16th World Congress in Computational Mechanics (WCCM)
21-26 July 2024, Vancouver, Canada
A. Korobenko, M. Laforest, S. Prudhomme, R. Vaziri (Eds)

# BEARING LIMITATION UNCERTAINTY ANALYSIS OF COMPOSITE BOLTED JOINTS CONSIDERING ASSEMBLY PROCESS PARAMETER DEVIATIONS

**QINGYUAN LIN*[1], YONG ZHAO[2], YUMING LIU[3], WEI PAN[4], WENCAI YU[5], YU REN[6] AND XIN ZHANG[7]**

[1] Shanghai Jiaotong University
qyuan_lin@163.com

[2] Shanghai Jiaotong University
zhaoyong@sjtu.edu.cn

[3] Shanghai Jiaotong University
Liu389658558@sjtu.edu.cn

[4] Shanghai Jiaotong University
pwmogic666@sjtu.edu.cn

[5] Shanghai Jiaotong University
yu790876644@sjtu.edu.cn

[6] Shanghai Jiaotong University
xcution@sjtu.edu.cn

[7] Northwestern Polytechnical University
zhangxin504@mail.nwpu.edu.cn

**Key words:** Composites Bolted Joint; Assembly Process; Uncertainty Analysis; Data Driven.

**Abstract:** Bearing limitation is a key performance indicator for composite bolted joints. Assembly process parameters such as washer structural parameters, interfacial friction coefficients and tightening process parameters have a significant effect on the bearing limitation. In the actual production process, there are inevitably deviations between the assembly process parameters and their design values. The accumulation of assembly process deviations leads to an obvious dispersion of the bearing limitation, which makes it difficult for composite bolted joints to be reliably in service. In this paper, the dispersion of assembly process parameters is experimentally tested to quantitatively characterize its uncertainty. Then, based on the high-fidelity finite element analysis method, a data set of bearing limitation under different assembly process parameters is prepared. A data-driven algorithm is used to establish a fast prediction model for bearing limitation. The fast prediction model is used to realize the uncertainty analysis and the reliability evaluation for the bearing limitation. The established analysis method and the obtained conclusions can provide a reference for the reliability design and analysis of composite bolted joints.

## 1 INTRODUCTION

Composite materials are widely used in aerospace, marine and other fields due to their excellent characteristics. In the assembly process of composite parts and components, the common connection forms include bolting, riveting, gluing and so on. Among them, bolt joints are easy to disassemble and bear large loads, which are the most common connection forms for composite materials[1]. There are essential differences between composite materials and traditional metallic materials in terms of their intrinsic relationship, stress redistribution capacity, and damage behavior[2–5]. The original design criteria and evaluation methods for metallic bolted joints are difficult to be applied to composite bolted joints.

Bearing limitation is the most important performance for composite bolted joints[6–11]. A lot of prediction methods have been proposed. Early scholars predicted the bearing limitation by analytical approach[12]. Later, with the development of finite element methods and the application of damage mechanics in composites, progressive damage analysis became the main method for failure analysis and bearing limitation prediction of composite joints[13].

Kolks[14] analyzed the effect of titanium reinforcement process of composite monolayer on the bearing limitation.Jiang[15] analyzed the effect of layup angle on bearing limitation, and the analytical results showed that the bearing limitation is the lowest when the composite laminate is designed with only ±45° layups; and the bearing limitation of is higher when the layups adjacent to the fastener are designed with 0° or 90°. Kelly[16] analyzed the effects of the width-to-diameter ratio W/D and the end distance ratio E/D on the structural strength, and the results showed that when W/D is lower than 2, W/D and structural strength showed a significant positive correlation; when W/D is greater than 2, the structure is damaged in the bearing failure mode, and at the same time, W/D no longer had a significant effect on the bearing limitation. The influence of E/D on the failure mode and bearing limitation is similar to that of W/D, and the critical value of E/D is 1.5.

In addition to the properties of the connected composite plate itself, the fastener structure, assembly interface properties and assembly process parameters are also important parameters that affect the bearing limitation. Arman[17] studied the influence of washer type on the. The study found that the bearing limitation using flat washers may be higher than that using other types of washers, such as lock washers and spring washers. Zhai[18] 's experimental results showed that reasonable tightening torque could increase the bearing limitation by more than 50%. The research results of Kelly[19] show that the difference in bearing limitation caused by different tightening torques may exceed 100%.

