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DETERMINATION OF THE REQUIRED PART-TURN OF THE NUT WITH RESPECT TO THE NUMBER OF FREE THREADS AT LOADED FACE OF THE FULLY TENSIONED HIGH STRENGTH FRICTION GRIP PROPERTY CLASS 8.8 BOLTS

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ABSTRACT

According to NZS 3404, High Strength Friction Grip (HSFG) property class 8.8 bolts, when installed in the Tension Bearing (TB) and/or Tension Friction (TF) bolt modes, must be installed based on the part-turn method of tightening or by using a direct-tension indication device. Both these first require bolt tightening to snug tight, intended to bring all plies into direct contact. Following snug tightening, the part-turn method of tightening requires rotating the item to be turned (typically the nut) by a specific amount to ensure reaching the code specified minimum bolt tension. The specific amount of the nut rotation is called the part-turn, and is identified by NZS 3404 with respect to the bolt length-to-diameter ratio and contact angle of the outer faces of the bolted parts. Additionally, there is a requirement identified by the most recent edition of NZS 3404 regarding the minimum number of clear threads run out beneath the nut after tightening for fully tensioned HSFG bolts. This necessitates the existence of five, seven, or ten free threads at nut loaded face with respect to different bolt length-to-diameter ratios.

However, there are theoretical as well as practical concerns about the current NZS 3404 recommended part-turn method of HSFG bolt tightening. As for the theoretical concern, the applied part-turn is actually a longitudinal strain that has been imposed on the loaded parts of the bolt to reach the required bolt tension. The free unloaded bolt threaded portion beyond the nut is the only part of the bolt which does not contribute in accommodating this applied strain. Hence, a more precise criterion should exclude this part to identify the required part-turn, however this is complex accommodate in practice. Regarding the practical concern, the joints' grip lengths are quite variable in practice and as a result, satisfying the minimum thread length requirement at nut loaded face has been an issue reported frequently by the industry, especially with bolts now having a higher ratio of shank length to total bolt length than was common when "the minimum number of threads in the grip length provisions" were introduced.

In this paper, the concept of the part-turn is analytically discussed followed by proposing a new criterion for identifying the part-turn, based on the joint grip length rather than the bolt length, in place of the code specified minimum thread length requirement. The results of experiments carried out on two different HSFG bolt sizes i.e. M20 and M24 from two different New Zealand suppliers are then presented. These includes the tensile tests to validate the bolts' material quality and then the tightening tests based on having one to eight threads at the nut loaded face to identify the required part-turn as well as the required turn to fracture the bolt. The tightening tests incorporated the pre installation inspection/preparation recommended by a previous research to reduce the possibility of under-achieving the code specified minimum bolt tension after applying the part-turn. Finally, the required part-turn to fully tension the bolts with respect to different numbers of the threads at nut loaded face are presented.

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Introduction

Bolts are one of two principal types of fasteners widely used in current construction of steel structures. The other type is welds. While welds are usually preferred to be used in the shop portion of the fabrication procedure, using specialized equipment and skilled operators and inspectors, bolts are preferred to be used on site. This is because, bolts are manufactured items, can be installed using simple equipment, and can be installed and inspected by people with a small amount of training to generate simple to rigid connections on site. However, design and specification of a bolted joint requires the structural designer to select the type of fasteners, understand how they are supposed to be used, and to recommend the appropriate methods of installation and inspection. On the other hand, for welded joints, the structural designer only requires to select a standardized specification, technique of inspection, and acceptance criteria, or soliciting the expertise of a specialist (Kulak and Eng 2005). As a result, the structural designers need to know more about the bolts than about welds.

There are two types of bolts, namely the common bolts (ordinary or machine or rough bolts) and the high strength structural bolts; this paper deals only with the latter. Traditionally, bolts made of mild steel were used occasionally in the early days of steel structures, while rivets were the principal fastener. Batho and Bateman (1934) first suggested that high-strength bolts can be used. They found that bolts having a yield strength of at least 372MPa can be pre-tensioned sufficiently to prevent slip of connected material. Another early study (Wilson and Thomas 1938) showed that pre-tensioned high-strength bolted joints have a fatigue life at least as good as that of the riveted joints.

