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Effect of ring-stiffened openings on the ultimate strength of a corrugated steel sandwich panel

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ABSTRACT

The strength of a laser-welded steel corrugated sandwich panel with a circular opening at the centre under compressive in-plane load is studied using the finite element method. The opening is stiffened with a ring and the effect of the stiffening ring on the strength of the sandwich panel is assessed. Corrugated sandwich panels are structural components that have good mechanical behaviour under impact, bending, and in-plane loading. Thus, they are widely used in structures that operate in severe loading conditions such as marine and aerospace structures. The sandwich panel is modeled in Ansys software using shell elements and the welding connection between the faceplate and corrugated core is modeled with shell elements. The contact between the faceplate and corrugated core is defined as frictionless contact, so the faceplate and core panel are both thin-walled structures that are free to buckle independently. It was deduced that the ring's thickness can change the strength of the sandwich panel, but it does not increase the strength up to the strength of the intact plate. It is also found that the opening diameter can decrease the strength of the sandwich panel dramatically.

Keywords: Corrugated Sandwich Panel, Strength, Ring reinforced holes, Plasticity

1. Introduction

Sandwich panels consist of a low-density core and two faceplates that have a high specific strength. Therefore, using them in ship structures can reduce weight and manufacturing costs accordingly. Corrosion and fatigue in these panels are decreased due to the special features of sandwich panels. On the other hand, in ship structures with continuous unidirectional corrugated cores, the flexural strength of the sandwich panel will increase, and the hull girder strength of the ship will rise consequently.

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Nomenclature

α	the angle of the side and base of the trapezoidal profile of corrugated core
a	length of the smaller base of the trapezoidal profile of corrugated core
l	length of the side of the trapezoidal profile of corrugated core
t_R	thickness of the ring
R	the radius of the circular opening

Steel sandwich panels are currently used in some merchant ships. The applied forces are mostly classified as transverse forces in these ships, which are mostly small. However, it is very important in designing long ships' structures to take into account the in-plane axial load in the plate panels. In these ships, due to hull girder bending, the deck and floor plate may bear significant in-plane stresses. So, it is necessary to study the behavior of these structures under axial in-plane loads.

Due to the importance of sandwich panels and their increasing usage in various industries, many pieces of research have been done in this field. The first step in designing a corrugated sandwich panel is understanding its behavior in the elastic region. The homogenized elastic or equivalent elastic properties are a useful method to estimate the corrugated sandwich panel behavior in the elastic region. Li et al. [1], and Ge et al. [2] performed numerical and analytical studies of a corrugated sandwich's equivalent modulus of elasticity.

The corrugated sandwich panels in a single-layer or multilayers form are effective structures for mechanical energy absorption. Their energy absorption capacity is estimated by conducting quasi-static compression tests, experimentally or numerically. Hou et al. [3], Foo et al. [4] and Kılıçaslan et al. [5] studied the crushing behavior and mechanical energy absorption capacity of the sandwich panels with different layouts and constructions.

In addition, when a sandwich panel is used in a structure, its strength under various load conditions is to be checked. In this regard, Taczala and Banasiak [6] studied the linear buckling of sandwich Panels. They analyzed sandwich panels subjected to compressive loading with the possibility of detecting both general and local buckling modes. The results showed that sandwich panels with an I-shape core are better than conventional structural designs in terms of stability. Tehrani et al. [7] studied the strength of a laser-welded sandwich panel and showed that the thickness of the core and faceplates strongly affected the deflection of the panel, while the welding distance has the largest share in the maximum shear force response. They also determined the shear capacity of the sandwich panel by analyzing the shear failure in the nonlinear region and the buckling analysis while increasing the height of the panel.

Poirier et al. [8] presented an optimization method based on a genetic algorithm for designing a laser-welded steel sandwich panel. Tongtong et al. [9] studied the strength of the O-core laser welded sandwich panel numerically and experimentally. Nilson et al. [10] introduced a simplified approach for accurately predicting the structural response of welded corrugated-core steel panels.

