AMERICAN CONSULTING ENGINEERS COUNCIL'S

HEAVY MOVABLE STRUCTURES MOVABLE BRIDGES AFFILIATE

3RD BIENNIAL SYMPOSIUM

NOVEMBER 12TH - 15TH, 1990

ST. PETERSBURG HILTON & TOWERS
ST. PETERSBURG, FLORIDA

SESSION WORKSHOP NOTES

Session (5-8)
"Torque Won't Discover 'Loose' Bolts",
Wayne Wallace, J & M Turner Inc.,
Burlington, Canada

Disclaimer

It is the policy of the Affiliation to provide a mean for information interchange. It DOES NOT propagate, recommend or endorse any of the information interchanged as it relates to design principles, processes, or products presented at the Symposium and/or contained herein. All Data are the author's and NOT the Affiliation's. Application of information interchanged is the responsibility of the user to validate and verify its integrity prior to use.

TORQUE WON'T DISCOVER "LOOSE" BOLTS

ABSTRACT

Movable bridges are assembled using high strength bolts, and normally the bolts are inspected with torque wrenches. Recent observations of bolts loosening in bridge connections has prompted re-examination of preload quality assurance procedures based on torque measurements. The author reviews recent preload data from ultrasonic bolt tension measurements, and other data, and shows that torque cannot be reliably related to bolt tension in a field situation. For some bolt/nut assemblies, the author shows that while torque can be very high, the tension in the bolt can be very low, and proposes that this is the probable root cause of the observed "bolt loosening" problem.

THE AUTHOR

Currently Vice-President Technical Services for J. & M. Turner Inc., Southampton PA, manufacturers of Direct Tension Indicators. Previously, Mr. Wallace graduated with a Masters' degree in civil engineering from McMaster University, and has worked in the steelmaking, consulting engineering, and structural steel fabricating and erecting industry both in Canada and the United States.

TORQUE WON'T DISCOVER LOOSE BOLTS

PRELOAD

The initial tension in a bolt after it has been installed is termed "preload". Bolts must be installed to a minimum level of preload, usually expressed (in United States) as kips, or thousands of pounds. An ASTM A 325 bolt, 7/8 " diameter, for example, is to be preloaded to 39 kips, or more. There is no upper limit to this specified preload, only a lower limit.

CAUSES OF LOOSENING BOLTS

No work has been done to the author's knowledge to try to establish the precise mechanism of bolt preload loss. It is thought that bolts unload due to one or several causes:

1. Inadequate preload (tension) during installation.

2. Underdesign of connections.

3. Relaxation.

4. High amplitude low cycle fatigue.

5. Poor initial fit-up.

Bridge connections are to be designed so that they do not slip under service loads. It is well known that once a connection "slips", the bolt preload is substantially lost (ref. 1, 2). Even when a connection does not "slip", for example in an end plate connection, if subjected to low cycle high amplitude fatigue (ref. 3), the bolt preload will "shake down" within a few cycles to a very low value. Subsequent to this, slip can occur easily. Of course, if a connection is subjected to unanticipated loadings from underdesign or higher than expected prying loads, the preload can be reduced to low values (ref 4).

Relaxation of bolt preloads, especially in galvanized bolts (ref 1, 18), can be on the order of 10%. This would not generally be considered a root cause of a bolt coming completely "loose", but can contribute.

The most common cause of apparently loosening bolts is, in the author's opinion, the fact that the bolt has not been properly preloaded during installation.

This paper discusses this most common and preventable cause of bolt preload "loss", viz. the bolt not having been highly preloaded during the initial installation.

HIGH INITIAL PRELOAD

If a bolt has been preloaded to over 70% of the minimum specified ultimate tension for it's grade, as external load is applied to a connection, the bolt "sees" only a change in tension which is a fraction of the external load. (Figure 1) The fraction seen is determined by the relative stiffnesses of the bolt vs the steel plate in the connection.

Conversely, (as in Figure 2), if a bolt has been preloaded only to a low value, the same external load fluctuation will produce a tension change in the bolt which is relatively higher compared to the initial preload.

Figure 3 shows how, for external load changes expressed as a percentage of bolt preload "P", the initial preload in the bolt will change expressed as a percentage of its preload. In the example used, the relative stiffness of the bolt to the clamped plates is 1:5, and it can be seen that a bolt in this situation preloaded to only 10% of "P" will experience a 100% tension change when subjected to an external load change of 50% of "P". When the external load change is more than this level, the bolt initially preloaded to only 10% of "P" will suddenly be required to take the entire external force. This is the point of plate separation, and it is this load change that can cause the bolt severe distress, and complete loss of preload. From this point on in the life of the connection, the bolt will remain loose. Subsequent vibration will often cause to bolt and nut to become separated.

Figure 4 shows the typical tension/elongation curve for an ASTM A 235 bolt loaded in pure tension. The specified minimum preload is 70% of the minimum specified ultimate strength (UTS) of the bolt, which is the highest point on its tension/elongation curve. Most high strength bolts have a minimum UTS somewhat higher than their specified minimum.

METHODS ALLOWED TO INSTALL BOLTS

AASHTO allows four methods:

1. Calibrated wrench
2. Turn-of-nut
3. Direct Tension Indicators
4. Other (Biach, Twist-Off, Huck, etc.)

The stated objective of all these methods is to produce an initial tension or preload in the bolt which is at or above 70% of the bolt's minimum ultimate tensile strength. The actual minimum preloads are listed on Figure 5.

THE "GUIDE" SHOWS WHAT PRELOADS ARE EXPECTED IN THE LAB

The "Guide" (ref 1) shows what preloads are achieved in the laboratory by calibrated wrench and turn-of-nut installation methods. Figure 6 is reproduced from the "Guide". Figure 6 shows that, in the laboratory, with all the controls possible on installation conditions, the mean preloads should be between 13% and 35% higher than the 70% minimum level, and shows that the expected standard deviations of these methods will (in the lab) be between 6% and 12%. Standard deviations are a measure of the variability of expected results. A standard deviation of 6%, for example, indicates that 99.73% of all results will be between the mean value less 18% as a lower bound, and the mean value plus 18% as an upper bound.

These preload probabilities are factored into the formulas developed in the guide for slip resistance. If these distributions of expected preloads are not achieved, the calculated slip resistance of the connection will not be achieved.

ULTRASONIC MEASUREMENTS HAVE SHOWN WHAT PRELOADS ARE ACHIEVED IN THE FIELD

By ultrasonically measuring the length of bolt after installation, then releasing the bolt and ultrasonically measuring the bolt length again, an indication of bolt elongation can now be accurately measured in the field. (ref 5) This length change can be calibrated by laboratory measurements on the same bolt/nut assembly to give an accurate measure of bolt preload which was in the bolt when it had been installed.

Some of the findings (ref 6, 7, 8) from these ultrasonic measurements have shown that many bolts (Figure 7) apparently were not preloaded to the minimums specified, and that the standard deviations of the results were far in excess of those from the "Guide". This, despite installation methods and quality assurance procedures compatible with AASHTO, Research Council, and AISC documents, now is direct evidence that many (literally thousands) bolts would have been left in structures without specified preloads. Many of these would have had virtually no preload at all.

Although conditions on each jobsite seem to be vastly different (see Figures 8, 9, and 10), and although the number of bolt preloads checked by this method is as yet small (less that 1000 bolts checked at random), it can be seen that the desired preloads are not being uniformly produced. Many of the bolts tested in this manner were, in fact, found to be essentially "loose", although site inspection teams had passed them by using torque measurements.

FIELD CONDITIONS CAUSE WIDE QUALITY VARIATIONS

It is no surprise that, in the field, often laboratory conditions cannot be duplicated. As applied to bolting, the differences include

1. Snug point -
   Where is the elusive "snug" point where theoretically the plates of a connection have been compacted? On a large bridge splice, this point is extremely difficult to determine. If the plates have not been brought together first, any of the specified installation methods are meaningless, because of the potentially large effect on previously tensioned bolts that tightening of fresh bolts may have (ref 2, 9). This effect is only controllable if two or more passes are made over the array of bolts.

2. Equipment -
   Is the impacting wrench being used capable of overcoming the torque resistance of the bolt/nut/washer assembly? If it is not, due to inadequate air pressure or condition of the wrench, the operator can only go to the point where the equipment refuses, and no further.

3. Hardware quality -
   Overtapped nuts, soft nuts, soft flat washers, improperly manufactured bolts, all can conspire to defeat the bolt installer. When bolt hardware from many suppliers is found on the same site, the installation crew may succeed with one combination but fail to get the required preload with another.

4. Operator diligence -
   Ironworkers are less disposed to do a thorough job today that they were ten or twenty years ago. Cost pressures today in a competitive industry force some installation crews to cut corners where they can do so. The entire installation procedure including a snug pass and a final pass may not have been done at all.

5. Nut rotation -
   Turn-of-nut procedures require that, after "snugging" the connection, a turn be made of the nut relative to

the bolt shank. Most field procedures in North America actually call for the wrench chuck to be turned, often ignoring the necessity of ensuring a relative turn being made between the nut and the bolt shank. Often, the field turn procedure is done to a timed interval, which is less reliable. And the calibration of such procedures, although theoretically done daily on Skidmores on site, are often neglected or, if done, fail to take into account the compression of the Skidmore device which is unlike the solid plates in a connection.

6. Time –
A bolt assembly one day after installation will demonstrate a different torque resistance when compared to a new bolt/nut just out of the keg. It has been demonstrated (ref 10) that after one or two weeks, with rain, heat, salt air, etc. acting on the threads and nut face, the torque resistance can change by more than 100 %. There is usually a time interval between fit-up bolting and final tightening on a jobsite.

TORQUE CANNOT BE RELATED TO PRELOAD

The torque resistance of a fastener assembly is said to be caused 50% by the thread/thread interface, 40% by the nut face, and only 10% by the stretching of the bolt itself (ref 4). While these proportions vary somewhat with size and grade of bolt (ref 11), it is evident that a large change in torque resistance can occur without a very large change in bolt preload.

To illustrate this point, (Figure 11) bolts from two jobsites were returned directly to a laboratory where they were all brought up to precisely the 70% preload level, and their torque resistances were accurately measured. Torque resistances of from 100 to 600 ft-lb. were measured, all bolts being at the same 70% preload level.

Notch (ref 6) has measured the "Torque-Tension" relationship on a project in Houston, for 1" and 1 1/4" bolts (see Figure 12 and 13). He found the standard deviations of torque resistance were from 30% to 40% of the mean values! (Figure 14).

(continued)

Grgas at the University of Toronto (ref 8) collected nut factor data from 231 bolts taken from the field (Figure 15), and found that the nut factors varied from 0.125 to 0.535, with a standard deviation of 21% of the mean. In this report, he found that a specific tension was produced by a torque which varied from +40% to -30% from the mean.

TORQUE BECOMES THE DEFAULT METHOD FOR INSTALLING BOLTS

Calibrated wrench installation of bolts is prohibited in Canada (ref 12), and its use is qualified by countries other than the USA (ref 13) to such an extent that it is rarely used. In the USA, however, it is still allowed, although the Research Council (ref 14) has seen fit to write several pages of commentary stating that its use should be considered as a last resort. Even the AISC (ref 15) has gone on record that its use should be discouraged.

