JOURNAL OF MECHANICAL ENGINEERING AND SCIENCES (JMES)
ISSN: 2289-4659 e-ISSN: 2231-8380
VOL. 16, ISSUE 4, 2022, 9289 – 9306
DOI: https://doi.org/10.15282/jmes.16.4.2022.10.0734

ORIGINAL ARTICLE

Mechanical response of galvanised steel sandwich structure with different numbers of web core and different spacing distance of web plate under bending load

N.K. Romli[1,2], M.R.M. Rejab[2,*], X.X. Jiang[2], S.M. Soffie[2] and M. Ishak[1,2]

[1] Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, 26600 Pekan, Pahang Malaysia
Phone: +6094246324
[2] School of Mechanical Engineering, Ningxia University, 750021 Yinchuan, China

ABSTRACT – Sandwich structures are widely used in a variety of industrial applications due to their ability to provide high bending stiffness while remaining lightweight. The deformation of this structure and its relation to the stiffness of the galvanized steel is investigated. A series of three-point bending response and subsequent failure modes in web-core laser-welded sandwich structure based on galvanised steel is also investigated. The web-core sandwich structure was manufactured using fibre laser welding technique to joint face and web plates perpendicularly to produce a range of lightweight sandwich structure. The role of the number of cores and spacing distance were purposed to determine the overall deformation of global deflection behaviour of the sandwich structure. The results were compared, and it is showed that the acted load produced bending on faceplate and caused debonding at weld joint (between faceplate and web plate). The continued bending was also caused debonding between PVC foam and adjacent plate. Subsequently, load-displacement trace was used as evidence of the comparison, where seven cores with 20 mm spacing distance exhibited higher force, approximately 1.091 kN. The three-point bending test results indicated that the higher number of cores possessed better performance in bending strength. The effect of the spacing distance of web plates in sandwich structure was also examined. In five cores specimen, it is showed that as the spacing distance decreased, the bending strength increased, where bending stiffness value of 18 mm (0.313 kN/mm) is higher than 19 mm (0.288 kN/mm) and 20 mm (0.281 kN/mm). The effectiveness of the sandwich structure depended on the optimal design as to achieve lightweight and its bending strength.

ARTICLE HISTORY
Received: 12th Sept. 2022
Revised: 26th Nov. 2022
Accepted: 02nd Dec. 2022
Published: 27th Dec. 2022

KEYWORDS
Number of cores
Sandwich structure
Spacing distance
Three-point bending
Web-core

INTRODUCTION

Sandwich structure [1-11] regarded as an excellent design to transfer bending load and can be classified as metallic sandwich and composite sandwich structures [2, 6, 8, 11-14]. The idea of sandwich construction has become increasingly popular among all possible design concepts, because of the development of man-made core materials and structure as a main component in a sandwich structure design. Sandwich structures consist of thin and durable face plates and separates by low density of core [15] as shown in Figure 1.

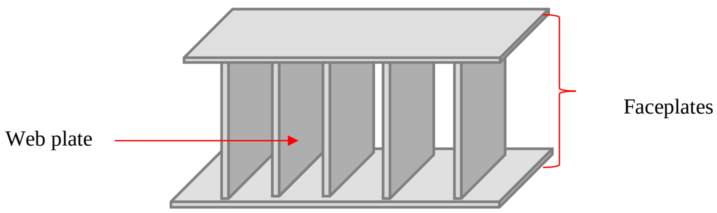

Figure 1. Illustration of a sandwich structure

Steel sandwich plates are light-weight structures made of thin face plates with corrugated cores in the middle by laser welding. Compared with the traditional structures such as stiffened plates, the sandwich plates have the advantages of reducing weight and space occupancy [16], isolating noise and vibration [17, 18], enhancing fire safety and thermal insulation [19, 20] improving crashworthiness and impact resistance [21, 22], decreasing manufacturing costs through precise prefabrication, rapid assembly, and modular manufacturing of plates and joints [23]. Among them, the laser-welded web-core sandwich plates have attracted more attention and interest from researchers because of the minimal configuration and the easy fabrication. Thus, the relevant studies on the laser-welded web-core sandwich plates have been widely reported since the beginning of the 20th century. A few years ago, monolithic plates have been used then it replaced with thin plates of sandwich panels. Welding works to assemble the monolithic plates have been done manually with conventional welding such as tungsten inert gas (TIG) and metal inert gas (MIG) [24]. The question arises, does simple design and centered welding can improve sandwich structure performance? The difficulties are due to the low mechanical

*CORRESPONDING AUTHOR | M.R.M. Rejab | ruzaimi@ump.edu.my

bending strength between the face and web plates, the fabrication cost of sandwich structure instead of using steel, aluminium alloy or stainless steel and weight of the sandwich structure. Most welding works in shipbuilding were done manually in part assembling using conventional welding equipment. However, the welding process of parts was finished semi-automatically, which was relatively cheaper cost than manual assembly. Generally, applying the sandwich structure can reduce cost production by 25% [25]. One of the main disadvantages of sandwich structure application involves large in-plane stresses, which is the relative low strength of joint on individual welded web-core [26]. The sandwich structure obtained through laser welding process and offers multiple advantages such as high stiffness-to-weight ratio, heat and noise insulation and high energy absorption under impulsive loads. When laser penetrates the faceplate thickness, the face-web plates will melt and create a joint. The surface of heat is highly localised, the thickness is not fully melted and called as crack like a notch. Even small gap within face and web plates are also present [27]. However, there are limited studies of weld joint failure effects on sandwich structure strength by fibre laser welding technology.

The development of laser welded sandwich structure with robot system has been started by United States Navy in 1980’s, where the first prototype was tested at Navy Joining Centre at Pennsylvania State University for limited applications such as antenna platforms on the US Navy ships [28-33]. Meanwhile, theoretical and experimental studies on behavior of steel sandwich structure under various loading and boundary condition have been taken over by School of Civil Engineering at the University of Manchester between of late 1980’s and early 1990’s [30, 33]. While numerous studies on laser-welded sandwich structures have been performed, the practical use of laser welding in the construction of ships is currently limited to a few prototype applications [34, 35]. This is because effective production and assembly in industrial circumstances have not been mastered enough for many applications and the structural behaviour of laser welded components is not adequately practiced under operating conditions. To gain practical experience with the new technology, realistic application on a ship has been required, indeed [30, 36, 37]. In addition, the need to investigate new materials and structural configurations in ship structures has been sparked by the high demand for lighter and safer structures [24, 30, 33]. Flat web plates perpendicular to the face plates forms the most basic geometry of all-metal sandwich structures [4, 5, 28, 34, 38, 39]. The web plates in this web-core system only run in one direction and are usually 10–100 times the thickness of the face plate. In the direction of the web plate, the core provides continuous support to the face plates, and distinct support in the transverse direction. As a result, the web-core panel has a high degree of orthotropy [4, 5, 30, 39].

Laser-welded web-core sandwich structures have attracted more attention and interest from researchers because of the simple configuration and easier in fabrication process. Thus, the relevant studies on the laser-welded web-core sandwich structure have been widely reported since the beginning of the century. A series of articles on the laser-welded sandwich structure with filler in the internal space were first published by Kolster and Zenkert [32, 40]. The buckling behaviours of the sandwich structure in the internal space are demonstrated in their work. In their studies, buckling behaviours of the sandwich structure in two different directions were analysed, and ultimate strength test was carried out, where the results showed a good agreement with the numerical results. Jelovica and Romanoff [39, 41] theoretically studied buckling and post buckling characteristics of the laser-welded sandwich structure subjected to in-plane compression. According to the studies, the local buckling of the faceplate would further reduce the sandwich structure stiffness. Later, Jiang [31, 42] conducted experimental and numerical studies on the geometrical properties of laser welds, their impact on the strength of the laser-welded web-core sandwich structure, and their failure modes. The author came to the conclusion that when determining the strength of the laser-welded web-core sandwich structure, the influence of the laser welds needed to be taken into account. Zhong and Wang [24] studied the ultimate strength characteristics of the welded web-core sandwich structure by accounting for geometric and material nonlinearity. In finite element analyses, initial local and global geometric deflections were introduced, and the effect of the initial deflection magnitudes on the ultimate strength was investigated [24].

Although there have been many studies on the laser-welded web-core sandwich structure, there is fewer study on strength improvement of sandwich structure when applying in ship hull. This research will provide new discoveries of three-point bending web-core laser-welded sandwich structure behaviours. In order to improve structural bending performance, which has been discovered with variant number of cores and spacing distance between web plate, research is being done to improve the structure of the sandwich by converting complex designs into simple and lightweight features. This study will be fit the shipbuilding industry in producing sandwich structure using the galvanised steel and the specific parameters of fibre laser welding. The study of the effect number of cores, and spacing distance between web plate are new scope in structural studies and is expected to achieve a better understanding of structural analysis and its performance.

This paper aims to investigate mechanical response of laser-welded web-core sandwich structure by varying cores and spacing distance. Hence, this research is to gain a quantitative understanding of the three-point bending response web-core laser-welded sandwich structure.

METHODS AND MATERIALS

The web-core sandwich plate is made up of laser welds that link the web and face plates. The web plates have a thickness of *tc* and a height of *hc* and are parallel to the *xz*-plane. The spacing between web plates is s. The thicknesses of the top and bottom face plates are denoted as tf, and they are parallel to the *xy*-plane. The plate is *L* in length, *B* in width, and $H=hc+tft+tfb$ in total height, and the neutral planes of the face plates are $d=hc+(tft+tfb)/2$ in distance. A unit cell is a representative cut of the sandwich plate in the *yz*-plane, whose boundaries are neighboring web plates and the parts of the faceplates between these are; the spacing distance s, and the height *H*. The sandwich plate has coordinated systems: global *xyz* as shown in Figure 2. At the plate and unit cell levels, global processes are used to explain a phenomenon in the structure. The centre of the global coordinate system *xyz* is located at the plate's geometrical mid-plane [33]. The Young's modulus is denoted by *E*, and the Poisson's ratio by *v*. The superscripts of *t*, *b*, and *c* denote the top face, bottom face, and network plates, respectively.