There has been an increasing amount of literature on sandwich panel strength over recent years. The mechanical behavior of the laser-welded corrugated sandwich panels in the ships' structures is not fully understood, especially in the ultimate strength region. On the other hand, the opening in the ship's deck is mainly used for the passage of pipes and equipment, and surveying can affect the strength of the deck. The effect of the opening on the strength of the corrugated steel panels has not been studied yet. In this paper, the effect of the ring stiffened opening on the strength of the steel panels is studied to fill this knowledge gap. To investigate the possibility of using sandwich panels on the decks of large ships, the strength of the laser-welded steel sandwich panel under the in-plane compressive load is studied. In order to test the strength of the sandwich panel with a circular hole reinforced with a ring, three different holes of 0.65 m, 0.6 m, and 0.5 m with different stiffener ring thicknesses are studied. The sandwich panel studied in this research is rectangular and the load is applied axially on its side surface in the in-plane direction.

2. Material and models

In this study, the structure of a sandwich panel with a core consisting of a trapezoidal corrugated sheet has been investigated. The core of these sandwich panels consists of a layer of trapezoidal corrugated sheet bonded to the faceplates by laser welding. The geometry of the studied sandwich panel is illustrated in Fig. 1, and the front view of the corrugation profile is shown in Fig. 2. The dimensions are given in Table 1. The core and faceplates are made of steel sheets of 6 mm with an elastic modulus of 200 GPa and a Poisson's ratio of 0.3. The studied panel is 1×1 m^2.

2.1. Finite element model

In order to analyze the laser-welded steel corrugated sandwich panel, this panel is made in ANSYS finite element software under in-plane compressive load. The model is made up of top and bottom faceplates, and a corrugated core. The faceplates and corrugated core thicknesses are small compared to other dimensions; thus, the shell elements are used to mesh the model. The faceplate is welded to the corrugated core using the laser welding. The laser welding connection between the core and the faceplates are modelled using long slender beams. The face plates' distance from the core at the contact regions is equal to the thickness of the sheets. The sheets are connected with shell elements at the weld lines. The finite element model details are shown in Fig. 3. The compressive ultimate strength of the panel is modelled in this paper. The load and boundary conditions are illustrated in Fig. 4.

