

Finite Element Failure Analysis of Single-Lap Bolted Connection Under Impact Load



Mingpo Zheng, Zhifeng Liu, and Magd Abdel Wahab

Abstract Bolted connections are widely used in various mechanical structures due to their structural and strength advantages. However, the bolted connection will fracture and lead to failure under the action of excessive load, which affects the service reliability of the structure. In this work, the mechanical performance of single-lap bolted connection under impact load was elaborated by finite element analysis. In order to obtain a more reliable connection, different parameters were considered, i.e. tightening torque, load amplitude, friction coefficients for the contact surfaces, etc. In order to investigate the effect of various friction coefficients on the structural slip under impact load, orthogonal tests were designed and carried out. The results showed that the influence ranking of each friction coefficient on the structural slip was as follows: contact friction coefficient, thread friction coefficient, head friction coefficient, and bearing surface friction coefficient. The performance under impact load was positively related to the magnitude of the tightening torque. Within a certain impact load amplitude threshold, the structural performance was relatively stable. The reference basis for the reliability design of bolted connections based on the service and structural performance can be obtained from the finite element analysis results.

Keywords Bolted connection · Slip distance · Impact load · Reliability design

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1 Introduction

Bolted joint is one of the most widely used connections in various mechanical structures. However, under external loads, threaded fasteners will be self-loosening and lead to performance degradation of the connection structure during its entire service life [1]. According to the mechanical performance requirements, bolted joints were divided into different categories [2, 3]. For some applications, slippage between bolted joints is prohibited, while, in other applications, it is considered to be failure when fracture occurs. Therefore, the design and use of reasonable and reliable bolted joints should be carried out according to the specific structural form and service performance requirements.

Refs. [4–6] showed that the mechanical properties of bolted joints under transverse loads exhibited staged characteristics. Furthermore, various mechanical properties of bolted joints were exhibited under different load forms and influencing factors. Abd-Elhady et al. [7] studied the effect of structural dimensions and tightening torque on the performance of bolted joints. Jalali et al. [8] found that the surface roughness of material also affected the tangential stiffness of the structure. Izumi et al. [9] found that the transverse load threshold when large slip occurs was positively related to the clamping force and friction coefficient. Subsequently, their finite element analysis results showed that when the external load did not exceed a certain limit of the slip threshold, the mechanical properties of the structure could remain relatively stable [10].

Various service conditions of bolted joints lead to different kinds of loads and failure modes. The form of load also inevitably affects the mechanical properties of the connection. Under impact loads, larger amplitudes may sometimes be reached in a short period of time, making the bolted joint more prone to failure. Herein, finite element analysis method is adopted to investigate the mechanical properties of bolted joints under impact load. Orthogonal tests are designed and carried out to investigate the effect of various friction coefficients of bolted joint on structural slip under transverse impact load. In addition, the displacement under different tightening torques and load amplitudes is also investigated. The reliability design of bolted joint can be carried out through the finite element analysis results under various influencing factors.

2 Finite Element Analysis Setup

2.1 Load and Boundary Conditions

In the finite element analysis, two plates made of the same dimensions were joined together by M16 bolts and nuts. The length and width of the connecting plate were 80 mm and 60 mm, respectively. The bolt hole diameter was 17 mm. There are a total of three analysis steps that were set during the finite element analysis. In

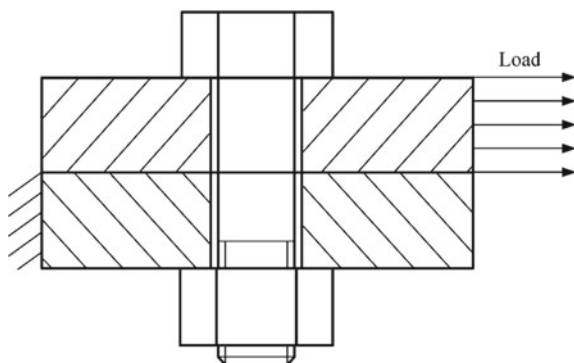


Fig. 1 Load and boundary conditions during loading step

the first analysis step, the tightening torque was applied to obtain the bolt preload. Afterwards, in the second analysis step, the loads and boundary conditions of the bolted connection were removed to simulate the service situation after tightening. In the third analysis step, a transient impact load was applied to the right side of the upper plate. Meanwhile, the left side of the lower plate was fully constrained. The schematic diagram of the load and boundary conditions of the single-lap bolted connection structure is shown in Fig. 1. The displacement at the loading point in the third analysis step was monitored for analysis and evaluation of the mechanical properties of the structure.

