

# Geometrical parameters influence on the stiffness of steel sandwich plates with web-core

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**Abstract.** Laser welded sandwich plates with web-core have found their position in the marine and land vehicles. To implement such design accurately, knowledge about the influence of geometrical parameters on the stiffness is necessary. In this paper, the over-hanging three points bending tests were performed on the laser welded web-core steel sandwich plate under quasi-static conditions, together with the finite element (FE) simulations. The following parameters were analysed: the thickness of the face plate, the spacing of the two core plates and the height of the core plates. The agreement between experimental measurements and FE results was considered to be good. It is shown that changes of these parameters can contribute to increase or decrease of the stiffness of web-core sandwich plate, but the height of the core plate has no effect on the shear stiffness as the spacing of the two core plates is known. There are linear, exponential and polynomial fitted relationships between the geometrical and the stiffness of the web-core sandwich plates.

## 1. Introduction

The demand for faster and lighter marine and land transports has increased the need for more efficient structures. All-metal sandwich plates offer an option that can fulfill these requirements. By using sandwich structures, it is possible to obtain high stiffness and strength to weight ratio, i.e., the sandwich structures were found to be 30-50% lighter than traditional stiffened plates in marine structures [1, 2]. Contemporary interest in steel sandwich plates has been awakened by the developments in laser welding technology which enables the efficient production of these plates. Elevated pre-fabrication accuracy of the components, high welding speed and the possibility to connect internal stiffeners with the face sheets from outside has led to a wide application of laser welding in the construction of steel sandwich plates [3, 4].



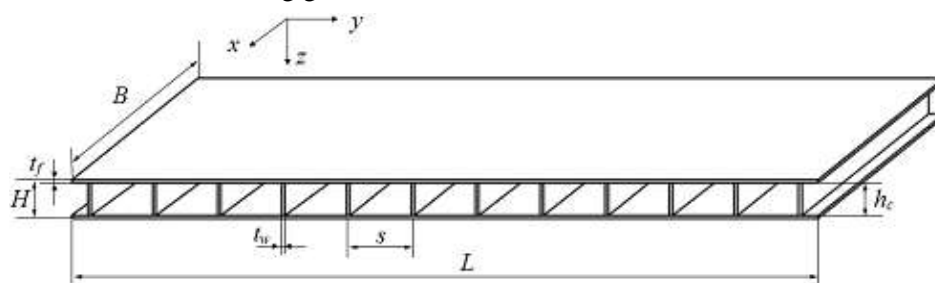
The web-core sandwich panel has perhaps the simplest core topology of all steel sandwich plates, as showed in figure 1. The laser-welded web-core steel sandwich panel is a set of steel plates assembled by utilizing a state-welded T-joint. The joint connects a vertical core plate called the web plate to the horizontal face plates that are located far from the mid-plane of the cross-section of the panel. The so-called sandwich effect is achieved by the coupled response of the connected web and face plates[5]. The design and production aspects of web-core panels in the shipbuilding industry have been explored by many authors [6-8] and in civil engineering [9-11]. The breadthwise penetration of the laser beam determines the thickness of the weld, which is lower than half of the thickness of the web plate. Consequently, the joint has two crack-like notches on each side of the weld. This makes the joint considerably less stiff than an equivalent fillet-welded T-joint. So numerous researchers are interesting in the stiffness of web-core sandwich plate. Ref. [12-15] have given us a good suggestion that we should consider the influence of weld width and notches of the T-joint on the stiffness laser welded web-core sandwich plate in the process of design and optimization. In addition to the effects of T-joint, the structural parameters are the primary factors affecting the stiffness of the web-core sandwich panel.

This paper presents a typical three-point bending testing on web-core steel sandwich plate to analyze its stiffness and to validate with finite element model. The FEM was performed to analyze the effect of the geometrical parameters (the thickness of the face plate  $t_f$ , the height of the core plate and the spacing of the two core plates) on the stiffness of web-core sandwich plate. Total of 17 finite element models were established by the simulation software Abaqus 6.13, and the bending and shear stiffness were calculated respectively according to the over-hanging three-points bending testing method.

