STATIC AND DYNAMIC PROPERTIES OF ANCHOR BOLTS FOR SIGN SUPPORTS

MICHIGAN DEPARTMENT OF TRANSPORTATION

MATERIALS and TECHNOLOGY DIVISION

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STATIC AND DYNAMIC PROPERTIES OF ANCHOR BOLTS FOR SIGN SUPPORTS

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Summary

Brief background information is presented concerning anchor bolt failures that have occurred in cantilever sign structures, along with some of the reasons suspected to be the cause of these failures. Objectives of this investigation were as follows: 1) to determine the effect of galvanizing on the fatigue life of typical anchor bolts; 2) to determine the effect of nut engagement on the static strength of typical anchor bolt assemblies; and, 3) to determine the effect of closeness of fit of the nut and bolt on the static strength of selected bolt-nut combinations. Static loading tests were performed on approximately 30 galvanized nut and bolt combinations in each of two sizes (1-1/2-in. and 2-in. diameter) for the purpose of determining the effect of nut engagement and closeness of fit. Fatigue evaluations were performed on groups of five bolts each from two different lots of steel in the 1-1/2-in. size, from each lot of steel five bolts were evaluated galvanized as purchased, and five bolts were stripped of galvanizing prior to fatigue testing. An additional batch of ten 2-in. diameter bolts was evaluated for fatigue life in two groups of five each, one group was galvanized as purchased and the other group was plain steel never having been galvanized but made from the same bar stock as the galvanized group. Two additional 2-in. samples were fatigue tested at a reduced load range. Thread interference information was obtained for many bolt-nut combinations from different suppliers. Nondestructive evaluations were performed with ultrasonic equipment and it was determined that fatigue cracks greater than 1/4 in. in size could easily be detected. Results of fatigue experiments showed that galvanizing dramatically reduced the fatigue life of anchor bolts and that thread root configurations can also affect fatigue life. Static test results showed that nut engagement should be at least equal to the diameter of the bolt plus 1/4 in. in order to develop the strength of the bolt and that variation of thread interference (closeness of fit) encountered in this experiment, all within specified tolerances, did not adversely affect the strength of the assemblies.

Conclusions based on experiments performed are: 1) galvanizing reduced the fatigue life of anchor bolts; 2) all bolts evaluated failed to meet specified requirements; 3) bolts obtained from the MDOT warehouse had unusually low fatigue lives; 4) the amount of nut engagement is an important factor in determining the static strength of the anchorage; and, 5) ultrasonic testing was found to be capable of finding fatigue cracks in the anchor bolts, even at relatively small crack sizes.

Initiation of the Investigation

There has been a series of failures of anchor bolts for cantilever sign supports. Some of these failures have resulted in the collapse of sign structures onto the roadway where vehicles have been damaged. There is evidence that initial bolt failures have been caused by fatigue after nuts had loosened under vibration of the structure, or after bolts had been reduced in section by long-term corrosion.

There also have been indications that some of the contractors do not fully understand the physical situations involved, where bolts have been cast in foundations in the wrong place or with too little projection. This has resulted in anchoring the support on bent anchor bolts or on anchor bolts with very little nut engagement. Although failures may not have occurred in such cases, it is obvious that the design capacity was not achieved. Also, the intended distribution of load was not being attained in many cases.

Previous research by others indicated that under some conditions, galvanizing had reduced the fatigue strength of structural parts. Since threaded fasteners have rather severe stress concentrations at the thread root, they are probable candidates for the occurrence of problems, if such fatigue strength reductions exist.

Also, it is known that wind blast from trucks, wind gusts, and vortex shedding cause dynamic loading and vibrations of the heavy cantilever structures. The type of loading at the anchorage is a complex combination of torsional and vertical loads; no known experimental measurements have been made to determine the dynamic effects of these complex loadings, or of the vibrational inertia of the huge structure.

Confirmation of, and solutions to these problems were needed; and therefore, this investigation was initiated. Effects of closeness of fit on static and fatigue strength also were considered.

Objectives

1. To determine the effect of galvanizing on the fatigue life of typical anchor bolts.

2. To determine the effect of nut engagement on the static strength of typical anchor bolt assemblies.

3. To determine the effect of closeness of fit of the nut and bolt on the static strength of selected bolt-nut combinations.

Scope

Seventy bolts and nuts with washers were purchased for this evaluation from a Michigan supplier. Fifty-five of these bolts were 2-in. in size, with 40 of them galvanized and 15 ungalvanized, all made from the same steel bar stock. Fifteen additional bolts from the same supplier were 1-1/2-in. in diameter and were galvanized. Forty 1-1/2-in. bolts also were obtained from regular stock at the MDOT warehouse to check those typically used for installations by MDOT forces, and to add a variable of steel batch and supplier. Twelve 2-in. hex head nuts, nongalvanized (and therefore not retapped oversize) were acquired from a local hardware dealer.

Static tests with variable nut engagement and fatigue evaluations were done.

Procedure

Testing for Fatigue Life - The Material Testing System in the Structural Research Laboratory was used to load the specimens cyclically as shown in Figure 1. Special loading fixtures, as shown, were built by the Laboratory's Machine Shop. Ten of the specially purchased 1-1/2-in. anchor bolt assemblies were separated into two groups of five. The first group was evaluated as galvanized, while the second group had the galvanizing chemically removed from the threads. Ten bolt assemblies from the Transportation warehouse were evaluated in the same manner. The load range for all 1-1/2-in. bolts was +34,000 lb (tension) to -13,000 lb (compression).

Twelve of the specially purchased 2-in. bolt assemblies were divided into two groups of five and one group of two. One group of five was fully galvanized (bolts and nuts) while the other five bolts made from the same steel but ungalvanized were fitted with galvanized nuts. These two groups were cyclically loaded to the full design range, from +47,000 lb (tension) to -11,000 lb (compression). The other two bolts were fully galvanized but they were tested at a load range of +35,000 lb to -8,000 lb which is 75 percent of design load. Only two bolts were evaluated at 75 percent of design load due to lack of specimens and because of equipment failure.

Testing for Effects of Nut Engagement - Thirty 1-1/2-in. galvanized bolt assemblies from the MDOT warehouse were divided into groups of five and were tested at six different amounts of nut engagement ranging from 1/4d to 2d where d is the nominal diameter of the bolt. The bolts were loaded statically to failure on the Tinius Olsen Universal testing machine.