The detailed thread structure of fasteners is ignored in the modeling process of the above studies, which leads to the real tightening process of the bolted joint cannot be simulated by finite element. Furthermore, the influence of interface friction coefficient, non-uniform distribution of thread stress and initial preload on the bearing limitation is also difficult to be effectively analyzed. Lin[20] realizes the high-fidelity simulation of the real tightening process and load bearing process of the composite bolted joint by establishing a fastener mesh model considering the detailed thread structure. Thus, the assembly process analysis and bearing limitation prediction under different washers, interface parameters and tightening process parameters can be realized.

## 2 UNCERTAINTY QUANTIFICATION OF ASSEMBLY PROCESS PARAMETERS

The assembly process parameters of a composite bolted joints include washer structure parameters, interface friction coefficients, and tightening process parameters. The above parameters affect the bearing limitation. In the actual manufacturing process, the assembly process parameters inevitably deviate from their design values, which leads to the bearing limitation deviating from its design value. Quantifying the uncertainty of the assembly process parameters is a prerequisite for analyzing the uncertainty of the bearing limitation.

### 2.1 Uncertainty quantization of washer structure parameters

Circular washer is a type of washer commonly used in the assembly of composite bolted joints. The washer has three structural parameters: outer diameter, inner diameter and thickness. The three structural parameters of the same types of washers are measured 20 times by vernier caliper. The uncertainty is quantitatively characterized by Gaussian distribution. The results are shown in **Table 1**.

**Table 1**
Statistical of washer structural parameter measuremental results

| Structural parameter | Mean(mm) | Standard deviation(mm) | Coefficient of variation |
|---|---|---|---|
| Outer diameter | 17.839 | 0.0104 | 0.0006 |
| Inner diameter | 6.774 | 0.0094 | 0.0014 |
| Thickness | 1.484 | 0.0109 | 0.0074 |

The probability density curves of each structural parameter are plotted using the normal distribution function shown in **Eq. 1** according to the mean value and standard deviation in **Table 1**, as shown in **Fig. 1**.

$$w(X_S) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(X_S-\mu)^2}{2\sigma^2}} \tag{1}$$

Where, $X_S$ represents the value of the uncertainty parameter, $\sigma$ represents the standard deviation of the uncertainty parameter, and $\mu$ represents the mean value of the uncertainty parameter. Coefficient of variation of uncertainty parameter $\psi = \sigma / \mu$.

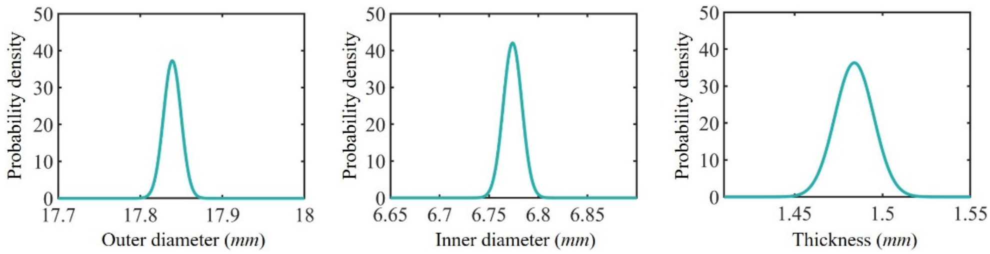


**Fig. 1** Probability density curve of washer structure parameters

The statistical results show that the three washer structure parameters have a degree of dispersion, in which the outer diameter dispersion is relatively small, while the thickness dispersion is relatively large.

## 2.2 Uncertainty quantization of interface friction coefficients

The interfacial friction coefficient is affected by many factors such as surface roughness, surface treatment state, temperature and so on, and its uncertainty comes from complex sources. As shown in **Fig. 2**, the friction coefficient test machine is used to perform 20 measurements of the friction coefficients of four types of friction surfaces in the bolted joints (interface between fasteners and washers $S_{NW}$, interface between washers and composite laminates $S_{CW}$, interface between composite laminates $S_C$, and thread friction interface $S_T$).

