Finite Element Analysis and Buckling Behaviour of I-shaped Beams with RHCFST Upper Flange

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Abstract. In order to analyse the buckling behaviour of I-shaped beams with rectangular high-strength concrete-filled steel tubular (RHCFST) upper flange, a total of 7 simply-supported beams are designed with height-width ratio of upper flange and span as the main parameters in this paper. Based on ANSYS software, the finite element models are established, and the eigenvalue buckling analysis of seven simply-supported beams are carried out. The buckling loads of the composite beams can be obtained and the influence of height-width ratio of upper flange and span on eigenvalue buckling loads of each order of the beams can be studied. The results show that the buckling loads of each order of the beams can be significantly improved with the decrease of the height-width ratio of upper flange and span. Height-width ratio of upper flange and span have greater influence on high-order buckling load of beams. When the first-order buckling mode of the beam is analysed, overall flexural-torsional buckling occurs and the overall linear displacement and angular displacement reach the maximum at the mid-span position of the beam. It can be concluded that the displacement of the beam is mainly out-of-plane displacement in Z direction, and the rotation of the beam is mainly in X direction. It lays a foundation for further nonlinear buckling analysis of such composite beams.

1. Introduction

Traditional I-shaped steel beams have the advantages of high strength and light weight, but due to its insufficient stability, it fails to make full use of high strength. In order to improve the overall stability of the I-shaped beams, Dempsey firstly proposed a novel type of cold-formed thin-walled steel tube beams, which replaced the flange of traditional I-shaped beams with steel tube. However, the compression hollow flange of the beam under large load was prone to occur local buckling. Therefore, a novel type of concrete-filled steel tubular flange beams was formed by adding ordinary concrete to the upper flange steel tube of the hollow flange beam by Wu et al [1]. Due that this type of section closed the original hollow flange with ordinary concrete, the stiffness of structure was significantly improved with better mechanical behaviors. Recently, the steel tube has been researched widely. Nonlinear buckling analysis of H-type honeycomb composite columns with concrete filled rectangular steel tube flange was carried out by Ji et al[2]. The bearing capacity of different-strength concrete filled double steel tube short columns under axial compression was obtained by Ji et al[3-4].

A type of I-shaped beams with rectangular high-strength concrete-filled steel tubular (RHCFST) upper flange is proposed in this paper, which is formed by pouring high-strength concrete into the hollow flange of composite beams. High-strength concrete-filled steel tube structure can meet the requirements
of high bearing capacity and good seismic behavior[5]. Because of the existence of high-strength concrete, the local buckling of hollow flange beams is delayed. The bearing capacity of structural members can be further improved by the confinement effect of steel tube on concrete. The mechanical properties of beams can be improved by synergistic effect of steel tube and concrete[6-7]. The eigenvalue buckling analysis of composite beams is carried out by ANSYS software, and the buckling load and buckling mode of this kind of beams can be obtained in this paper.

2. Establishment of finite element model

2.1 Specimen design

In order to analyze the buckling behavior of I-shaped beams with RHCFST upper flange, 7 simply-supported beams are designed in this paper. The specific design parameters of specimens are shown in Table 1. The cross-sectional diagram of specimens is shown in Figure 1. Considering that it is easy for the composite beams to occur local deformation at the position of bearing supports, two end plates with a thickness of 20mm are set at the end of the beam. In order to prevent local distortional buckling, the transverse stiffener is set at the mid-span position. The size of the bottom flange is 60mm×6mm, and the size of web plate is 245mm×5mm. The structure of simply-supported beams can be seen in Figure 2.

| Specimens | $b_1\times h_1 \times t_1$ (mm$^3$) | $L$ (m) |
|-----------|-------------------------------|--------|
| B-1       | 60×30×3                       | 4      |
| B-2       | 65×30×3                       | 4      |
| B-3       | 70×30×3                       | 4      |
| B-4       | 75×30×3                       | 4      |
| B-5       | 60×30×3                       | 5      |
| B-6       | 60×30×3                       | 6      |
| B-7       | 60×30×3                       | 7      |

Table 1. Design parameters for 7 specimens

Fig. 1. The cross-sectional diagram of specimens

Fig. 2. The structure of simply-supported beams
2.2 Element type and material properties
SOLID 65 element is adopted for concrete and SHELL181 element is used to simulate steel tube, bottom flange and web plate. Eigenvalue buckling analysis of simply-supported beams is carried out in this paper, therefore, both concrete and steel are in elastic stage. The material properties are shown in Table 2.

Table 2. The properties of materials

| Material | Material grade | $E_s$ (Pa) | $\mu$  | $\rho$ (kg·m$^{-3}$) |
|----------|----------------|-----------|--------|----------------------|
| Concrete | C60            | 3.65e10   | 0.167  | 2450                 |
| Steel    | Q235           | 2.06e11   | 0.300  | 7850                 |

2.3 Geometric model and meshing
The geometric models of I-shaped beams with RHCFST upper flange can be established according to Table 1, as shown in Figure 3. The method to meshing is to divide 100 elements along the length of the beam, to divide 10 elements along the height of web plate, to divide 4 elements along the width of flange, and to divide 2 elements along the height of flange\(^8\), as shown in Figure 4.