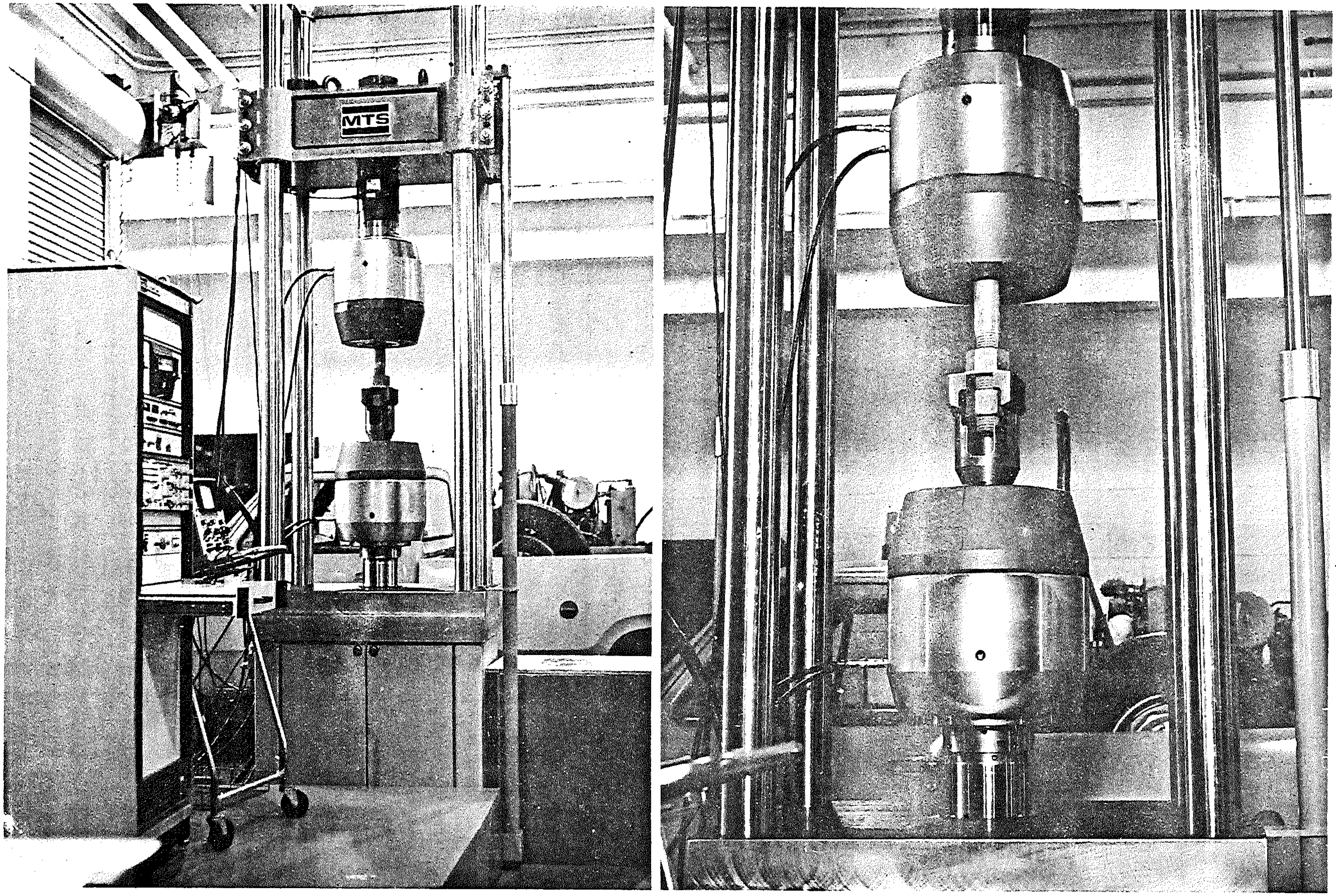


Figure 1. Cyclic testing of samples in the MTS 200 kip capacity load frame.

Thirty specially purchased 2-in. galvanized bolt assemblies were also divided into six groups of five each for static evaluation. Within each group, two assemblies were included that contained ungalvanized nuts. The ungalvanized nuts were used to evaluate the effect of the additional thread interference provided by nuts that had not been tapped oversize. Specifications for galvanized bolts require the nuts to be tapped oversize to obtain sufficient clearance in the threads to allow ease of assembly. The bolt assemblies were then tested to failure in the Testing Laboratory's 600 kip Universal testing machine, and the load recorded along with the type of failure; nut engagement and thread interference were measured and recorded. Only two assemblies were evaluated at 2d engagement since it had already been determined that lesser amounts of engagement would, in all cases, develop the strength of the bolt.

<u>Testing for Effects of Closeness of Fit</u> - Every bolt assembly that was used in the aforementioned tests was measured prior to testing, for closeness of fit or thread interference. The value for thread interference is derived by subtracting the minor diameter of the nut from the major diameter of the bolt. Each value represents the average of measurements at three different locations along the threads. (See Figure 2 for typical measurement.)

Amount of thread interference = major diameter of bolts - minor diameter of nut

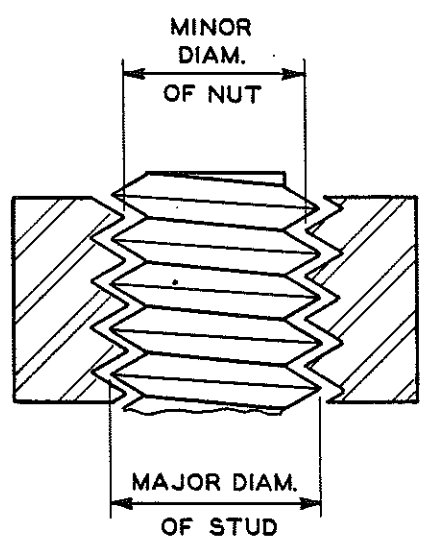


Figure 2. Method of determining thread interference.

The amount of thread interference for each bolt-nut assembly is shown in the tables.

