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Analysis and Experiment on Bending Performance of Laser-Welded Web-Core Sandwich Plates

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Abstract

The bending performance is the main performance index of the sandwich structure. This paper is used to analyse and test showing that: the range of the elastic limit and the maximum bearing capacity is 25 ~ 30 kN and 34.9 ~ 54.8 kN, respectively; the average of bending stiffness and shear stiffness measured by test is 810 kN. m and 1717 kN/m, respectively; In elastic stage (U2 = 6 mm), plate material in the weld junction of web (n = 5)and face plates appear local yield, which shows that the most unfavorable area of sandwich panels is the weld junction of web and face plates.
*Keywords:*web-core; sandwich plates; laser-welded; stiffness; three points bending test; bending performance

1. Introduction

Due to the all metal laser-welded sandwich plates not only have light weight and high strength characteristics, but also have other higher superior performance, it has been widely used in aerospace, shipbuilding and civil construction etc. All metal laser-welded sandwich plates have multiple structures according to the core with different shape. one of all is laser-welded web-core sandwich plates, their web and panel is connected with laser welding, the webs arrange along a direction, which provide two supports for the panel decorate along a direction,

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namely the continuous support of the web direction and the discrete support of vertical to the web direction, structure and weld geometrical arrangement is shown in Fig. 1.

In the approach to the study of sandwich plate, the most widely used is two-dimensional linear model [1] (Reissner, Hoff, Прусаkob-Du Qinghua theory model) and numerical methods. the foreign research of full metal sandwich panel is earlier. Romanoff and Varsta [2, 3] have presented the theory method of calculating four bending response for laser-welded I-core sandwich plate. Kolsters [4] applied equivalent stiffness model, and gives out the equivalent stiffness analytical formula of Laser-welded I-core sandwich plate with foam-core. At present, the domestic research is less for all steel laser-welded sandwich plates [5]. The test method of sandwich structure bending performance is given in GB/T 1456-2005 [6]. Li and Zeng [7] proposed the experimental method about separation stiffness for composite honeycomb sandwich plates. Wu, et al. [8] established a new solution on unified bending control equation using energy principle for bending problem of the square honeycomb sandwich plate. Zhang, et al. [9] carried out the three-points bending experiment for the aluminum alloy foam sandwich panel prepared by composite rolling technique with a metallurgical bonding interface, which was used to demonstrate the practical bonding property of the interface and the bending resistance. Sun [10] have put forward the method of structural optimization design according to the factors of the equivalent stiffness and quality for Laser-welded sandwich plate.

In this article, test and finite element simulation analysis were carried out for three points bending performance of the laser-welded web-core sandwich plate. The ultimate bearing capacity, stiffness, stress distribution and failure destruction form of the sandwich plate were determined, which will play important guiding significance for design and application of the sandwich plates in future.

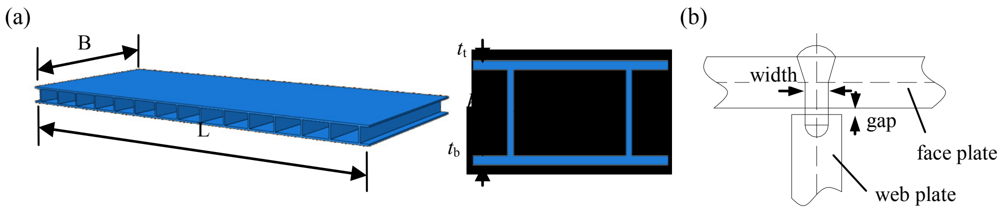

Fig. 1. (a) Overall structure arrangement of laser-welded web-core sandwich plates. (b) T-joint weld geometrical arrangement of laser-welded web-core sandwich plates.

2. Theoretical Stiffness of web-core sandwich plate

Due to the distribution of Web plate of laser-welded web-core sandwich plates along the horizontal and longitudinal is continuous and discrete, respectively, its structure is anisotropic. The discrete core layer can be converted to a homogeneous continuous layer by using equivalent stiffness characteristics, which make plate structure into a 2D orthogonal anisotropic plate [4]. The equivalent stiffness of model and force distribution as shown in fig. 2.

