Engineering Journal

American Institute of Steel Construction

Second Quarter 2012 Volume 49, No. 2

www.aisc.org

Effect of Washer Placement on Performance of Direct Tension Indicators with Curved Protrusions

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ABSTRACT

A series of tests was performed to evaluate the effect of a hardened washer placed between the turned element and a direct tension indicator (DTI) with curved protrusions. Configurations with ¾-, ⅞- and 1.0-in.-diameter bolts with and without hardened washers were evaluated. Tests were also performed with ¾- and ⅞-in. bolts using a new type of DTI, where the DTI is staked to a nut. The purpose of these tests was to compare the performance of the various configurations, as measured by the number of gaps open at the specified pretension level, the load required to close at least half of the gaps, and the tensile load on the bolts when all or all but one of the gaps in the DTI are closed. When an ASTM A563 grade DH nut was used for a given bolt diameter, some differences were observed to be statistically significant. However, no consistent trends were observed in these differences, and the actual differences were of the same order of magnitude as the load increments used in testing. Therefore, it was concluded that there are no practical differences between the various configurations considered when grade DH nuts are used. However, the DTI did not perform well without a secondary hardened washer when an ASTM A563 Grade C nut was used.

Keywords: direct tension indicators, hardness, washers, bolting.

Tension indicating washers, commonly called direct tension indicators (DTIs), are one of several methods used to achieve or demonstrate adequate bolt pretension when such pretension is required in a bolted connection. Other methods include turn-of-the-nut, calibrated wrenches, and twist-off-type tension-control bolts. ASTM F959-09 states that a direct tension indicator is a "*washer-type element inserted under the bolt head or hardened washer, having the capability of indicating the achievement of a required minimum bolt tension by the degree of direct tension indicator plastic deformation*." The plastic deformation is indicated by the collapse of protrusions on the face of the tension indicating washer. The extent to which the protrusions have collapsed is determined by the number of gaps between protrusions that a 0.005-in.-thick indicator can be inserted. Direct tension indicators were introduced in the 1960s and their design has evolved over the ensuing years. Previous studies of use of DTIs in structural connections can be found in the literature (Schmeckpeper et al., 1999; Struik et al., 1973).

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The Research Council on Structural Connections (RCSC, 2004) *Specification for Structural Joints Using ASTM A325 or A490 Bolts* notes that washers are not required in pretensioned joints and slip-critical joints except in cases of sloping surfaces, oversized or slotted holes, and for certain situations with lower yield strength base material and A490 connectors. In addition, there are requirements for the use of washers under turned elements when using calibrated wrench pretensioning, twist-off-type, tension-control bolt pretensioning and direct tension indicators. As noted in the Commentary of Section 6 of the RCSC specification, "The primary function of washers is to provide a hardened non-galling surface under the turned element, particularly for torque-based pretensioning methods…" Although direct tension indicators are not torque-based, the specification does require an ASTM F436 washer between the direct tension indicator and the turned element.

The original tension indicating washers developed by Cooper and Turner Ltd. required use of hardened washers per the manufacturer's installation instructions because the indicator protrusions in some cases were outside the bearing surface of the bolt or nut. In addition, the protrusions were harder and had a straight-sided shape that could cut or gall the bearing surface of the turned element (Laboratory Testing Inc., 1999). An amendment to ASTM F959 in 1993 ensured that DTIs conforming to that specification would have protrusions that fall within the geometric limits of bolt or nut bearing surfaces. The hardness of current DTIs varies by manufacturer.

