PERFORMANCE OF HIGH STRENGTH STRUCTURAL BOLTS IN TENSION: EFFECTS OF TOLERANCE CLASSES

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ABSTRACT

Structural bolts have been manufactured for building construction for hundreds of years. In practice, failure of high strength structural bolts might be caused by their tolerance classes or coating procedures, which may weaken their internal or external threads. However, this research work is dedicated to understanding a bit more on bolt performance in tension, accounting for effects of tolerance classes in the applied numerical simulation for assessment of performance of structural bolts subjected to tensile loading. In addition, different constitutive relationships has also been taken into account in the numerical analysis in use of both implicit and explicit methods. The observed simulation results demonstrated two failure mechanisms for structural bolts, threads stripping and bolt shank failure, which has proved to be associated with their tolerance classes and coating procedures applied. As a result of this, carefully selecting bolts and nuts is a deliberate solution in preventing the premature failure (threads stripping) in bolted connections for performance-based steel construction.

KEYWORDS

High strength bolts, tension, numerical simulation, threads stripping.

INTRODUCTION

In modern steel construction, bolted connections are commonly in use for assembling steel beams and columns for a steel-framed building, transmitting the loads applied from one steel member to another. Based on their stiffness, strength and rotational capacity, a classification system has been proposed in the research work of Nethercot et al. (1998) and four categories, including fully connected, partially connected and pin connected and non-structural connections, are specified for both serviceability and ultimate limit states in the classification. It ought to be worthy of understanding that the rotational capacity of a bolted connection is rooted from the deformation of its components and the interactive mechanism between them (Kuhlmann and Furch 1997). In fire, mechanical performance of steel connections may be variable due to deterioration of material properties, i.e. strength and Young's modulus. Certainly, the interactive mechanism may be another interesting point for these connections, which, however, will not be discussed in this paper.

In addition, failure in structural bolts might be a critical phenomenon in a fire situation, which has been found for bolted connections in a series of experimental tests (Wang et al. 2010), also discovering two primary failure mechanisms: thread stripping and bolt shank necking. For engineers and designers, failure in threads means reduction of tensile resistance of structural bolts in a fire or non-fire situation, which has been proved in the experimental tests of Kirby (1995) and Hu et al. (2007). They also indicated that fire performance of assembled bolts and nuts would be affected by these failure modes plus factors related to the manufacturing process and variation in tolerance classes. As a result, tensile performance of high strength structural bolts in fire needs to be carefully examined through application of finite element simulation in this research work.

FINITE ELEMENT SIMULATION

Helical Thread Model for Structural Bolts

In simulation of bolt performance in tension, the simplified approach was applying a two-dimensional FE model to represent a three-dimensional problem (Chen and Shih 1999). However, this simplification would result in stacking an appropriate number of threads in the threaded portion for the FE models, unable to catch helical effects in external and internal threads, e.g. loosening phenomena of bolted joints. Therefore, Fukuoka and Nomura (2008) highlight that, when analyzing the mechanical behavior of bolted connections with three-dimensional analysis, it has been a common practice that using helical thread models for the threaded portion of bolts has asymmetrical geometry. The general details on geometrical dimension for a single fastener are illustrated in Figure 1. In addition, as presented in the research work of Kirby (1995) and Hu et al. (2011), the tolerance class (the degree of fit) and over-tapping process (for accommodating the extra zinc coating layer) may have an influence on bolt performance in tensile failure. So internal and external threads have been set up for producing thread difference of tolerance classes in the numerical analysis. General details on tolerance classes for high strength hexagonal bolts are determined in accordance with specification of BS 4190 (BSI 2001), BS 3692 (BSI 1967) and BS EN ISO 4014 (CEN 2001) for the proposed helical thread model. Thread profile details are available in the specification of BS 3643-1 (BSI 1981) and ISO 965-5 (ISO 1998).

