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A study on simulation analysis for laser-welded I-core sandwich plate with different material properties and T-joint weld characteristic

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ABSTRACT

Stiffness and strength of sandwich plate vary depending on similar (SI) or dissimilar (DSI) material element (faceplate or core) and laser weld geometry. The issues of I-core sandwich plate characteristics are essential to attain practical sandwich plate application. Hence, research on different material properties and T-joint weld characteristics of I-core sandwich steel plate presents a positive understanding of various character factors that affect sandwich plate bending performance. In this paper, the I-core sandwich steel plate characteristic was investigated using finite element analysis (FEA). The 3-point bending with a fine meshing, interaction of elements, and load applied was kept constant. The partition size at the laser weld geometry is smaller, and the partition size continuously grows when further away from the weld geometry. The result shows that a combination of weak and strong material on either element will reduce I-core sandwich's stiffness and strength unless strong material is assigned at the faceplate and core. Moreover, there is a significant change when rootgap is present. This influencing the centric and eccentric of the weld. The weld width produces a perfect bending as wholesome T-joint, yet to achieve such traits is impossible in reality but possible when the weld length is closer to the length of the core. The exploration of these characteristics in response to I-core sandwich steel plate holds a good response in engaging for the multiple variables that affect the plate's stiffness and strength.

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1. Introduction

Demand for a lighter, safer and modular structure would inspire the researcher to explore new material and the structural framework in an application (for example, ships, building, and bridges). The demand needs to prevent instability of structure or reduce impact damage due to collision [1]. Manufacture of a sandwich-like element was construct in various industrial branches not earlier than the 1950s. The sandwich can select by various materials such as aluminium, steel, titanium or carbon fibre reinforced plastic (CFRP). Moreover, the sandwich element (refer Fig. 1) comprises of a simple faceplate and core which solely depend on the topologies that can be demonstrate in many styles: flats, corrugate core [1–4], C-core [3], Z-core [6,7], X-core [6], Hat-core [7] and I-core [8,9]. The selection of core is entirely dependable on the application under consideration. A standard core such as Z-core is easier to fabricate with an accurate measurement for laser welding demand. Unique cores like Corrugate core and I-core, need specific equipment to perform; nevertheless, they result in a light panel. Hence, lightweight. Sandwich plate with complex cores significantly increases the strength, but it remains complex to estimate the strength values.

The I-core sandwich plate define as in Fig. 2. The global arrangement of breadth denotes as B with a total length, L and height, $H = 2t_f + h_c$. The distance between two adjacent sides of I-core known as a. The thickness of I-core denotes as t_c while t_f is the thickness of faceplate. n denote as number of I-core. Subscript h_c is the length between bottom-top and top–bottom faceplate, also known as height of core. Whereas P is the load apply at a central rotation of the entire sandwich plate.

An earlier failure experiment was proposed in 1987, along with a complete description to obtain sandwich panel failure mode. Since the material is abundance, a researcher can choose any desire material. Through 3-point bending, the core can be express by two methods which are foam and metallic core. Triantafillou et al. has performed and obtained result for rigid polyurethane foam [8],

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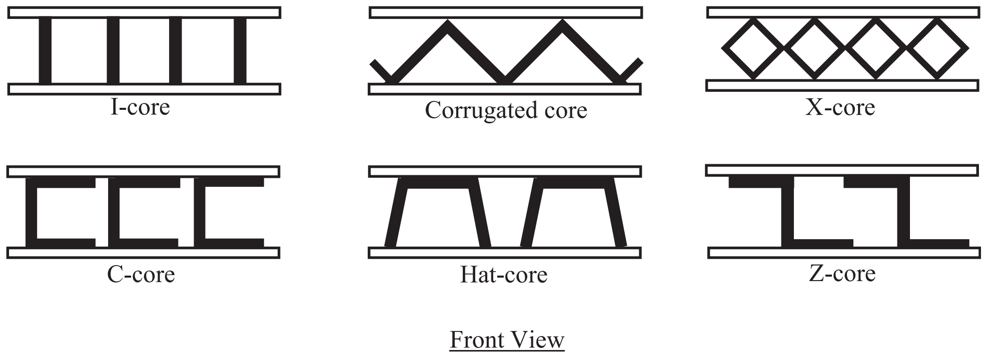


Fig. 1. Different topologies of sandwich plate.

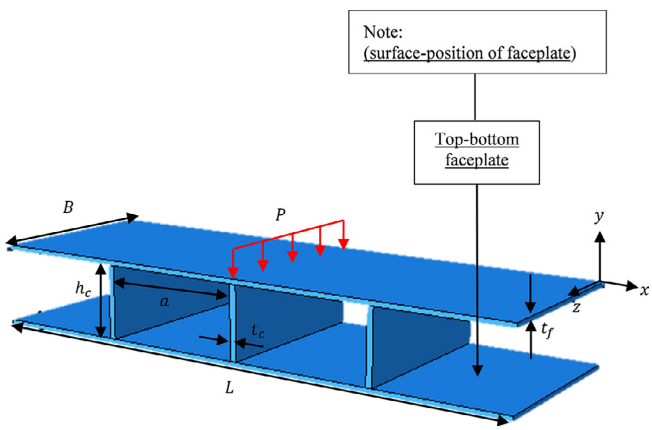


Fig. 2. The structure of I-core sandwich steel plate.

while Banghai Jiang et al. produced an analytic solution for aluminium foam with similar interaction with aluminium faceplate [9]. For instance, various metallic core, nomex honeycomb, corrugate, truss, and other core topologies are some well-known example used in sandwich application. Sadighi et al. studied on nomex honeycomb core where he utilises cross-ply glass–epoxy [10], while Petras et al. investigated failure modes on laminated glass fibre reinforced plastic (GFRP) as a base material for faceplate [11]. Considering the use of carbon fibre reinforced plastics (CFRP) is widely explored, Ye Yul et al. used both elements and exploits work based on simulation and analytical research [12]. Through discussion and evolution of sandwich failure present in Fig. 3, one can conclude that the material selection for similar and dissimilar material on or either element has been made before. This paper includes, combine weak material on both faceplate and core or strong material on both faceplate and core. A few studies focus on I-core sandwich plate consist of weak and strong material; hence, it is very interesting to explore this kind of plate behaviour.

