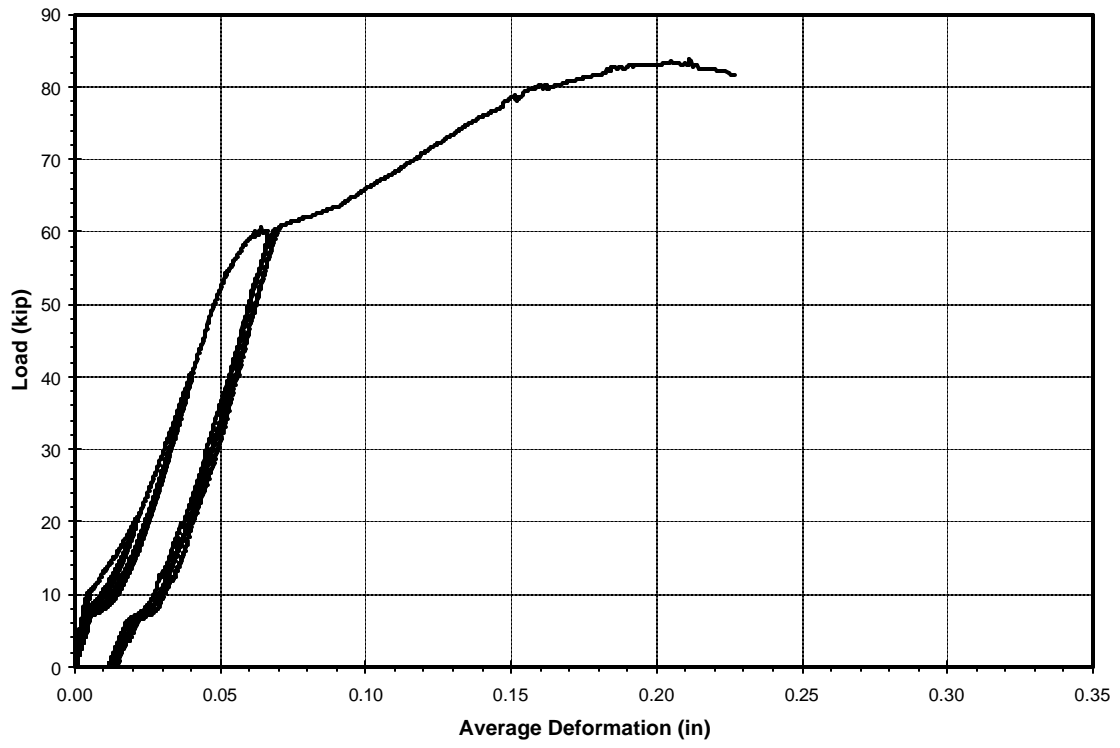
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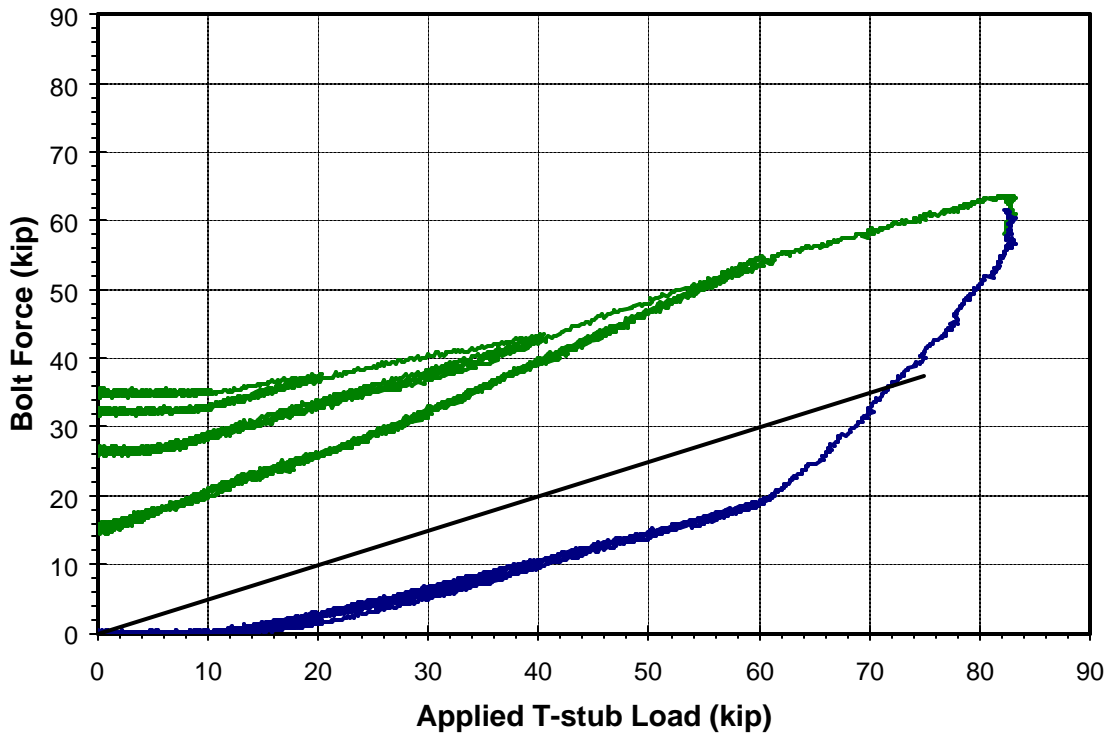
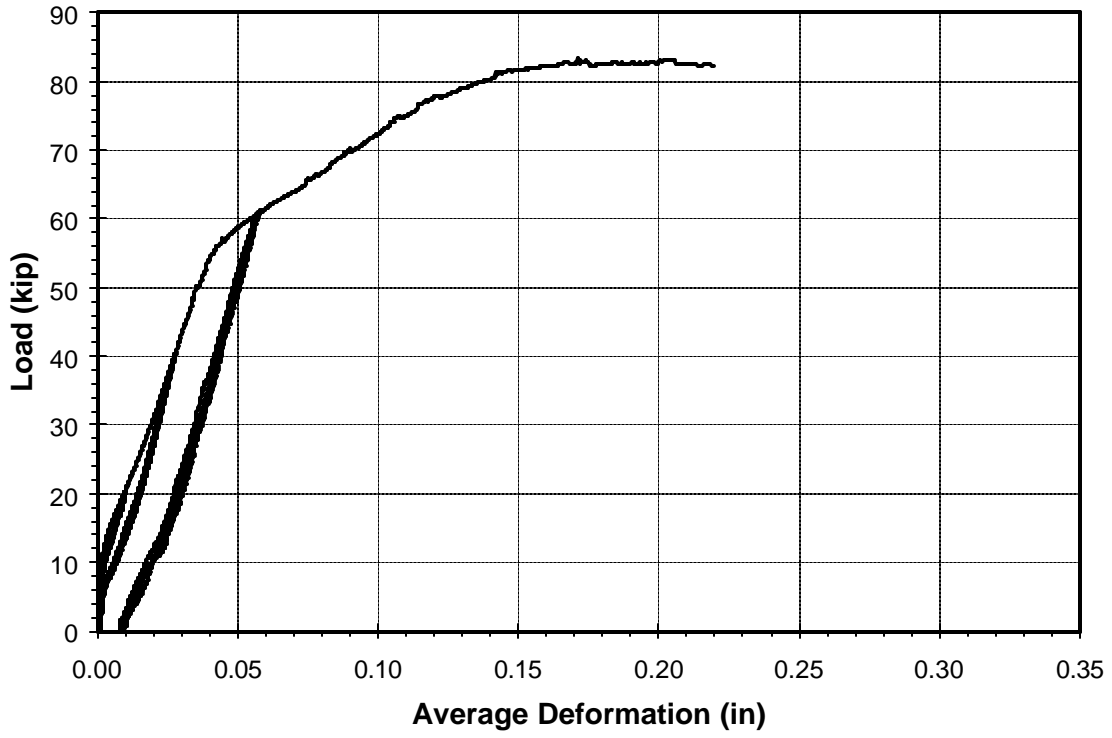
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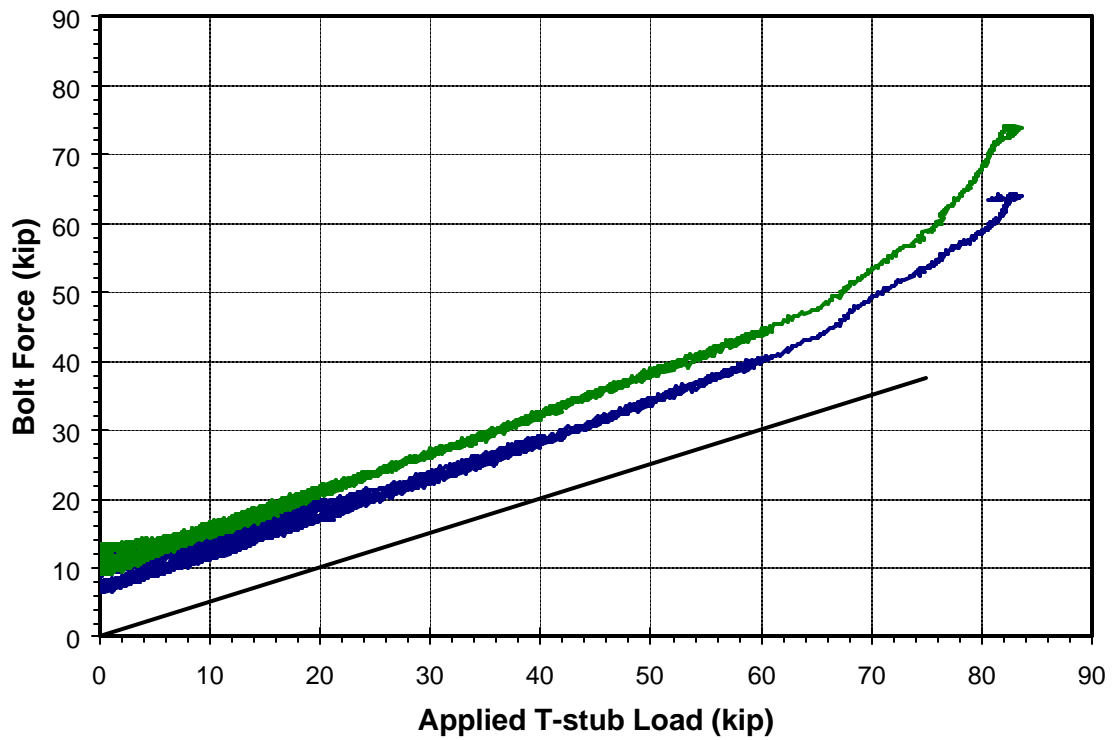
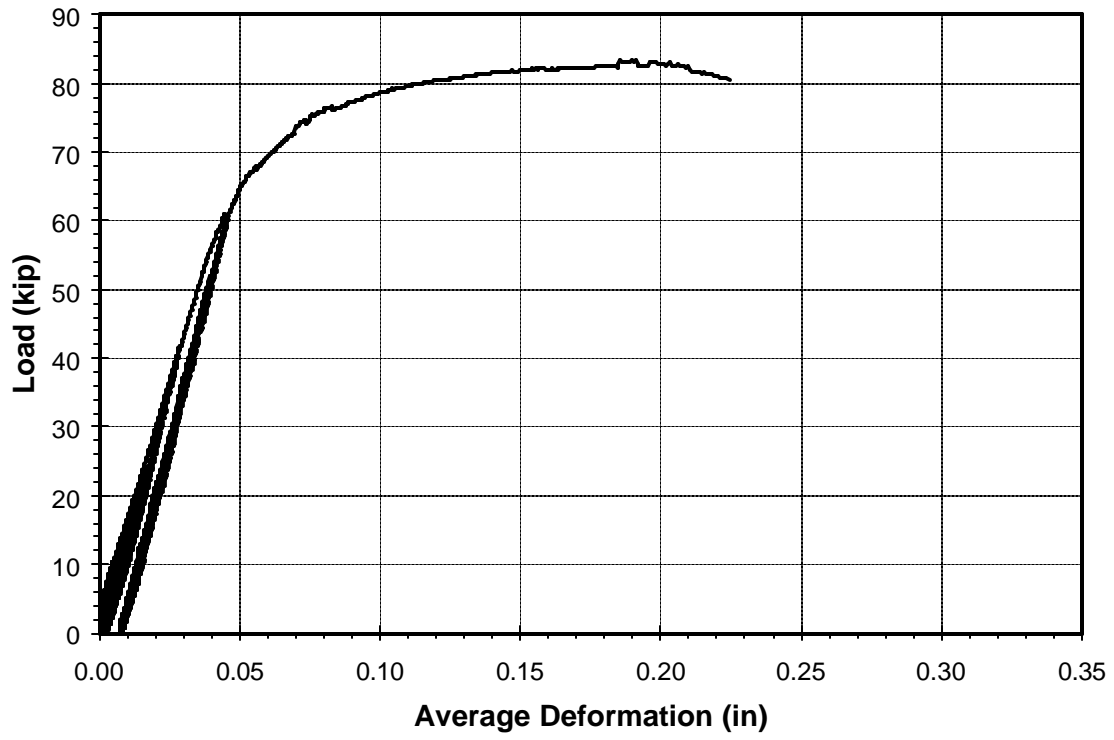
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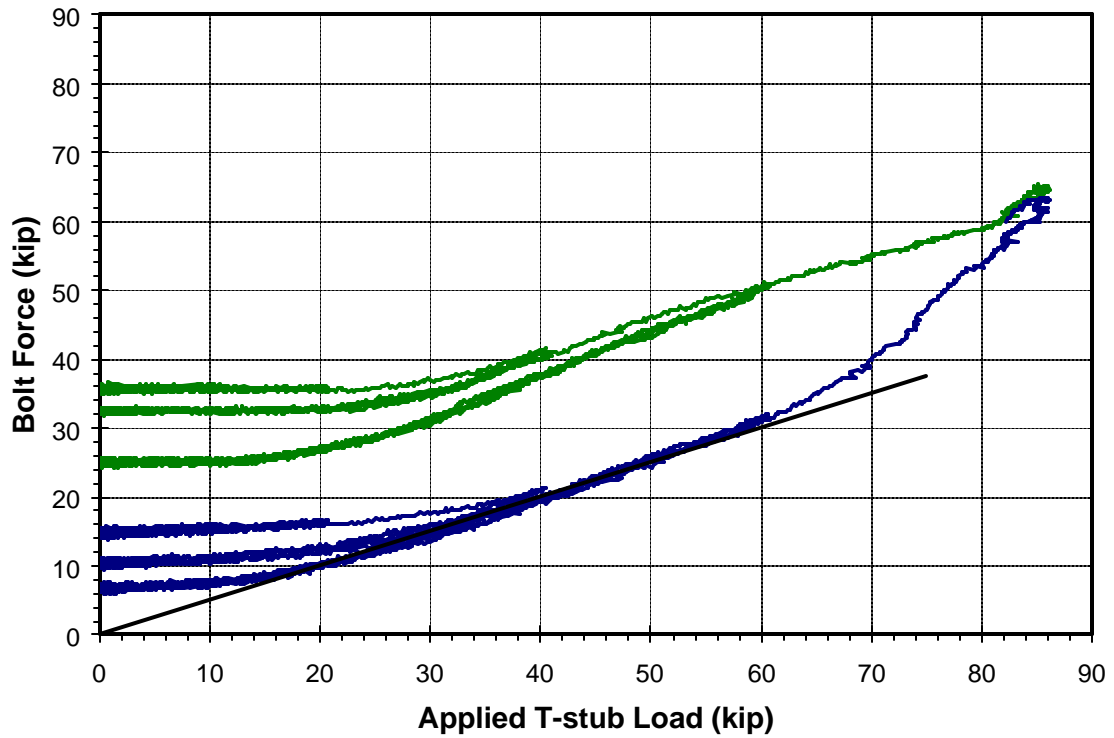
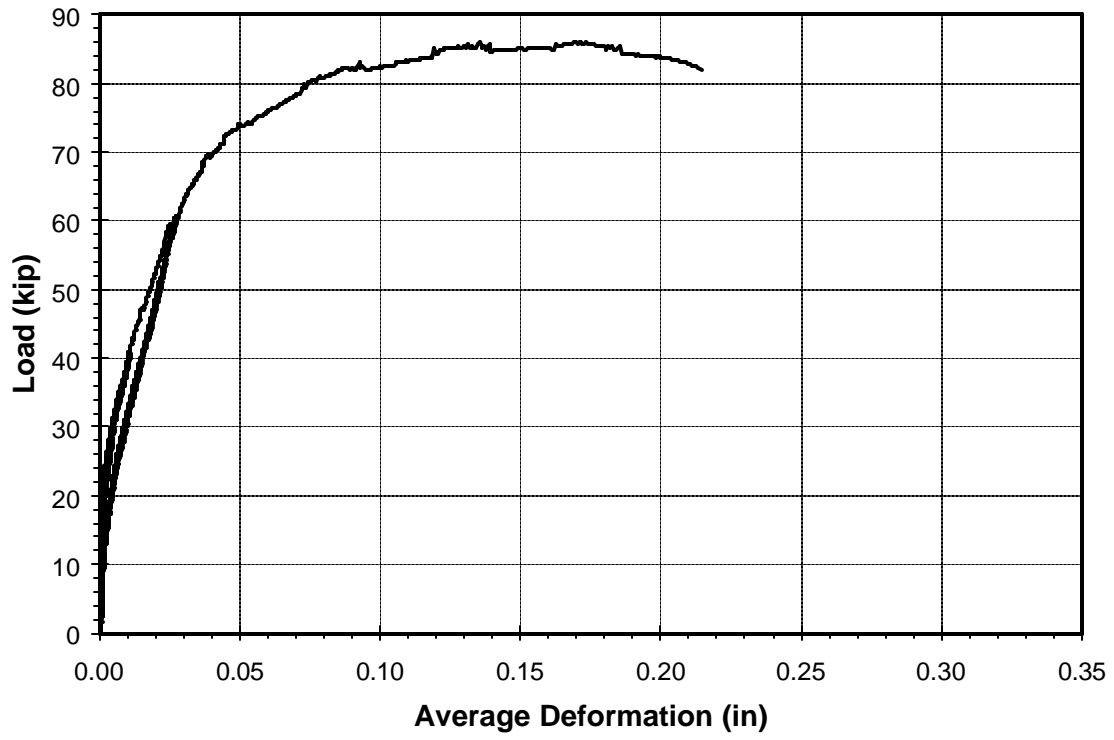
FT-2B



