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# Method for Evaluating Bolt Competitive Failure Life Under Composite Excitation

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## Abstract

In this study, the competitive failure mechanism of bolt loosening and fatigue is elucidated via competitive failure tests on bolts under composite excitation. Based on the competitive failure mechanism, the mode prediction model and “load ratio—life prediction curve” ( $\xi$ - $N$  curve) of the bolt competitive failure are established. Given the poor correlation of the  $\xi$ - $N$  curve, an evaluation model of the bolt competitive failure life is proposed based on Miner’s linear damage accumulation theory. Based on the force analysis of the thread surface and simulation of the bolt connection under composite excitation, a theoretical equation of the bolt competitive failure life is established to validate the model for evaluating the bolt competitive failure life. The results reveal that the proposed model can accurately predict the competitive failure life of bolts under composite excitation, and thereby, it can provide guidance to engineering applications.

**Keywords** Bolt, Competitive failure life, Evaluation model, Mode prediction model, Composite excitation

## 1 Introduction

Bolt connection is widely used in construction, rail vehicles, automobiles, and ships. When a bolt connection is subjected to impact, vibration, thermal stress, and random loading, the clamping force can easily decrease, which results in two failure modes: bolt loosening and fatigue fracture [1–3]. The initial stage of bolt loosening potentially does not affect the normal operation of mechanical equipment. However, with further aggravation of loosening, it can result in the failure of the entire structure. Additionally, bolt fatigue failure leads to severe consequences because bolt fatigue fracture is sudden and cannot be prevented easily [4–6]. Therefore, it is extremely important to examine bolt loosening and fatigue failure for engineering applications.

Research on bolt loosening has shown that the transverse cyclic load perpendicular to the screw is the main

factor that leads to bolt loosening [7–10]. The local slippage of the thread surface is a precondition for bolt loosening, and the overall slippage of the pressure-bearing surface under the bolt head is a necessary condition for bolt loosening [11]. Yang et al. [12] found that there are three stages in the process of bolt loosening through the Junker test under transverse cyclic loading, and normalized the loosening clamping force curve of bolts to a single mathematical equation, that is, a phenomenological model. Gao et al. [13] found that the stress under bolt pre-tightening is mainly concentrated on the contact part of the bolt’s head and bar. Under the transverse displacement load, the sliding of the bolt can be divided into three stages: full contact, viscous contact, and full slip. Fan et al. [14] found that fatigue wear is the main wear mechanism of bolts through the bolt loosening test under transverse displacement load, and the increase in the amplitude of cyclic transverse displacement worsens the thread damage and increases the loosening degree of bolted structures. It can be seen that the current research on bolt loosening is mainly focused on establishing the “transverse displacement—loosening life” curve ( $D$ - $N$  curve) of bolts by performing the transverse vibration

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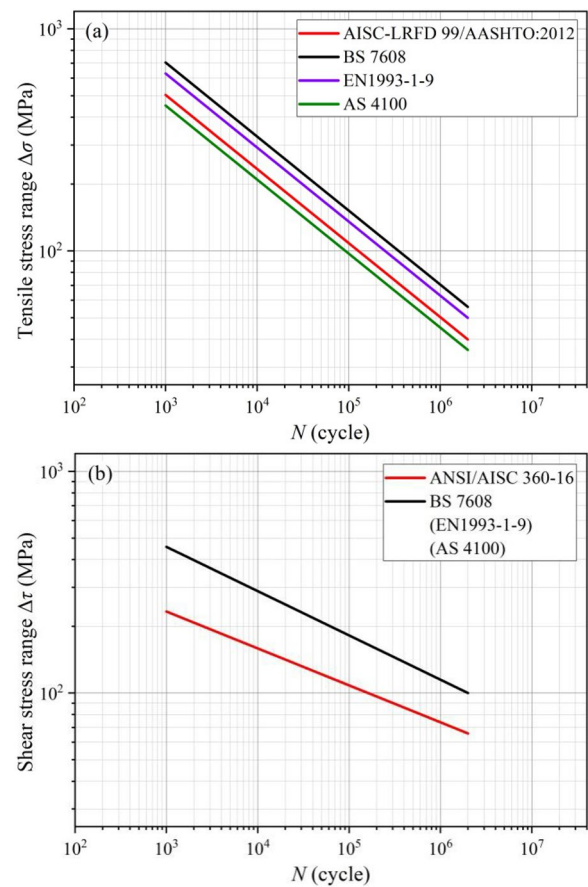
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test [15, 16], simulating the loosening process via finite element simulation [17, 18] and solving the critical loosening load via numerical calculation [19, 20].

Research on bolt fatigue shows that an axial cyclic load parallel to the screw is the main factor that leads to bolt fatigue [21, 22]. The most commonly used standards for assessing bolt fatigue are VDI 2230-2003 [23], JIS B 1081-1997 [24], and GB/T 13682-1992 [25]. In addition to the aforementioned standards, Table 1 and Figure 1 provide several design specifications, namely, ANSI/AISC 360-16 [26], AISC-LRFD 99 [27], AASHTO:2012 [28], BS 7608 [29], EN 1993-1-9 [30], and AS 4100 [31], which also consider the  $S-N$  curve of steel bolts. The tension and shear  $S-N$  curves of the bolts specified in BS 7608 are the most stringent, followed by those in EN 1993-1-9, AS 4100, ANSI-LRFD 99, and ANSI/AISC 360-16, which are relatively conservative in estimating the fatigue life of bolts under tension and shear loading. In addition, Zhang et al. [32] obtained the fatigue failure modes of the bolts under cyclic displacement with constant amplitude and the fatigue life based on the tensile capacity degradation from the fatigue tests, and proposed a fatigue life prediction method based on cyclic displacement amplitude, equivalent stress amplitude and local plastic strain. Li et al. [33] found that the wear mechanisms of bolts are fatigue wear, oxidation wear and abrasive wear on threads through the fatigue tests of bolts under axial excitation, and the smaller the stress amplitude on the section of the screw, the longer the fatigue life of the bolt connection. Maljaars and Mathias [34] obtained the  $S-N$  curve of bolts through thousands of bolt fatigue tests and updated the European standard EN 1993-1-9. Based on the residual slip strain development, Xue et al. [35] proposed a nonlinear inverted S-shaped cumulative fatigue damage model of bolts for different upper stress levels. It can be seen that the current research on bolt fatigue is mainly focused on establishing bolt  $S-N$  curve based on axial vibration tests, establishing bolt fatigue evaluation method through numerical analysis, and simulating the fatigue process through a finite element model.