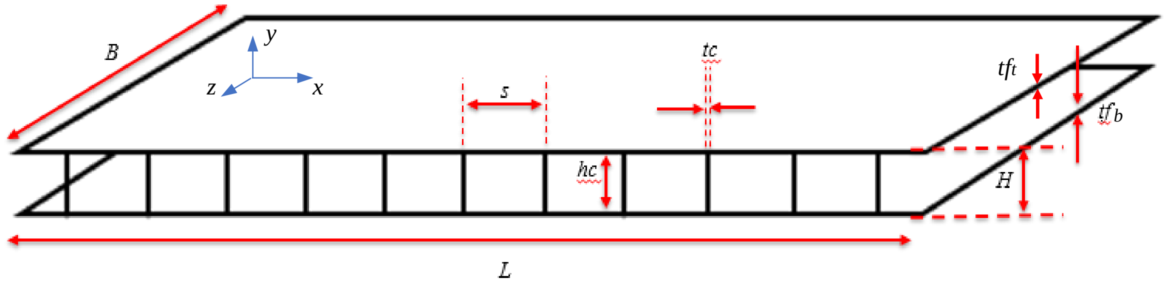

Figure 2. Illustration of web-core sandwich structure

Face and web plate thicknesses of 1 and 2 mm, respectively, were used to produce web-core sandwich structures. The sandwich structure was exalted as shown in Figure 2, with a width of 50 mm and a face plate length of around 220 mm. The thickness and height of the web plate were 2 and 52 mm, respectively. In order to achieve the purpose of study, the sandwich structures were designed with different number of cores, which includes 5, 6 and 7 cores. The dimensions of sandwich structures were indicated in Table 1, where the table was designed according to two types of variables, such as spacing distance, *s* and number of cores. The variables would give effect on load capability of sandwich structure.

Table 1. Dimension of sandwich structure with different parameters

Test	*L* (mm)	*B* (mm)	*H* (mm)	h_c (mm)	*s* (mm)	t_f (mm)	t_c (mm)	No. of cores	Quantity
1	220	50	53	52	18	1	2	5	3
2	220	50	53	52	18	1	2	6	3
3	220	50	53	52	18	1	2	7	3
4	220	50	53	52	19	1	2	5	3
5	220	50	53	52	19	1	2	6	3
6	220	50	53	52	19	1	2	7	3
7	220	50	53	52	20	1	2	5	3
8	220	50	53	52	20	1	2	6	3
9	220	50	53	52	20	1	2	7	3

Welding Jig

Welding jigs are key components in the manufacturing process because they influence productivity, product quality, and cost. These expenses cover the material, assembly, operation, and design of the jigs [43] and, according to studies by Zhang and Bi [44], the jigs can contribute as much as 10% to 20% of the overall product manufacturing expenses. Furthermore, Ordieres [45] stated that jigs are also responsible for over 70% of geometric errors in welded assemblies. A jig is a piece of equipment that is used to locate, hold, and support a workpiece during a specific industrial procedure, such as welding [43, 45-47]. They are critical production tools since they are required in the majority of manufacturing, inspection, and assembly operations. Welding jigs are commonly hired tool for aligning and retaining various parts during welding [48]. Welding jigs are designed to hold several pieces together, endure high heat and sputter, and conduct electricity to provide grounding in the case of arc welding. They ensure that the welding dimensions are precise, and that thermal distortion is minimized [43, 47].

The following are the main features of welding jigs, which were substituted into welding jig design for this study [43]:

i. Opening ability: Welding is a procedure that joins numerous parts together, so the welded structure enlarges in size over time. To make loading and unloading welding jigs as simple as possible, this necessitates a good opening ability.

ii. Adjustability: Throughout their lifespan, welding jigs are subjected to numerous loading and unloading cycles. Hence, welding jigs need to be adjustable by the result of this, indeed. Shim plates are used to change the jigs adjustability, which enables the correction of the jig elements in manufacturing tolerances.

In this study, a specific design of welding jig was designed using SOLIDWORKS. The welding jig was manufactured with a wire cut machine. As mentioned earlier, the jig was designed using heat resistant material, which steel and aluminium were selected as the material. The welding jig was designed by considering research design of sandwich structure as summarised in Table 1, which the specimens were customized with various number of cores. Aluminium blocks were utilised to align the face and web plates in a perpendicular and 90-degree configuration throughout the assembly process. Figure 3 shows an illustration of assembling face and web plates on the welding jig.

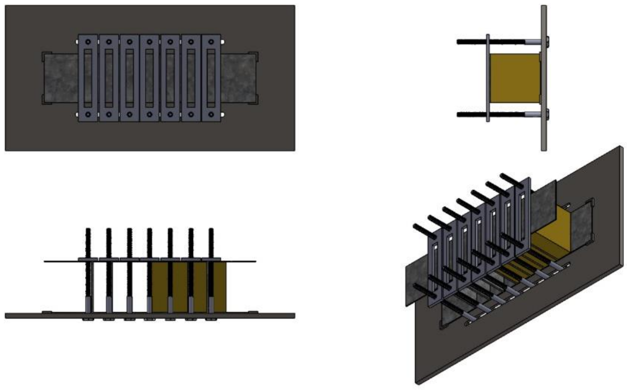

Figure 3. Welding jig to setup a web-core sandwich structure

Experimental Set-Up on Galvanised Sandwich Structure

Laser welding technology is a method of fabricating a metal with high precision. Laser welding can provide better automation of the laser welding process, such as higher welding speeds, consistency, and accuracy, when compared to conventional welding. Laser welding produced a smaller and more reliable weld than traditional welding. Sandwich structural response was not attracting more attention from industries due to a lack of relevant data. Commercially available galvanised steel sheets were employed in constructing of this web-core sandwich structure. Meanwhile, the chemical compositions of the galvanised steel sheets were investigated using a Energy Dispersive X-ray (EDX) analysis microscope and are shown in Table 2. Before the laser welding operation, all the sheet metals were cleaned using acetone to remove any dirt and grease. The purpose of EDX analysis is to verify the material used is galvanised steel. Besides that, the material elements were also confirmed as mentioned by Azimi [49, 50].

Table 2. Material elements of galvanised steel

Element	C	Si	Mn	P	S	Al	N	Fe
Weight (%)	0.033	0.009	0.207	0.012	0.008	0.005	0.059	Balance

Figure 4 depicts a schematic design of the experimental welding setup. The laser welding machine was showed in Figure 5 and manufactured by an *IPG Photonic, where the machine operated with an average power of 200 Watt. The average power is the output energy of the beam, which is a particular time divided by that period, where the employed duration should be long compared to the pulse interval as means to obtain a representative power. The fibre welding machine was operated under quasi-continuous wave, which ideal for high-precision welding application. Note that high energy was required to initiate or sustain laser-material connection.

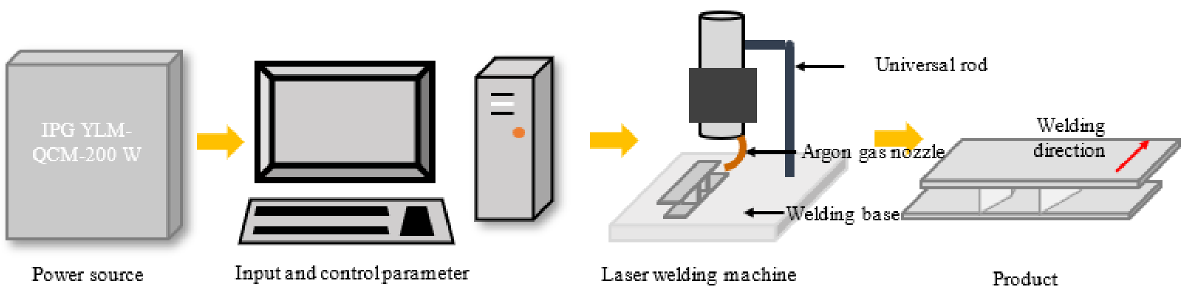

Figure 4. Schematic diagram of laser welding process on web-core sandwich structure

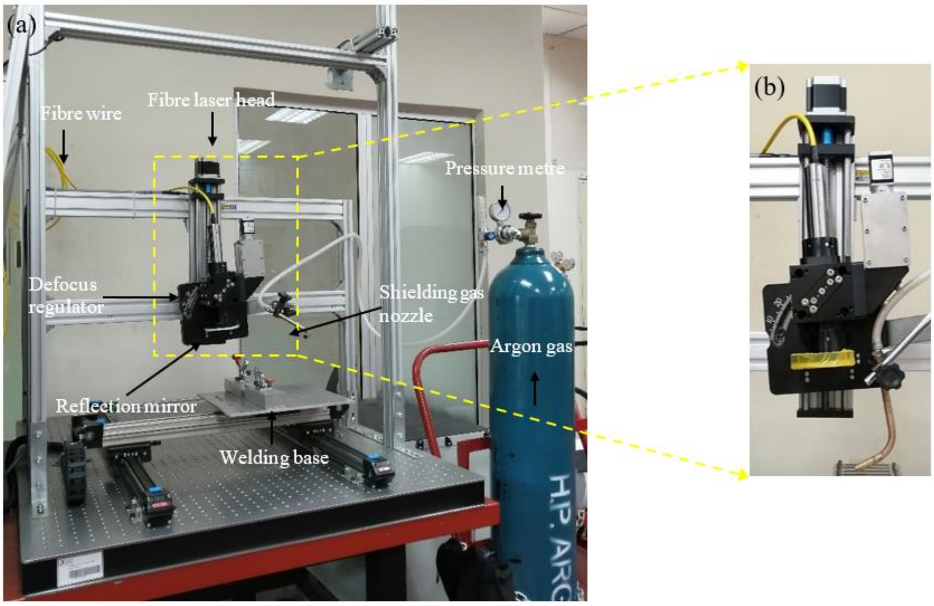

Figure 6. (a) Laser welding setup with complete installation equipment of welding process, (b) close-up of fibre laser head

Process of laser welding was controlled by pulse repetition rate and width; 20 Hz and 2 ms, respectively, where to control the heat into the weld area. The wavelength range was fixed about 1060 nm, and the process was running at speed of 100 mm/min. The laser was transmitted by a focus point of 152 mm lens, where the defocus point was about -2 mm. In welding experiments, argon gas was supplied as a shielding gas at a constant flow rate of 20 L/min. The laser welding parameters was summarised in Table 3.

