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Simplified numerical model for high-strength bolted connections

Zhongwei Zhao*, Bing Liang, Haiqing Liu, Yongjing Li

School of Civil Engineering, Liaoning Technical University, Fuxin 123000, China

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ABSTRACT

Numerical method has become one of the main methods for investigating the mechanical behavior of high-strength bolts. However, its high computation cost and non-convergence make its application in joints containing refined bolted models impossible. A new bolt-slip model was proposed for the simulation of high-strength bolted connection based on this background. The method to determine the real constant of the friction element was also proposed. The results derived by the newly proposed bolt-slip model were compared with the results derived by the existing numerical model and experimental work. The comparison results indicated that the sliding phenomenon can be well captured and the friction force with enough accuracy can be derived by the proposed bolt-slip model. Results indicate that the proposed bolt-slip model can significantly reduce computation time with high accuracy kept.

1. Introduction

Finite element method has been the main analytical method used in almost all research fields, such as mechanical and civil engineering. Numerical analysis can help determine the potential failure modes and ultimate loading capacity of all kinds of connections. High-strength bolts have been widely adopted in connections between beams and columns in building structures. The contact state of high-strength bolt is a kind of highly nonlinear mechanical behavior, which requires several iterations and intensive computation during numerical analysis and even yields divergent results.

High-strength bolts have a significant influence on the overall mechanical behavior of beam–column joints. Many researchers have incorporated the refined numerical model of bolts into the full finite element model of joints [1–3]. Ma et al. [4] proposed a numerical model of fully grouted bolts and simplified the bond–slip relationship of the bolt–rock interface, which is represented by a trilinear model. Hwang [5] constructed a detailed 3D model of the joint and used finite element dynamic simulation to simulate the installation process of the bolt by gradually applying torque until the bolt failed. McCarthy et al. [6] developed a 3D finite element model to analyze the effects of bolt–hole clearance on the mechanical behavior of bolted composite (graphite/epoxy) joints. The researches mentioned above are conducted based on numerical model in small scale. The refined model need amazing computational power to complete numerical analysis and it is almost impossible to conduct static analysis based on refined numerical model in large scale, let alone the cyclic analysis. In addition, nonconvergence is always a problem for existing numerical models due to the large amount of contact element.

Rigorous calculation is the key problem in the numerical analysis of bolted connections. Many researchers have conducted studies to reduce computational cost for bolt connections. Liu and Chen [7] proposed a global–local finite element numerical method to reduce the computation time and resources. Bogdanovich and Kizhakkethara [8] performed stress analysis based on the sub-modeling approach and concluded that the sub-modeling approach provides an efficient computational tool for enhancing stress analysis in the sites of high-stress gradients. Gunnion et al. [9] and Breitweg [10] showed that PLINK can capture the strength, stiffness, and energy absorption of bolted joints within a single element formulation. Pearce [11] presented the quasi-static and dynamic modeling of bolted composite structures using the explicit finite element method. But these models did not reduce computation cost in nature. It was always time consuming to establish these models. So, it is urgent to put forward an efficient bolt model with high accuracy. This model should be suitable for static analysis and cyclic analysis at the same time.

A simplified joint model can ensure the excellent balance between accurate joint behavior and computation cost. A bolt-slip model was put forward based on commercial software ANSYS to resolve the problems mentioned above. The commercial software ANSYS has always been adopted for establishing refined numerical model of bolt connections in small scale. Both refined and newly proposed bolt-slip models were established based on ANSYS in the present study. The results derived by the newly proposed bolt-slip model were validated by the results

* Corresponding author.
E-mail address: zhaozhongwei@lntu.edu.cn (Z. Zhao).

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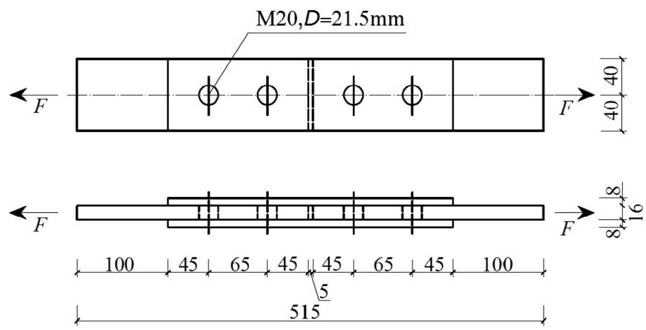

Fig. 1. Geometric parameters of the adopted specimen (unit: mm).

derived through the existing numerical model and experimental work.

2. Establishing the numerical model

The existing and newly proposed numerical models of high-strength bolted connections that were established are discussed in this section. The specimen used in the experiment conducted by Li et al. [12] was adopted in this study. The geometric parameters of the adopted specimen are shown in Fig. 1. The length and width of the specimen were 515 and 80 mm, respectively. The material of this high-strength bolt was 20MnTiB and this material was recommended for high strength bolt in GB/T 1231-2006 of China. The yield strength of the bolts was 940 MPa, and the tension strength was 1040 MPa. The pretightening force in the bolts was 155 kN. The material of the steel plates was Q235B whose yield strength, elastic modulus, Poisson ratio, and density are 235 MPa, 210 GPa, 0.3, and 7800 kg/m^3. The diameter of the bolt hole was larger than the bolt by 1.5 mm. The results derived can be compared with those derived by the experiment for validation.

