Journal of Constructional Steel Research 126 (2016) 15–25

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Failure modes of bolt and nut assemblies under tensile loading

E.L. Grimsmo *, A. Aalberg, M. Langseth, A.H. Clausen

Structural Impact Laboratory (SIMLab) and Centre for Advanced Structural Analysis (CASA), Department of Structural Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 3 December 2015
Received in revised form 27 June 2016
Accepted 28 June 2016
Available online xxxx

Keywords:
Bolts
Failure
Tension
Experiments
Simulations

ABSTRACT

Thread failure of bolt and nut assemblies subjected to tension is generally undesired because it is a less ductile failure mode than fracture of the threaded shank of the bolt (denoted bolt fracture). Another issue is that incipient failure of the threads due to over-tightening is difficult to detect during installation. Thus, it is appropriate to investigate the causes of thread failure. A parameter that seems to govern the failure mode of bolt and nut assemblies, despite receiving limited attention in the literature, is the length L_t of the threaded bolt shank located within the grip. This is particularly relevant for partially threaded bolts, where L_t may be short. In the current study, direct tension tests were performed on M16 bolt and nut assemblies with different lengths L_t. The tests showed that $L_t \leq 9$ mm resulted in thread failure, whereas $L_t \geq 17$ mm resulted in bolt fracture. For the intermediate range of L_t, both failure modes were observed in replicate tests. Validated finite element simulations were conducted to gain insights into the mechanisms of failure. When L_t was short, necking of the bolt occurred close to the nut so that the overlap between the threads of the bolt and the nut was reduced, which further induced thread failure. This paper suggests several practical approaches for reducing the probability of thread failure.

1. Introduction

There are three common failure modes of bolt and nut assemblies under tension: bolt fracture, bolt thread failure, and nut thread failure. Hereafter, the two latter failure modes are both denoted as thread failure. This paper demonstrates that using partially rather than fully threaded bolts in connections may increase the chance of thread failure. This failure mode is less ductile than bolt fracture and is therefore generally not desired. Another important aspect noted by Alexander [1] is that incipient thread failure may go undetected when over-tightening bolt assemblies during installation of a structure because it is a gradual failure process. Thus, the assembled structure may enter service with weakened or partially failed fasteners.

The standard ISO 898-2: *Mechanical properties of fasteners made of carbon steel and alloy steel – Part 2* [2] states that bolt fracture is the intended fracture mode of bolt and nut assemblies with regular nuts. Additionally, other references emphasize that threaded fasteners loaded under tension should fail by bolt fracture and not by thread failure [3,4]. Despite this, thread failure in destructive tests of bolted connections seems to be a recurring phenomenon [5–9]. Moreover, Grimsmo et al. [10] performed tests on bolted end-plate connections of the type shown in Fig. 1a, where the intended failure mode was end-plate bending deformation combined with tensile bolt fracture. The curves showing moment vs. rotation of the joint in Fig. 1b were determined from two replicate quasi-static tests, where one nut per bolt was used in one test and two nuts in the other. Employing one nut led to thread failure, whereas two nuts led to bolt fracture. Furthermore, two nuts gave an approximately 10% increase in the maximum measured joint moment and a 130% increase of the joint rotation upon initiation of bolt failure. In this case, it is clear that bolt fracture would be preferred. Note that end-plate connections are conventionally designed so that the connections fail by end-plate bending only, and not by bolt fracture.

The failure mode of bolt and nut assemblies subjected to tensile loading is determined by several factors, such as geometry and dimensions (e.g., the cross-sectional area of the bolt, thread dimensions, and thread engagement length), mechanical properties of the bolt and nut material, and the length L_t of the bolt shank located within the grip length L_g. These lengths are defined in Fig. 2 along with the thread engagement length, which is slightly shorter than the nut height due to countersinks on both sides of the nut.