Table 3. Parameter of laser welding which was employed in the fabrication process of web-core sandwich structure

Parameter	Value
Power	2 kW
Wavelength range	1060 nm
Speed	100 mm/min
Focal position	152 mm (defocus = -2 mm)
Gas flowrate	20 L/min
Pulse repetition rate	20 Hz
Pulse width	2 ms

Various testing methodologies were developed to continue the evolution of sandwich structures using laser welding technology to counter this. In this study, a standard testing methodology of three-point bending was used to assess the sandwich structure’s bending performance, which following ASTM C393. Furthermore, the sandwich structures were tested using INSTRON 3369 universal testing machine. The testing was running under a constant crosshead displacement 2 mm/min. The span length of 220 mm was used during the testing, which the value was decided according to the length of sample. Top indenter was positioned at middle of specimen, as to compare the load condition on even and odd number cores samples. Before starting the test, every specimen was marked. Hence, constant variables in this research were included the thickness of face plate and parameters of laser welding.

RESULTS AND DISCUSSION

Three-Point Bending Performance of Web-Core Laser-Welded Sandwich Structure: Without Foam

Web-core laser-welded sandwich structures of 5core_19 and 6core_19 specimens were performed under three-point bending loading and tested using Instron universal testing machine at control room temperature. The changes in the specimens were captured using a digital video camera. The results were analysed in load-displacement traces as shown in Figures 6 and 7. Upon loading, the specimen had an initial linear response. As a result, the initial deformation of the structure is likely to affect the successful flattening of the specimen. After this initial "stiffening", the specimen reacts linearly (Region I) to the first peak in the trace, with the deformation being symmetrical on the loading axis. One of the web plates from the structure was partially unattached after hitting the peak load and thus, resulting in a decrease in overall rigidity.

The faceplate had been partially bent after meeting the peak load. Consequently, the load required to deform further was decreased gradually due to the distribution of the global deformation between web plates over the spacing distance. The response was then gradually nonlinear (Region II). In Region III, the web cores adopted the sandwich configuration, and the applied force was strengthened because of interactions between the web plates and the uppermost faceplate. The structure lost its stability because of the plastic deformation and then dropped abruptly in the load [15]. The web cores in Region IV were eventually totally lowered, leading to particular failure modes such as bending and debonding between the foam and the faceplate. Debonding could have also happened between web plate and faceplate The debonding was affected by the quality of adhesion between the foam and faceplate was not sufficiently applied to transmit shear forces to the core. Findings from these metallic sandwich structure experiments were revealed that the dominant mode of failure in this material were elastic and plastic deformations [51].

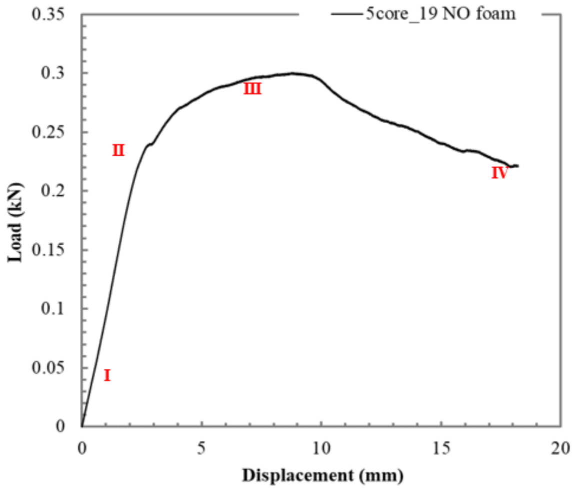

Figure 6. Load-displacement trace on three-point bending test of five cores with spacing distance, s = 19 mm

Damage development of web-core laser-welded sandwich structures under three-point bending loading on 5core_19 6core_19 (without foam) specimens were shown in Figures 7 and 9 respectively. Based on these findings, it was cleared that both were progressively well deformed. However, the sandwich structures of 5core_19 only had bending at bottom faceplate and caused global bending. The damage was due to the large area at right and left sides. The area was not supported with any web plate and core. As mentioned, the web plate was used to provide bending rigidity. Moreover, the core also provided most shear rigidity of the sandwich structure [52]. Besides that, a load was applied at centre of web plate as showed in Figure 7 and caused reaction forces that acted in the opposite direction to an action force. In this case, the reaction forces were at the bottom pins. The reaction forces were resulted a friction from a surface interaction and adhesion during sliding

Generally, a sandwich structure was designed to carry a bending load. Bending stiffness was characterised through applied force and vertical displacement of a point application force. In the three-point bending loading case of a sandwich structure with web plate, some occurrence of local effects such as indentation and web plate damage could be affected on the sandwich structure. The indentation on a sandwich structure was a main contributor to the bending [3]. Meanwhile, the 6core_19 specimen bent at top and bottom faceplates, where a load was applied at centre between two web plates and caused a global and local bending. According to Romanoff [5], local bending in sandwich structure was corresponded to the elongation of the faceplates. The global bending was due to the elongation of top and bottom faceplate in opposite direction. Global and local bending were resulted from vertical force that applied on the sandwich structure, indeed. Furthermore, the three-point bending response under load-displacement trace was explained clearly by showing the mechanical behaviour of the specimen according to the stage as labelled in the trace. From the observation, 6core_19 specimen withstands with higher force than 5core_19 specimen, which offered higher energy absorption capability, where 6core_19 trace had greater area under the curve than to the other specimens. The compression load increase dramatically as the number of unit cells increased [15].

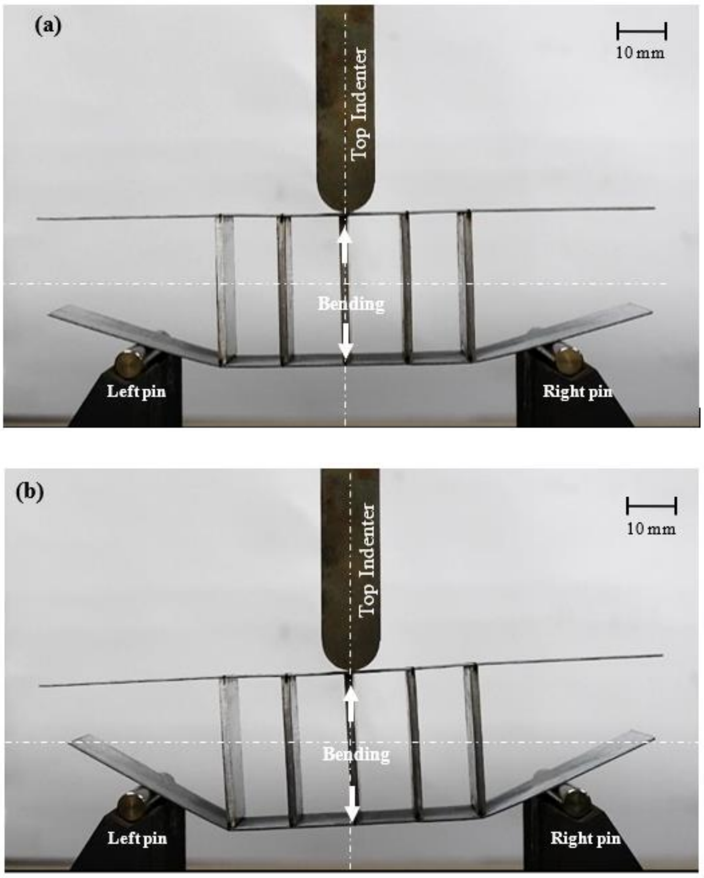

Figure 7. (a) and (b) Photographs of damage development in five cores with spacing distance, *s* = 19 mm

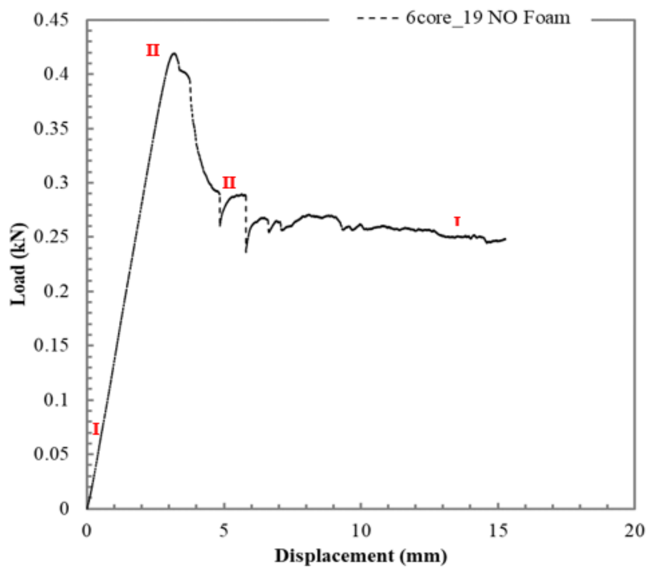

Figure 8. Load-displacement trace on three-point bending test of six cores with spacing distance, *s* = 19 mm