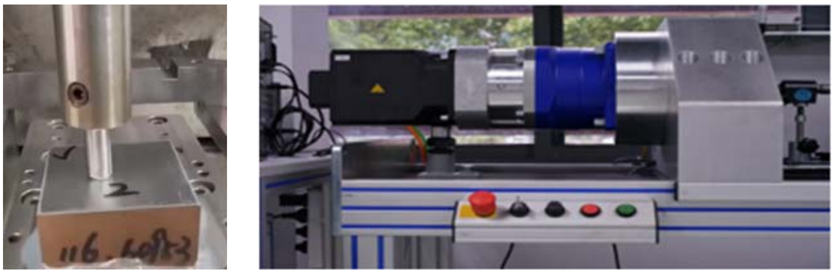

**Fig. 2** Test equipment for interfacial friction coefficient of CBJ: (a) Plane friction coefficient test machine, (b) Tread friction coefficient test machine.

The uncertainty of interfacial friction coefficients are quantitatively characterized by Gaussian distribution. The results are shown in **Table 2** and **Fig. 3**.

**Table 2**
Statistical of interface friction coefficient measuremental results

| Interface | Mean | Standard deviation | Coefficient of variation |
|---|---|---|---|
| $S_{NW}$ | 0.180 | 0.0023 | 0.0126 |
| $S_{CW}$ | 0.483 | 0.0012 | 0.0024 |
| $S_C$ | 0.478 | 0.0017 | 0.0035 |
| $S_T$ | 0.189 | 0.0101 | 0.0536 |

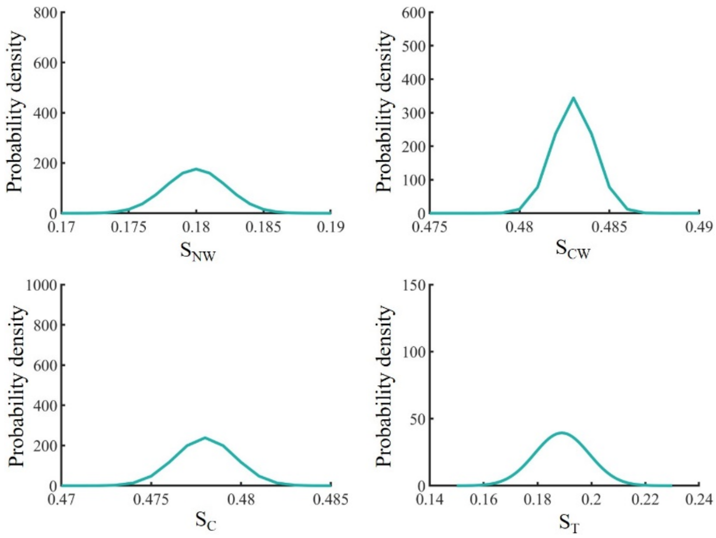


**Fig. 3** Probability density curve of interface friction coefficients

## 2.3 Uncertainty quantization of initial bolt tension

The initial bolt tension is the key index of the connection state of the composite bolted joint. As shown in **Fig. 4**, the assembly experiment is designed. The tightening torque is applied and monitored through the torque wrench as the control quantity. The initial bolt tension is taken as the target quantity and measured by ultrasonic bolt tension measuring equipment.

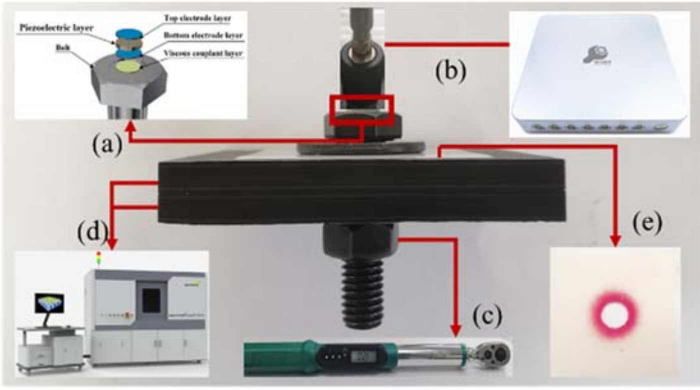


**Fig. 4** Assembly experiment of CBJ: (a) Piezoelectric ceramic patch, (b) Ultrasonic tension measuring instrument, (c) Torque wrench, (d) Industrial CT (e) Pressure sensitive paper.

The experiment is repeated 20 times. The uncertainty of initial bolt tension is quantitatively characterized by Gaussian distribution. The result is shown in **Table 3** and **Fig. 5**.