Table 1. Matrix of Configurations Considered in Testing

	Diameter, in.	Type	Surface Finish	Hardened Washer	Nut Grade	Number of Tests
TurnaSure DTI						
Lot 343I76	¾	325	Plain	Yes	DH	30
Lot 343I76	¾	325	Plain	No	DH	30
Lot 783F63-3	⅞	325	Plain	Yes	DH	30
Lot 783F63-3	⅞	325	Plain	No	DH	30
Lot 014B10	1	490	Plain	Yes	DH	30
Lot 014B10	1	490	Plain	No	DH	30
Lot 343I74	¾	325	Plain	No	DH	10
Lot 783F63-3	⅞	325	Plain	No	C	10
TurnAnut DTI						
34TNA6A	¾	325	Plain	No	DH	30
34TNA7A	¾	325	Galvanized	No	DH	30
78TNA6A	⅞	325	Plain	No	DH	30
78TNA6A	⅞	325	Galvanized	No	DH	30

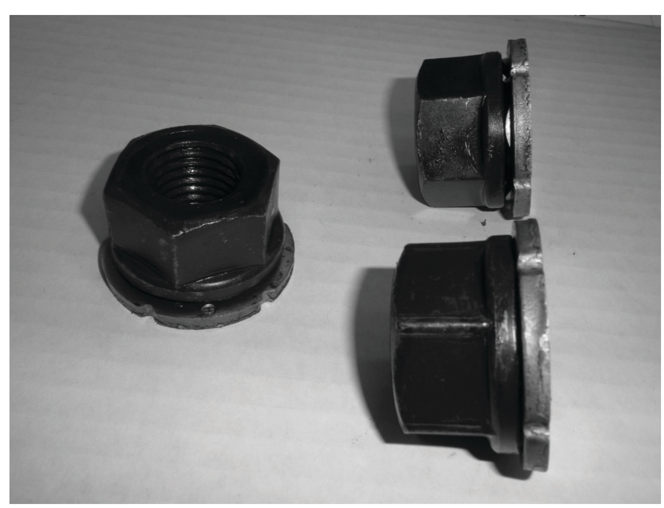
PURPOSE AND SCOPE

The purpose of this study was to evaluate the performance of direct tension indicators with curved protrusions for various washer configurations under controlled laboratory conditions. Tests were performed for ASTM A325 ¾- and ⅞-in.-diameter bolts and ASTM A490 1-in.-diameter bolts with standard ASTM F959 direct tension indicators, with and without ASTM F436 standard hardened washers against ASTM A563 Grade DH nuts. For the ASTM A325 ¾- and ⅞-in. bolts, both galvanized and plain finish proprietary TurnAnut DTIs are also evaluated. The TurnAnut DTI consists of a nut to which a DTI has been attached by staking. An additional test series with ⅞-in.-diameter bolts with ASTM A563 Grade C nuts was also performed. All DTIs were manufactured by TurnaSure, LLC. The test conditions are summarized in Table 1.

CODE REQUIREMENTS FOR DIRECT TENSION INDICATORS

Direct tension indicators must meet the requirements of ASTM F959. Section 7 of the RCSC *Specification* describes the requirements to verify that fastener assemblies

(a) TurnaSure DTI



(b) TurnaSure TurnAnut DTI

Fig. 1. Views of TurnaSure DTI and TurnAnut DTI. The images show the devices before and after testing.

Table 2. Relevant Tensile Forces for Pretensioned and Slip Critical Bolts						
Nominal Bolt Diameter, d_b, in.	Specified Minimum Bolt Pretension, T_m, kips		1.05 times Specified Minimum Bolt Pretension, kips		Minimum Tensile Capacity, kips	
	ASTM A325 Bolts	ASTM A490 Bolts	ASTM A325 Bolts	ASTM A490 Bolts	ASTM A325 Bolts	ASTM A490 Bolts
¾	28	—	29	—	40	—
⅞	39	—	41	—	56	—
1	—	64	—	67	—	91

and procedures result in the required post tightening performance (RCSC, 2004). The specification calls for the use of a tension calibrator to confirm the performance of the fastener assembly and the pretensioning method to be used by the bolting crew. Section 8 describes installation of fastener components. Section 8.2.4 specifically describes direct-tension-indicator pretensioning.

