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TENSION LOSS IN HIGH-STRENGTH BOLTS

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This paper reports on a series of experiments on M16 and M22 high-strength hexagonal head bolts and 22 mm diameter high-strength torque-control bolts (TC22). The experiments are primarily to determine the effects of bolt type, surface treatment of gripped plates, number of gripped plates, thickness of gripped plates, thread lubrication, bolt length and the presence of washers on short-term tension loss of initial bolt tension. Each specimen was tested for a period of 7 days. It was found that the loss of initial bolt tension was greatest for specimens with gripped plates painted with red primer paint and least for plates with polished (mirror) surface.
Keywords: high-strength bolts, tension loss

1. Introduction

In order to determine the actual behavior of steel connections using high strength bolts, it is important to know the actual tension in the bolt at any particular time for assessing the remaining load-carrying capacity of steel sections during its service life. It has been reported that the bolt tension at any given time may be different from the pretension given at construction period. Due to high stress levels in the threaded part of an installed bolt, some bolt tension loss will occur that could affect the bolt's performance. Since the result of insufficient bolt tension may be that the connection slips and fails in bearing and in shear, the determination of bolt tension is all the more important.

Early studies were done by Chesson and Munse[1] to study bolt tension loss. Immediately upon completion of torquing, the average bolt tension loss was 5%. Although no current data exists, grip length and number of gripped plies are believed to influence the amount of tension loss. There was an additional 4% loss after 21 days, although 90% of this loss occured during the first day. During the remaining 20 days, the rate of change of loss decreased in an exponential manner.

North[2),3)] reported some works done to measure the existing tension of large high-strength bolts on site using ultrasonic extensometers. The measurement of bolt length was done by measuring the travel time of sound pulses echoing from one end to the other. The installed length was compared with uninstalled bolts and load-elongation curves were then used to determine the existing tension. Measurements were done in 15,000 locations. The field measurements indicated that insufficient bolt pre-load was common in existing connections. The author recommended that additional research should be done on the effects of bolt tension loss.

The objectives of this investigation are to determine the amount of bolt pre-tension (or pre-load) loss of high-strength bolts when the factors listed below are varied.

(i) Type of bolts:
- (a) M16 hexagonal-head bolt;
- (b) M22 hexagonal-head bolt;
- (c) TC22 torque-control (shear) bolt.

(ii) Number of plates gripped:
- (a) 2 plates;
- (b) 3 plates.

(iii) Thickness of gripped plates:
- (a) 16 mm thick plates;
- (b) 22 mm thick plates;

(iv) Surface condition of gripped plates:
- (a) original mill scale;
- (b) painted with red primer paint;
- (c) polished to a mirror finish;
- (d) galvanised.

(v) Lubrication of bolt threads:
- (a) original residue oil;
- (b) multi-purpose heavy grease.

(vi) Presence of washers:
- (a) with washers;
- (b) without washers.

(vii) Length of bolts:
- (a) 150 mm (short bolts);
- (b) 165 mm.

2. Specimens and tension loss tests

2.1 Test cases

A total of 12 specimens were tested in two batches. Each specimen was tested over a seven day period. The specimen number, name, code and comparison cases are given in Table 1. The specimen codes are designated using Table 2. The comparison cases are designated using Table 3.

Table 1 Test specimens

No.	Specimen Name	Specimen Code	Comparison Cases
1	control	T2-N1-P1-S1-L2-W1-B2	B,C,D,E,G
2	primed	T2-N1-P1-S2-L2-W1-B2	D
3	mirror	T2-N1-P1-S3-L2-W1-B2	D
4	3 plies	T2-N2-P1-S1-L2-W1-B2	B
5	thick plate	T2-N1-P2-S1-L2-W1-B2	C
6	M16	T1-N1-P1-S1-L2-W1-B1	A
7	TC22	T3-N1-P1-S1-L2-W1-B1	A
8	no washers	T2-N1-P1-S1-L2-W2-B2	F
9	greased M22	T2-N1-P1-S1-L1-W1-B2	E
10	short M22	T2-N1-P1-S1-L2-W1-B1	A,F,G
11	galvanised	T2-N1-P1-S4-L2-W1-B2	D
12	greased M16	T1-N1-P1-S1-L1-W1-B1	E

Table 2 Specimen code designation

Parameter	Code	1	2	3	4
Bolt Type	T	M16	M22	TC22	-
No. of Plates	N	2	3	-	-
Plate Thickness	P	16mm	22mm	-	-
Surface Condition	S	mill scale	red paint primer	mirror finish	galvanised
Lubricated Threads	L	grease	residue oil	-	-
Presence of washers	W	yes	no	-	-
Bolt Length	B	150 mm	165 mm	-	-

