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Compression after low velocity impact tests of marine sandwich composites: Effect of intermediate wooden layers

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ABSTRACT

In the present work, compression after impact (CAI) behavior of sandwich composite materials with intermediate wooden layers was investigated. Sandwich panels were manufactured by using vacuum assisted resin transfer molding (VARTM) method with pinewood and ashwood intermediate layers. 15 and 25 mm thick PVC foams with a same density of 80 kg/m^3 were chosen in conjunction with the face sheets composed of non-crimp biaxial E-glass fabrics and bisphenol-A epoxy vinyl ester resin material system. Impact tests were performed under 30 J (low) and 60 J (high) energy levels with conical and hemispherical impactors. CAI tests were conducted in accordance with the ASTMC364/C364M-07 standard. Using pinewood and ashwood intermediate layers increased the residual CAI strength and decreased the depth of the impact damage. The intermediate wooden layers have also a potential to reduce the thickness of the composite face sheets and foam core which may increase the proportion of the recyclable wooden materials within the sandwich structure.

1. Introduction

Lightweight composites, entirely or partially made of wood–based materials, are widely used for meeting the requirements of marine applications in particular for their sustainability, recyclability and esthetical appearance in addition to high stiffness and low weight characteristics [1]. They are mainly used as components of the structural bulkheads and decks, partitions or elements for ceilings and floor structures for boat interior applications [2]. Wood-based lightweight composites belong to the family of sandwich panels, comprise of two thin and stiff skins bonded to a thick, inner soft core. Currently, the most common type of core used in wood-based panels is the cross-linked PVC foam. Wooden sandwich panels with PVC core and marine plywood skins are commercially available [3,4].

This research focused on a multilayered marine sandwich structure made of thermo-wood materials, namely, heat-treated pinewood and ashwood which have been used as the intermediate layers between E-glass/vinyl ester face sheets and the PVC foam core. Heat-treated wood (ThermoWood®) has been used in indoor and outdoor marine applications such as furniture, decking, cladding and flooring of the boats [5]. The main benefits of this process are distinct enhancements in hygroscopicity, dimensional stability and biological durability [6].

Foreign object impact (such as tool drop during maintenance, moorings or floating objects, ice floes and debris) is one of the most common threats for conventional sandwich panels used in marine and ship structures [7]. Such contacts commonly occur at low velocities, in the range of 1 to 10 m/s and can reduce the strength of whole structure under quasi-static and dynamic loadings [8,9]. It is well known that the resistance of foam core sandwich composite structures against localized impact damage is inherently low because of thin face sheets with low bending rigidity and low strength of the foam core materials. Generally, when a sandwich structure is subjected to an impact load, a part of the impact energy is used for elastic deformation of the structure while the excessive energy is dissipated through numerous failure mechanisms within the face sheet and core materials.

Damage patterns in sandwich structures due to the low velocity impact (LVI) have been identified by Abrate [8], including delamination within the skin laminates, matrix cracking and fiber breakage, debonding between the skin and the core, shear failure and crushing of the foam. These resulting damages may significantly reduce the tensile, compressive, bending and shear strength of conventional sandwich composites as much as 50–70% [9]. Especially the compressive strength is highly sensitive to the impact damage due to delamination and fiber breaks in the impacted face

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sheet, and core crushing damage all of which reduce the stability of the structure [10–12]. Therefore, the compression after impact test (CAI) is commonly conducted in the impact characterization process of sandwich composite panels [13]. CAI tests can be applied by column compression [14,15], in-plane compression [13,16], or through four-point bending [17] loading cases.