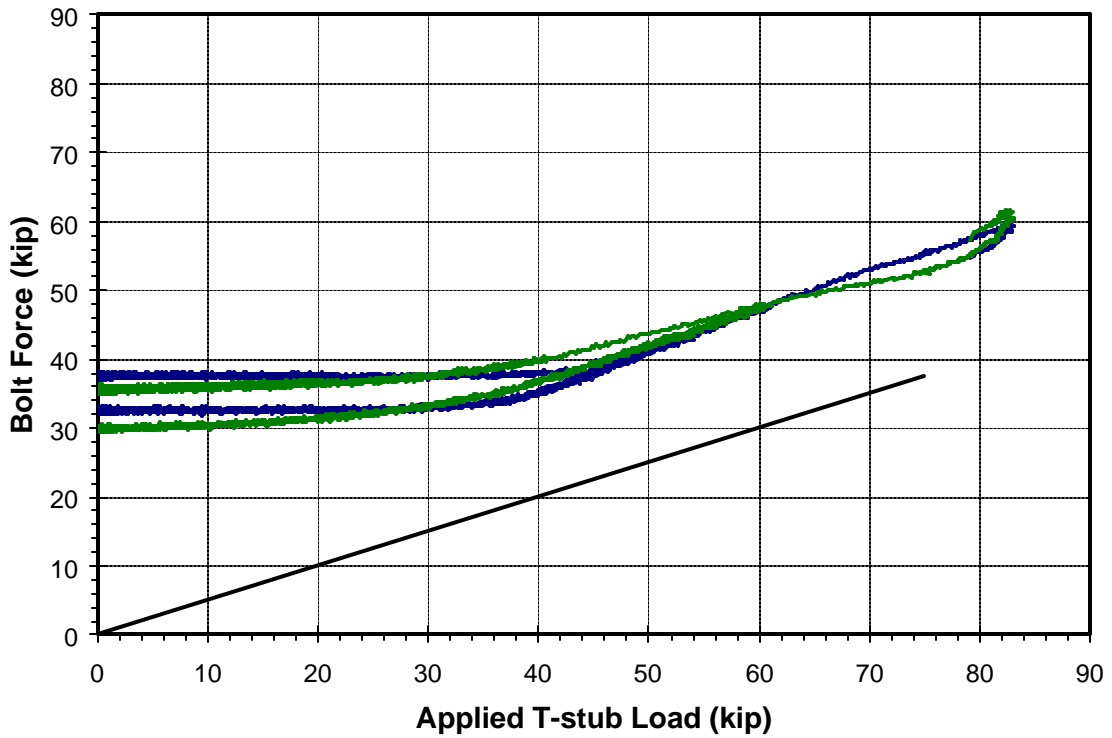
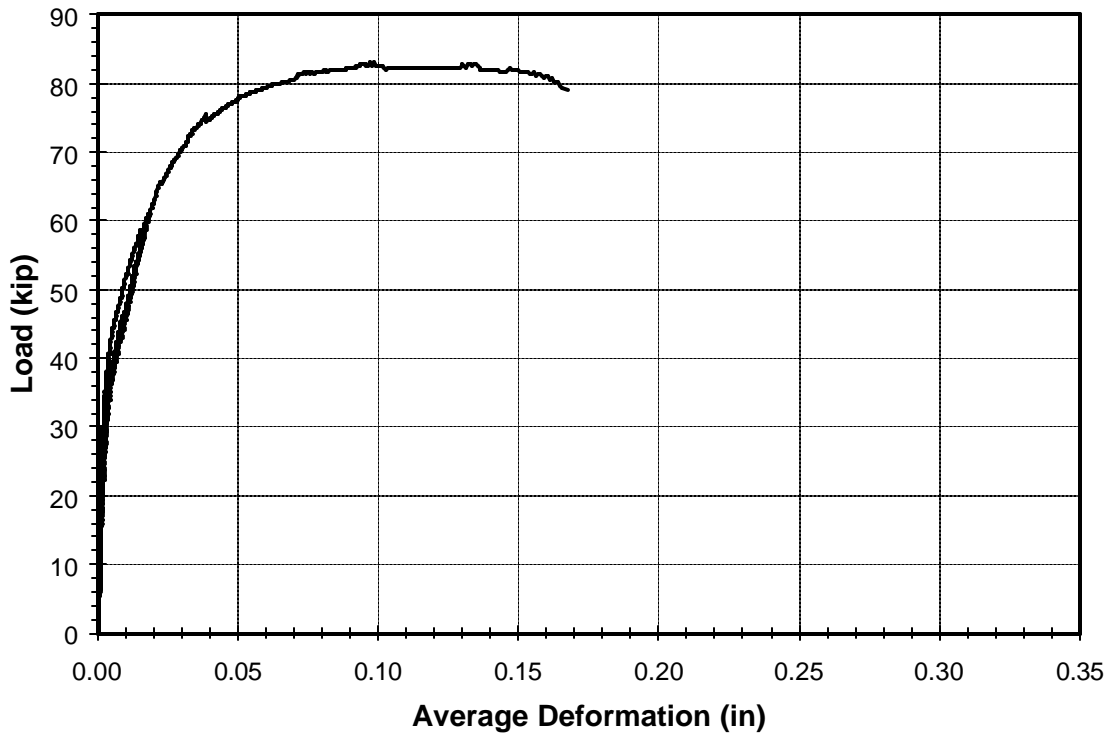
SS-2B