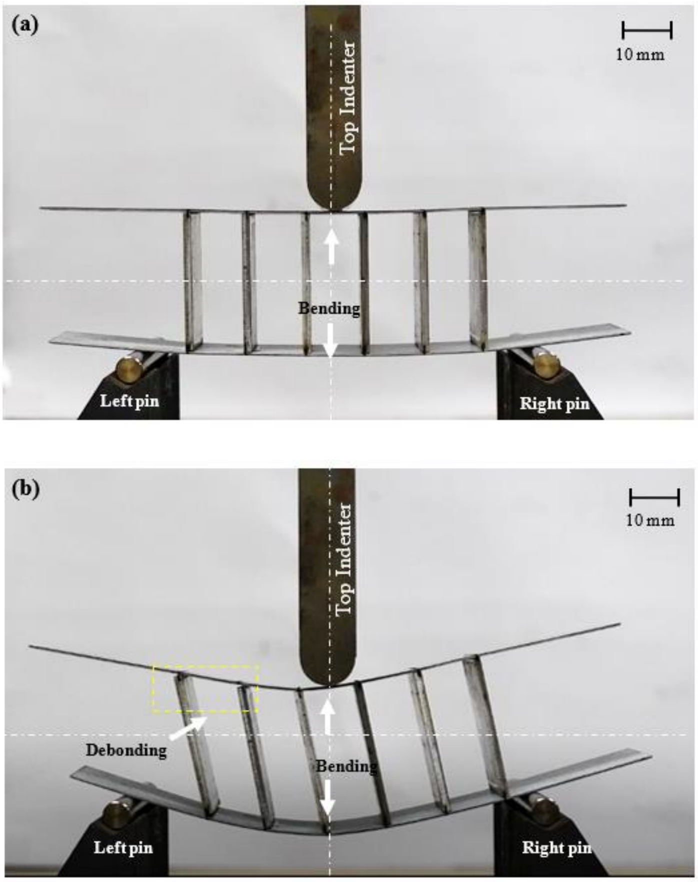

Figure 9. (a) and (b) Photographs of damage development in 6 cores with spacing distance, s = 19 mm

Three-Point Bending Performance of Web-Core Laser-Welded Sandwich Structure of Five Cores: With Foam

Besides that, Figure 10 shows the load-displacement trace regarding three-point bending tests on galvanised steel sandwich specimens based on the different spacing distances, s. The performances were noticeable in those specimens, which were deformed acceptably. From the investigation, a 5core_20 specimen withstood the highest three-point bending load and provided a higher energy absorption capacity (larger region under the curve) relative to the other specimens. The figure demonstrated that web-core sandwich structures with foam performed greater three-point bending loads than conventional web-core structures. Figure 10 shows that the load was initially increased linearly up to the first peak, with deformation in the core being symmetrical about the loading axis. At the early stage, the sandwich structure was sustained by the rigid PVC foam at the right and left sides. Even so, Figure 10 demonstrated that the elastic performance of 5core_19 and 5core_20 specimens had a pre-failure at Region I, as determined by the structure stiffness. Under continuous loading, the load remains constant until all the structures constituents (upper plate, core, and bottom plate) come into contact, at which point the core densifies. In the meantime, the elasticity was compared by calculating the stiffness of five core specimens. Each specimen was stated that 5core_18 had better stiffness than 5core_19 and 5core_20 specimens, which about 0.4189, 0.2875, and 0.2808 kN/mm, respectively. Furthermore, the pre-failure was found at the weld joint during a load that acted on the sandwich structure. Thus, the cracking on the weld joint was generated by continued loading until it caused an obvious deformation on the specimen, which the noticeable deformation was referred to as bending. The bending was induced by plastic deformation (Region II), which was increased steadily until the maximum load was reached. Similarly, Romanoff [38] found that bending response could remarkably influence the global deformation on a structure.

Figure 11 shows that damage development in the five cores sandwich structures under bending was followed by certain failures at maximum force. As the weld joints between the cores began to fracture and the foam was compressed, the load gradually decreased. Next, interlayer contact and debonding failures between the top faceplate and web plate were involved. The development of those failures eventually crused the weld joint, as shown in Figure 11. Finally, some web plates were dissembled from the upper faceplate. As a result of the interaction between the web core and the added foam, the peak load nearly doubles and energy absorption was enhanced.

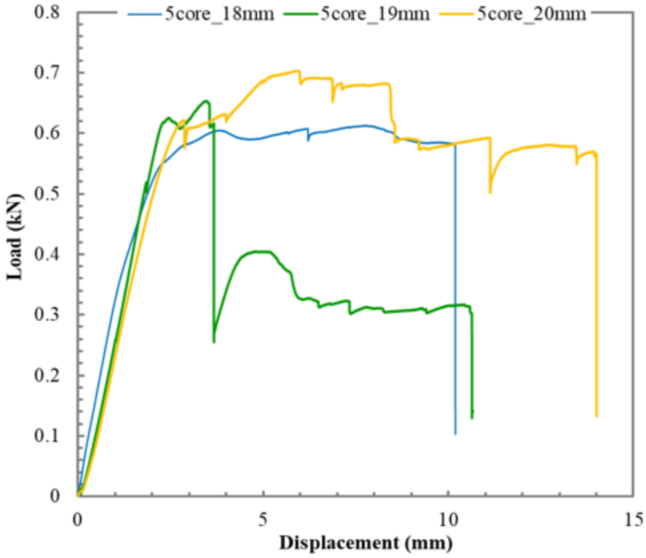

Figure 10. Load-displacement trace on three-point bending test of five cores with different spacing distances, *s* = 18, 19, and 20 mm

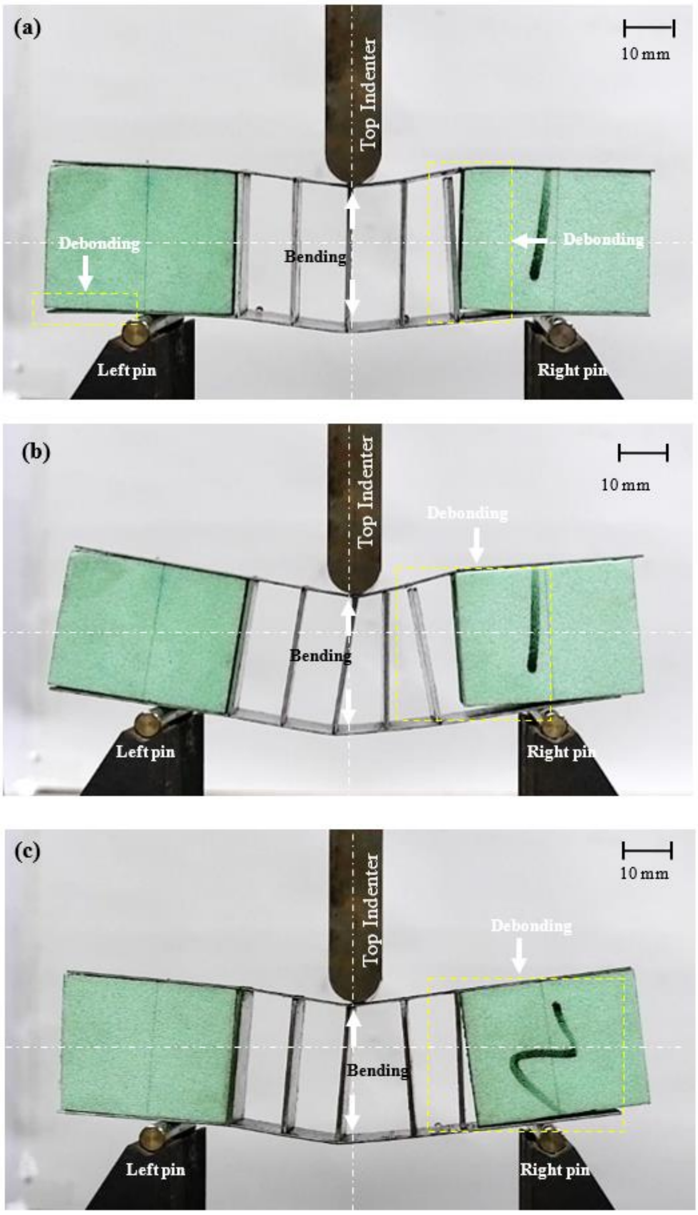

Figure 11. Photographs of damage in five cores with different spacing distance, *s:* (a,b) 18 mm, (c) 19 mm

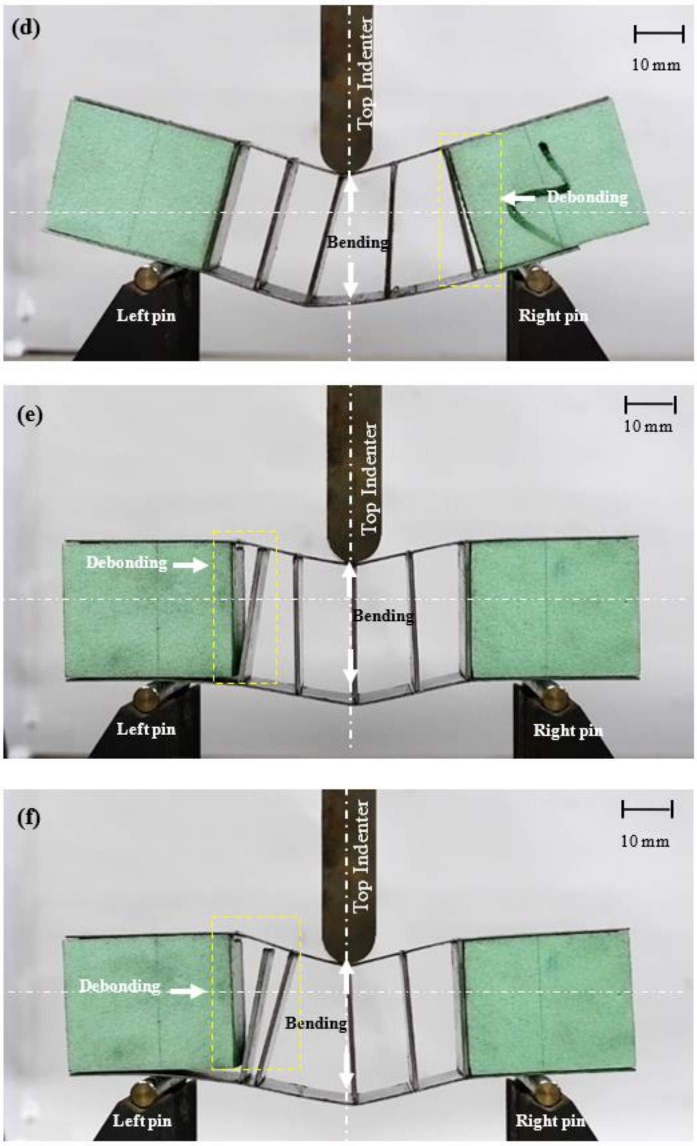

Figure 11. Photographs of damage in five cores with different spacing distance, *s:* (d) 19 mm, and (e,f) 20 mm (cont.)