Another issue that receives high attention from researchers worldwide is the effect of laser weld geometry upon the performance of sandwich plate. Laser weld geometry on sandwich plate plays a crucial part in sandwich plate performance. As stated by Ref. [12], the influence of T-joint is very sensitive, and up to 90% of possible failure occurs at the contact [13]. The parameter to describe the laser weld geometry on the sandwich plate illustrate in Fig. 4. The height of rootgap, h_{rg},consider a vertical space between the element, whereas the height of penetration, h_p, show the beam's length pass through the elements. Better penetration is desirable to produce a perfect weld joint profile. The weld width, t_{weld}, is a horizontal distance between the connecting faceplate and I-core. The larger the focal length from the focus point, the wider the laser beam width. For example, as the focal length increases from the focus point over time, defocus arises due to low laser power [14]. As a result of welding geometry, researchers start to employ it in various modes of an experiment. Benyounis et al has investigated the response of laser weld bead geometry and heat input that effectively influence to produce a laser weld bead 'key-hole' [15]. Malek Ghaini et al found that despite the full weld penetration, there are notable responses to the microstructure and hardness of weld due to rapid solidification [16]. Jani Romanoff et al conducted an experiment on distinct rootgap and weld (centric and eccentric) to obtain the rotation stiffness effect at the T-joint [17]. However, limit resource establishes for weld

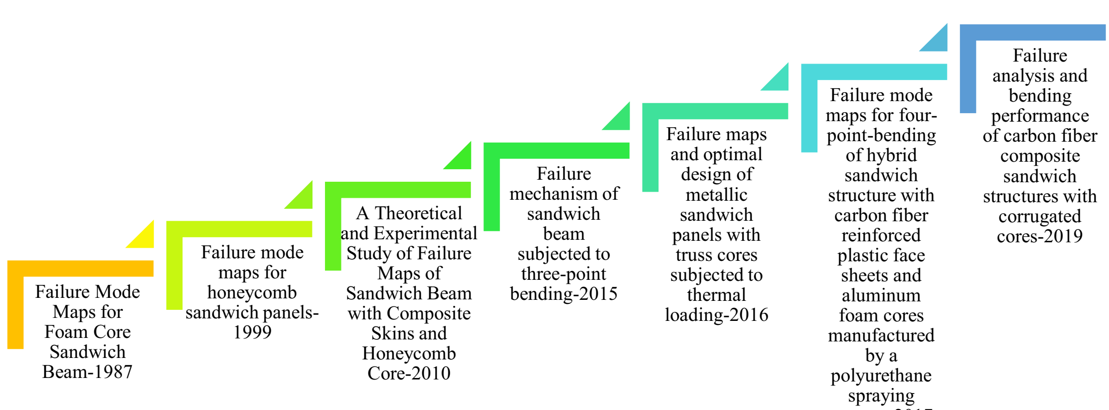


Fig. 3. Evolution of sandwich failure.

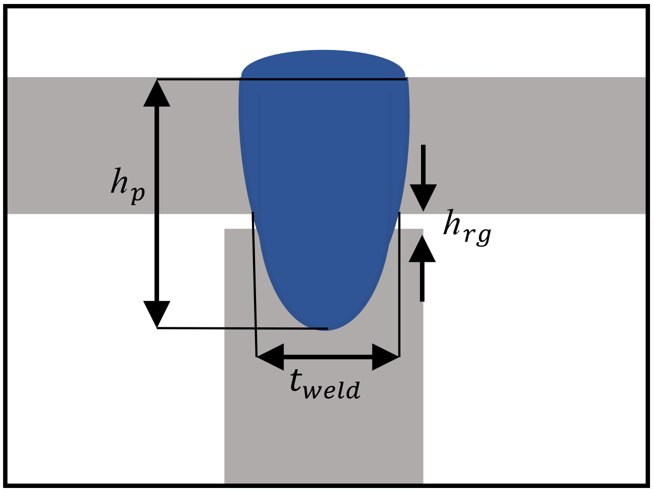


Fig. 4. Illustration of laser weld geometry parameter.

width and T-joint contact arise for I-core sandwich steel plate on 3-point bending test.

In conclusion, this paper attempt to overcome issues toward a combination of weak and strong material on both elements (faceplate and I-core) or either element for metallic core topologies. The effect of laser weld geometry and T-joint contact on the failure mode sandwich plate is another focus in this study. The utilization of steel and aluminium for weak and strong material gave an advantage to sandwich plate. Due to steel excellent strength performance and aluminium exhibit a lightweight characteristic, both materials display a good potential to solve the issues at hand. The previous discussion concerning T-joint weld, weld width, and T-joint contact at the element is a crucial matter to evaluate. Considering 3-point bending apply in this paper, the simulation work was initiate using Abaqus 2017 solver. Finally, analysis of simulation result and conclusion on the bending strength are discuss and establish.

2. Methodology

The simulation method obtain from this data were taken from a technique used to compare experiment and simulation data of galvanise steel sandwich plate. The sandwich plate with foam infill (dimension: 220 × 50 × 52 mm^3, n: 5, t_f: 1 mm and t_c: 2 mm) produce a good graph of elastic region. The percentage error between each work is less than 10% (see Fig. 5), thus, the technique is acceptable to conduct FEM model to evaluate the stiffness and strength of sandwich plate in regard to different material properties and T-joint weld characteristic.