The RCSC *Specification* calls for a representative sample of fastener assemblies to be tested for each combination of diameter, length, grade and lot to be used. In the snug-tight condition at least half of the DTI gaps must remain open. Testing then proceeds until at least half of the gaps are closed to a 0.005-in. feeler gage. The purpose of the testing is to ascertain that the fastener assembly and fastening procedure develops a pretension equal to or greater than 1.05 times the values specified in Table 8.1 of the RCSC *Specification*. The values from Table 8.1 of interest to this test program, as well as the values scaled by 1.05 used for initial pretensioning in this study are reported in Table 2.

EXPERIMENTAL PROGRAM

The experimental program consisted of tension tests of TurnaSure DTIs (Type 325 ¾ in., ⅞ in. and Type 490 1 in.) and TurnaSure TurnAnut DTIs (Type 325 ¾ in. diameter and ⅞ in. diameter). The devices tested are shown in Figure 1. The tests of DTIs were performed with four configurations, including plain-finish DTIs bearing directly against the face of the nut, plain-finish DTIs bearing against a hardened washer, and both plain and mechanically galvanized TurnAnut DTIs as shown in Figures 1 and 2. In the initial round of testing, 30 assemblies of each configuration were tested with Grade DH nuts. All DTIs of the same size were from the same production lot in the initial round of testing. Two additional series consisted of 10 assembly tests each. The first employed ¾-in.-diameter assemblies with Grade DH nuts and no hardened washer, employing DTIs from a different production lot than was used in the initial round. The second additional series was for ⅞-in. assemblies using the same DTI lot as the initial series against Grade C nuts without hardened washers. The nuts were turned with an electric wrench. A summary of the program was provided in Table 1. The Rockwell hardness measurements for all DTIs, nuts, and washers used are shown in Table 3.

While the nuts were tightened, the tension of the bolts was measured with a Skidmore-Wilhelm bolt tension calibrator with a digital readout. For loading, the bolts were placed through the back of the calibrator and the nut was the turned element. The bolts were initially tensioned to 1.05 times the load specified in Table 8.1 of the RCSC *Specification*. The number of gaps open more than 0.005 in. was determined using a feeler gauge. The bolts were then subjected to incremental increases in tension, with the number of open gaps measured and recorded at each increment, until only one gap remained open. The load increments were on the order of 1 kip to 3 kips. In some instances, the final load increment resulted in all gaps closing. The tension load required to close all or all but one gap was recorded. After loading, it was verified that the nut could be rethreaded for the length of the bolt. The loading plates of the bolt tension calibrator required re-facing at regular intervals. No more than 20 test repetitions were performed on a plate without re-facing. The test equipment is shown in Figure 3.

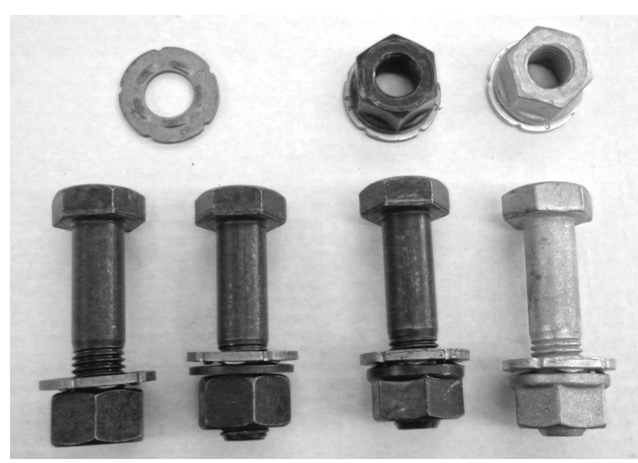


Fig 2. Test configurations from left to right; DTI without washer, DTI with washer, plain TurnAnut DTI, galvanized TurnAnut DTI.