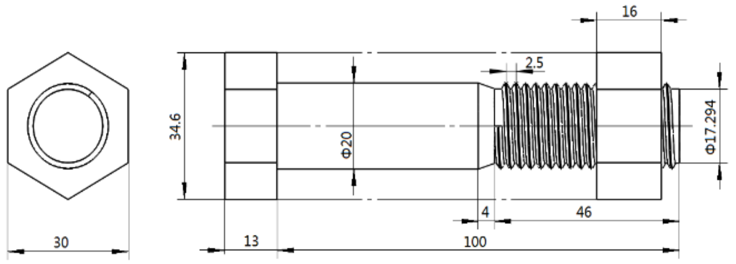


Figure 1 Geometrical details for a single fastener

Tolerance Class

Tolerance class is defined as a number and letter combination for indicating the degree of fit between internal and external threads: the figure representing the tolerance grade and the letter indicating the tolerance position, as illustrated in Figure 2. The previous standards (BS 3643-1, ISO965-4 and ISO 965-5) present the specified tolerance classes for internal threads to mate with external threads. The British standards (BS 4190, 2001) accept the tolerance class 7H/8g as the specification, while a closer fit (6H/6g) for internal and external threads has been adopted in the European standards (BS EN ISO 4014, 2001). The British standard also states that, when a thick protective coating is applied to a structural bolt of grade 8.8 or 10.9, internal threads are required to be over-tapped for protection of bolt threads. Normally, a zinc-based metallic layer has been applied to these threads based on the ISO standard (ISO 965-5, 1998) through calculating fundamental deviations, EI_{AX} or EI_{AZ}, where the over-tapped thickness for the coating is about 0.4 mm. This process may result in a problem on weakening the internal (nut) threads for structural bolts. The thread profiles for internal and external threads, including the major, pitch and minor diameters, are already available in the standard BS 3643-1 (1981), where their tolerance positions and thread profiles are also demonstrated in Figure 2.

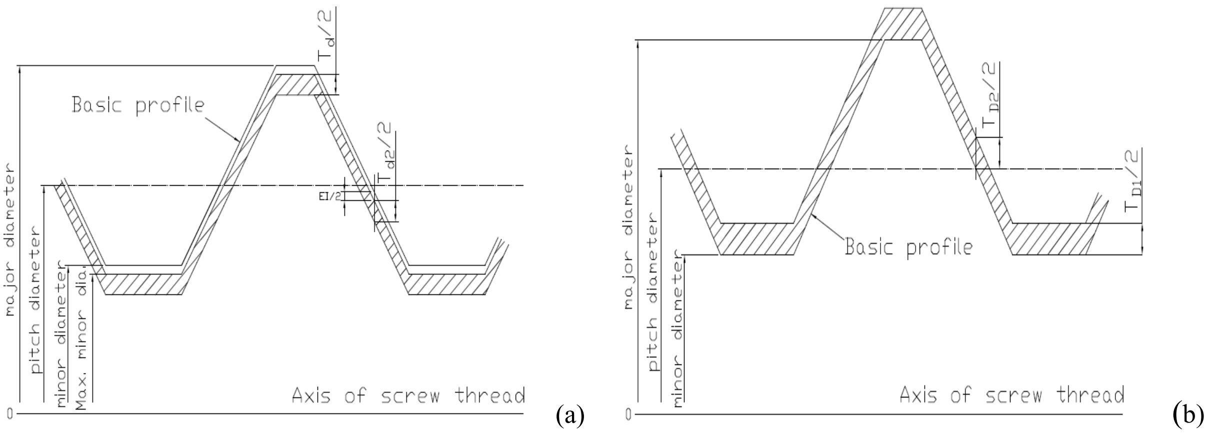


Figure 2 thread profiles for external and internal threads: a) tolerance position g for external threads; b) tolerance position H for internal threads