Recently, a concept of a hybrid sandwich structure with wood intermediate layers between the face sheets and the core material was introduced by Mamalis et al. [18]. This new concept is expected to provide a better resistance to local core crushing in comparison with the single layer sandwich structures due to the increased stiffness in the impact direction. Moreover, the intermediate layers could absorb most of the deflection during the impact by separating the foam core from the impacted face sheet. It was suggested to use thicker plywood intermediate layers with lower modulus of elasticity in order to reduce the extent of LVI induced damage in sandwich panels. Suvorov and Dvorak [19,20] proposed a modified design based on inserting a ductile interlayer under the external facings in order to protect the foam core from LVI damage. Using a stiff and incompressible interlayer reduced overall and local deflections of the face sheet, local compression of the foam core, and the residual stresses. However, a compliant and compressible elastomeric foam interlayer provides a much better protection against core crashing under compressive loading despite increased overall and local deflections. Jiang and Shu [21] studied on the effects of the internal sheet inserted into the core in different locations under LVI loading. Local displacement of the core along the direction of the impact load was reduced significantly by introducing the internal sheet into a traditional single sandwich structure. Using the internal sheet decreased the local effect of the impact energy and the impact energy was spread in a wider area within the structure. In another investigation, the mechanical behavior of sandwich panels made of wood veneers of Aleppo pine as face sheets and cork agglomerate as core was evaluated. The strength of the multilayer panels was increased with increasing the number of wood veneer layers. These wood layers protected the cork agglomerate core from crushing and increased its strength under longitudinal compression loading [22]. Iejavs and Spulle [23] studied on the compression properties of three-layer cellular wood panels for structural applications. Results indicated that cellular wood core materials can be strengthened with solid timber face sheets and rib elements when the panels were loaded in a parallel direction to the skins (the load bearing direction of the solid timber is parallel to the grain direction), but no significant enhancement was observed in the transverse direction. Fang et al. [24], introduced innovative multilayered sandwich composites made of glass fiber reinforced polymer (GFRP) skins and Paulownia wood core with bamboo intermediate layers. Experiments were conducted to investigate the effects of the thickness of GFRP and bamboo layers on the overall structural performance under flexural loading. Increasing the thickness of the GFRP skin and bamboo intermediate layer significantly improved the flexural stiffness and ultimate failure load of the sandwich beams. Zhang et al. [25] studied the flexural behavior of hybrid composite beams consisting of GFRP box section, a polyurethane foam core, a bamboo layer, and GFRP lattice ribs. Flexural tests revealed that the bamboo layer and lattice ribs increased the bending stiffness and strength.

In this context, the present work focused on the development of a new multilayered sandwich structure intended for marine applications. By using intermediate wooden layers, the aim was to prevent the excessive local damage of the core under the impact point, and to improve the residual CAI strength of the sandwich panels. In addition to the increased mechanical properties, the intermediate wooden layers allow the use of thinner composite face sheets and foam core which minimizes the foam core material consumption and increase the proportion of the recyclable wooden materials within the sandwich structure.

2. Materials and manufacturing

Sandwich panels were manufactured by vacuum assisted resin transfer molding (VARTM) method. Previous studies have shown that the VARTM method is suitable for multilayered sandwich panel production [25,26]. The core material used for the sandwich panel was closed cell polyvinyl chloride (PVC) foam (Airex C70.75 supplied from Airex AG Inc.) with a density of 80 kg/m^3. The top and bottom face sheets were made of 2 layers of E-glass [0/90] biaxial stitch bonded non-crimp fabric with an areal density of 850 g/m^2. Bisphenol-A epoxy vinyl ester resin was used as the matrix material. Heat treated pinewood with a density of 430 kg/m^3 and ashwood with a density of 650 kg/m^3 were used as the intermediate layers for the multilayer sandwich structures. These intermediate layers were much stiffer in comparison to the foam core material, and also lightweight enough and relatively thicker than the face sheets. This is also consistent with the concept developed by Mamalis et al. [18]. In addition, the grain directions of wooden intermediate layers were parallel to the longitudinal axis of sandwich panels during the VARTM process (Fig. 1) which provides higher compressive strength [27].