Table 3. Rockwell Hardness of Connection Components (Scale)				
	Diameter, in.	DTI Avg./STD	Washer Avg./STD	Nut Avg./STD
TurnaSure DTI Tests with DH Nuts				
Lot 343I76	¾	87.6/3.09 (B)	39.1/2.48 (C)	30.1/0.42 (C)
Lot 783F63-3	⅞	94.4/1.74 (B)	40.2/1.64 (C)	26.6/1.75 (C)
Lot 014B10	1	83.4/8.91 (B)	42.8/0.84 (C)	28.9/2.53 (C)
Lot 343I74	¾	90.4/3.80 (B)	43.0/2.53 (C)	30.3/2.84 (C)
TurnaSure DTI Tests with C Nuts				
Lot 783F63-3	⅞	94.4/1.74 (B)	Not used	88.37/3.00 (B)

RESULTS

Results of three key load points are reported in this study. The first result reported is the number of gaps open when the pretension in the bolt reaches 1.05 times that specified in Table 8.1 of the RCSC *Specification*. These required pretension values were noted in Table 2. These data are used, similar to pre-installation verification of assemblies as outlined in Section 7 of the RCSC *Specification*, to verify that the required pretension is reached. The required pretension values should be reached prior to half of the DTI gaps closing. The second result reported is the load required to close all or all but one of the DTI gaps. The third finding is the distribution of measured bolt tensions when the DTI indicated that the specified bolt pretension requirements were met (half of the gaps closed).

The average numbers of gaps open at 1.05 times the minimum pretension load and the standard deviation of these results are provided in Table 4. Table 5 provides the distribution of the number of gaps open at this load from tests on ¾-, ⅞- and 1-in.-diameter bolts, respectively. The preload values were 29 kips for ¾-in.-diameter A325 bolts, 41 kips for ⅞-in.-diameter A325 bolts, and 67 kips for 1-in.-diameter A490 bolts.

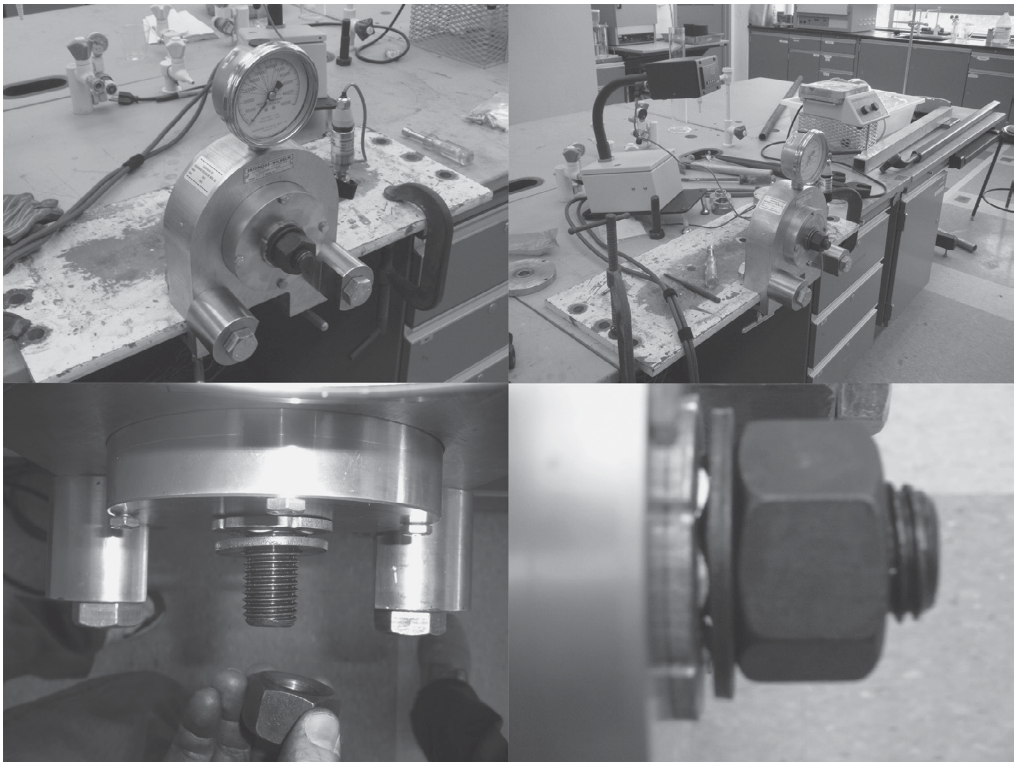


Fig. 3. Test setup.

