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Experimental Study on Fatigue Performance of Bolted Connectors in Timber-Concrete Composite Structures

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Abstract

To study the fatigue performance of bolted connections in timber-concrete composite structures(TCC), this paper adopts a combination of experimental research and theoretical analysis to design 15 push out specimens for static and fatigue tests. The changes in mechanical properties such as fatigue life, residual slip development, shear bearing capacity, and stiffness of bolted connections are obtained. On this basis, the fatigue failure mode is analyzed to provide reference for the fatigue design of TCC.

Keywords

Timber-Concrete Composite Structure; Shear Connectors; Fatigue Test; Residual Slippage; Fatigue Life.

1. Introduction

TCC is a new type of structure that combines concrete slabs and wooden beams with shear connectors to work together. This structural form allows the upper concrete slab to be compressed and the lower wooden beam to be tensioned, fully utilizing the material characteristics of both. Compared with traditional wooden structures, the wood concrete composite structure effectively improves the bearing capacity and stiffness of wooden beams, and improves their fire resistance and sound insulation performance [1].

In recent years, scholars have conducted many studies on the static performance of TCC[2,3]. However, wood concrete composite bridge structures not only bear static loads but also cyclic loads such as vehicle loads and wind loads. Under cyclic loads, the structure will produce a certain degree of fatigue damage, and its mechanical properties will continuously deteriorate. After damage accumulation, it will eventually lead to structural failure. As an important component in wood concrete composite beams, the fatigue damage of shear connectors directly affects the service life and performance of the structure, and has become a key issue that urgently needs to be solved. Weaver [4], Yeoh [5] and others studied the fatigue performance of various shear connectors through fatigue tests. Yuan Shuai et al. [6] conducted on-site full-scale tests on wooden concrete composite beam bridges, using slotted and bolted connectors. The test results show that the overall integrity of the entire bridge is good, and the concrete slab and wooden beam can work together well; The shear connection degree has a significant impact on the slip at the interface of composite beams, and the slip amount of incomplete shear connection is greater than that of complete shear connection. This paper adopts a combination of experimental research and theoretical analysis to conduct static load failure tests and fatigue tests on a total of 15 push out specimens. Explore the fatigue failure mode of the structure based on experiments. The research results can provide reference for the fatigue design of TCC.

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2. Test Program

2.1. Test Specimens

To study the fatigue failure mechanism of bolted connections in TCC, 15 specimens with the same parameters were designed in this experiment, divided into 5 groups (one group for static testing and 4 groups for fatigue testing). The wood used was larch. During the process of specimen production, efforts should be made to ensure that the dimensions and material ratios of all specimens are completely consistent, in order to reduce the variability of experimental results. One end of the bolt is inserted into wood by 80mm, and the other end is fixed on the template to prevent displacement during pouring. The specimens were all poured using the same batch of mixed concrete. After pouring, they were placed on a vibration table for compaction, and then placed under the same conditions for 28 days of curing. The dimensions of the specimen are shown in Figure 1.

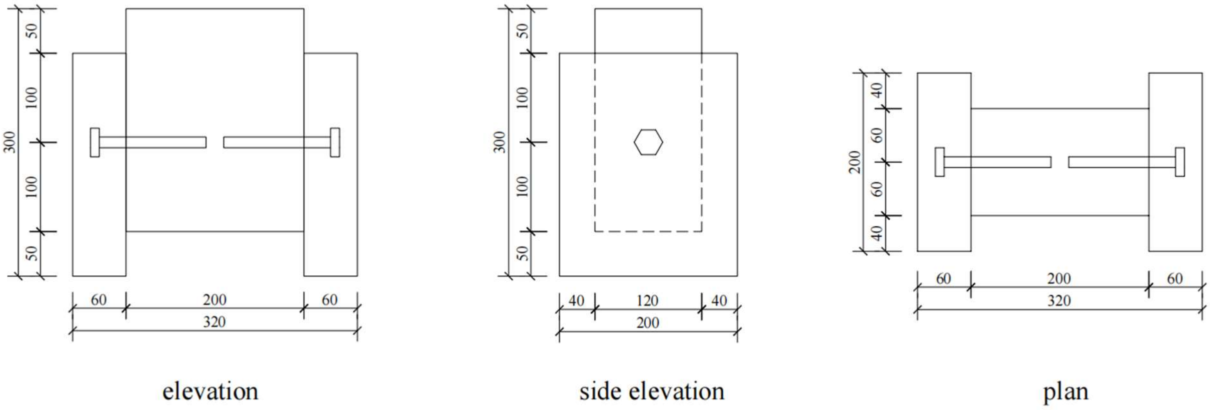

Figure 1. Geometry of the specimen (dimensions in mm)

2.2. Test Setup and Loading Procedure

The static test first adopts load control mode, loading at a speed of 3kN/min to 30kN, and then adopts displacement control mode, loading at a speed of 3mm/min until the specimen fails. The fatigue loading adopts a constant amplitude sine loading mode, with a loading frequency of 20Hz. Static loading is carried out by stopping the machine a certain number of times per cycle. The loading system of the European standard EN 26891-1991 [7] is used to load up to the upper limit of the fatigue load. The fatigue loading parameters are shown in Table 1.