Classical sandwich structures (CSS) and multilayer sandwich structures (MSS) are schematically shown in Fig. 1. Overall thicknesses of sandwich panels were measured after the VARTM process. CSS samples consisted of 1.5 mm thick face sheets and 25 mm thick PVC foam (Fig. 1a), while the MSS samples comprised

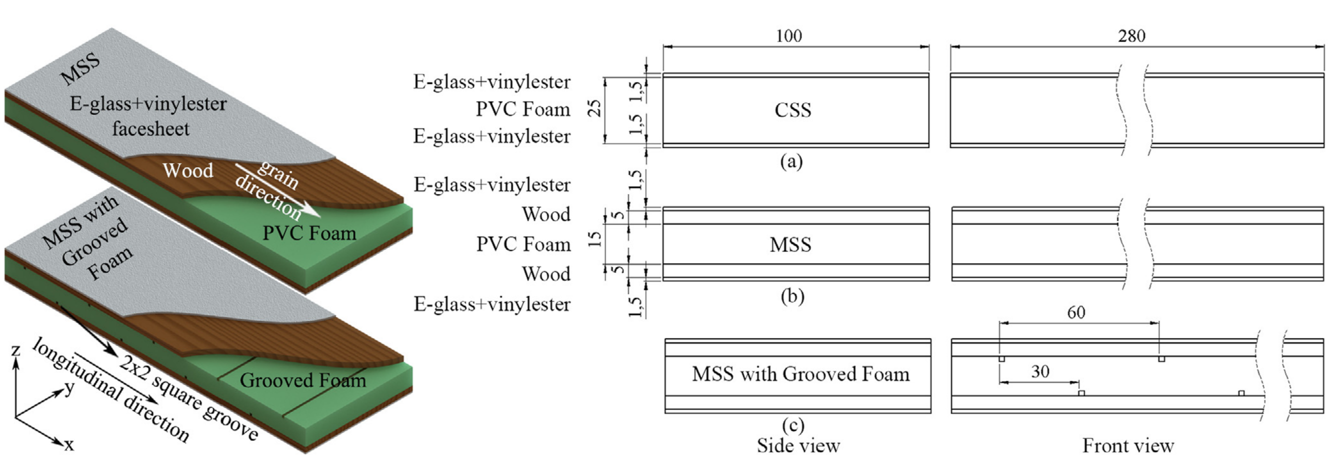

Fig. 1. Schematic drawing of CSS and MSS samples (a) CSS (b) MSS (c) MSS with grooved core.

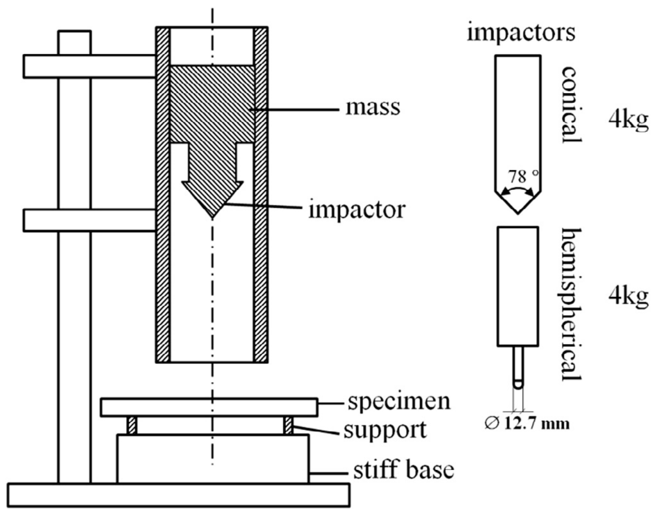

Fig. 2. A schematic of the impact tower with impactor geometries.

of 1.5 mm thick face sheets, a 5 mm thick intermediate layer and 15 mm thick PVC foam (Fig. 1b, c). The nominal thickness of the sandwich panels was 28 mm for both CSS and MSS samples. In order to improve the resin flow during the VARTM process and investigate its effect on the mechanical performance of selected impacted panels, 2 mm × 2 mm grooves were milled on the top and bottom surfaces of the PVC foam core as illustrated in Fig. 1 (c). For the impact tests, the overall dimensions of the CSS and MSS specimens were 280 mm (length) × 100 mm (width) × 28 mm (thickness).