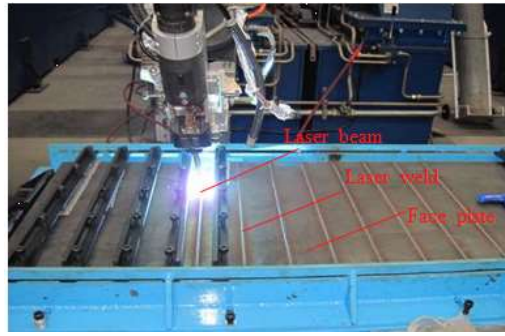
## 2. Experimental and finite element model

### 2.1 Web-core plate geometrical characteristics and dimensions

The sandwich plate with the web-core as shown in figure 1, consists of two flat plates – faces of thickness  $t_f$  and the core plate thickness  $t_w$ . The dimensions of the plate are as shown in figure 1.  $L$  is the length of the sandwich plate,  $B$  is the width of the sandwich plate,  $H$  is the height of the sandwich plate,  $h_c$  is the height of the core-plate, and  $s$  is the distance between two adjacent core plates. The base metal used in this paper is high strength steel SPFH780. Its yield strength is 631MPa. The face and core plates are connected by laser welding, as shown in figure 2. The welding power is 12 kW, and the speed is 1000 mm/min. The shielding gas is carbon dioxide.



**Figure 1.** Geometrical characteristics of web-core sandwich plate



**Figure 2.** The laser welding is manufacturing the web-core sandwich plate

Table 1 is the dimensions of sandwich plates with different geometrical parameters. For all the web-core sandwich plates, they have the same length and width, 1200 mm x 500 mm. The other geometrical parameters will be changed. Among, the variable is the thickness of the face-plates for the 1st plate to the 4<sup>th</sup> plate, and the variable is the height of the core-plate  $h_c$  and the distance between two adjacent core-plates  $s$  for the sandwich plate from the 4<sup>th</sup> to the 16<sup>th</sup>.

**Table 1.** Dimensions of sandwich plates with different geometrical parameters

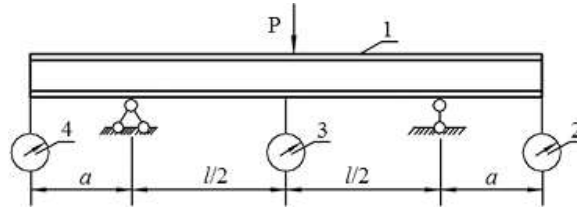
Parameters	$L/\text{mm}$	$B/\text{mm}$	$H/\text{mm}$	$h_c/\text{mm}$	$s/\text{mm}$	$t_f/\text{mm}$	$t_w/\text{mm}$
Test <sub>1,2,3</sub>	1200	500	60	50	100	2.5	5
1st	1200	500	60	50	100	1.5	5
2nd	1200	500	60	50	100	2.5	5
3rd	1200	500	60	50	100	3	5
4th	1200	500	60	50	100	4	5
5th	1200	500	60	50	100	5	5
5th	1200	500	40	35	55	2.5	5
6th	1200	500	40	35	70	2.5	5
7th	1200	500	40	35	85	2.5	5
8th	1200	500	40	35	100	2.5	5
9th	1200	500	50	40	55	2.5	5
10th	1200	500	50	40	70	2.5	5
11th	1200	500	50	40	85	2.5	5
12th	1200	500	50	40	100	2.5	5
13th	1200	500	60	50	55	2.5	5
14th	1200	500	60	50	70	2.5	5
15th	1200	500	60	50	85	2.5	5
17th	1200	500	60	50	100	2.5	5

The thickness of the face-plate is 2.5 mm for the sandwich plate from the 4<sup>th</sup> to the 16<sup>th</sup>. As a result, there are twelve web-core sandwich plates to research more on their stiffness. Besides 3 testing specimens, which are marked as Test<sub>1</sub>, Test<sub>2</sub> and Test<sub>3</sub>, the others are FE models. Among them, there

are 5 web-core sandwich plates will be used to study the relationship between the face plates's thickness and the stiffness of the sandwich plates. There are twelve web-core sandwich plates will be used to study the relationship between the geometrical parameters of core plates and the stiffness of the new plate. Three sets of data for the height of the core plates  $h_c$ , and the one height of the core plates  $h_c$  corresponds 4 sets of data of the spacing of the two core plates  $s$ .

## 2.2 Testing method and equipment

**2.2.1 Over-hanging three points bending testing.** Generally, to measure the bending stiffness and shear stiffness of one web-core sandwich plate, it should be conducted in two types of testing which are three points bending testing and four points bending testing for the same web-core sandwich plate. This method is not only increasing the number of testing, but also increases the error of the measurement data. It is noteworthy that a method called over-hanging three points bending testing, as showed in figure 3, can be used to determine the bending stiffness together with shear stiffness.



\*where 1 is a testing specimen; 2,4 is the left and right over-hanging displacement sensor, respectively; 3 is the middle displacement sensor; P is loading sensor;  $l$  is span, in m;  $a$  is the distance between over-hanging displacement sensor and the middle displacement sensor.