In engineering applications, although bolt connections are subjected to strict transverse vibration loosening tests



**Figure 1** Comparison of  $S-N$  curves as per different standards [26–31]: (a) Tension  $S-N$  curve, (b) Shear  $S-N$  curve

and axial vibration fatigue tests, in accordance with relevant vibration standards, bolt loosening and fatigue fracture are still common problems. This is due to the fact that bolt loosening and fatigue tests are conducted separately; therefore, the actual combined vibration mode of the bolt is not considered. Generally, bolt loosening is due to transverse loads, whereas bolt fatigue is due to axial loads [7–10, 21, 22]. When the bolt connection is subjected to composite excitation (simultaneous application of transverse and axial loads), the axial load

**Table 1** Expressions of  $S-N$  curve of steel bolts as per different standards [26–31]

Standard	Tension $S-N$ curve	Tensile fatigue strength	Shear $S-N$ curve	Shear fatigue strength
AISC-LRFD 99, ANSI/AISC 360-16, AASHTO:2012	$\Delta\sigma^3 N = 1.28 \times 10^{11}$	$[\Delta\sigma]_{2 \times 10^6} = 40\text{N/mm}^2$	$\Delta\tau^6 N = 1.62 \times 10^{17}$	$[\Delta\tau]_{2 \times 10^6} = 65.5\text{N/mm}^2$
BS 7608	$\Delta\sigma^3 N = 3.51 \times 10^{11}$	$[\Delta\sigma]_{2 \times 10^6} = 56\text{N/mm}^2$	$\Delta\tau^5 N = 2 \times 10^{16}$	$[\Delta\tau]_{2 \times 10^6} = 100\text{N/mm}^2$
EN1993-1-9	$\Delta\sigma^3 N = 2.5 \times 10^{11}$	$[\Delta\sigma]_{2 \times 10^6} = 50\text{N/mm}^2$	$\Delta\tau^5 N = 2 \times 10^{16}$	$[\Delta\tau]_{2 \times 10^6} = 100\text{N/mm}^2$
AS 4100	$\Delta\sigma^3 N = 9.33 \times 10^{10}$	$[\Delta\sigma]_{2 \times 10^6} = 36\text{N/mm}^2$	$\Delta\tau^5 N = 2 \times 10^{16}$	$[\Delta\tau]_{2 \times 10^6} = 100\text{N/mm}^2$

aggravates bolt loosening failure, while the transverse load aggravates bolt fatigue failure [36, 37]. Hence, bolt loosening and fatigue are not independent processes under composite excitation, but rather a competitive relationship exists between the two failure modes [38, 39]. At present, experts and scholars have made great contributions to the failure mechanism of bolt loosening or fatigue, failure life prediction methods, simulation methods, test methods, and analysis of influencing factors. However, the research on the competitive failure mechanism, mode prediction method and life evaluation method of bolt loosening and fatigue under composite excitation is still insufficient. Therefore, it is necessary to study the method for evaluating bolt competitive failure life under composite excitation, which is of great scientific and engineering significance for optimizing bolt connection parameters, preventing sudden fatigue fracture failure, and ensuring the safe operation of mechanical equipment.

In this study, the competitive failure mechanism of bolt loosening and fatigue was elucidated via a bolt competitive failure test, and the mode prediction model and “load ratio – life prediction” curve ( $\xi-N$  curve) of the bolt competitive failure were established. Given the poor correlation of the  $\xi-N$  curve, a model for evaluating the bolt competitive failure life was proposed. Subsequently, the theoretical equation of the bolt competitive failure life was established and used to validate the bolt competitive failure life evaluation model by performing force analysis of the thread surface and simulation analysis of the bolt connection under composite excitation.

## 2 Competitive Failure Tests on Bolts

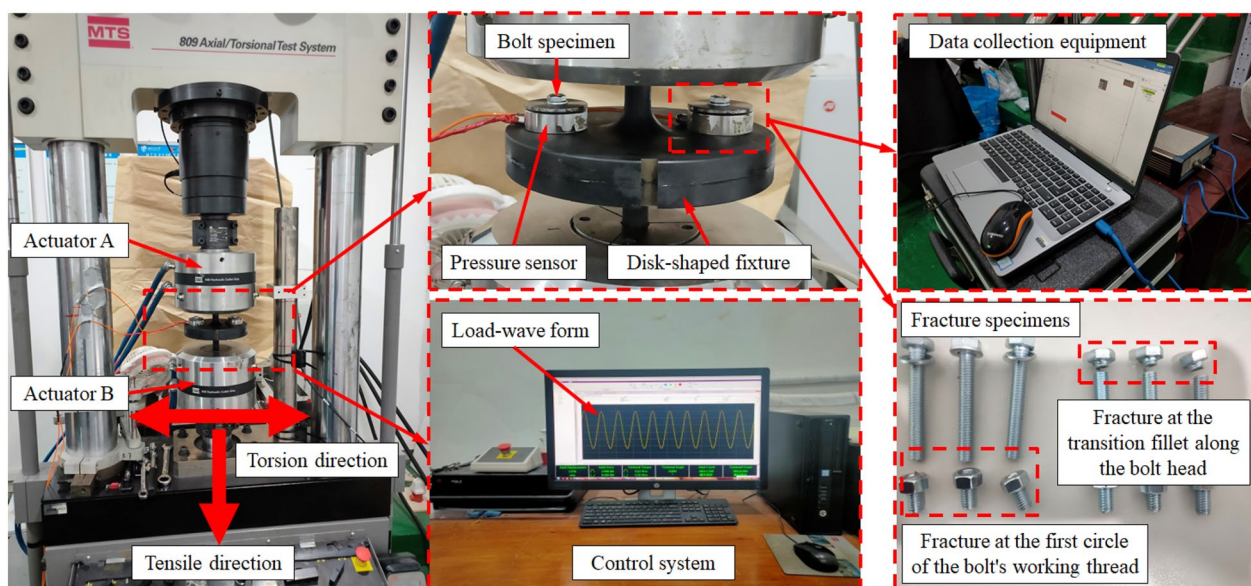
### 2.1 Test Details

As shown in Figure 2, competitive failure tests with regard to bolt loosening and fatigue were performed using an MTS 809 tensile–torsional testing machine. The fixture was designed as a disk-shaped symmetrical structure that can apply composite excitation (transverse and axial loads) to the bolt. The bolt connection was a slip-critical connection with 8.8 grade  $M8 \times 1.25 \times 70$  high-strength bolts. The mechanical properties of bolts are shown in Table 2. To ensure that the load was not eccentric, two bolts were installed at symmetrical positions of the fixture at each time [40]. The transverse and axial loads were loaded in sinusoidal form with a phase difference of  $90^\circ$ , and the test frequency was 10 Hz. The axial load was controlled by the force, and the load ratio was zero. The transverse load was controlled by the angular displacement, and the load ratio was  $-1$  [36–39]. The initial preload of the bolt was 14.05 kN, and the clamping force of the bolt was recorded using an EVT-14T3-10T pressure sensor and a DH5983 portable dynamic collector.

The amplitude range of the transverse load applied in the test was 0–1666.7 N, and the maximum axial load

**Table 2** The mechanical properties of bolts [37]

Young's modulus (MPa)	Poisson's ratio	Yield strength (MPa)	Tangent modulus (MPa)	Tensile strength (MPa)	Density (g/cm <sup>3</sup> )
205,000	0.3	640	22,500	900	7.85



**Figure 2** Schematic diagram of the test setup

range was 0–14400 N. The composite excitation combinations of the competitive failure tests of the bolts are listed in Table 3 ( $F_{T,a}$  denotes the transverse load amplitude,  $F_{A,a}$  denotes the maximum axial load,  $\xi$  denotes the transverse-to-axial load ratio,  $\xi = F_{T,a}/F_{A,a}$ ). Given that the bolts exhibit different failure modes under different transverse-to-axial load ratios, the load sequence of the bolt competitive failure tests adopted the up-and-down method, and the test was stopped when the bolt failed. The test process is illustrated in Figure 3.