Fig. 3. The geometric models of specimens

Fig. 4. The meshing diagram of specimens

2.4 Boundary conditions
The displacement of X, Y, Z direction and the rotate of X direction ($UX_1=UY_1=UZ_1=RX_1=0$) are constrained at the left end of beams, while the displacement of Y, Z direction and the rotate of X direction ($UY_2=UZ_2=RX_2=0$) are constrained at the right end of beams.

2.5 Load application
The SOLID65 element and MASS21 element are freely coupled at a point through the “CERIG” command, as shown in Figure 5. The magnitude of concentrated load is 0.1kN.
3. The results and analysis of finite element simulation
According to the finite element simulation analysis, the displacement and rotation in three directions for the first order of specimen B-1 can be obtained, as shown in Figure 6.
Fig. 6. The first order of specimen B-1

From Figure 6, it is shown that the overall flexural-torsional buckling occurs when specimen B-1 is subjected to concentrated load. The results show when the concentrated force is applied at the mid-span position of the beam, the overall linear displacement and rotation reach the maximum at the mid-span position of the beam. On the one hand, the maximum displacement along X direction of the beam appears at the end of the beam, while the maximum displacements along Y and Z directions of the beam appear at the mid-span position. On the other hand, the rotation along X direction reaches the maximum at the mid-span position of the beam, while the rotation along Y direction reaches the maximum at the end position of the beam. To sum up, the displacement of the beam is mainly out-of-plane displacement in Z direction, and the rotation of the beam is mainly in X direction.

4. Parameters analysis

The finite element calculations of the specimens shown in Table 1 are carried out, and the influences of the height-width ratio of the upper flange and span of the specimens on the buckling loads of each order of the beams are studied.

4.1 The height-width ratio of the upper flange

The buckling loads of specimens with different height-width ratio ($\zeta$) of the upper flange are shown in Table 3 and the comparisons of buckling loads are shown in Figure 7. It can be seen that with the decreasing of the height-width ratio of the upper flange, the buckling loads of beams are improved significantly. It can be concluded that the tangent slopes of four curves significantly increase, which indicates the height-width ratio of the upper flange has a greater influence on high-order buckling load of beams.

| Specimens | $\zeta$ | First order | Second order | Third order | Fourth order |
|-----------|--------|-------------|--------------|-------------|--------------|
| B-1       | 0.50   | 6.47        | 17.32        | 30.06       | 47.75        |
| B-2       | 0.46   | 7.32        | 20.45        | 35.77       | 57.28        |
| B-3       | 0.43   | 8.24        | 23.90        | 42.10       | 67.89        |
| B-4       | 0.40   | 9.22        | 27.68        | 49.07       | 79.62        |

Note: The unit of the buckling load is kN.
4.2 The span of beams
The buckling loads of specimens with different spans of beams are shown in Table 4 and the comparisons of buckling loads are shown in Figure 8. It can be seen that with the decrease of span of the beams, the buckling loads of beams are improved remarkably. From Figure 8, it can be concluded that the tangent slopes of four curves significantly increase, which indicates the span of beams has a greater influence on the high-order buckling load of beams.

Table 4. The buckling load of each order of the specimens

| Specimens | Span | First order | Second order | Third order | Fourth order |
|-----------|------|-------------|--------------|-------------|--------------|
| B-1       | 4    | 6.47        | 17.32        | 30.06       | 47.75        |
| B-5       | 5    | 4.60        | 10.44        | 17.80       | 27.48        |
| B-6       | 6    | 3.62        | 6.98         | 11.80       | 17.74        |
| B-7       | 7    | 3.03        | 5.00         | 8.45        | 12.37        |

Note: The unit of the buckling load is kN.

5. Conclusions
Based on ANSYS software, the eigenvalue buckling analysis of 7 I-shaped beams with RHCFST upper flange is carried out in this paper. The buckling modes of the specimens are obtained, and the influences
of different parameters on the buckling loads of the composite beams are studied. The conclusions can be drawn as follows:

(1) The overall flexural-torsional buckling of I-shaped beams with RHCFST upper flange occurs under concentrated load and both the overall linear displacement and rotation reach the maximum at the mid-span position of the beam. During the process of instability failure, in-plane deformation precedes out-of-plane deformation. The displacement of the beam is mainly out-of-plane displacement in Z direction, and the rotation of the beam is mainly in X direction.

(2) The buckling loads for each order of the beams can be significantly improved with the decrease of the height-width ratio of upper flange and span. Height-width ratio of upper flange and span have greater influence on high-order buckling load of beams.

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