Three-Point Bending Performance of Web-Core Laser-Welded Sandwich Structure of Six Cores: With Foam

In present study, the indenter was placed at the middle of two web plates, as illustrated in Figure 13, where the performance of a sandwich structure was slightly lower than the performance of five cores, which was due to the indenter position that acted on the sandwich structure. Figure 13 shows that the specimens were deformed with elasticity and plastic deformation influences, where 6core_20 was obviously exhibited with the highest three-point bending load. Nevertheless, the structure elasticity of 6core_19 was lower than 6core_18. Thus, 6core_19 was analysed from the load-displacement trace, where the specimen started to have flaws earlier than 6core_18. The flaw was due to the contact between the upper faceplate and PVC foam, where there was less interaction between the upper faceplate and the PVC foam. Hence, the structure was partially dissembled and weaker by its strength. Therefore, the elasticity performance was proved by stiffness calculation on the 6core_18, 6core_19, and 6core_20, which were about 0.4154, 0.3062, and 0.4583 kN/mm, respectively.

Figure 13 shows that the 6core_18 specimen was attempted to fail on the weld joint, resulting in debonding between the web plate and faceplate. Besides that, a comparison was referred in Figure 8 and showed that the first failure of 6core_18 was greater than 6core_19. An analysation was run on the 6core_18, and the changes were recognised due to the specimen material deformation. The changes could also cause a few defects in the structure. Hence, failure would also affect the structural strength and rigidity. Contact between PVC foam and upper and bottom faceplates was reduced upon the three-point bending loading, and the interaction became dissembled afterward. Meanwhile, the web plates sustained the damaged structural after reaching a peak load (Region III) and tend to have more bending due to the acted load. In the same vein, in his article Romanoff and Varsta [4], stated that the core provided continuous faceplate support in the web plate direction and discrete support in the transverse direction. Therefore, the structure would even crush under extensive loading.

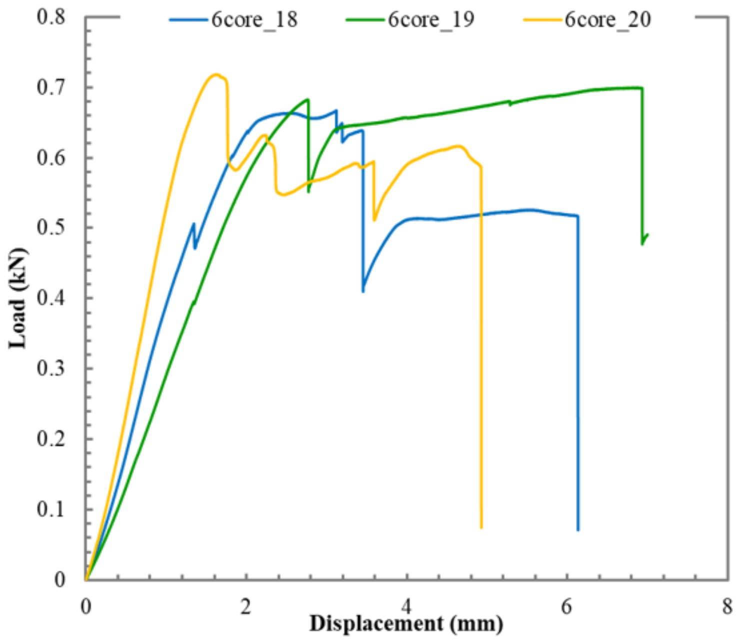

Figure 12. Load-displacement trace on three-point bending test of six cores with different spacing distance, *s* = 18, 19, and 20 mm

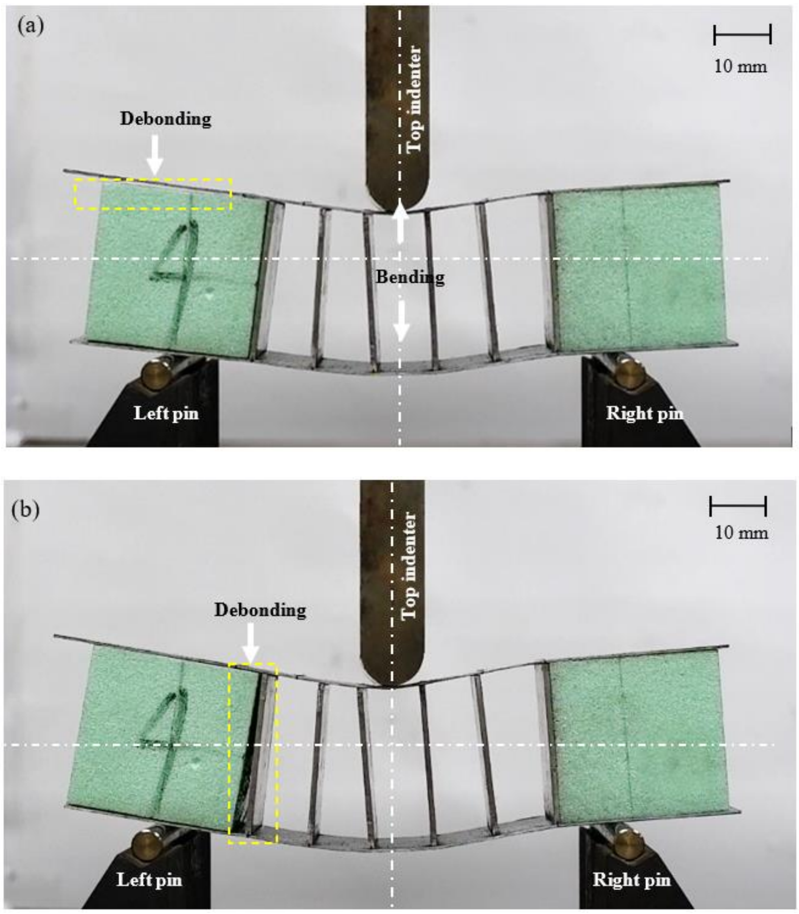

Figure 13. Photographs of damage in six cores with different spacing distance, *s:* (a,b) 18 mm

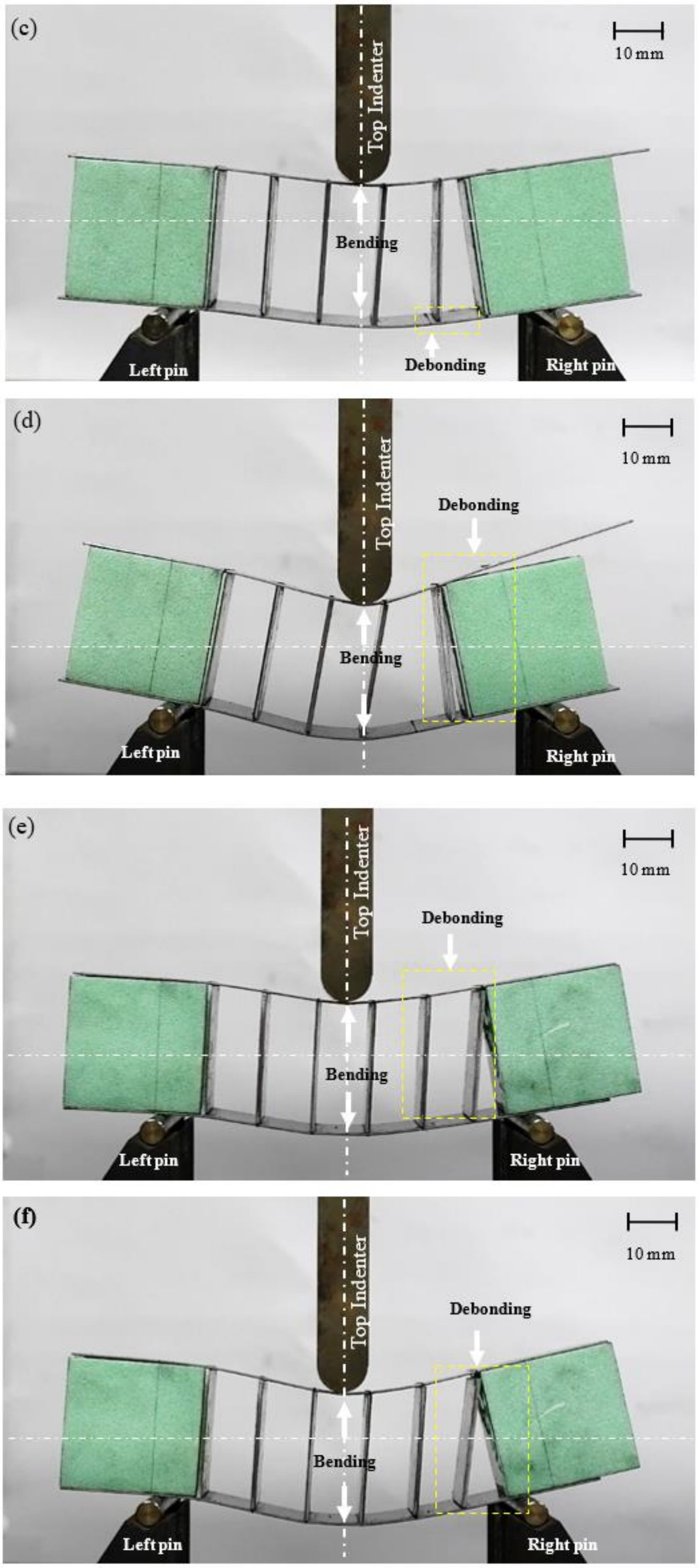

Figure 13. Photographs of damage in six cores with different spacing distance, *s:* (c,d) 19 mm, and (e,f) 20 mm (cont.)