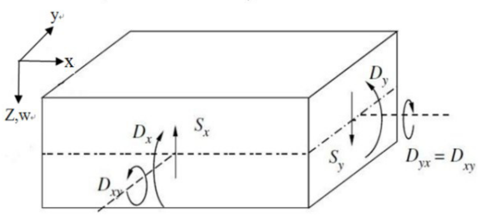

Fig. 2. Equivalent model of 2D orthotropic plate.

Analytical formulas of equivalent stiffness for laser-welded web-core sandwich plates unit as shown in formula (1) ~ (5):

$$D_x = \frac{2E_f t_f^3}{12} + \frac{E_f d^2 t_f}{2} + \frac{E_w h^3}{12}\left(\frac{t_w}{(a+t_w)}\right) \tag{1}$$

$$D_y = \frac{E_f d^2 t_f}{2} + \frac{2E_f t_f^3}{12} \tag{2}$$

$$D_{xy} = G_f d^2 t_f \tag{3}$$

$$S_x = 2G_w t_w \left[\frac{d^2 t_f}{(a+t_w)ht_w} + \frac{1}{6}\left(\frac{h}{a+t_w}\right)^2\right]\left[\frac{t_f}{t_w} + \frac{h^2}{3(a+t_w)d}\right]^{-1} \tag{4}$$

$$S_y = G_{zy}\frac{d^2}{h} \tag{5a}$$

$$G_{zy} = \frac{1}{\gamma_{zy}}\frac{h}{d^2} \tag{5b}$$

$$\gamma_{zy} = \frac{2}{E_f t_f^3}\frac{2}{(a+t_w)}\left(\frac{a}{2}\right)^3 + \frac{1}{E_w t_w^3}\frac{(a+t_w)}{2}d\left[\left(\frac{t_f}{d}\right)^3 - 3\frac{t_f}{d} + 2\right] \tag{5c}$$

where: t_f、t_w、h is the thickness of pace plates and web and the height of web, respectively, d is the distance between the top and bottom panel neutral axis, a is the distance between two neighboring web plate, as shown in Fig. 1. E_f、E_w、G_f、G_w is young's modulus and shear modulus of face and web plates, respectively; D_x、D_y、D_{xy} is the bending rigidity of *xz, yz* plane and torsional rigidity of *xy* plane, respectively; S_x、S_y is the shear stiffness of *xz*、*yz* plane, respectively.

3. Three points bending test

3.1. Confirmation of specimen material and size parameters

3.1.1. The optimization of section size

According to the bending rigidity, shear stiffness and quality of Laser-welded I-core sandwich plates, the optimization section size has been found In Ref. [8], the basic dimensions is shown in tab. 1 and Fig. 1, The thickness of the top plate, bottom plate, web and web height are denoted with t_t, t_b, t_w and h, respectively, the number of web is n, the distance between two webs is s, Length and width are L and B.

Tab. 1. Section basic size of laser-welded I-core sandwich plates

H (mm)	s (mm)	n	t_t= t_b=t_w (mm)	L (mm)	B (mm)
40	78	15	4	1200	500

3.1.2. Material properties test for sandwich plates

Considering the sandwich plate is mainly used in ship structure, the selection of material is CCS-B Marine board. When the basic research and finite element simulation are needed for the Laser-welded sandwich plate, the mechanical properties of plate must been characterized. The weld and base metal properties can been determined through the tensile test. Two kinds of specimens for Base metal have been made in parallel rolling direction and vertical rolling direction. Weld specimen have been made along the weld length direction. In order to study the joint action under T-joint performance of weld and base metal, joint specimen has been made in vertical weld length direction. The 4 kinds of tensile test and specimens fractured after test as shown in Fig. 3, respectively. The above test's engineering stress-strain curve as shown in Fig. 4, which provides the basis material property parameter for the finite element simulation.

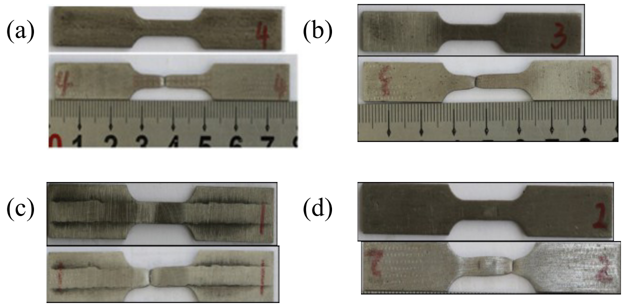

Fig. 3. (a) Parent metal (along the rolling direction). (b) Parent metal (vertical rolling direction). (c) Weld. (d) Joint.