As shown in Fig. 1, the bolt connection consists of four parts. The hexahedral element global mesh size of the two connecting plates was 2 mm. The local mesh size was refined at the bolt hole locations. The hexahedral mesh element of the threaded fastener had a global size of 1 mm. Among them, there are only tetrahedral mesh elements at the thread, with which the local size was 0.5 mm. There were a total of 25,325 hexahedral elements and 119,586 tetrahedral elements for bolted joint. Six contact pairs are set for the four parts, namely: the contact between the bolt head and the upper plate (head friction coefficient, μ_h), the contact between the two connecting plates (contact friction coefficient, μ_m), the contact between the lower plate and the nut (bearing friction coefficient, μ_b), the contact surface between threads (thread friction coefficient, μ_t), and the contact between the bolt hole in the two plates and the outer surface of the bolt. In the first analysis step (tightening step), different tightening torques were applied to analyze the mechanical properties under different clamping forces, ranging from 150 to 210 Nm with 15 Nm intervals. In addition, the magnitude of the instantaneous impact load was also considered. The load amplitudes applied in the third analysis step (loading step) ranged from 5 to 25 kN at 5 kN intervals.

2.2 Design of Orthogonal Analysis

In engineering applications, various manufacturing parameters of bolted joints lead to different surface quality. Moreover, the friction coefficient of each contact surface of the bolted connection is also an important factor affecting its resistance to external loads. Orthogonal tests on the friction coefficients of each contact surface were designed to explore the mechanical properties of the bolted joints under transverse impact loads under different friction coefficients. Corresponding orthogonal table are shown in Table 1. There were four friction coefficients to be considered: head friction coefficient, contact friction coefficient, bearing friction coefficient, and thread friction coefficient. Among them, four levels were selected for each friction coefficient, ranging from 0.10, 0.14, 0.18, and 0.22. The orthogonal test category was *L16*, with four factors and four levels. Therefore, a total of 16 tests of finite element analysis were carried out. Since under large transverse loads, the plate where the load was applied may come into contact with the bolt, the contact of the bolts with the bolt holes of the two plates was set with a friction coefficient of 0.15.

Table 1 Orthogonal experimental design table

S. No.	Friction coefficients of the structure			
	μ_h	μ_m	μ_b	μ_t
1	0.10	0.10	0.10	0.10
2	0.10	0.14	0.14	0.14
3	0.10	0.18	0.18	0.18
4	0.10	0.22	0.22	0.22
5	0.14	0.10	0.14	0.18
6	0.14	0.14	0.10	0.22
7	0.14	0.18	0.22	0.10
8	0.14	0.22	0.18	0.14
9	0.18	0.10	0.18	0.22
10	0.18	0.14	0.22	0.18
11	0.18	0.18	0.10	0.14
12	0.18	0.22	0.14	0.10
13	0.22	0.10	0.22	0.14
14	0.22	0.14	0.18	0.10
15	0.22	0.18	0.14	0.22
16	0.22	0.22	0.10	0.18

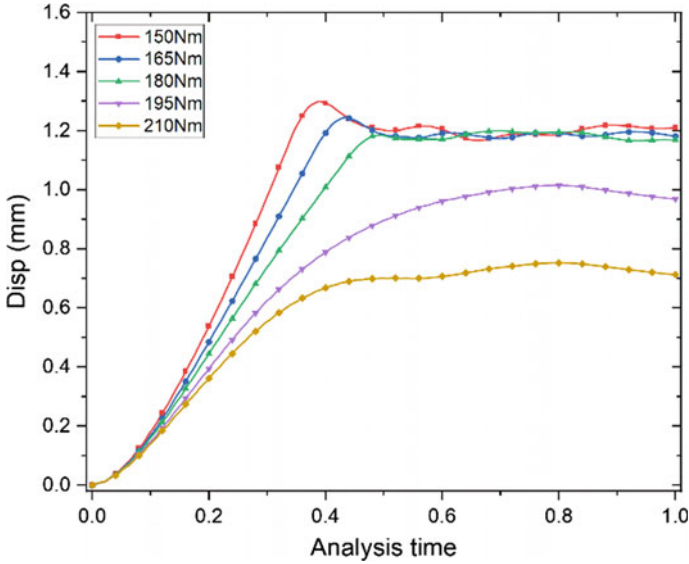


Fig. 2 Slip distance of bolted connection under impact load with different tightening torque