Three-Point Bending Performance of Web-Core Laser-Welded Sandwich Structure of Seven Cores: With Foam

Three-point bending responses of web-core sandwich structures with foam on seven cores with different spacing distances were introduced in Figure 14, where the specimens were tested under constant crosshead displacement. Figure 14 revealed that 7core_18 was exhibited with a higher stiffness than 7core_19 and 7core_20, which showed that the 7core_18 had better elastic performance than 7core_19 and 7core_20. The performance was caused by material elongation, where the change in length, to the original length, l was smaller than other specimens. In addition, elasticity was referred to as a material ability to revert to its original shape after being subjected to a force that causes it to change shape. However, 7core_19 had lower stiffness, which was due to interaction failure between upper plate and foam, which led to dissemble on the interaction factor. The dissemble occurred due to an acted load, where caused bending on the sandwich structure. The bending ensued regarding plastic deformation on the material itself. The plastic deformation corresponded according to a physical phenomenon of breaking bonds with original atom neighbours and reforming bonds with new neighbours, where many atoms or molecules moved relative to one another [53]. Furthermore, Figure 14 shows that 7core-20 exhibited the highest force and attempted to fail earlier than 7core_18 and 7 core_19. Figure 4.17 revealed that 7core_20 had pre-failure at elasticity zone (Region I) obviously. Upon the problem, 7core_20 was analysed during the experiment, where the weld joint was started to break, resulting in the web plate completely dissemble due to the joint failure. Similarly, Romanoff [5] also mentioned that web-core was considered highly orthotropic. The orthotropic was emphasised by laser welding, where laser weld thickness was typically less than faceplate thickness. However, the performance of 7core_20 was supported continuously by other weld joints and strengthened interaction between faceplate and PVC foam.

Meanwhile, the performances of 7core_19 and 7core_20 specimens were also distracted with sudden failure between PVC foam and the upper faceplate (between Region I and II). The failure occurred due to less interaction of adhesive layer between the PVC foam and upper faceplate. This view was supported by Huaguan [54], who wrote that an adhesive layer was undoubtedly used to improve the interaction strength. Li et.al [54] also pointed out that the interaction strength would depend on the reasonable quantity of the adhesive. Hence, the failure phenomenon was shown with a few photographs of damage development in seven cores specimens through Figure 15. Nevertheless, the force was increased again due to the support loading of the web plates on the sandwich structure. According to Jani Romanoff [38], web and faceplates interacted and would cause considerable stress on the web-core and faceplates. Rejab and Cantwell [15] stated that the weld joint strength could be affected under continuous loading. The load might also be reduced when the sandwich structure fully reached the crosshead displacement limit.

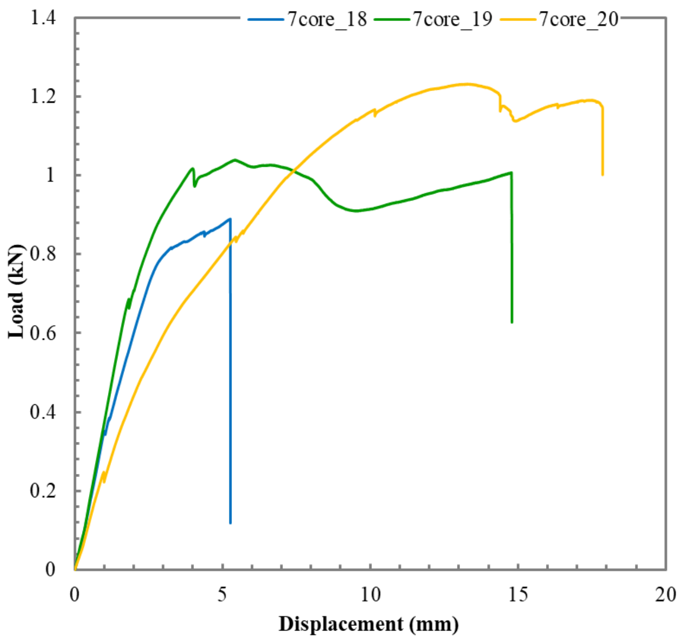

Figure 14. Load-displacement trace on three-point bending test of seven cores with different spacing distances, *s* = 18, 19, and 20 mm

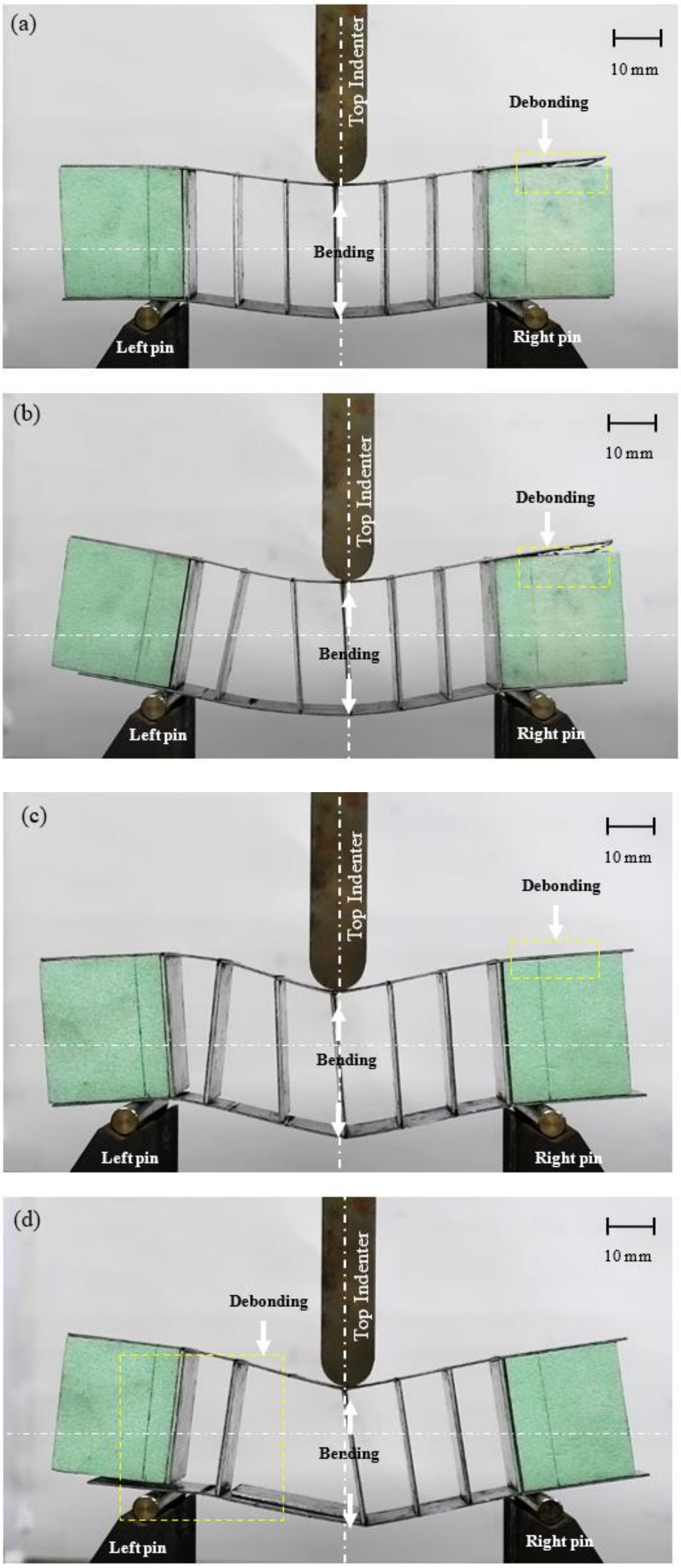

Figure 15. Photographs of failure development in seven cores with different spacing distances, *s*: (a,b) 18mm, (c,d) 19 mm

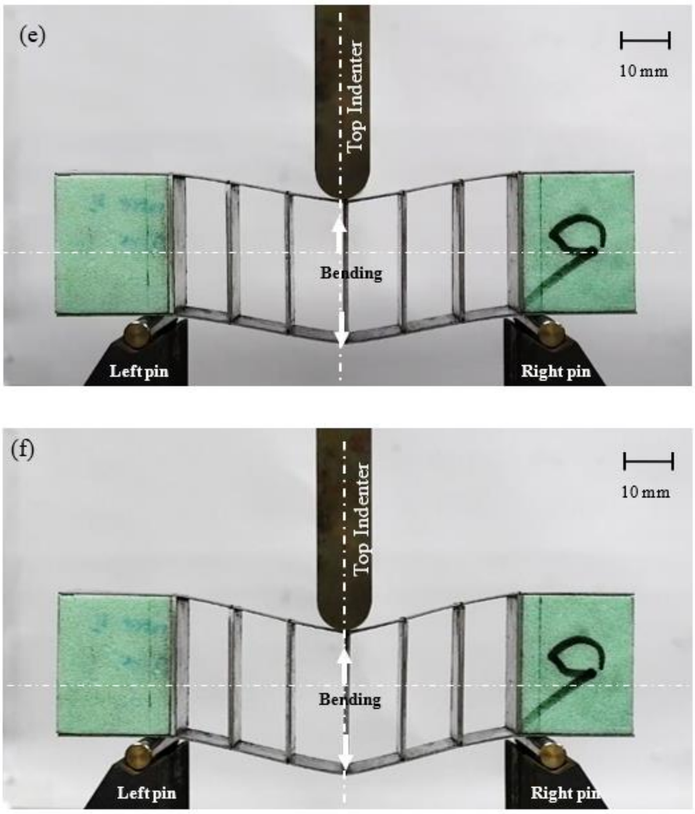

Figure 15. Photographs of failure development in seven cores with different spacing distances, *s*: (e,f) 20 mm (cont.)