The primary objective of this paper is to study how the threaded length L_t affects the tensile behavior of bolt and nut assemblies, particularly in terms of the failure mode. There are few studies on this topic in the literature. Troup and Chesson [11], and Sterling and Fisher [12] performed both direct and torqued tension tests on ASTM A490 bolt and nut assemblies. They observed more occurrences of thread failure in bolt assemblies when L_t was reduced, but they gave no substantial explanation for this result. Alexander [1] briefly discussed how few threads within the grip, i.e., short-threaded length L_t, may induce thread stripping due to necking of the bolt occurring close to the engaged threads. Unfortunately, he did not provide results from experimental

* Corresponding author.
E-mail address: erik.l.grimsmo@ntnu.no (E.L. Grimsmo).

http://dx.doi.org/10.1016/j.jcsr.2016.06.023
0143-974X/

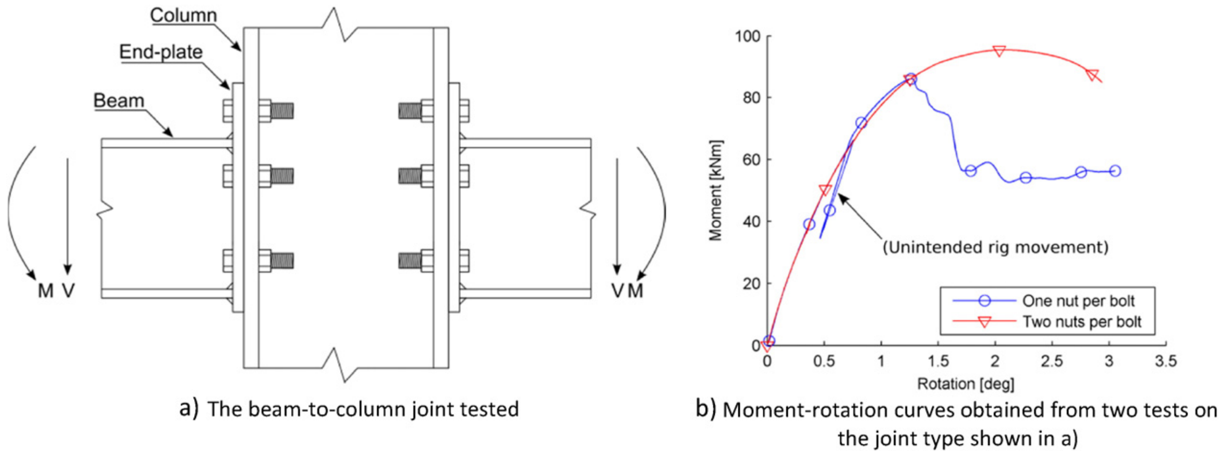

Fig. 1. Grimsmo et al. [10] tested beam-to-column joints with one and two nuts per bolt.

studies. More recently, Fransplass et al. [13,14] studied the behavior of threaded rods at elevated strain rates. They observed that reducing the number of threads within the grip length changed the failure mode from shank failure to thread failure, both in tests and in numerical simulations. The rods were screwed into threaded holes in bars with much higher strength, which experienced practically no deformation during the tests. Thus, the work by Fransplass et al. did not incorporate the effects from internal thread deformation and nut dilatation, i.e., outward radial displacement of the nut.

Note that the available literature is ambiguous in terms of the influence of the threaded length L_t on the failure mode. Amrine and Swanson [15] experienced only bolt fracture when they tested ASTM A325 bolt and nut assemblies with a varying number of threads in the grip. Nevertheless, to our knowledge, no publications in the literature have the purpose of investigating how the threaded length L_t affects the failure mode in bolt and nut assemblies.

The current paper presents results from a series of direct tension tests on partially and fully threaded bolt and nut assemblies, where the grip length L_g, and thus the threaded length L_t, was varied. A finite element (FE) model of the tests is also presented, primarily for investigating the mechanisms determining the failure modes and for evaluating the test results. After validating the FE model against the experimental tests, the model was employed to investigate how the response was affected by varying the yield strength and hardening of the nut, and whether thread failure could be prevented by using a high nut.