Table 4. Average Numbers of Gaps Open at 1.05 Times Minimum Pretension Load (Grade DH Nut Unless Otherwise Indicated)		
Assembly (Preload)	**Avg. Number of Gaps Open**	**Standard Deviation**
¾-in. A325 (29 kips)	(5 possible)	
Lot 343I76 without washer	4.10	0.82
Lot 343I76 with washer	3.57	0.73
Lot 343I74 without washer	4.10	1.10
Plain TurnAnut DTI	4.87	0.43
Galvanized TurnAnut DTI	5.00	0.00
⅞-in. A325 (41 kips)	(5 possible)	
Lot 783F63-3 without washer	3.72	0.80
Lot 783F63-3 with washer	3.49	0.85
Lot 783F63-3 without washer (Grade C Nut)	0.91	1.14
Plain TurnAnut DTI	4.93	0.37
Galvanized TurnAnut DTI	4.27	0.74
1-in. A490 (67 kips)	(7 possible)	
Lot 014B10 without washer	6.60	0.89
Lot 014B10 with washer	5.33	1.35

For ¾-in.-diameter assemblies with Grade DH nuts, 39 of 40 tests without a washer and 30 of 30 tests with a backing washer passed simulated pre-installation verification testing. For the ⅞-in.-diameter assemblies with Grade DH nuts, 30 of 30 tests without a washer and 26 of 30 tests with a backing washer passed. All 1-in.-diameter assemblies with DH nuts, with or without a washer, passed the test. All TurnAnut assemblies also passed the simulated pre-installation verification testing. Use of a DTI alone resulted in a higher average number of gaps open at the preload compared to use of a DTI with a hardened washer against the face of the DH nut for all size bolts tested. The TurnAnut DTI, whether plain or galvanized, tended to have the most gaps open at preload and the smallest spread in the results.

The tests of ⅞-in. assemblies with Grade C nuts and without a hardened washer resulted in most of the gaps indicating as closed with the feeler gage at the specified preload (ASTM value times 1.05). This poor performance of the DTI coincided with significant galling of the surface of the Grade C nut.

The average loads required to close all but one or all of the DTI gaps are reported in Table 6. Excluding the results from Grade C nuts, on average, these peak loads are 82 to 96% of the specified minimum tensile capacity of the bolts. Five of 30 tests of galvanized ¾-in. bolts exceeded the minimum specified tensile capacity of the bolt when all or all but one gap was closed. Two tests with ¾-in. galvanized TurnAnut exceeded the minimum specified tensile capacity of the bolt. No other tests exceeded the minimum. Use of a hardened washer against the face of the nut tended to result in a slightly greater spread in the peak load data compared with a DTI directly against the nut face. All nuts could be rethreaded for the length of the bolt after testing, indicating that the bolt did not undergo significant plastic deformation.

Cumulative density functions of the loads measured when at least half of the DTI gaps were first observed to be closed are shown in Figures 4, 5 and 6 for ¾-, ⅞- and 1-in.-diameter assemblies with Grade DH nuts, respectively. These figures indicate the spread in pretension measured under the acceptance condition. The minimum pretension had been developed under this condition for all assemblies tested. The spread of the results was smaller for tests without a hardened washer for ¾- and ⅞-in. assemblies and larger for the 1-in. assemblies. The TurnAnut produced higher pretension than the assemblies in which the washer, DTI or both were free to "float" while the assembly was tightened.

