Experimental study and finite element simulation of shear resistance performance of stainless steel beams

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Abstract. Stainless steel structures have gradually become high-performance green building materials in the field of engineering construction due to their advantages such as good corrosion resistance and ease of maintenance. However, stainless steel exhibits strain-hardening characteristics, and existing design specifications for calculating the shear bearing capacity of I-section beams are relatively conservative. This paper conducts experimental and finite element studies on the shear buckling bearing performance of stainless steel I-section beams, considering the effects of material nonlinearity, geometric nonlinearity, and local geometric initial imperfections. Based on the experimentally verified finite element numerical model, a parametric analysis of the influence on the shear bearing capacity of beams is carried out to explore the influence patterns of various key parameters, and the results are compared with the calculation results of current specifications (Chinese, American, European). The results indicate that, with the thickness of the web plate and other parameters remaining unchanged, the ultimate bearing capacity of the stainless steel I-beam web plate decreases as the width-to-height ratio of the web plate increases. The calculation results of the Chinese specification are relatively conservative and lower than the actual shear bearing capacity of the component.

1 Introduction

With the development of stainless steel research and the revision of relevant design specifications, the application of stainless steel in the field of civil engineering is becoming increasingly widespread. Stainless steel structures have gradually become high-performance green building materials in the field of engineering construction due to their excellent corrosion resistance and ease of maintenance.

Foreign research on stainless steel structures was earlier and relatively mature. Hassanein [1] conducted numerical simulations on transverse unsupported I-shaped austenitic stainless steel plate beams with non rigid stiffeners by studying the influence of strength and performance of duplex stainless steel plate beams. By comparing the finite element strength with the design specifications, it was demonstrated that the calculation

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method of the current specifications is relatively conservative. Saliba and Gardner [2] considered the influence of the aspect ratio and aspect ratio of the web on the bearing capacity of the component, and studied the failure mode of bidirectional stainless steel plate beams through experiments. There is relatively little research on the shear resistance of stainless steel in China. Chen Xiaowan et al. [3] studied the critical buckling stress of welded stainless steel beams with I-shaped cross-sections under the combined action of bending and shear through experiments and finite element analysis. Jiang Kaifu [4] revised the calculation formula for stainless steel load. Using finite element software, the influence of nonlinearity of stainless steel material on the buckling and bearing capacity of simply supported plates with four sides was analyzed. Yuan Huanxin et al. [5] conducted shear buckling loading tests on seven stainless steel thin web plates and analyzed the shear buckling bearing performance of stainless steel welded beams using finite element method.

Through the research results of domestic and foreign scholars, it can be found that there is currently a lack of experimental data in the study of mechanical properties, local stability, and residual stress of stainless steel materials. Especially for the stability theory of I-beam belly plates under shear action, there are still significant shortcomings in related research. For the shear performance design of stainless steel I-beams, current American, Chinese, and European standards have not fully considered the post buckling strength of the web plate, making it difficult to obtain a reasonable and economical design.

This article conducted shear performance tests on stainless steel I-section beams, analyzed their stress characteristics, failure models, buckling deformation and other related mechanisms, and used ABAQUS finite element software to establish a refined nonlinear finite element model. The accuracy and reliability of the finite element model were verified from multiple perspectives such as failure modes and load displacement curves. Parameter analysis was conducted based on the finite element results verified by experiments, covering different geometric and mechanical parameters.

2 Experimental study

2.1 Specimen design

This experiment conducted a mid span shear local stability performance test on four austenitic S304 stainless steel welded I-section beams. All specimens are equipped with head ribs at both ends. The geometric schematic diagram of the specimen is shown in Figure 1, and the specimen numbers and geometric nominal dimensions are shown in Table 1. The experiment adopts a three-point bending loading device for simply supported beams, with vertical loading provided by a 5000kN hydraulic actuator.

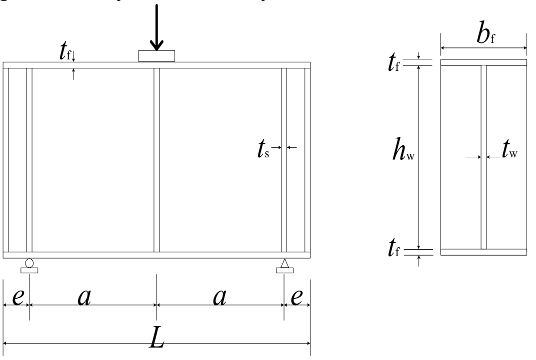


Fig. 1. Schematic of specimen geometry.