The 3-point bending simulation were conduct using standard ASTM C393 configuration [18]. Stress distribution are study at the loading. Table 1 and Table 2 summarize the overall model dimension in this study. The material properties were taken from the experimental work of Karimzadeh on Aluminium 1100 [19] and Jiang Xiaoxia on Hull Steel CCS-B [20]. The loading is place at the sandwich plate's central rotation with a displacement of 30 mm (reference node) and a radius of 15 mm. It is a challenge to weld T-joint without proper setup and equipment when the sheet's thickness is 1 mm. Hence, the simulation model for faceplate thickness is fix at 3 mm. The material characteristic divide into two models, similar (SI) material on both elements and dissimilar (DSI) material on either element. As for T-joint weld characteristic, the work present by T-joint contact and weld width. The reason to conduct two simulation type number of I-core (n:3 and n:4) is because the response act on the steel sandwich plate model for material properties and weld width due to the present and absent of core under the top indenter (Table 3).

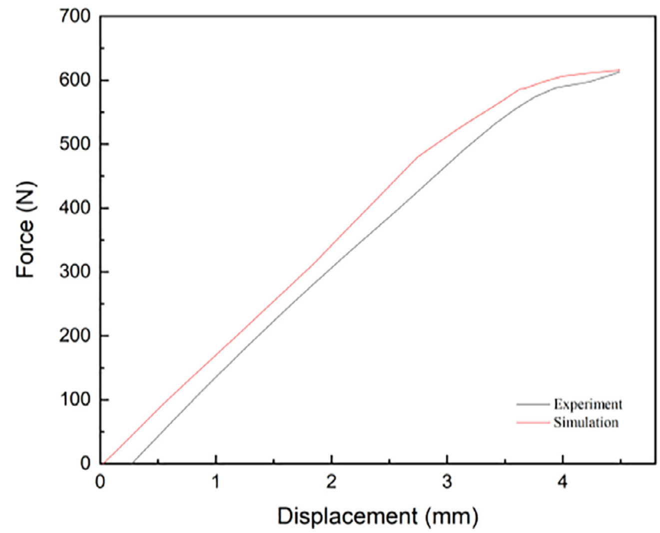


Fig. 5. Experiment and simulation comparison for laser-welded I-core galvanize steel sandwich plate.

The width length was estimated from the data comparison between Jiang et al. [21], Jani Romanoff et al. [22] and from the previous project [23]. The faceplate and I-core model with a 3D solid linear hexahedral element (HEX-C3D8R) with a well-structure meshing method apply to overall body. A fine mesh control at the T-joint area, and coarser mesh apply to the rest of the sandwich plate to reduce time work integration. In this simulation, since the contact made between the welding geometry are define and, in a way, do not penetrate each other while bending, thus, the model can be seen as a perfect model. Failure mode such as intra-cell wrinkling or local indentation are not noticeable. For an easy understanding, Fig. 6 display the summary for methodology process flow.

3. Simulation result and discussion analysis

3.1. Material properties

In the legend, 'S' implies steel while 'A' denotes as aluminium. The selection of material on or either element would give different outcomes. SI and DSI material display a similar sequence in both figures where steel produces the highest stiffness while aluminium produces the lowest stiffness. The stiffness calculation in this discussion are obtain from the elastic gradient of the graph. The sequence of I-core sandwich plate stiffness for different material properties for each model is as below:

$$\text{Face (A)} + \text{Core (A)} < \text{Face (A)} + \text{Core (S)} < \text{Face (S)} + \text{Core (A)} < \text{Face (S)} + \text{Core (S)}$$

Based on the observation, the result divide into two part based on the base material use at the element. The dominant part is Face (S) + Core (S) and Face (S) + Core (A) whereas the minor part is Face (A) + Core (S) and Face (A) + Core (A). From this observation, one can conclude that faceplate is the most important element in I-core sandwich plate when selecting a material that produce high stiffness. The stiffness produces by Face (S) + Core (S) in Fig. 7 and Fig. 8 is 1.95 kN/mm and later is 2.24 kN/mm. Hence, a model made by similar material shows that the higher number of cores, the higher the elastic stiffness generate.

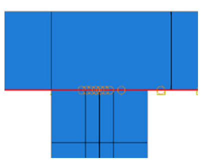
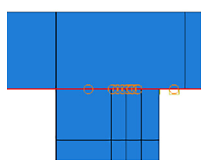
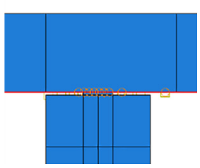
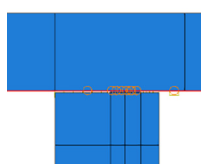
Table 1
Simulation model dimension.

Steel Sandwich plate dimension	Length, L (mm)	Height of core, h_C (mm)	Breath, B (mm)	Spacing, a (mm)	Thickness of faceplate, t_f (mm)	Thickness of core, t_c (mm)
	360	51	120	89	3	4

Table 2
Different characteristic with detail description of each model.

Characteristic		Significant	Material	Number of I-cores, n	Width length (mm)
Material properties		Similar (SI) and Dissimilar (DSI) material on both or either element	Aluminium 1100 Hull Steel CCS-B	3 4	t_{weld}: 1.15, h_{rg}: 0.10
T-joint weld	T-joint contact	Ideal Centric + root gap Eccentric + No root gap Eccentric + root gap	Hull Steel CCS-B	3 4	t_{weld}: 1.15, h_{rg}: 0.10
	Weld width	Different weld width at T-joint	Hull Steel CCS-B	3 4	t_{weld}: 3.04, 1.152, 0.76h_{rg}: 0.10

Table 3
Finer mesh at the T-joint focus area.

Type	Centric	Eccentric
Absent of rootgap		
Present of rootgap		

A V-shape deformation (failure mode: face yielding) structure can be seen in Fig. 7e as the load increases. This deformation effect on n:3 contributes to the effect graph less curvy. If one looks closely at Fig. 8, the graph curve is more prominent on an even number of cores (n:4) compare to the odd number of cores (n:3). It is because of the position of the loading. The loading for an odd number of cores is directly place under the I-core (failure mode: face buckling). It acts as an oppose mechanism to resist the force create on the sandwich plate during bending. The disadvantage of this result can influence the core which welded to the faceplate. In reality, the weld width produce is smaller than a full weld width of similar core length. Therefore, the core is note as a weakness since it can disengage itself from the faceplate due to the external force and thus, damage the core performance.

