Bending Shear Bearing Ultimate Capacity for Hybrid Welding I-Shaped Steel Web Plates

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Abstract
In order to fully study the mechanical properties of the mixed steel beams, the bending and shear ultimate bearing capacity of the hybrid steel beams are studied by the method of numerical analysis. And the effect of yield strength of the web is also analyzed and reasonable web and flange yield strength ratio are achieved, deducing the elastic-plastic deformation formula. In order to understand the welding I-shaped hybrid girder bearing capacity limit state, using finite element method of welded I-beam webs under shear, bending, local pressure alone and combined effects of ultimate bearing capacity were calculated. The results show that mixed steel I-shaped laminated composite beam can give full play to the flange and web of steel strength and ensure the enough safety storage. It can significantly improve the flexural bearing capacity and decrease the weight of the structure. At the same time, the high thickness of the web has a very high post buckling strength, the high thickness ratio of the web and the spacing between the transverse ribs are the main factors affecting the shear ultimate bearing capacity of the web plates.
Key words: WELDING I-SHAPED STEEL, WEB PLATE, MIXED STEEL, FLEXURAL BEARING CAPACITY, FINITE ELEMENT ANALYSIS

1. Introduction

Hybrid beam refers to using different strength grade steel combination beam, simply supported plate girder flange with higher strength grade of steel webs with low strength grade of steel. The commonly method is used in engineering I-beam section as an example, with the yield strength decreased by half, flexural strength decreased less than 10%. Compared with ordinary steel beams, it is equipped with the advantages of low weight, low cost, etc..

The research of hybrid steel beam began in 1940s, but its application in engineering has a substantial breakthrough in the high performance steel HPS. HPS steel has high strength and good performance, but the price is expensive, and the total cost of the steel beam made of HPS steel is not necessarily the cost. Flange, ordinary steel webs of hybrid girder steel HPS, under strength did not decrease significantly, engineering cost significant savings is not always good solution. Hybrid steel girder has been used for many years in foreign countries, but it is still a blank in China [1].

Ma Jingsheng earlier on the steel I-beam mixed bending done theoretical research on bearing capacity. The high performance steel was studied through experiments.

The morphology of HPS485W and ordinary steel mixed design I-beam bending bearing capacity, deformation characteristics and failure [2]. Wang Pengfei studied on strengthening flange type single axisymmetric mixed I-beam ultimate flexural capacity. With the development of high strength steel, hybrid girder design gradually get attention, two kinds of steel can be maximized, give full play to the superiority of force performance.

It is found that web on flexural bearing force contribution is only about 30% of the flange in the engineering application of I-beams, usually in web and flange area similar.

Steel structure in our country's application is more and more extensive, including the important infrastructure, the large-scale public building, the bridge, the industry and the civil construction and so on [3-4]. In many projects, the existing H type steel specifications meet the design requirements, which need a large number of welded steel beam. In order to ensure economic and rational, welding I-beam webs are usually designed high and thin, such webs on the critical buckling load is very small, in order to enhance the web plate of the critical load, usually set transverse stiffeners, sometimes still at the central section of the beam setting longitudinal stiffeners. In the traditional design method, the buckling of the web is the ultimate state of load bearing capacity. In fact, web buckling will not lead to the loss of carrying capacity. For in-depth understanding of welded I-beam real bearing capacity limit state. In this paper, the limit of welded I-beam webs under shear, bending, local pressure alone and combined effects of bearing capacity of in-depth theoretical analysis and experimental study.

2. Static Analysis and Modeling

2.1. Calculation method

Based on the Lagrangian description of the degenerated three-dimensional curved hull isoparametric element with the finite element method calculation of welded I-beam limit bearing capacity. Geometric nonlinearity and physical nonlinearity are considered in the calculation. In the calculation model, the rigid connection of the stiffening rib and the web, and the displacement in the plane of the upper and lower flange is only coupled [5].