The requirement to place a hardened washer between the turned element and a DTI was because of the potential for DTIs to gall the underside of the nut or bolt head, resulting in incorrect indication of tension. Following this testing, a selection of washers and nuts were inspected both visually and with a profilometer. Visual observation shows that the DTI produced limited polishing of the washer or Grade DH nuts in a ring described by the indicators' protrusions. The profilometer measurements showed no evidence of surface galling. However, the surface of the polished region was

Table 5. Distribution of Gaps Open at 1.05 Times Minimum Pretension Load (Grade DH Nut Unless Otherwise Indicated)						
Assembly (Preload)	Percentage of Tests with Number of Gaps Open					
¾-in. A325 (29 kips)	**5**	**4**	**3**	**2**	**1**	**0**
Lot 343I76 without washer ($n = 30$)	38	34	28	0	0	0
Lot 343I76 with washer ($n = 30$)	13	30	57	0	0	0
Lot 343I74 without washer ($n = 10$)	50	20	20	10	0	0
Plain TurnAnut DTI ($n = 30$)	90	7	3	0	0	0
Galvanized TurnAnut DTI ($n = 30$)	100	0	0	0	0	0
⅞-in. A325 (41 kips)	**5**	**4**	**3**	**2**	**1**	**0**
Lot 783F63-3 without washer ($n = 30$)	21	31	48	0	0	0
Lot 783F63-3 with washer ($n = 30$)	13	32	42	13	0	0
Lot 783F63-3 without washer (Grade C nut) ($n = 10$)	0	0	20	30	10	40
Plain TurnAnut DTI ($n = 30$)	97	0	3	0	0	0
Galvanized TurnAnut DTI ($n = 30$)	43	40	17	0	0	0
1-in. A490 (67 kips)	**7**	**6**	**5**	**4**	**3**	**2**
Lot 014B10 without washer ($n = 30$)	80	6	7	7	0	0
Lot 014B10 with washer ($n = 30$)	37	0	23	40	0	0

noticeably smoother, possibly due to limited removal of mill scale as the nut or washer rotated relative to the DTI protrusions. This result was expected because the DTI material is softer than that of either the washer or Grade DH nut. As noted previously however, there was significant galling of the Grade C nuts when the DTI was used without a hardened washer.

ANALYSIS AND DISCUSSION

The test program clearly shows that the tested DTI cannot be used without a hardened washer between it and a Grade C nut. However, in the case of a hardened nut, the extra washer does not appear to be necessary. For the assemblies tested with a sample size of 30 tests, independent sample t-test analyses were performed to determine if there were statistically significant differences in the average loads required to close all but one or all of the gaps of the DTI to refusal of the 0.005-in. feeler gauge. The Shapiro-Wilk test was used to assess the validity of the normality condition ($\alpha = 0.2$). Non-pooled t-tests were used when the larger standard deviation was more than twice the value of the smaller standard deviation. Results of this analysis, which are exclusive to testing with Grade DH nuts, were:

- The differences in the measured average peak loads were not statistically significant when comparing the "with-washer" configuration to the TurnAnut DTI configuration for plain A325 ¾- or ⅞-in.-diameter bolts.

- The differences in the measured average peak loads were statistically significant when comparing the "with-washer" configuration to the TurnAnut DTI configuration for galvanized A325 ¾-in. bolts. However, the difference was not statistically significant when comparing the "with-washer" configuration

Table 6. Average Loads Required to Close All But One or All of the DTI Gaps (Grade DH Nuts Only)			
Assembly (Minimum Specified Tensile Strength)	**Avg. Peak Load (kips)**	**Standard Deviation (kips)**	**Percent of Minimum Specified Tensile Strength**
¾-in. A325 (40 kips)			
Lot 343I76 without washer	35.1	1.03	88
Lot 343I76 with washer	35.9	1.74	90
Lot 343I74 without washer	34.6	2.27	87
Plain TurnAnut DTI	35.3	1.50	88
Galvanized TurnAnut DTI	38.2	1.60	96
⅞-in. A325 (56 kips)			
Lot 783F63 without washer	45.8	1.42	82
Lot 783F63 with washer	47.4	2.46	85
Plain TurnAnut DTI	48.2	0.89	86
Galvanized TurnAnut DTI	47.2	1.65	84
1-in. A490 (91 kips)			
Lot 014B10 without washer	80.0	3.47	88
Lot 014B10 with washer	77.4	3.92	85

to galvanized A325 ⅞-in.-diameter TurnAnut DTIs. The "with-washer" configuration with ¾-in.-diameter bolts resulted in lower peak bolt tension required to close one or all gaps than was required with the galvanized TurnAnut DTI.