2.1. Establishing the existing refined model

The existing refined model was established based on the proposed general finite element code ANSYS. SOLID185 was used for the meshing of the bolt and steel plate. SOLID185 is used for the 3D modeling of solid structures and is defined by eight nodes that have three degrees of freedom at each node, namely, translations in the nodal *x*-, *y*-, and *z*-directions. The element has plasticity, hyperelasticity, stress stiffening, creep, large deflection, and large strain capabilities. Contact elements CONTA174 and TARGE170 were used in modeling the mechanical behavior of bolts and different steel plates. CONTA174 is used to represent the contact and sliding between the 3D "target" surfaces (TARGE170) and the deformable surface defined by this element. The element is applicable to 3D structural and coupled field contact analyses. PRETS179 was adopted to apply pretightening load to the bolt. PRETS179 is used to define a 2D or 3D pretension section within a meshed structure. The pre-tension element (PRETS179) has one translation degree of freedom along a defined load direction [13].

The existing refined model of a bolted connection is shown in Fig. 2. The amount of penetration between contact and target surfaces depends on the normal stiffness (FKN) and the max value allowed for FKN is 1. The penetration can be reduced by increasing the value of FKN. So, the normal contact stiffness FKN was 1, and the default values of the other parameters were adopted. The penalty function and Lagrange multiplier were chosen for the contact algorithm. Sliding between steel plates was permitted.

2.2. Establishing the newly proposed bolt-slip model

The contact state between the different parts of the bolted connection exhibits a kind of highly nonlinear behavior. The element size must be sufficiently small to derive accurate results. Establishing the existing refined models of bolted connections is tedious, and the computation cost is unreasonable. Thus, a simplified numerical modeling technology of high-strength bolted connection is necessary, and based on which the mechanical behavior of bolted connection can be accurately predicted and the computation cost can be reduced. Then, a large-scale numerical model of connection, such as the beam–column connection, can be established.

A bolt-slip model that is suitable for high-strength bolted connections was proposed in this study. The steel plate can be simulated by shell elements, such as the SHELL181 element in ANSYS, to reduce the tedious work required for establishing the existing refined model of bolted connections. Beam elements, such as BEAM188, were adopted to simulate the fastener shank. The compression-only spring element, COMBIN39, was adopted to simulate the contact behavior between the fastener shank and the steel plate. COMBIN39 is a unidirectional element with nonlinear generalized force-deflection capability that can be used in any analysis. The element has longitudinal or torsional capability in 1-D, 2-D, or 3-D applications. The longitudinal option is a uniaxial tension-compression element with up to three degrees of freedom at each node: translations in the nodal x, y, and z directions. COMBIN39 was also adopted to simulate friction between different components. All the spring elements were established at the nodes around the bolt hole. That is, each node around the bolt hole had one contact spring element and one friction spring element. The rigid beam option of the MPC184 element was adopted to connect the nonlinear springs, including the contact and friction springs, and the nodes of BEAM188 (fastener shank). MPC184 comprises a general class of multipoint constraint elements that apply kinematic constraints between nodes. The constraint may be as simple as that of identical displacements between nodes. Constraints can also be more complicated, such as those modeling rigid parts. A schematic of the newly proposed bolt-slip model is shown in Fig. 3. The coordinates of Node I and Node I′ were the same.

The nonlinear friction element adopted should be able to capture the mechanics characteristic of friction, i.e. the friction value was

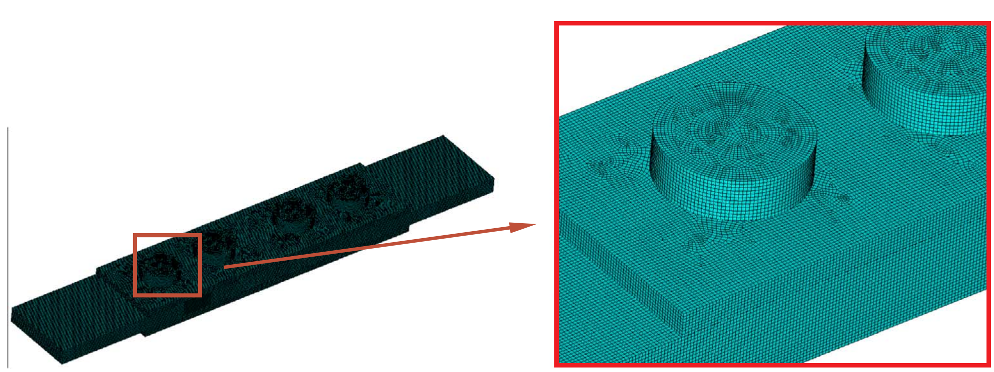

Fig. 2. The existing refined model of a bolted connection.