3 Finite Element Analysis Results

3.1 Tightening Torque

The finite element analysis results obtained under different tightening torques are shown in Fig. 2. The magnitude of the impact load applied was 15 kN. In the loading step, the transverse impact load reached the pre-set value at the moment of initial application, and the corresponding acceleration was generated. Therefore, the maximum slip distance could only be reached within a certain period of time after the load was applied. It can be seen from the figure that the displacement amplitude under impact load was negatively correlated with the tightening torque. At lower tightening torques, a certain drop occurred after the maximum slip distance. However, under the larger tightening torque, the displacement after reaching the maximum displacement amplitude remained relatively stable. It showed that the ability to resist transverse impact load could be improved by means of increased tightening torque.

3.2 Load Amplitude

To investigate the effect of transverse impact load amplitude on the mechanical properties of bolted connections, different load amplitudes were used in this work. The

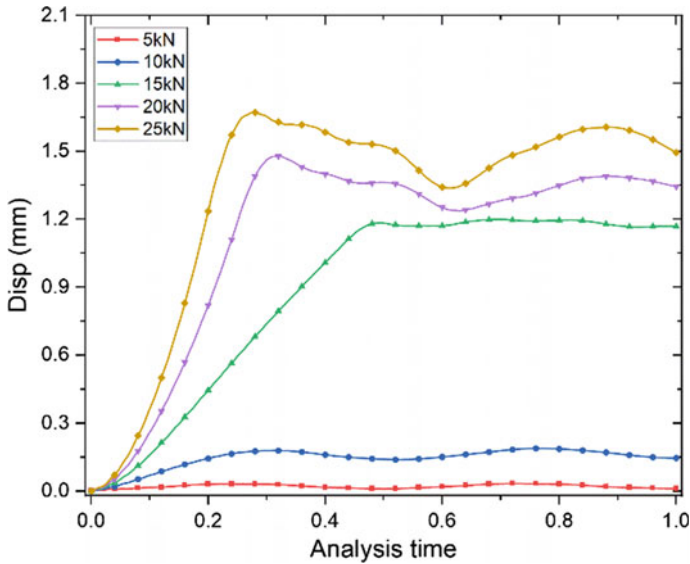


Fig. 3 Slip distance of bolted connection under impact load with different load amplitude

same tightening torque of 180 Nm was selected in the finite element analysis. Similarly, after reaching the maximum slip distance under heavier loads, it subsequently decreased. When the load did not exceed 15 kN, it remains relatively stable after reaching the maximum slip distance. The slip distance did not exceed 0.3 mm under the action of the load amplitude of 10 kN. When the load was reduced to 5 kN, the corresponding slip distance was almost negligible. It should be noted that when the load amplitude was increased from 10 to 15 kN, the generated slip distance rapidly increased to a larger amplitude. It showed that there was a certain threshold value below which the external impact load can remain stable (Fig. 3).

3.3 Orthogonal Test Results

The finite element analysis was carried out according to the orthogonal series in Table 1. The results obtained were shown in Fig. 4. In order to avoid the influence of the clamping force amplitude on the analysis results, the clamping force was controlled. The average clamping force was 55.44 kN (the error does not exceed $\pm 1.1\%$). It could be seen from the figure that the largest slip distance was in the first group of tests, in which the friction coefficient of each contact surface was at a low level (0.10). This was consistent with the expected result that a smaller coefficient of friction is detrimental to transverse load resistance. The first four groups of tests with larger slip