Table 3 Comparison case designation

Case	Parameter	Specimen Name	Comparison between:
A	Bolt Type	short M22	M22
		M16	M16
		TC22	shear bolt
B	No. of Plies Gripped	control	2 plates
		3 plies	3 plates
C	Thickness of Plates	control	16 mm
		thick plate	22 mm
D	Surface Condition	control	mill scale
		primed	red primer
		mirror	polished
		galvanised	galvanised
E	Lubricated Threads	control	residue oil
		greased M22	grease
		M16	residue oil
		greased M16	grease
F	Presence of washers	short M22	yes
		no washers	no
G	Bolt Length	control	165 mm
		short M22	150 mm

For example, from Table 1, specimen 5 has the name "thick plate" and the code T2-N1-P2-S1-L2-W1-B2. From Table 2, the different components from this code can be seen as M22 bolt, 2 gripped plates, 22mm thick gripped plates, mill scale plate surface, bolt thread lubricated with residue oil, washers present and bolt length of 165mm. From the last column of Table 1, it can be seen that specimen 5 or "thick plate" is part of the comparison case C, which compares the parameter "Thickness of Plates". It is compared with "control"(specimen 1) which has a plate thickness of 16mm.

2.2 Apparatus for tension loss tests

Apart from the aforementioned bolts, nuts, washers and plates which make up the specimens, other equipment required are listed below.

(i) Two types of strain gage loads cells were fabricated for this experiment. The load cells were made from hardened steel, cylindrical, 80mm in height and had a protective coating to seal in the strain gages on its outer surface. The load cells used were:
  (a) cells for 16mm diameter bolts(M16) capable of measuring compressive loads of up to 15 tonf;
  (b) cells for 22mm diameter bolts (M22 and TC22) capable of measuring compressive loads of up to 30 tonf.

(ii) Torque wrenches capable of tightening the bolts up to 50 tonf were used. A special pneumatic torque wrench was used to tighten the TC22 bolts. The tip of the bolt sheared off at about 20 tonf bolt tension.

(iii) A multi-channel data logger was used for logging readings from the load cells at preset intervals.

2.3 Procedure

Each specimen that is to be tested will be assembled with a precalibrated load cell (see Fig. 1). The load cell is placed between the head and the gripped plates. Tightening of the specimen was done by turning the nut with a torque socket wrench. Another socket wrench is used on the bolt head to provide a reaction force.

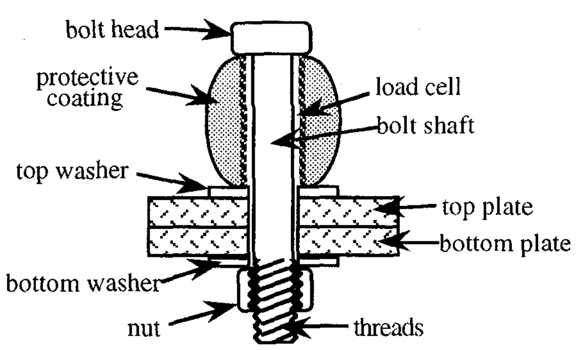


Fig. 1 Cross sectional view of an assembled specimen

The bolt specimens were tightened by applying a torque wrench to the nut until the required bolt tension is reached. The bolt tension required is in the 19 - 22 tonf range for the 22 mm diameter bolts and 10 - 12 tonf range for the 16 mm diameter bolts. After torque is released, readings of the load cells are taken. In order to discount the effect of immediate elastic recovery of the bolt and plate material, readings one minute after torque release are taken as the true indication of tension loss[1].

Yabotnov[4] stated that since the modelling of creep relaxation can only realistically be made in the steady-state short-term portion of the tension loss, it seems pointless to try to model the long-term data. Due to this and the fact that long-term data is available for extrapolating shorter term results, the data of bolt tension for all specimens except one were sampled for a maximum of seven days. In addition, seven-day sampling provided enough information for comparison of the various parameters concerned. Due to unavoidable circumstances during the experiment, sampling for the "no washer" specimen was abandoned after 2 days.

Readings of the bolt tension were sampled for every:

(i) 1 minute for the first 10 minutes;
(ii) 10 minutes for the next 50 minutes;
(iii) 1 hour for the next 23 hours;
(iv) 2 hours for the next 48 hours;
(v) 4 hours for the last 96 hours.

3. Results and discussion

The results from this series of experiments are divided into three basic groups for easier comparison:

(i) first hour results;
(ii) first day results;
(iii) 7 day results.

Table 4 summarizes the tension loss of each specimen at the end of the time periods mentioned above. The results indicate that tension loss was less than previously found by Chesson and Munse[1]. They found that up to 4% loss was obtained for 0.75 inch (19mm) diameter A325 (U.S. Standards) bolts up to 21 days with about 3.6% loss on the first day. The surface condition of the gripped plates used were all of the mill-scale type. On the contrary, neither the M16 nor the M22 specimens with mill-scale surface plates in the present experiments lost more than 2% of the initial bolt tension.