In practical engineering, the geometrical imperfection of the plate is objective. In determining the ultimate bearing capacity of the stability problem analysis, must be considered. The initial geometric imperfections of the plate are various, and the actual size of the plate is not required to be known in practice. In this paper, the initial geometric imperfections are considered by introducing initial uniform defects, i.e., the distribution of initial geometric imperfections is the same as that of the first buckling mode.

2.2. The static behavior of hybrid steel beams

By mixed beams of pure bending load, with the section is the increase of stress, webs on the lower edge of the first appears to yield and flange to yield f accordingly can be divided into four stages of the force. And the beam cross section schematic diagram is shown in figure 1.

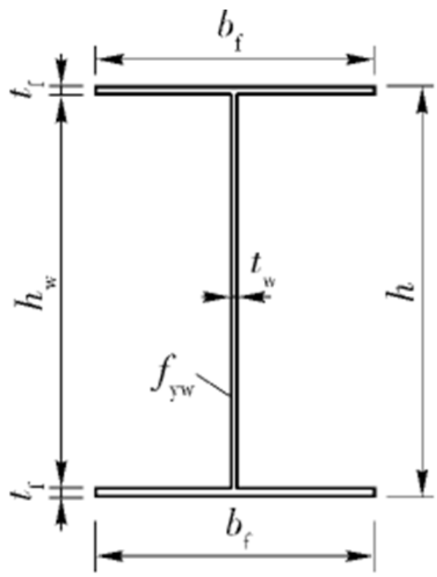

Figure 1. The beam cross section schematic diagram

Stage 1 is the elastic stress stage. In this stage, there is no difference between the force and the ordinary steel beam at this stage. The maximum elastic moment is calculated as the following formula.

$$M_e = k\frac{h}{h_w}M_y \tag{1}$$

$$k = \frac{f_{yw}}{f_{yf}} \tag{2}$$

Where, k is a web and flange which is a very virtual service. $M_y = f_{yf}W$, which is the yield bending moment for ordinary steel beam. f_{yw} and f_{yf} are respectively in web and flange yield strength.

When the normal stresses on the lower edge of the webs exceeds the yield strength after entering the stress stage 2. The web can be treated as an elastic plastic state. And the flange also remains elastic state, is shown in Figure 2. The beam stiffness decreased. Web elastic zone height of y , then the bending moment is calculated as follows.

$$M_{ep} = M_{pw}[1-\frac{1}{3}(\frac{y_s}{h_w})^2]+k\frac{h-t_f}{y_s}M_{pf} \tag{3}$$

In the equation, the plastic bending moment $M_{pw} = 1/4t_w h_w^2 f_{yw}$. The flange plastic moment

$M_{pf} = A_f(h - t_f)f_{yf}$. The maximum bending moment is the bending moment M_{ep1} at the beginning. The height of the elastic region of web is y_s , $y_s = kh$.

$$M_{ep1} = M_{pw}[1 - \frac{1}{3}(\frac{kh}{h_w})^2] + \frac{h - t_f}{y_s} M_{pf} \quad (4)$$

From flange to yield to submit completely, this is the stage 3. Since the thickness of flange of the same section height compared to the very small and the stress process is very short, section stiffness decreases rapidly. The maximum bending moment is the bending moment M_{ep1} of flange in wholly yield and the height of the elastic region of web is y_s , $y_s = kh_w$.

$$M_{ep2} = M_{pw}[1 - \frac{1}{3}k^2] + M_{pf} \quad (5)$$

After the cross section bending moment is over M_{ep2} , the elastic area of the whole section is only partially in the neutral axis of the web, and the section stiffness is small, and the plastic bending moment of the section is quickly reached M_p .