Table 1. Loading Parameters of Fatigue Test

Series	Peak Value of Cyclic Loading (kN)	Range of Cyclic Loading (kN)	Loading Ratio
F1	20	16	0.45
F2	16	12	0.36
F3	14	10	0.31
F4	12	8	0.27

Note: Loading ratio is defined as the ratio of the peak value of cyclic loading to the ultimate static strength.

3. Results

3.1. Static Load Test Results

The test phenomena of the three specimens are similar: there is no obvious phenomenon during the initial loading stage; When the load is increased to around 35kN, the wood undergoes deformation due to the compression of the bolts; When loaded to around 37kN, micro cracks appeared at the bolt on the outer side of the concrete slab. As the load increased, the relative slip gradually increased, and the cracks gradually expanded, with new cracks emerging; When loaded to 40kN, the crack width increased and concrete powder continued to fall. Finally, the concrete split and failed. After removing the specimen for observation, the bolt underwent double hinge bending failure, resulting in significant bending deformation between the two plastic hinges.

3.2. Fatigue Test

3.2.1. Experimental Phenomenon

During the early stage of fatigue loading, concrete powder continuously falls off and the specimen emits a subtle sound; Continuing to load, there is a gap at the interface between concrete and wood; After 1 million cycles of loading, the relative slip between wood and concrete increased rapidly. After 1.17 million cycles of loading, the specimen was damaged, the concrete was crushed, the wood was crushed, and the bolt broke at the plastic hinge. The test phenomenon of specimen F1 is shown in Figure 3. After fatigue loading 6.2 million and 5.3 million times respectively, there was no obvious phenomenon in specimens F3 and F4. After static loading, the failure mode and shear bearing capacity were basically consistent with the static loading test. Therefore, low load ratio loading has a relatively small impact on the ultimate bearing capacity of bolted connections.

3.2.2. Variation of Stiffness

To study the stiffness degradation law of bolted connections in TCC under fatigue loads, a stiffness variation curve with the number of cycles was plotted. The stiffness calculation formula in this experiment adopts the modified initial slip stiffness in the European standard EN 26891 [7].

$$K_s = \frac{0.4F_{est}}{\frac{4}{3}(s_{0.4}-s_{0.1})}. \quad (1)$$

Among them: the slip value corresponding to 0.4 times the estimated ultimate load; Estimate the slip value corresponding to 0.1 times the ultimate load.

Commonly used to represent the slip stiffness of connectors under normal use, as shown in Figure 2.21, the stiffness of specimens F1 and F2 decreased by 27.12% and 22.04%, respectively, while the stiffness of specimens F3 and F4 decreased by 1.79% and 5.8%, respectively. Therefore, the load ratio has a significant impact on the stiffness of bolted connections. When the load ratio is high, the stiffness of specimens F1 and F2 shows an S-shaped monotonically decreasing trend with the increase of the number of cycles, that is, under the action of fatigue load, the stiffness deteriorates rapidly in the early stage, stabilizes in the middle stage, and deteriorates rapidly in the later stage. When the load is relatively low, the stiffness of specimens F3 and F4 shows a trend of rapid degradation first and then maintaining stability. It should be noted that the initial stiffness of each specimen is slightly different, which is caused by errors in specimen fabrication and testing. The variation curve of the stiffness of the specimen with the number of cycles is shown in Figure 2.