**Table 3**
Statistical of tightening process parameters measuremental results

| Tightening process parameters | Mean | Standard deviation | Coefficient of variation |
|---|---|---|---|
| Tightening torque(Nm) | 0.180 | 0.0023 | 0.0126 |
| Initial bolt tension(kN) | 0.189 | 0.0101 | 0.0536 |

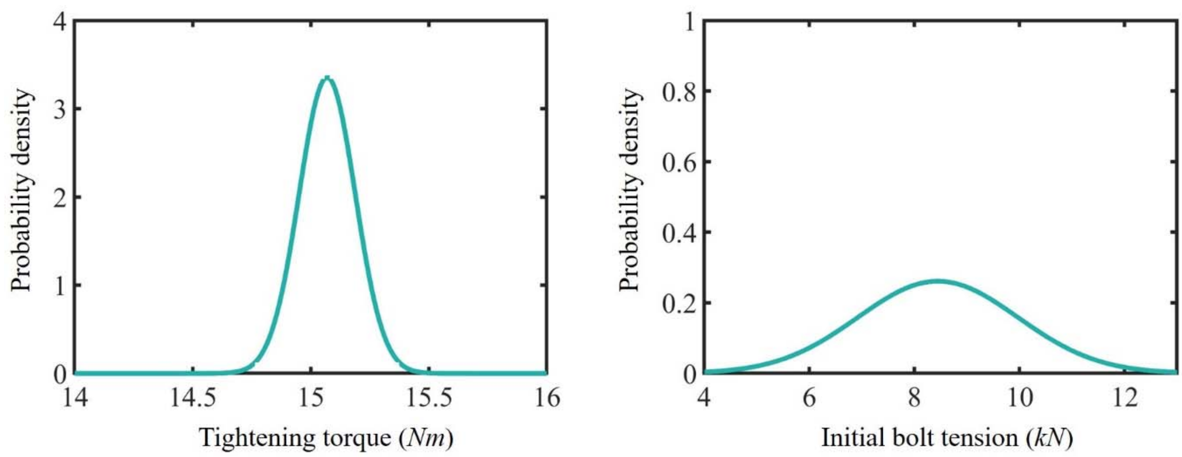


**Fig. 5** Probability density curve of tightening process parameters

## 3 FAST PREDICTION MODEL FOR BEARING LIMITATION

Bearing limitation is the key performance of CBJ. As shown in **Fig.6**, in order to establish the fast prediction model for bearing limitation, it is necessary to establish the high-fidelity finite element model first. Then the assembly process parameters are sampled, and the bearing limitation corresponding to different assembly process parameters are obtained by batch simulation. Further, the data set obtained by batch simulation is used as training sample, and the fast prediction model of bearing limitation is established by data-driven method.

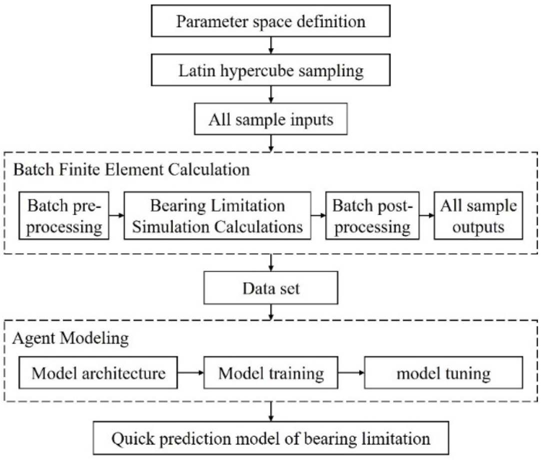


**Fig. 6** Establishment process of fast prediction model for bearing limitation

### 3.1 High fidelity finite element model of composite bolted joints

The virtual assembly-tensile test of the bolted joint is carried out by using a high-fidelity finite element model. As shown in **Fig. 7**, in order to analyze the influence of assembly process parameters, firstly, the finite element mesh model with detailed thread structure is established. The contact model based on Coulomb friction is used to characterize the friction behavior of each interface. The assembly process is simulated by controlling the nut tightening boundary conditions. Then the tensile load is applied with the initial assembly state as input. The maximum value of the tensile load in the tensile process is the bearing limitation of the CBJ. In the whole simulation process, the microscopic damage and macroscopic failure behavior of the composite are characterized by progressive damage analysis.