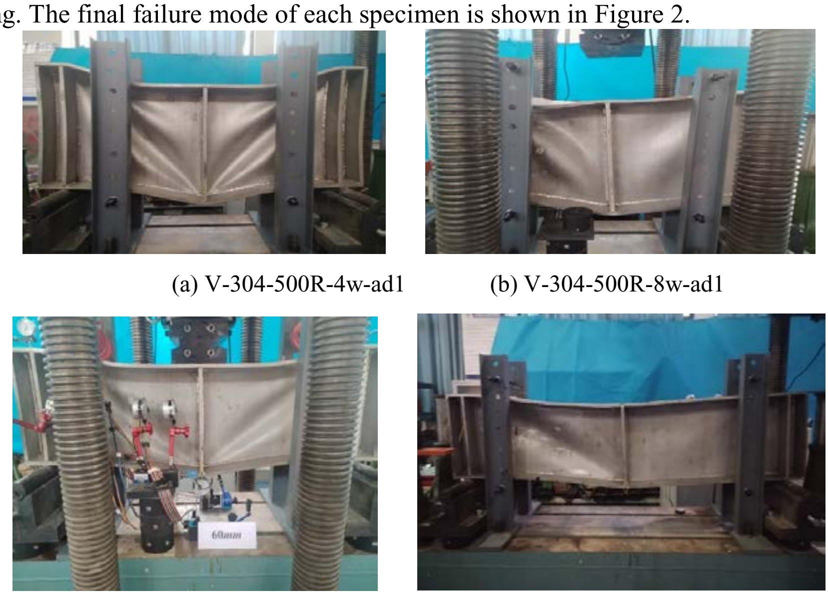
Table 1. Specimen marking and nominal geometry.

Number	L/mm	a/mm	h_w/mm	b_f/mm	t_f/mm	t_w/mm	a/h_w	e
V-304-500R-4w-ad1	1174	500	500	200	14	4	1	80
V-304-500R-8w-ad1	1174	500	500	200	14	8	1	80
V-304-400R-ad1.5	1374	600	400	200	14	4	1.5	80
V-304-400R-ad2	1774	800	400	200	14	8	2	80

2.2 Experimental phenomenon

During the loading process of specimens V-304-500R-4w-ad1 and V-304-400R-ad1.5, as the load and vertical displacement continue to increase, the web plate of the beam undergoes bulging deformation towards the plane and gradually develops. A tension band is formed in the middle of the web plate, resulting in a certain degree of post buckling strength of the I-shaped stainless steel beam. The failure mode of specimen V-304-500R-8w-ad1 shows a significant overall left tilt, with the flange and stiffeners forming a frame constraint, exhibiting much higher stiffness deformation than other specimens, and its ultimate bearing capacity is also higher than other specimens.

When specimens V-304-500R-4w-ad1 and V-304-400R-ad1.5 reach shear buckling, the vertical displacement at the mid span flange is not significant. As the load gradually increases, the tension band in the web plate gradually expands and distributes in the diagonal grid, exhibiting strong plastic characteristics. Due to the thickness of the web plate, specimens V-304-500R-8w-ad1 and V-304-400R-ad2 exhibit strong ductility after unloading. The final failure mode of each specimen is shown in Figure 2.



(a) V-304-500R-4w-ad1 (b) V-304-500R-8w-ad1

(c)V-304-400R-ad1.5 (d)V-304-400R-ad2

Fig 2. Specimen damage form.