Turn-of-nut procedures often become essentially torque controlled for the reasons mentioned above, and, where strain controlled installation methods are not used (like Direct Tension Indicators or Biach tensioners or Huck bolts), torque becomes the usual inspection method.

But the extreme variability of torque often defeats the installation method, right from the start. Bolts are installed using impacting equipment, and as long as the torquing force is present, the combined torsional and tension stresses can lead to bolt failure before the required preload has been achieved (Figure 16). High frictional resistance can cause an installer to believe that a bolt has been "tightened" sufficiently, or indeed almost fractured torsionally as it occasionally will be, whereas the bolt can be virtually untensioned at all as ultrasonic inspection has shown.

"Twist-off" bolts, where the bolt shank is engineered to break off at a specific torque, are another example of torque installation, with the added variable of twist-off torque. This type of fastener is subject to all the variability of any other bolt/nut assembly, and, even worse, is usually impossible to inspect even with a torque wrench.

(continued)

BETTER TECHNOLOGY IS AVAILABLE

Strain controlled bolt installation is now considered standard practice in many industries other than structural steel (ref 16, 17). Biach tensioners, which pull the bolt into direct tension hydraulically, have now been used in some critical movable bridge applications. Deformable nut fasteners such as the "Huck" product have proven to be economical on occasion.

The most often encountered alternative to torque dependence is the compressible washer, called by ASTM a "*Direct Tension* Indicator", or DTI (see Figure 17). It is usually installed under the head of the bolt, and simply compresses to a *minimum* gap (or less) at the specified bolt preload. DTI's are not dependent on torque in any way (ref 11), and make inspection of the bolting process easy and accurate.

In the laboratory, the DTI demonstrates a *mean* load of 10% above the minimum specified, and a standard deviation of 2.5% (Figure 18). Field studies using ultrasonics (ref 8) show similar mean values and only a slightly wider standard deviation of about 12% (Figure 19). These results compare very favorably with the preloads needed to assure non-slip connection performance.

When plotted on the bolt tension/elongation curve in "torqued tension", the frequency distribution of *preloads* at the specified minimum gap can be shown as in Figure 20. Following industry practice to compress the DTI's to a "nil" gap will raise the expected preloads just slightly higher. The use of a DTI allows the installer to judge "by eye" when the *minimum preload* has been exceeded.

INSTALLING BOLTS TO YIELD OR ABOVE

It is not an easy concept to grasp, but the best bolting *minds* in the world (ref 2, 17) have concluded that, in virtually every application, preloading the bolt to yield (0.2% offset) *or above* will enhance the service life of the connection. This applies to tension loading, shear before slip, prying, and fatigue. High preloads will minimize the possibility of tension loss. Also, the addition of a compressible element in the clamp of the bolt can "soften" the bolt response to external load (ref 17).

Once the torquing effort of installation is removed, the bolt can behave in load/elongation as a bolt in pure tension (Figure 21). Even though the bolt has been almost torsionally broken during the combined stresses of installation, it will still demonstrate performance to minimum specified ultimate tensile strength (ref 17). Even bolts which have begun to "neck" during torque installation will perform to specification in tension after the torque wrench has been removed.

This is not a recommendation for intentionally straining all the bolts to the point where they begin to neck. But if some bolts in a connection happen to have been necked, and if some bolts have actually been broken (and replaced), it is a sign that the majority of bolts probably are getting installed to the correct level of preload or above.

CONCLUSION

Loosening bolts in any type of structure will be minimized by maintaining installation and inspection practices which are torque independent, and which are aimed at obtaining bolt preloads uniformly in excess of the minimum preloads specified in the applicable codes.

REFERENCES

1. Kulak, G. L., J. W. Fisher, and J. H. A. Struik, "Guide to Design Criteria for Bolted and Riveted Joints", 2nd edition, New York: John Wiley and Sons, 1987.

2. Mann, Allan P., and Linden J. Morris, "Lack of Fit in High Strength bolted Connections", Journal of Structural Engineering, Vol. 110, No. 6, June 1984.

3. Ghobarah, A., A. Osman, and R. M. Korol, "Behaviour of Extended End Plate Connections Under Cyclic Loading", Journal of Engineering Structures.

4. Milenkovich, Milosh D., Chief Metallurgist, Lake Erie Screw Corp., "Why Bolts Fail", American Fastener Journal, January 1984.

5. Notch, J. S., "Bolt Preload Measurements Using Ultrasonic Methods", Engineering Journal, American Institute of Steel Construction, 2nd Quarter 1985.

6. Notch, J. S., "A Field Problem with Preload of Large A 490 Bolts", The Structural Engineer, Vol. 64A, No. 4.

7. Bickford, John H., "Study of the Tension Achieved in A 325 and/or A 490 Bolts When Tightened Under Normal Field Conditions By Currently Specified Procedures", A Project of Committee 20 of The RCSC, Raymond Engineering Inc., Middletown, Connecticut, June 1986.

8. Grgas, Nick, "Field Investigation and Evaluation of the Pretension of High Strength Bolts", Draft Thesis Submitted for the Degree of Master of Applied Science in the University of Toronto, 1990, tabled for use of Committee 20 of the Research Council on Structural Connections, Denver, May 1990.

9. Birkemoe, Peter C., "Installation Tension of High Strength Bolts in Connections With Out-Of-Flat Plates", IABSE International Colloquium, Bolted and Special Structural Joints, USSR, Moscow, May, 1989.

10. Pittsburgh Testing Laboratory, "Tests on 1" A 490 Conventional and Twist-Off High Strength Bolts and Direct Tension Indicators Conducted in the As Received Condition and After Weathering", Report to J. & M. Turner Inc., May, 1986.

11. Ghobarah, A., "Work Required to Install Large Diameter High Strength Bolts", Report to J. & M. Turner Inc., McMaster University, Hamilton, Ontario, Canada, April 1990.

12. CAN3-S16.1-M84, "Steel Structures for Buildings (Limit States Design)", ISSN 0317-5889, Canadian Standards Association, Rexdale, Ontario, M9W 1R3, 1984.

13. Piraprez, E., "The Tightening of High Strength Bolts On Site", IABSE International Colloquium, Bolted and Special Structural Joints, USSR, Moscow, May, 1989.

14. Research Council on Structural Connections, 1987, "Specification for Structural Joints Using ASTM A 325 or A 490 Bolts", including Commentary on same.

15. Disque, Robert O., and Reidar Bjorhovde, "Design of Bolted Connections By LRFD", IABSE Colloquium on Bolted and Special Structural Connections, Moscow, May 1989.

16. Metalworking News, June 1988, "Cummins Using New Bolt-Tightening Equipment", Jamestown, New York.

17. Gill, Peter J., "The Yielding of Fastenings During Tightening", reprinted from the Japanese translation of same, submitted to the 11th plenary meeting of ISO/TCI, Stockholm, Sweden. Mr. Gill was head of Technology Services of GKN Fasteners, West Midlands, England. This paper is believed to have originated in the mid 1970's.

18. Vitelleschi, Silvio, and Lewis C. Schmidt, "Damping in Friction-Grip Bolted Joints", Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, Vol. 103, July, 1977.