Effect of Number of Core and Spacing Distance in Bending Stiffness of Web-Core Laser-Welded Sandwich Structure

Figure 16 shows the comparison of three-point bending performance on five, six and seven cores specimens with different spacing distance, s 18, 19 and 20 mm. The performance was demonstrated the variation in sandwich structure strength and stiffness as a function of web plate thickness. As expected, the strength was increased in the non-linear trendline as web plate thickness increased. The maximum load of three-point bending response in seven cores with spacing distance 20 mm was recorded with a value of 1.091 kN. In addition, the force value was increased linearly as the structural changes occurred on the sandwich structure, where the changes in stiffness was also affected. Nevertheless, the traces in Figure 16 showed a comparison on structure stiffness, where the structure stiffness could also affected on specimen performance. Therefore, the stiffness of five core specimens with 2 mm web plate thickness was calculated for 18, 19 and 20 mm, which the stiffness values were about 0.313, 0.338 and 0.281 kN/mm, respectively. Figure 16 revealed that the value related to the web plate thickness was lower than predicted. The inconsistency was related to the manufacturing challenges of the laser welding procedures. The presence of the manufacturing flaws significantly reduced the structure rigidity [15].

Figure 16 was obtained when the specimen was subjected to a three-point bending loading, which was caused bending deformation on the specimen. The material was experiencing length changes during loading. Besides that, the deformation was responded to the material elasticity and plastic deformation. In addition, the stiffness was affected by a specific structure failure after a force acting on the specimen, where debonding between web plates and PVC foam occurred at both sides. Hence, weld joint was considered in specimen performance, where a failure at the weld joint could also affect the specimen stiffness. The trace was analysed and proved that specimens were bent and defected under three-point bending loading. Upon that statement, the specimens were discovered and had a pre-failure at the weld joint. In fact, the weld thickness was smaller than the web plate thicknesses. Based on Karttunen [27] study, the author found that bending at welded T-joint was due to shear deformation that opposed to web direction. Given that Figures 11, 13 and 15 demonstrated the deformation of two different web plate thicknesses, 2 mm under three-point bending loading by normal stress distribution. Mechanical performances of specimens on web plate thicknesses of 2 mm were identified in three-point bending testing. Both web plate thicknesses were compared. The bending response on specimens resulted in reduced interlayer interaction between PVC foam and faceplate, where the defect caused reduced its stability and strength on the sandwich structure. Theoretically, interaction between the PVC foam and faceplate were bonded by a thin layer of adhesive. Thus, the failure would occur easily due to small thickness of adhesive layer compared to faceplate thickness.

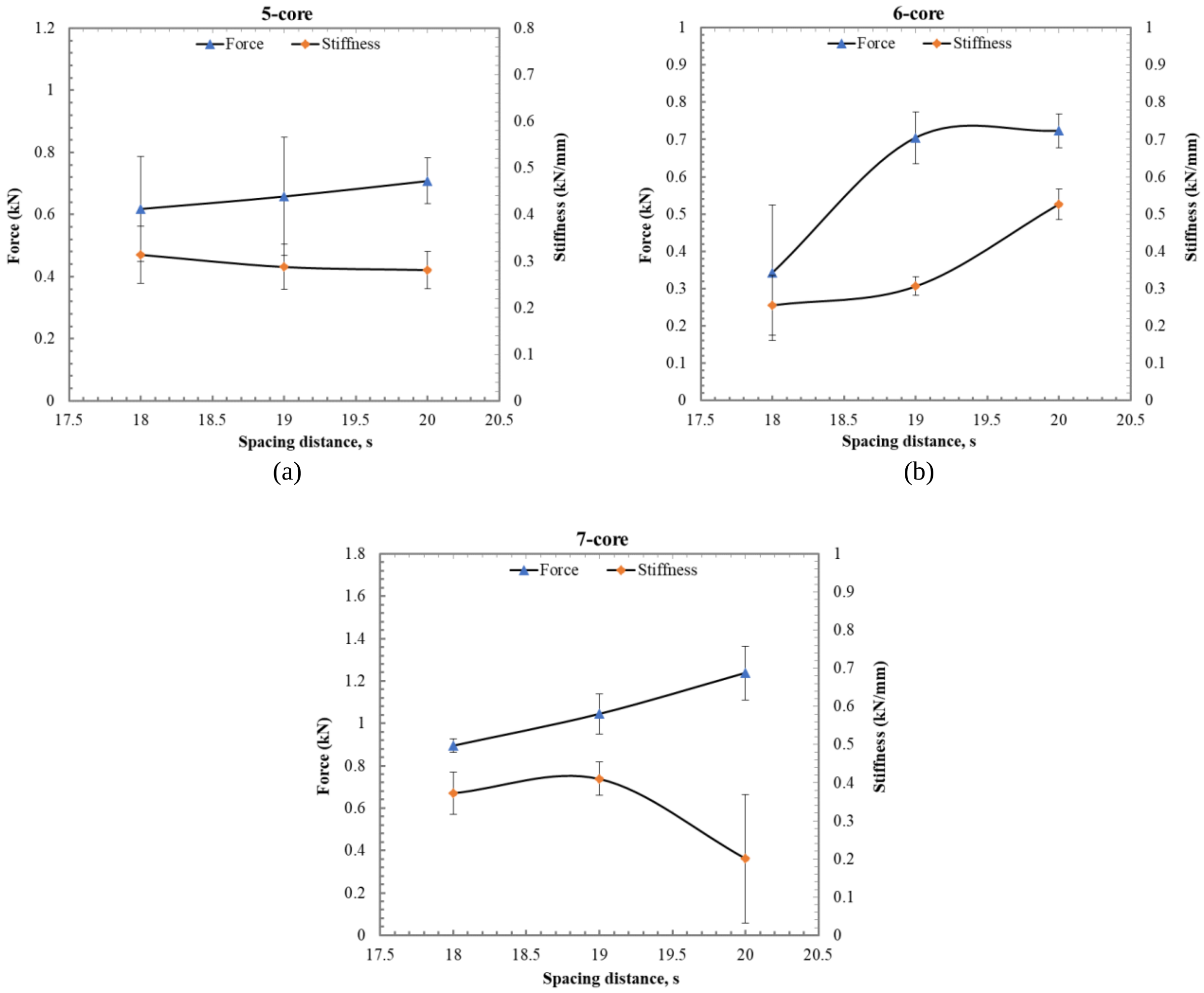

Figure 16. Comparison of sandwich structure stiffness on different number of cores with variant spacing distance, *s:* (a) 18, (b) 19, and (c) 20 mm

CONCLUSIONS

The purpose of the research is to present the experiment's findings in mechanical response of web-core laser-welded sandwich structure under three-point bending loads. The different number of cores and spacing distances were considered. The testing was carried out on 1 mm faceplate thickness and 2 mm web plate thickness. Both plates were joined with fibre laser welding under controlled parameters. Three-point bending experiments revealed that the bending stiffness and failure mode were depended on number of core and spacing distance. The number of cores, and spacing distance all have a significant impact on the web-core sandwich structure three-point bending performance. Bending strength increase in proportion to the number of cores, and spacing distance of specimen. However, performance of the sandwich structure could affect due to failure at weld joint and debonding between foam and face or web plates. These failures could decrease bending stiffness of the sandwich structure. Besides that, filling the inside of the web-core sandwich structures with PVC foam significantly improved the structures specific strength, where the rigidity of sandwich structure was increased doubly.

ACKNOWLEDGMENTS

The authors are grateful to the Universiti Malaysia Pahang for funding this research with PGRS1903155 and a research grant from Ningxia High School Scientific Research Project (Excellent Young Teacher Training Fund Project: NGY 2017016). This research work is strongly supported by SUPREME Focus Group which provided the research materials and equipment. The authors are also grateful to Kolej Kemahiran Tinggi MARA (KKTM), Kuantan for cooperating in making this research a success.

REFERENCES

[1] J. Bühring, M. Nuño, and K.U. Schröder, "Additive manufactured sandwich structures: Mechanical characterization and usage potential in small aircraft," *Aerospace Science and Technology,* vol. 111, p. 106548, 2021.

[2] J. Vinson, *"The behavior of sandwich structures of isotropic and composite materials,"* Routledge, New York, 1999.

[3] A. Cernescu and J. Romanoff, "Bending deflection of sandwich beams considering local effect of concentrated force," *Composite Structures,* vol. 134, pp. 169-175, 2015.

[4] J. Romanoff and P. Varsta, "Bending response of web-core sandwich plates," *Composite Structures,* vol. 81, no. 2, pp. 292-302, 2007.

[5] J. Romanoff and P. Varsta, "Bending response of web-core sandwich beams," *Composite Structures,* vol. 73, no. 4, pp. 478-487, 2006,

[6] E. Wang, N. Gardner, and A. Shukla, "The blast resistance of sandwich composites with stepwise graded cores," *International Journal of Solids and Structures,* vol. 46, no. 18-19, pp. 3492-3502, 2009.

[7] A. Jamil, Z.W. Guan, W.J. Cantwell, X.F. Zhang, G.S. Langdon, and Q.Y. Wang, "Blast response of aluminium/thermoplastic polyurethane sandwich panels – experimental work and numerical analysis," *International Journal of Impact Engineering,* vol. 127, pp. 31-40, 2019.

[8] V. Crupi, G. Epasto, and E. Guglielmino, "Comparison of aluminium sandwiches for lightweight ship structures: Honeycomb vs. foam," *Marine Structures,* vol. 30, pp. 74-96, 2013.

[9] W. Huang, W. Zhang, D. Li, N. Ye, W. Xie, and P. Ren, "Dynamic failure of honeycomb-core sandwich structures subjected to underwater impulsive loads," *European Journal of Mechanics - A/Solids,* vol. 60, pp. 39-51, 2016.

[10] N. Ye, W. Zhang, D. Li, W. Huang, W. Xie, X. Huang and X. Jiang, "Dynamic response and failure of sandwich plates with PVC foam core subjected to impulsive loading," *International Journal of Impact Engineering,* vol. 109, pp. 121-130, 2017.

[11] K. Arslan and R. Gunes, "Experimental damage evaluation of honeycomb sandwich structures with Al/B4C FGM face plates under high velocity impact loads," *Composite Structures,* vol. 202, pp. 304-312, 2018.