**Figure 3.** Over-hanging three points bending testing

In the elastic segment, according the loading which is measured by the loading sensor, the left deflection which is measured by the left over-hanging deformation sensor, the middle deflection which is measured by the left middle deformation sensor and the right deflection which is measured by the right over-hanging deformation sensor, the bending stiffness and the shear stiffness are determined. The formula as follows:

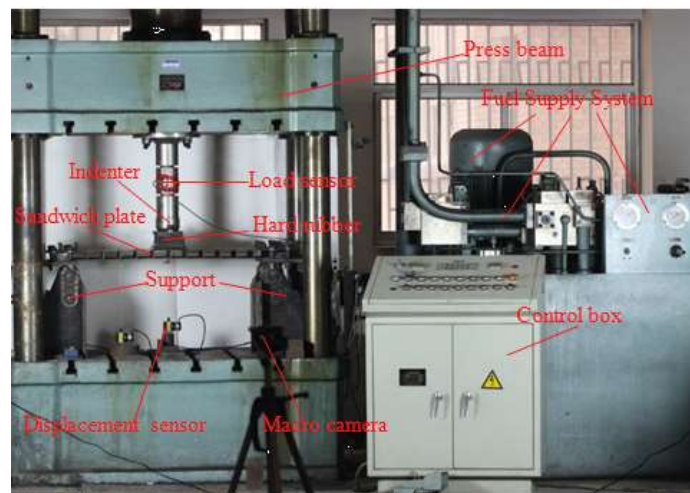
$$D_y = \frac{\Delta P \cdot l^3}{48 \cdot B \cdot \omega_b} \quad (1)$$

$$D_{Qy} = \frac{\Delta P \cdot l}{4 \cdot B \cdot (\omega - \omega_b)} \quad (2)$$

\*where  $D_y$  is bending stiffness, in N.m;  $D_{Qy}$  is shear stiffness, N/m;  $\Delta P$  is load increment, in N;  $l$  is span, in m;  $B$  is the width of specimen, in m;  $\omega$  is the increment of mid-span deflection, which is total deflection, in m;  $\omega_b$  is the increment of left or right over-hanging deflection, which is the bending deflection, and  $\omega_b = (\omega_l + \omega_r)/2$ , in m;  $\omega_s$  is the shear deflection, and  $\omega_s = \omega - \omega_b$ , in m.

**2.2.2 Equipment.** According to ASTM C393-00 Standard test method for flexural properties of sandwich structures and GB/T 1456-2005 Performance test methods for sandwich structures, a special test setup which is suitable for simply support, as be shown in figure 3, was developed to measure the bending and shear stiffness of web-core sandwich plates. The experiments were carried on a 3150 kN four-column hydraulic machine, as be shown in figure 4. Here, we can see a sandwich plate is during

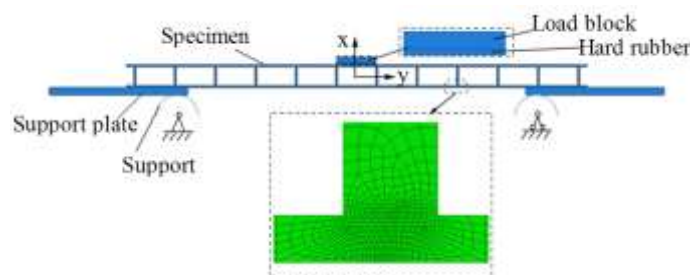
three points bending testing. The span is 936 mm, and the loading speed is 5 mm/min.



**Figure 4.** Four - column hydraulic press machine and a sandwich plate during testing

### 2.3 Finite element modeling

The Abaqus 6.13 standard solver was employed to analyze the stiffness of sandwich plates with various structural dimensions. Figure 5 shows one of the 2D models. In the modeling of sandwich plate, the welds are all at the middle of each core plate, and the root gap is zero. In this model, the elements used are CPE8R. In general the aspect ratio in rectangular elements is kept close to 1:2 and the angle in quadrangular between  $45^\circ$ - $135^\circ$  to avoid problems in accuracy of solution. After the model has been verified by the experimental results, some modification of variables of the thickness of the panel and other geometric parameters to study the stiffness of the web-core sandwich plate. The geometric parameters are studied in this paper has been shown in table 1.