The High Strength Friction Grip (HSFG) property class 8.8 bolts are widely being used in steel structures construction. A common application of the HSFG 8.8 bolts is to provide the friction-type (or slip-critical) connections with the required clamping force to satisfy the design provisions under the serviceability and ultimate limit state earthquakes (SLS and ULS). The use of friction-type connections in the earthquake resistant buildings is growing as the key energy dissipating components for the low damage structural systems such as the Asymmetric Friction Connection (AFC) in the Sliding Hinge Joint (SHJ)(Clifton 2005).

According to NZS3404 (1997/2001/2007), the HSFG property class 8.8 bolts, when installed in the Tension Bearing (TB) and/or Tension Friction (TF) bolt modes, must be installed based on the part-turn method of tightening or using a direct-tension indication device. Both these first require bolt tightening to snug tight, intended to bring all plies into direct contact. Following snug tightening, the part-turn method of tightening requires rotating the item to be turned (typically the nut) by a specific amount i.e. part-turn to ensure reaching the code specified minimum bolt tension. The minimum bolt tension at installation is specified in NZS 3404 as being approximately equivalent to the minimum proof load given in AS/NZS1252 (1996). The part-turn is identified by NZS 3404 with respect to the bolt length-to-diameter ratio and contact angle of the outer faces of the bolted parts.

Another requirement identified by NZS 3404 is the projection of all types of bolt from the nut face to be one clear thread, which is approximately one pitch of the thread. This provision is intended to ensure that full thread engagement over the total nut depth has been achieved. This is accepted practice for snug-tight bolting categories, but is of critical importance for tensioned bolting categories (8.8/TF and 8.8/TB), where the achievement of the specified initial bolt tension is only possible if full thread engagement is achieved. Moreover, a requirement identified by NZS 3404 is regarding the minimum number of clear threads run out beneath the nut after tightening for fully tensioned HSFG bolts. This necessitates the existence of five, seven, or ten free threads under the nut loaded face with respect to different bolt length-to-diameter ratios.

The drivers of this research were the practical and theoretical concerns about the current NZS 3404 recommended part-turn method of HSFG bolt tightening. The joints' grip lengths are quite variable in practice and as a result, satisfying the minimum thread length requirement at nut loaded face has been an issue reported frequently by the industry, especially with bolts now having a higher ratio of shank length to total bolt length than was common when "the minimum number of threads in the grip length provisions" were introduced. Additionally, the applied part-turn is actually a longitudinal strain significantly beyond yield that has been imposed on the loaded parts of the bolt to reach the required bolt tension. The free unloaded bolt threaded portion beyond the nut is the only part of the bolt which does not contribute in accommodating this applied strain. Hence, a more precise criterion should exclude this part to identify the required part-turn, otherwise the applied part-turn can lead to excessive tightening of long bolts with short grip lengths. This is more complex to account for in specification and design, however.

In this research, the concept of the part-turn is analytically discussed followed by proposing a new criterion for identifying the part-turn, based on the number of free threads at the loaded face of nut rather than the bolt length. The results of the experiments carried out on two different HSFG bolt sizes i.e. M20 and M24 from two different New Zealand suppliers are then presented. These includes the tensile tests to validate the bolts material quality and then the tightening tests based on having 1, 3, 4, 5, 6, 7, and 8 threads at the nut loaded face to identify the required part-turn as well as the required turn to fracture the bolt. The tightening tests incorporated the pre installation inspection/preparation recommended by a previous research (Ramhormozian, Clifton et al. 2015) to reduce the possibility of under-achieving the code specified minimum bolt tension after applying the part-turn. Finally, the required part-turn to fully tension the bolts as well as to fracture them with respect to different numbers of the threads at nut loaded face was found experimentally.

Calculating the amount of the part-turn

Ramhormozian, Clifton et al. (2014) proposed a set of equations to calculate the required turn of the nut to tighten the bolts with Belleville springs up to an arbitrary amount of the bolt preload. Considering the zero deflection for the Belleville springs, their equations can be simplified and re written as Equations 1-3 to calculate the required turn of the nut to tighten the bolt up to a certain amount of the elastic bolt preload.

$$K_{bolt} = \frac{AE}{L} \tag{1}$$

$$\Delta_e = \frac{N}{K_{bolt}} = \frac{NL}{AE} \tag{2}$$

$$R = \frac{\Delta_e}{P} \times 2\pi \tag{3}$$

where:

K_{bolt}=longitudinal elastic stiffness of the bolt;

A=effective cross sectional area of the bolt. This can be considered as a weighted average of the bolt shank and thread cross sectional areas with respect to their lengths.