HIGH BOLT PRELOAD

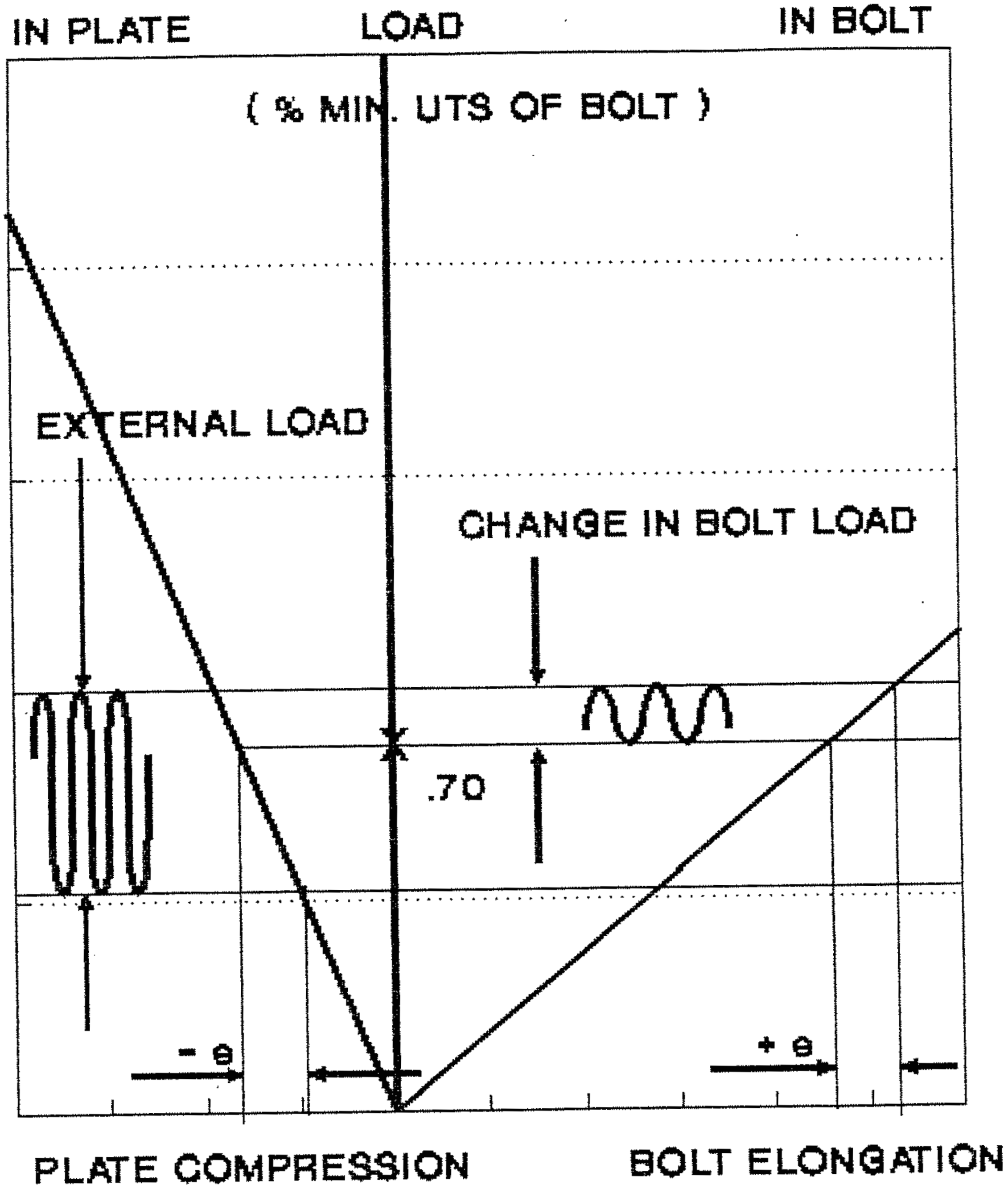


FIGURE 1

LOW BOLT PRELOAD

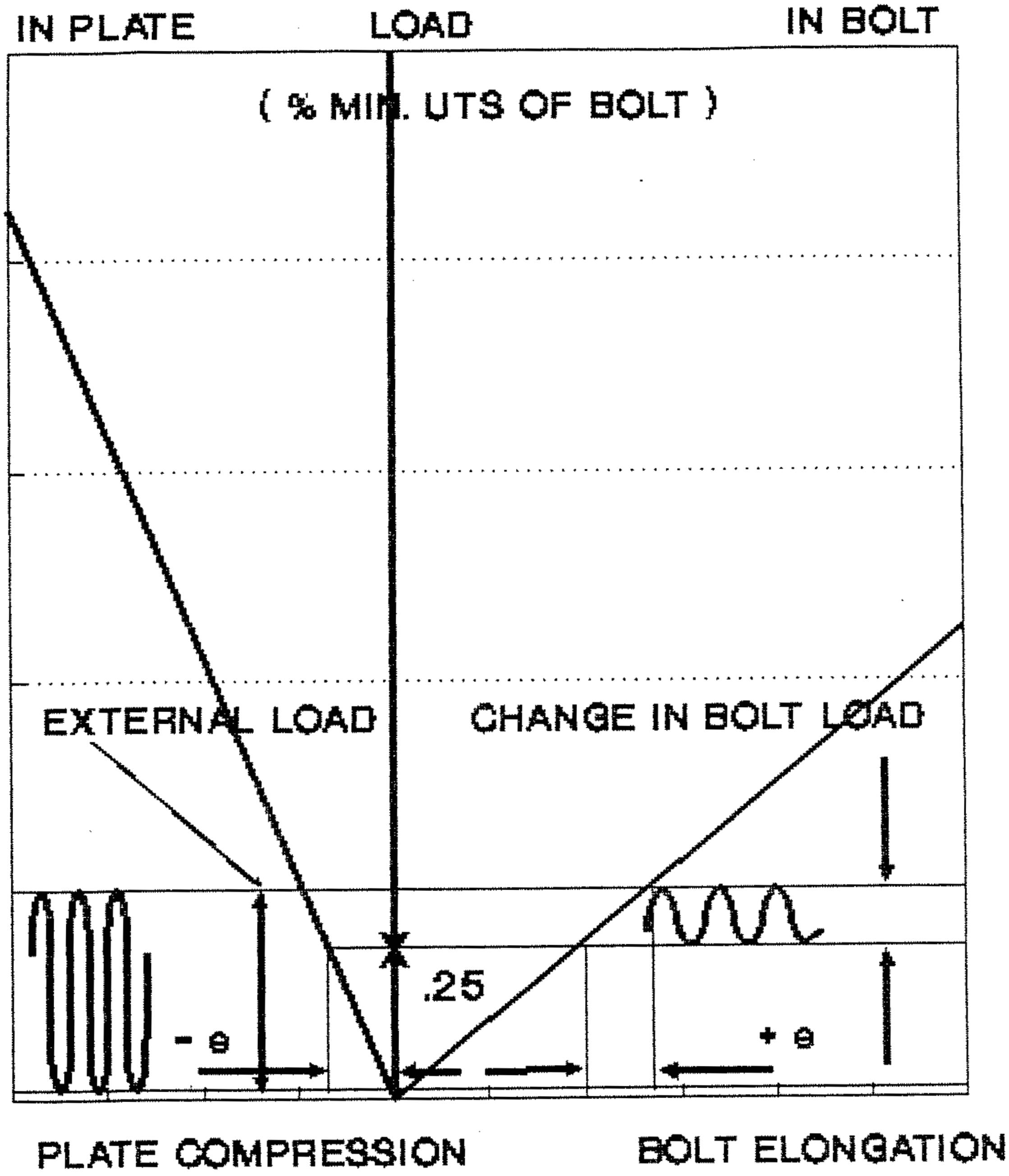


FIGURE 2

EFFECT OF EXTERNAL LOAD CHANGE ON BOLT LOAD

EXTERNAL LOAD CHANGE (AS % OF P)	BOLT LOAD CHANGE		
	INITIAL PRELOAD		
	P	.25P	.1P
35% P	7%	28%	70%
50% P	10%	40%	100%
60% P	12%	50%	600%

FOOTNOTES

P = 70% MIN UTS OF BOLT
PLATES SEPARATE
ASSUMING STIFFNESS RATIO OF 1:5 BOLT:PLATE

FIGURE 3

PRELOAD REQUIRED BY CODE

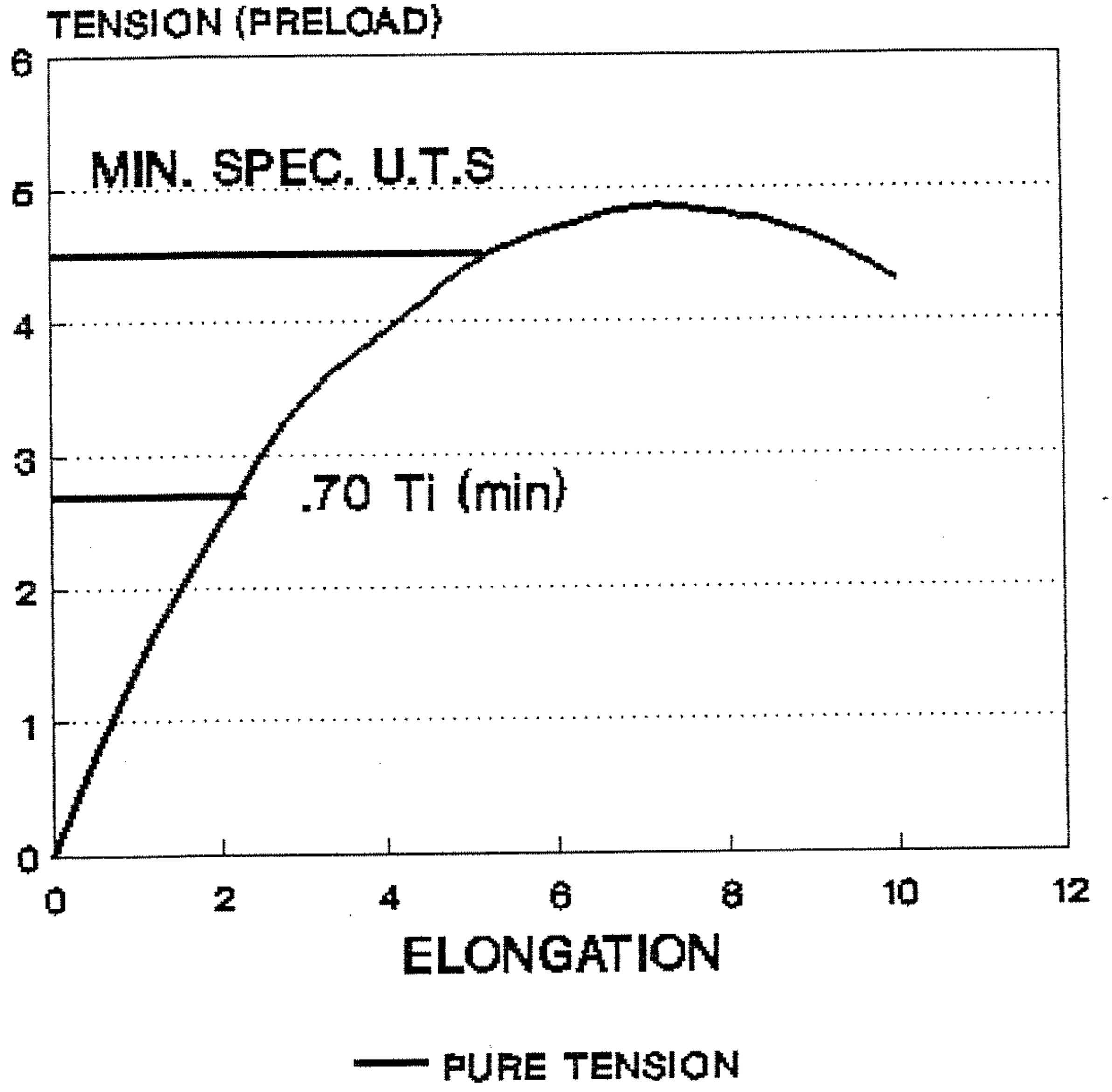


FIGURE 4

MINIMUM PRELOADS REQUIRED

(KIPS)

- DIA	A325	A490
- 3/4	28	35
- 7/8	39	49
- 1	51	64
- 1-1/8	56	80
- 1-1/4	71	102

FIGURE 5

PRELOADS ACHIEVED (IN THE LAB)

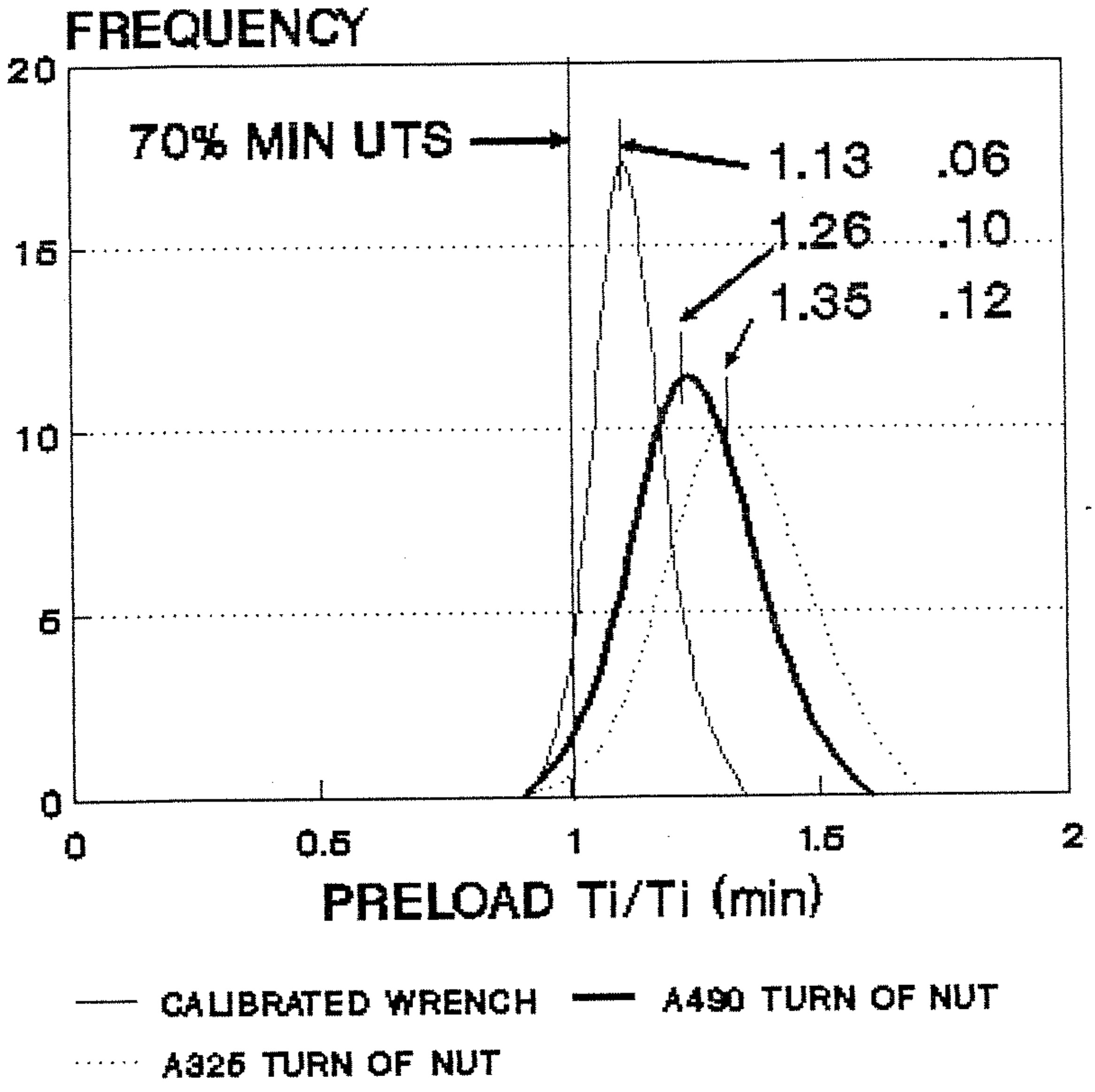


FIGURE 6

GUIDE FIG. 5.9

PRELOADS ACHIEVED (IN THE FIELD)