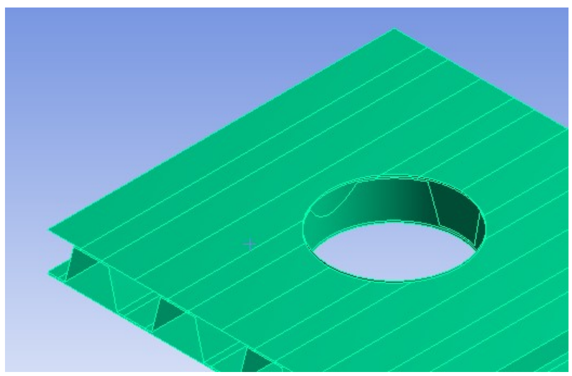

Fig. 1. Isometric view of the corrugated sandwich panel

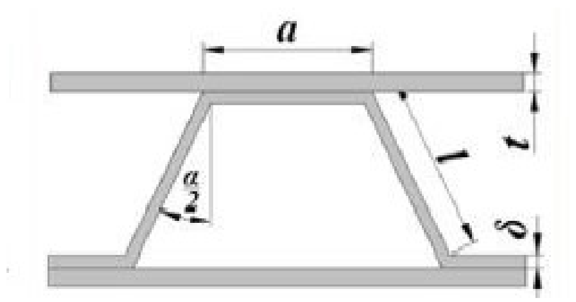

Fig. 2. Front view of a unit cell of the corrugated sandwich panel

Table 1. Geometric parameters of the corrugated sandwich panel

A (mm)	L (mm)	A (°)
100	103	30

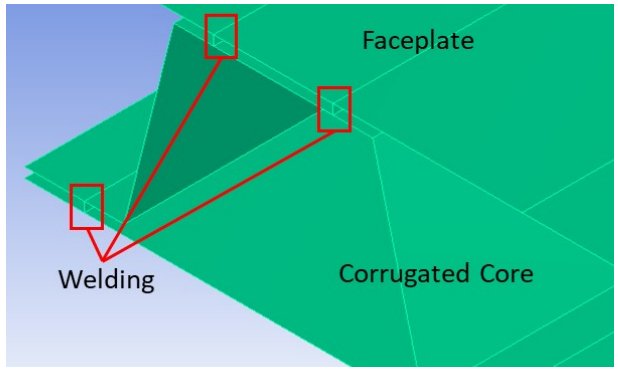

Fig. 3. The welding connection in the finite element model

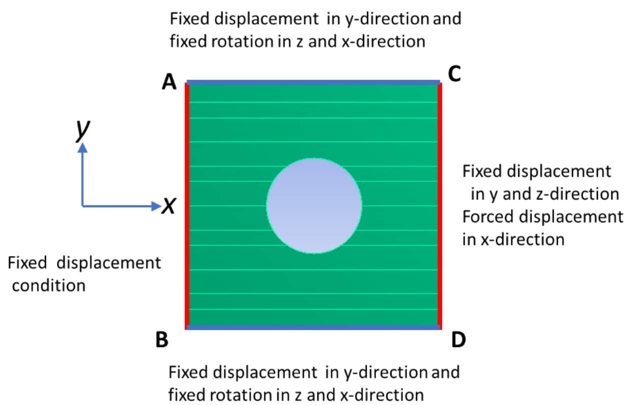

Fig. 4. Boundary and loading conditions

3. Results and discussion

3.1. Verification

For the verification of the finite element method used in this research, the results of the presented method are compared with those of the Kuzack's research [11] with regard to the strength of the sandwich panels. The force-displacement diagram of the sandwich panel under compression is shown in Fig. 5, which validates the present work and compares it with the research by Kuzack [11]. The results show that the error is equal to 5%.

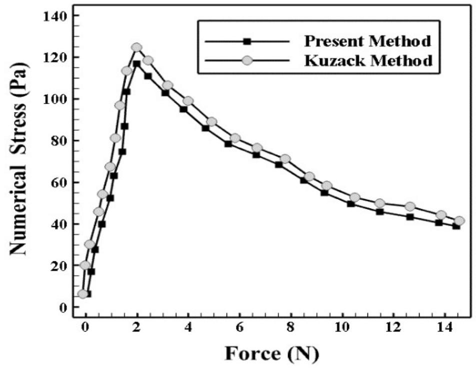

Fig. 5. The compression of the presented method and the Kuzack [11] experiment results

3.2. Results

It is a known fact that increasing the thickness of the stiffening ring and the thickness of the faceplate and core increases the ultimate strength and rigidity of the panel. Moreover, an increase in the dimensions of the hole can reduce the strength of the panel. However, in this research, the effect of different parameters on the mechanical behavior of the steel corrugated sandwich panel made by the laser welding method and the propagation of failure are studied.

First, we examine the growth of the plastic area in the specimen with a hole of 0.65 m and without any stiffening ring. Figure 6 shows the nominal stress-nominal strain and the plastic strain distribution of this specimen. In this sandwich panel, the plastic region starts to grow at the strain of 0.06 on the side of the hole. This strain is exactly equivalent to the stress calculated based on the stress concentration factor. As the strain increases, the plastic area grows further in the transverse direction until the specimen reaches its ultimate strength and after that, the elastic region grows rapidly, and the load-bearing capacity decreases.

In this nominal stress-nominal strain diagram, the nominal stress is obtained through dividing the compressive axial force by the nominal area over which the force is applied, i.e., the area of the faceplates and corrugated core and welds without considering the hole. The nominal strain value is also obtained via dividing the axial displacement by the length of the sandwich panel.

The trend of the nominal stress-nominal strain diagram shows three regions: The first region, in the elastic area, is of linear behavior. The slope of the diagram in this section indicates the rigidity of the structure and the elastic properties of the structure. If the load of the structure remains in the elastic range, it will return to its original shape after the load is lifted. In the second area, the slope of the graph decreases, this area indicates the beginning of the plasticization of the steel. As the load carried by the areas where the plasticization has occurred does not increase, the slope of the graph in this area decreases. After that, the structure reaches the ultimate strength, and the trend of the nominal stress-nominal strain diagram decreases. In this area, the plastic area grows around and the force required to deform decreases. The nominal stress-nominal strain diagram for sandwich panels with the opening of 0.5m, 0.6 m, and 0.65 m diameters are shown in Fig. 7 to Fig. 9, respectively. t_R is the thickness of the stiffening ring.