3 Numerical simulation

The characteristics of stainless steel material are calculated using the Rambery Osgood formula [6] to obtain its true stress-strain curve, The Rambery Osgood related formulas are shown in equations (1) and (2). Where E is the elastic modulus, n and m are the first stage strain strengthening coefficient and the second stage strain strengthening coefficient, fy is the nominal yield strength, and fu is the ultimate tensile strength of the material, $E_{0.2}$ is the tangent modulus corresponding to the nominal yield strength point, and ε and $ε_{0.2}$ are the total strains of stress corresponding to 0.2% strain and plastic strain, respectively.

$$0 < f < f_y, \frac{f}{E} + 0.002\left(\frac{f}{f_y}\right)^n \tag{1}$$

$$0 < f < f_y, \varepsilon = \frac{f - f_y}{E_{0.2}} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{f_u - f_y}{E_{0.2}}\right)\left(\frac{f - f_y}{f_u - f_y}\right)^m \tag{2}$$

3.1 Finite element model

The shear performance test of stainless steel I-beams was numerically simulated using the finite element software ABAQUS. The four node shell element S4R with simplified integration is adopted, and 5 integration points are taken in the thickness direction. S4R can effectively calculate material and geometric nonlinear problems. And it has been proven to be applied in numerical analysis of the stability performance of stainless steel components. The boundary conditions of the model are: binding the upper wing edge to the mid span reference point of the upper wing edge to form a rigid end face, and restricting the joint between the two supports of the lower wing edge at x The displacement of the lines in two directions, y Rotate in two directions to match the experimental loading conditions. The finite element modeling is shown in Figure 3. Initial imperfections can affect the load-bearing capacity and failure of test specimens. The first-order mode calculated using eigenvalue buckling of the finite element model is taken as its local geometric initial imperfection, as shown in Figure 4 The geometry of the corresponding nodes in the model is updated using the *IMPERFECTION command. The initial stress field is defined using the *INITIAL CONDITION, TYPE=STRESS command. The local imperfection value is B/100 (B is the flange width).

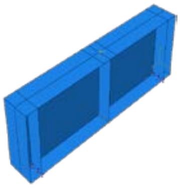


Fig.3. Finite element geometric model

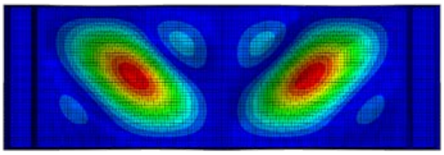


Fig.4. First order flexural modes

3.2 The results of numerical simulation

3.2.1 Load-displacement curve

The test results of the specimen V-304-500R-4w-ad1 of the austenitic stainless steel S30408 model were compared and analyzed with the finite element calculation results, as shown in Figure 5. In the early stage of loading, the web was in a pure shear state (i.e., the principal plane was inclined at 45° to the horizontal plane). Once the applied shear force exceeded the elastic shear buckling load, the stress along the tensile diagonal continued to increase, while the stress along the compressive diagonal developed at a smaller rate, thus the principal plane began to rotate towards the horizontal direction. Eventually, the web yielded under the combined stress field and reached the ultimate bearing capacity.

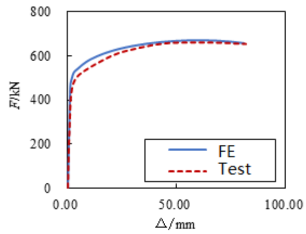


Fig. 5. Comparison of limit element and test result data.

3.2.2 Failure mode analysis

Taking specimen V-304-R500ad1 as an example, the comparison between the buckling instability test results and the finite element results is shown in Figure 6. All the finite element model specimens of the I-shaped stainless steel beams experienced buckling instability, which was in good agreement with the test failure mode. This indicates that the adopted finite element analysis method can accurately simulate the entire process of the shear buckling test of the stainless steel beams.

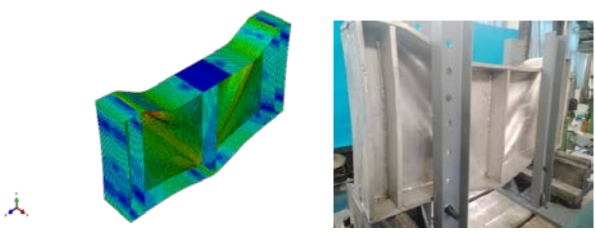


Fig. 6. Comparison of damage modes between test and finite element simulation results.

4 Conclusion

(1) The I-shaped stainless steel beams all experienced shear buckling failure, with bulging deformation of the web plate towards the outer plane, developing into obvious tension bands, and ultimately experiencing severe deformation. Plastic hinges appeared on the transverse stiffeners at the upper flange and two supports.

(2) By comparing the experimental results with the finite element simulation results, the failure modes of the two are basically consistent. Verified the accuracy and reliability of the established finite element model.

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