E=elastic modulus of the bolt material;

Δ_e=elongation of the bolt due to the preload N;

R=amount of rotation of the nut in radians to reach the bolt to the preload N from the point at which the bolt tension is just zero;

P=pitch of the bolt threads;

L=effective length of the bolt; this is the summation of the shank length (l_s) and length of the loaded part of the thread (l_t), and can be assumed approximately as the joint grip length i.e. thickness of the plies to be clamped.

Equation 1 can also be re calculated more precisely as Equation 4, which considers the bolt shank and threaded part as two springs in series:

$$K_{bolt} = \frac{A_s A_t E}{l_s A_t + l_t A_s} \tag{4}$$

where; A_s=shank cross sectional ares, and A_t=thread cross sectional area.

Equations 1-3 assume that the plies are longitudinally much stiffer than the bolt, hence can be considered as rigid. It is also assumed to calculate the nut rotation from the point at which the plies are firmly in contact and the bolt tension is just zero. A detailed set of equations are also proposed by (Ramhormozian, Clifton et al.) taking the flexibility of the joint, the bolt head and the nut into account to calculate the required nut rotation. The start point of applying the part-turn in practice is from the snug-tight condition. It is readily possible to modify the proposed equations to calculate the required part turn after the snug tight condition. However, a challenge is the variable nature of the snug tight bolt tension. This challenge is currently being investigated by the authors.

Bolt tensile tests

Six M20 and six M24 bolts i.e. three bolts of each size from each supplier i.e. STEELMASTERS and EDL were at first tensile tested (Figure 1) to validate the bolt material quality according to the NZ3404 and AS/NZS4291 (1995). The speed of loading imposed by the MTS machine was less than 25mm/min specified by AS/NZS 4291. Eight free threads were at the loaded face of the nut for the bolts which were tensile tested according to AS/NZS 4291. Figures 2 and 3 show the bolt tension vs MTS arm displacement of the tensile tests.

The ultimate bolt tensions of the weakest and strongest bolts of each size/manufacturer were 230kN and 234kN, and 221kN and 224kN for M20 bolts from EDL and STEELMASTERS respectively, and 337kN and 343kN, and 317kN and 371kN for M24 bolts from EDL and STEELMASTERS respectively.

All of the bolts behaved as expected in the tensile tests according to the inspection certificates provided by each bolt supplier. The fracture surfaces of the tensile tested bolts are shown in Figure 1. All of the fractured surfaces confirmed the ductile fracture of the bolts in tensile tests.

Figure 1: Bolt tensile test on 500kN MTS (left) and Fracture surfaces of the tensile tested bolts (right)

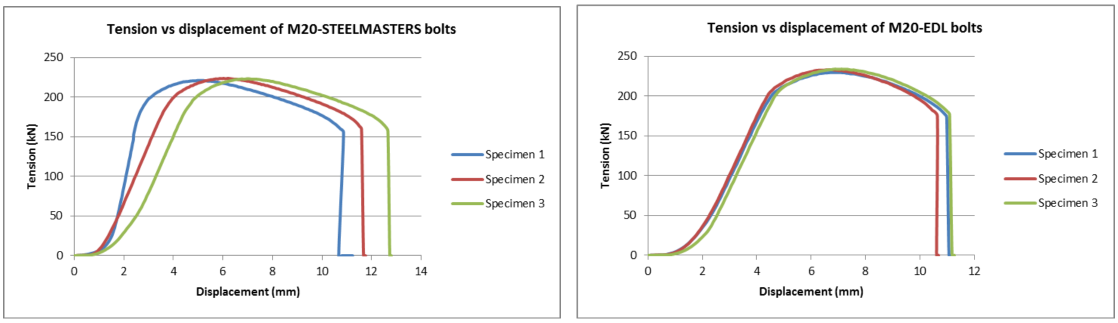


Figure 2: The tensile tests bolt tension vs MTS displacement graphs of M20 bolts: STEELMASTERS (left) and EDL (right)