$$M_p = M_{pw} + M_{pf} \quad (6)$$

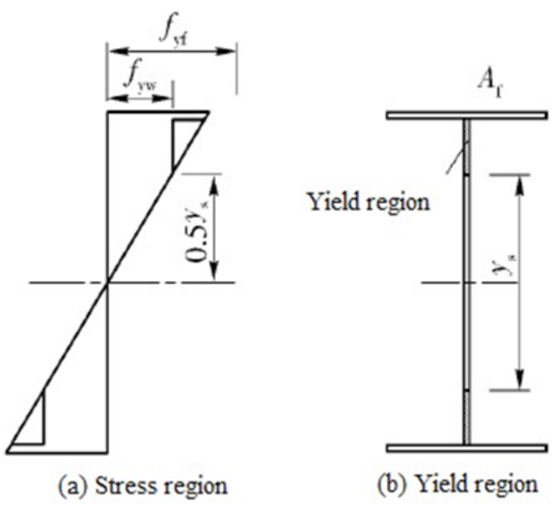

Figure 2. The elastic plastic distribution of stage 2

3. Shear web

3.1. Effect of Web Yield Strength

In the calculation of the mixed steel beam with different span and section, the influence of the web yield strength was calculated by adjusting the parameters of k .

When $k = 1.0$, then $M_{ep1}/M_y = 1.0$. When $k = 0.50$, then $M_{ep1}/M_y = 0.91$. The calculation results show that web yield strength is reduced by nearly a half flange yield moment only than the ordinary beam decreased by 7%, which shows the advantage of hybrid girder.

When $k = 0.91$, then $M_{ep1}/M_p = 0.85$. When $k = 0.54$, then $M_{ep1}/M_p = 0.92$ .The calculation results show that flange yield moment and plastic moment is very close to each other, considering from the safety reserve. The web yield 0.6 times the intensity should not be lower than the flange.

3.2. Determination of critical stress of shear buckling

The traditional design method is based on the stability theory of thin plate to determine the buckling critical stress of the web. But for the four sides simply supported the pure shear plate, shear buckling critical stress calculation is as the following formula [6].

$$\tau_{cr} = \frac{\chi_s k_s \pi^2 E}{12(1 - \nu^2)} \left(\frac{t_w}{h_0} \right)^2 \quad (7)$$

In this equation, χ_s is the constraint coefficient of flange on the web. k_s is the shear buckling coefficient of steel plate. And ν is the Poisson's ratio.

According to the calculating formula of shear critical buckling stress, the value of χ_s cannot be calculated accurately. Usually according to the flange stiffness, $\chi_s = 1.0 \sim 1.21$, the actual welding I-beam webs is a continuous plate, and flange and stiffening rib is connected. In this paper, the finite element method calculating the critical buckling stresses.

3.3. Effect of the stiffness of the flange and the lateral stiffening rib on the ultimate strength of shear

Figure 3 is a model of the shear web, as shown in the following. Lattice beam end webs mainly bear shear. A series of span are calculated, with the same height and thickness of the web and transverse stiffener spacing, wing edge thickness t_f width b and the thickness of the stiffeners t_s different shear webs shear buckling critical stress force τ_{cr} , ultimate strength τ_u and strength increase value $\tau_u - \tau_{cr}$. The results show that to meet the provisions of the code for design of steel structure of flange and stiffening rib plate slenderness ratio limit, flange and transverse stiffener stiffness on the web shear buckling critical force and the ultimate strength of very small). In Figure 4, the relationship between the thickness $b = 240mm$ of the flange and the ultimate strength of the t_f is listed.