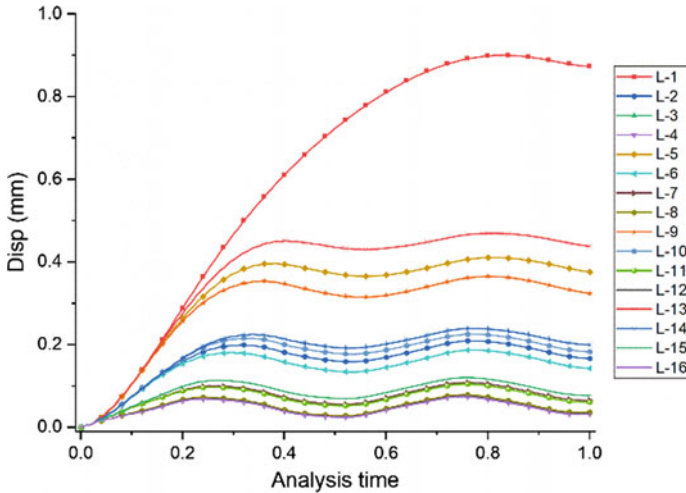
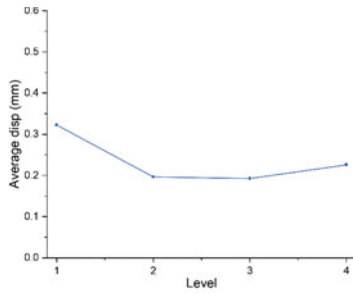


Fig. 4 Orthogonal test results under impact load

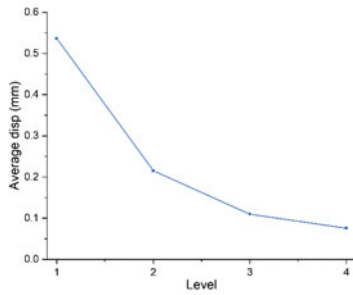
distance in the figure were when the friction coefficient of the contact surface was smaller. It showed that the friction coefficient of the contact surface had the greatest influence on the slip distance of the structure.

According to the obtained orthogonal test results, the analysis results of each influencing factor and its level are shown in Fig. 5. Similar to the results in Fig. 4, the slip distance is negatively correlated with the contact friction coefficient. The results showed that when the friction coefficient of the bearing surface was increased, the slip distance can be significantly reduced. While for the friction coefficients of other contact surfaces, when the friction coefficient was at a low level (0.10), the slip distance is larger. However, when the coefficient of friction is increased, the slip distance obtained is somewhat reduced. As it increases further, the slip distance remains relatively stable. It showed that when the friction coefficient was lower than a certain limit, the slip distance would be greatly improved. The results showed that the excessively small friction coefficient should be avoided in the design and use to improve the mechanical properties of the bolted connection.

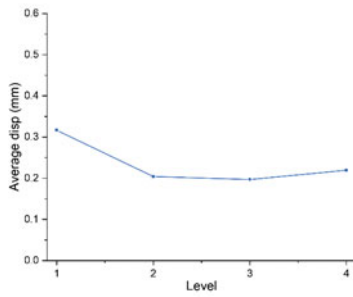
Under the same load amplitude, the influence ranking of various factors on the slip distance is shown in Table 2. It can be seen from the table that the contact friction coefficient had the greatest influence on the slip distance. The second is the thread friction coefficient. The head friction coefficient and the bearing surface friction coefficient have less influence and are almost identical. It is because the relative rotation of the bolt will be driven when the plate on which the load is applied slips greatly. As the weak link of the structure, the threaded part will be more prone to slip.



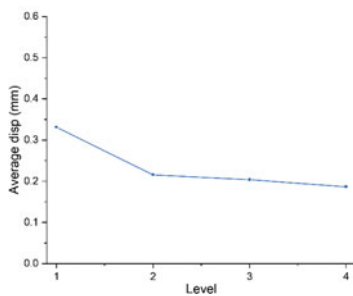
a) head friction coefficient



b) contact friction coefficient



c) bearing friction coefficient



d) thread friction coefficient

Fig. 5 Orthogonal test analysis results, **a** head friction coefficient, **b** contact friction coefficient, **c** bearing friction coefficient, **d** thread friction coefficient

Table 2 Orthogonal test results for friction coefficients

Conditions	μ_h	μ_m	μ_b	μ_t
Delta	0.1296	0.4607	0.1193	0.1444
Rank	3	1	4	2

4 Conclusions

Through the designed finite element analysis orthogonal test, the influence of the slip distance of each contact surface of the bolted joint was obtained, followed by, contact friction coefficient, thread friction coefficient, head friction coefficient, and bearing friction coefficient. Increasing the tightening torque improved the resistance to transverse impact loads. Under certain service conditions, when the load did not exceed a certain threshold, the slip distance was relatively stable. The finite element analysis results carried out herein can provide reference values for the reliability design of single-lap bolted joints.

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