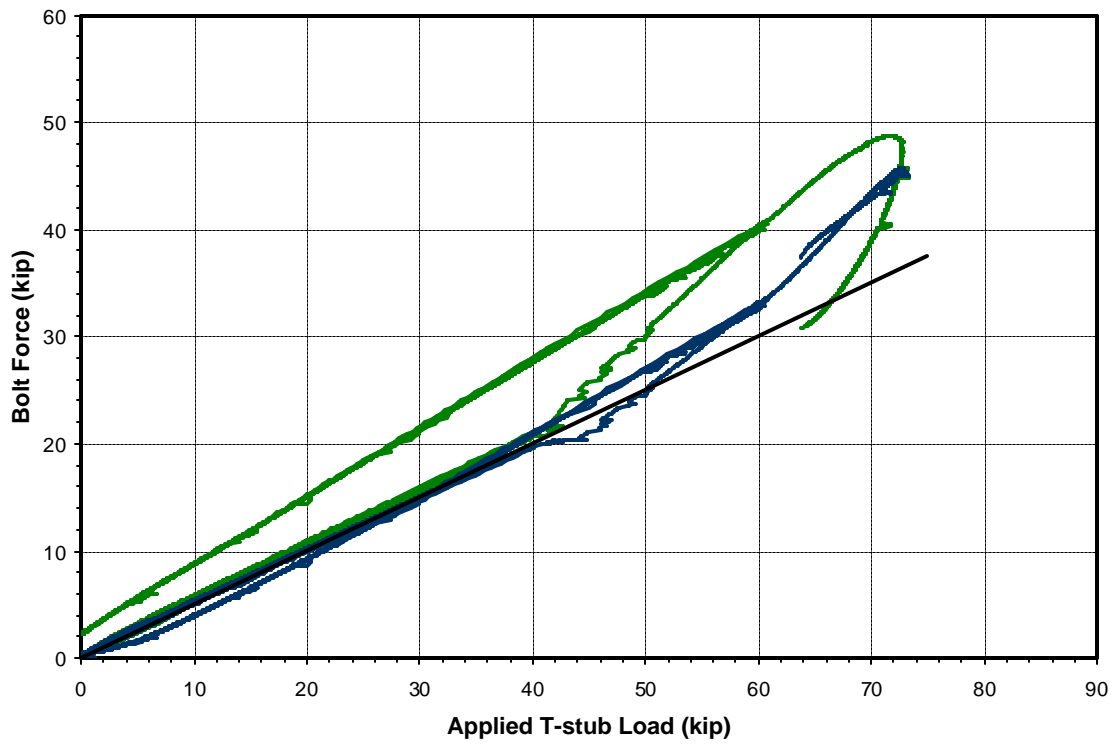
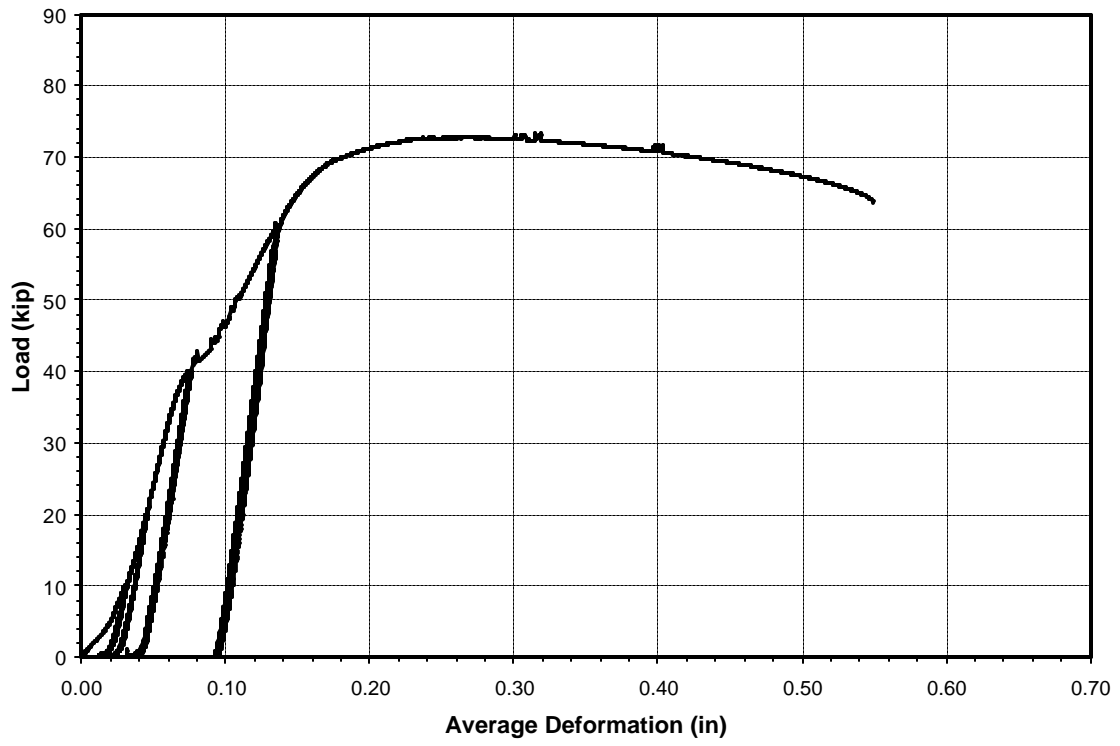
ST-2B