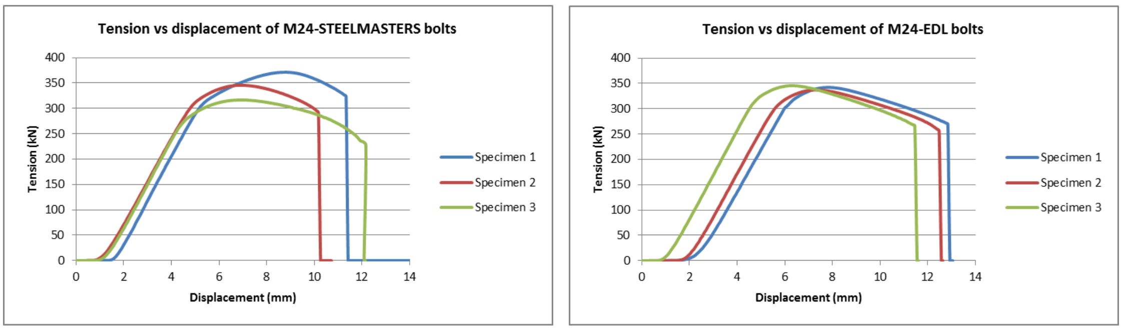


Figure 3: The tensile tests bolt tension vs MTS displacement graphs of M24 bolts: STEELMASTERS (left) and EDL (right)

Bolt tightening tests

A test setup was designed for the tightening tests. This test setup included different 250mm×250mm mild steel plates. Each plate included four standard holes. The plates came with different thicknesses so that the grip length could be adjusted as required to ensure having the desired number of free threads at loaded face of the nut. This test setup is shown in Figure 4 (a). The upper plate was marked to measure the nut turn, as shown in Figure 4 (b). According to Clause 14.3.6.3 of NZS 3404, oil, dirt, loose scale, loose rust, fins and any other defects on the surfaces of contact, which prevent solid seating of the parts in the snug-tight condition, shall be removed. This was done in the tests.

The HSFG Property class 8.8 M20 and M24 bolts were purchased from two different specialist bolt manufacturers, EDL Fasteners and STEELMASTERS. The bolts were tensile tested at first with three repeats for each bolt size from each supplier, as is described in previous section, to validate the bolt material quality. The bolts with 1, 3, 4, 5, 6, 7, and 8 free threads at the loaded face of the nut were tested in the part turn tightening experiments of the bolts with three repeats for each case. Each test concluded by tightening the bolts to fracture, to investigate the required turn of the nut after snug tight condition to fracture the bolt.

The bolts were 100mm long HSFG M20 with 50mm long shank, and 110mm HSFG M24 with 55mm long shank. A physical pre-installation check was undertaken for all of the bolts before the tightening tests in accordance with the recommendations of (Ramhormozian, Clifton et al. 2015) to ensure the nut could run freely over the whole threaded part of the bolt, both down and back up the bolt threads. All of the bolts were lubricated before the tightening tests by GA 50 MULYBUND paste containing 50% molybdenum disulphide. The lubricant was applied along the threads, and the nut was then turned over the whole threaded part of the bolt to spread the lubricant all around the threads. The specialist donut load cells were used to monitor the bolt tension during tightening (Figure 4 (d)). The load cells were sandwiched between two appropriate grade 350 steel washers that were designed and supplied to maximize the accuracy of the load cell readings. The LWO-80 and LWO-60 load cells were used for M24 and M20 bolts respectively. The load cells were supplied by Transducer Techniques Company.

a) b) c) d)

Figure 4: Bolt tightening test setup (a), Measuring the nut turn (b), The torque wrench to apply the part turn (c), and The load cell (d)

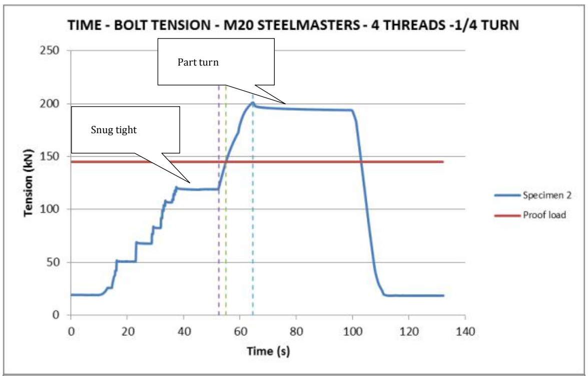
As recommended in clause 15.2.5.2 of NZS 3404, a 100mm long M20 or a 110mm long M24 bolt (i.e. Over 4 diameters but not exceeding 8 diameters of M20 and M24 bolts), the part-turn that should be applied to fully tension the bolts is 1/2 turn. However, this recommendation is based on having at least 7 free threads at the loaded face of the nut. Table 1 shows the applied turn of the nut applied in the tightening tests after snug tight condition for the cases with different numbers of free threads at the nut loaded face.