Table 4 Total bolt tension loss

Specimen Name	Initial Bolt Tension (tonf)	% of initial value		
		1 hour	1 day	7 days
primed	21.098	1.337	2.526	3.588
galvanised	21.203	1.575	2.636	3.363
greased M22	21.670	1.301	1.892	2.298
control	21.582	0.880	1.511	1.918
greased M16	11.448	0.734	1.380	1.904
3 plies	21.010	0.881	1.428	1.823
thick plate	21.018	0.709	1.170	1.503
TC22	19.980	0.532	1.121	1.476
no washers	20.847	0.769	1.067	-
M16	11.354	0.388	0.960	1.330
short M22	20.728	0.425	0.893	1.254
mirror	21.023	0.504	0.837	1.070

3.1 Effect of bolt type

In the first 60 minute data (see Fig. 2), the losses bolt tension for the M16, short M22 and TC22 bolts were similar. During the tightening process, the shear bolt tip sheared off at about 20 tonf while the M22 bolt was tightened to about 20.7 tonf. The M16 bolt, was tightened to about 11.4 tonf. The drop in tension in the first 10 minutes was almost identical. Bolt tension loss was in the region of 0.3% to 0.5% at one hour.

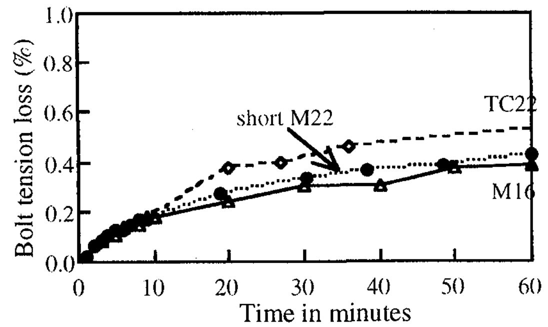


Fig. 2 First hour results for "TC22", "M16" and "short M22" specimens

However the shear bolt (TC22) had a greater loss after one hour (Fig. 3 and 4) than the hexagonal-head bolts. The TC22 specimen lost 1.48% of initial bolt tension while the values for the M22 and M16 specimens were 1.26% and 1.33% respectively.

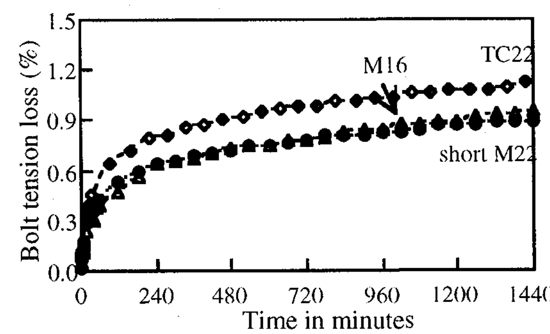


Fig. 3 First day results for "TC22", "M16" and "short M22" specimens

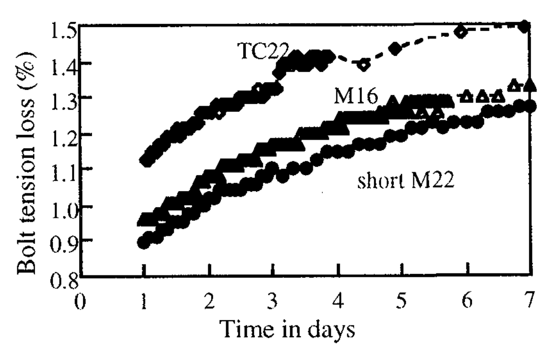


Fig. 4 7-day results for "TC22", "M16" and "short M22" specimens

3.2 Effect of number of plies

Changing the number of plies gripped by the bolts from 2 plies to 3 plies does not seem to have any effect on the tension loss of high-strength bolts (Fig. 5, 6 and 7).

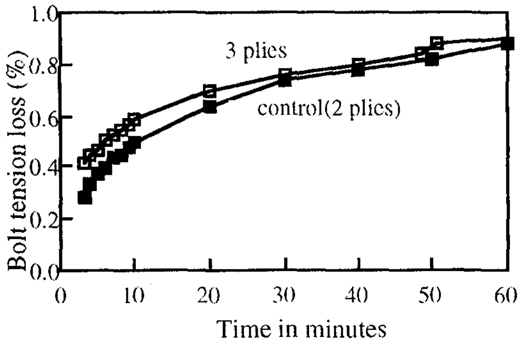


Fig. 5 First hour results for "control" and "3 plies" specimens

The "3 plies" specimen ultimately lost less tension than the "control" specimen (Fig. 8). Greater number of plates gripped means that more of the gripped plate lies in the threaded portion of the bolt. (see Fig. 6). The grip length in the threaded portion is 4mm and 20mm for the "control" and "3 plies" specimen respectively.