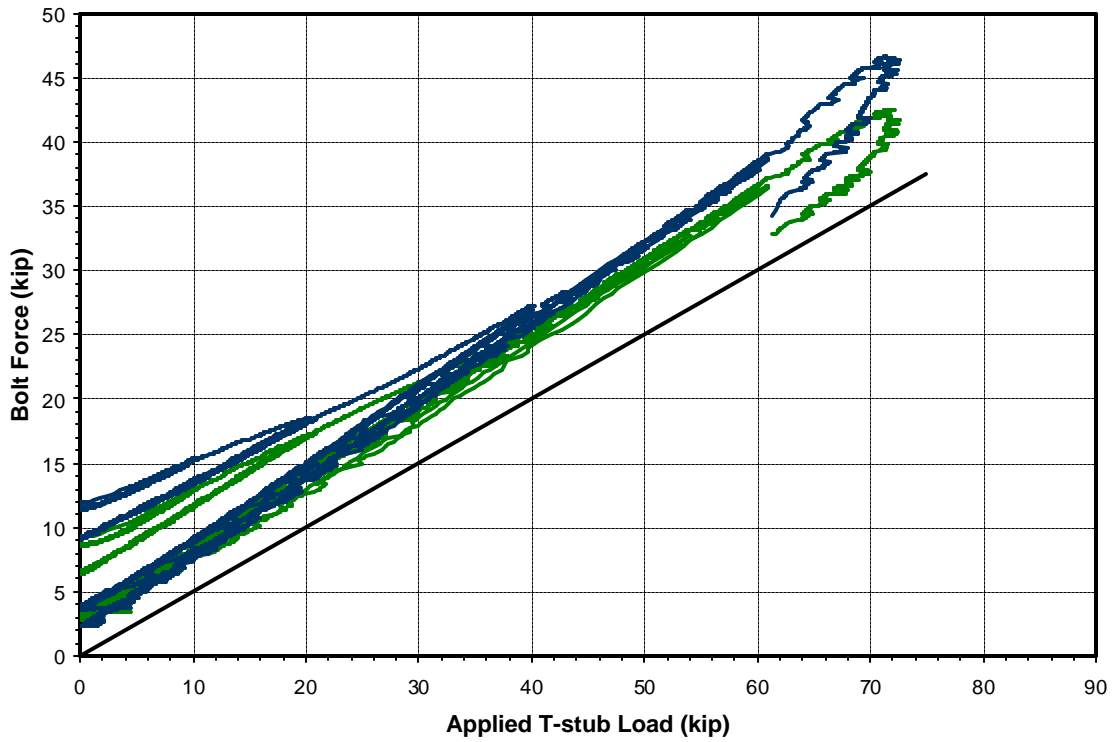
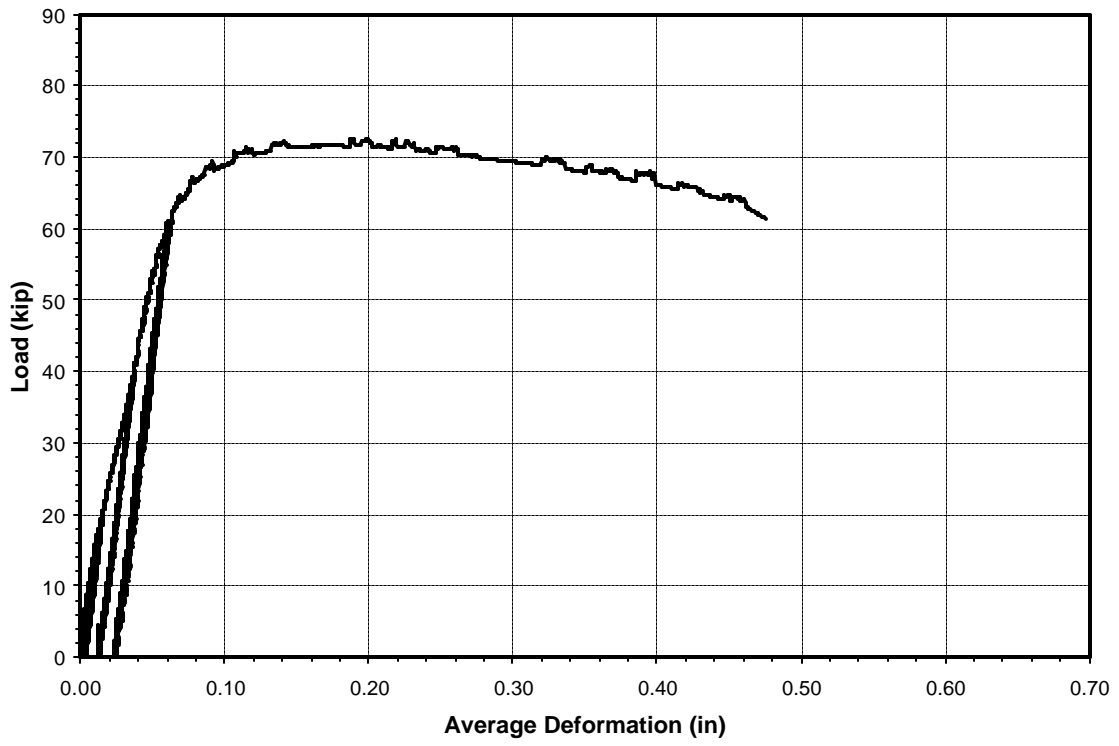
TT-2B



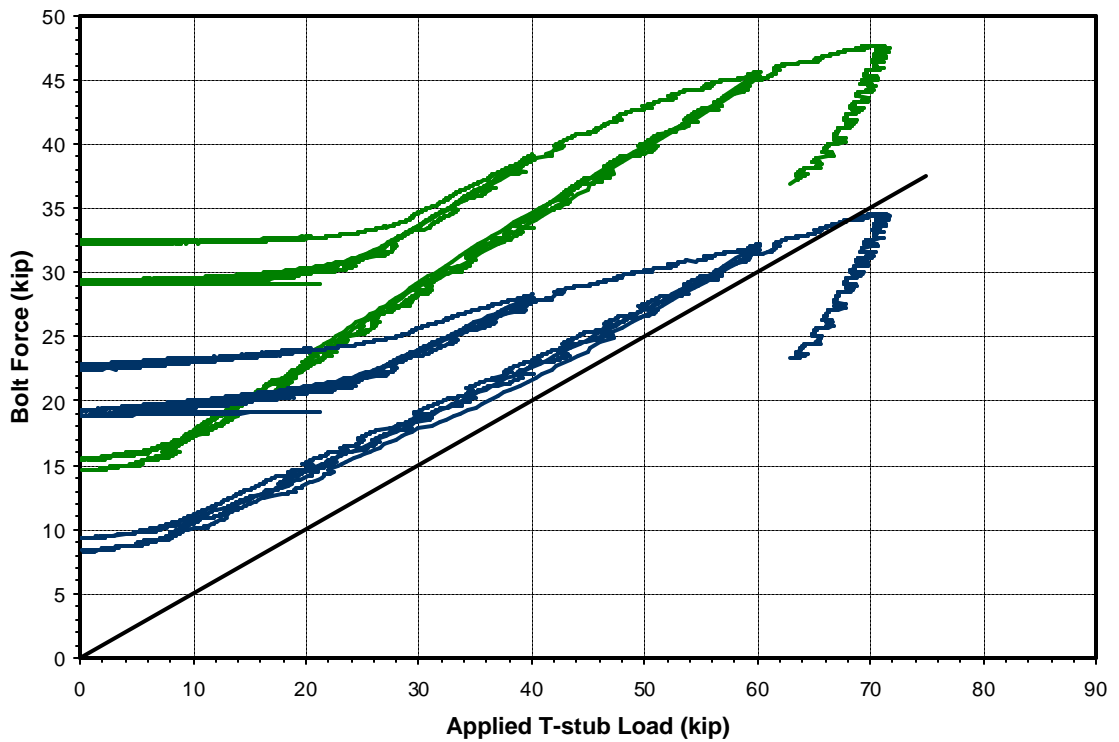
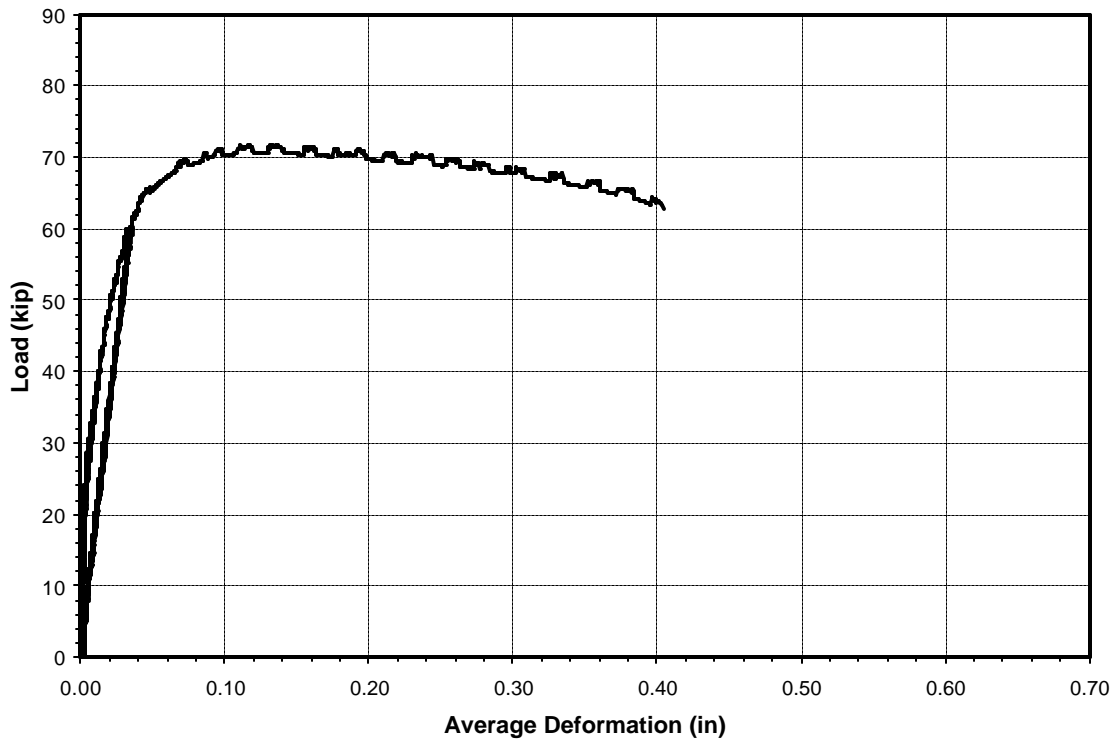
FF-3