Table 1: The applied part turn for each number of bolt free threads

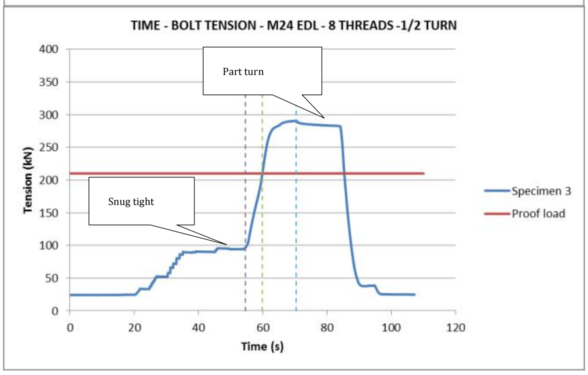
The number of free threads at nut loaded face	The applied part-turn			
	M20 Bolt		M24 Bolt	
	Turn	Degree	Turn	Degree
1	1/4	90	1/4	90
3	1/4	90	1/4	90
4	1/4	90	1/4	90
5	1/4	90	1/4	90
6	3/8	135	1/4	90
7	1/2	180	1/2	180
8	1/2	180	1/2	180

The tightening tests included the following steps: At first, four bolts were snug tightened to firmly bring the plates into contact. One bolt then was removed and the target bolt was installed with the load cell. The nut was turned by a standard wrench according to the snug tight definition presented in NZS3404. Then the part turn values shown in table 1 were applied to the associated bolt nuts using an electronic torque multiplier (Figure 4 (c)). After tightening the bolt, the nut was turned in reverse direction using the electronic torque wrench to untighten the bolt.

The bolt tension was continuously recorded by the donut load cell. This includes the bolt snug tight tension and the bolt part turn tension. Considering the constant rotational velocity applied by the electronic torque wrench for the part turn, the required rotation to just reach the bolt proof load was calculated. After stopping the part turn, a small drop of the bolt tension was observed before reaching the stable part turn bolt tension. This bolt tension drop was also calculated. Figure 5 shows two typical bolt tension-time graphs of the tightening tests with their associated data analysis tables.



No	DATA ANALYSIS OUTCOMES	Unit	Values
1	Snug tight tension	kN	121
2	Proof load	kN	145
3	Bolt tension after applying the part turn	kN	201
4	Bolt tension drop after tightening	%	3
5	Applied turns (After snug tight)	Turn	0.25
6	Applied rotation (After snug tight)	Degree	90
7	Required turn recommended by NZS 3404	Turn	N/A
8	Required rotation recommended by NZS 3404	Degree	N/A
9	The turn required after snug tight to just reach the proof load	Turn	0.08
10	The rotation required after snug tight to just reach the proof load	Degree	27
11	The turn to fracture after snug tight	Turn	1.3125
12	The rotation to fracture after snug tight	Degree	472.5
13	Nut turning condition before tightening test		Free
14	Nut turning condition during untightening		Free



No	DATA ANALYSIS OUTCOMES	Unit	Values
1	Snug tight tension	kN	97
2	Proof load	kN	210
3	Bolt tension after applying the part turn	kN	290
4	Bolt tension drop after tightening	%	2
5	Applied turn (After snug tight)	Turn	0.5
6	Applied rotation (After snug tight)	Degree	180
7	Required turn recommended by NZS 3404	Turn	0.5
8	Required rotation recommended by NZS 3404	Degree	180
9	The turn required after snug tight to just reach the proof load	Turn	0.29
10	The rotation required after snug tight to just reach the proof load	Degree	105
11	The turn to fracture after snug tight	Turn	1.25
12	The rotation to fracture after snug tight	Degree	450
13	Nut turning condition before tightening test		Free
14	Nut turning condition during untightening		Free

Figure 5: Typical bolt tension vs time graphs of the tightening tests (left) and associated data analysis tables (right)

Bolt fracture tests

All of the tested bolts were cleaned by mineral turpentine so that all of the particles generated by the tightening tests were removed. The bolts then were lubricated by GA 50 MULYBUND paste, which had also been used for the initial tightening tests. Then the target bolts were tightened up to the snug tight condition, using the same procedure carried out for the tightening tests. Four hardened washers as thick as the load cell were used at head side of the bolts instead of the load cell. This was to prevent damaging the load cells given the expected higher tension forces expected. Using the electronic torque multiplier, the target bolt nut was turned to tighten the bolt until the bolt was fractured. The amount of the nut turn from the snug tight condition up to the point of fracture then was visually measured and recorded.