As for Face (S) + Core (A), the stiffness produces for n:3 is 1.59 kN/mm while stiffness produces for n:4 is 1.83 kN/mm (see Fig. 9). When compare Face (S) + Core (S) and Face (S) + Core (A), its display that a combination of weak material (Aluminium) on core and strong material (Steel) on either elements can reduce its elastic performance.

The response for the minor part does follow the statement made previously, yet Face (A) + Core (A) significantly increase and overcome the curve of Face (A) + Core (S) at a displacement of 14 mm. Both models generate similar bending behaviour when carefully observe the deformation occur on the I-core sandwich

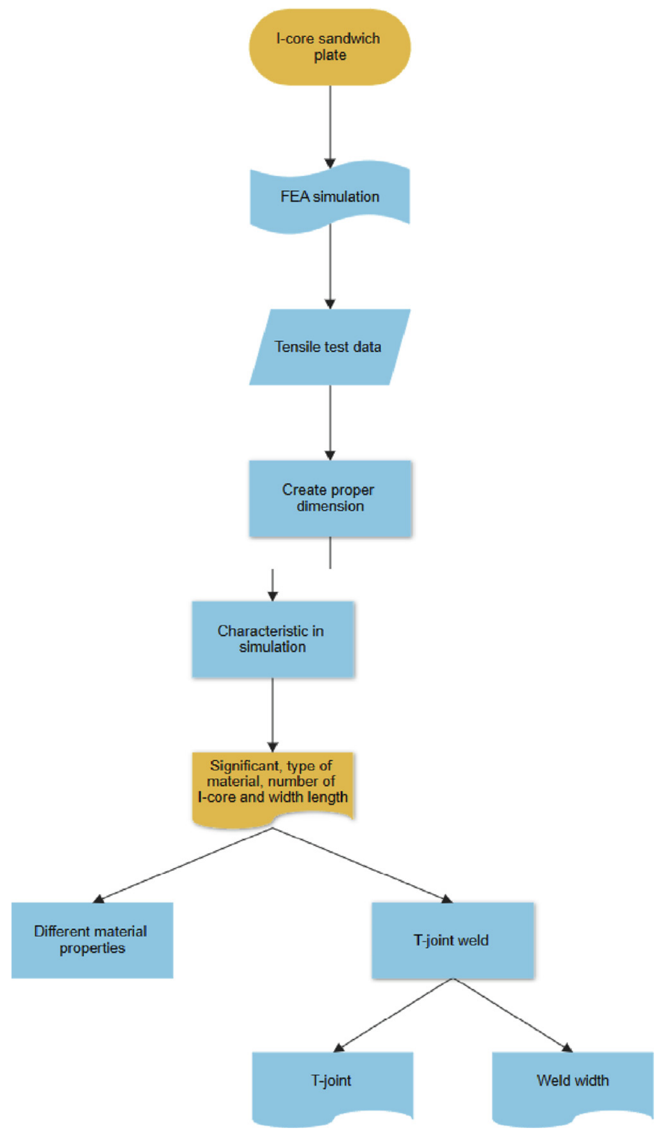


Fig. 6. Methodology process flowchart.