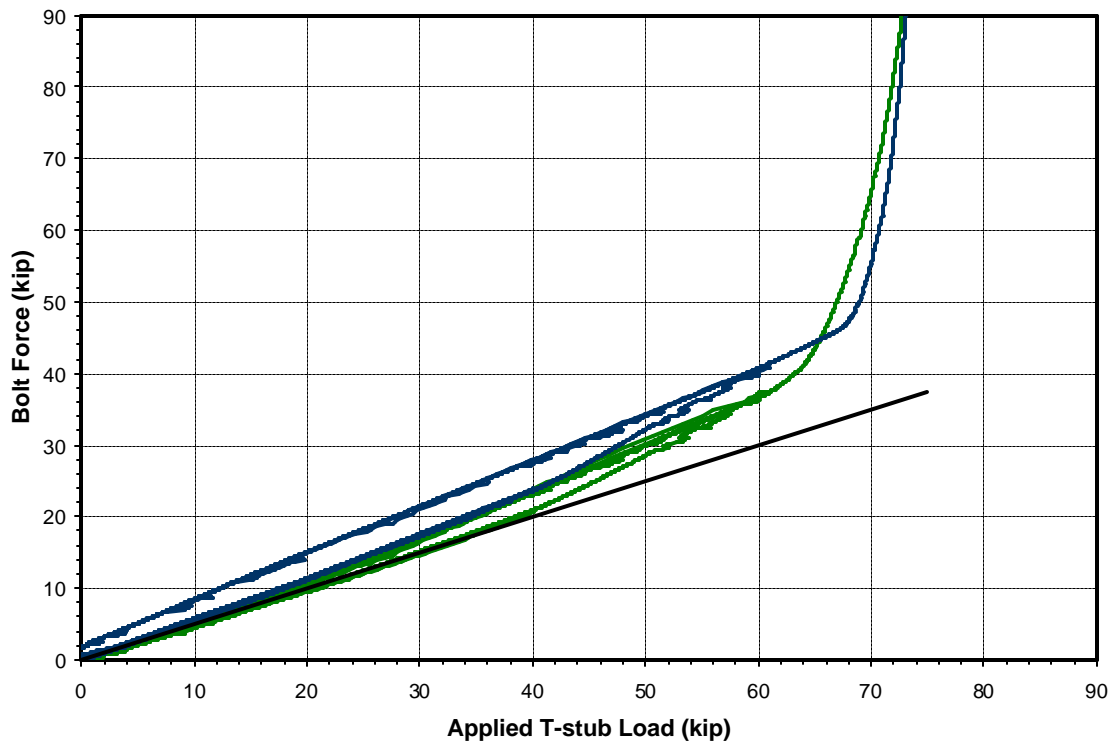
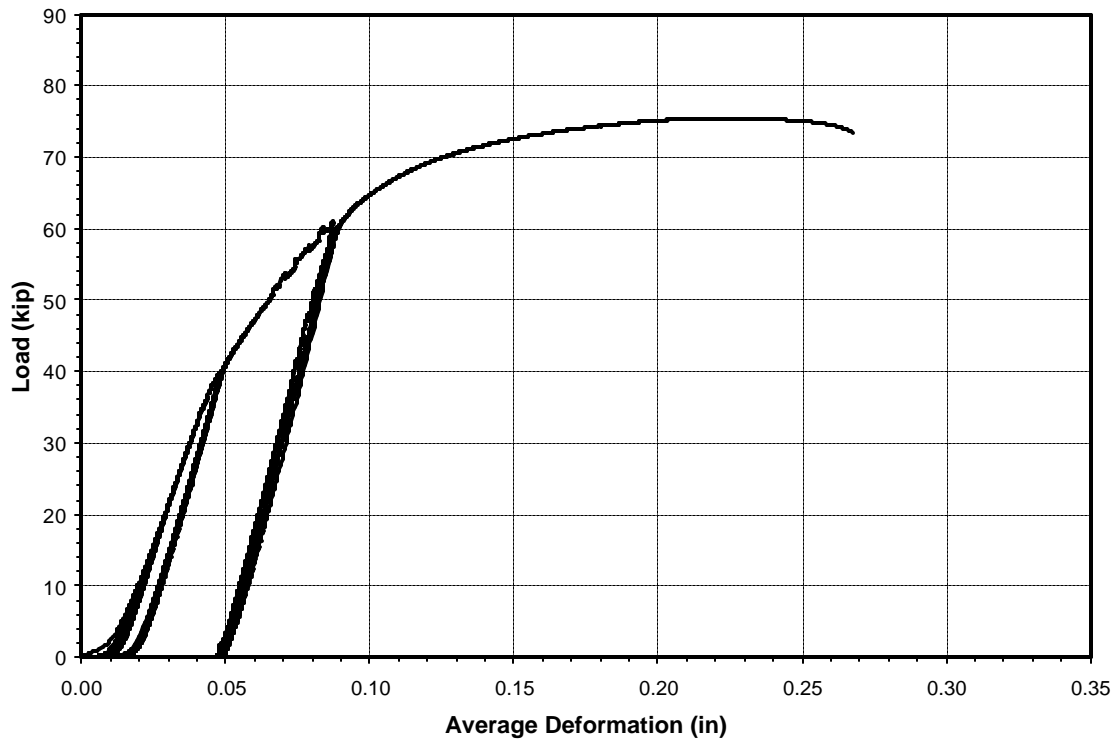
SS-3



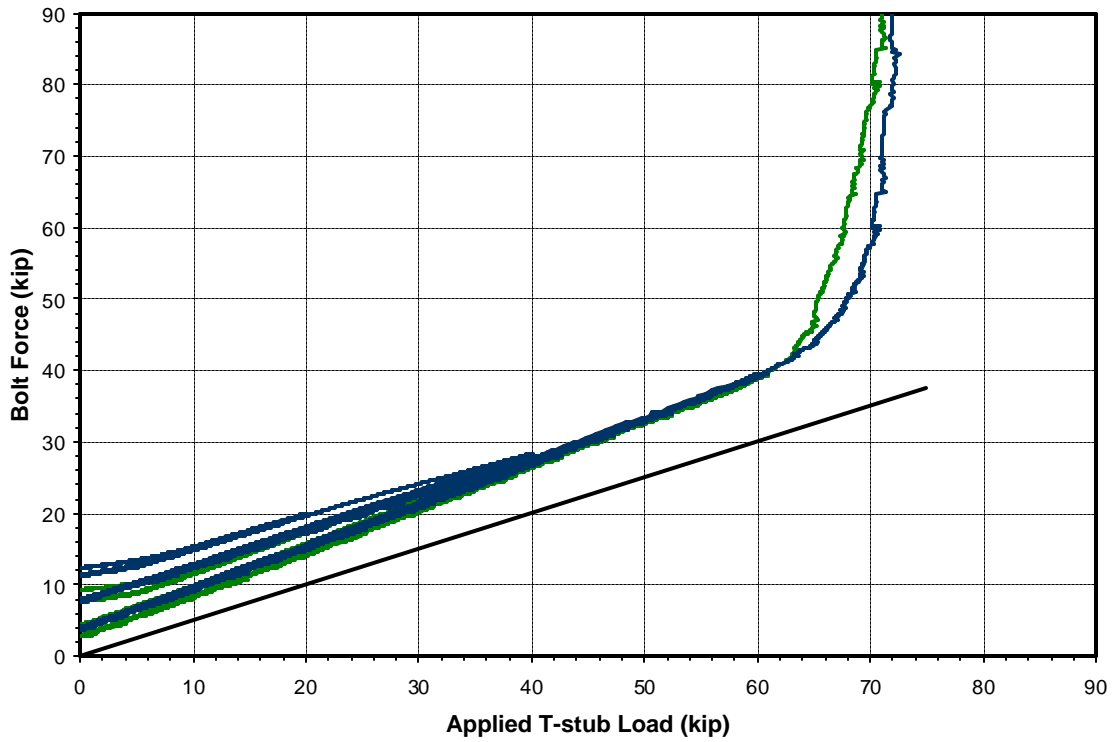
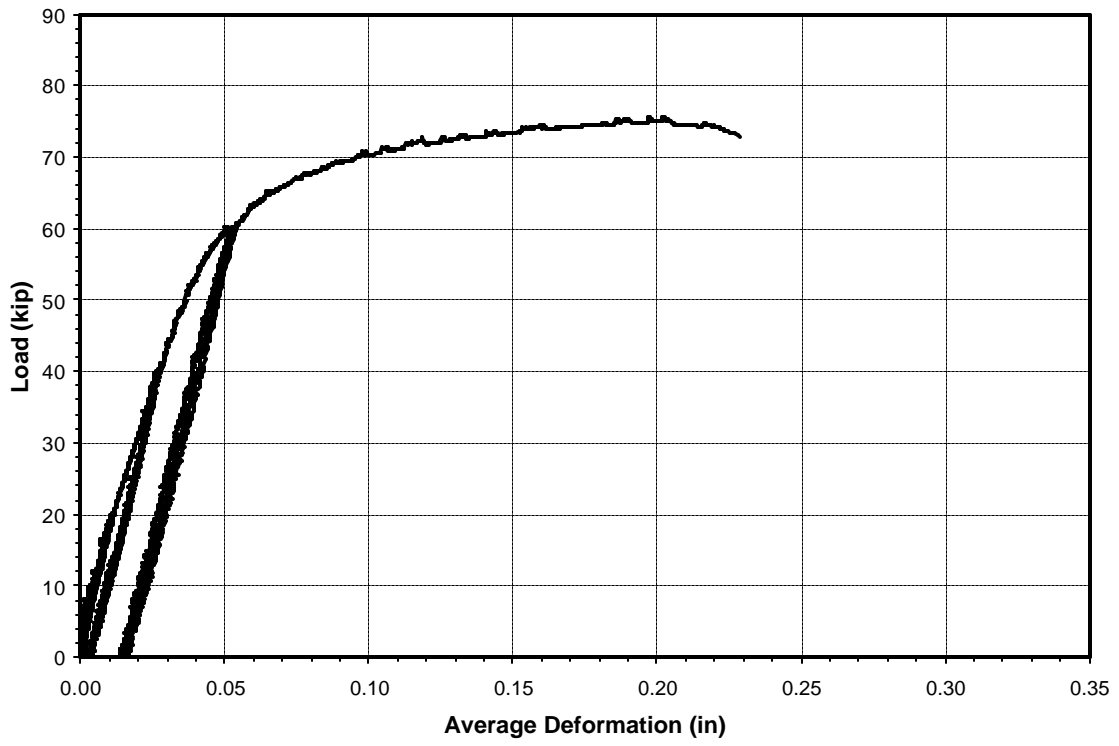
TT-3