**Figure 5.** 2D FEM model

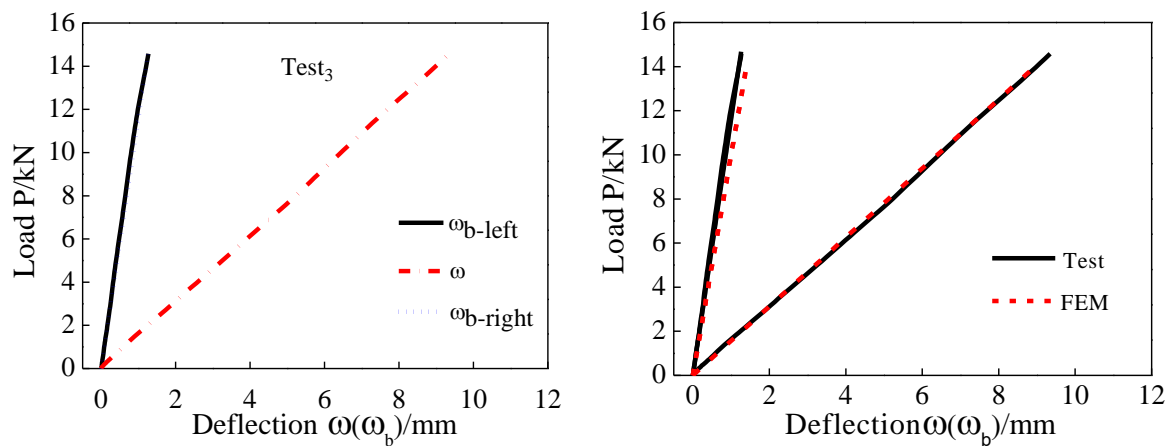
## 3. Results and discussion

### 3.1 The results of experimental and FEM

In order to ensure that the deformation of the sandwich plate is in the elastic range, the load is lower than 20 kN. Each specimen was tested for three times, and figure 6 shows the typical load-deflection curve of the sandwich plate. It is found that the load-left deflection and load-right deflection curve are almost completely coincident for each plot, which indicates: (1) the testing plate has excellent welding

quality. If one welding has defects, there is no doubt that the two curves will be deviated, which can be got a strong support from my previous research. (2) the experimental installation is accurate, especially for the displacement and load sensor installation location. If the location of the two over-hanging displacement is asymmetric about the displacement sensor in the middle, where assume that the position of the middle sensor is accurate, then the result is that the curve does not coincide. (3) the experimental result has a good repeatability and reliability. So according to the equations (1) and (2), it is calculated that the bending stiffness is  $2.92 \times 10^5 \text{ N} \cdot \text{m}$ , and the shear stiffness is  $8.12 \times 10^5 \text{ N/m}$ . Certainly, the stiffness is an average value which is calculated by 9 sets data from 3 specimens.

Figure 6(b) shows the load-deflection curve of the experimental method and the FE method. Obviously, the simulation results agree well with the experimental values. Because the expensive manufacture costing, the experimental testing and analysis costing, finite element analysis method is really at a best choice to analyze the sandwich plates with different geometric parameters. This is not simply to solve the costing problems, but to modify the model is very convenient. After the model has been validated and improved, it is a perfect method to calculate the stiffness of the sandwich plate which we are stimulating, as the following contents.