### 2.2 Mechanism of Competitive Failure of the Bolt

The real-time clamping force recession curve of the bolt was obtained using a pressure sensor. As shown in Figure 4, the typical bolt clamping force recession curve can be divided into three stages: the material loosening stage ( $0-N_M$ ), the structural loosening stage ( $N_M-N_T$ ), and the fatigue fracture stage ( $N_T-N_E$ ). Point  $N_M$  denotes the dividing point between the material loosening and structural loosening stages. Given that the bolt will not fail during the material loosening stage,  $N_M$  is not specified in this study. The intersection of the midline of the clamping force recession curve and  $45^\circ$  tangent (point  $N_T$  in Figure 4) can be used as the dividing point between the structural loosening and

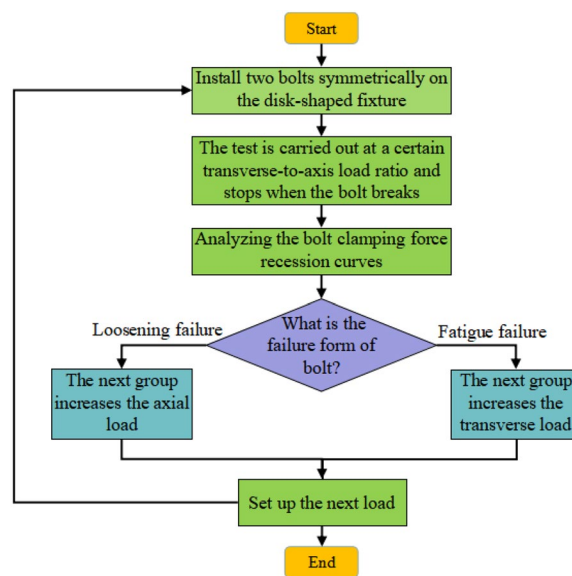
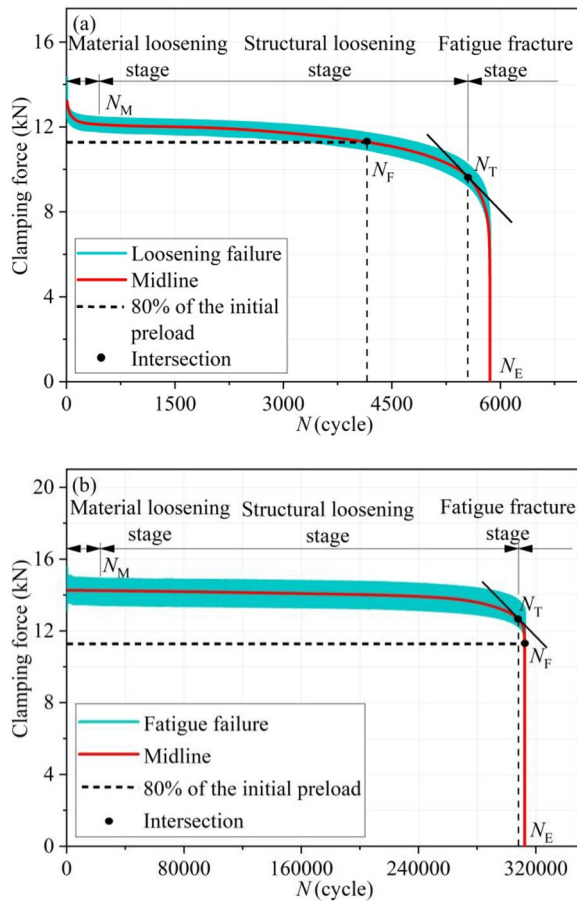


Figure 3 Test process

fatigue fracture stages. When the clamping force was reduced to 80% of the initial preload, the bolt entered a structural loosening stage. Therefore, the moment

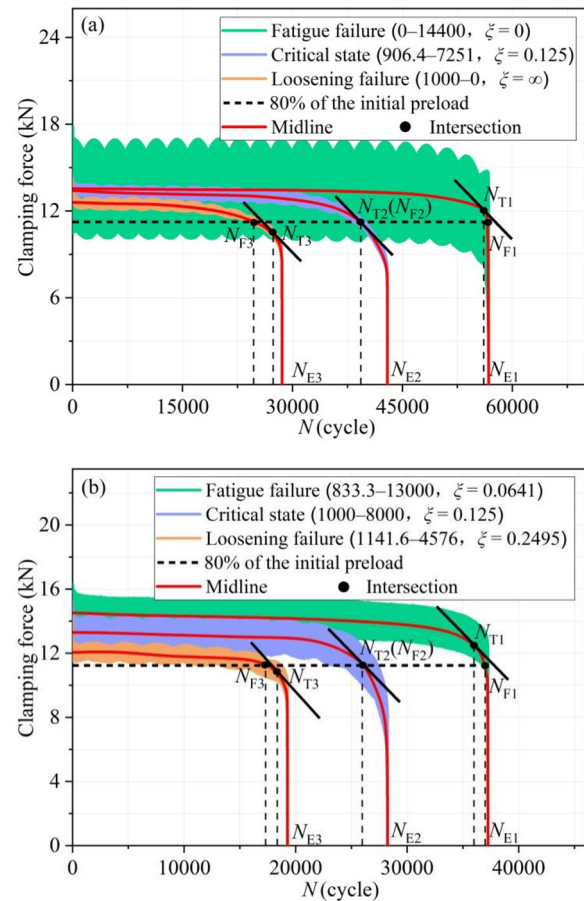
Table 3 Composite excitation combinations of competitive failure tests

Group number	$F_{T,a}$ (N)	$F_{A,a}$ (N)	$\xi$	Number of valid specimens	Group number	$F_{T,a}$ (N)	$F_{A,a}$ (N)	$\xi$	Number of valid specimens
1	666.7	0	$\infty$	2	22	1333.3	13000	0.1026	5
2	833.3	0	$\infty$	2	23	1500	13000	0.1154	4
3	1000	0	$\infty$	3	24	666.7	14400	0.0463	3
4	1166.7	0	$\infty$	4	25	833.3	14400	0.0579	5
5	1333.3	0	$\infty$	3	26	1000	14400	0.0694	4
6	1500	0	$\infty$	3	27	1166.7	14400	0.0810	3
7	1666.7	0	$\infty$	3	28	1333.3	14400	0.0926	6
8	0	12000	0	3	29	1500	14400	0.1042	4
9	0	13000	0	3	30	1166.7	9000	0.1296	3
10	0	14400	0	3	31	1333.3	10000	0.1333	3
11	666.7	12000	0.0556	3	32	833.3	6666.7	0.1250	2
12	833.3	12000	0.0694	3	33	1166.7	9333.3	0.1250	3
13	1000	12000	0.0833	5	34	875	7000	0.1250	2
14	1166.7	12000	0.0972	2	35	1125	9000	0.125	2
15	1333.3	12000	0.1111	4	36	833.3	3333.2	0.2500	2
16	1500	12000	0.1250	5	37	1000	3909.8	0.2558	2
17	1666.7	12000	0.1389	4	38	1142	4567.3	0.2500	3
18	666.7	13000	0.0513	4	39	1333.3	5209.3	0.2560	3
19	833.3	13000	0.0641	3	40	907.3	3628.6	0.2500	2
20	1000	13000	0.0769	4	41	1127.3	4602.0	0.2500	2
21	1166.7	13000	0.0897	3	42	1293.5	5172.9	0.2500	2