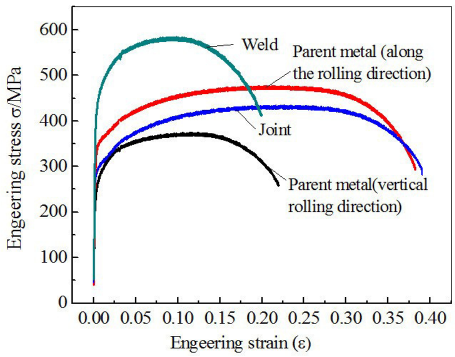

Fig. 4. The properties of sandwich plate

The Fig. 3 shows that the strength of base metal in parallel rolling direction is higher than that in vertical rolling direction, the strength of the weld is higher than that of the base metal, the joint specimen first fractured in the base metal place in the Fig. 3 (d), it illustrates better this point, and weld's ductility is worse than the base metal. Four kinds specimen material properties as shown in tab. 2. The Young's modulus, Poisson's ratio, yield strength and tensile strength and breakdown strength are denoted with E, ν, σ_s and σ_b, σ_u respectively.

Tab. 2. Properties of laser-welded I-core sandwich plates

specimen	E(GPa)	*ν*	σ_s (MPa)	σ_b (MPa)	σ_u (MPa)
(a)	2.10×10^3	0.3	343	475	292
(b)			204	371	259
(c)			360	563	433
(d)			251	429	289

3.2. Test device

Test loading device by using the four-column hydraulic press of key laboratory of Lanzhou university of technology. According to the stiffness of separation process as shown in Ref. [8, 9] to design test model, and general device as shown in Fig. 5 (a). Using the pressure head with spherical structure to prevent eccentric action in the process of load eccentricity, backing plate is made of two layers of steel casting steel plate with 120mm Width and 20mm thickness, its height is 77mm, and in the central of backing plate is a spherical notch in contact with the spherical pressure head in the loading process, the role of the whole backing plate is to disperse the concentrated loading force to a linear distribution force and load onto the specimen. There is a hard rubber pad with 510mm length and 150mm width and 5mm thick between the pressure head and specimen, which has two aspects of the role, one is weak the stress concentration between the backing block and specimen, the other one is constraining the transverse displacement of specimen through friction, as shown in Fig. 5 (b). Bearing with left and right sides is symmetrical roller bearing (φ=110 mm), each side plate adopts two groups support with two line contact roller bearing, which can achieve the free rotation, and then achieve both sides simply supported conditions, support and clamping device as shown in Fig. 5 (c). According to the surface of the table size of the hydraulic press and specimen size the support spacing L is determined as 1m. Displacement sensor from left to right are numbered 1 ~ 3 in turn, No.1 and 3 on the overhanging end, the distance from them to support is L/3 as 333 mm, No. 2 at mid span as L/2.

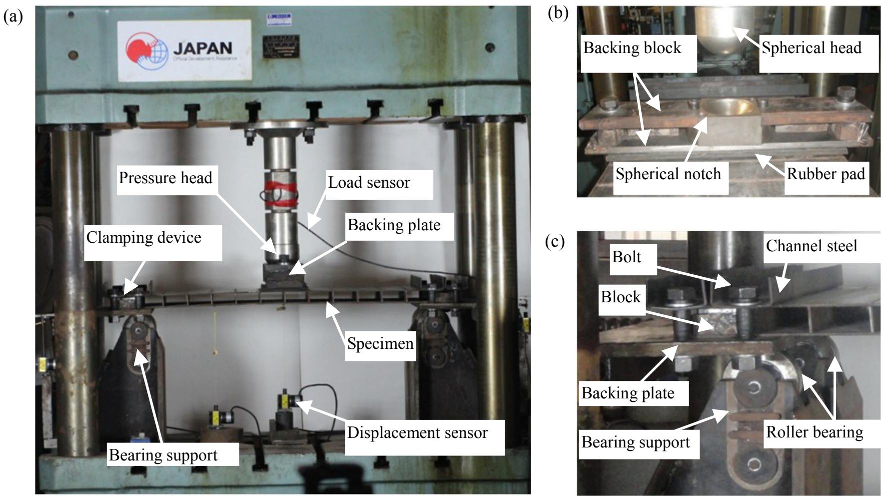

Fig. 5. (a) General Drawing of Test Device. (b) Detail of Pressure Head and Backing. (c) Detail of Support and Clamping Device.