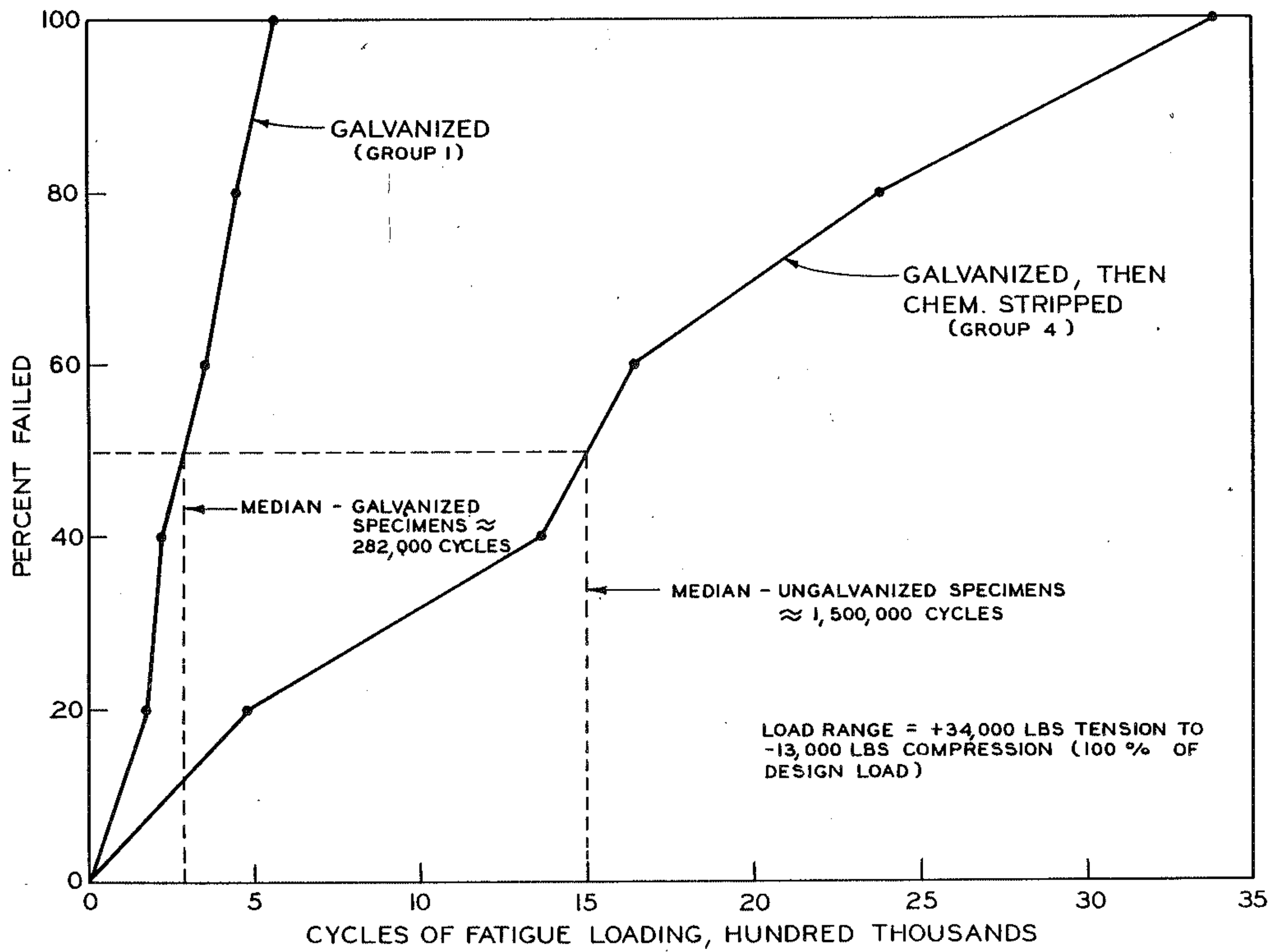


Figure 3. Result of fatigue tests, Groups 1 and 2 (1-1/2-in. bolts specially purchased).

Nondestructive Evaluation

Ultrasonic nondestructive evaluation equipment was used to check specimens for fatigue cracks, and it was found that cracks greater than 1/4 in. in size could be detected quite easily.

Results

Fatigue Experiments - The first test here involved 10 each 1-1/2-in. bolt assemblies. The galvanizing was removed from five of these assemblies and five remained galvanized. The cyclic stresses used were 100 percent of design live load and the samples used for each group were selected at random from a total of 15 bolts. The results, recorded in Table 1 and shown graphically in Figure 3, indicate that removing the galvanizing increased the number of cycles to failure by about five times, based on either the average or the median. Only one bolt assembly from the ungalvanized group failed at less than 1,300,000 cycles of stress, while the longest lived bolt in the galvanized group failed at 565,000 cycles (Table 1, Groups 1 and 2, and Fig. 3).

Ten galvanized bolt assemblies were then randomly selected from the MDOT warehouse, and the galvanizing removed from five of them. They were then subjected to the same loading as the aforementioned bolts. Results are shown in Table 1 (Groups 3 and 4) and in Figure 4.

Changes in life weren't so dramatic as in the previous case. The bolts with the galvanizing removed proved to be about 1.8 times longer lived based on the average but more than 3.5 times based on the median. Two of the galvanized bolts performed as well as some of the plain bolts. However, note the difference in horizontal scale on Figure 4 as compared to Figure 3. Notice that even the galvanized then stripped specimens from the warehouse lasted not even as long as the galvanized specimens specially purchased. Fatigue life is very poor for these bolts, whether galvanized or not. An examination of the thread profile on the bolts obtained from the warehouse revealed that the root of the thread had a shape with a flat bottom and quite sharp corners on each side, while the specially purchased bolts had a round bottomed shape. This may help explain the relatively short lives of even the ungalvanized specimens shown in Figure 4, since sharper notches tend to concentrate load and initiate earlier fatigue failures. The sharp notch configuration is one that may be encountered in any supply of bolts. It is permissible, by industry standards, to allow a sharp cornered notch thread form on new tools. As the tool wears, the sharp notches become rounded thus resulting in round bottomed shaped threads. There also may be differences in the metallurgical structure of the steel, but this was not investigated.

TABLE 1
RESULTS OF FATIGUE EVALUATION

Source	Group	Sample No.	Sample Type	Sample Size, in.	Load Range, lb	Number of Cycles to Failure	Location and Type of Failure
Specially Purchased	Group 1	10B	Galvanized	1-1/2	+34,000 to -13,000	183,190	Failure at top of lower nut
		12B	Galvanized	1-1/2	+34,000 to -13,000	221,410	Failure at top of lower nut
		9B	Galvanized	1-1/2	+34,000 to -13,000	564,670	Failure at top of upper nut
		3B	Galvanized	1-1/2	+34,000 to -13,000	350,610	Failure at two threads above upper nut
		5B	Galvanized	1-1/2	+34,000 to -13,000	459,200	Failure within lower nut. Unusual multiplane fracture.
					Avg =	355,816	
	Group 2	8B	Galvanizing removed	1-1/2	+34,000 to -13,000	2,381,050	Failure at one thread into upper nut
		6B	Galvanizing removed	1-1/2	+34,000 to -13,000	1,641,000	Failure at one thread above upper nut
		1B	Galvanizing removed	1-1/2	+34,000 to -13,000	3,389,550	Failure at upper grip lower edge
		7B	Galvanizing removed	1-1/2	+34,000 to -13,000	1,358,420	Failure at one thread above upper nut
		11B	Galvanizing removed	1-1/2	+34,000 to -13,000	487,400	Failure at one thread above upper nut
					Avg =	1,851,484	
From MDOT Warehouse	Group 3	38	Galvanized	1-1/2	+34,000 to -13,000	80,970	Failed at 15th thread from threaded end
		32	Galvanized	1-1/2	+34,000 to -13,000	53,090	Failed at 15th thread from end, cup shaped fracture
		35	Galvanized	1-1/2	+34,000 to -13,000	77,100	Failed at 15th thread from end
		39	Galvanized	1-1/2	+34,000 to -13,000	317,820	Failed at 15th thread from end
		36	Galvanized	1-1/2	+34,000 to -13,000	251,620	Failed at 13th thread from end, cup shaped fracture
					Avg =	156,120	
	Group 4	41	Galvanizing removed	1-1/2	+34,000 to -13,000	354,120	Failed at top of lower nut
		34	Galvanizing removed	1-1/2	+34,000 to -13,000	288,450	Failed at top of lower nut
		37	Galvanizing removed	1-1/2	+34,000 to -13,000	267,040	Removed specimen and performed U.T. inspection. Fatigue cracks were evident
		40	Galvanizing removed	1-1/2	+34,000 to -13,000	158,570	Failed at top of lower nut
		33	Galvanizing removed	1-1/2	+34,000 to -13,000	368,840	Failed at top of lower nut
					Avg =	287,404	