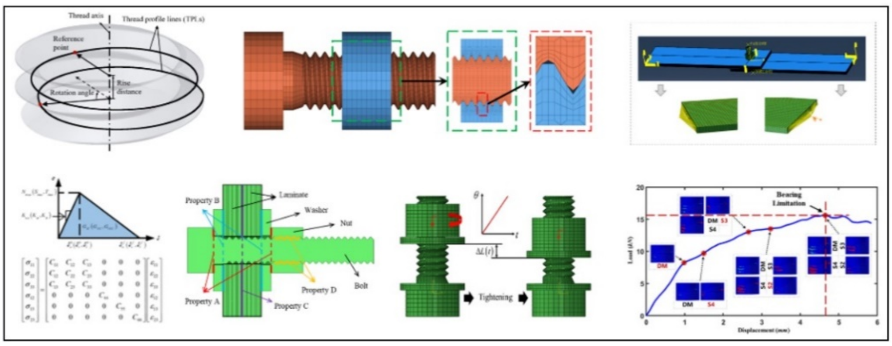

**Fig. 7** Virtual assembly-tensile test of the bolted joint

### 3.2 Data set preparation and fast prediction model of bearing limitation

As shown in **Fig. 8**, the input sample space is established by taking into account ten key parameters of washer structure, interface friction coefficient and nut tightening Angle during the assembly process. Through the high-fidelity virtual assembly-stretching experiment, the bearing limitation corresponding to each input parameters is obtained. The multi-dimensional value-value mapping model is established by LightGBM (Light Gradient Boosting Machine) to achieve fast prediction.

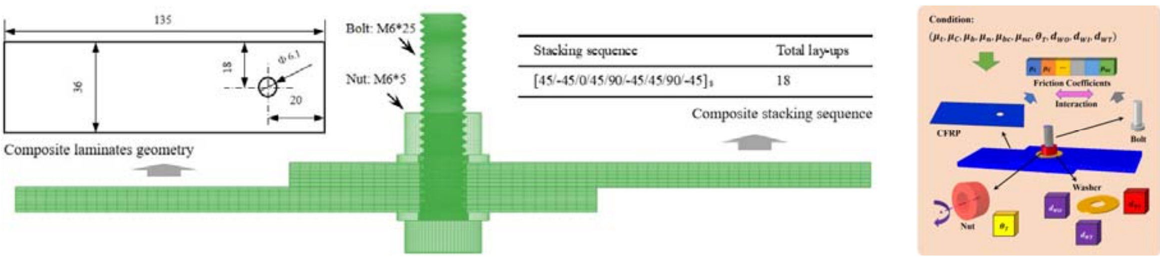


**Fig. 8** Typical composite bolted joint and parameter space

Use PyCharm as your development environment. The data set is divided using the cross-validation method. The data set is divided into $k_d$ subsets of similar size, and the union of $k_d - 1$ subsets is used as the training set each time, and the remaining subsets are used as the test set for training and testing. Finally, the mean value of the $k_d$ test is taken as the result of the model.

## 4 UNCERTAINTY ANALYSIS OF BEARING LIMITATION

With the quantization results of assembly process parameter uncertainty as input, the statistical characteristics of bearing limitation are calculated based on Monte Carlo method, and the calculation process is shown in Fig. 9(a). The calculation results are shown in Fig. 9(b).