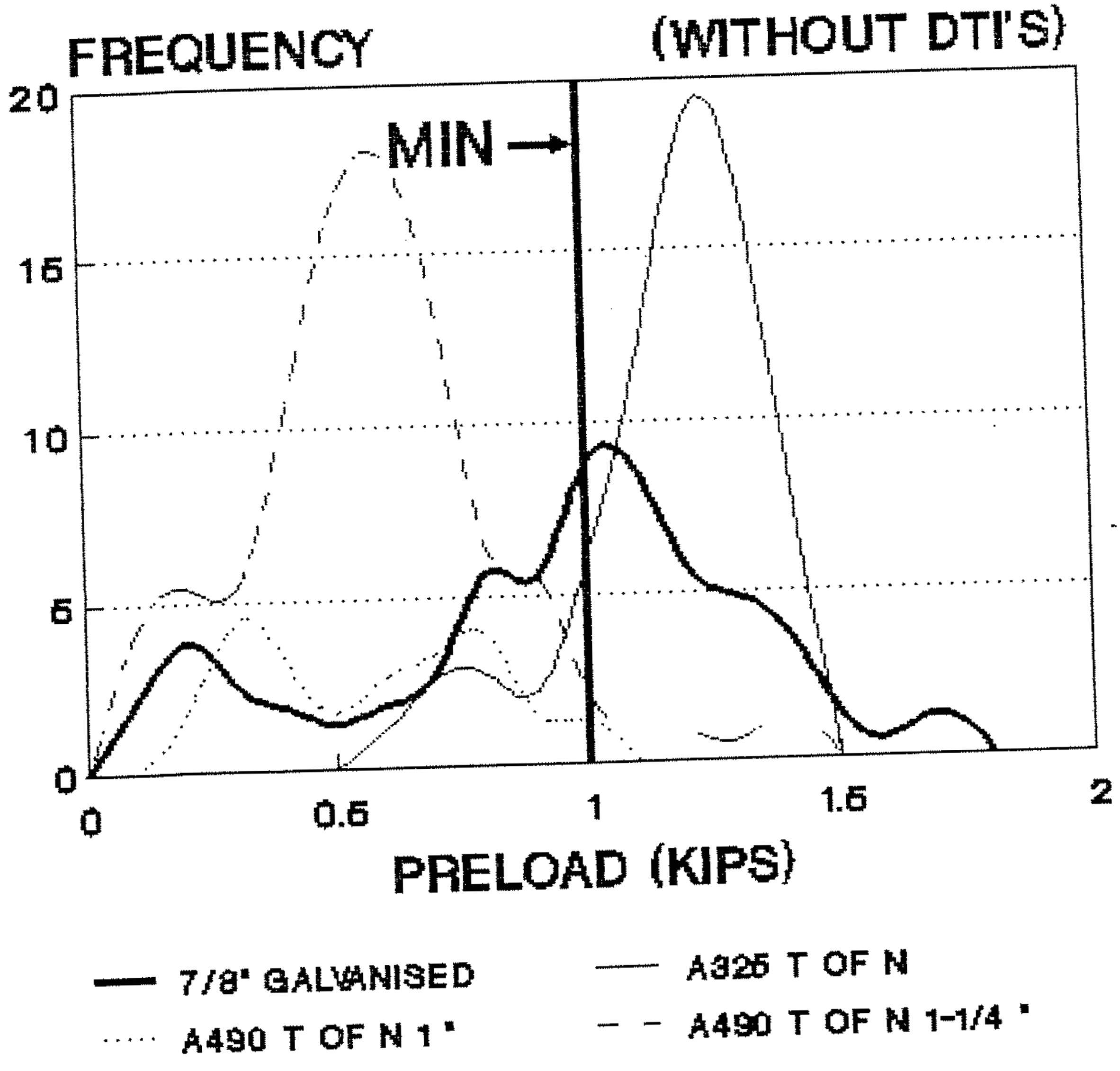


FIGURE 7

NOTCH, GRGAS, R.C.S.C
(ULTRASONIC TESTS)

FIELD PRELOADS WITHOUT DTI'S

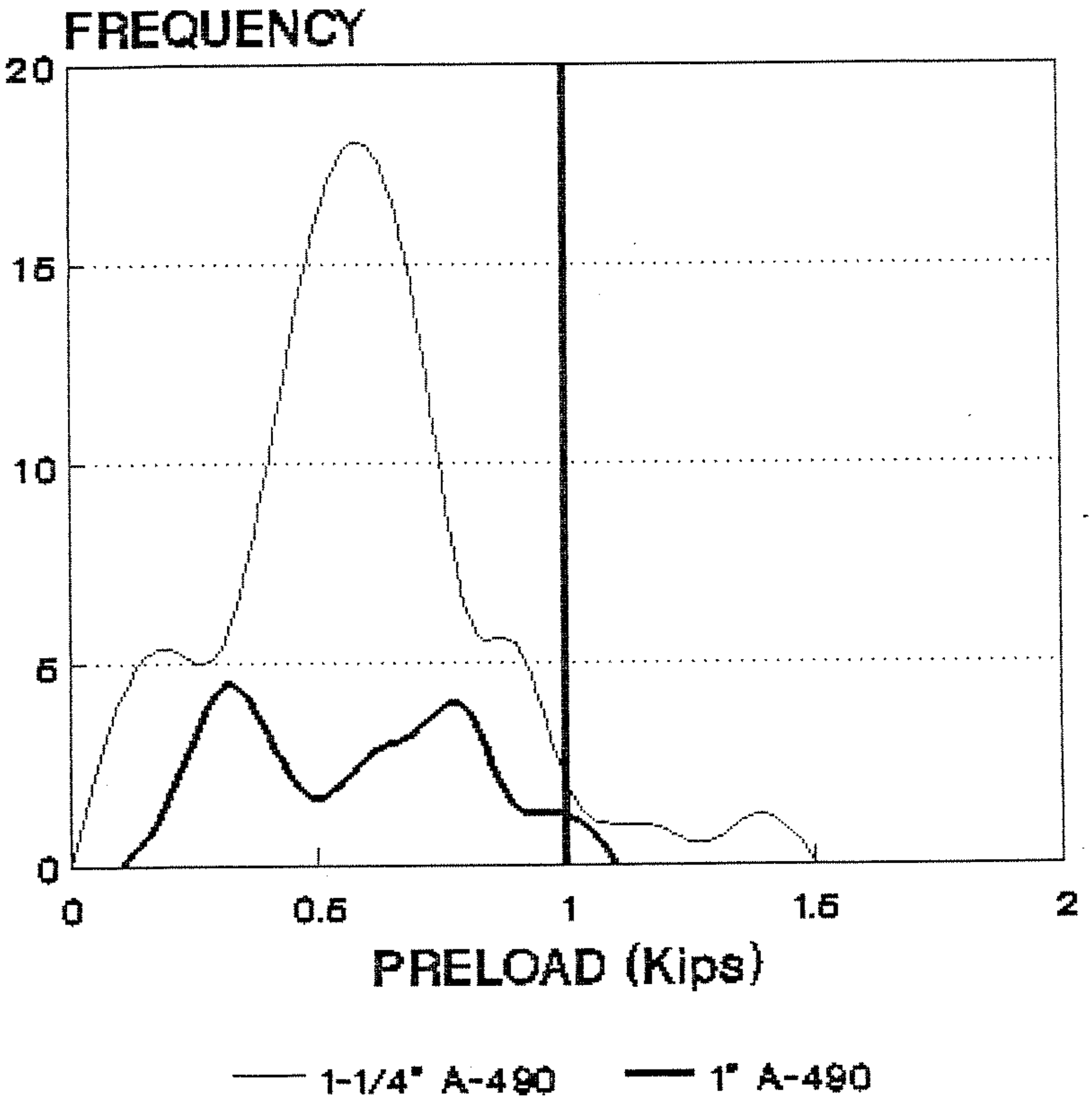
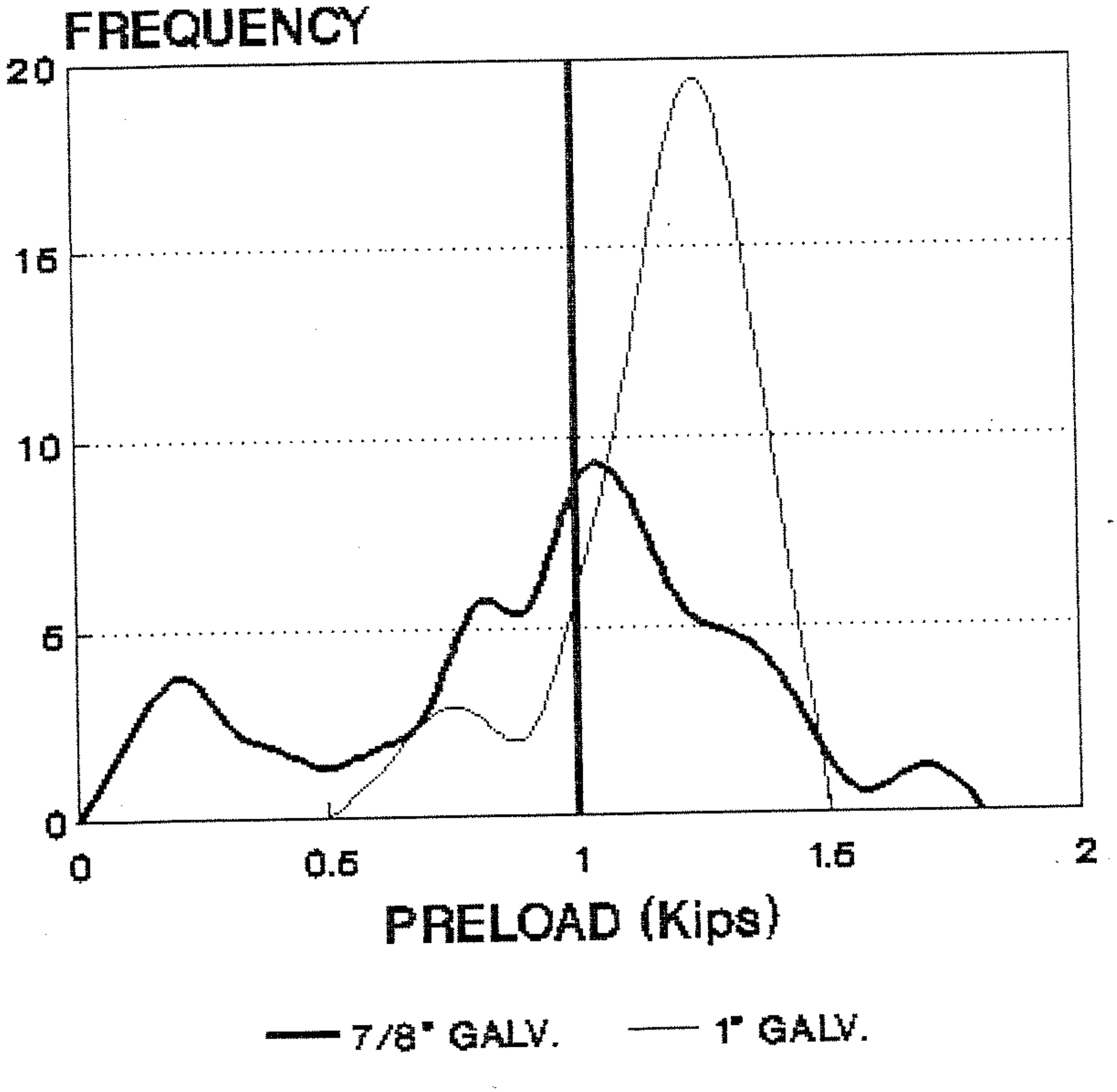