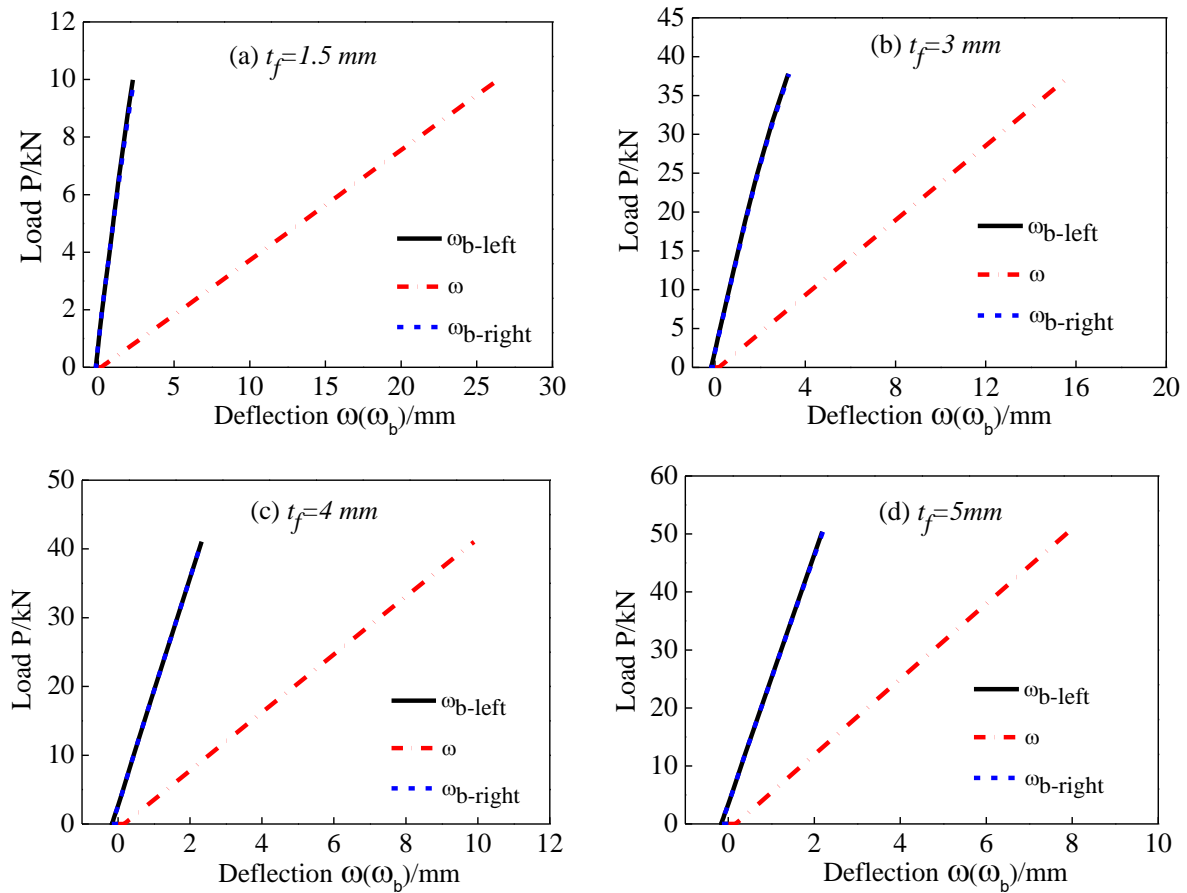
(a) Load-deflection curve of testing

(b) Comparison of Testing and FEM

**Figure 6.** Load-deflection curves for different face plate thickness

### 3.2 The influence of the thickness of face plates on stiffness

Figure 7 shows the curves of load-deflection from the finite simulation results. As the thickness of the face plate increases, we can make a conclusion that the slope of the curve is changed, and the stiffness value will be changed too. The bending stiffness be calculated according to the formula (1), and the shear stiffness be calculated according to the formula (2). The stiffness be shown in figure 8, and there are 5 discrete data points in each figure. As the thickness of the faceplate increasing, the bending stiffness and shear stiffness are increased, though the form of increasing is different.



**Figure 7.** Load-deflection curves for different face plate thickness

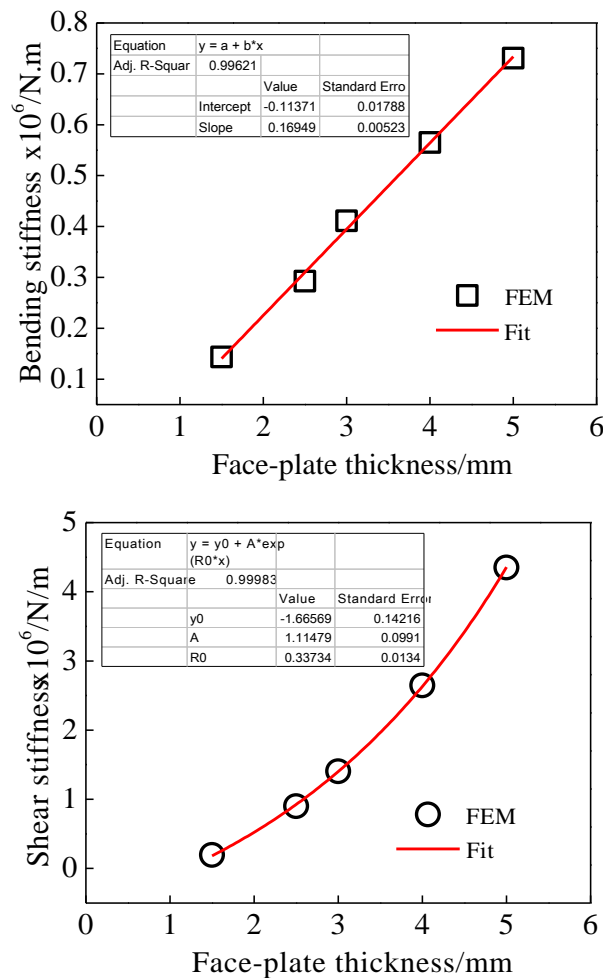
Figure 8 is also the relationship between the face-plate thickness and stiffness. From figure 8(a), the bending stiffness increased linearly, when the face-plate increasing from 1mm to 5mm. Using the Origin software tool, the best fitting equation is:

$$D_y = 0.17 \cdot t_f - 0.1 \quad (3)$$

From figure 8(b), the shear stiffness increased non-linearly, and the fitting equation is:

$$D_{Qy} = 1.12 \cdot e^{0.34 t_f} - 1.67 \quad (4)$$





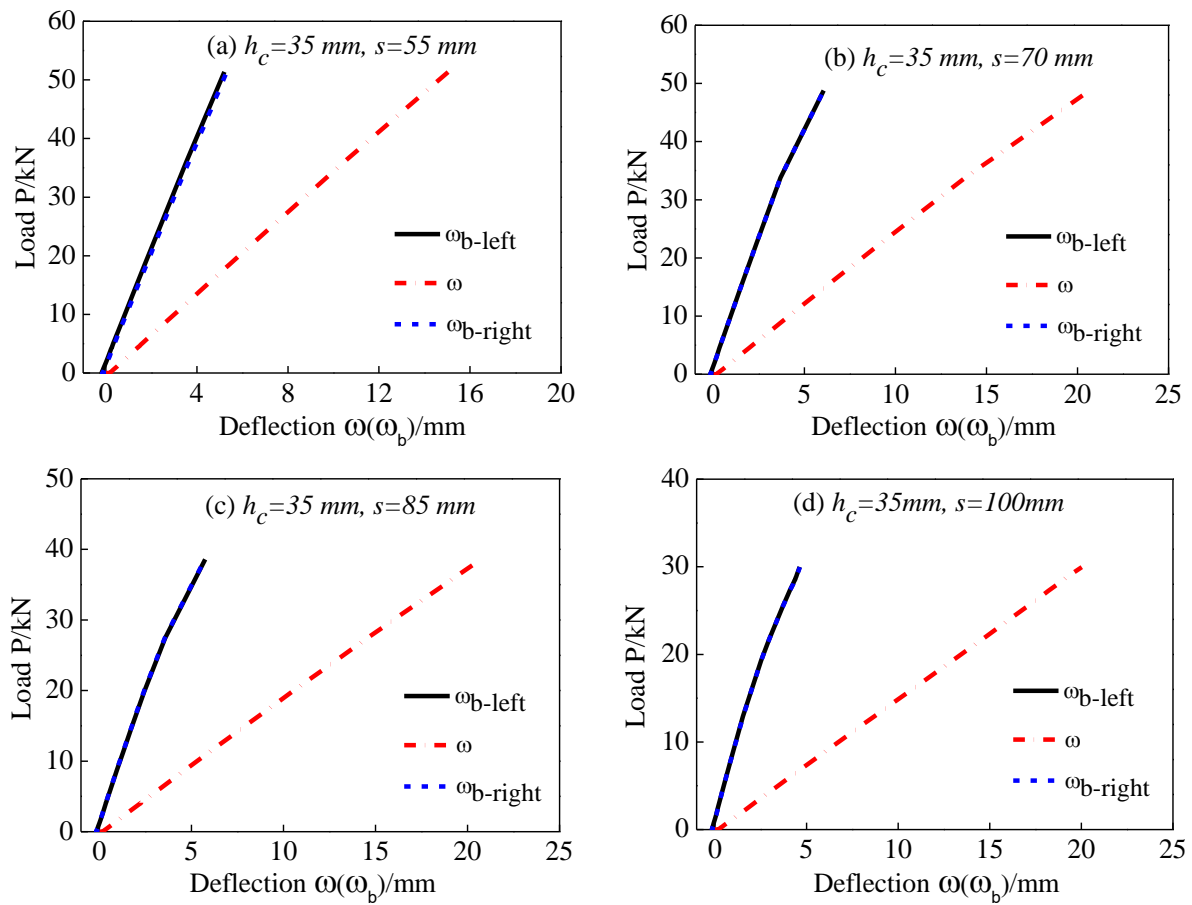
(a) Face-plate thickness and bending stiffness (b) Face-plate thickness and bending stiffness

**Figure 8.** The relationship between face-plate thickness and stiffness

### 3.3 The influence of core plates's geometrical parameters on stiffness

According to the data of table1, there are twelve finite element models were conducted to study the stiffness of web-core sandwich plates which have different core plate's geometrical parameters. As we know that the height of core plate  $h_c$  is 35 mm, 45 mm and 55 mm, respectively. Also the spacing of the two core plates  $s$  is 55 mm, 70 mm, 85 mm, and 100 mm, respectively. Figure 8 shows the load-deflection curves for web-core sandwich plate ( $h_c=35\text{mm}$ ) with different  $s$ . Because the other figures are similar with these figures, not all are shown in this paper. Certainly, the bending stiffness for each web-core sandwich plate is calculated by equation (1) and the shear stiffness is calculated by equation (2). The values are shown in figure 10.