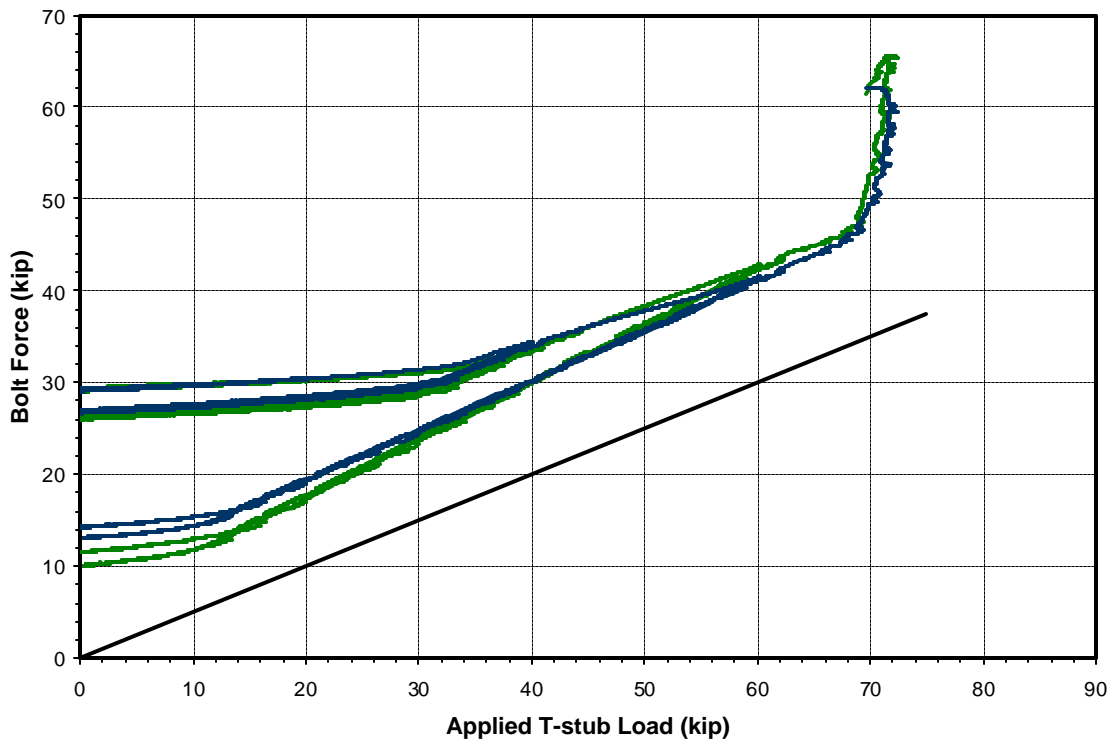
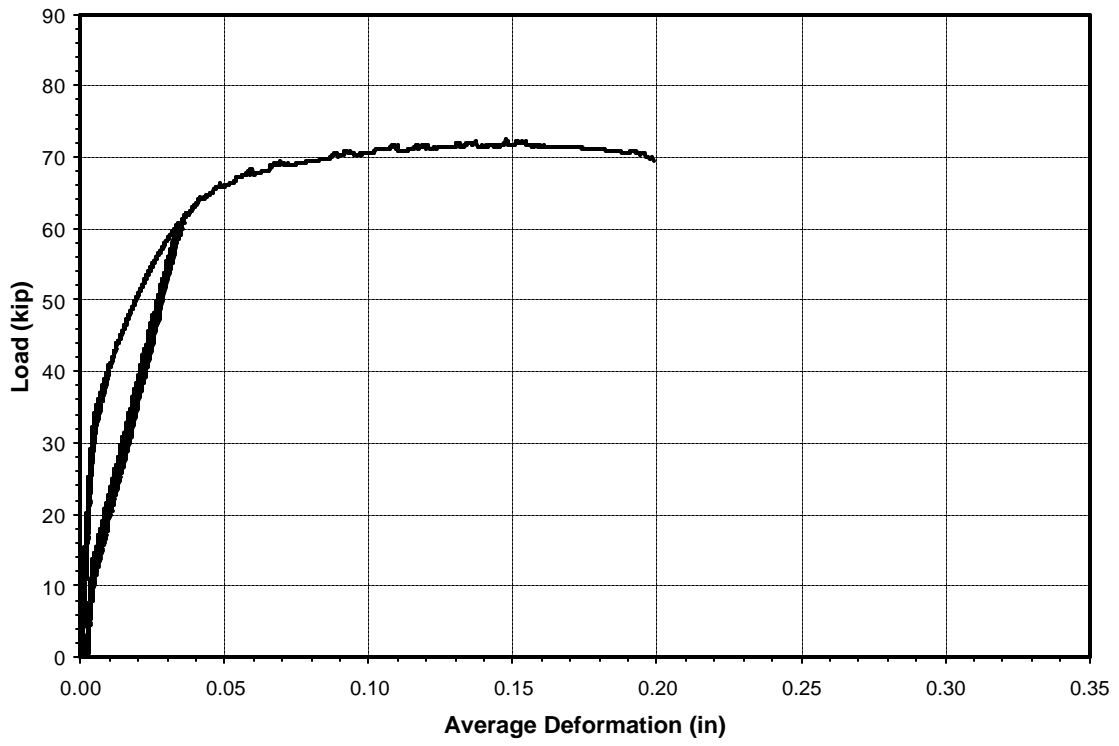
FF-4