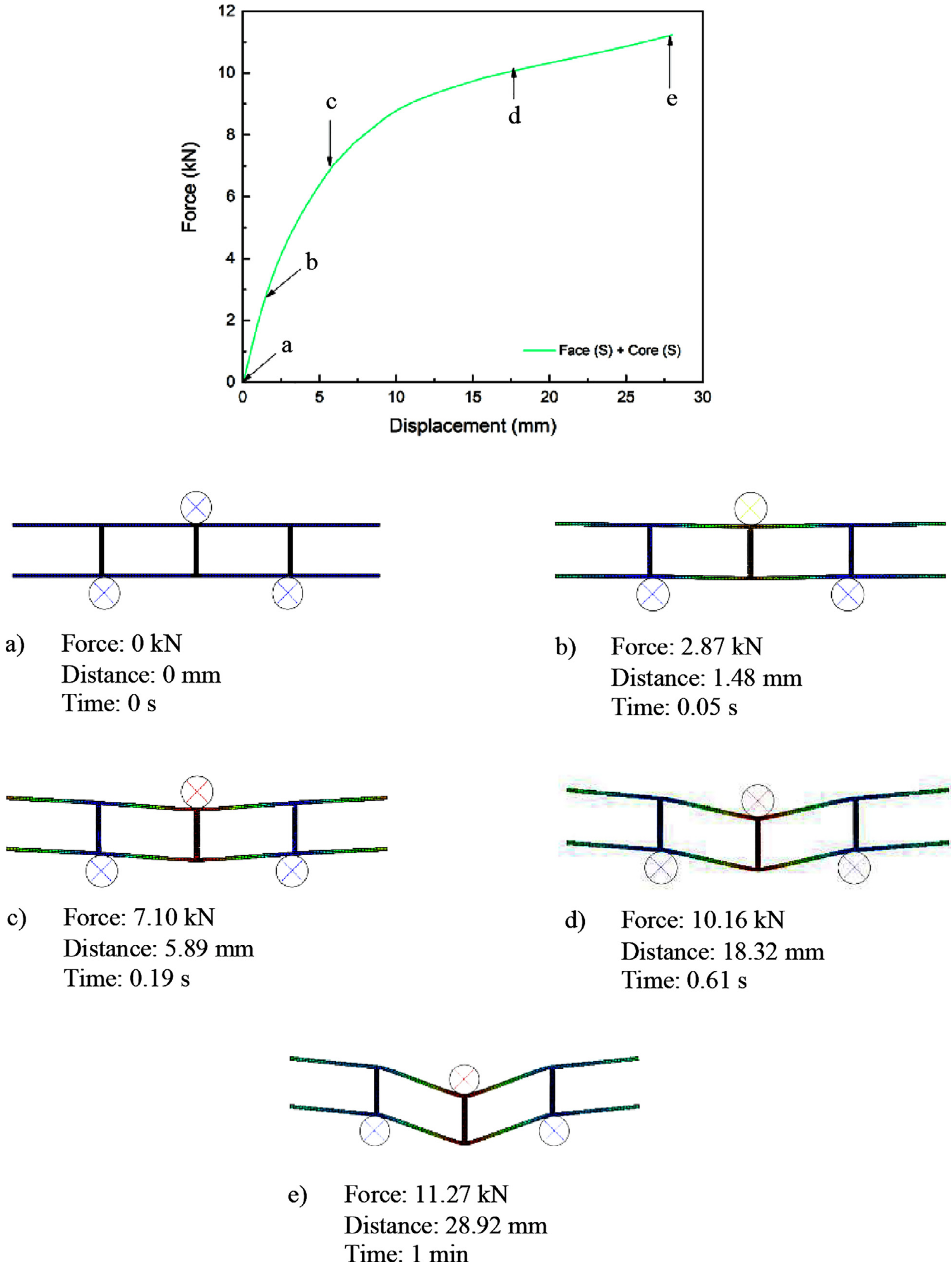


Fig. 7. Bending behaviour of I-core steel sandwich plate on n: 3.

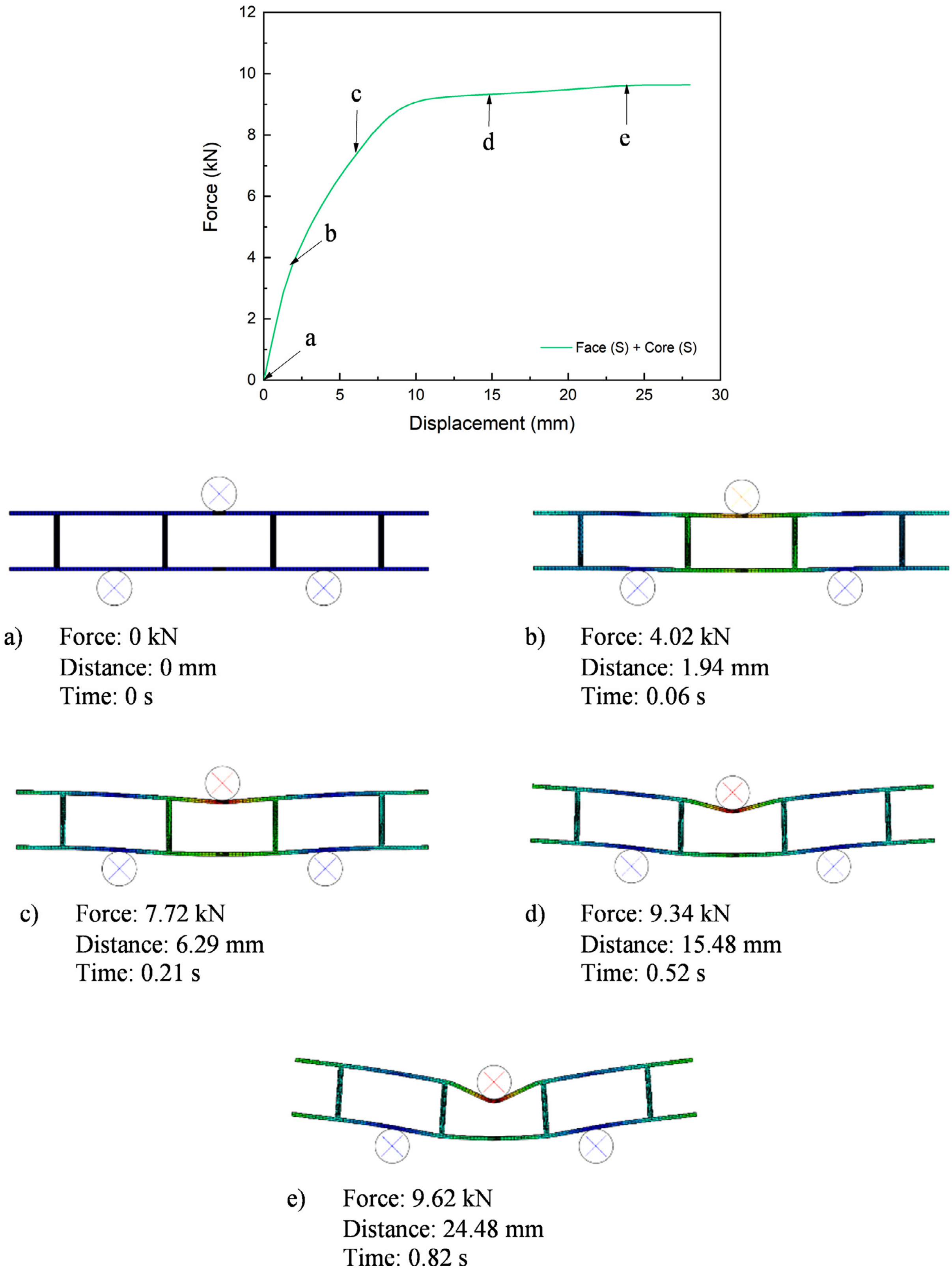


Fig. 8. Bending behaviour of I-core steel sandwich plate on n: 4.