**Figure 9.** Load-deflection curves for web-core sandwich plates with different core plate geometrical parameters

Figure 10(a) shows the bending stiffness of web-core sandwich with different height of the core plate  $h_c$  and the spacing of the two core plates  $s$ . Analysis of the results as follows:

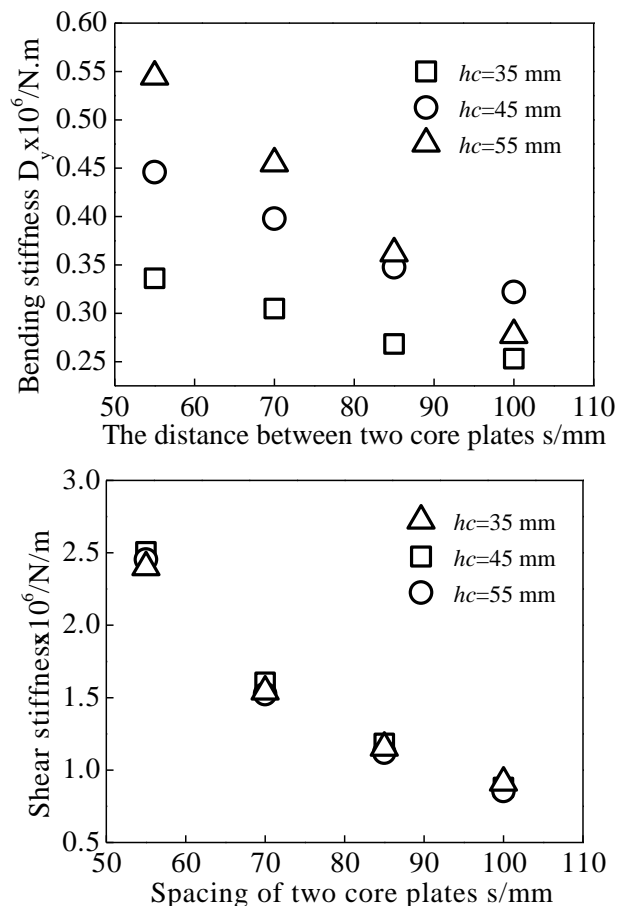
- (1) For the web-core sandwich plate with the same core plate's geometrical parameter  $s$ , the higher of the core plates, the greater the bending stiffness, which except the bending stiffness of web-core sandwich ( $h_c = 55 \text{ mm}, s = 100 \text{ mm}$ ). Obviously, its stiffness is lower than the bending stiffness of web-core sandwich ( $h_c = 45 \text{ mm}, s = 100 \text{ mm}$ ).
- (2) For the web-core sandwich plate with the same core plate's geometrical parameter  $h_c$ , the larger spacing of the two core plates  $s$ , the smaller of the bending stiffness, and the reduction is proportional. The higher of the core plate, the more the bending stiffness decreased as the height of the core plate increasing. This phenomenon is due to the fact that the higher of the core plate, the greater the spacing of the two core plates, the local deformation of the face plate could reduce the total stiffness of the web-core sandwich plate. The future research works will provide a more comprehensive explanation.

Figure 10(b) shows the shear stiffness of web-core sandwich with different height of the core plate  $h_c$  and the spacing of the two core plates  $s$ .

- (1) For the web-core sandwich plate with the same core plate's geometrical parameter  $s$ , all of the web-core sandwich plates almost have the same shear stiffness. In other words, the

height of the core plates hasn't any influence on the total shear stiffness of the web-core sandwich plates.

- (2) For the web-core sandwich plate with the same core plate's geometrical parameter  $h_c$ , the larger spacing of two core plates  $s$ , the smaller of the shear stiffness. The reduction is not proportional. The larger the spacing of the two core plates, the smaller the shear stiffness decreased. The future research works will also give a perfect answer.



(a) Core plate's parameters - bending stiffness      (b) Core plate's parameters - shear stiffness

**Figure 10.** (a) Bending and (b) Shear stiffnesses of web-core sandwich with different height of the core plate  $h_c$  and the spacing of the two core plates  $s$

#### 4. Conclusions

Based on the experimental investigation, and validation with the finite element models to numerically analyze the stiffness of the web-core sandwich plate with various geometrical parameters, such as thickness of the face plates  $t_f$ , the height the core plates  $h_c$  and the spacing of the two core plates  $s$ . The following conclusions can be drawn:

- (1) Over-hanging three points bending testing were conducted to measure the bending and shear stiffness of the web-core sandwich plate ( $t_f=2.5 \text{ mm}$ ,  $h_c=55 \text{ mm}$ ,  $s=100 \text{ mm}$ ). As the result of the bending stiffness is  $2.92 \times 10^5 \text{ N.m}$ , and the shear stiffness is  $8.12 \times 10^5 \text{ N/m}$ . The FEM results show great agreement with these testing values.