Mesh Generation and Contact

Fukuoka and Nomura (2008) advised researchers to use some sophisticated functions of commercial software for an effective modeling. So the mesh generation scheme proposed here may be executed with the help of commercial software e.g. ABAQUS. The finite element mesh for a single bolt with its boundary conditions is illustrated in Figure 3, with applying 3D continuum hexahedral elements in numerical analysis, recommended by Sherbourne and Bahaari (1994 and 1997). Regarding the FE model shown in Figure 3, for the bolt cylinder, axial displacements are fully restrained at the bottom surface of a bolt, and the axial force is applied as a uniform displacement to a nut surface. For contact simulation, there are two formulations (small sliding and finite sliding) available for modeling the interaction between two contacting surfaces. Comparison has been performed for small sliding and finite sliding, and it has been realized that the small sliding formulation is less expensive in computation than the finite element sliding approach (Abaqus 2014). Regarding the contact friction, Fukuoka and Nomura (2008) present that coefficients of friction μ are varied from 0.05 to 0.20, with coefficient of friction = 0.15 employed within this study. Master surfaces and slave surfaces are specified for internal and external threads, as illustrated in Figure 3. In addition, general details for integration methods, element types, contact formulations and applied displacements are collected for the simulation in Table 1.

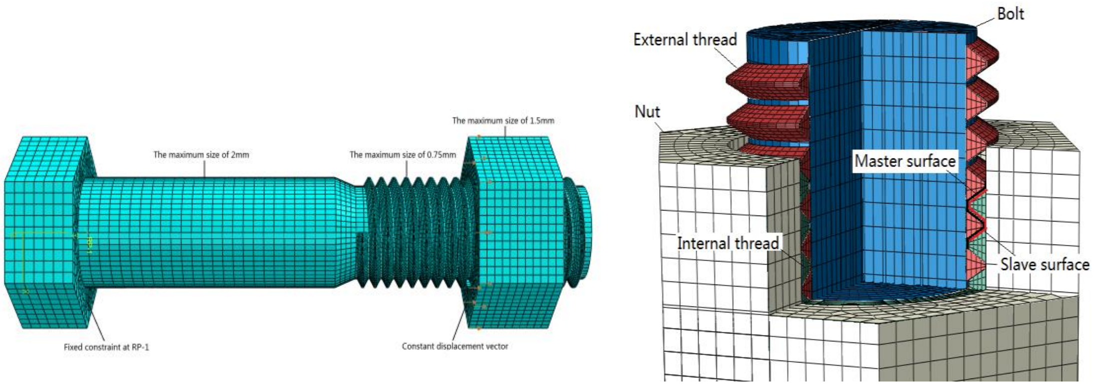


Figure 3 Finite element mesh with boundary conditions

Table 1 Detailed information of the numerical model

Bolt group	Bolt standards	Nut standards	Tolerance class	Integration method	Element type	Contact simulation	Failure mode
Bolt group B	Grade 8.8 (BS EN ISO 4014)	Grade 10 (BS EN ISO 4032)	6H/6g	Explicit	C3D8R	Small sliding	Ductile necking
Bolt group B				Implicit	C3D8I	Small sliding	Ductile necking
Bolt group C	Grade 8.8 (BS 4190)	Grade 8 (BS 4190)	7H/8g	Explicit	C3D8R	Small sliding	Threads stripping
Bolt group C				Implicit	C3D8I	Small sliding	Threads stripping

Material Laws

It has been a common practice that structural bolts and nuts are made from low alloy metals or carbon steels, whose Young's modulus and Possion's ratio are 200 GPa and 0.3, respectively. Four different constitutive relationships, demonstrated in Figure 3, are represented with engineering stresses and engineering strains for bolt materials, proposed in the research work of Hu et al. (2010), Bahaari & Sherbourne (1997) and Dessouki et al.(2013). The von Mises yield criterion is commonly applicable to the metal-based materials for prediction of the onset of yielding, and the behavior on further yielding is predicted by the associative 'flow rule' and hardening law. The bi-linear material model, shown in Figure 4 (a), assumed the onset of yielding at the strain ε_p corresponding to the proof stress, and simply determining the value of 5% as the ultimate strain for the bolt material. Bahaari and Sherbourne (1997) presented a trilinear stress-strain model displayed in Figure 4 (b), the yield stress was considered to take place at a strain of 0.006 and the ultimate strength presumed at a train of $8\varepsilon_p$, where ε_p is the proof strain. Dessouki et al. (2013) modified the previous trilinear stress-strain relationship for the bolt material, as illustrated in Figure 4 (c), where the yielding strain was assumed as $3.5\varepsilon_p$, corresponding to the 'yielding' strength ($0.67f_u + 0.33f_{0.2p}$). The ultimate strength and strain adopted are the same as previously described. The final trilinear material model, as displayed in Figure 4 (d), assumed a yielding plateau between ε_p and $3\varepsilon_p$, and the ultimate strength is specified at a strain of 5% for the numerical analysis.