FIGURE 8

J & M TURNER (NOTCH)

FIELD PRELOADS WITHOUT DTI'S



J & M TURNER
(RCSC,GRGAS)

FIGURE 9

WHY THE DIFFERENCE
9 JOB SITES (254 BOLTS)

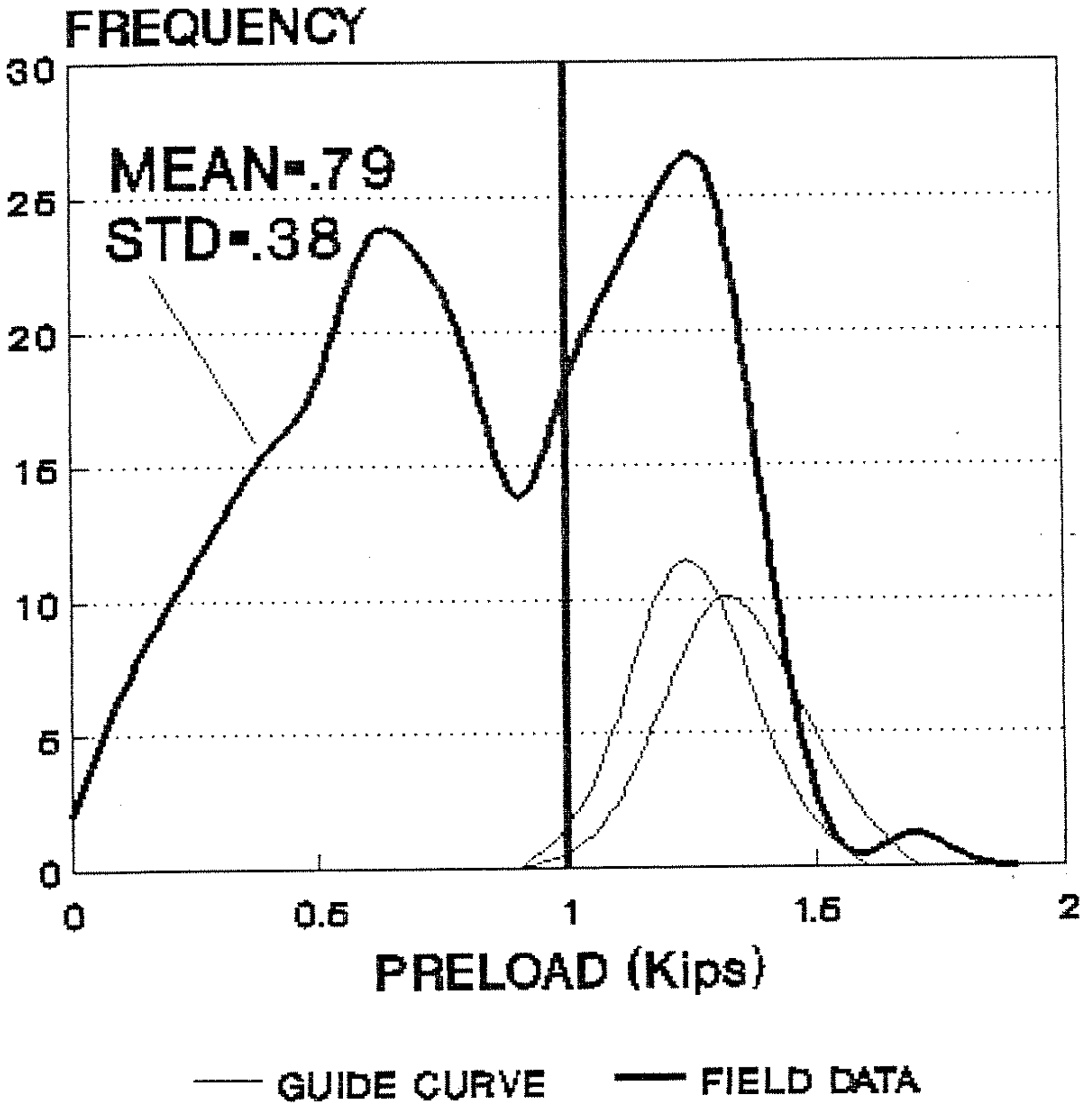
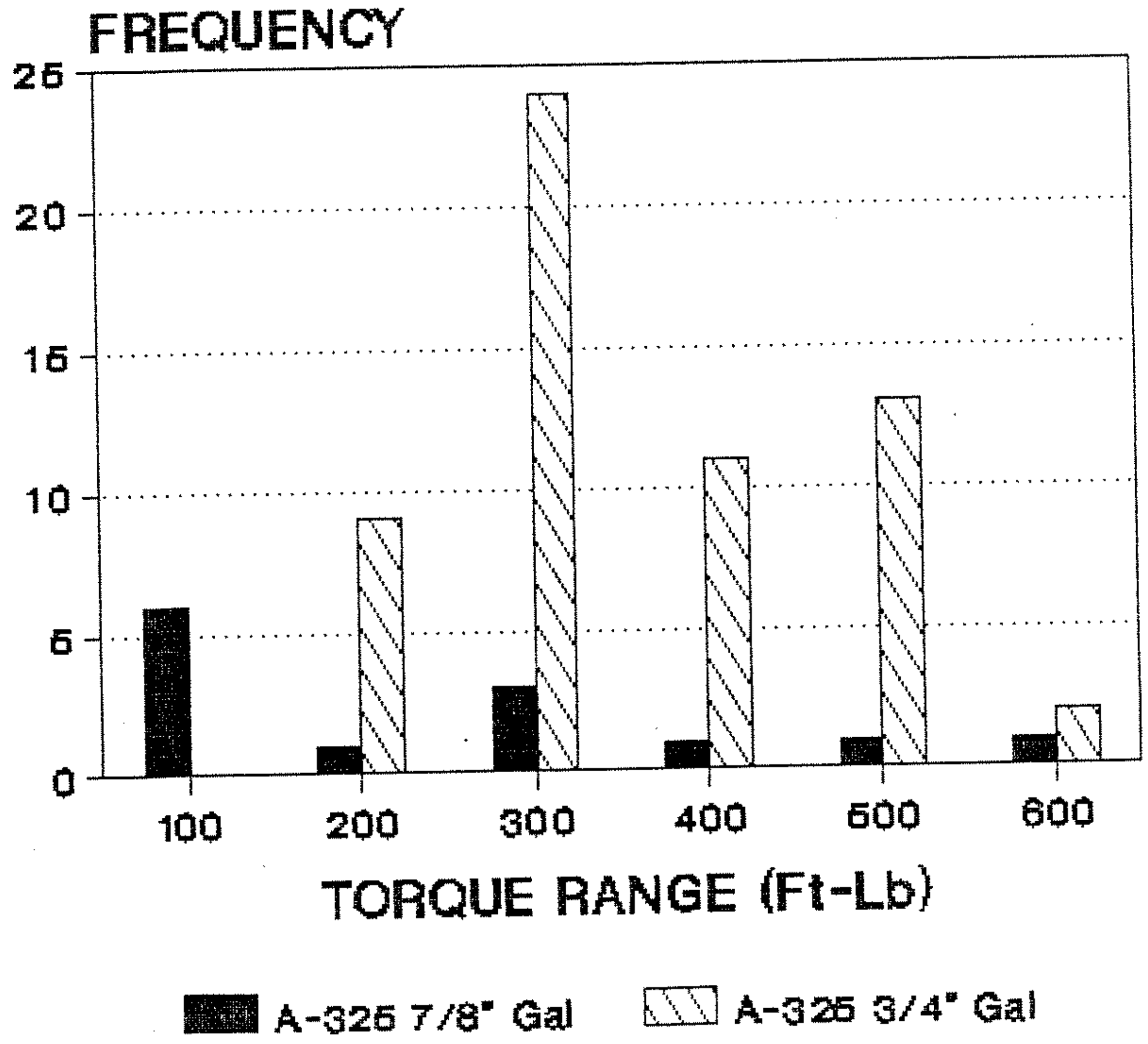


FIGURE 10

J & M TURNER

LOOK AT THE TORQUE VARIATION AT THE SAME PRELOAD



HEMPSTEAD/U. OF T. 1988

FIGURE 11

TORQUE-TENSION "RELATIONSHIP"