4. ABAQUS Finite Element Model (FEM)

Numerical simulation of the test model using ABAQUS finite element software can clear specimen stress of all parts, and then the three points bending performance of sandwich plate can be better understood. In order to contrast with the test data, and analyze the correctness of the test and numerical simulation, FEM model was consistent with the test. In order to reduce the calculation time, the half model is established, and as shown in Fig. 6.

In the FEM model, loading method is the displacement loading; All of the parts are 3D solid element, the element type is C3D8I; The support are the bearing(φ=110mm) support, and their center distance is 1m, which achieve simply-supported (U2=U3=UR1=UR2=0) in both of the sides; Weld size is 4×6mm; The web from the left to mid-span are numbered 1 ~ 8 in turn for the convenience of the results discussed, No.3 and 8 are marked typically.

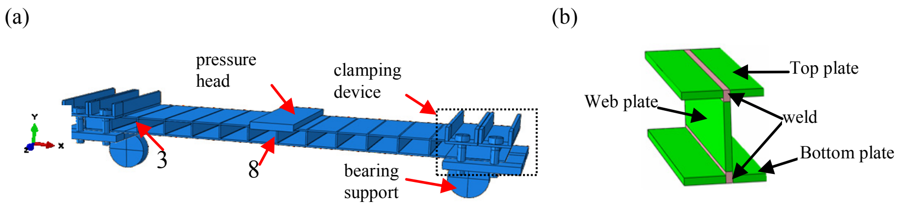

Fig. 6. (a) Overall model of ABAQUS finite element model. (b) The weld geometrical arrangement of ABAQUS finite element model.

5. Results and discussion

5.1. Load - displacement curve

Three groups of tests are made according to the test device shown in Fig. 5, No.1 specimen has initial welding defects, which web in left span are slightly tilted among them. In plastic stage backing block and specimen were horizontal displacement in tests due to the horizontal direction without constraint, namely load eccentric action happened. For comparison of finite element simulation and test, two models were considered in the simulation, one is not considered eccentric action, the other one is considered of that. The eccentric action occurred after the maximum bearing capacity shown in test loading video. In order to achieve eccentric action of the pressure head block in the finite element modeling in the loading process, give head block to be 4mm initial eccentricity. According to tests and FEM simulation results, can get the load displacement curve and value of characteristic points on the curve, as shown in Fig. 7 and tab. 3, respectively.

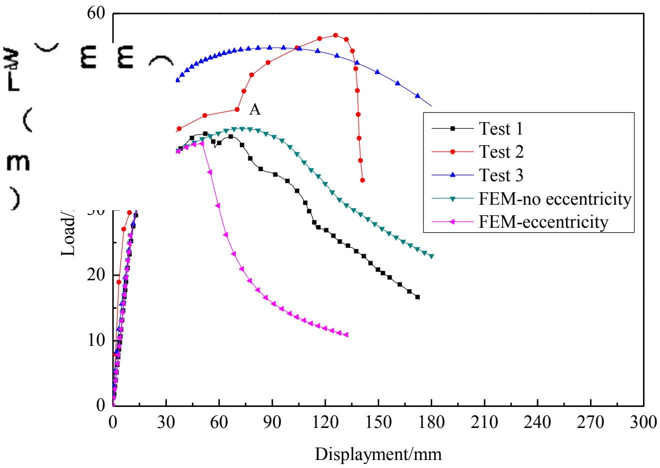

Fig. 7. Load - displacement curve in mid span.