3. Experimental study

Weight drop tests of sandwich panels were conducted with the release of 4 kg impactor from a height of 0.75 and 1.5 m to create impact energies of 30 J and 60 J, respectively. Weight drop tests were performed by a testing apparatus as defined by Nordtest test method (NT MECH 042) [28]. Two different impactor shapes were used, one hemispherical (HS) with a 12.7 mm diameter and one conical (CN) shaped with a peak angle of 78° and a tip radius of 3 mm. A schematic of the impact tower with impactor geometries is illustrated in Fig. 2. To keep the variables minimum, the same energy levels were used for both impactors. Thus, for high energy level (60 J), the 12.7 mm hemispherical impactor resulted in deeper penetration at the front face of all specimens than the conical impactor (Table 1).

In order to observe the damage state in the cross-section of the face sheets and the foam core, a destructive sectioning method was used. CAI tests were performed in accordance with the ASTM standard C364/C364M [29]. Displacement controlled uniaxial (in the 0° direction) column compression loading was applied to the specimens using a Zwick Roell 250 kN testing machine with 2 mm/min loading rate, as shown in Fig. 3a. A detailed view of edgewise compression test with the test fixture and specimen dimensions is schematically given in Fig. 3b. It must be noted that the edges of the panels were milled to ensure uniform load transfer and avoid local yielding of the facings at the contact surfaces with the loading head [14,17]. Hereafter, the MSS specimens with ashwood intermediate layers will be referred to as "AWP" and "AWG" with plain and grooved foam cores, respectively. "PWP" will be used to refer to the specimens with a plain foam core and pinewood intermediate layers.

Table 1
Damage sizes of sandwich panels in cross-sectional views.

Impactor type	Damage size	Samples impacted at 30 J		Samples impacted at 60 J		
		AWP	PWP	CSS	AWP	PWP
Conical	Damage width (mm)	18	18	22	24	28
	Penetration depth (mm)	9	9	12.5	9	12
Hemispherical	Damage width (mm)	15	15	18	22	22
	Penetration depth (mm)	5	7.5	24	13	14

Note: "Damage width" and "Penetration depth" are illustrated in Fig. 4b.

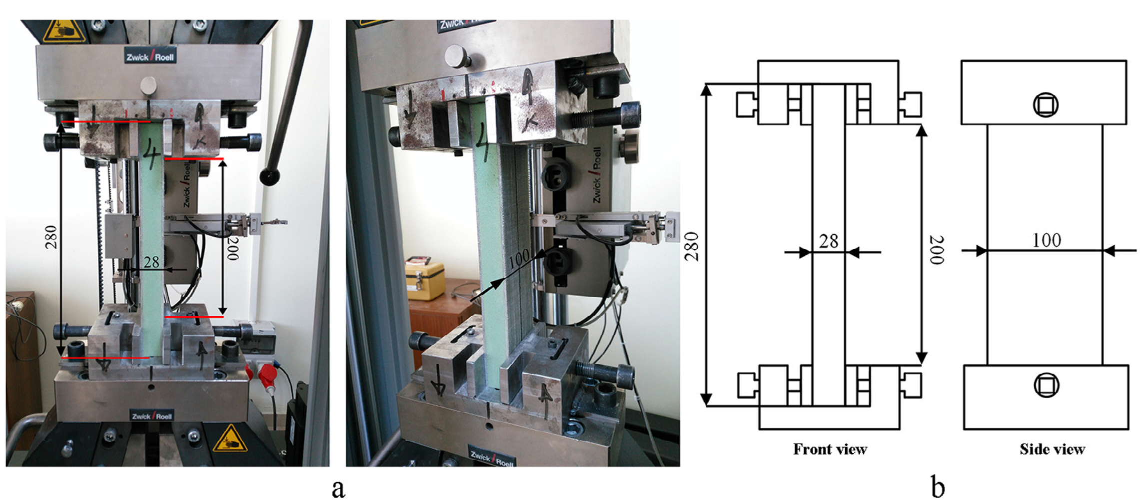

Fig. 3. a. Photograph of sandwich composite prior to loading in edgewise compression. b. Schematic view of edgewise compression test with fixture and specimen dimensions.