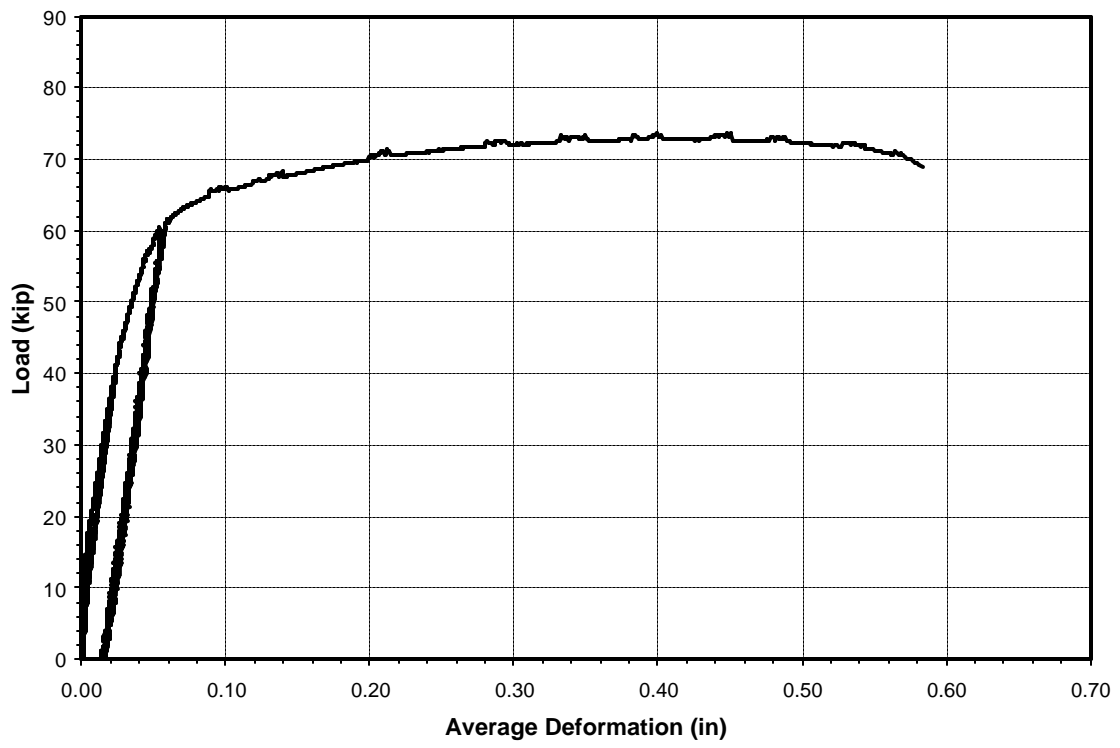
SS-4



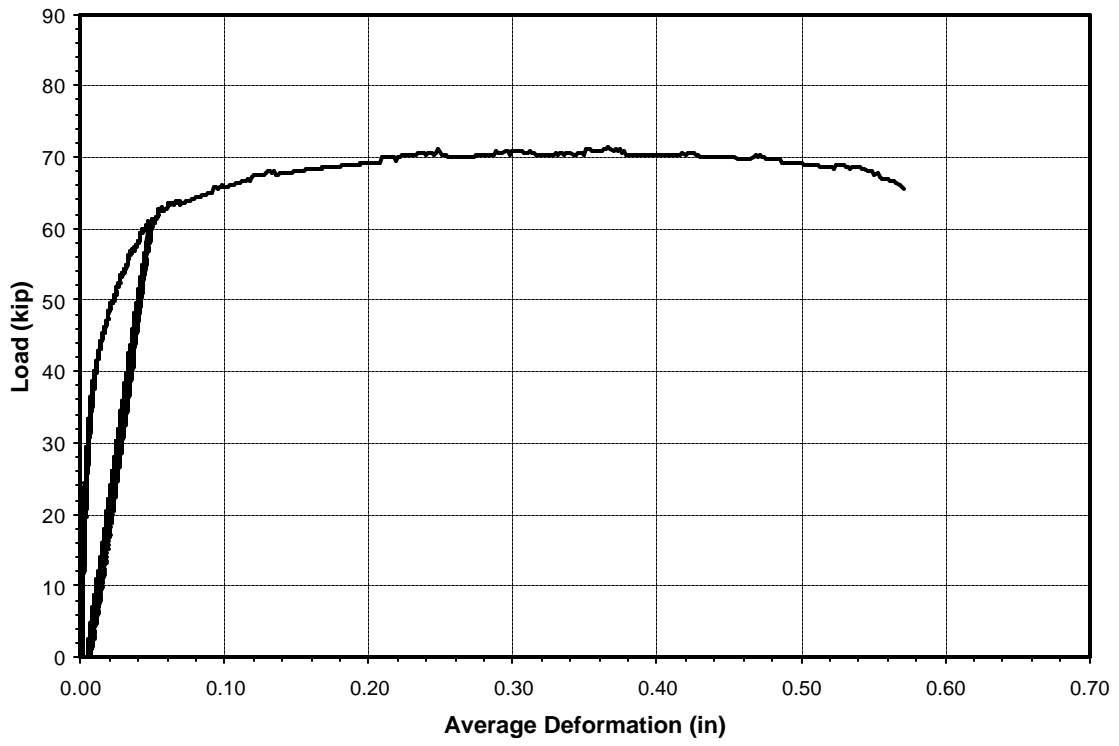
TT-4



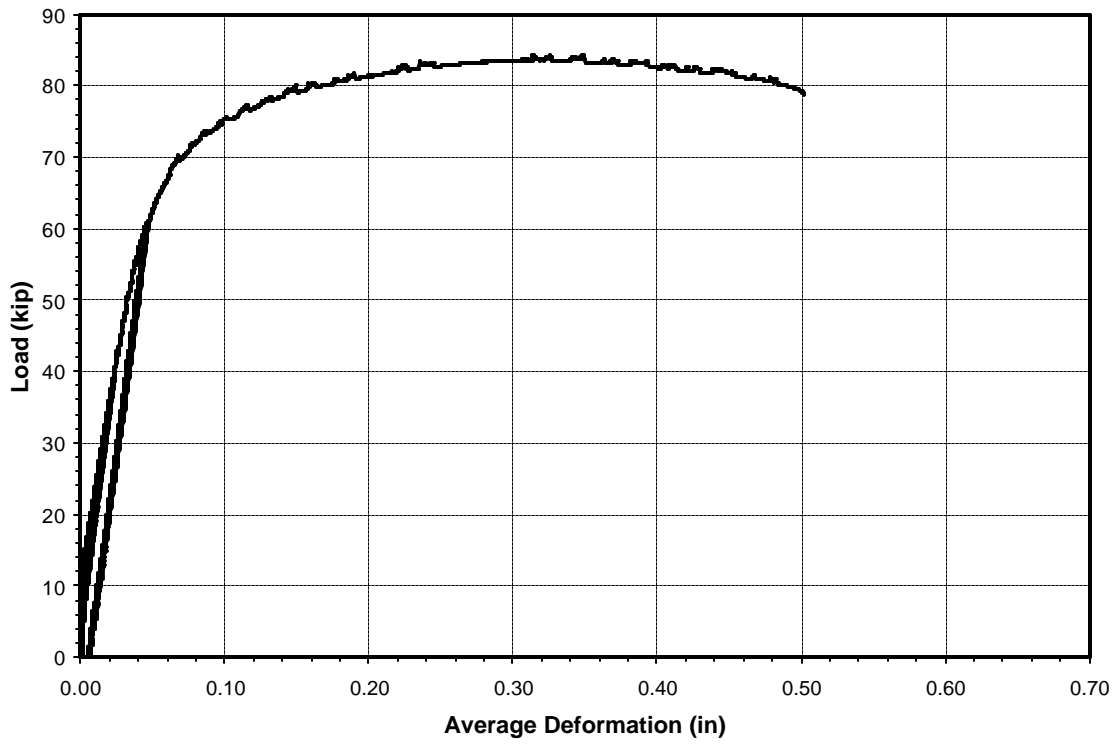
Gr5-SS



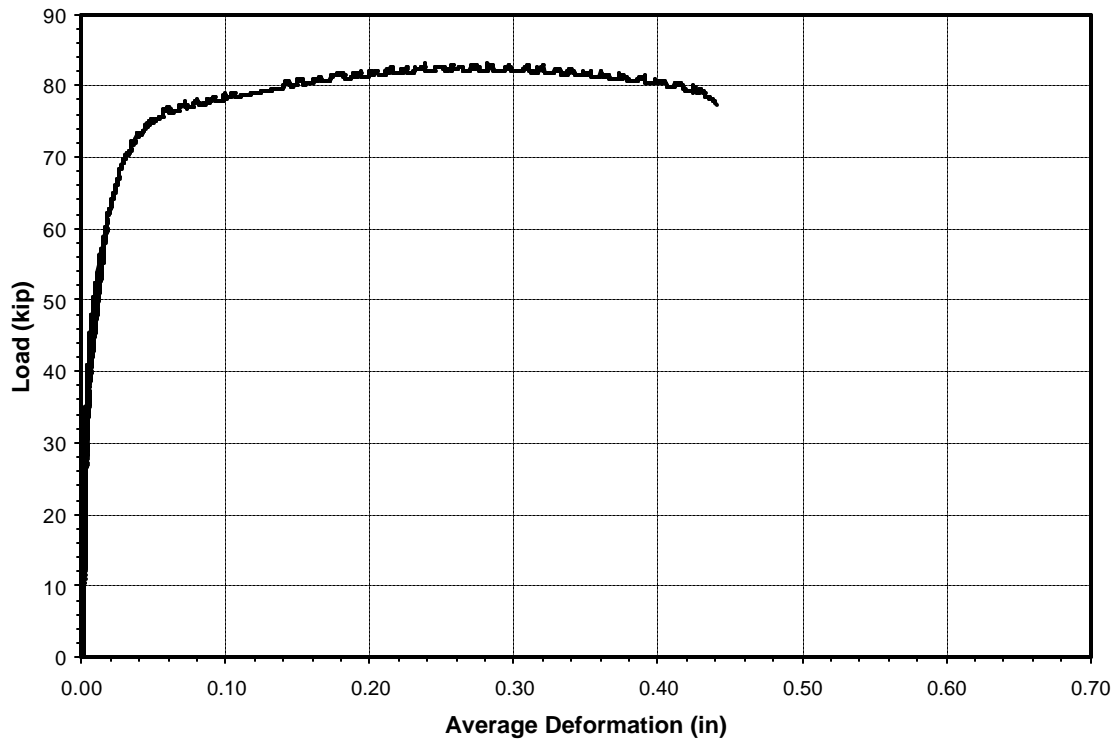
Gr5-TT