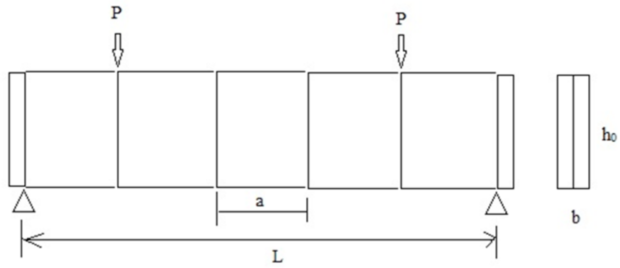

Figure 3. The calculating model of web under shearing

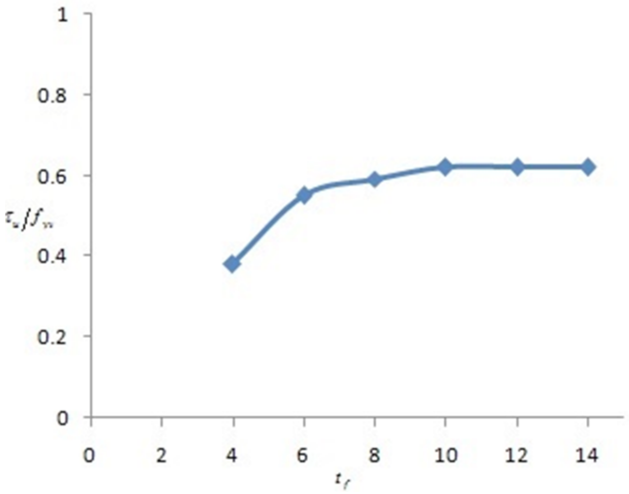

Figure 4. The ultimate shear capacity and flange thickness

3.4. Influence of web height and thickness ratio on shear strength of shear

The critical stress and ultimate strength of shear buckling of a series of shear webs with a series of span, flange dimensions, cross section shape coefficient, and web thickness ratio are calculated.

The web is very thick and thick, and the value of the web is very low. This is because the web is high and thick, and its shear buckling critical stress is very high, even more than its shear yield point. So that $\tau_u - \tau_{cr}$ is very small. When the web height and thickness ratio increased, the $\tau_u - \tau_{cr}$ value was significantly increased. But the high thickness ratio of webs increases to a certain extent increased, $\tau_u - \tau_{cr}$ decreased. The reason is not enough to support the web is too thin, the compression flange, so that the pressure is too large to one side of the web buckling.

According to the calculation results, it is found that although the encryption of the transverse stiffeners prevents shear buckling, but did not get the expected effect. The pure bending region lattice did not occur in the web buckling failure, but adjacent regions occurred shear failure, lattice, the lattice of maximum bending moment and the pure bending region and bears a lot of shear force. It can be seen that the bending stress of the web is little affected by the bending stress of the beam. Literature refers to the use of Web buckling strength, the general no longer consider setting longitudinal stiffening rib. For Q235 steel, compression flange torsion restrained beam, when the web height to reach 200, the flexural bearing capacity and the full cross section of the beam, compared to only 6% less.

In the middle of the continuous beam, the bending shear interaction of the adjacent webs is calculated, and the bending moment is less affected by the bending moment when the bending moment is smaller than that of the flange. The failure mode is still the shear buckling of the web, but the ultimate bearing capacity is improved. This is because the middle support of continuous beam in the right and left sides are connected with the web. Such stiffening ribs in the two direction are subject to tension, can be anchored in the tension field. Therefore, it is suggested that the bending shear of the continuous beam support can be calculated by the shear, but the bending moment can be considered.

4. Experimental research

The calculation shows that welding steel I-beam webs of ultimate bearing capacity is influenced by many factors, in order to verify the correctness, this article has carried on the experimental study.

4.1. Flexural ultimate bearing capacity

The ultimate flexural capacity of steel beam depends on the plastic bending moment, torsional buckling, flange and web local buckling etc.. By limiting the web height, thickness ratio and flange width to thickness ratio, the local buckling does not occur in front of the flexural torsional buckling, which can separate studies of flexural torsional buckling ultimate load [7].

Hybrid girder in loading process, web before flange partial yield, geometric property of section advance to change, the flexural torsional buckling and the ordinary beam there must be different. ANASYS finite element calculation method is taken into use, considering material and geometric nonlinearities, geometrical imperfections and residual stresses, arc length method for solving mixed beam flexural torsional buckling ultimate load.

In order to reflect China's steel production process level, introduced in reference for construction of highway bridges and culverts specification for steel bridge deck section of steel making three kinds of deviation limit as geometric imperfections, respectively for the web a plane convex curved, flange plate tilt and steel beam integral transverse bending. The flange end of the tilt a maximum of not more than 2mm. The overall horizontal deviation according to the total length of the beam has different provisions, the maximum not more than 5mm. These deviation limits are actually the maximum value of geometric defects of engineering structures, which is used to calculate the geometric imperfections, and the results should be conservative. Hybrid girder is welded steel beams and bridge with steel beam flange is flame cut processing, in the web and flange connected, the longitudinal residual stress to the respective yield strengths.