TABLE 1 (Cont.)
RESULTS OF FATIGUE EVALUATION

		Sample No.	Sample Type	Sample Size, in.	Load Range, lb	Number of Cycles to Failure	Location and Type of Failure
Specially Purchased	Group 5	1Z	Plain stud, galvanized nut	2	+47,000 to -11,000	825,700	Double plane fracture, 13th and 14th threads from end of stud
		2Z	Plain stud, galvanized nut	2	+47,000 to -11,000	851,170	Double plane fracture, 12th and 13th threads from end of stud
		7Z	Plain stud, galvanized nut	2	+47,000 to -11,000	2,276,920	Single plane fracture, last full thread of stud at shaft
		11Z	Plain stud, galvanized nut	2	+47,000 to -11,000	3,240,420	Double plane fracture, 12th and 14th threads from end of stud
		12Z	Plain stud, galvanized nut	2	+47,000 to -11,000	3,317,690	Single plane fracture, 11 threads from end of stud
					Avg =	2,102,380	
	Group 6	7A	Galvanized	2	+47,000 to -11,000	520,910	Failure at 14 threads from end, cup type fracture
		5A	Galvanized	2	+47,000 to -11,000	260,660	Failure at 5 threads from start of threads
		6A	Galvanized	2	+47,000 to -11,000	277,200	Failure at 14 threads from start of threads
		20A	Galvanized	2	+47,000 to -11,000	241,450	Failure at 9 threads from start of threads
		18A	Galvanized	2	+47,000 to -11,000	1,768,360	Multiple plane fractures between 13th and 16th threads from end
					Avg =	613,716	
	Group 7	35A	Galvanized	2	+35,000 to - 8,000*	3,188,287	Not taken to failure
		36A	Galvanized	2	+35,000 to - 8,000*	3,000,000	Not taken to total failure. U.T. revealed fatigue failure through 3/4 of the diameter of the bolt

* Load range = 75 percent of design load.

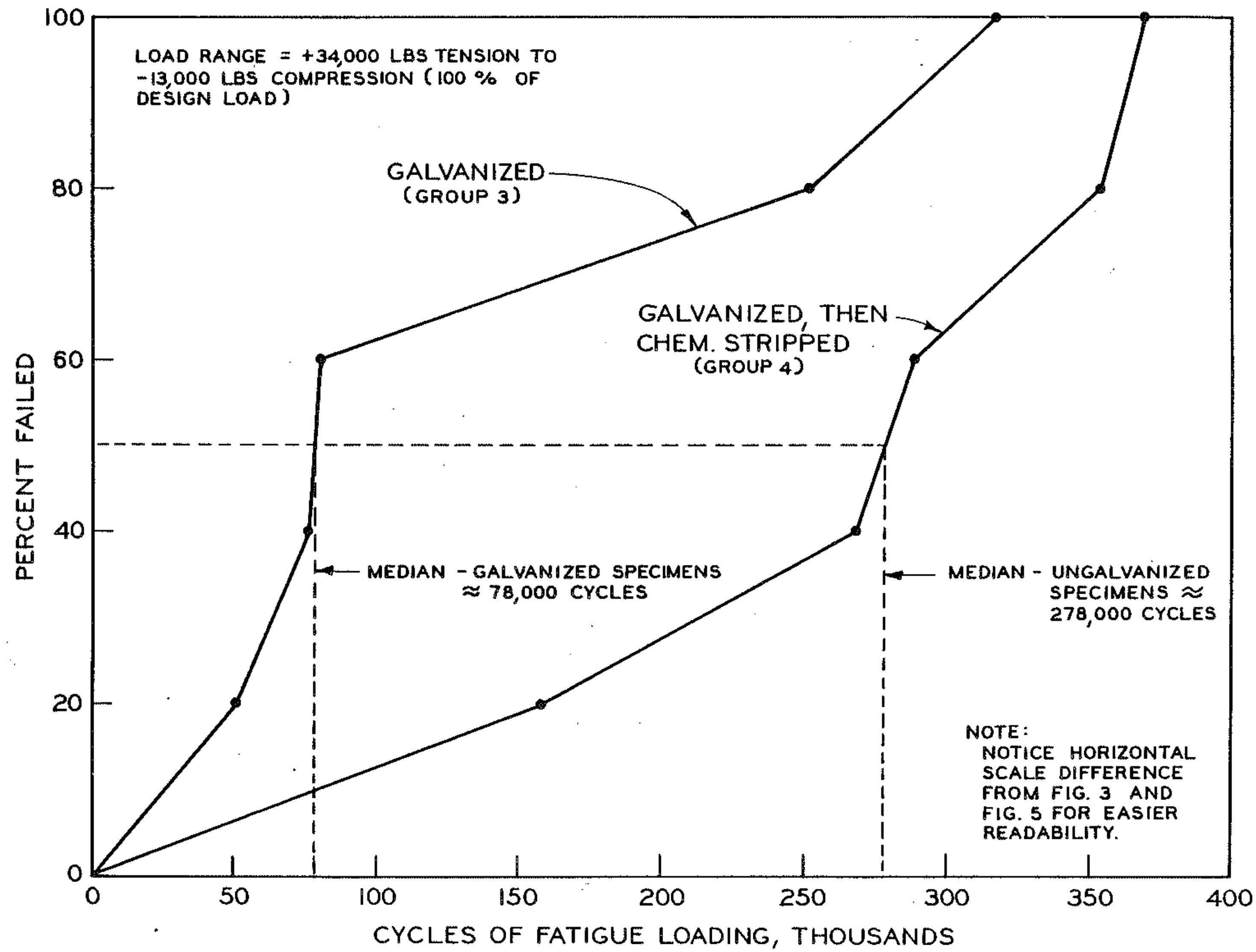


Figure 4. Result of fatigue tests, Groups 3 and 4 (1-1/2-in. bolts from MDOT warehouse).

Ten 2-in. bolt assemblies were then tested from the samples specially acquired for this evaluation; all fabricated from the same lot of steel. Five of these bolts were tested with galvanizing in place. The other five were tested using galvanized nuts with oversize tap, but with the bolt never having been galvanized. The assemblies were loaded through a range of +47,000 lb to -11,000 lb which represents 100 percent of the design load. Results are shown in Table 1 (Groups 5 and 6) and in Figure 5. Here again, the results indicate a dramatic difference in fatigue strength. Ungalvanized specimens lasted about three times as long based on the average; and nearly six times as long based on the median.

Based on results to this point, it was decided to use the remaining specimens to determine the effect of a reduction in stress on the life of the galvanized bolts. Loading for these galvanized specimens was reduced to about 75 percent of that used for all other specimens of the same size (see Table 1, Group 7, and upper right hand corner of Fig. 5). One specimen was found to have fatigue cracks through about three-quarters of its diameter at slightly above three million cycles. The second specimen was still without significant cracking at about 3-1/4 million cycles when it was inadvertently overloaded, and was removed from further evaluation. The loading fixture fractured, early in the life of the next specimen, ending the tests. Since there was no more experimentation to be done in addition to this series, the fixture was not rebuilt and the loading program was terminated. Thus, the final specimen evaluated had an indeterminate life, somewhere above 3-1/4 million cycles.

Discussion

Notwithstanding the variance in the results obtained from the MDOT warehouse bolts, the evidence would definitely indicate that galvanizing dramatically decreases the fatigue life in bolt-nut assemblies. Analysis of the results by the Statistical Analysis Unit indicated that the reductions are statistically significant at the 95 percent confidence limit. They also noted that for fatigue life data such as these, the median values are better estimates of the life than are the average values.