Tab. 3. Value of characteristic points on load - displacement curve

Curve	yield point		Maximum bearing capacity point	
	Displacement /mm	Load/ kN	Displacement /mm	Load/kN
Test1	11.5	27.5	56.1	36.9
Test 2	9.96	29.37	70.25	44.4
Test 3	9.4	25.1	91.2	54.8
Average	10.29	27.32	72.51	45.37
FEM-no eccentricity	10	26.17	73.9	42.9

FEM- eccentricity	10	26.05	50.5	40.1
Average	10	26.11	62.2	41

Note: the maximum point of bearing capacity is mutations point A in test 2

The Fig. 7 and tab. 3 shows that finite element simulation in the elastic stage in good agreement with the tests, and this shows that the simulation data accuracy is higher, and the finite element model can be used in a subsequent stress analysis. In the elastic stage, the range of load and displacement of proportional limit for sandwich plates is 25~30 kN, 9~11 mm, respectively. These 5 curves are linear growth at the beginning of loading, and all the yield point is close to. For the average yield point of test and FEM, displacement difference is 2.8%, load difference is 4.4%; In the plastic stage, the range of the largest bearing capacity is 34.9 ~ 54.8 kN; Due to the specimen with initial defects and deviations exist in the welding process, three test curve discreteness is larger, especially in test 1 curve in which the largest bearing capacity point appears earliest, and compared test 1 with the test 2 and 3, displacement difference are 20% and 38.5%, respectively, and the load difference are 16.9% and 32.7% , respectively. In FEM, influence of initial eccentricity is larger, and compares FEM-no eccentricity with FEM-eccentricity, difference of displacement and load is 31.7% and 6.5%, respectively. The largest bearing capacity of the average of 3 tests and FEM-no eccentricity is (72.51 mm, 45.37 kN) and (73.9 mm, 42.9 kN), respectively, the difference of displacement and load is 1.9% and 5.4% respectively. In buckling failure stage, with the continue loading, the bearing capacity began to decline, structure also appear as local buckling failure. Therefore, the elastic deformation of sandwich plate is small, and the plastic zones is longer, Structure appear local buckling failure after the maximum bearing capacity, and the structure also has bigger bearing capacity.

5.2. Determination of stiffness

In the tests, according to the date of load and displacement sensors get the load deflection curve of No. 1 and 3 on the overhanging end and No. 2 on mid-span，and example in test 2, as shown in Fig. 9, where, the displacement of overhanging end is upward and mid-span is downward, regardless of the displacement of the positive and negative in the figure. According to the Fig. 8 get the calculation parameter curve corresponding formula 6, they are deflection w_b of overhanging end, different shear deflection w_s and total deflection w_c of mid-span, respectively.

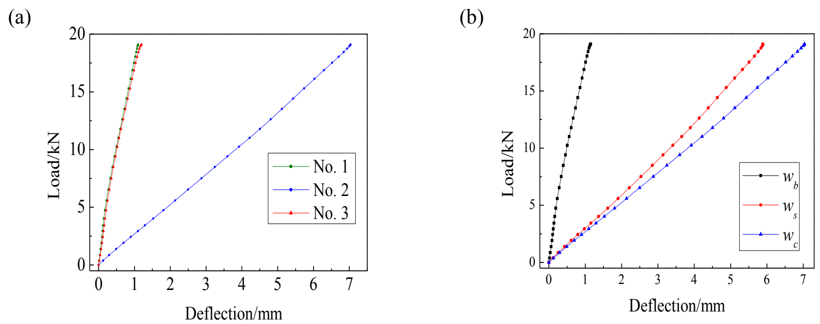

Fig. 8. (a) The load deflection curve in elastic stage (test). (b) Stiffness calculation parameters curve in elastic stage (test).

The Fig. 8 shows that deflection caused by shear value is bigger for Web - core laser-welded sandwich plate in bending, namely the shear effect is bigger, for example, w_c is 7.01 mm, w_b is 1.13 mm and w_s is 5.88 mm when the load is19 kN, the shear deflection is 5.2 times of bending deflection, it means that sandwich plates have a very big difference with normal homogeneous beams. Therefore, the research and application of laser-welded sandwich plate shouldpay higher attention to shear effect.

According to the Fig. 8, get the test stiffness of sandwich plate, and according to the formula 2 and 5, get the theoretical calculation of stiffness, as shown in tab.4, where, D/B, U/B (B = 500 mm) is per unit width of the stiffness.