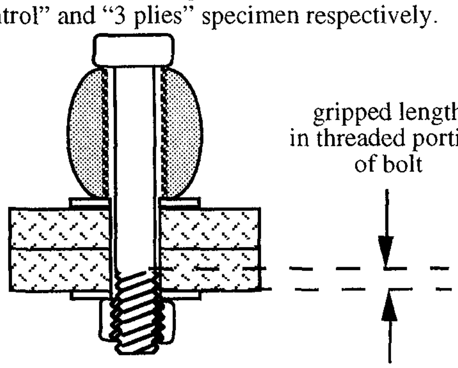


Fig. 6. Gripped length of plate

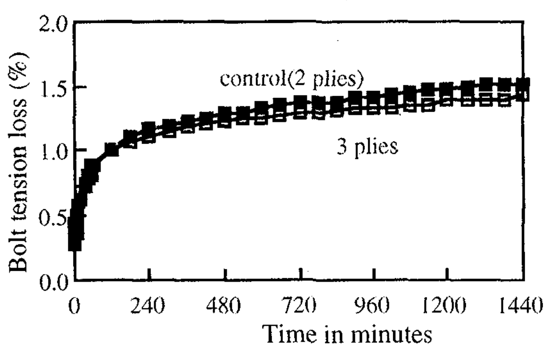


Fig. 7 First day results for "control" and "3 plies" specimens

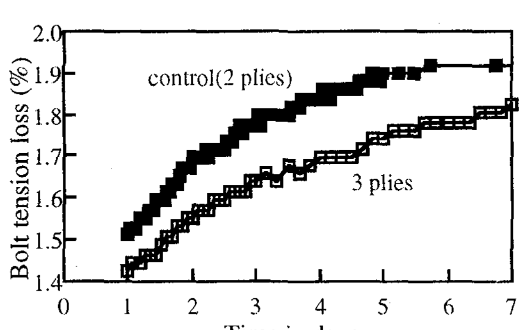


Fig. 8 7-day results for "control" and "3 plies" specimens

3.3 Effect of plate thickness

There seems to be no significant difference between 16mm plates and 22mm plates for the first 10 minutes (Fig. 9). Thereafter, the bolt tension loss became greater for the 16mm plates compared to the 22mm plates (Fig. 10 and 11).