From a first consideration of the subject, some have concluded that the changes in the fatigue life were due to the heat of the galvanizing cycle. However, while some of the above bolts had never been galvanized, others were initially galvanized and then had the galvanizing stripped from half the specimens. These stripped specimens had lives about equivalent to specimens never galvanized, evidently confirming that the fatigue life reduction was a direct result of the coating itself.

A recent report furnished to us by the American Hot Dip Galvanizers Association gives details of related research done in England. The conclusion was that fatigue cracks initiated in the 'delta' iron-zinc alloy layer

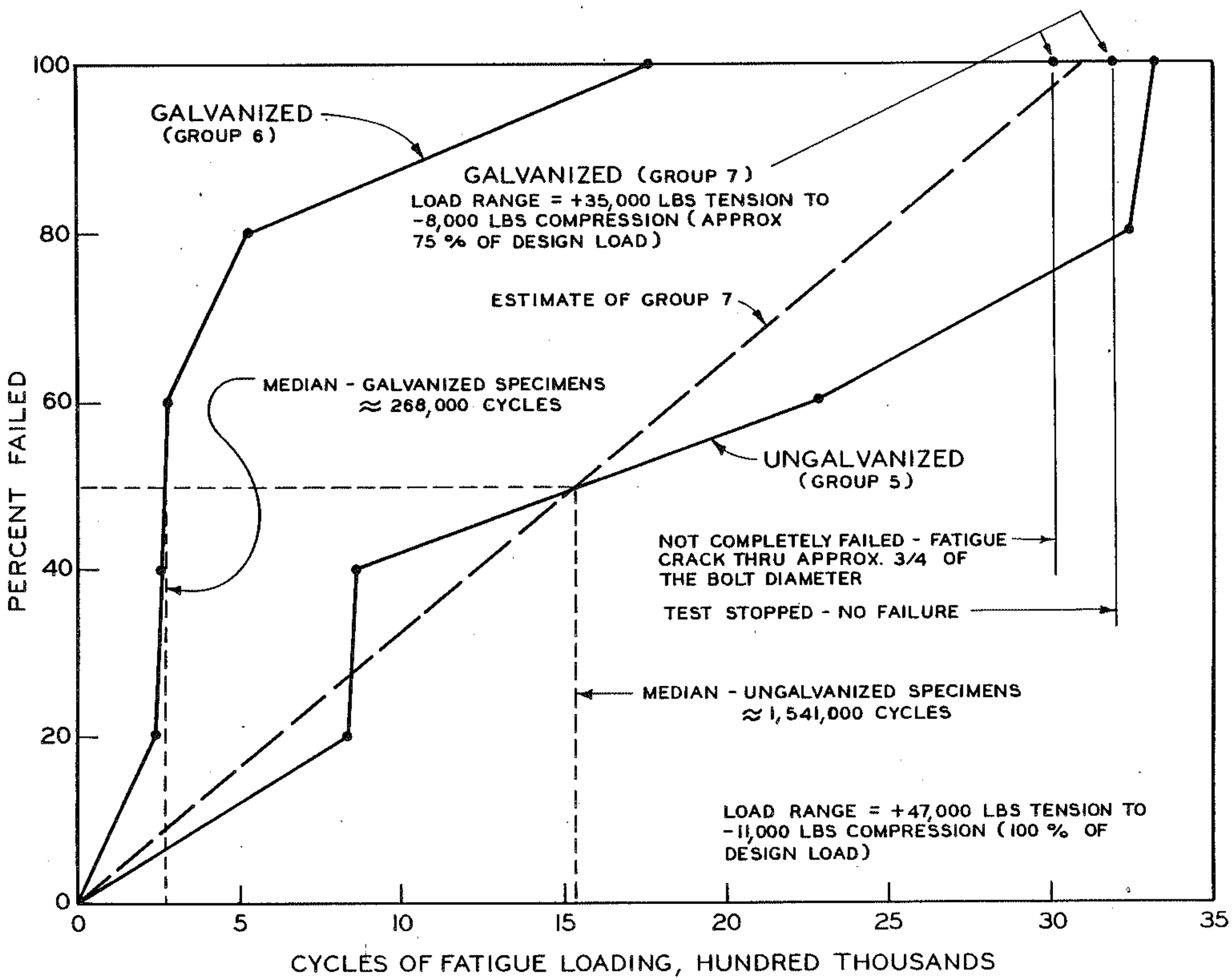


Figure 5. Result of fatigue tests, Groups 5 and 6 (2-in. bolts specially purchased).

and propagated both inward and outward. Sometimes the cracks stopped at the steel interface, but in other cases they went on into the steel and initiated a fatigue fracture. If we accept this conclusion, it could explain the variation in results we obtained when testing the galvanized versus ungalvanized specimens. Whatever the specific cause, it is obvious that removing the galvanizing from the studs greatly increases the fatigue life of the bolt assemblies and brings them in line with those specimens never having been galvanized. It should also be noted here, however, that when two 2-in. galvanized bolt assemblies were fatigue tested at 75 percent of design load they exhibited much higher fatigue life. This would seem to indicate that galvanized fasteners should have a lower design stress than ungalvanized. The 25 percent reduction tried here on a small number of samples brought the fatigue life up to approximately the same level as for ungalvanized fasteners at full design stress. The extremely small sample size prevents accurate conclusions, but it is well known that stress reductions increase fatigue life and the results are in line with expectations based on previous experience.

Previous results also have shown, as should be expected, that corrosive attack also reduces fatigue life. Therefore, it seems reasonable, in highly corrosive locations like anchor bolts for highway signs or light standards, to use galvanized fasteners with reduced design loads until such time as more adequate treatments may become available. A recently developed stainless clad steel bar, or some similar device may provide a better solution in the long run.

Nut Engagement - Table 2 shows the results of static tension tests performed on specimens with different degrees of nut engagement, ranging from one quarter the bolt diameter to twice the bolt diameter. The results are similar regardless of the size of bolt or whether or not the nut is galvanized. These results, shown graphically in Figure 6, clearly show that for the limited sample of material properties and thread engagements evaluated, over 90 percent of the capacity of the bolt-nut connection is developed when the nut engagement reaches three-quarters of the bolt diameter. The rate of increase in capacity is greatly reduced above the 3/4d engagement although an increase is always experienced from 3/4d to 1d. The aforementioned conclusion is further evidenced when the type of failure is considered at each engagement. All of the failures below the nut engagement of 3/4d were thread failures; whereas, failures of the bolt began to occur at 3/4d and above (Table 2). The results of these tests would then indicate that the amount of nut engagement should definitely be a consideration, as would be expected. Nut engagement should not be less than 1d. It should also be noted here that while the ultimate strength of these bolts was specified to be 85,000 psi, with 50,000 psi yield strength, in no case did a tested bolt meet both specified strength requirements. Physical properties of the steel used in the anchor bolts are given in Table 3.