Tab. 4. The stiffness of theory and test of web - core sandwich plate

stiffness	D_y (kN.m^2)	D_y/B (kN.m)	U_y /kN	U_y/B （kN/m）
Test 1	192.8	385.6	877.5	1755
Test 2	407.65	815.3	851	1702
Test 3	402.35	804.7	866	1732
theory	422.4	844.8	4824	2412

The tab.4 shows: There is a big error between test 1 and test 2, 3, which caused by itself welding defects of specimen 1. Stiffness measured by test 2 was close to by test 3, the averages of bending stiffness and shear stiffness for both tests is 810 kN.m and 1717 kN/m, respectively, this has certain error with theoretical calculation of the stiffness, and bending stiffness error is smaller, shear stiffness error is large, and is 4%, 29%, respectively. This is due to the tests themselves exists error, and not consider the influence of weld in theoretical formula. As a result, the welding quality has a great influence on stiffness of the sandwich plates; it should be guarantee in actual processing in order to achieve the stiffness requirement in practical application.

5.3. Mises equivalent stress analysis

Because of FEM-no eccentricity model is axisymmetric along the center axis, so stress analysis is conducted in the limits of $0 \leq x \leq L/2$ and $0 \leq z \leq B/2$. When loading displacement U2 is 6 mm and 10 mm mises stress nephogram is shown in Fig. 9.

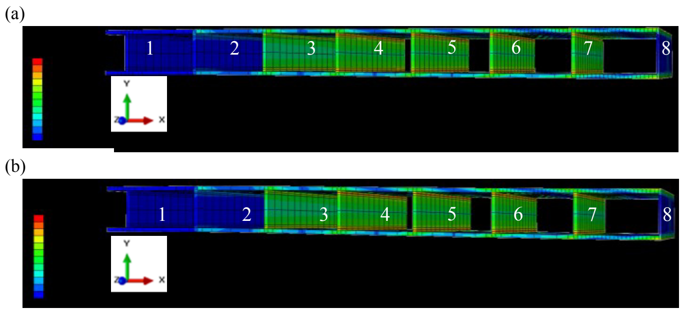

Fig. 9. (a) Mises stress nephogram(U2=6mm，RF2=14kN). (b) Mises stress nephogram(U2=10mm，RF2=26.17kN).

Fig. 9 shows that: (1) when Loading displacement U2 is 6 mm, the mises stress reaches 357.1 MPa on the junction of the web place(No. 5) and weld for the first time, and is greater than the parent metal yield strength (σ_s=343.9MPa),which shows that the plate has been partial to yield at this time. (2) when Loading displacement U2 is 10 mm, the mises stress have reached more than the yield strength on the junction of web (No. 3,4,5,6,7) and weld, and is less than the tensile strength (σ_b=343.9MPa). Accordingly, in the elastic stage, the most unfavorable area of sandwich panels is the junction weld of web and pace plates. In order to avoid weld first breaking in the loading process, the quality of weld should be guaranteed in the plate making.

5.4. Deformation failure analysis

In section 4.1, on the loading process of sandwich plate have had a certain understanding based on the analysis of load - displacement curve. The following, coupled with the stress analysis of section 4.4, will analyze the various stages of macroscopic deformation of sandwich plate under loading to understand the deformation failure process.

Specimen 1 exist initial weld defects, which deformation buckling are representative, specimen 2 and 3 deformation buckling position similar, here combined with the finite element simulation to analyze the specimen 1 and 3, the deformation of specimen failure process as shown in Fig. 10.