From Fig.7, 8, and 9, it can be deduced that by increasing the thickness of the stiffening ring, the stiffness of the reinforcing panel (slope of the average stress-moderate strain diagram in the elastic region) increases such that the sandwich panel's stiffness with the ring thickness of 12 mm exceeds the stiffness of the intact sandwich panel without any opening.

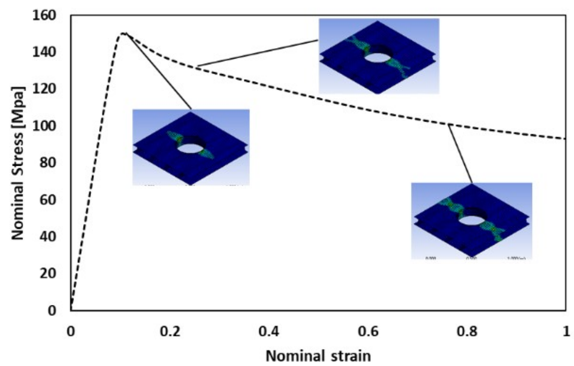

Fig. 6. The load-displacement and the plastic strain distribution of the specimen without any stiffening ring

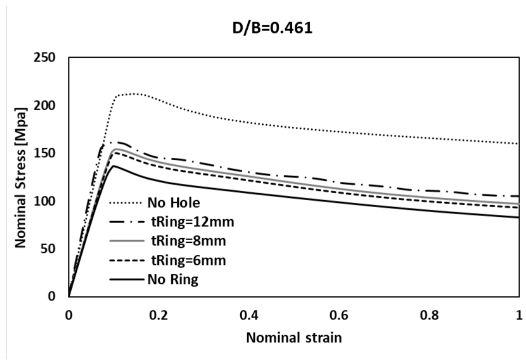

Fig. 7. Nominal stress- Nominal strain for the sandwich panel with the diameter of 0.6 m

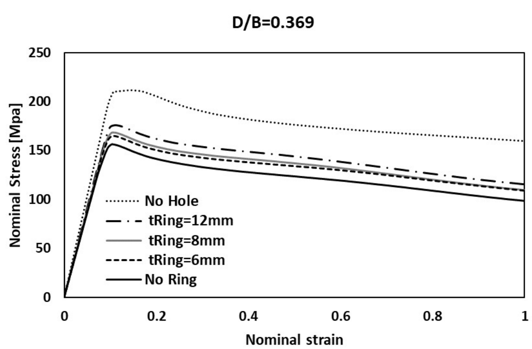

Fig. 8. Nominal stress- Nominal strain for the sandwich panel with the diameter of 0.6 m

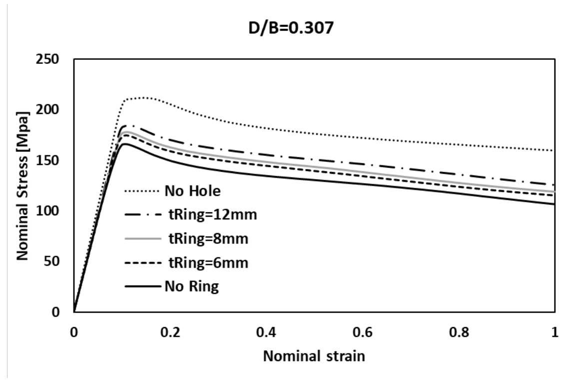

Fig. 9. Nominal stress- Nominal strain for the sandwich panel with the diameter of 0.6 m

Since our goal is to add a stiffening ring to increase the strength to the level of the intact sandwich panel, comparisons have been made with the strength in this case. Table 2 shows the rate of increase in strength compared to the no stiffening ring in percentage for the specimens under study. As it turns out, when the opening in the sandwich panel is larger, the effect of increasing the reinforcing ring on the ultimate strength is greater and is about 10%. However, for smaller holes, this effect is around 5%. Increasing the thickness of the stiffening ring by 1 mm increases the ultimate strength by 1 to 1.5 percent.

Figure 10 shows a comparison of how the stiffening ring thickness affects the ultimate strength of the sandwich panel under consideration. It is clear from this diagram that by making a hole in the sandwich panel, its strength can change up to 0.65 of the ultimate strength in the intact state. However, by adding a stiffening ring, the amount of its ultimate strength may increase up to 18% depending on the thickness of the reinforcing ring.