This article is organized as follows. Section 2 specifies the types of bolt and nuts used in the experimental program. The results from the material tests obtained from standard uniaxial tension tests and hardness measurements are provided in Section 3. In Section 4, the setup and results of the tests on the bolt and nut assemblies are presented. The FE model and simulation results follow in Section 5. Finally, discussions and conclusions are provided in Sections 6 and 7, respectively.

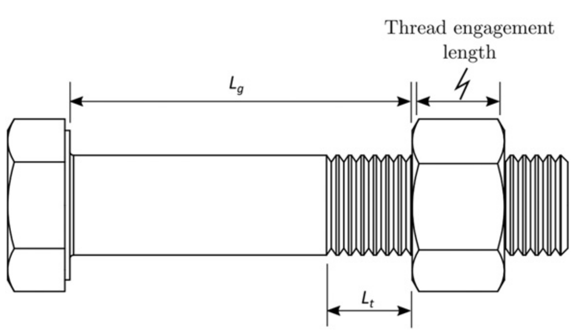

Fig. 2. Definitions of grip length L_g, threaded length L_t, and thread engagement length.

2. Bolt and nut specimens

The tested bolts were partially threaded (PT) or fully threaded (FT) M16 × 160 mm bolts of grade 8.8 manufactured according to the standards ISO 4014: *Hexagon head bolts* [16] and ISO 4017: *Hexagon head screws* [17], respectively. The property class of the nuts was 8, and they were manufactured according to ISO 4032: *Hexagon regular nuts* [18]. Fig. 3 shows the two types of bolt and nut assemblies tested herein. The chosen specimens were generic bolts and nuts, in that they were not certified according to the standards NS-EN 15048-1: *Non-preloaded structural bolting assemblies – Part 1* [19] or NS-EN 14399-1: *High-strength structural bolting assemblies for preloading – Part 1* [20]. Nevertheless, the results in Section 4.2 demonstrate that the bolt and nut assemblies satisfied the minimum tensile resistance requirement (130 kN) of the former standard. Moreover, the bolts and nuts are shown to satisfy the relevant requirements of mechanical properties and dimensions found in appropriate ISO standards.

3. Material tests

3.1. Tension tests

Quasi-static tension tests were performed on specimens machined from both the partially (PT) and fully threaded (FT) bolts. As depicted in Fig. 4, the uniaxial tension specimens were machined to a reduced diameter of 12 mm over a parallel length of 72 mm. The tests were conducted in a screw-driven machine at a strain rate on the order of 10^{-4} s^{-1}. All the tests were monitored with a digital camera. A speckle pattern was sprayed on the specimens so that local strains in the neck could be acquired from digital image correlation (DIC) analyses.

Five replicate material tests were performed on each of the two bolt types, PT and FT, giving the results shown in Fig. 5. The engineering strain was determined by DIC analysis. As observed in the figure, the PT bolt material is clearly stronger, both in terms of yield and ultimate

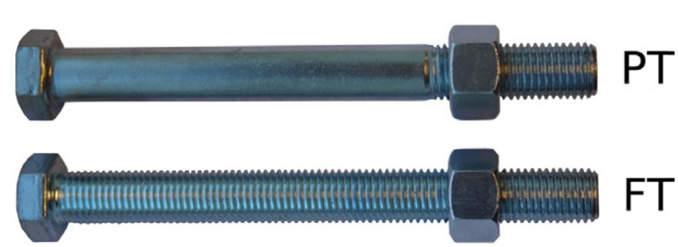

Fig. 3. Photo of the two types of bolt and nut assemblies employed in the tests, one with a partially threaded (PT) bolt and the other with a fully threaded (FT) bolt. The grip length L_g = 118 mm for both these assemblies.