Analysis of Flexural Performance of Steel-timber Composite Cantilever Beam

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Abstract. Steel-timber composite member is a new kind of structural member composed of steel plates and planks which are connected by bolts. The finite element analysis results on the flexural behavior of steel-timber composite cantilever beam show that the stress of steel plate exceeds the yield strength before the bearing capacity of the composite beam is lost. Under the premise of ensuring the yield of the steel plate, the increase in the thickness of plank has little effect on the in-plane bending stiffness of composite beam, and the lateral bending stiffness of the composite beam is obviously improved which means the plank can effectively restrain the lateral buckling of the core steel plate. Based on the deflection analysis of composite beams, the deflection coefficient of steel-timber composite is derived.

1. Introduction

Considering the national sustainable development strategy, it will be a general trend to select green building materials with less consumption of resources and energy, less impact on the ecological environment and higher recycling efficiency [1,2]. In the summary report on construction and climate change issued by the United Nations Environment Programme in 2012, it was pointed out that the annual greenhouse gas emissions of the construction industry accounted for 30% of the global annual greenhouse gas emissions, while consuming 40% of the global energy. If no rectification measures are taken, the greenhouse gas emissions of the construction industry in the next 20 years will be twice as much as the present.

Steel has the advantages of light weight, high strength, recyclable, less environmental pollution and fast construction speed, but stability has always been a key concern in steel structure design [3]. Timber is a kind of natural environmental protection and renewable material, but it has obvious anisotropic characteristics, and the design strength is relatively low, so it is limited in the application of large-span and high-rise buildings, and the failure is always brittle [4,5]. The steel-timber composite member is a close and effective combination of steel plate and plank through bolts, which is showed in Fig. 1. Steel with high strength is used to bear external load directly, and wood is used as surface material to provide enough lateral and torsional stiffness for core steel plate, so that the core steel plate will not occur global instability and local buckling before yielding [6,7], so that the design strength can be fully utilized [8].
2. Finite Element Analysis of Steel Wood Composite Cantilever Beam

For comparing and analyzing the bending performance of steel cantilever beam and steel-timber composite cantilever beam, and considering the influence of timber thickness on the bending performance of composite beam[9,10], a set of finite element calculation models of cantilever steel beam and three groups of steel-timber composite cantilever beam are designed.

2.1. Component Design

For the steel-timber composite cantilever beam, both sides of the board provide enough lateral bending stiffness and torsional stiffness for the composite beam, which can effectively suppress the overall buckling instability of the core steel plate. In order to ensure that the local buckling of the steel plate will not occur before yielding, the bolt spacing is reasonably designed by using the thin plate theory. The specific design parameters are shown in Table 1. A transverse concentrated load of 4.5kN is applied on the upper surface of the cantilever end of the steel plate, which ensures that the maximum stress at the fixed end of the steel plate can reach the yield strength.

Table 1. Design parameters of components.

| Model number | Dimensions of steel plate (Length×width×thickness/mm) | Dimension of one side board (Length×width×thickness/mm) | Transverse spacing of bolts (mm) | Longitudinal spacing of bolts (mm) |
|--------------|--------------------------------------------------------|--------------------------------------------------------|----------------------------------|----------------------------------|
| M1           | 1400×150×6                                             | —                                                     | 110                              | 200                              |
| M2           | 1400×150×6                                             | 1400×150×18                                           | 110                              | 200                              |
| M3           | 1400×150×6                                             | 1400×150×24                                           | 110                              | 200                              |
| M4           | 1400×150×6                                             | 1400×150×30                                           | 110                              | 200                              |

2.2. Mechanical Properties of Materials

The mechanical properties of steel and timber are tested respectively. The specific results are shown in Table 2.