(2) As the thickness of the faceplate increasing, the bending stiffness and shear stiffness are increased, though the form of increasing is different. The fitting equations (3) and (4) expresses the influence of the face-plate thickness on the bending and shear stiffness, respectively.

(3) The geometrical parameters core plates a significant effect on the stiffness of the web-core sandwich plates. If the spacing of two core plates  $s$  is not changing, the higher of the core plates, the greater the bending stiffness, which except the bending stiffness of web-core sandwich ( $h_c=55$  mm,  $s=100$  mm). If the height of the core plates  $h_c$  is not changing, the larger of the spacing of the two core plates  $s$ , the smaller of the bending stiffness, and the reduction is proportional. The higher of the core plate, the more the bending stiffness decreased as the height of the core plate increasing.

(4) If the spacing of two core plates  $s$  is not changing, the height of the core plates  $h_c$  has no any influence on the total shear stiffness of the web-core sandwich plates. If the sandwich plate has the same height of the core plates  $h_c$ , the larger spacing of two core plates  $s$ , the smaller of the shear stiffness, and the reduction is not proportional.

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## References

- [1] Kujala, P. and Klanac, A. 2005. Steel sandwich panels in marine applications. *Brodogradnja*, **56**(4), 305-314.
- [2] Allen, H. G. 2013. Analysis and design of structural sandwich panels: the Commonwealth and international library: Structures and Solid Body Mechanics Division. Elsevier.
- [3] Kozak, J. 2009. Selected problems on application of steel sandwich panels to marine structures. *Polish Maritime Research*, 9-15.
- [4] Romanoff, J. and Varsta, P. 2007. Bending response of web-core sandwich plates. *Composite Structures*, **81**(2), 292-302.
- [5] Frank, D., Romanoff, J. and Remes, H. 2013. Fatigue strength assessment of laser stake-welded web-core steel sandwich panels. *Fatigue & Fracture of Engineering Materials & Structures*, **36**(8), 724-737.
- [6] Klanac, A., and Kujala, P. 2004. Optimal design of steel sandwich panel applications in ships. In The Proceedings of The Ninth International Symposium on Practical Design of Ships and Other Floating Structures, Lübeck-Travemünde (pp. 907-914).
- [7] Metschkow, B. 2006. Sandwich panels in shipbuilding. *Polish Maritime Research*, 5-8.
- [8] Romanoff, J., Naar, H., and Varsta, P. 2011. Interaction between web-core sandwich deck and hull

girder of passenger ship. *Mar Syst Ocean Technol*, **6**(1), 39-45.

- [9] Pyszko, R. 2006. Strength assessment of a version of joint of sandwich panels, *Polish Maritime Research*, Special Issue 2006/S1, pp. 17-20.
- [10] Caccese, V., and Yorulmaz, S. 2009. Laser Welded Steel Sandwich Panel Bridge Deck Development: Finite Element Analysis and Stake Weld Strength Tests. *Finite Element Method*.
- [11] Briscoe, C. R., Mantell, S. C., Davidson, J. H., and Okazaki, T. 2011. Design procedure for web core sandwich panels for residential roofs. *Journal of Sandwich Structures & Materials*, **13**(1), 23-58.
- [12] Jiang, X. X., Zhu, L., Qiao, J. S., Wu, Y. X., Li, Z. G., and Chen, J. H. 2014. Bending properties of laser welded web-core steel sandwich plates.. *Advanced Materials Research*, **936**, 1451-1455.
- [13] Jiang, X. X., Fei, S. C., Zhang, S., Ji, H. and Zhu, L. (2017). Failure Analysis of the Laser-Welded Web-Core Steel Sandwich Panel with Narrow Weld Width T-Joints. *Applied Mechanics & Materials*, **863**.
- [14] Romanoff, J., Remes, H., Socha, G., Jutila, M and Varsta, P. 2007. The stiffness of laser stake welded T-joints in web-core sandwich structures. *Thin-Walled Structures*, **45**(4), 453-462.
- [15] Romanoff, J. 2014. Optimization of web-core steel sandwich decks at concept design stage using envelope surface for stress assessment. *Engineering Structures*, **66**, 1-9.