In many design cases for common loads, designs are made in the range of elastic stresses. Therefore, checking the stress concentration coefficient as well as the stress distribution in structures can lead to important structural design knowledge. For this reason, the samples with a 0.65 m hole with and without a stiffened ring are studied. The stress distribution in this sample when the applied average stress is 96 MPa is shown in Fig. 11. It is clear that in this sample, the stress flow in the side region of the sample (Region 1) is relatively uniform and varies between 118 MPa and 140 MPa. In the middle area (Region 2), as expected, we have zero stress and tensile stress, and in Region 3, the stress is concentrated in the side area of the hole, the stress is compressive and has its highest value. It is based on this stress that the stress concentration coefficient is calculated.

Table 2. The increase of the ultimate strength concerning the sandwich panel without any stiffened ring

t_R	R=0.65 m	R=0.6 m	R=0.5 m
6 mm	10%	5%	5%
8 mm	13%	8%	7%
12 mm	18%	12%	11%

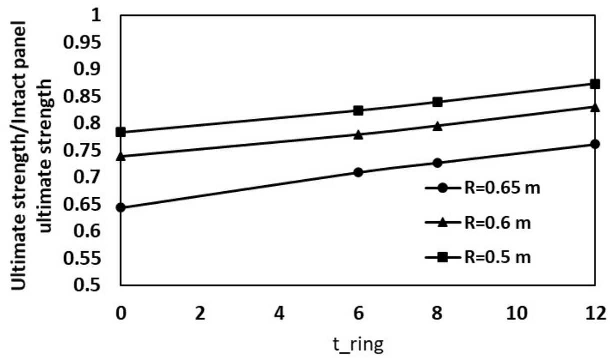

Fig. 10. Effect of stiffening ring thickness on the ultimate strength of the sandwich panel

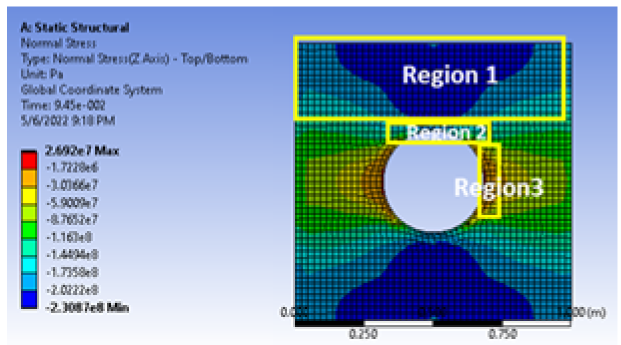

Fig. 11. Stress distribution in the elastic range for sandwich panel with non-stiffened hole

Figure 12 shows the stress distribution in the sample with a 0.65 m hole and a 8 mm stiffening ring in thickness. In this Figure, we can see that with the addition of the stiffening ring, the stress is distributed more uniformly in Region 1 at a short distance from the hole. And the place of largest stress is no longer around the hole but on the sides. The stress distribution in this sample is the same for samples with rings of different thicknesses.

In Fig. 13, using the stress concentration factor, the yield strength (beginning of yielding) has been calculated for the sample with a hole with a diameter of 0.65 m. It is clear that adding a ring has a significant effect on increasing yield strength. Because it changes the stress distribution in the sample and there is a more uniform stress distribution in the stress transition area. However, with the increase in the thickness of the ring, the yield strength does not change much and remains almost constant. Because the stress distribution in these samples is similar.

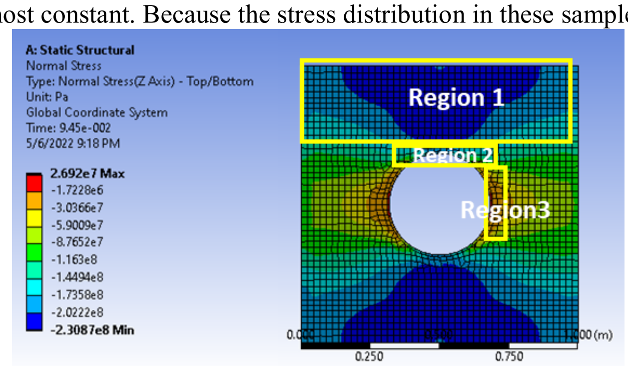

Fig. 12. Stress distribution in the elastic range for sandwich panel with stiffened hole