TABLE 2
STATIC TEST RESULTS

Source	Group	Sample No.	Sample Size, in.	Nut Engagement (d = bolt dia.)	Thread Interference	Ultimate Load, lb	Remarks
From MDOT Warehouse	Group 8	1	1-1/2	1/4d	0.107	35,000	Failure of stud threads
		2	1-1/2	1/4d	0.101	37,500	Failure of stud threads
		3	1-1/2	1/4d	0.109	33,000	Failure of stud threads
		4	1-1/2	1/4d	0.101	33,500	Failure of stud threads
		5	1-1/2	1/4d	0.104	29,000	Failure of threads from stud and nut
		6	1-1/2	1/2d	0.103	57,250	Failure of stud threads
		7	1-1/2	1/2d	0.106	63,000	Failure of stud threads
		8	1-1/2	1/2d	0.106	63,250	Failure of stud threads
		9	1-1/2	1/2d	0.108	59,250	Failure of stud threads
		10	1-1/2	1/2d	0.107	67,000	Failure of stud threads
		11	1-1/2	3/4d	0.105	77,250	Failure of stud
		12	1-1/2	3/4d	0.112	75,250	Failure of stud
		13	1-1/2	3/4d	0.105	77,500	Failure of stud
		14	1-1/2	3/4d	0.106	75,000	Failure of stud threads
		15	1-1/2	3/4d	0.107	77,000	Failure of stud threads
		16	1-1/2	1d	0.096	76,250	Failure of stud
		17	1-1/2	1d	0.097	76,750	Failure of stud
		18	1-1/2	1d	0.103	79,000	Failure of stud threads
		19	1-1/2	1d	0.104	76,000	Failure of stud
		20	1-1/2	1d	0.100	77,250	Failure of stud
		21	1-1/2	1-1/2d	0.096	76,000	Failure of stud threads
		22	1-1/2	1-1/2d	0.107	77,000	Failure of stud
		23	1-1/2	1-1/2d	0.100	77,250	Failure of stud
		24	1-1/2	1-1/2d	0.106	77,000	Failure of stud
		25	1-1/2	1-1/2d	0.105	77,500	Failure of stud
		26	1-1/2	2d	0.106	78,500	Failure of stud
		27	1-1/2	2d	0.104	81,000	Failure of stud
		28	1-1/2	2d	0.094	78,250	Failure of stud threads
		29	1-1/2	2d	0.110	76,000	Failure of stud
		30	1-1/2	2d	0.100	78,000	Failure of stud threads
Specially Purchased	Group 9	39A Stud 39A Nut	2	1/4d	0.142	70,500	Failure of stud threads
		30A Stud 30A Nut	2	1/4d	0.150	78,300	Failure of stud threads
		38A Stud 38A Nut	2	1/4d	0.147	72,300	Failure of stud threads
		29A Stud 12K Nut	2	1/4d	0.204	78,300	Failure of stud threads
		14A Stud 4K Nut	2	1/4d	0.187	72,300	Failure of stud threads
		37A Stud 37A Nut	2	1/2d	0.149	137,000	Failure of stud threads
		34A Stud 34A Nut	2	1/2d	0.155	144,400	Failure of stud threads
		33A Stud 33A Nut	2	1/2d	0.144	122,100	Failure of stud threads
		26A Stud 9K Nut	2	1/2d	0.188	143,200	Failure of stud threads
		28A Stud 6K Nut	2	1/2d	0.190	138,600	Failure of stud threads

TABLE 2 (Cont.)
STATIC TEST RESULTS

		Sample No.	Sample Size, in.	Nut Engagement (d = bolt dia.)	Thread Interference	Ultimate Load, lb	Remarks
Specially Purchased	Group 9 (Cont.)	12A Stud 12A Nut	2	3/4d	0.154	177,300	Failure of stud threads
		13A Stud 13A Nut	2	3/4d	0.156	180,800	Failure of stud threads
		23A Stud 23A Nut	2	3/4d	0.162	175,100	Failure of stud threads
		27A Stud 8K Nut	2	3/4d	0.188	178,900	Failure of stud threads
		4A Stud 3K Nut	2	3/4d	0.189	181,700	Failure of stud
		11A Stud 11A Nut	2	1d	0.152	179,100	Failure of stud
		22A Stud 22A Nut	2	1d	0.164	184,000	Failure of stud
		25A Stud 25A Nut	2	1d	0.160	183,300	Failure of stud
		3A Stud 10K Nut	2	1d	0.200	179,600	Failure of stud
		15A Stud 2K Nut	2	1d	0.193	182,900	Failure of stud
		24A Stud 24A Nut	2	1-1/2d	0.149	181,700	Failure of stud
		9A Stud 9A Nut	2	1-1/2d	0.162	183,500	Failure of stud
		10A Stud 10A Nut	2	1-1/2d	0.152	182,200	Failure of stud
		2A Stud 11K Nut	2	1-1/2d	0.194	181,700	Failure of stud
		40A Stud 7K Nut	2	1-1/2d	0.193	181,200	Failure of stud
		21A Stud 21A Nut	2	2d	0.162	187,200	Failure of stud
		8A Stud 8A Nut	2	2d	0.159	183,000	Failure of stud

NOTE: A designates galvanized, K designates nongalvanized.