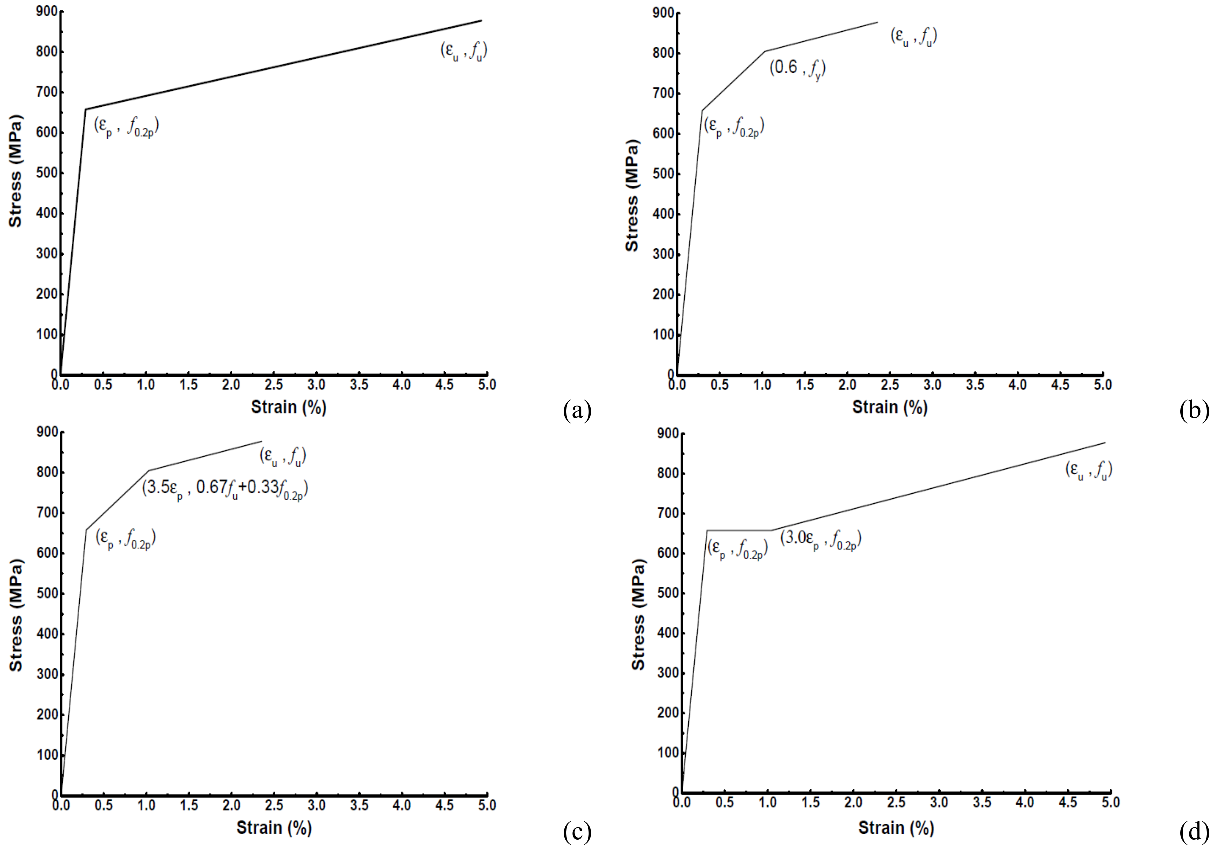
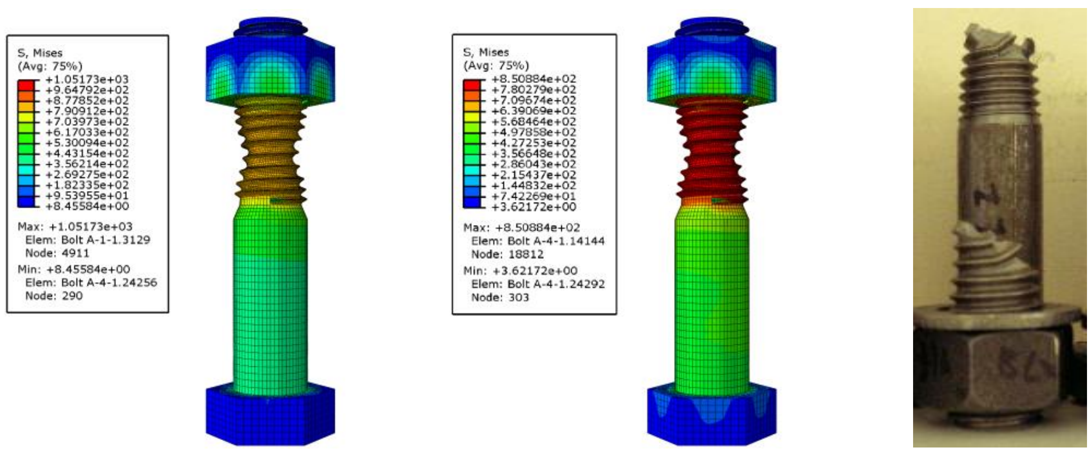