**Figure 4** Criteria for assessing bolt competitive failure mode: (a) Loosening failure, (b) Fatigue failure

corresponding to when the clamping force was reduced to 80% of the initial preload (point  $N_F$  in Figure 4) was considered as the evaluation criterion for the complete loosening of the bolt [36–39]. The essence of bolt loosening under transverse load or bolt fatigue under axial load is the result of damage. The difference is that the damage leading to bolt loosening is mainly caused by transverse load, while the damage leading to bolt fatigue is mainly caused by axial load. The failure mode of bolts is determined by the proportion of loosening damage and fatigue damage in the whole stress-time history, and the specific external performance is the recession process of bolt clamping force. The criteria for assessing the bolt competitive failure mode based on the clamping force recession curve corresponds to the relative position of the point when the clamping force is reduced to 80% of the initial preload and intersection point of the 45° tangent, i.e., the relative positions of  $N_F$  and  $N_T$ . If  $N_F < N_T$ , the proportion of loosening damage is relatively large, and the bolt is considered to have undergone loosening failure; if  $N_F > N_T$ ,



**Figure 5** Bolt failure modes divided based on bolt clamping force recession curve: (a) Single load and composite excitation, (b) Composite excitation

the proportion of fatigue damage is relatively large, and the bolt is considered to have undergone fatigue failure [40].

Based on the criterion for assessing the bolt-competitive failure mode, the relative positions of  $N_F$  and  $N_T$  in the clamping force recession curves of all bolts were divided, and the failure modes of all bolts were obtained. As shown in Figure 5(a), a single transverse load (1000–0,  $\xi = \infty$ ) led to bolt loosening failure, while a single axial load (0–14400,  $\xi = 0$ ) led to bolt fatigue failure. Further, it was verified that the transverse cyclic load is the main factor that causes bolt loosening, while the axial cyclic load is the main factor that causes bolt fatigue. Additionally, as shown in Figure 5, the bolts exhibited different failure modes with different transverse-to-axial load ratios. Therefore, there is an obvious competitive failure relationship between the loosening and fatigue of bolts under composite excitation. When  $\xi$  was large ( $\xi > 0.125$ ), the proportion of loosening damage was relatively large, and the bolts exhibited obvious loosening failure; when

$\xi$  was small ( $\xi < 0.125$ ), the proportion of fatigue damage was relatively large, and the bolts exhibited obvious fatigue failure. Therefore, under composite excitation, the transverse-to-axial load ratio is the main factor for determining the bolts' competitive failure mode. Additionally, when  $\xi = 0.125$ , the bolt was in the critical state of loosening or fatigue failure, and  $\xi$  was the critical transverse-to-axial load ratio ( $\xi_c$ ). Notably,  $\xi_c$  is an inherent property of the bolt, and it is related to the bolt material, size parameters, and assembly method. However, it is irrelevant to the load [37].

### 2.3 Model for Predicting Bolt Competitive Failure Mode

With respect to the product failure mechanism, system failure is generally classified into degradation failure and sudden failure. Competitive failure occurs between degradation failure and sudden failure based on the relative relationship between the degradation degree and failure threshold. The analysis presented in Section 2 reveals that the transverse-to-axial load ratio under composite excitation is the main factor for determining the competitive failure mode of bolts. Its essence is that the failure mode of bolts is determined by the proportion of loosening damage and fatigue damage in the whole stress-time history. As  $F_{A,a}$  increases,  $\xi$  gradually decreases. Therefore, in the competitive failure relationship between degradation failure and sudden failure,  $\xi$  is considered as the degradation degree and  $\xi_c$  is considered as the failure threshold of bolt loosening and fatigue competitive failure. The assessment standard of the mode prediction model of the bolt competitive failure is the relative size of  $\xi$  and  $\xi_c$ . If  $\xi < \xi_c$ , the degradation degree does not reach the failure threshold, and the proportion of fatigue damage is relatively large, so the bolt is considered to have undergone fatigue failure; if  $\xi = \xi_c$ , the degradation degree is equal to the failure threshold and bolt is in a critical state of loosening or fatigue failure; if  $\xi > \xi_c$ , the degradation degree exceeds the failure threshold, and the proportion of loosening damage is relatively large, so the bolt is considered to have undergone loosening failure. Figure 6 shows the mode-prediction model of bolt loosening and fatigue competitive failure.

## 3 Evaluation of Bolt Competitive Failure Life

### 3.1 Load Ratio-Life Prediction Curve

Currently, the prediction of the bolt loosening life under single transverse excitation is generally based on the  $D-N$  curve, and the prediction of the bolt fatigue life under a single axial excitation is generally based on the  $S-N$  curve. Based on the prediction curve of the bolt loosening life and fatigue life, the  $\xi-N$  curve can be established for predicting bolt loosening and fatigue competitive failure life under composite excitation. As

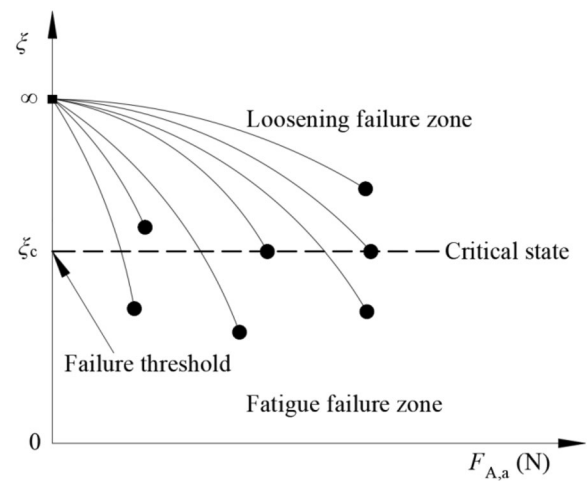


Figure 6 Mode prediction model of bolt loosening and fatigue competitive failure

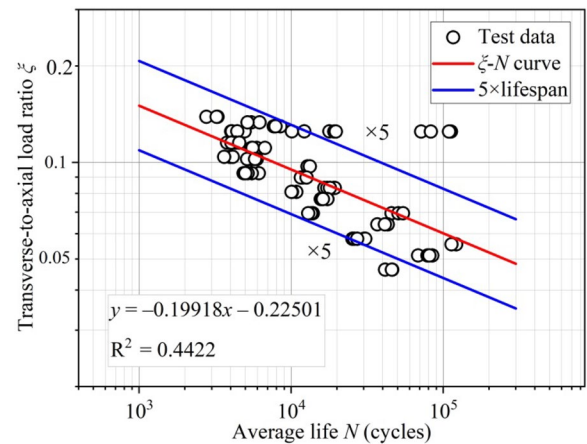


Figure 7  $\xi-N$  curve of bolt competitive failure

shown in Figure 7, the  $\xi-N$  curve of the bolt competitive failure was obtained based on the transverse-to-axial load ratio and life of each bolt competitive failure test. As shown, the test data are highly dispersed, and certain test data points exceeded the lifespan by five times (hereinafter referred to as 5×lifespan). The square of the correlation coefficient ( $R^2$ ) of the  $\xi-N$  curve obtained by fitting the test data based on the least squares method is 0.4422, which indicates that the correlation between the transverse-to-axial load ratio of the composite excitation and competitive failure life is very poor. This is because the failure mode of bolts is determined by the proportion of loosening damage and fatigue damage in the whole stress-time history, while the transverse-to-axial load ratio  $\xi$  cannot reflect the damage characteristics of the bolt. Therefore, it is

impossible to directly predict the competitive failure life of bolts under composite excitation based on the  $\xi-N$  curve.