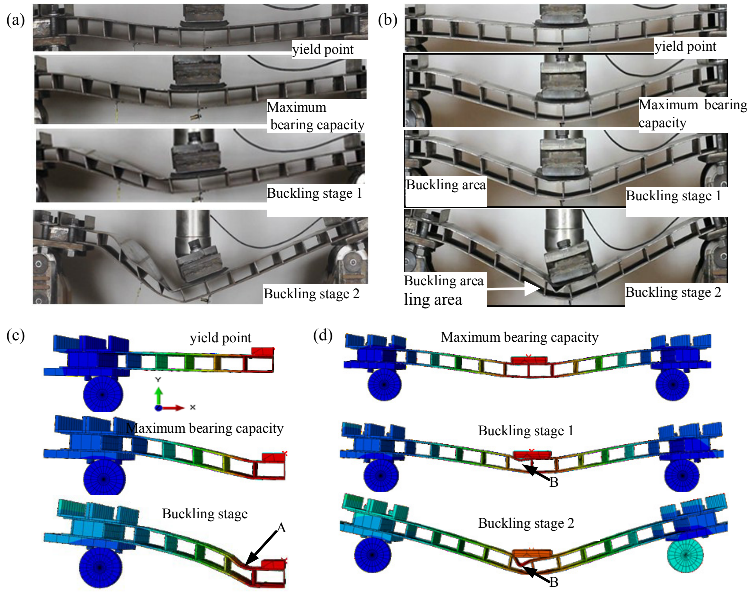

Fig. 10. (a) Deformation failure process of specimen1 in test and finite element simulation. (b) Deformation failure process of specimen3 in test and finite element simulation. (c) FEM-no eccentricity. (d) FEM- eccentricity (4 mm).

Fig. 10 shows that: (1) For the specimen 1,due to the left span exists initial welding defects, the web and pace plates have no obvious deformation in the yield point of sandwich plates; after the maximum bearing capacity, the left and right span began to appear asymmetric deformation, and face plates appear buckling, and web plates of left span occur slope deformation; in the buckling stage, the deformation continues to expand, the joint of web of left half span and pace plates occur local fracture, but the pace plates and web plates of right half span have no obvious buckling and slope deformation. (2) For the specimens 3, deformation is more symmetrical evenly at the yield point and the maximum bearing capacity; the left side of the face plate under pressure head block appears buckling deformation after the maximum bearing capacity point, and the pressure head block is sliding and rotating, which lead to Loading eccentrically; With the loading the buckling deformation continue to increase, while the rest area without obvious buckling; For the web plates, in the loading stage, no longer perpendicular to the face plates and occur slope deformation. (3) For the finite element simulation, buckling area of no eccentricity and eccentric model is different, the former in area A similar with specimen 1, the latter in position B similar with specimen 3. Accordingly, when the weld quality is unqualified, the destruction of the sandwich plate parts occurred the earliest in the seam of web and face plates; when that is better sandwich plate buckling failure finally, and damaged parts is the face plates of mid-span area, and eccentric action can cause changes of the buckling part of the sandwich plate.

6. Conclusion

Based on three points bending test of the web-core laser-welded sandwich plate, and combined with the Abaqus finite element numerical simulation in this paper, the following conclusions is obtained:

(1) The analysis on load displacement curve of sandwich plate shows that: the range of load of the elastic limit and the largest bearing capacity for sandwich plates is 25~30 kN, 34.9 ~ 54.8 kN, respectively. The largest bearing capacity of the average of 3 tests and FEM - no eccentricity is (72.51 mm ,45.37 kN) and (73.9 mm , 42.9 kN), respectively, the difference of displacement and load is 1.9% and 5.4% respectively.

(2) The averages of bending stiffness and shear stiffness is 810 kN.m and 1717 kN/m, respectively, the error with theoretical calculation of the stiffness is 4%, 29%, respectively.

(3) The measured strain and the strain value of the finite element simulation on the bottom face plates of sandwich plate shows that: the strain between the two web show cyclical changes, the maximum strain appears in

the location near the weld in T-joint node in a cycle, and decreases and tends to zero along the vertical path of bottom pace plates, and are turning into a negative value sequentially, namely the plate from under tension gradient compressed state.

(4) From the analysis results of FEM stress concluded that: a) in the sandwich plate elastic stage, when the loading displacement U2 = 6 mm, plate material in the weld junction of web (n = 5)and face plates appear local yield, which shows that the most unfavorable area of sandwich panels is the weld junction of web and face plates; b) In the x direction, the normal stress S11 of top and bottom pace plates changes periodically, a cycle is two web plate spacing a; The upper surface of left side plates in T-joint under tension and lower surface under pressure， the right side of plates on the contrary; c)the normal stress S22 distribution along the central axis of the web is antisymmetric on the left side and the right side of the web plate, and S22 is zero on the central axis.

(5)The analysis on deformation and failure of the test and FEM simulation shows that the final local buckling failure of sandwich plates occurred in the top pace plates area of the mid-span, and eccentric action can make change of the sandwich plate buckling location.

Acknowledgments

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