[12] W. Lestari and P. Qiao, "Damage detection of fiber-reinforced polymer honeycomb sandwich beams," *Composite Structures,* vol. 67, no. 3, pp. 365-373, 2005.

[13] S. Shi, Z. Sun, X. Hu, and H. Chen, "Flexural strength and energy absorption of carbon-fiber–aluminum-honeycomb composite sandwich reinforced by aluminum grid," *Thin-Walled Structures,* vol. 84, pp. 416-422, 2014.

[14] M. He and W. Hu, "A study on composite honeycomb sandwich panel structure," *Materials & Design,* vol. 29, no. 3, pp. 709-713, 2008.

[15] M. R. M. Rejab and W. J. Cantwell, "The mechanical behaviour of corrugated-core sandwich panels," *Composites Part B: Engineering,* vol. 47, pp. 267-277, 2013.

[16] F. Roland and T. Reinert, "Laser welded sandwich panels for the shipbuilding industry," *Lightweight Construction–latest Developments,* pp. 1-12, 2000.

[17] J. Lou, L. Wu, L. Ma, J. Xiong, and B. Wang, "Effects of local damage on vibration characteristics of composite pyramidal truss core sandwich structure," *Composites Part B: Engineering,* vol. 62, pp. 73-87, 2014.

[18] A. S. Sayyad and Y. M. Ghugal, "Bending, buckling and free vibration of laminated composite and sandwich beams: A critical review of literature," *Composite Structures,* vol. 171, pp. 486-504, 2017.

[19] B. Wicklein *et al.*, "Thermally insulating and fire-retardant lightweight anisotropic foams based on nanocellulose and graphene oxide," *Nature Nanotechnology,* vol. 10, no. 3, pp. 277-283, 2015.

[20] J. Xie, R. Zhang, G. Xie, and O. Manca, "Thermal and thermomechanical performance of actively cooled pyramidal sandwich panels," *International Journal of Thermal Sciences,* vol. 139, pp. 118-128, 2019.

[21] Z. Xue and J. W. Hutchinson, "Crush dynamics of square honeycomb sandwich cores," *International Journal for Numerical Methods in Engineering,* vol. 65, no. 13, pp. 2221-2245, 2006.

[22] T. Ali, Y. Peng, Z. Jinhao, L. Kun, and Y. Renchuan, "Crashworthiness optimization method for sandwich plate structure under impact loading", *Ocean Engineering,* vol. 250, p. 110870, 2022.

[23] P. Kujala and A. Klanac, "Steel sandwich panels in marine applications," *Shipbuilding: Theory and practice of shipbuilding and marine engineering,* vol. 56, no. 4, pp. 305-314, 2005.

[24] Q. Zhong and D. Wang, "Ultimate strength behavior of laser-welded web-core sandwich plates under in-plane compression," *Ocean Engineering,* vol. 238, p. 109685, 2021.

[25] J. van der Zwaal, "Feasibility study of an all-sandwich superstructure for hopper dredgers," *Master Thesis*, TU Delft, 2005.

[26] J. Kortenoeven, B. Boon, and A. de Bruijn, "Application of sandwich panels in design and building of dredging ships," *Journal of Ship Production,* vol. 24, no. 3, pp. 125-134, 2008.

[27] A. T. Karttunen, J. N. Reddy, and J. Romanoff, "Two-scale micropolar plate model for web-core sandwich panels," *International Journal of Solids and Structures,* vol. 170, pp. 82-94, 2019.

[28] S. Yan and J. Jelovica, "Buckling and free vibration of laser-welded web-core sandwich panels: Extreme sensitivity to variation of weld rotational stiffness," *Engineering Structures,* vol. 244, p. 112737, 2021.

[29] P. Paczos, P. Wasilewicz, and E. Magnucka-Blandzi, "Experimental and numerical investigations of five-layered trapezoidal beams", *Composite Structures,* vol. 145, pp. 129-141, 2016.

[30] J. Romanoff, P. Varsta, and H. Remes, "Laser-welded web-core sandwich plates under patch loading," *Marine Structures,* vol. 20, no. 1, pp. 25-48, 2007.

[31] X.X. Jiang, J.M. Li, R. Cao, L. Zhu, J.H. Chen, Y.X. Wu, and Z.G. Li, "Microstructures and properties of sandwich plane laser-welded joint of hull steel," *Materials Science and Engineering: A,* vol. 595, pp. 43-53, 2014.

[32] H. Kolsters and P. Wennhage, "Optimisation of laser-welded sandwich panels with multiple design constraints," *Marine Structures,* vol. 22, no. 2, pp. 154-171, 2009,

[33] J. Romanoff, H. Remes, G. Socha, M. Jutila, and P. Varsta, "The stiffness of laser stake welded T-joints in web-core sandwich structures," *Thin-Walled Structures,* vol. 45, no. 4, pp. 453-462, 2007.

[34] Y. Sun, M. Saafi, W. Zhou, C. Zhang, and H. Li, "Analysis and experiment on bending performance of laser-welded web-core sandwich plates," *Materials Today: Proceedings,* vol. 2, pp. 279-288, 2015.

[35] K. Liu, L. Ke, Y. Sha, G. Wu, P. Wang, and Z. Wang, "Dynamic response of laser-welded corrugated sandwich panels subjected to plane blast wave," *International Journal of Impact Engineering,* vol. 164, p. 104203, 2022.

[36] Z. Guo, R. Bai, Z. Lei, H. Jiang, J. Zou, and C. Yan, "Experimental and numerical investigation on ultimate strength of laser-welded stiffened plates considering welding deformation and residual stresses," *Ocean Engineering,* vol. 234, p. 109239, 2021.

[37] S. Chowdhury, Y. Nirsanametla, M. Muralidhar, S. Bag, C. P. Paul, and K. S. Bindra, "Identification of modes of welding using parametric studies during ytterbium fiber laser welding," *Journal of Manufacturing Processes,* vol. 57, pp. 748-761, 2020.

[38] J. Romanoff, "Periodic and homogenized bending response of faceplates of filled web-core sandwich beams," *Composite Structures,* vol. 113, pp. 83-88, 2014.

[39] J. Romanoff, J. Jelovica, J. N. Reddy, and H. Remes, "Post-buckling of web-core sandwich plates based on classical continuum mechanics: success and needs for non-classical formulations," *Meccanica,* vol. 56, no. 6, pp. 1287-1302, 2021.

[40] H. Kolsters and D. Zenkert, "Buckling of laser-welded sandwich panels. Part 1: Elastic buckling parallel to the webs," *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment,* vol. 220, no. 2, pp. 67-79, 2006.

[41] J. Jelovica and J. Romanoff, "Load-carrying behaviour of web-core sandwich plates in compression," *Thin-walled structures,* vol. 73, pp. 264-272, 2013.

[42] X. X. Jiang, L. Zhu, J. S. Qiao, Y. X. Wu, Z. G. Li, and J. H. Chen, "The strength of laser welded web-core steel sandwich plates," in *Applied Mechanics and Materials,* vol. 551, pp. 42-46, 2014.

[43] G. Schuh, G. Bergweiler, K. Lichtenthäler, F. Fiedler, and S. d. l. Puente Rebollo, "Topology optimisation and metal based additive manufacturing of welding jig elements," *Procedia CIRP,* vol. 93, pp. 62-67, 2020.

[44] B. Zhang, X. Wang, and H. Wang, "Virtual machine placement strategy using cluster-based genetic algorithm," *Neurocomputing,* vol. 428, pp. 310-316, 2021.

[45] J. Ordieres, E. Rodríguez, A. Bayón, J. Caixas, A. Barbensi, and P. Guglielmi, "Improvement of manufacturing jigs design for reduction of welding distortion in Vacuum Vessel PS1 through finite element analysis," *Fusion Engineering and Design,* vol. 146, pp. 2168-2171, 2019.

[46] A. Kampker, G. Bergweiler, A. Hollah, K. Lichtenthäler, and S. Leimbrink, "Design and testing of the different interfaces in a 3D printed welding jig," *Procedia CIRP,* vol. 81, pp. 45-50, 2019.

[47] N. Ma, H. Huang, and H. Murakawa, "Effect of jig constraint position and pitch on welding deformation," *Journal of Materials Processing Technology,* vol. 221, pp. 154-162, 2015.

[48] J. Ordieres, E. Rodríguez, A. Bayón, J. Caixas, A. Barbensi, and C. Martín, "Determination of the influence of clamping on welding distortion applied to PS2 mock-up using finite element simulations," *Fusion Engineering and Design,* vol. 166, p. 112327, 2021.

[49] A. Azimi, F. Ashrafizadeh, M. R. Toroghinejad, and F. Shahriari, "Metallurgical analysis of pimples and their influence on the properties of hot dip galvanized steel sheet," *Engineering Failure Analysis,* vol. 26, pp. 81-88, 2012.

[50] A. Azimi, F. Ashrafizadeh, M. R. Toroghinejad, and F. Shahriari, "Metallurgical assessment of critical defects in continuous hot dip galvanized steel sheets," *Surface and Coatings Technology,* vol. 206, no. 21, pp. 4376-4383, 2012.

[51] P. Ren *et al.*, "High-velocity impact response of metallic sandwich structures with PVC foam core", *International Journal of Impact Engineering,* vol. 144, p. 103657, 2020.

[52] Y. Deng, N. Zhou, X. Li, X. Wang, G. Wei, and H. Jia, "Dynamic response and failure mechanism of S-shaped CFRP foldcore sandwich structure under low-velocity impact," *Thin-Walled Structures,* vol. 173, p. 109007, 2022.

[53] F. Z. Utyashev and G. I. Raab, "Influence of large and severe plastic deformation mechanisms on structure formation in metals," *Materials Letters,* vol. 302, p. 130241, 2021.

[54] H. Li, Y. Hu, X. Fu, X. Zheng, H. Liu, and J. Tao, "Effect of adhesive quantity on failure behavior and mechanical properties of fiber metal laminates based on the aluminum–lithium alloy", *Composite Structures,* vol. 152, pp. 687-692, 2016.