### 3.2 Method for Evaluating Bolt Competitive Failure Life

Given the poor correlation of the  $\xi-N$  curve, it is necessary to establish a more general method for evaluating the bolt competitive failure life. Jiao et al. [41] used the modified Miner linear cumulative damage theory to estimate the fatigue life of 40Cr high-strength bolts. It was found that the error between the theoretical estimated life and the test life was not large, which proved that Miner's linear damage accumulation theory was suitable for the failure life prediction of bolts. According to Miner's linear damage accumulation theory, the assessment of fatigue damage is based on the following relationship:

$$D = \sum_1^k \frac{n_i}{N_i}, \tag{1}$$

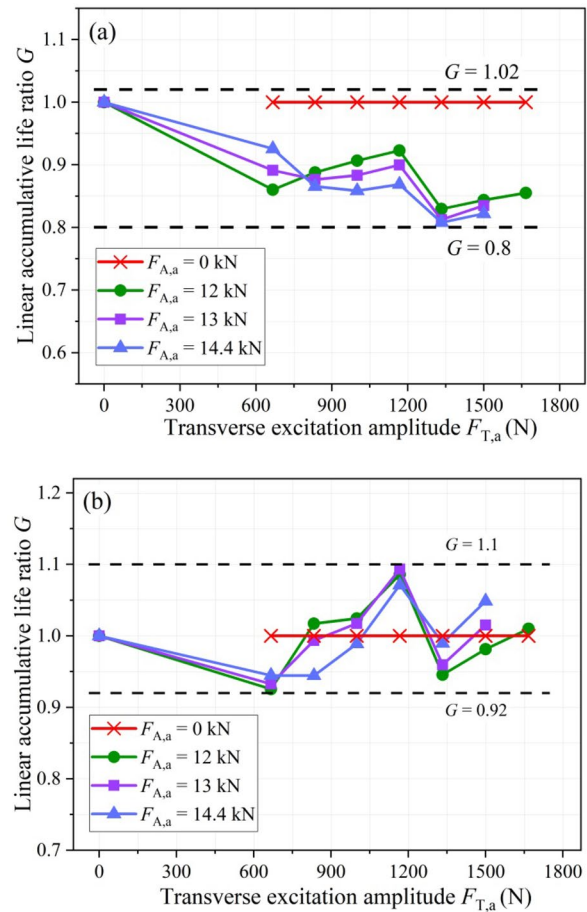
where  $D$  denotes the total damage,  $N_i$  denotes the life under each constant-amplitude stress cycle, and  $n_i$  denotes the number of cycles under each constant-amplitude stress.

The method for evaluating the bolt competitive failure life under composite excitation is based on Miner's linear damage accumulation theory. Composite excitation is considered as the cumulative result of transverse excitation and axial excitation, respectively, and the linear cumulative life ratio of the bolt can be obtained as follows [36]:

$$G = N_{i-j} \left( \frac{1}{N_{i-0}} + \frac{1}{N_{0-j}} \right), \tag{2}$$

where  $G$  denotes the linear cumulative life ratio,  $N_{i-0}$  denotes the life under a single transverse excitation,  $N_{0-j}$  denotes the life under a single axial excitation, and  $N_{i-j}$  denotes the life under composite excitation.

The equation for calculating the linear cumulative life ratio of the bolt included the bolt failure lives under a single transverse excitation, a single axial excitation and composite excitation. These failure lives were obtained under the combined action of load mean and load amplitude. Therefore, the average stress effect of loads was considered in the model for evaluating the bolt competitive failure life. By substituting the competitive failure life of bolts corresponding to single transverse excitation, single axial excitation, and composite excitation in Table 3 into Eq. (2), the uncorrected  $G-F_{T,a}$  curve of the bolt competitive failure is established as shown in Figure 8(a). As shown,  $G$  is in the range of 0.8–1, which proves that the bolt competitive failure life under composite excitation can be approximated based on Eq. (2).



**Figure 8**  $G-F_{T,a}$  curve of bolt competitive failure: (a) The uncorrected curve, (b) The corrected curve

However, different transverse-to-axial load ratios lead to certain data point dispersion; therefore, the influence of  $\xi$  cannot be ignored. Hence, a correction term for  $\xi$  and the life ratio is introduced into Eq. (2), and the corrected linear cumulative life ratio can be obtained as follows:

$$G_\xi = N_{i-j} \left( \frac{1}{N_{i-0}} + \frac{1}{N_{0-j}} \right) + K(\xi) \frac{N_{i-j}^2}{N_{i-0}N_{0-j}}, \tag{3}$$

where  $G_\xi$  denotes the corrected linear cumulative life ratio, and  $K(\xi)$  denotes the correction coefficient related to  $\xi$ .

Assuming that  $G_\xi$  denotes the most ideal case, i.e.,  $G_\xi = 1$ , the fitting curve of  $K(\xi)-\xi$  can be obtained as shown in Figure 9, where it can be observed that  $K(\xi)$  is a power function with respect to  $\xi$ ,  $R^2 = 0.914$ , with high correlation, and  $K(\xi)$  can be accurately predicted. The  $G-F_{T,a}$  curve corrected by  $K(\xi)$  is shown in Figure 8(b). It can be seen that the corrected  $G$  is in the range of 0.92–1.1, which is closer to the ideal situation  $G_\xi = 1$ . It is proved

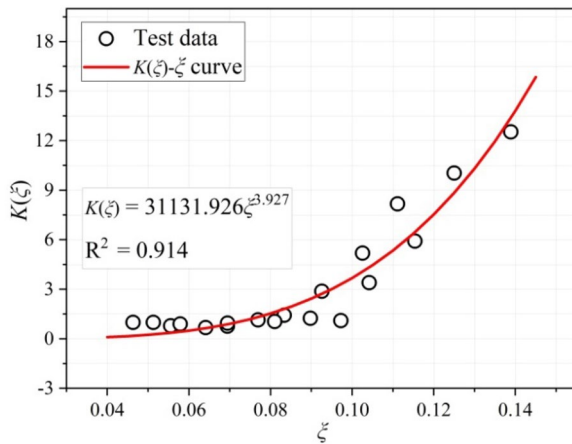


Figure 9 Fitting curve of  $K(\xi)-\xi$

that the corrected linear cumulative life ratio has a better prediction effect. Therefore, the evaluation method for the bolt competitive failure life can be obtained using Eq. (4). If the bolt life under single transverse and single axial excitations is known, the competitive failure life of the bolt under composite excitation can be predicted based on the proposed life evaluation model. This can provide a useful reference for engineering applications.