- The differences in the measured average peak loads were statistically significant when comparing the "with-washer" condition to the "without-washer" configuration for all sizes tested. However, the differences were not in the same direction for all sizes. For A325 ¾-in. or ⅞-in.-diameter bolts, the force required to close one or all of the gaps to less than 0.005 in. was higher for the hardened washer configuration. The trend was reversed in the 1-in.-diameter A490 bolts.

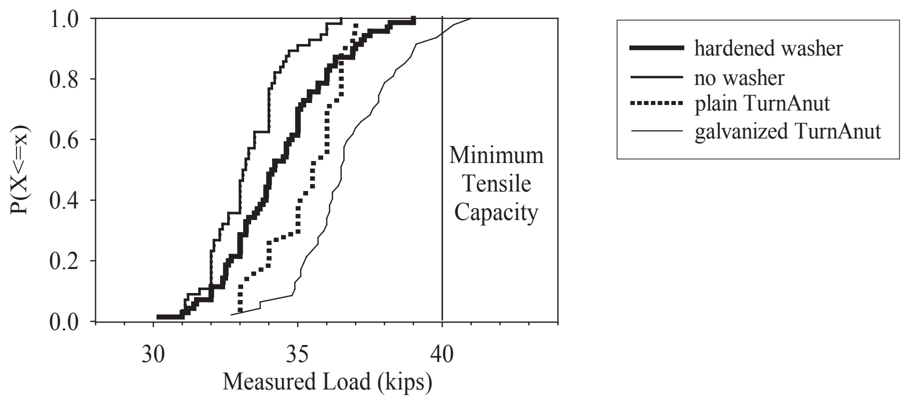


Fig. 4. Cumulative density function of loads required to close half of the gaps, ¾-in.-diameter A325 bolts (minimum pretension is 28 kips and minimum tensile strength is 40 kips).

While the analysis performed indicates there are statistically significant differences in some of the measured results, there was not a consistent trend in these differences. In addition, these statistical findings must be considered in light of the test program itself. The peak loads recorded were those required to close all but one or all of the gaps between the DTI and washer or bolt. This was because in some instances the load increment applied to the bolt resulted in enough gaps closing to bypass the one-gap-closed condition. In addition, the load increments typically ranged from 0.4 kip to 1.5 kips. Therefore, the load increments are equal to or of the same magnitude as the measured differences in peak load values. Given these considerations, these results should not be extended beyond stating that the comparable behavior was achieved with all of the bolt/DTI/washer/nut configurations considered.

SUMMARY AND CONCLUSIONS

Tests of bolt assemblies that involved direct tension indicators with curved protrusions were performed to evaluate the effect of nut and washer configuration on pretension loads achieved. Test configurations included plain DTIs against the face of the nut, DTI's and hardened washer against the face of the nut, and plain and mechanically galvanized

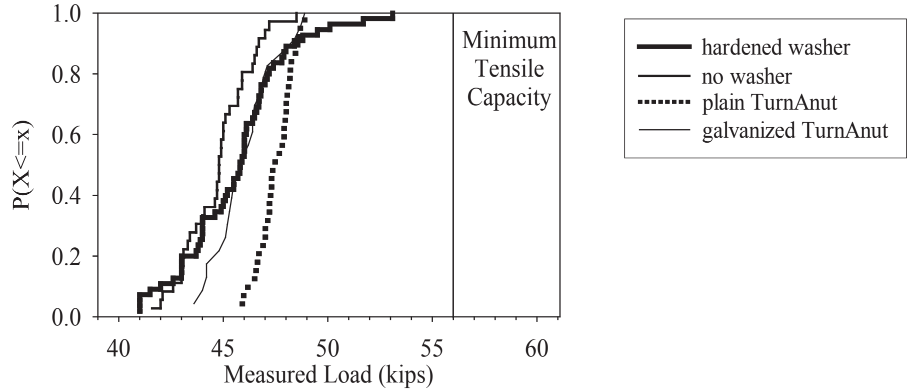


Fig. 5. Cumulative density function of loads required to close half of the gaps, ⅞-in. A325 bolts (minimum pretension is 39 kips and minimum tensile strength is 56 kips).