4.2. The design for test piece

According to different experimental purposes, 8 specimens were designed, and the sample size was shown in Table 1. The material was Q235, the yield strength was 320MPa, and the elastic modulus was 204000.

The purpose of the test is to study the shear ultimate bearing capacity and its variation law of the web in different high thickness ratio and different transverse stiffening rib spacing. P4 is a continuous beam, because the P3 is a continuous beam, and the bending moment and shear force of the web can be obtained. The purpose of the test is to observe the effect of local concentrated load on the buckling and ultimate bearing capacity of the web without the support of the P5. The purpose of P6 is to obtain the ultimate bearing capacity of the beam subjected to pure bending moment. P7 test piece is used to observe the influence of the longitudinal stiffening rib on the buckling and bending ultimate bearing capacity of the web. Welded I-beam specimens of P8 transverse stiffeners for unilateral.

4.3. The test results and analysis

The theoretical calculation results are in agreement with the experimental results, which can be seen in Table 1 [8, 9].

Specimen P1 to P3 were failure in shear failure of Web buckling end zone, lattice appeared obvious tension field. The experimental results show that the buckling critical stress of the web shear ultimate strength is much higher than that of the theoretical calculation, and the law of the theory is the same, the higher the web is (h_0/t_w) or (a/h_0), and the ultimate load is more than 3 times. In the experiment, the lateral deformation of the web is small, less than the thickness of the web, and it shows that the resistance of the web to shear buckling is relatively large. When the load exceeds the buckling critical load of many, the web to see some convex curved deformation, when added to the destruction of the first level load, tension field strip convex curved deformation suddenly increases, for what happened before the lateral deformation of several times.

Table1. Details of specimens

Test Piece Number	L/mm	h_0/mm	t_w/mm	b/mm	t_f/mm	a/mm	h_0/t_w	a/h_0	Theoretical value/ KN	Experimental value/ KN	$\varepsilon/\%$
P1	4000	800	5	250	12	750	200	1.00	352.6	352.6	1.85
P2	4000	800	5	250	12	900	200	1.25	420.2	400.3	8.25
P3	4000	800	5	250	12	1200	200	1.55	300.6	452.3	-2.0
P4	8000	800	5	250	12	1000	225	1.00	387.9	385.6	6.74
P5	6000	1000	8	310	12	150	180	1.15	950.5	885.3	4.84
P6	4000	800	5	250	12	220	180	1.00	850.2	862.5	1.2
P7	6000	1500	8	380	14	250	225	1.25	1000.2	1114.8	5.3
P8	6000	1500	8	410	16	250	225	1.25	256.3	286.9	2.8

5. Conclusions

The spacing between the high and thickness ratio of the web and the spacing of the transverse stiffening rib is the main factor affecting the ultimate bearing capacity of the web. The (h_0/t_w) or (a/h_0) is larger, and the shear ultimate bearing capacity of the web is greater. But the web is too thin, not enough to support the compression flange, which side to the web under too much pressure buckling. When the high thickness ratio is large, the lateral deflection of the web is increased, the web is high and thin.

The bending moment of bending shear joint action of the web, when the bending moment is smaller than that of the flange, the bending moment has little effect on the ultimate bearing capacity, and the failure form is still the shear buckling of the web.

Using the post buckling strength for anchoring force field transverse stiffeners are symmetrically arranged at both sides of, can be used to set the end sealing plate tectonic measures, to strengthen the tension of the endwall lattice field effect.

At the same time, the high thickness of the web has a very high post buckling strength, the high thickness ratio of the web and the spacing between the transverse ribs are the main factors affecting the shear ultimate bearing capacity of the web plates. mixed steel I-shaped laminated composite beam can give full play to the flange and web of steel strength and ensure the enough safety storage. it can significantly improve the flexural bearing capacity and decrease the weight of the structure.

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