$$G_{\xi} = N_{i-j} \left[ \left( \frac{1}{N_{i-0}} + \frac{1}{N_{0-j}} \right) + 31131.926 \xi^{3.927} \frac{N_{i-j}}{N_{i-0} N_{0-j}} \right]. \quad (4)$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & \sin \beta \\ 0 & -\sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} \cos \alpha & 0 & \sin \alpha \\ 0 & 1 & 0 \\ -\sin \alpha & 0 & \cos \alpha \end{bmatrix} \begin{bmatrix} b \\ \tau \\ n \end{bmatrix}, \quad (5)$$

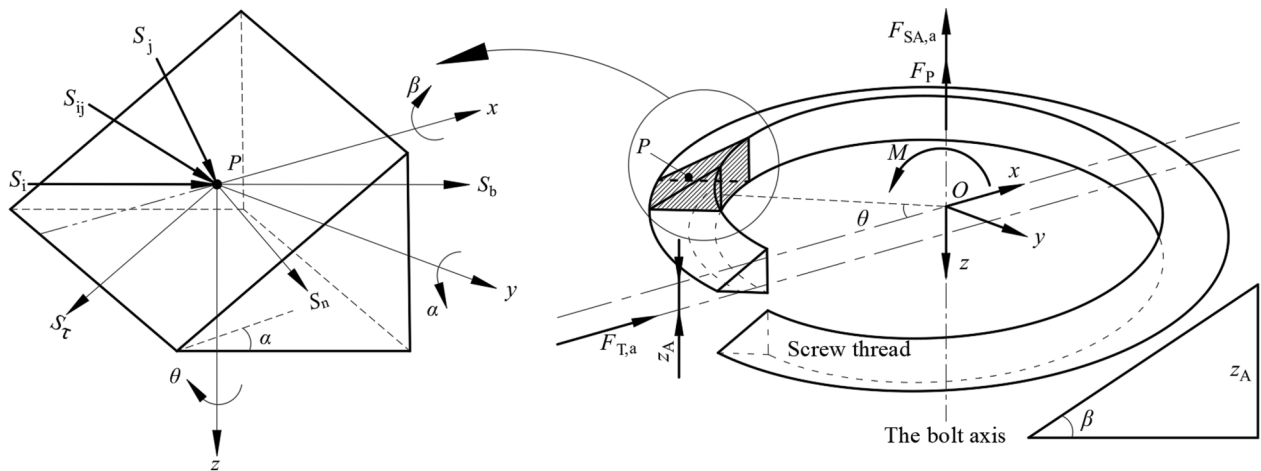


Figure 10 Force on thread surface and micro element under composite excitation [40]

## 4 Validation of Method for Evaluating Bolt Competitive Failure Life

### 4.1 Theoretical Equation of Bolt Competitive Failure Life

To verify the accuracy and reliability of the method for evaluating the bolt competitive failure life, a theoretical equation of the bolt competitive failure life was established via the force analysis of the thread surface. As shown in Figure 10, a screw thread is placed along the center (point  $O$ ) of a crosscutting circle of the bolt, and the overall coordinate system  $xyz$  is established with point  $O$  as the origin. The  $x$  direction is the action direction of  $F_{T,a}$ , and  $z$  direction is the reverse direction of the additional axial maximum load ( $F_{SA,a}$ ) of the bolt;  $F_P$  denotes the bolt preload, and  $M$  denotes the additional bending moment generated by  $F_{T,a}$ . The unit length micro-element is considered point  $P$ , and the local coordinate system  $b\tau n$  is established. Specifically,  $S_i$  denotes the transverse force generated by  $F_{T,a}$ , and  $S_j$  denotes the resultant force generated by  $F_P$ ,  $M$ , and  $F_{SA,a}$  in the micro-element. Furthermore,  $S_b$ ,  $S_\tau$ , and  $S_n$  are the radial, tangential, and normal stresses, respectively, along the thread. Eqs. (5)–(7) can be obtained based on the relationship between the global coordinate system  $xyz$  and local coordinate system  $b\tau n$  and the balance conditions of the  $x$ ,  $y$ , and  $z$  coordinate axes [40].



where  $\beta$  denotes the lead angle,  $\alpha$  denotes half of the thread angle, and  $\theta$  denotes the angle between the radial direction of the screw cross-section at point  $P$  and direction of the transverse load at this position.

According to the balance conditions of  $x$ ,  $y$ , and  $z$  coordinate axes, the following relationships can be obtained:

$$\begin{cases} S_b(\cos\theta \cos\alpha + \sin\theta \sin\beta \sin\alpha) - (S_\tau - S_j \sin\beta) \sin\theta \cos\beta + (S_n + S_j \cos\beta)(\cos\theta \sin\alpha - \sin\theta \sin\beta \cos\alpha) + S_i = 0, \\ S_b(\sin\theta \cos\alpha - \sin\alpha \cos\theta \sin\beta) + (S_\tau - S_j \sin\beta) \cos\theta \cos\beta + (S_n + S_j \cos\beta)(\sin\theta \sin\alpha + \cos\theta \sin\beta \cos\alpha) = 0, \\ -S_b \sin\alpha \cos\beta - (S_\tau - S_j \sin\beta) \sin\beta + (S_n + S_j \cos\beta) \cos\beta \cos\alpha = 0, \end{cases} \quad (6)$$

$$\begin{cases} S_\tau = S_i \sin\theta \cos\beta + S_j \sin\beta, \\ S_n = S_i(\sin\theta \sin\beta \cos\alpha - \cos\theta \sin\alpha) - S_j \cos\beta, \\ S_b = -S_i(\cos\theta \cos\alpha + \sin\theta \sin\beta \sin\alpha), \end{cases} \quad (7)$$

where  $S_i = \frac{F_{T,a} \cos\alpha}{N_k A_{slip}}$ ,  $S_j = \frac{F_{SA,a}}{N_k A_{slip}} + \frac{F_p}{N_k A_{slip}} + \frac{M d_2 \cos\theta}{2 I_{by} \cos\alpha}$ ,  $M \approx \frac{1}{2} F_{T,a} l_2$ ,  $N_k$  denotes the number of turns of the effective meshing thread;  $A_{slip}$  denotes the contact area of a single thread, and  $A_{slip} = \frac{\pi(d^2 - d_1^2)}{4}$ , where  $d$  denotes the major diameter of the thread;  $d_1$  denotes the minor diameter of the thread;  $d_2$  denotes the pitch diameter of the thread;  $I_{by}$  denotes the moment of inertia of the bolt cross-section with respect to the  $y$ -axis, and  $l_2$  denotes the screw clamping length.

Then, the resultant force on the micro element can be expressed as follows:

$$S_{ij} = \sqrt{S_\tau^2 + S_n^2 + S_b^2}. \quad (8)$$

By substituting Eq. (7) into Eq. (8), the following equation is obtained:

$$S_{ij} = \sqrt{(S_i \sin\theta \cos\beta + S_j \sin\beta)^2 + [S_i(\sin\theta \sin\beta \cos\alpha - \cos\theta \sin\alpha) - S_j \cos\beta]^2 + S_i^2(\cos\theta \cos\alpha + \sin\theta \sin\beta \sin\alpha)^2}. \quad (9)$$

For the bolt specimen,  $\beta = 3^\circ$ ,  $\alpha = 30^\circ$ , and  $\theta = [0^\circ, 360^\circ]$ ; therefore, the following equation is obtained:

$$S_{ij} = \sqrt{(1.029 \sin^2\theta + 0.5 \cos^2\theta + 0.866 \cos\theta) S_i^2 + 0.753 S_j^2 + (0.026 \sin\theta + 0.866 \cos\theta) S_i S_j}. \quad (10)$$

The condition under which the thread does not produce a relative slip is when the tangential resultant force of the external load along the thread surface is less than or equal to the friction, i.e., when the following relationship holds [17, 19, 20, 40]:

$$\sqrt{S_\tau^2 + S_b^2} \leq \mu_s S_n, \quad (11)$$

where  $\mu_s$  denotes the friction coefficient of the thread surface.