Figure 4 Material laws for structural bolts (a) Bi-linear model, (b) Trilinear model 1, (c) Trilinear model 2, (d) Trilinear model 3

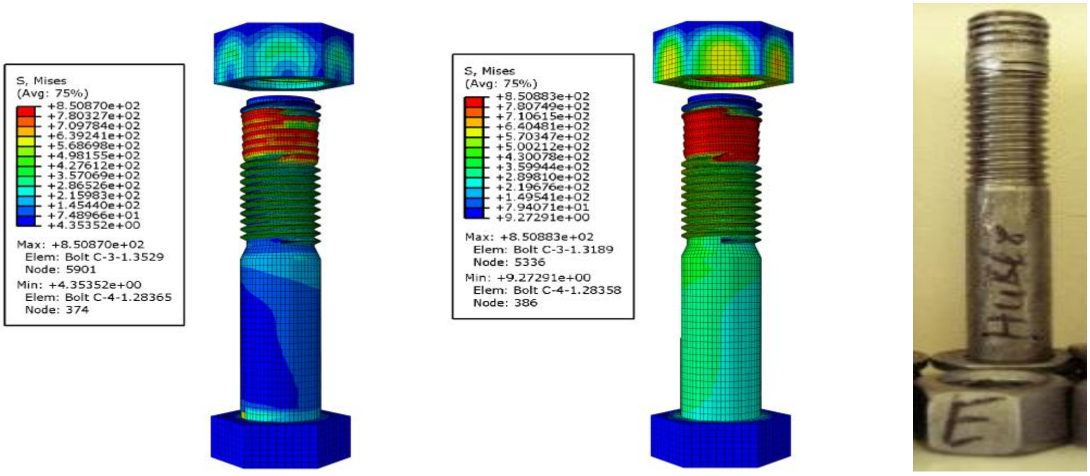
NUMERICAL RESULTS AND DISCUSSION

Failure Mechanisms

Failure of structural bolts in the numerical simulation has been illustrated in Figure 5, in comparison with bolt failure mechanisms in experimental testing. It has been observed that the failure mechanisms produced from the numerical analysis are consistent with experimental tests, including ductile necking and threads stripping for structural bolts. However, the numerical analysis is not capable of addressing the fracture behavior for these components, owing to no failure criteria introduced into the numerical simulation.