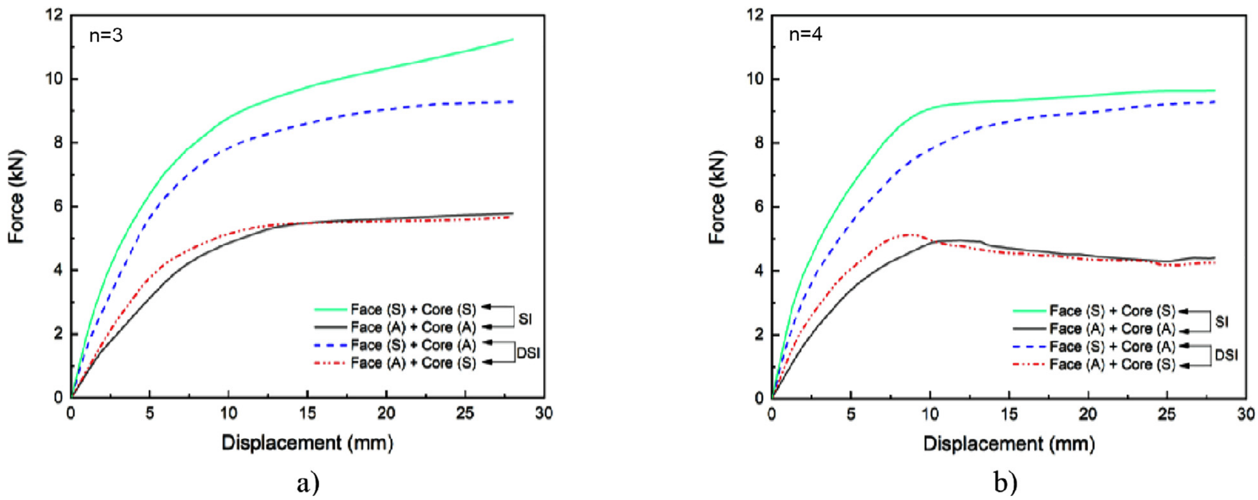


Fig. 9. Result for SI and DSI material on or either element of I-core Sandwich plate: a) n: 3, and b) n: 4.

plate simulation. Higher stress concentration mainly occurs at the area near the loading, while lower stress concentration occurs at both supporters. Hence, as the load continue to decent, the core, which is further away from the loading, has less effect as a stiffener on the sandwich plate when utilizing strong material (steel) unless the faceplate is a weak material (aluminium).

In conclusion, I-core and faceplate highlight an important element since it gave continuous support and carried the I-core sandwich plate's in-plane load. Various material properties on or either element are very crucial to consider when designing sandwich plates. Moreover, I-core stress concentration need to reduce to prevent failure mode, such as core buckling, from arising. Thus, an increase number of cores as well as smaller cell core size overcome the issues.

3.2. T-joint contact

The weld geometry is kept constant throughout the simulation. The design made at the T-joint was inspired by simulation analysis on the effect of laser weld conducted [24]. Moreover, the contact at T-joint weld geometry contributes to the performance of the sandwich plate. Based on Fig. 11 and Fig. 12, the result divide into dominant (no rootgap) and minor part (with rootgap). 'N' in the legend indicates no rootgap. Hypothetically, an ideal trait will give a dominant result in comparison to other T-joint failures. 'Ideal' trait characterises as centric and absent of rootgap between faceplate and I-core.

The issue on Jani Romanoff where contact between faceplate and I-core pass through each other (collide) have been solved by surface-to-surface contact between the I-core and faceplate (see Fig. 10). One can observe that the dominant (centric + rootgap (N) and eccentric + rootgap (N)) and minor (centric + rootgap and eccentric + rootgap) part produce a 36.78% percentage difference. It shows that the present and absent of rootgap simulate an important notion towards I-core welding at the T-joint. Moreover, the dominant part gave a significantly slight percentage difference of force of 1.68%, while the minor part produces a 1.32% difference between the centric and the eccentric joint. The percentage different formula express as follows:

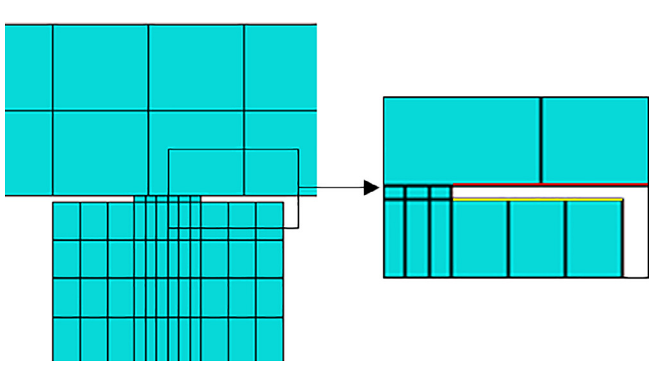


Fig. 10. Meshing made at the T-joint.

$$Pecentage\ \ difference(\%) = \frac{a}{b} \times 100\%$$

$$a = measure_1 - measure_2$$

$$b = \frac{measure_1 + measure_2}{2}$$

where $measure_1$denotes the previous data while $measure_2$ denotes the following or subsequent data. Hence, the present and absent rootgap display a small effect between centric and eccentric. Furthermore, centric properties display a higher stiffness with 6.86 kN compare to eccentric properties of 6.09 kN for T-joint with no rootgap. Thus, centric generate a better weld character than eccentric. Based on Fig. 11 and Fig. 12, C2 define as sandwich with centric + rootgap and C3 define as a sandwich with eccentric + rootgap characteristic. To support the analysis made, one can look upon the deflection angle produce at the T-joint during bending for C2, which is 13.32, yet C3 illustrate a higher angle of 19.10. Furthermore, from the deflection angle produce between n:3 and n:4, one can summarise that there is a big deflection made for C3 (deflection difference is 3.64.) while a slight deflection for C2 (deflection difference is 0.78) due to the plate bending.

In conclusion, the absence of rootgap generates a higher stiffness compare to the present of rootgap at the contact surface, thus, T-joint defect leading to a defective sandwich plate. Likewise, the effect of centric and eccentric can impact the strength of the sandwich plate even when the weld geometry is fix. Therefore, the third simulation on different weld width execute.