From Eq. (11), the extreme value ( $\theta_0$ ) of  $\theta$  that prevents the thread from slipping can be obtained [19, 40]. By substituting  $\theta_0$  into Eq. (10), it can be observed that  $S_{ij}$  denotes a function of  $S_i$ ,  $S_j$ ,  $F_{T,a}$ , and  $F_{SA,a}$ . Given that  $\xi = F_{T,a}/F_{SA,a}$ ,

the correction coefficient  $f(\xi)$  for  $\xi$  is introduced into Eq. (9), and the following equation is obtained as follows:

$$S_{ij} = f(\xi) \sqrt{S_i^2 + S_j^2}. \quad (12)$$

The  $S$ - $N$  curves of the bolts under single transverse excitation, single axial excitation, and composite excitation are as follows:

$$\begin{cases} S_i^{m_i} N_{i-0} = C_i, \\ S_j^{m_j} N_{j-0} = C_j, \\ S_{ij}^{m_{ij}} N_{i-j} = C_{ij}. \end{cases} \quad (13)$$

By substituting Eq. (13) into Eq. (12), the theoretical equation of the bolt competitive failure life can be obtained as follows:

$$N_{i-j} = C_{ij} f(\xi)^{-m_{ij}} \left[ \left( \frac{C_i}{N_{i-0}} \right)^{\frac{2}{m_i}} + \left( \frac{C_j}{N_{j-0}} \right)^{\frac{2}{m_j}} \right]^{-\frac{m_{ij}}{2}}. \quad (14)$$

## 4.2 Simulation Analysis

The stresses of bolt  $S$ - $N$  curves under single transverse

excitation, single axial excitation, and composite excitation were obtained via finite element simulation. As shown in Figure 11, the solid finite element model of the bolt connection is established using the HyperMesh software. The element type was set as SOLID185, the mesh size of the model was 2.5–0.04 mm, in which the mesh size of the fixture was 2.5 mm, and the mesh of the thread was refined to 0.04 mm. The load and boundary conditions were consistent with the test conditions. The upper plate of the clamped parts was fully constrained, while

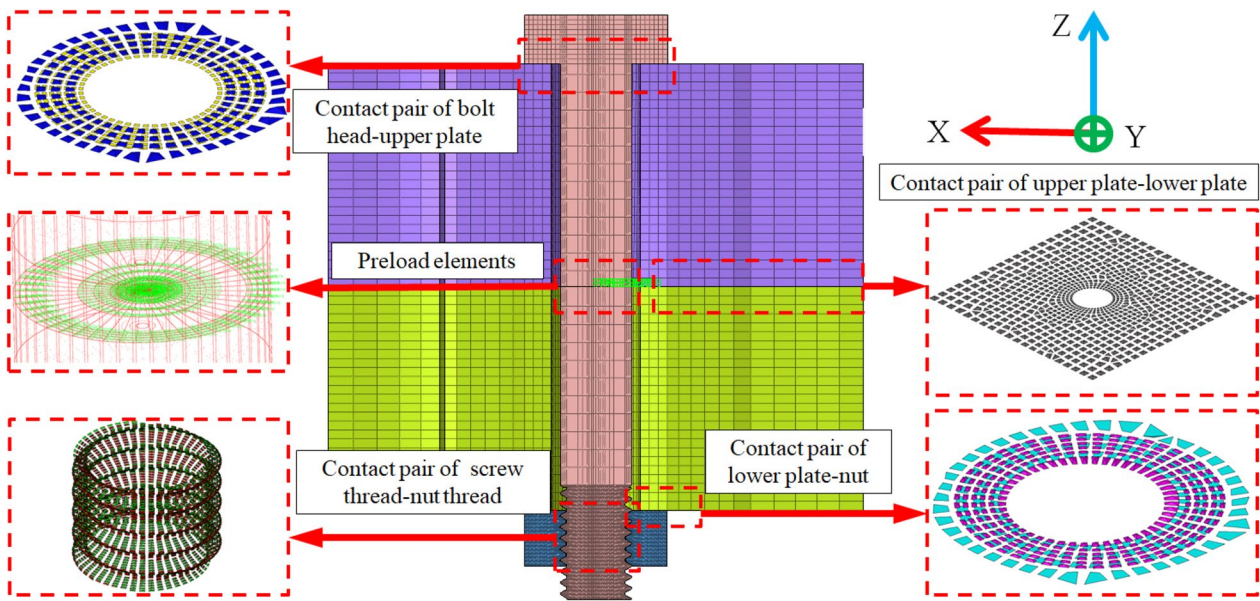


Figure 11 Finite element model of the bolt connection

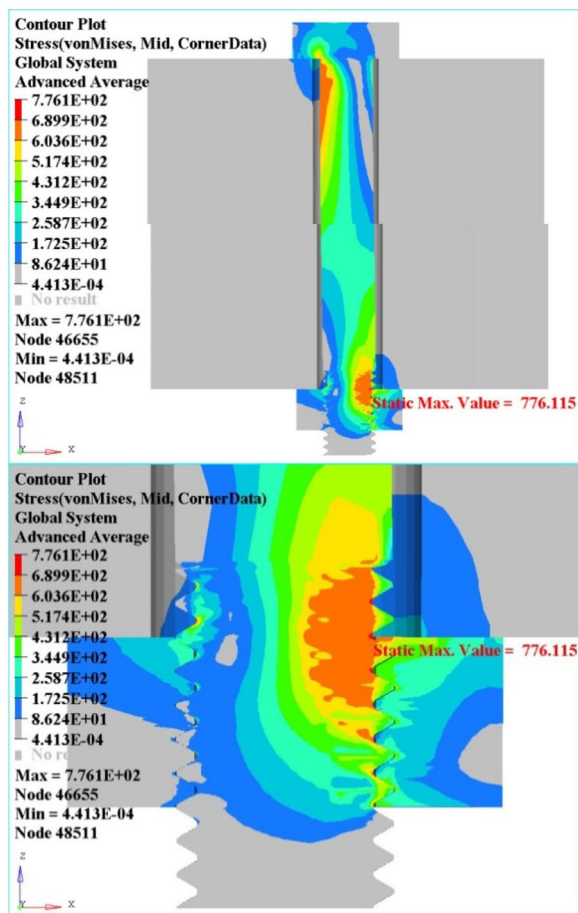


Figure 12 Simulated stress with composite excitation of 1000–12000

the lower plate was solely constrained in the translational degrees of freedom along the  $y$ -axis. Axial excitation was applied in the  $z$ -axis and transverse excitation was applied in the  $x$ -axis. Four contact pairs, namely, the “bolt head–upper plate,” “upper plate–lower plate,” “nut–lower plate,” and “screw thread–nut thread” were established, and the friction coefficient was set to 0.2 [37]. The bolt and nut material corresponded to bilinear elastic-plastic steel. The preload elements were set on the nodes in the middle of the bolt, and the preload value was 14.05 kN [38].