(a)



(b)

Figure 5 Failure mechanisms: a) bolt shank failure; b) threads stripping

Force-Displacement Curves

Previous discussion tends to be focused on producing the failure of structural bolts in the numerical analysis. Nevertheless, influence of various constitutive models on bolt performance may be worthy of further investigation. As a result, the force-displacement curves produced from the numerical simulations considered different constitutive material laws, as illustrated in Figure 4. In accordance with the European Standards (CEN 4014/4017), the yielding and ultimate loads (161 kN and 203 kN) are derived analytically for structural bolts, displayed in Figure 6. Then the numerical analysis has been performed through implicit and explicit integration procedures. From these numerical simulations, it should be very clear that before the yielding limit (161 kN), forces and displacements recorded are almost identical for all the plotted curves in Figure 6. After the material yielding, the load-deformation relationships for Bilinear model and Trilinear model 3 are almost consistent in the numerical analysis. In a similar way, the plotted curves for Trilinear model 1 and Trilinear model 2 are in good agreement with each other in the displayed figure below. In addition to this, the numerical simulation discovered that the bearing capacity of a single bolt was highly dependent on its failure mechanism. The numerical models with bolt shank failure overestimated their bearing capacities in comparison with the theoretical value calculated from the standards. For bolts failed with threads stripping, the numerical models might underestimate the peak values in the analysis.

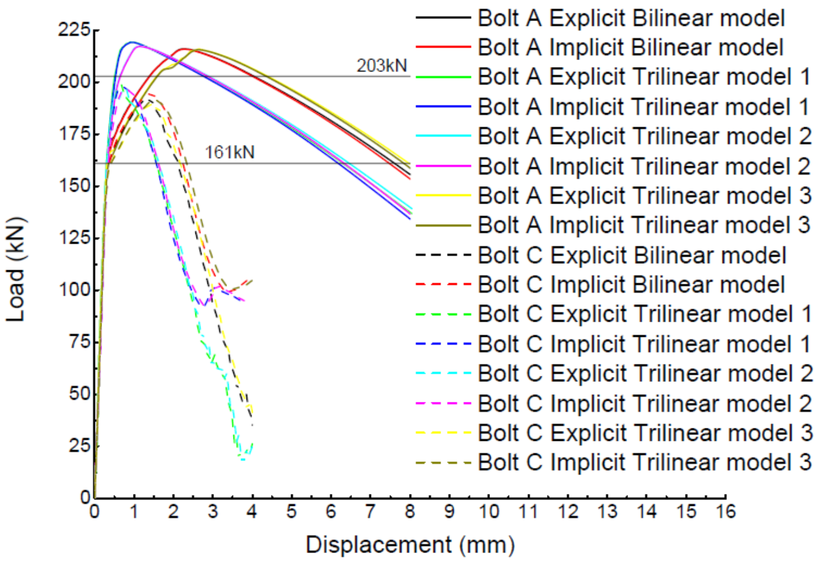


Figure 6 Numerical simulation results for constitutive laws

CONCLUSIONS

This research work investigated tensile performance of high strength structural bolts with determined tolerance classes in their threads in use of the numerical analysis. It also considered the influence of different material laws and numerical integration procedures on numerical results. After compared with experimental and analytical results, it should be clear that the numerical simulation is capable of predicting the failure modes of structural bolts. Secondly, the bearing capacities of bolts are closely dependent on their failure mechanisms achieved in pure tension, confirmed by experimental testing and numerical analysis. Thirdly, the numerical prediction on the bearing capacity for a single bolt is generally in the acceptable region compared with the theoretical value (203 kN). Overestimation or underestimation to failure loads of bolts might be observed in the simulation relying on their failure modes produced.

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