3.3. Weld width

Weld width characteristic is very significant in determining the shear stiffness and stability of the plate. Three models with different weld width name D1 (3.02 mm), D2 (1.152 mm) and D3 (0.76 mm) are generate. As mention in the previous section, the present and absence of the rootgap show a significant effect on

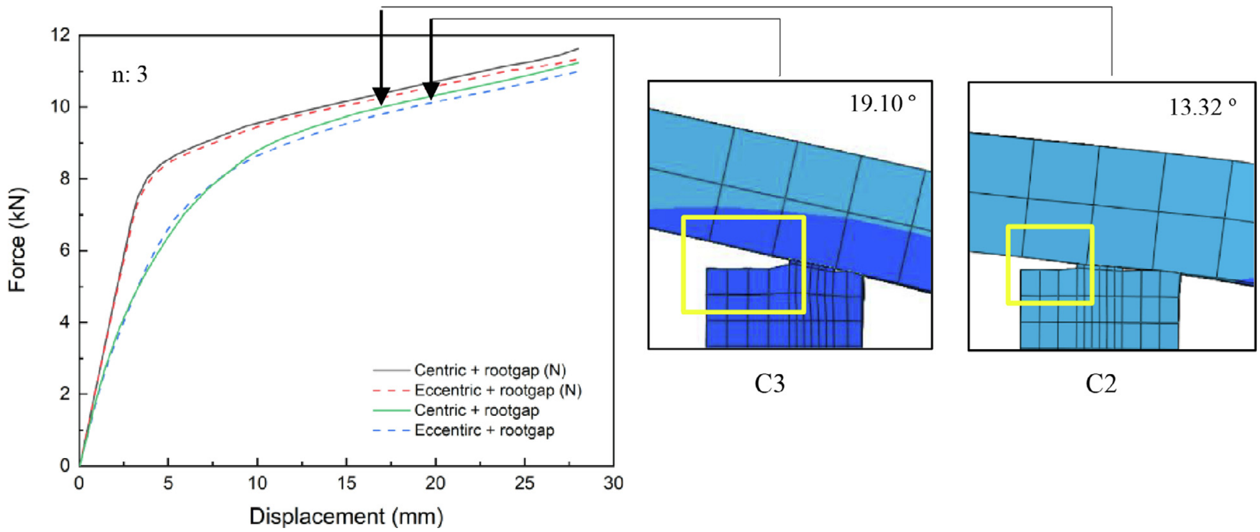


Fig. 11. Failure of weld position at n:3 T-joint: centric + rootgap (C2), and eccentric + rootgap (C3).

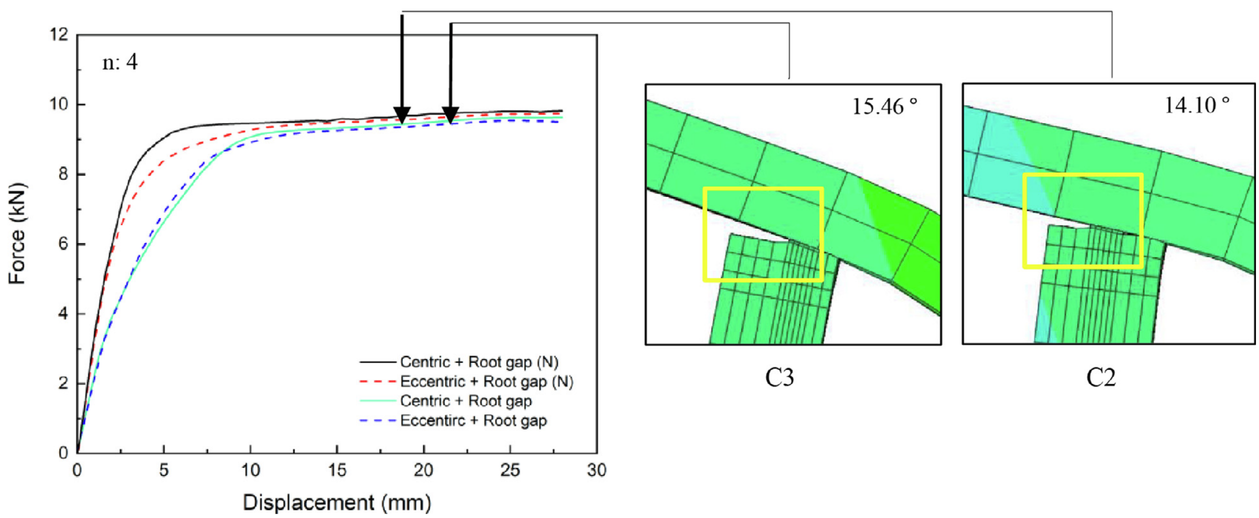


Fig. 12. Failure of weld position at n:4 T-joint: centric + rootgap (C2), and eccentric + rootgap (C3).

the centric and eccentric sandwich plate. Hence, it causes defectiveness. In order to parametrically study the sole effect of weld width, the model of Face (S) + Core (S) weld using centric joint and with rootgap is select.

Both n:3 and n:4 show similar but small differences in stiffness result where n:4 produce 3.39 kN and n:3 produce 2.45 kN for Weld D1. Hence, a higher number of cores with similar weld shall produce distinguish stiffness value. Moreover, it displays that the larger the weld width (according to the core size), the larger the sandwich plate's force can withstand. Thus, defining the sandwich with higher strength. As shown in Fig. 13b, there is a significant increase in plastic stiffness where it reaches the highest peak of 10.07 kN and then a decline after maximum load. This show that the sandwich plate is in plastic deformation until failure generate at the top faceplate only.