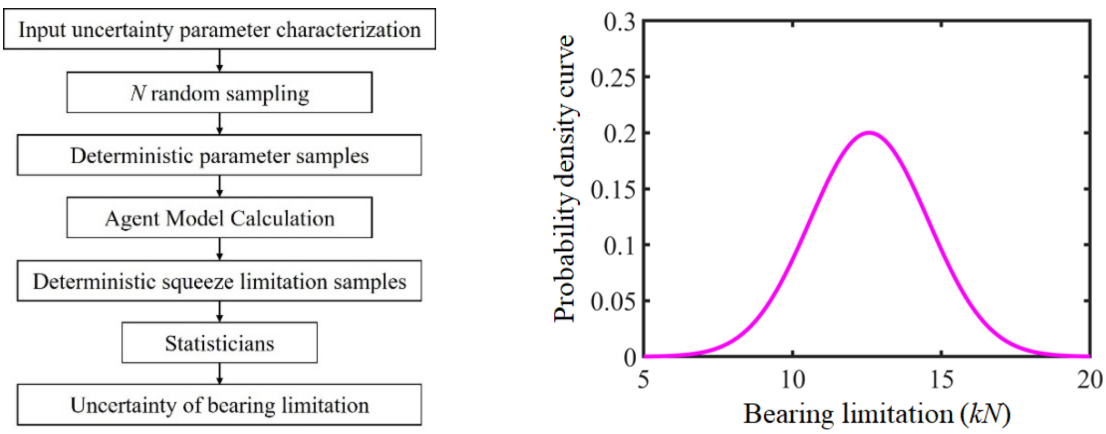


**Fig. 9** Uncertainty analysis for bearing limitation of CBJ: (a) Calculation process, (b) Calculation results

Without considering the uncertainty of structural performance caused by the uncertainty of assembly process parameters, the design process only needs to ensure that the design value of performance is higher than the maximum load it needs to bear to ensure the effective service of the structure. Considering the parameter uncertainty, the structural performance is a statistical variable, and it is necessary to evaluate the effective service of the structure from a statistical point of view. In a broad sense, reliability refers to the probability that a given product can complete the design requirements, and for the bearing reliability of the composite bolted joints, it refers to the probability that the load level does not exceed its bearing limitation. The bearing reliability is obtained by integrating the probability density curve with the load value as the boundary and the direction of its abscissa value increasing. As shown in **Fig. 10**, with the increase of load, the bearing reliability gradually decreases. The bearing reliability values corresponding to different loads can be predicted, which provides reference for the performance check of the structure. In the design stage, the reliability is usually taken as the design goal, and the load that the structure can bear is calculated. As shown in **Fig. 10**, the maximum load decreases gradually with the increase of extrusion reliability requirement. The load-bearing capacity of the structure can be calculated according to the desired bearing reliability design objective in the design stage of the structure. In the actual engineering design process, the dispersion of the design object is often considered by setting the safety factor. As shown in **Fig. 10**, the bearing reliability increases with the increase of the safety factor. The calculated relation between bearing reliability and safety factor can provide reference for rational selection of safety factor in the process of structural design.

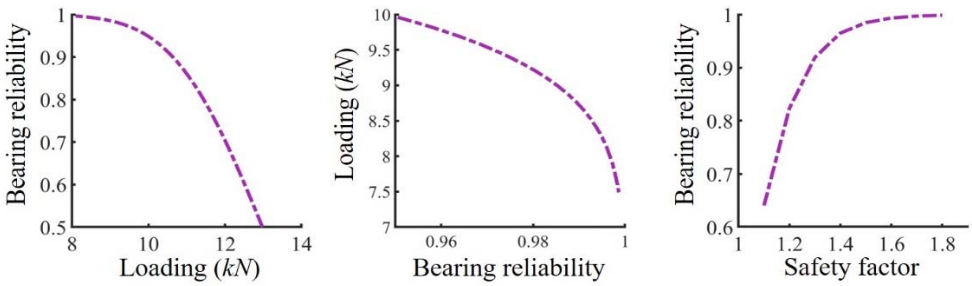


**Fig. 10** Analysis results for bearing reliability of CBJ

## 5 CONCLUSIONS

Based on the results of statistical experiments, the uncertainties of washer structure parameters, interfacial friction coefficient and tightening process parameters are quantitatively characterized. Based on the high-fidelity finite element simulation method, the fast prediction model of bearing limitation of bolted composite joints with assembly process parameters as input is established. Based on the Monte Carlo method, the bearing limitation uncertainty analysis and bearing reliability evaluation of bolted composite joints under the action of multiple uncertain factors are realized by using this fast prediction model. The following conclusions are obtained:

Among the three washer structure parameters, the outer diameter has a small dispersion, while the thickness has a large dispersion. Among the interface friction coefficients, the under bearing friction coefficient and thread friction coefficient between fastener and washer are more dispersed.

In the scenario where the tightening torque is taken as the control object of the assembly process, the initial bolt tension formed will appear significantly dispersed. If the initial bolt tension is taken as the control object, the assembly quality can be effectively improved.

The uncertainty of assembly process parameters leads to the uncertainty of bearing limitation. The fast prediction model can effectively reduce the calculation cost, obtain the probability density curve of the bearing limitation, and then realize the uncertainty analysis and the bearing reliability evaluation, so as to carry out the reliability design and analysis of the composite bolted joints.

## ACKNOWLEDGEMENT

This work was supported by the National Key Research and Development Program of China [Grant No. 2019YFA0709001], the National Key Research and Development Program of China [Grant No.2022YFF0605700], Science and Technology Commission of Shanghai Municipality [21NL2600200], and the National Natural Science Foundation of China [Grant No. 51975349].

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