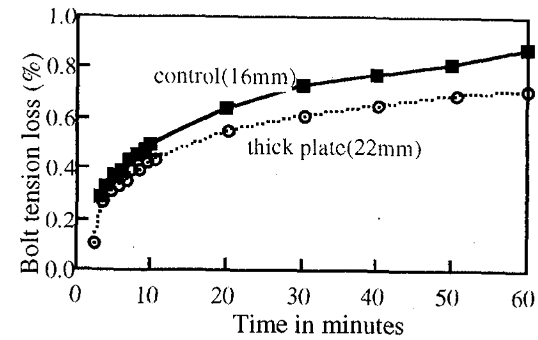


Fig. 9 First hour results for "control" and "thick plate" specimens

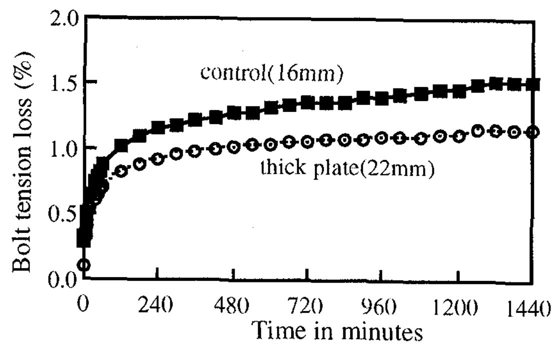


Fig. 10 First day results for "control" and "thick plate" specimens

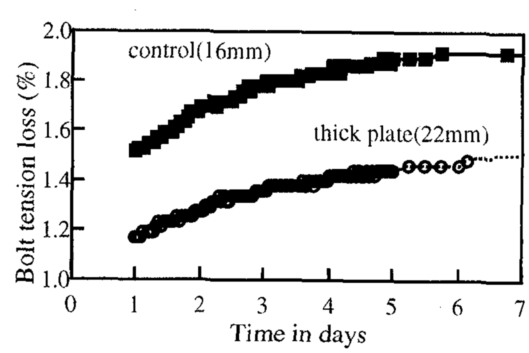


Fig. 11 7-day results for "control" and "thick plate" specimens

There is a similarity in the comparison of plate thickess and number of plates gripped. The significance of a thicker plate is that more of the gripped plate lies in the threaded portion of the bolt. (Fig. 6). The grip length at the threaded portion was 4mm and 16mm for the 16mm plates and 22mm plates respectively. It would seem that tension loss is less for a specimen with longer gripped length in the threaded portion of the bolt. However, if the number of plates gripped are increased, this may not be the case as can be seen in Table 5. One would expect that the "3 plies" specimen to have a smaller tension loss than the "thick plate" specimen if it is compared solely on grip length in the thread. Since the thickness of plates gripped are not similar, we can only say that the bolt tension loss is lesser for a specimen with greater grip length in the thread if the number of plates gripped are the same.

Table 5 Relaxation for differing grip lengths in threaded portion of bolt

Specimen Name	grip length in thread(mm)	Bolt tension loss (%)		
		1 hour	1 day	7 days
control	4	0.880	1.511	1.918
thick plate	16	0.709	1.170	1.503
3 plies	20	0.881	1.428	1.823

3.4 Effect of surface condition

As can be seen from Fig. 12, Fig. 13 and Fig. 14, there is a significant difference of tension loss for specimens with different surface condition of gripped plates. "Galvanised" and "primed" specimens exhibit the greatest tension loss, while "mirror" had the least. One possible reason for this could be the compression of the coating layer of the "galvanised" and "primed" specimens. The subsequent tension loss of this layer could contribute to the increased tension loss. Even with the "control" specimen, it would seem that the layer of mill scale plays a part in the tension loss. The contact faces of the "mirror" specimen had earlier been polished to a mirror finish. Thus the abscence of mill scale and coating in the "mirror" specimen, caused it to lose the least amount of bolt tension.

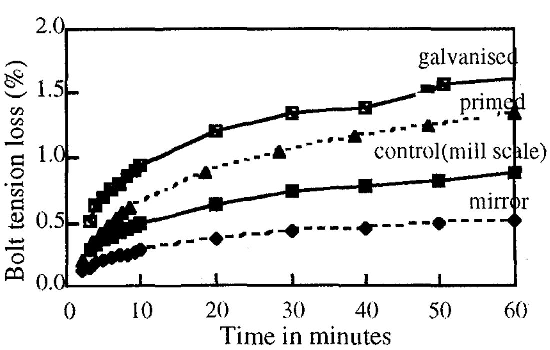


Fig. 12 First hour results for "control", "primed", "galvanised" and "mirror" specimens

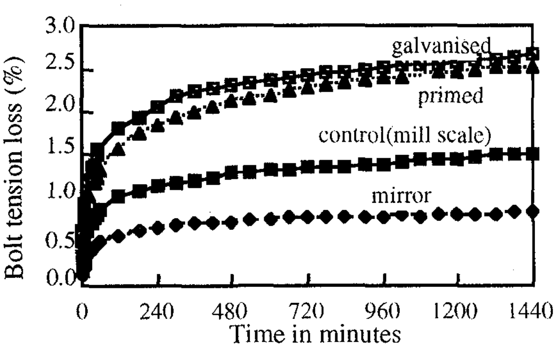


Fig. 13 First day results for "control", "primed", "galvanised" and "mirror" specimens

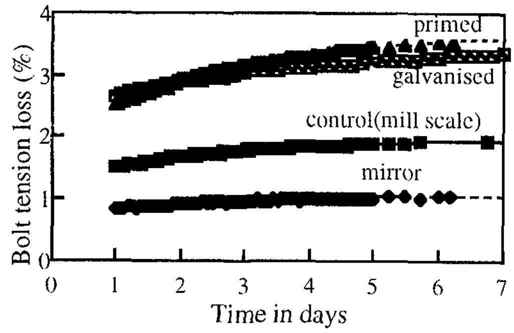


Fig. 14 7-day results for "control", "primed", "galvanised" and "mirror" specimens

3.5 Effect of lubricated threads

Specimens with threads which are greased with heavy grease compared with those that are coated with original residue oil showed greater tension loss. This is evident for both M16 and M22 bolts (Fig. 15, 16 and 17). Lubricated threads could mean that the nut could more easily "back off" the thread when the bolt is under high tensile stress, thus relieving the bolt of some of the tension.