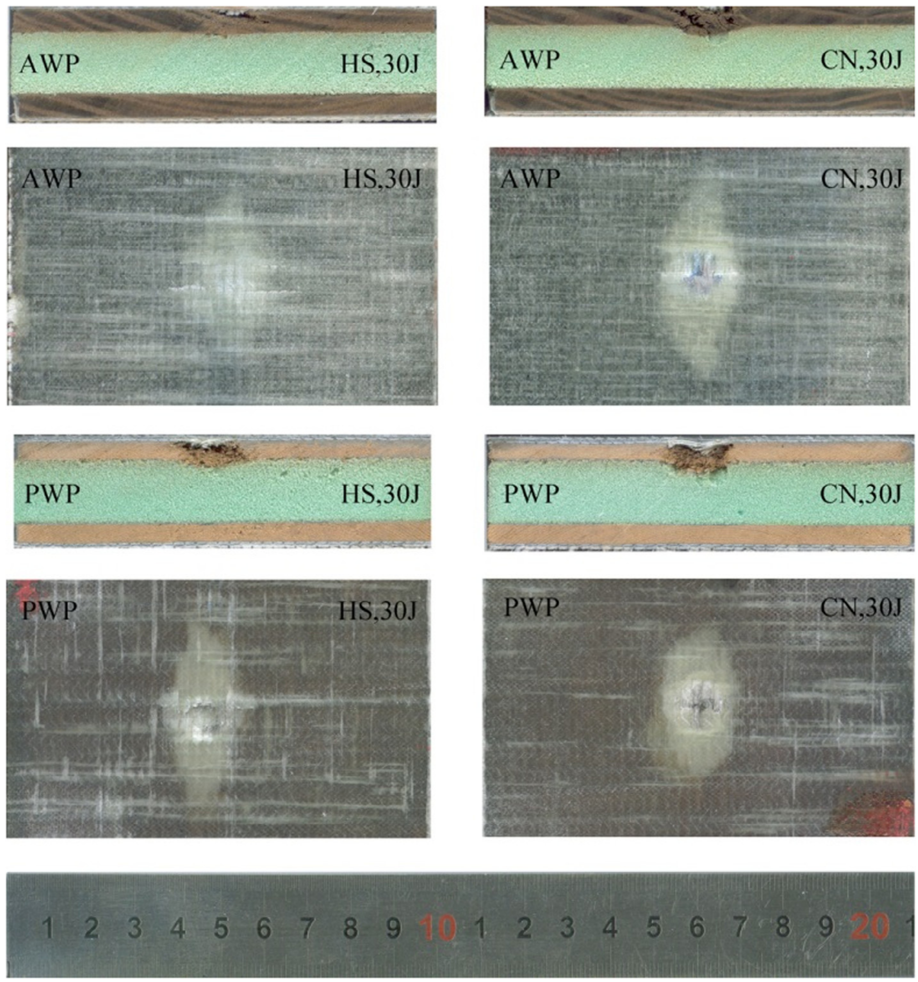

Fig. 4a. Cross-sectional damage views of PWP and AWP sandwich panels after 30 J impact with HS and CN impactors.