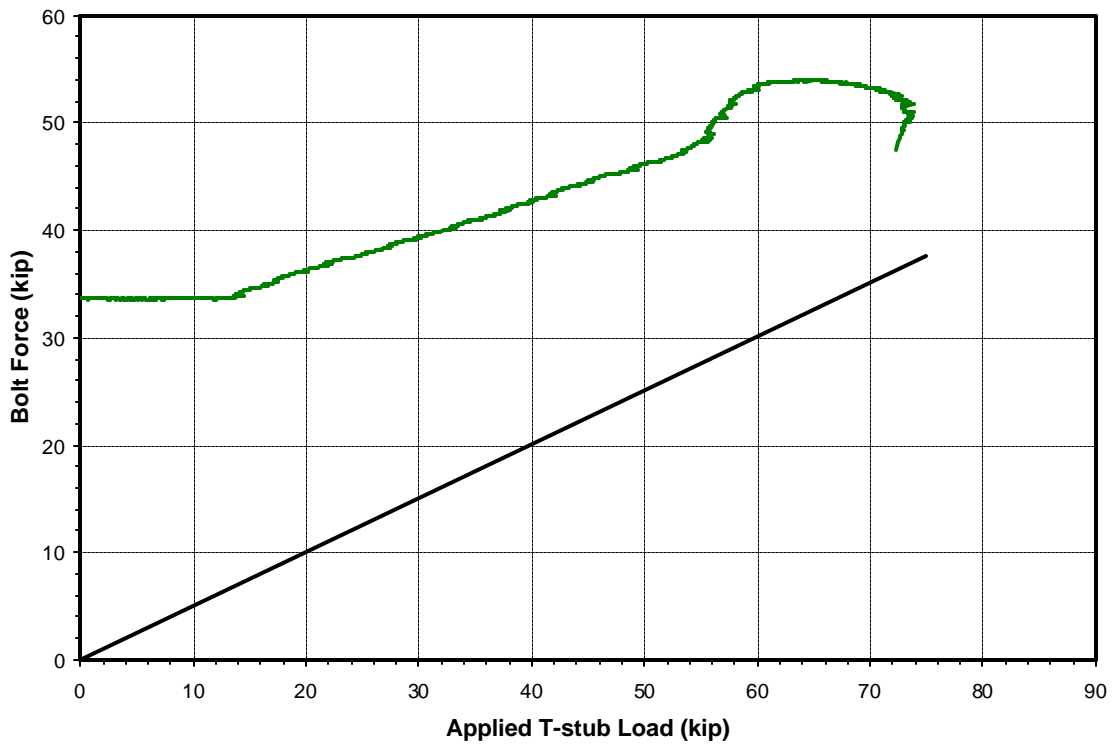
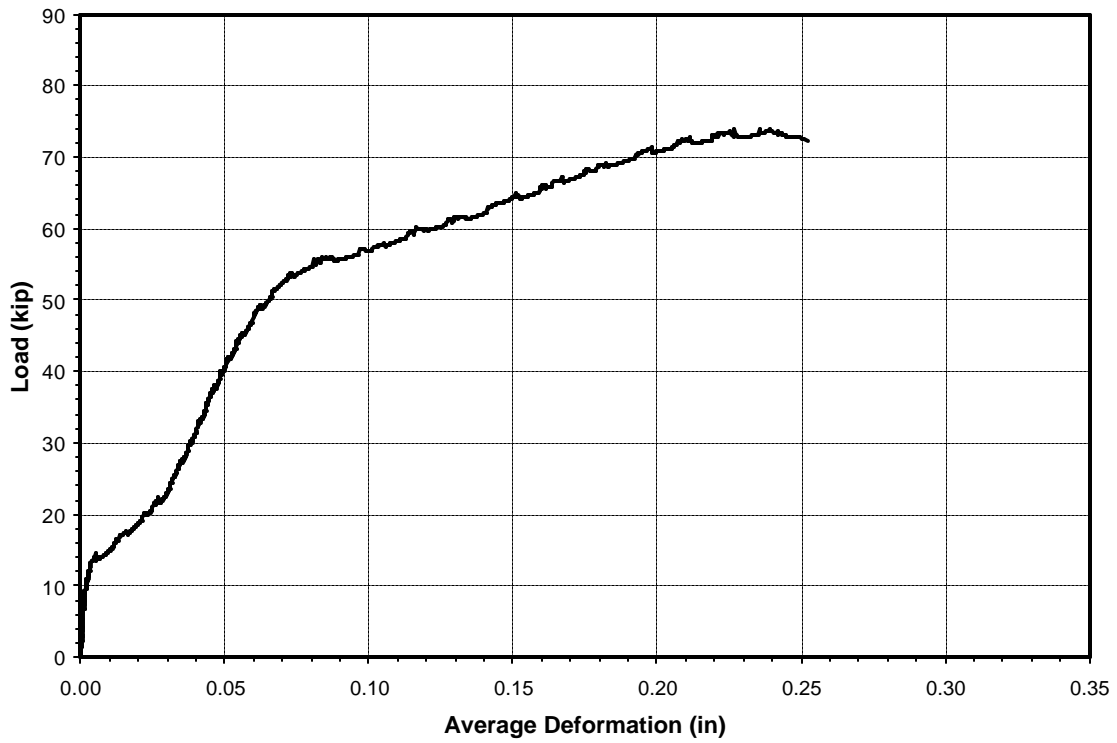
Gr8-SS



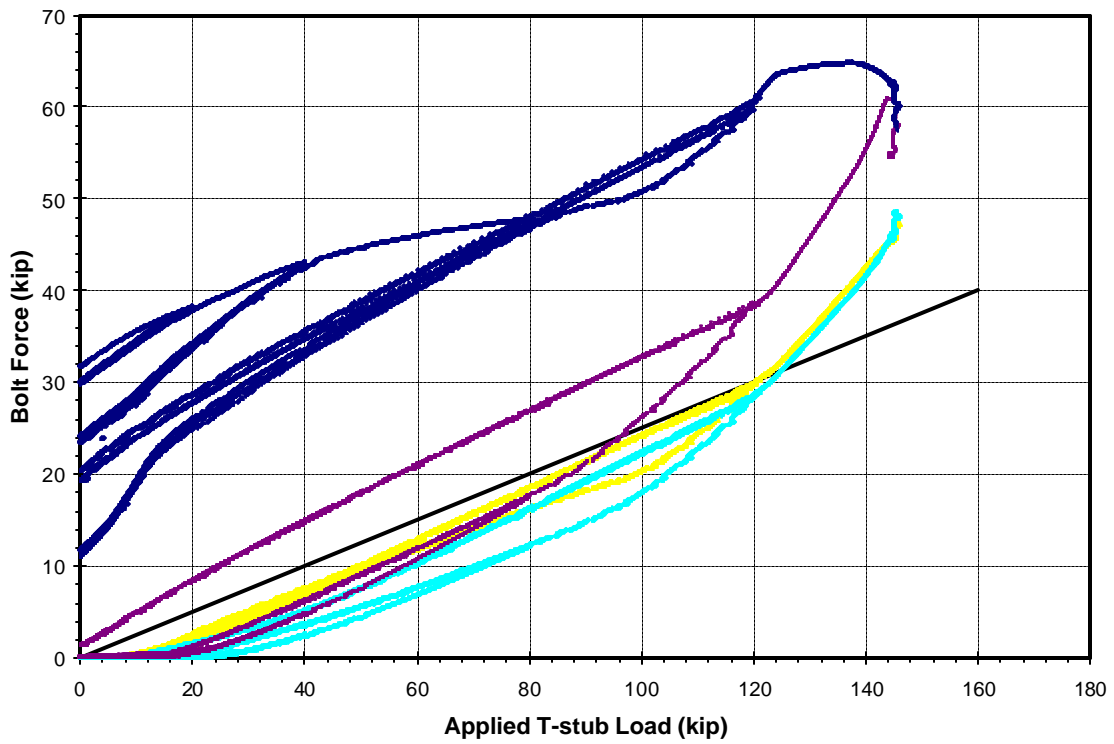
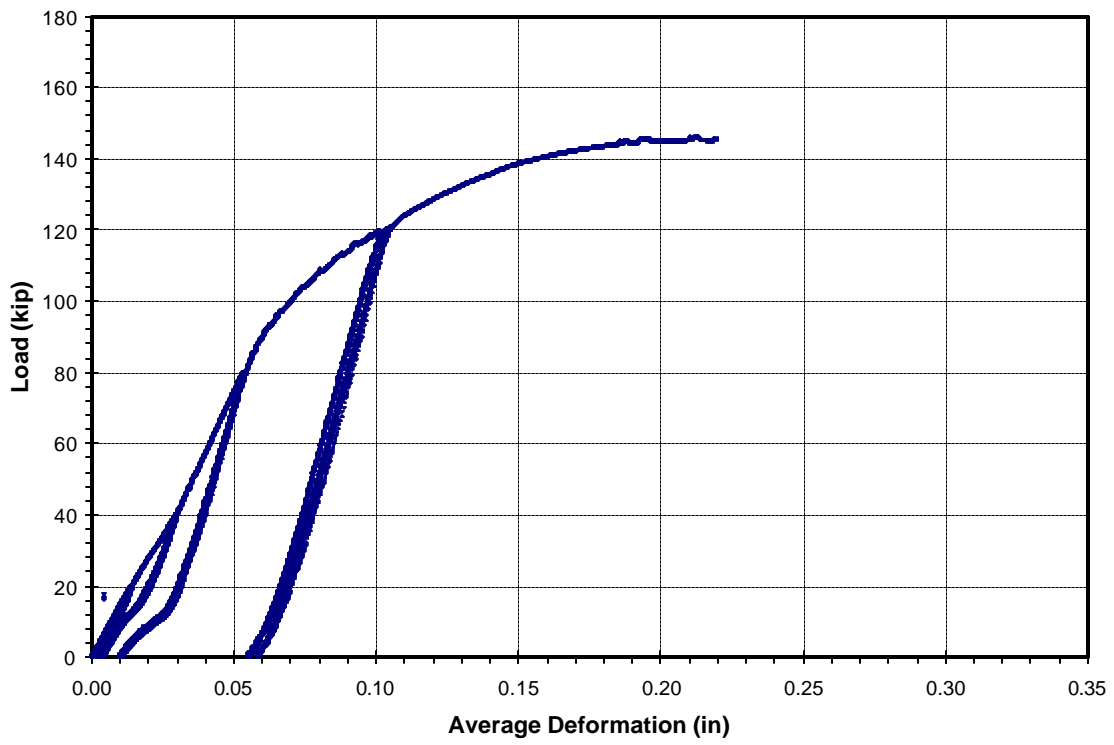
Gr8-TT



FT-1E



4 Bolt-A



4 Bolt-B