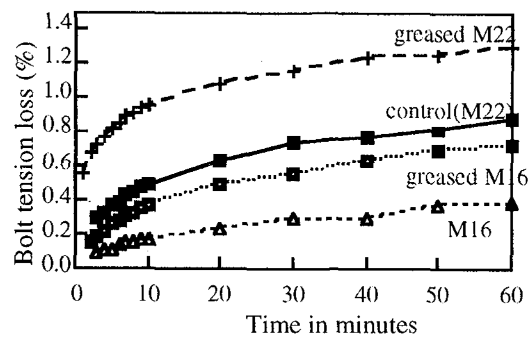


Fig. 15 First hour results for "control", "M16", "greased M22" and "greased M16" specimens

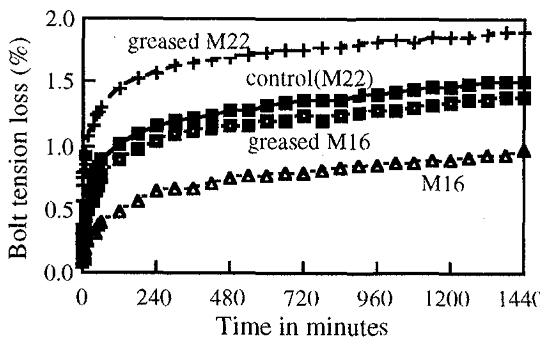


Fig.16 First day results for "control", "M16", "greased M22" and "greased M16" specimens

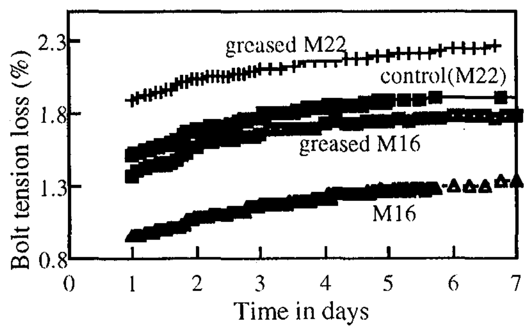


Fig. 17 7-day results for "control", "M16", "greased M22" and "greased M16" specimens

3.6 Effect of presence of washers

Only data up to the first day is available for the "no washer" specimen as mentioned earlier. First hour data indicate that there is no difference in the tension loss characteristics of specimens with or without washers (Fig. 18). However, after one hour, the "no washer" specimen seems to exhibit less tension loss than "control". Contrary to previous data[1] there seems to be a difference between the tension loss characteristics of specimens with and without washers.

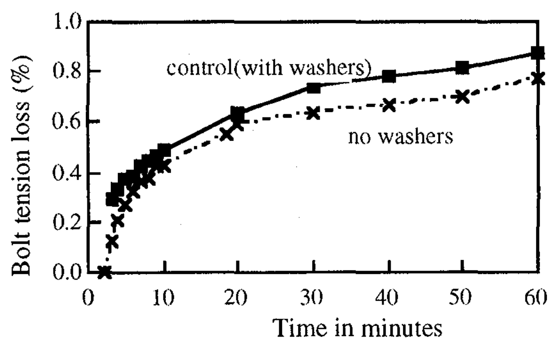


Fig. 18 First hour results for "control" and "no washers" specimen

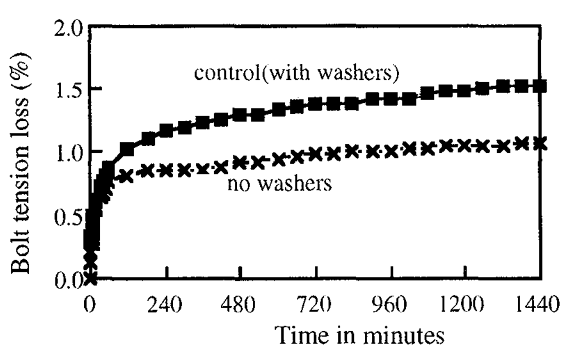


Fig. 19 First day results for "control" and "no washers" specimen

3.7 Effect of bolt length

As seen from Fig. 20, Fig. 21 and Fig. 22, the 150mm bolt seems to lose less tension than the 165mm bolt. A longer bolt means that the amount of threaded portion of the bolt is less than a shorter one (see Fig.23). This means that the effective cross-sectional area of the shorter bolt is less than the longer bolt.