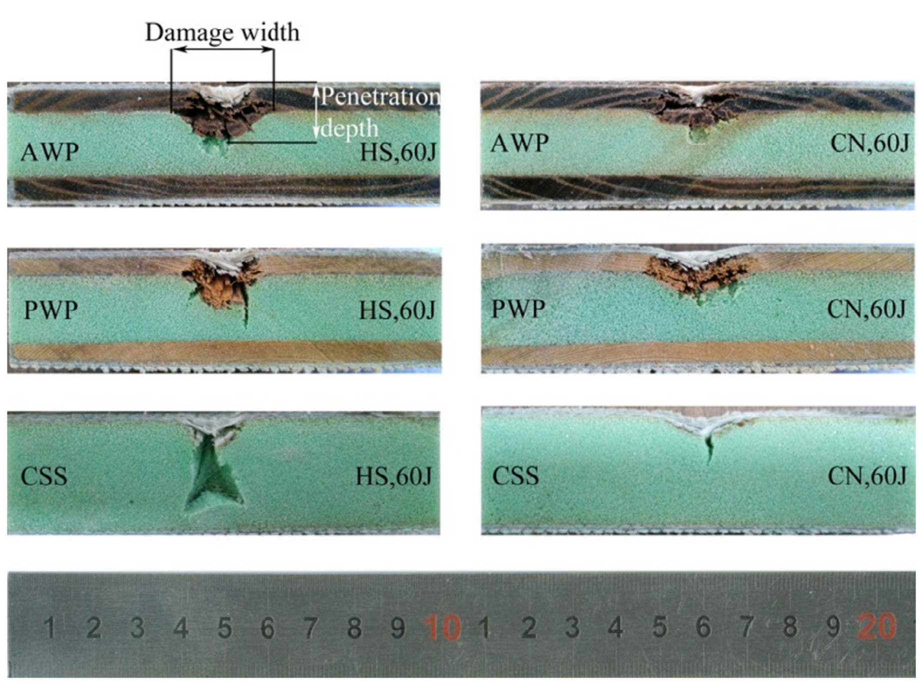

Fig. 4b. Cross-sectional damage views of sandwich panels after 60 J impact with HS and CN impactors.

Table 2
Compression test results of virgin and impacted panels.

Samples		CSS 25 mm PVC		AWP 15 mm PVC		PWP 15 mm PVC		AWG 15 mm Grooved-PVC	
		F_{max} (N)	σ_{fmax} (MPa)	F_{max} (N)	σ_{fmax} (MPa)	F_{max} (N)	σ_{fmax} (MPa)	F_{max} (N)	σ_{fmax} (MPa)
Virgin samples		29,693	99	93,023	77.5	89,399	74.5	94,510	78.8
HS impactor	30 J	Not tested		78,520	65.4	68,639	57.2	92,920	77.4
	60 J	26,937	89.8	72,244	60.2	62,842	52.4	83,081	69.2
CN impactor	30 J	Not tested		Unaff.	Unaff.	72,750	60.6	Unaff.	Unaff.
	60 J	25,079	83.6	Unaff.	Unaff.	59,639	49.7	Unaff.	Unaff.

Note: F_{max} (N): failure load, σ_{fmax} (MPa): compressive strength after impact (ASTM C364-94). Unaff.: (Unaffected) No change in the compressive strength after impact test.

4. Results and discussion

4.1. Destructive sectioning method

A profile of the damaged area in the cross-section of the sandwich panels was measured by means of a vernier caliper, in two perpendicular directions across the impacted region. Table 1 summarizes the damage size of the sandwich panels in cross-sectional views. Localized delamination was observed as "whitening" spots on the top surface of face sheet of all specimens after 30 J impact as illustrated in Fig. 4a. For PWP and AWP samples impacted at 30 J energy level, the conical impactor caused fiber breakage, and the hemispherical impactor caused delamination and matrix cracking in the upper face sheets (Fig. 4a).

Fig. 4b illustrates the cross-sectional damage views of CSS and MSS samples impacted at 60 J energy levels. The face sheet penetration and crushed foam with the cavity right under the impact location can be detected by visual inspection. The penetration depth of MSS samples with pinewood and ashwood intermediate layers were found to be the same for hemispherical impactor as seen in Table 1. Moreover, the hemispherical impactor created the penetration in the CSS samples nearly twice as deeper as the MSS samples while conical impactor produced the almost same damage depth in all samples. As expected, MSS panels exhibit more resistance to the localized impact damage when compared to the CSS samples for both impactors.