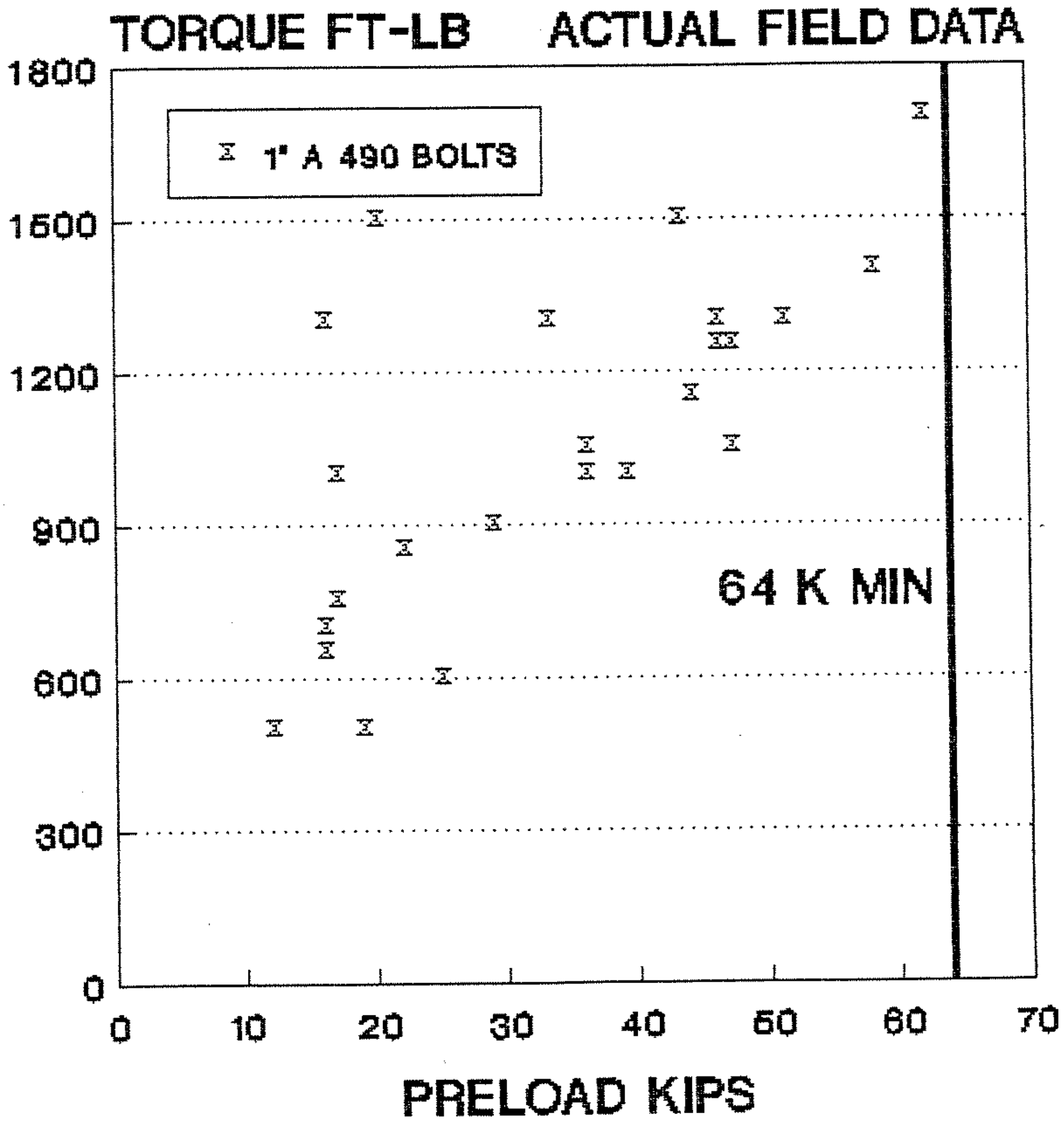


FIGURE 12

NOTCH APR 86

TORQUE-TENSION "RELATIONSHIP"

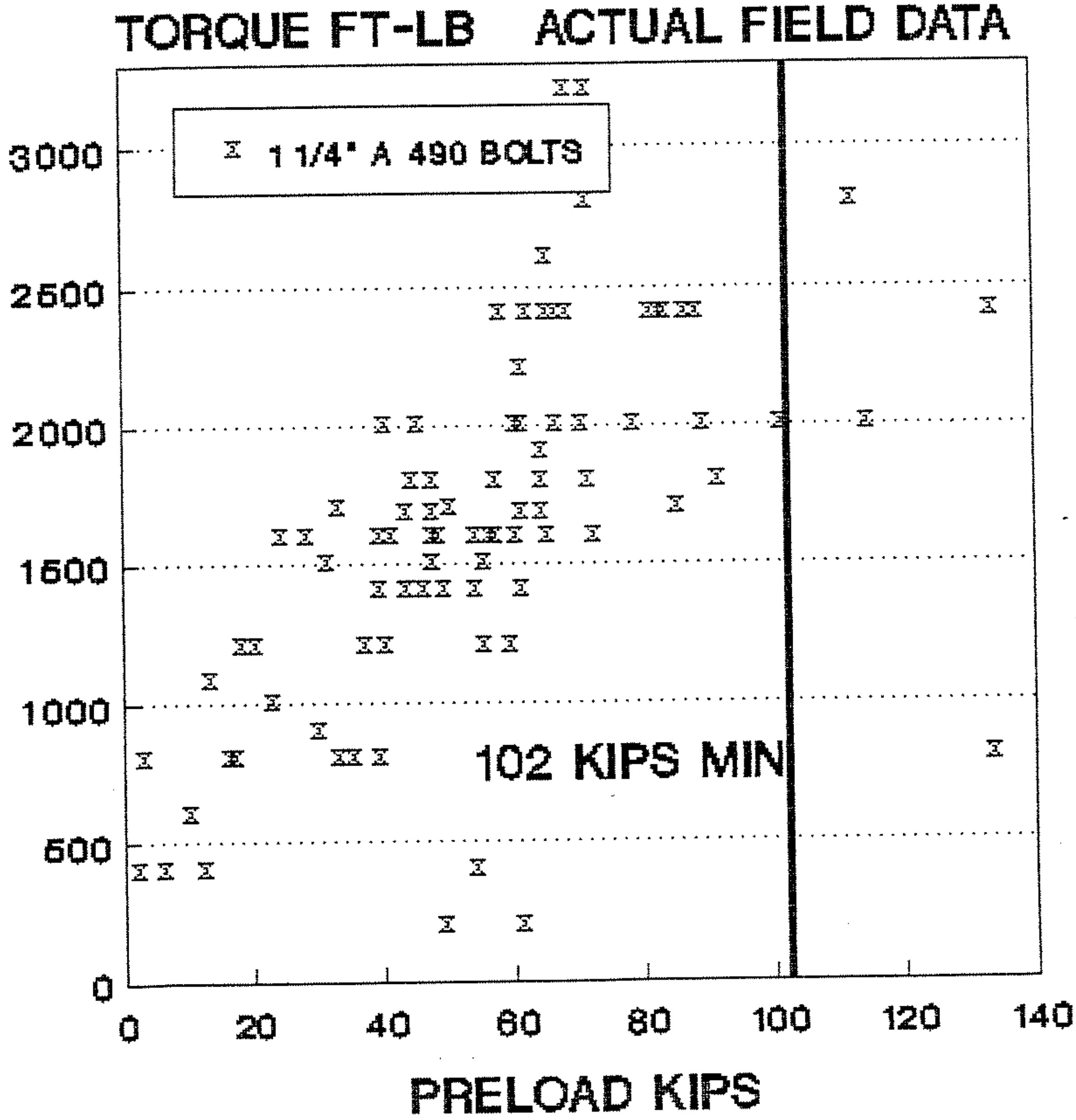


FIGURE 13

NOTCH APR 86

TORQUES MEASURED
AT PRELOAD ACHIEVED

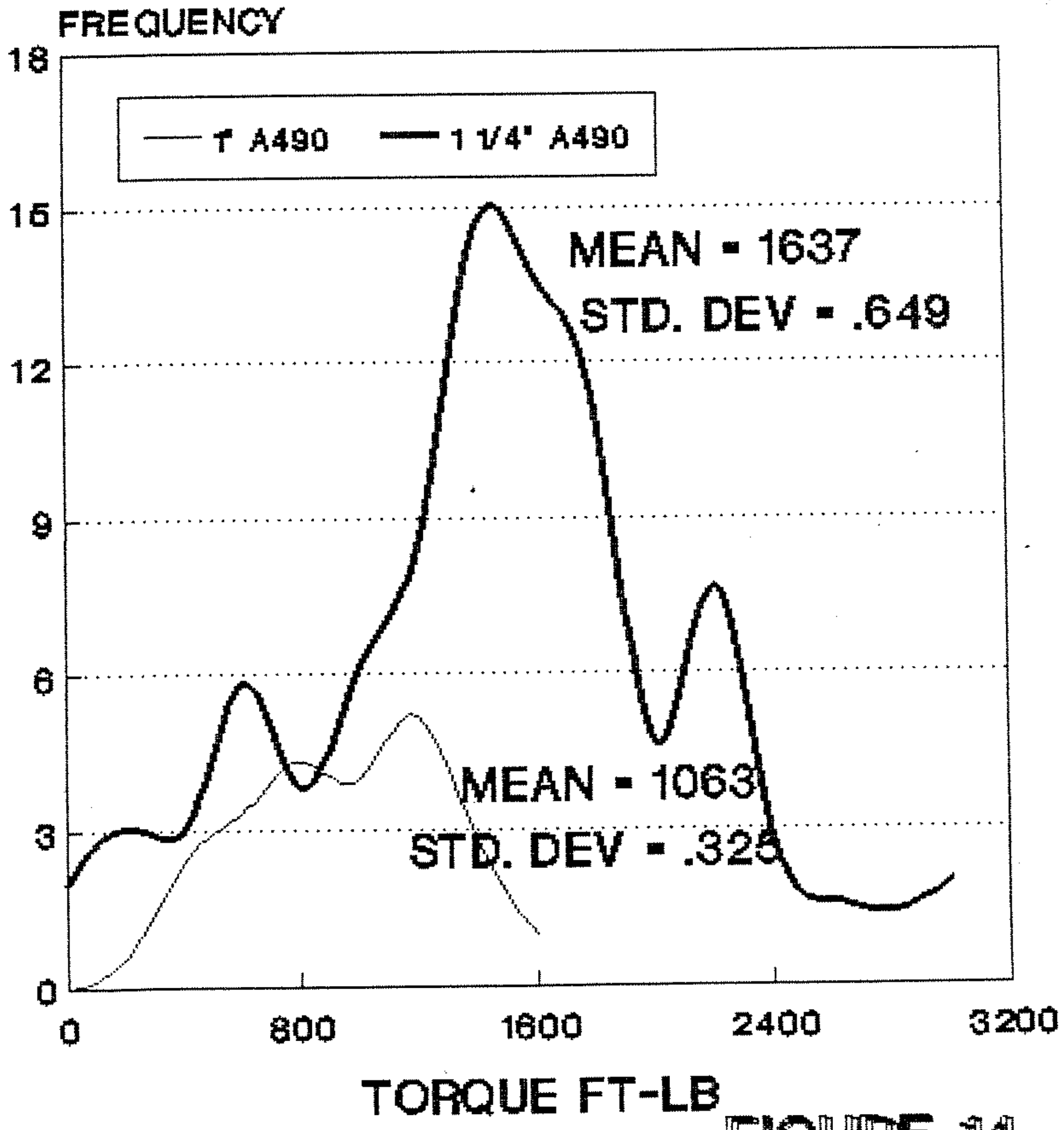


FIGURE 14

NOTCH APR 86

EVEN THE NUT FACTORS VARY !