Local plastic hinge only produced when defining the element as one T-joint because the weld covers every contact surface between the elements. Thus, making it wholesome. As for D1, D2 and D3, due to the interaction of elements is not a whole, the joint will yield locally. It can be seen during the simulation that the vertical I-core structure change to a non-directly proportional core with respect to the faceplate (see Fig. 7 or Fig. 8 for sandwich plate structure deformation during bending). Furthermore, the response that occur at both D2 and D3 is due to bending weld deformation (failure mode: debonding). When the weld width is smaller than I-core's thickness, plastic hinge produces globally at the T-joint. Below shows the stiffness response of I-core sandwich plate stiffness for different weld width:

$$D3_3 < D3_4 < D2_3 < D1_3 < D2_4 < D1_4$$

$$1541.52 < 1836.52 < 1934.50 < 2446.44 < 2494.97 < 3385.72$$

In conclusion, the weld width contributes to the plate's stress when a certain displacement consider.

4. Conclusion

Overall, the studies present in this paper have introduce simulation analysis for laser-welded I-core sandwich plate with different material properties and T-joint weld characteristic. From the simulation work, three conclusions can be drawn:

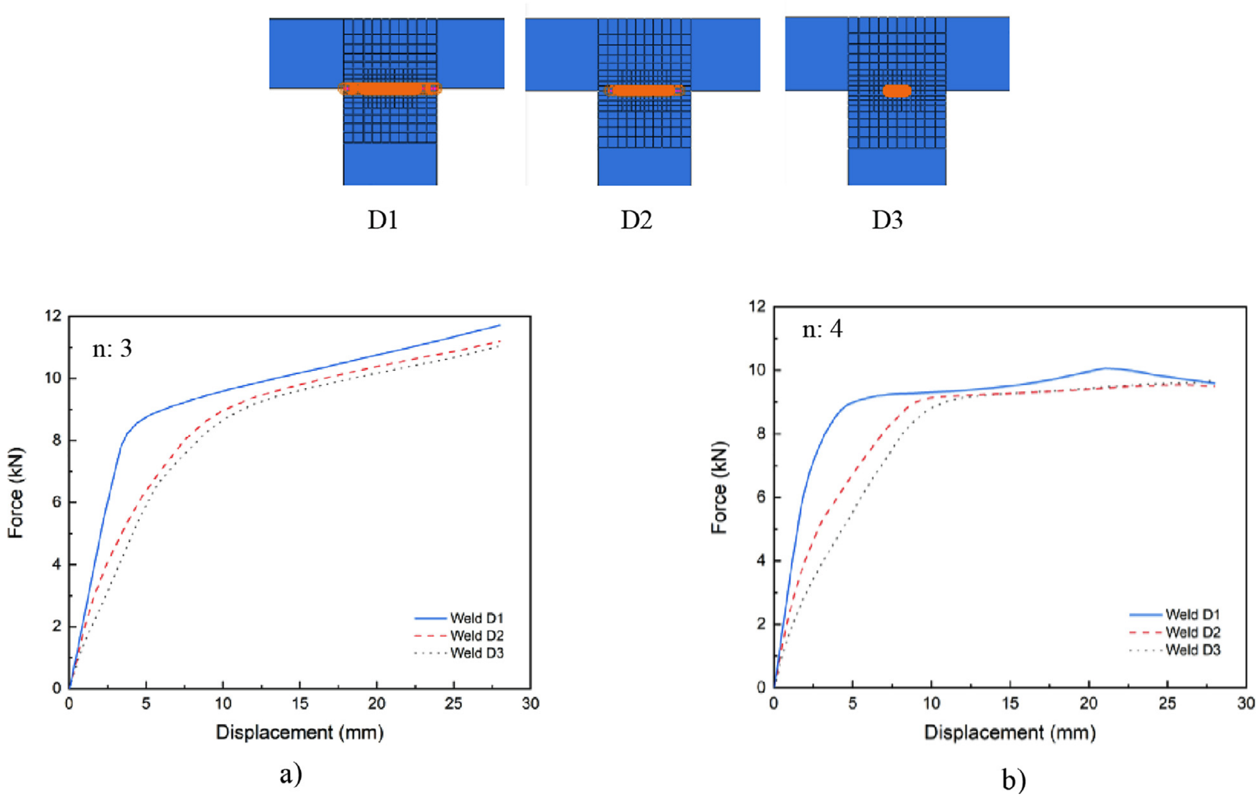


Fig. 13. Weld width comparison of different length D1, D2, and D3 for n: 3 and n: 4.

- Different material properties on either element reduce elastic stiffness compare to material properties fix on both elements. Faceplate plays an important element in the sandwich plate based on the sequence produce. One can observe that when steel utilize as core and aluminium is fix as faceplate, the stiffness of the sandwich plate will reduce. If aluminium fix at both elements, at certain point, the curve overtakes Face (A) + Core (S) curve. The graph develops very curvy graph when utilize higher number of cores; thus, greater elastic stiffness generates. I-core stress concentration need to reduce to prevent failure mode, such as core buckling, from arising. Thus, an increase number of cores as well as smaller cell core size overcome the issues
- The T-joint contact discusses the effect of rootgap and eccentricity on the weld geometry. The data divide into two parts that clearly show significant results for present of rootgap and no rootgap. The absence of rootgap generates a higher strength compare to the present of rootgap at the contact surface, thus, T-joint defect leading to a defective sandwich plate. Likewise, the effect of centric and eccentric can impact the strength of the sandwich plate even when the weld geometry is fix.
- Based on weld width result, a hypothesis can be made for this analysis. The larger the weld thickness, the higher the work done. Thus, the greater the stiffness and better stability generate. Weld width display greater elastic stiffness when both elements were interacting as a whole T-joint. Nevertheless, to achieve such a wholesome T-joint can be challenging in reality. Hence, it is best to conclude that the weld length should be as near as the length of the core.

This study has provided a better understanding of the effect of material properties, t-joint contact, and weld width on laser-welded I-core sandwich plate bending behaviour. However, some challenges remain a concern to achieve a complete understanding. Therefore, it will be very interesting to conduct different I-core topologies placement (parallel or directly proportional) with the sandwich plate's subject to force. Furthermore, sandwich plate simulation with both faceplate and I-core produce as a whole model or these elements produce separately can contribute to another finding on bending properties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further reading

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