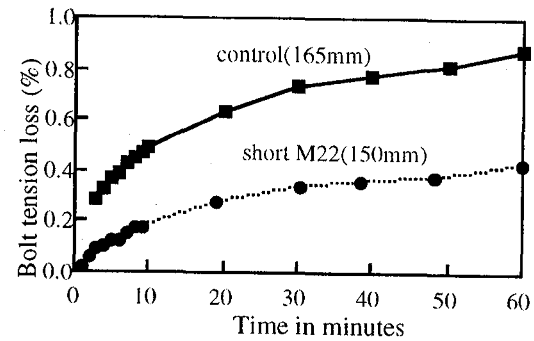


Fig. 20 First hour results for "control" and "short M22" specimens

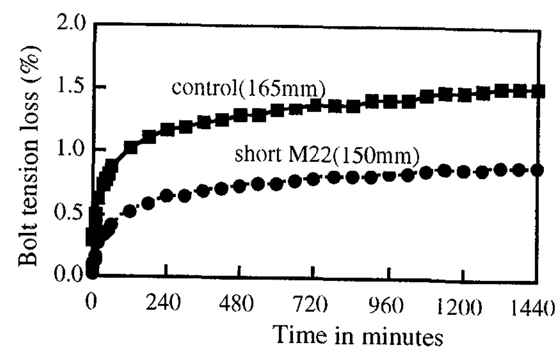


Fig. 21 First day results for "control" and "short M22" specimens

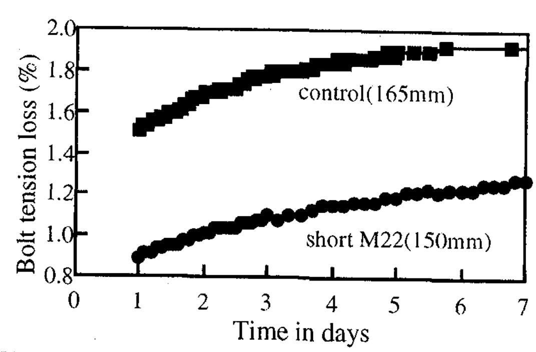


Fig. 22 7-day results for "control" and "short M22" specimens

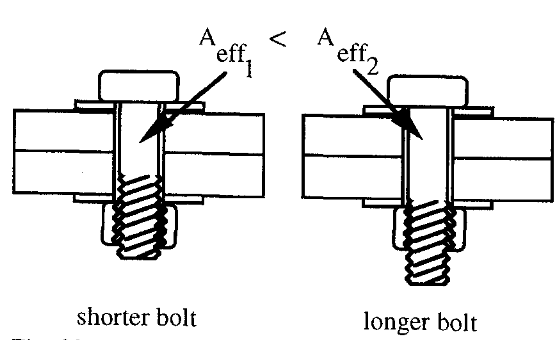


Fig. 23 Effective cross section area of bolt shaft in gripped plates

If we represent the bolt shaft between the head and nut as a spring of stiffness k, where $k = A_{eff}.E/L$ (see Fig. 24) and E is the elastic modulus of the shaft, the stiffness of the specimen with the longer bolt is greater than the specimen with the shorter bolt. Although the length of the bolt between the head and nut is the same, A_{eff} for the longer bolt specimen is greater than that of the shorter bolt specimen.

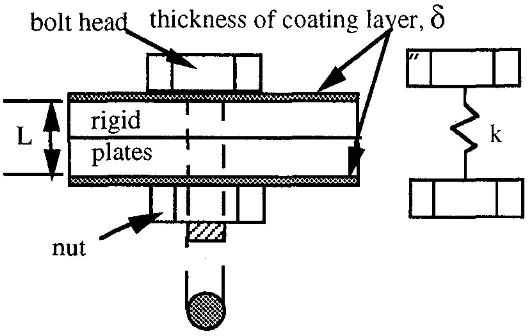


Fig. 24 Model of bolt shaft between head and nut

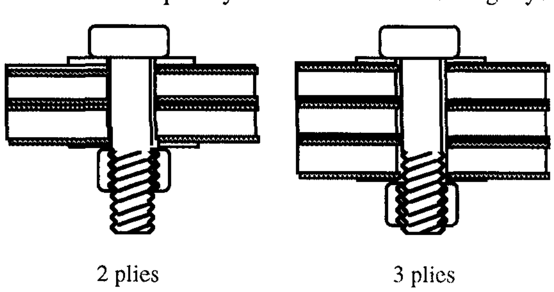
If we now consider that the gripped plates are rigid, the coating layer of the plate (thickness, δ) under the head and nut will compress as the bolt is tightened. As the layer decompresses, the loss in bolt tension is given by,

$$\Delta T = k\sum\delta = \frac{A_{eff}.E}{L}\sum\delta$$

Since the stiffness of the longer bolt specimen (between the head and nut) is greater, it will lose more tension than the shorter bolt specimen.

Using this model, it would also explain the greater tension loss of specimens with thicker plates. Since specimens with thicker plates have more threaded portion in the gripped plates, it will lose less tension.

Similarly, specimens with more gripped plates, which also have more threads in the gripped plates, loses less tension. However, the tension loss is less than if the thickness of the plates were simply increased. This is because the number of coating layer compressed would be more if there are more gripped plates (see Fig. 25). Thus, from the equation for tension loss above, the value of ΔT will increase with increase in the number plates and subsequently in the number of coating layers.