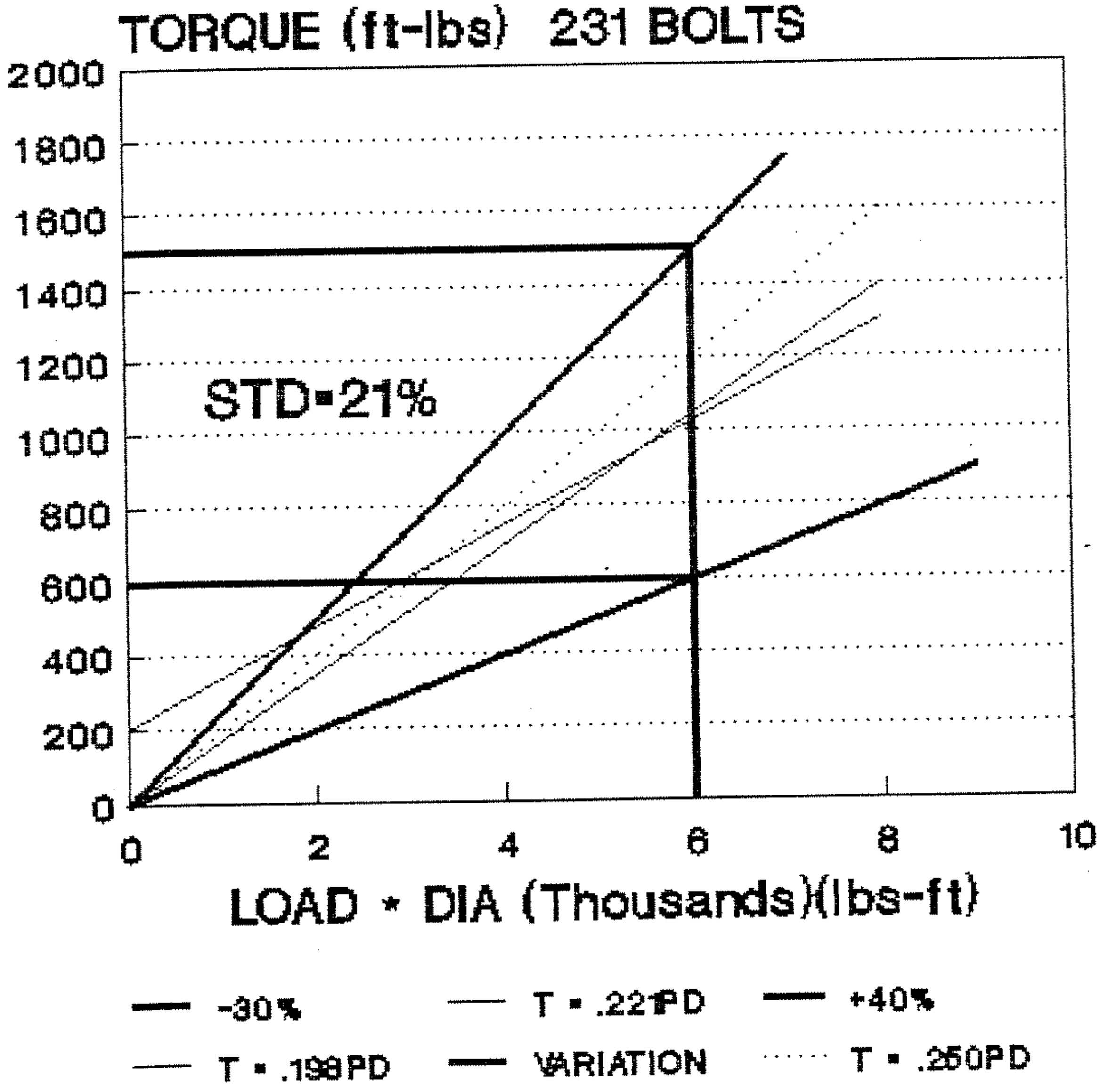


FIGURE 15

GRGAS U. OF T.

COMBINED STRESSES DURING INSTALLATION

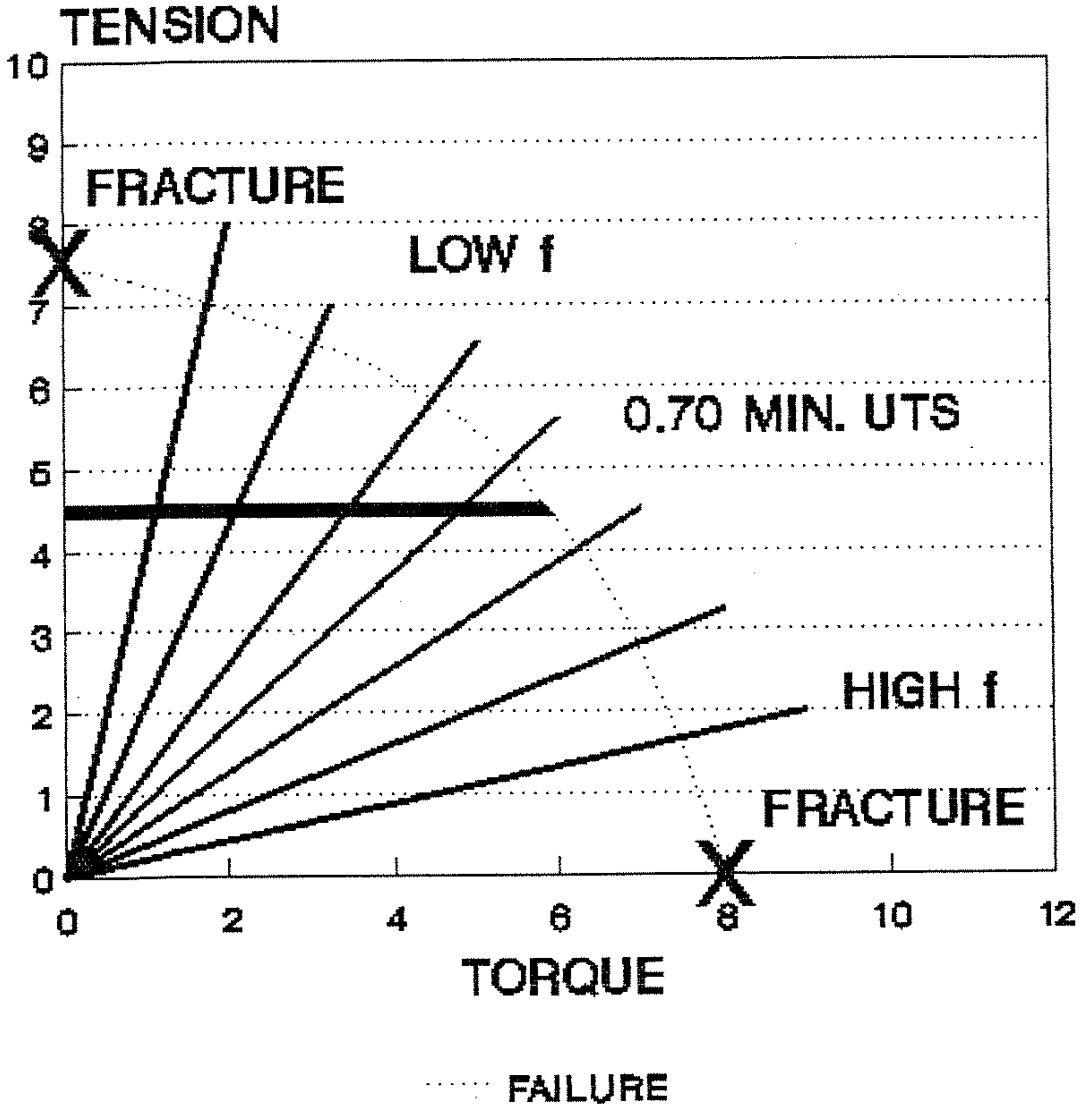


FIGURE 16

AVOID TORQUE BY USING DTI'S

- THEY'RE THE SIMPLEST METHOD OF ASSURING BOLT PRELOAD.

FIGURE 17

PRELOADS ACHIEVED (IN LABORATORY)

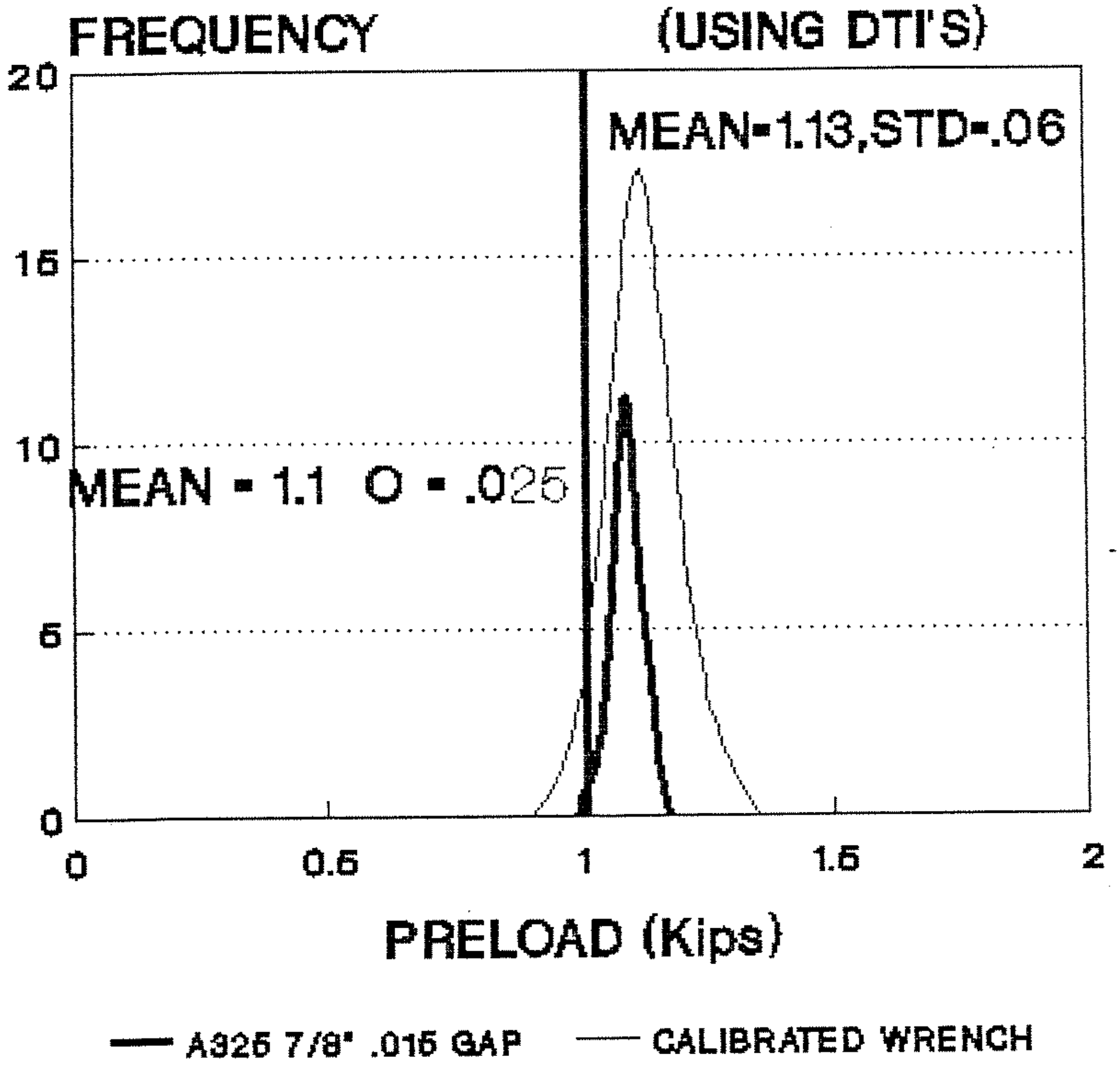


FIGURE 18

J. & M. TURNER INC.
JUNE 1990

PRELOADS ACHIEVED (IN THE FIELD)