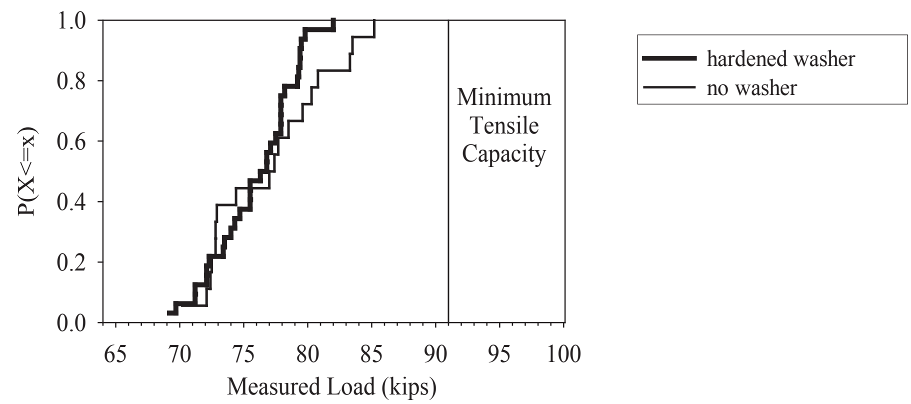


Fig. 6. Cumulative density function of loads required to close half of the gaps, 1-in. A490 bolts (minimum pretension is 64 kips and minimum tensile strength is 91 kips).

TurnaSure TurnAnut DTIs. For all tests, the nut was the turned element. It was found that a hardened washer is necessary if a DTI is used with a Grade C nut. However, it was found that when a Grade DH nut was used, the assembly performed just as well with or without the hardened washer placed between the DTI and the nut.

Additional findings specific to Grade DH nuts were

- Use of a DTI alone resulted in a higher average number of gaps open at the preload compared to use of a DTI with a hardened washer against the face of the nut for all size bolts tested, even when such DTIs were from the same production lot.
- The TurnAnut DTI, whether plain or galvanized, tended to have the most gaps open at preload and the smallest spread in the results.
- In simulated pre-installation verification testing, similar performance of DTI assemblies with or without a hardened washer was observed with a small percentage of assemblies not passing the testing.
- Use of a hardened washer against the face of the nut tended to result in a slightly greater spread in the peak load data compared with a DTI directly against the nut face. For the condition of half of the gaps closed the finding was similar for ¾- and ⅞-in.-diameter assemblies but opposite with 1-in.-diameter assemblies.
- In some cases statistically significant differences were measured for the average tensile loads required to close all but one or all of the gaps to less than 0.005 in. However, the trends were not consistently in the same direction and the differences in the means were less than or comparable to the load increments being applied during the testing.

Based on the results of this test program, it is concluded that the use of direct tension indicators with curved protrusions with or without hardened washers against the turned element for ASTM A325 ¾- and ⅞-in.-diameter bolts and ASTM A490 1-in.-diameter bolts results in comparable performance in providing the required bolt pretension if a Grade DH or harder nut is used. In addition, the presence or absence of the hardened washer made no difference in the performance of the direct tension indicators at the load levels required to close all but one or all of the gaps. The staking of a direct tension indicator to a nut to produce the TurnAnut DTI configuration with either plain or galvanized surfaces also resulted in behavior comparable to a DTI with and without a hardened washer against the turned element. However, the testing does not support elimination of the hardened washer for softer grades of nuts.

ACKNOWLEDGMENTS

The work presented was sponsored by Turnasure, LLC. The views presented do not necessarily represent those of the project sponsors. The testing was carried out by undergraduate research assistants Mr. Matt Janas and Mr. Ryan Headley with assistance from Mr. Charles Linderman.

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