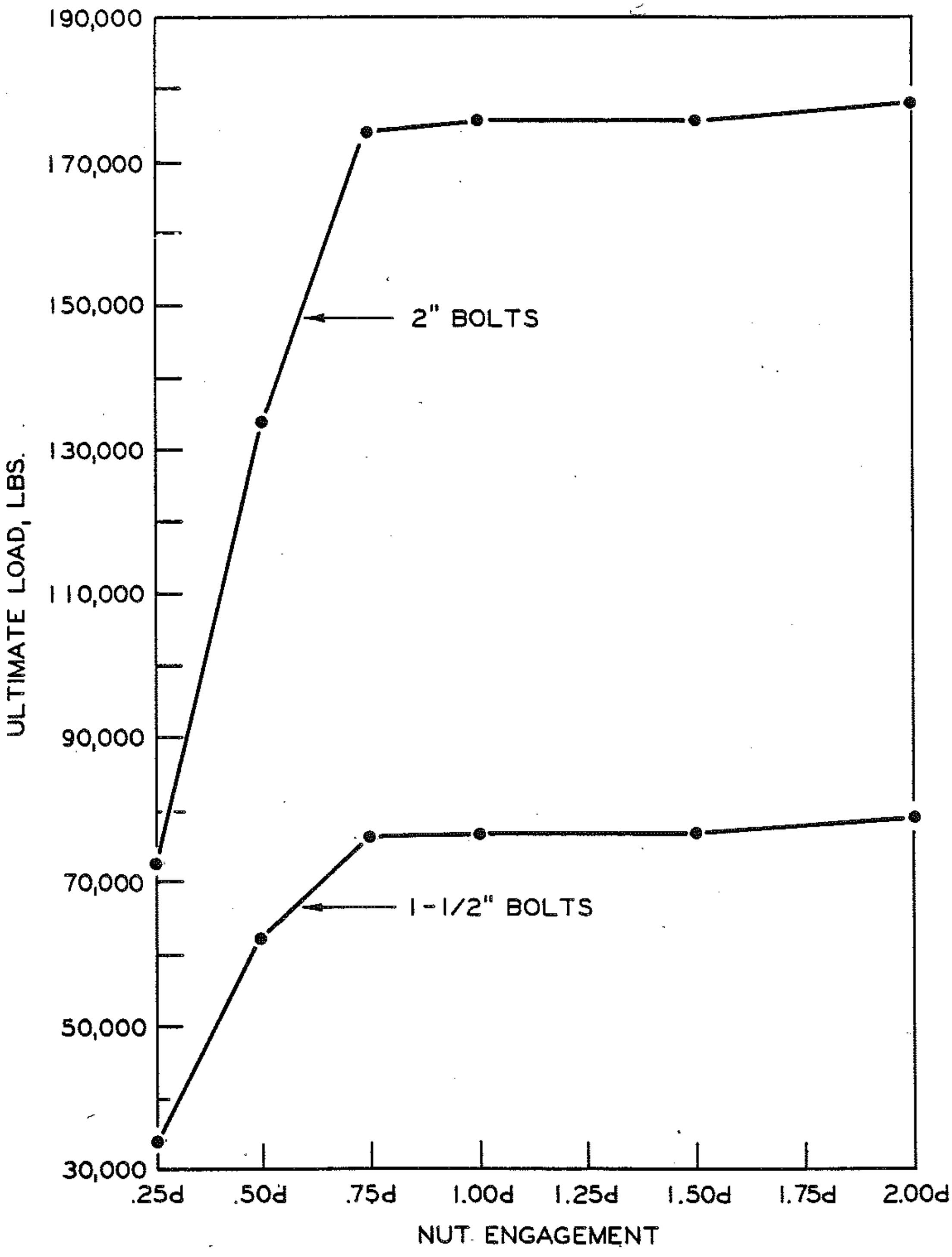


Figure 6. Variation of strength with nut engagement.

TABLE 3
PHYSICAL PROPERTIES OF STEEL
USED IN ANCHOR BOLTS

Specimen No.	Bolt Diameter, in.	Source of Bolt	Specimen Type*	Yield Point, psi	Ultimate Strength, psi	Elongation, percent
1	2	Specially Purchased	Full Size	44,600	71,500	27
2	2	Specially Purchased	Full Size	45,900	72,000	27
3	2	Specially Purchased	Reduced Section 0.505 in. Diameter	44,500	72,000	33
4	2	Specially Purchased	Reduced Section 0.505 in. Diameter	44,000	71,000	35
5	1-1/2	Specially Purchased	Reduced Section 0.505 in. Diameter	51,000	81,500	30
6	1-1/2	Specially Purchased	Reduced Section 0.505 in. Diameter	50,500	81,500	30
7	1-1/2	MDOT Warehouse	Full Size	48,600	77,500	30
8	1-1/2	MDOT Warehouse	Full Size	48,800	77,500	30

NOTE: Specification requirements are: yield point, 50,000 psi minimum; ultimate strength, 85,000 psi minimum; and elongation, 12 percent minimum.

* Full size specimens were from shank portion of bolt and 8 in. gage length. Reduced section specimens, 2 in. gage length.

Closeness of Fit - The closeness of fit or amount of thread interference was measured for all bolts tested as indicated in Table 2. The tolerances specified for this application were compared to values measured in the experiment, and it was found that the thread sizes are within the specified limits, but shifted within those limits toward the low side of thread interference. The amount of interference for the 1-1/2-in. bolt-nut combination ranged from 0.096 in. to 0.112 in. which is only a range of 0.016 in. and likely would not influence the results. The amount of thread interference on the 2-in. bolts ranged from 0.142 in. to 0.164 in. (0.022 in. range) for the galvanized bolt and nut combinations, and from 0.187 in. to 0.204 in. (0.017 in. range) for the galvanized bolt and plain unretapped nut combinations. ("K" series nuts are plain unretapped nuts.) These values are all indicated in Tables 1 and 2. Since we have figures on the closeness of fit for all specimens, we can easily check the groups tested where the type of failure was predictable and any change in the results due to lack of thread interference would be identifiable.

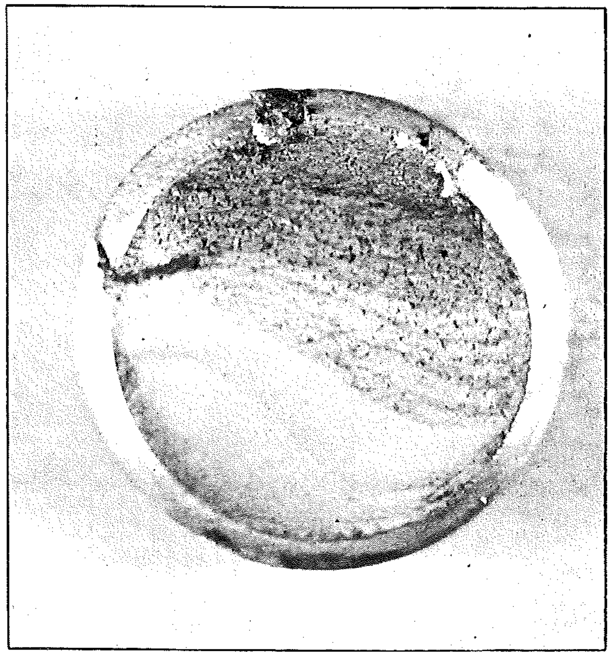
A review of the results indicates that the small amount of variation in thread interference does not appear to be a significant factor in the failures that occurred. This does not mean that thread interference is unimportant, but rather that all bolt-nut combinations evaluated had sufficient interference to develop the strengths required of this type of fastener.

Appearance of Fracture in Fatigue

Typical examples of the fracture surfaces of the fatigue specimens are shown in Figure 7, showing evidence of the progression of the fatigue crack across the face and the resulting total failure with very little plastic deformation of the bolt. Static tests (not illustrated) give an entirely different type of failure, where large deformations, distortion of the threads, and considerable reductions in area occur. These, of course, are the result of overload to failure in one single, slowly applied cycle of loading; while the fatigue failures result from thousands or millions of applications of significantly lower loads.

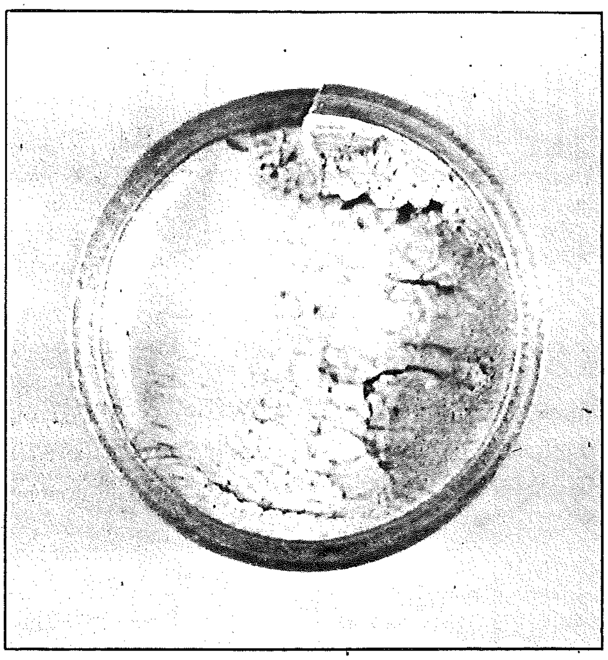
The fatigue fracture faces shown in Figure 7, also are typical of the failures that have occurred on actual structures in the field.