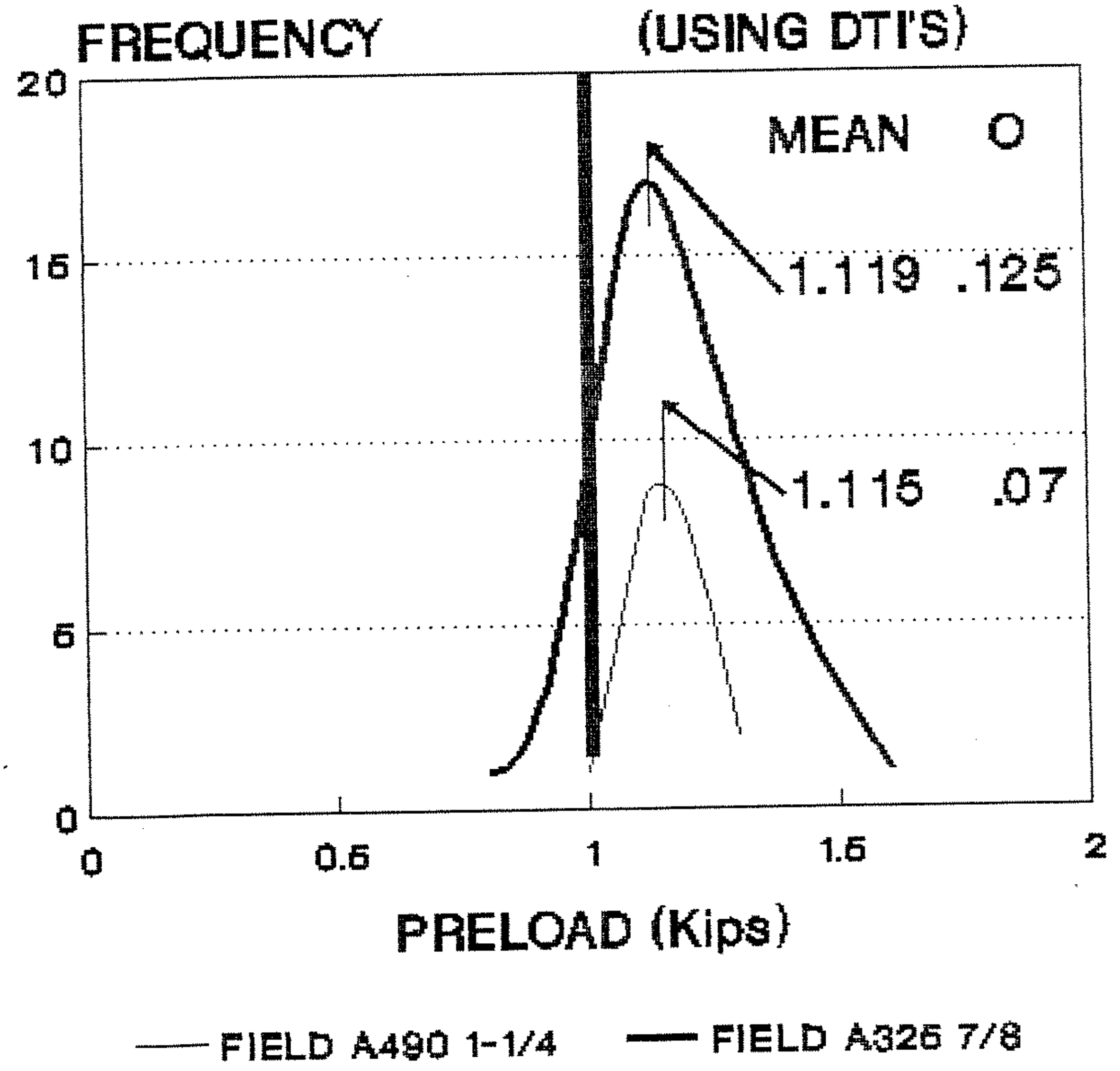


FIGURE 19

McMASTER UNIVERSITY
TORONTO UNIVERSITY

DTI'S COMPRESS JUST OVER THE MINIMUM

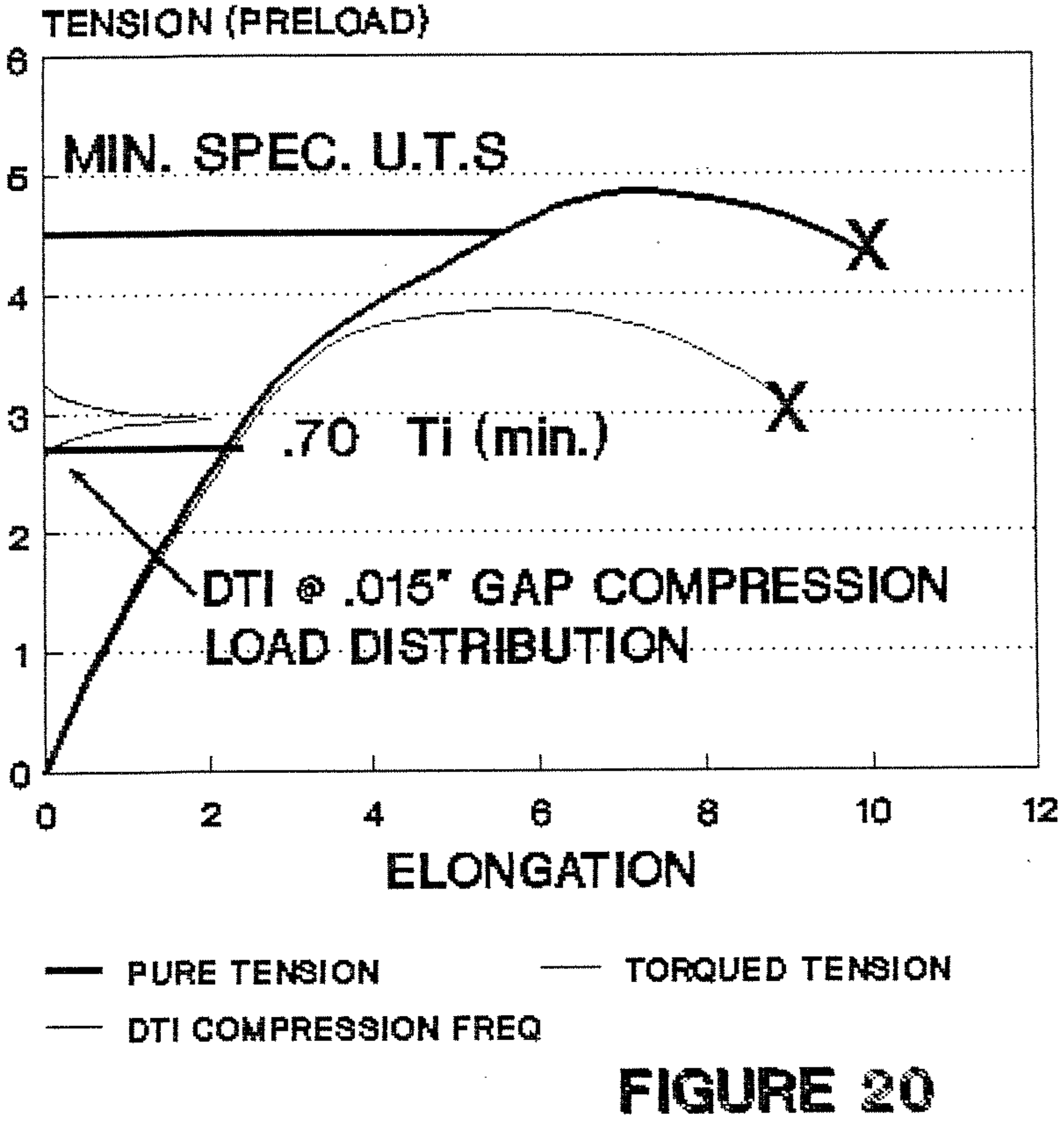


FIGURE 20

ONCE THE TORQUE IS REMOVED, THE BOLT WILL BE CAPABLE OF THE MINIMUM UTS IN PURE TENSION

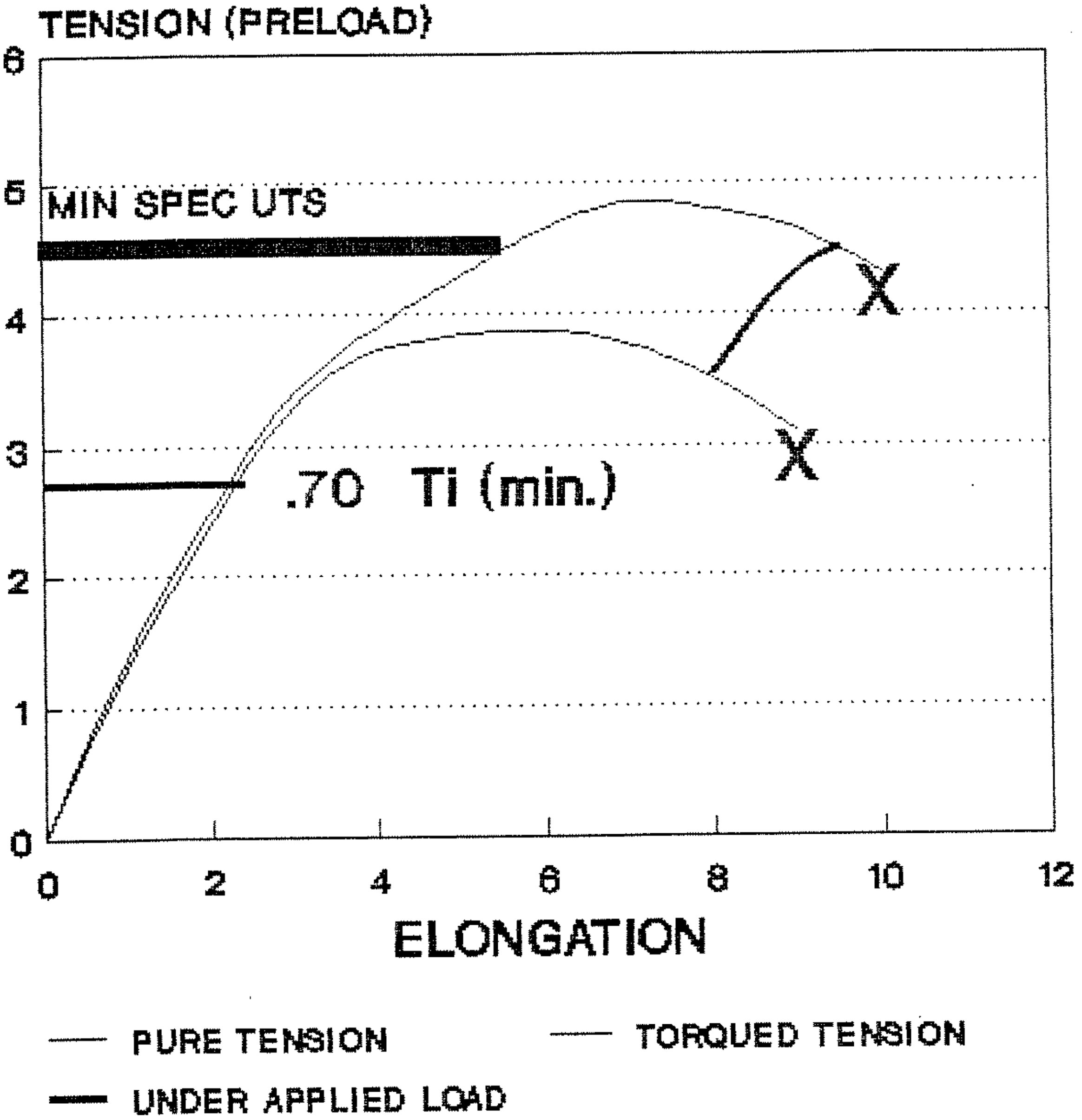


FIGURE 21