2 plies 3 plies

Fig. 25 Coating layers of 2 and 3 plate specimens

It is true that the amount of thread in the gripped portion of the plates would remain constant in practice regardless of the bolt length. This is due to the requirement that the projected length of the bolt shaft from the nut (about 0.25 inch) and the length of the thread must be constant. So, as the thickness of the gripped material changes, the total length of the bolt shaft must be changed to maintain these requirements. The varying of gripped length of the threaded portion in this experiment is to gather information about what would happen to the tension loss if this is done. Not much information concerning this is available. It was thought necessary to assess such a situation. Such information would be useful to bolt manufacturers for example in deciding whether to increase the thread length in bolt manufacturing. Such an action would mean that the amount of threads in the gripped plates would increase, thus decreasing the bolt tension loss (see section 3.3. and 3.7).

Current practice tries to exclude as much of the threads from the shear plane, which leads to short thread lengths. But work has been done on fully-threaded bolts as reported by Owens[5]. The fully threaded bolt was reported to have a greater deformation capacity. In addition, consistent with this work, the fully threaded bolt would also have less tension loss than a normal threaded one.

4. Conclusions

These conclusions were reached for bolt tension loss experiments over a seven-day period:

(i) Torque-control bolt specimens had a slightly greater tension loss than hexagonal-head bolt specimens after about 1 hour from the release of tightening torque;
(ii) After the first day, increasing the number of plates gripped from two plates to 3 plates slightly decreased the tension loss;
(iii) Increasing gripped plate thickness from 16mm plates to 22mm plates decreases the tension loss;
(iv) Relaxation is greater for specimens with lesser grip length if the number of plates gripped are kept constant;
(v) Specimens with gripped plates with a coating layer exhibited larger tension loss than those without;
(vi) Specimens with gripped plates with a polished (mirror) surface had a smaller tension loss than ones with mill scale surface;
(vii) Specimens with greased bolt threads showed greater tension loss than those that did not;
(viii) Specimens without washers showed slightly less tension loss than specimens with washers;
(ix) Specimens with shorter bolt lengths showed less tension loss.

5. Further Research

This work was a preliminary study of the effects of various parameters on bolt tension loss. Therefore as an extension of this work, it is felt that the number of specimens of the same type should be increased to reduce experimental errors.

It is also felt that further research can be done by extending the tests to specimens subjected to cyclic loads. This will give a more accurate picture of bolt tension loss under actual service conditions. As the connection is subjected to cyclic loads such as that experienced from vehicular traffic, the tension loss is bound to increase. Previous work by Chesson and Munse[1] as well as other researchers found that bolt tension loss due to cyclic loading was about 15% on the average. The major portion of this loss occured only in the first 5 cycles. Not much work however has been done on the influence of location of a bolt in a connection to the degree of tension loss. Are certain locations in a bolt group more susceptible to tension loss? What would be the effect on the connection's load carrying capacity and its rotational capacity, for example.

More work should also be done on the effects of other surface conditions and the effect of weathering and corrosion on bolt tension loss. Exposure to extreme environmental conditions such as that experienced in marine structures and bridges, can lead for example, to the corrosion of bolts. This may in turn decrease the effective diameter of the bolts and subsequently influence the pre-tension in the bolts. If this occurs throughout the whole bolt group or a major portion of it, it could lead to reduced effectiveness as a friction-type connection. In addition, the stiffness of structural members joined together with bolted connections may be reduced significantly if the frictional resistance given by the pre-tension in high-strength bolts is reduced.

The significance of bolt tension loss on bolt group load-carrying capacity should be investigated. It is also important to understand how loss of pre-tension in certain locations may affect the remaining load carrying capacity of the whole connection.

Finally, as discussed earlier, there is some advantage to using fully threaded bolts. In addition to having a larger deformation capacity, the fully threaded bolt would have lesser bolt tension loss because the effective cross-section area between bolt head and nut is less than for a normal bolt. Therefore, it would seem worthwile to further investigate fully threaded bolts in relation to tension loss.

References

1) Chesson, E. Jr., Munse, W.H., *Studies of the Behavior of High-Strength Bolts and Bolted Joints*, Engineering Experiment Station Bulletin No. 469, U. of Illinois, Urbana, Illinois, 1965.

2) North, J.S., *A Field Problem with Pre-Load of Large A490 Bolts*, The Structural Engineer, Vol. 64A, No.4, April 1986, pp 93-99

3) North, J.S., *Bolt Pre-Load Measurement Using Ultrasonic Methods*, Engineering Journal, AISC, 22, No.2, 1985

4) Yabotnov, Y. N., *Elementary Creep Theories*, Creep Problems in Structural Members, North-Holland Pub. Co., 1969, pp 195-200

5) Owen, G.W., *The use of fully threaded bolts for connections in structural steelwork for buildings*, The Structural Engineer, Vol. 70, No. 17, 1 September 1992, pp 297-300

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