Table 2. Mechanical properties of materials.

|                                | Steel     | Timber |
|--------------------------------|-----------|--------|
| Yield strength (N/mm²)         | 280       | —      |
| Ultimate tensile strength (N/mm²) | 432     | —      |
| Bending strength parallel to grain (N/mm²) | —        | 14.3   |
| Flexural modulus of elasticity (×10⁴ N/mm²) | 2.017 | 0.112  |

2.3. Results of Finite Element Analysis

According to the shape of the first buckling mode, the initial defect is introduced into the model, and then the large deformation analysis is carried out on the model including the initial defect, and the
material nonlinearity is considered at the same time. When the program is calculated to 0.3397 times of the applied load, the calculation does not converge and the calculation is terminated. The vertical and lateral deformation of cantilever end of each load step are shown in Figure 2 and Figure 3. We can see that the steel plate is far from yielding.

![Figure 2. The vertical deformation under the load.](image1)

![Figure 3. The lateral deformation under the load.](image2)

After the static small deformation analysis of three kinds of steel-timber composite cantilever beam, the buckling analysis is carried out, and the buckling mode is obtained. After reading the first buckling mode, the model is loaded with initial defects, and the large deformation analysis is carried out with material nonlinearity considered. The vertical and lateral deformation of cantilever end and the lower surface point of fixed end of each load step are read as shown in Figure 4 and Figure 5.

![Figure 4. The vertical deformation with various thickness.](image3)

![Figure 5. The lateral deformation with various thickness.](image4)

3. Theoretical Analysis

3.1. Lateral Bending Stiffness of Steel-timber Composite Cantilever Beam

The results of finite element analysis show that the lateral deformation of steel-timber composite beam is small in elastic stage, and its bending stiffness can be calculated according to Eq. (1). When the thickness of the board is 30mm, the calculation results are shown in Table 3.
\[ EI = E_s I_s + E_t I_t \]  \hspace{1cm} (1)

**Table 3. Flexural rigidity of steel plate, board and composite beam.**

| \( E_s I_s (\times 10^3 \text{mm}^4) \) | \( E_t I_t (\times 10^4 \text{mm}^4) \) | \( EI (\times 10^3 \text{mm}^5) \) |
|--------------------------------|--------------------------------|-----------------|
| 3.40                          | 1.90                          | 5.30            |

3.2. **Transverse Deformation of Steel-timber Composite Cantilever Beam**

Through the analysis of finite element calculation data, the deflection coefficient of steel-timber composite beam is defined as \( \beta_{st} \). The deflection of the cantilever end of the composite beam is calculated in Eq. (2).

\[ f_{\text{max}} = \beta_{st} \frac{FL^3}{3EI} \]  \hspace{1cm} (2)

Taking model 4 as an example, the specific calculation results are shown in Table 4. The deflection coefficient of steel-timber composite is obtained by the following results, \( \beta_{st} = 1.180 \) averaged by the values in the table.

**Table 4. Calculation results of the deflection coefficient.**

| \( F \) / kN | \( f \) / mm | \( \beta_{st} \) |
|--------------|--------------|-----------------|
| 0.78         | 1.58         | 1.174           |
| 1.23         | 2.50         | 1.178           |
| 1.83         | 3.73         | 1.181           |
| 2.13         | 4.34         | 1.181           |
| 2.58         | 5.26         | 1.181           |
| 3.03         | 6.18         | 1.182           |
| 3.48         | 7.09         | 1.181           |
| 3.93         | 8.01         | 1.181           |
| 4.23         | 8.63         | 1.182           |

4. **Conclusion**

1. Through the finite element analysis and calculation, the steel cantilever beam loses its bearing capacity due to the premature lateral buckling instability. Due to the sufficient lateral stiffness of the composite members provided by the boards on both sides, there is no obvious stiffness mutation of the composite members under the load. The stress of the core steel could reaches the yield strength, and the bearing capacity and ductility of the steel wood composite cantilever beam are significantly improved.

2. After the steel reaches the yield, the increase of the thickness of the board has less effect on the transverse bending stiffness of the composite beam. Therefore, in the design of steel-timber composite components, the thickness of wood board should be controlled to reduce the weight of the structure and the cost.

3. The deflection coefficient of steel-timber composite beam is deduced. It can be seen from the calculation results that the deflection coefficient of the composite beam has little difference under different loads, and the calculation result is reliable.

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