The finite element model is calculated via ANSYS software, and the simulated stress cloud diagram with composite excitation of 1000–12000 ( $F_{T,a} = 1000$  N,  $F_{A,a} = 12000$  N) is obtained as shown in Figure 12. According to the simulated stress and test life of the bolt, the  $S$ – $N$  curves of the bolt under single transverse excitation, single axial excitation, and composite excitation were obtained as shown in Eq. (15).

$$\begin{cases} S_i^{7.019} N_{i-0} = 1.2187 \times 10^{19}, \\ S_j^{6.827} N_{j-0} = 8.5911 \times 10^{19}, \\ S_{ij}^{7.564} N_{i-j} = 5.8993 \times 10^{20}. \end{cases} \quad (15)$$

The simulated stresses of the bolt under single transverse excitation, single axial excitation, and composite excitation are denoted by  $S_i$ ,  $S_j$ , and  $S_{ij}$ , respectively. Eq. (16) can be obtained based on Eq. (12). It can be observed that  $f(\xi)$  can be obtained when  $S_i$ ,  $S_j$  and  $S_{ij}$  are known. By

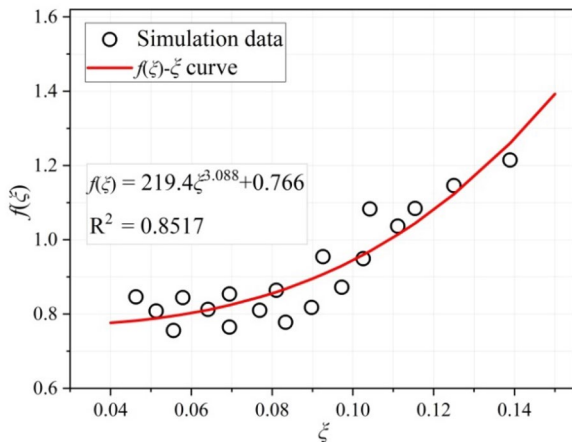


Figure 13 Fitting curve of  $f(\xi)-\xi$

fitting the data of  $S_i$ ,  $S_j$  and  $S_{ij}$ , it is observed that  $f(\xi)$  is a power function with respect to  $\xi$  as shown in Figure 13.

$$f(\xi) = \sqrt{\frac{S_{ij}^2}{S_i^2 + S_j^2}} \tag{16}$$

### 4.3 Validation of the Life Evaluation Method

Based on the aforementioned simulation analysis, the theoretical equations of bolt loosening and fatigue competitive failure life were obtained as expressed by Eqs. (14) and (15), respectively. By substituting the test lives  $N_{i-0}$  and  $N_{0-j}$  into Eq. (14), the theoretically predicted life  $N_{i-j}$  of the bolt under composite excitation was obtained. Additionally,  $G_\xi$  in Eq. (4) was assumed as 1, and test lives  $N_{i-0}$  and  $N_{0-j}$  were substituted into Eq. (4) to predict life  $N_{i-j}$  based on the model for evaluating the competitive failure life of the bolt. A comparison of the two predicted lives is shown in Figure 14(a). As shown, most data points are within the 5×lifespan, which proves that the theoretically predicted life is very close to that predicted via the evaluation model, and this in turn validates the evaluation model. Figure 14(b) shows a comparison between the bolt test life and life predicted by the evaluation model. As shown, all data points are within 2×lifespan. This further proves that the model for the evaluation of the bolt competitive failure life can accurately predict the competitive failure life of bolts under composite excitation.

### 5 Conclusions

In this study, the competitive failure mechanism of bolt loosening and fatigue was elucidated, and the mode prediction model and life evaluation model of bolt competitive failure were established. The accuracy of the life

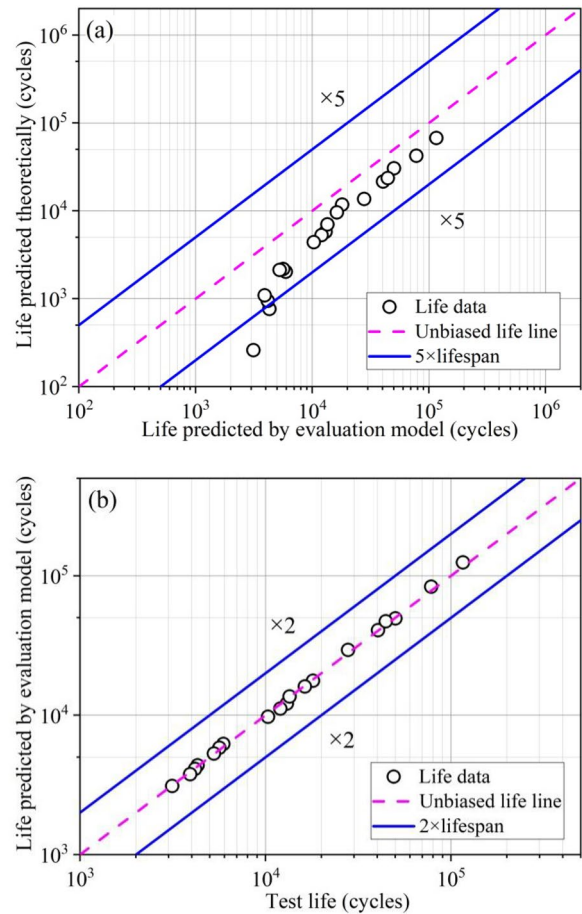


Figure 14 Comparison of bolt life: (a) Theoretically predicted life and that predicted via evaluation model, (b) Life predicted by evaluation model and test life

evaluation model was verified using the theoretical equation of the bolt competitive failure life. The following conclusions were drawn based on the results.

- (1) The degradation degree of the mode prediction model of bolt competitive failure under composite excitation corresponds to the transverse-to-axial load ratio, the failure threshold corresponds to the critical transverse-to-axial load ratio, and the assessment standard of the mode prediction model of bolt competitive failure is the relative size of  $\xi$  and  $\xi_c$ .
- (2) The correlation between the transverse-to-axial load ratio of the composite excitation and competitive failure life is very poor, and it is impossible to directly predict the competitive failure life of bolts under composite excitation based on the  $\xi-N$  curve.
- (3) A model for evaluating the bolt competitive failure life is proposed based on Miner’s linear dam-

age accumulation theory. The proposed model can predict the bolt competitive failure life under composite excitation based on the bolt life under single transverse and single axial excitation.

Based on the force analysis of the thread surface and simulation analysis of the bolt connection under composite excitation, a theoretical equation of the bolt competitive failure life was established, and the model for evaluating the bolt competitive failure life was validated using this theoretical equation. The findings of this study can provide a useful reference for engineering applications.

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#### Author contributions

LY and GY were in charge of the whole trial; LY wrote and revised the manuscript; LY, HZ, HD, BY and SX assisted with experiments and data analysis. All authors read and approved the final manuscript.

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#### Data availability statement

The data are available from the corresponding author on reasonable request.

#### Declarations

#### Competing Interests

The authors declare no competing financial interests.

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