Results and discussion

EDL bolt samples:

- For the M20 bolts that had 1,3, 4, and 5 free threads at loaded face of the nut, applying 1/4 turn as the part turn after the snug tight was sufficient to reach the bolts' proof load.
- For the M20 bolts that had 6 free threads at loaded face of the nut, applying 3/8 turn as the part turn after the snug tight was sufficient to reach the bolts' proof load.
- For the M20 bolts that had 7 free threads at loaded face of the nut, applying 1/2 turn as the part turn after the snug tight, which is specified by NZS3404, was sufficient to reach the bolts' proof load.
- For the M20 bolts that had 8 free threads at loaded face of the nut, applying 1/2 turn as the part turn after the snug tight, which is specified by NZS3404, was not sufficient to reach 1 out of 3 bolt samples to the proof load.
- For the M24 bolts that had 1, 3, 4, 5 and 6 free threads at loaded face of the nut, applying 1/4 turn as the part turn after the snug tight was sufficient to reach the bolts' proof load.
- For the M24 bolts that had 7 and 8 free threads at loaded face of the nut, applying 1/2 turn as the part turn after the snug tight, which is specified by NZS3404, was sufficient to reach the bolts' the

proof load.

STEELMASTERS bolt samples:

- For the M20 bolts that had 1, 3, 4, and 5 free threads at loaded face of the nut, applying 1/4 turn as the part turn after the snug tight was sufficient to reach the bolts to the proof load except for one sample with 1 free thread.
- For the M20 bolts that had 6 free threads at loaded face of the nut, applying 3/8 turn as the part turn after the snug tight was sufficient to reach the bolts' proof load.
- For the M20 bolts that had 7 free threads at loaded face of the nut, applying 1/2 turn as the part turn after the snug tight, which is specified by NZS3404, was sufficient to reach the bolts' proof load.
- For the M20 bolts that had 8 free threads at loaded face of the nut, applying 1/2 turn as the part turn after the snug tight, which is specified by NZS3404, was not sufficient to reach 1 out of 3 bolt samples to the proof load.
- For the M24 bolts that had 1, 3, 4, 5 and 6 free threads at loaded face of the nut, applying 1/4 turn as the part turn after the snug tight was sufficient to reach the bolts to the proof load except 1 out of 3 samples of having 4 free threads as well as 1 out of 3 samples of having 5 free threads.
- For the M24 bolts that had 7 and 8 free threads at loaded face of the nut, applying 1/2 turn as the part turn after the snug tight, which is specified by NZS3404, was sufficient to reach the bolts' proof load.

Figures 6 and 7 demonstrates the required part turn value for each bolt sample of each manufacturer to just reach the bolt proof load and to fracture them for M20 and M24 bolts, respectively. As was expected, the bolts with the greater number of free threads at loaded face of the nut required more part turn of the nut to reach the proof load. As was also expected, the variability of the snug tight tension was high. 4.76% of the bolts were failed to reach the proof load by applying the associated part turn values. The bolt tension drop after applying the part turn was calculated as 1% to 4% for most of the bolts. However, this bolt tension drop was calculated as 5% to 13% for a few cases. Due to wearing of the threads, which prevented the nut being able to continue to tighten the bolt, seven bolts failed to reach the point of bolt fracture.