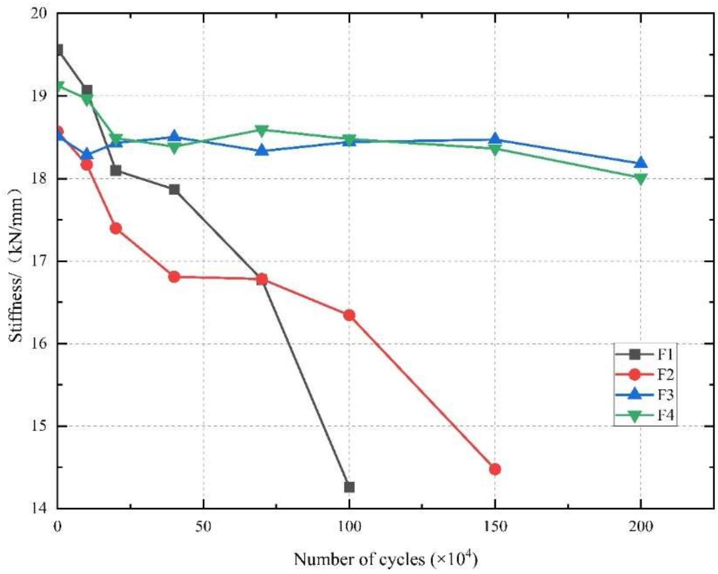

Figure 2. Variation of stiffness

3.2.3. Residual Slip

Residual slip can be used to measure the cumulative damage of specimens after fatigue loading. Figure 3 shows the variation of residual slip with the number of fatigue cycles. As shown in the figure, the residual slip of specimens F1 and F2 that have undergone fatigue failure increases rapidly in the early stage of fatigue loading; In the middle stage of fatigue loading, residual slip is in a relatively stable stage; In the later stage of fatigue loading, residual slip increases rapidly, and fatigue failure occurs in the shorter cycle of the specimen. The specimens F3 and F4, which did not experience fatigue failure, showed a slight increase in residual slip during the early stage of loading. However, after continuous loading, the residual slip remained relatively stable. Therefore, when the load is relatively small, the residual slip of the specimen will tend to be relatively stable after experiencing millions of fatigue loads; When the load is relatively large, the residual slip of the specimen will show a rapid growth trend in the early stage of fatigue failure.

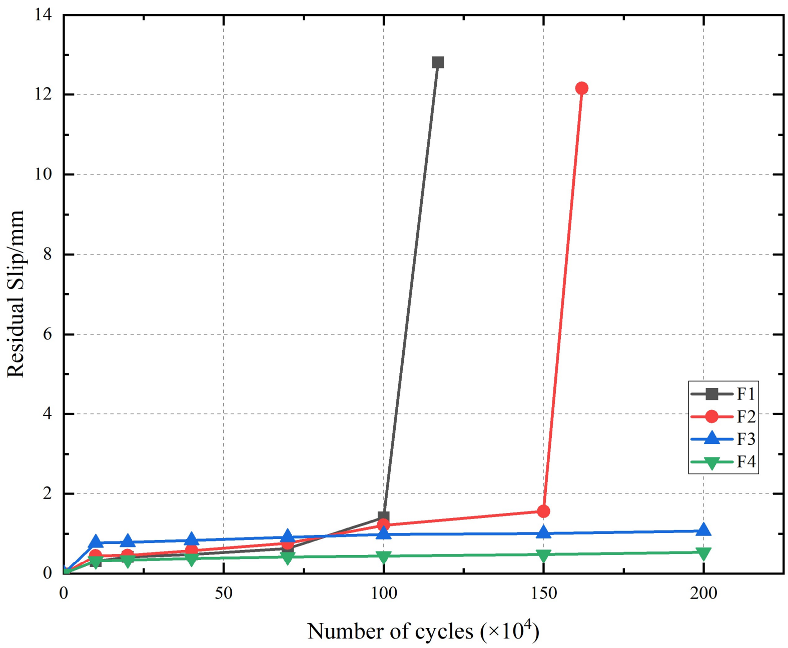

Figure 3. Residual slip

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3.2.4. Fatigue Life

Table 2 summarizes the fatigue life of specimens loaded with different load ratios. It can be seen from the table that the fatigue life of specimens is greatly affected by the load ratio. When the load ratio is greater than 0.36, the load ratio increases and the fatigue life decreases; If the load ratio is less than 0.31 and the fatigue life is greater than 2 million times, that is, no fatigue failure occurs, the critical load ratio for fatigue failure can be set as 0.31.

Table 2. Fatigue Life

Series	Peak Value of Cyclic Loading (kN)	Loading Ratio	Fatigue Life
F1	20	0.45	117×10^4
F2	16	0.36	162×10^4
F3	14	0.31	$>200 \times 10^4$
F4	12	0.27	$>200 \times 10^4$

4. Conclusion

This article explores the changes in bearing capacity, stiffness degradation, and residual slip development of bolted connections under fatigue loads through model experiments. Based on this, the fatigue failure mode of bolted connections in TCC is analyzed and revealed. The research results can provide reference for the fatigue design of TCC. The main conclusions are as follows:

The fatigue life of the specimen is related to the load ratio. Under fatigue loading, the stiffness first rapidly decreases with the number of cycles, then slowly decreases, and finally rapidly decreases when approaching failure. The residual slip exhibits three stages as the number of cycles increases: first rapid increase, then gradually stable and finally rapid increase.

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