Group 2, No. 7B



Group 4, No. 34

Group 2, No. 8B



Group 4, No. 41

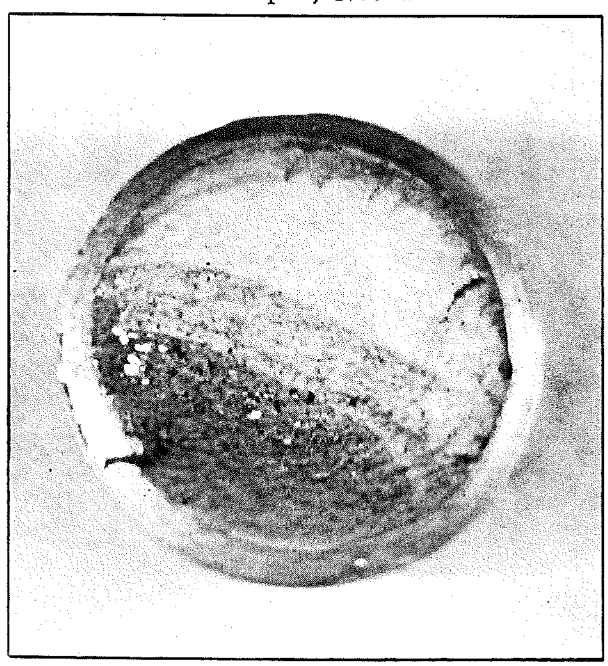


Figure 7. Typical examples of the appearance of the fatigue fracture surface.

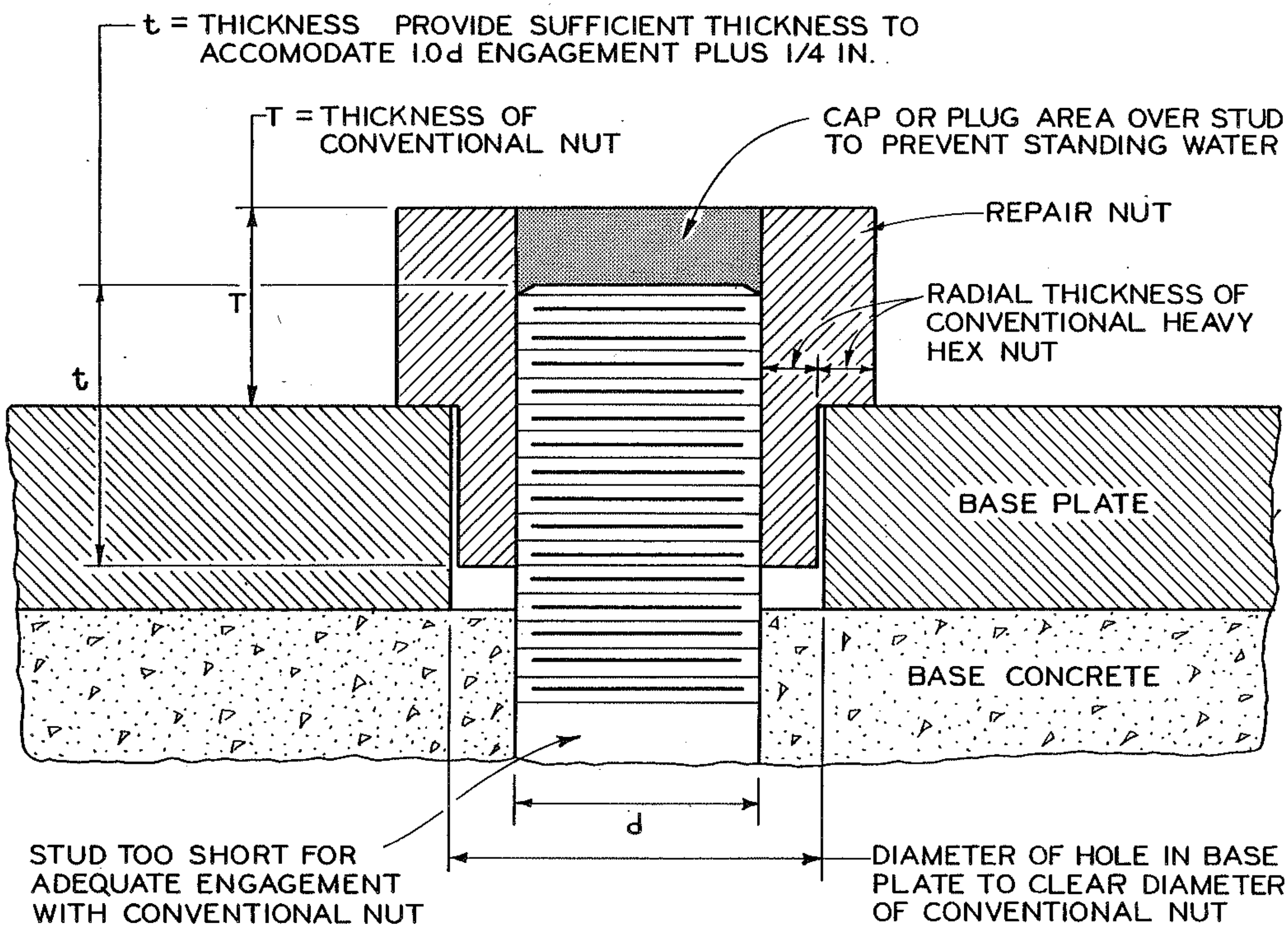


Figure 8. Schematic of proposed method of repair for studs that are too short to provide adequate engagement with conventional nuts.

Conclusions

1. Galvanizing reduced the fatigue life of the anchor bolts.

2. Anchor bolts obtained by special purchase and from the MDOT warehouse failed to meet the specified requirements for yield and ultimate strength.

3. Bolts obtained from the warehouse had unusually low fatigue lives.

4. The amount of nut engagement is an important factor in determining the strength of an anchorage. Less than one diameter of engagement reduces the strength.

5. Ultrasonic nondestructive evaluation was found to be capable of finding fatigue cracks in the anchor bolts, even at relatively small sizes.

Recommendations

1. It is recommended that a directive or specification be written to the effect that on all bolted connections the nut be threaded onto the stud for at least the full depth of the nut plus 1/4 in. If the projection isn't sufficient to accomplish this, and there are compelling reasons for not removing and replacing the foundation, effective engagement should be obtained by making larger holes in the plate and using a special oversize nut with a reduced section and shoulder. This type of device was developed many years ago for such applications, and is schematically shown in Figure 8.

2. Design stresses for galvanized anchor bolts should be reduced by 25 percent, especially for cantilever type sign supports.

3. Additional acceptance testing should be conducted on anchor bolts to improve the probabilities that specified strengths are obtained.

4. Experimental measurements should be done to determine the actual dynamic stresses in anchor bolts for large cantilevers in service.

5. An inspection program using ultrasonic inspection equipment should be carried out to determine the condition of existing anchor bolts in the field. Any loose nuts should be tightened.

6. Further work should be done to identify corrosion resistant anchor bolts that are less susceptible to fatigue.