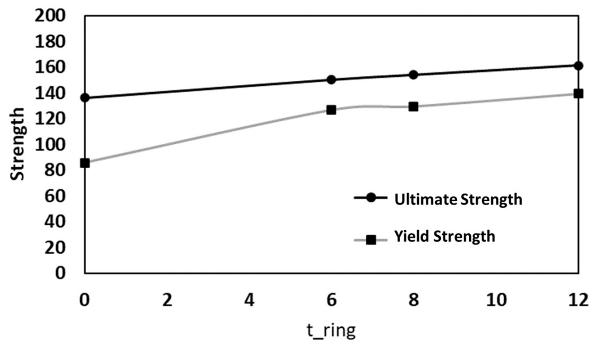

Fig. 13. The yield strength and ultimate strength of the sandwich panel with a hole

4. Conclusions

The mechanical behavior of a laser-welded steel corrugated sandwich panel with a ring-stiffened circular opening at the centre under compressive in-plane load is investigated. It is deduced that:

a) The failure of the sandwich panel starts with yielding in the vicinity of the opening due to stress concentration. By increasing the forced displacement, the plastic region grows in the transverse direction.
b) By adding a stiffening ring to the sandwich panel, the stress distribution around the hole will change dramatically and the stress concentration point will be distanced from the vicinity of the hole and the stress concentration factor will decrease. Consequently, the yielding starts at higher nominal stress, and the ultimate strength increases.
c) Increasing the stiffening ring's thickness by 2 mm will not change the stress distribution dramatically. Thus, the ultimate strength of the studied panels does not change greatly.

References

[1] Li, H., Ge, L., Liu, B., Su, H., Feng, T., Fang, D., 2020. An equivalent model for sandwich panel with double-directional trapezoidal corrugated core. Journal of Sandwich Structures and Materials. 22(7), 2445-2465.
[2] Ge, L. Jiang, W., Zhang, Y., Tu, S., 2017. Analytical evaluation of the homogenized elastic constants of plate-fin structures. International Journal of Mechanical Sciences, 134, 51-62.
[3] Hou, S., Shu, C., Zhao, S., Liu, T., Han, X., Li, Q., 2015. Experimental and numerical studies on multi-layered corrugated sandwich panels under crushing loading. Composite Structures, 126, 371-385.
[4] Foo, C.C., Chai, G.B., Seah, L.K., 2006. Quasi-static and low-speed impact failure of aluminium honeycomb sandwich panels. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 220(2), 53-66.
[5] Kılıçaslan, C., Güden, M., Odacı, İ.K., Taşdemirci, A., 2013. The impact responses and the finite element modeling of layered trapezoidal corrugated aluminum core and aluminum sheet interlayer sandwich structures. Materials & Design, 46, 121-133
[6] Taczała, M., Banasiak, W., 2004. Buckling of I-core sandwich panels. Journal of Theoretical and Applied Mechanics, 42(2), 335-348
[7] Tehrani, M., Hedayati Dezfuli, F., Alam, M.S., Milani, A.S., 2017. Parametric study on mechanical responses of corrugated-core sandwich panels for bridge decks. Journal of Bridge Engineering, 22(5), 04017002
[8] Poirier, J.D., Vel, S.S., Caccese, V., 2013. Multi-objective optimization of laser-welded steel sandwich panels for static loads using a genetic algorithm. Engineering Structures, 49, 508-524
[9] Tongtong, A., Redzuan, N., Jiang, X.X., Yuan, Y., 2023. The Strength Behavior of O-Core Sandwich Pipe. Journal of Physics: Conference Series, 2519,012052
[10] Nilsson, P., Atashipour, S.R., Al-Emrani, M., 2023. Laser-Welded Corrugated-Core Sandwich Composition—Numerical Modelling Strategy for Structural Analysis. Journal of Composites Science, *7*(9), 349;
[11] Kozak, J., 2009. Selected problems on application of steel sandwich panels to marine structures. Polish maritime research, 16, 9-15