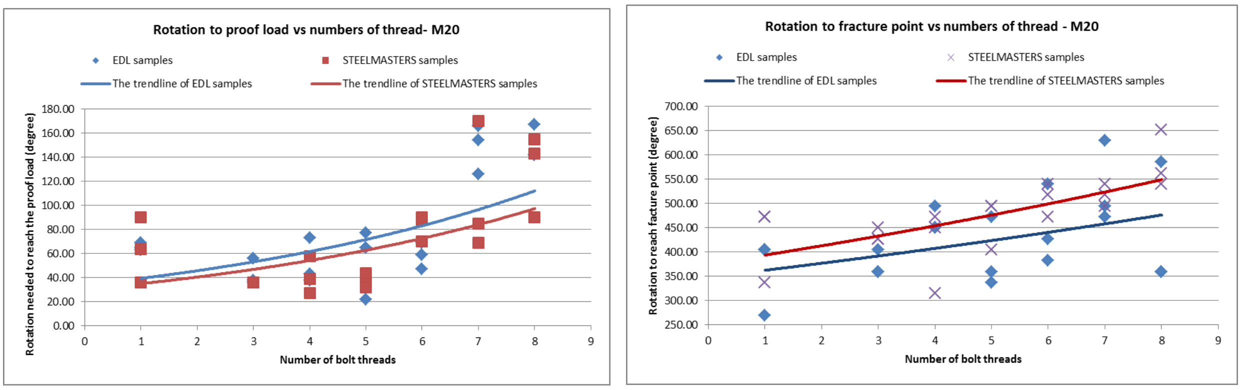


Figure 6: The nut rotation "after snug-tight condition" needed to: just reach the M20 bolt proof load (left) and reach the M20 bolt facture point (right)

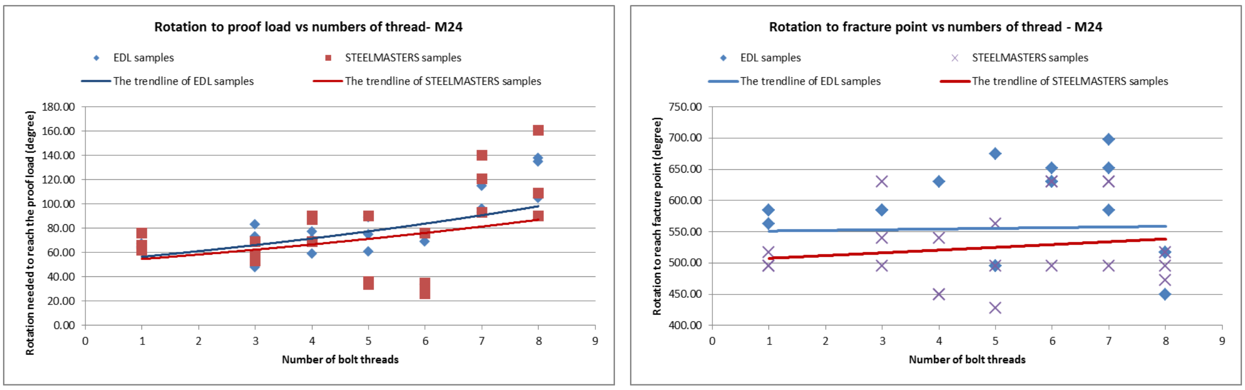


Figure 7: The nut rotation "after snug-tight condition" needed to: just reach the M24 bolt proof load (left) and reach the M20 bolt facture point (right)

Further considerations and recommendations

Regarding the lubrication, three categories can be named for the bolts that were purchased from the suppliers as follows:

- The bolts that had fresh lubricant around the bolt/nut threads. These bolts were the best as there were no need to apply extra lubrication and they could be used if the thread/finish quality was OK.
- The bolts with no sign of any lubricant. These bolts were also OK if the thread/finish quality was OK so could be used after lubricating before the test.
- The bolts which had been lubricated, but due to being stored probably for a long time and/or in an inappropriate place, the lubricant was dried and possibly had absorbed some dust or other tiny particles and became a problem causing the bolts to fail in pre-installation "free turn of nut down and up the bolt treads" inspection/check.

It is recommended that the bolts are lubricated when they are very close to be used in construction. This can be done by one of the following ways:

- The bolts are delivered to the erector in dry/not lubricated condition, and the erector will lubricate and/or check the bolts on site. This will increase the construction time.
- The supplier lubricates and/or checks the bolts just before sending them off on site. This may increase the bolt price.

Additionally, it is found that brushing the bolt threads by a metal handle brush for just few seconds will remove the tiny particles and upgrade the "almost-freely" bolts to "free" category. These categories are proposed by Ramhormozian, Clifton et al. (2015). This can be an additional operation that the suppliers may need to do to the bolts before they sell them e.g. by adding a charge to the bolt sales. Hence the bolt users will receive a guaranteed set of clean bolts and pay slightly more per bolt set than to have to check each one and do this cleaning themselves. Also the users should have a contractual arrangement with the bolt manufacturer to take the payment for this work from the manufacturer who should be supplying clean bolt sets. It is worth noting that for all bolts to be installed /T mode or into friction sliding joints, the test for free running of the nut along the bolt should be carried out and any bolt/nut set that fails that test not used. This is highly recommended as a necessary requirement in the contract documents with written guarantees from the erectors that this has been done.

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