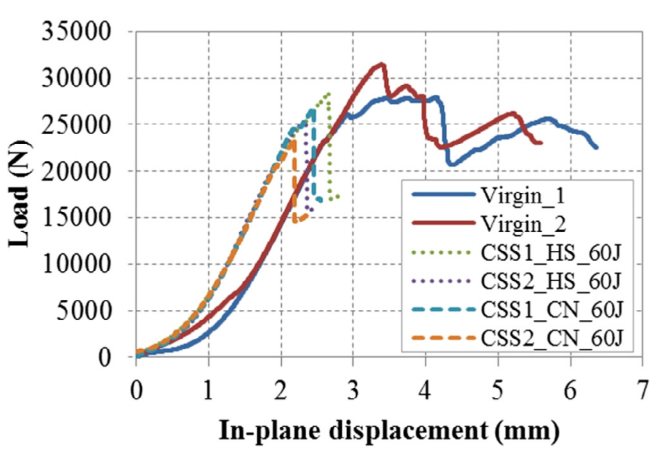

Fig. 5. Load-in plane displacement curves of virgin and CSS samples after 60 J impact with HS and CN impactors.

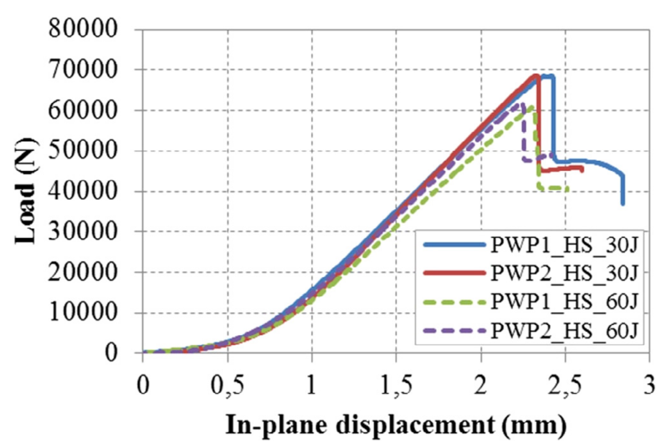

Fig. 7. Load-in plane displacement curves of PWP samples damaged with a hemispherical (HS) impactor.

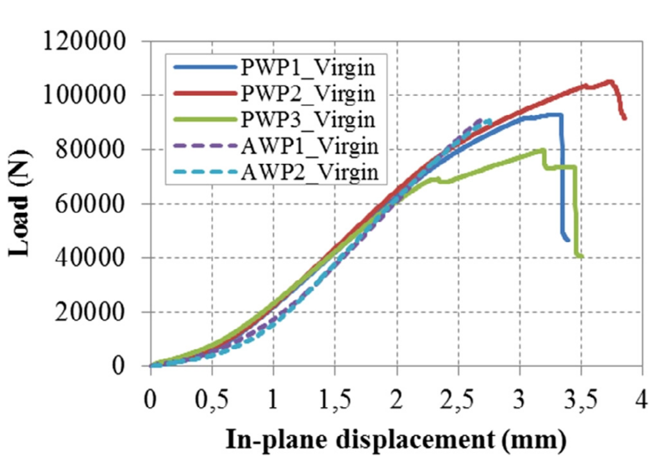

Fig. 6. Load-in plane displacement curves of virgin PWP and AWP samples.

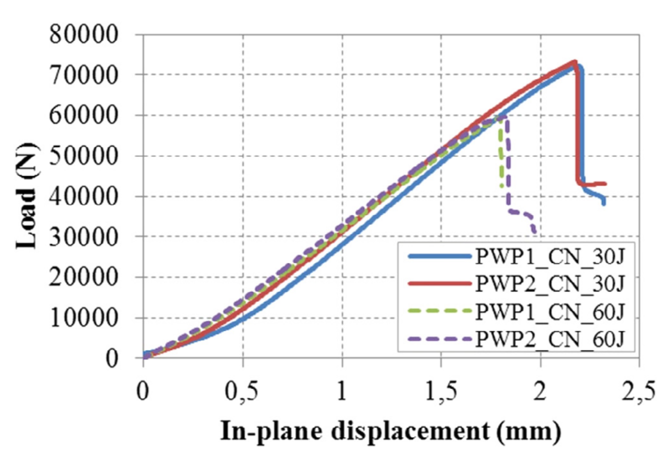

Fig. 8. Load-in plane displacement curves of PWP samples damaged with a conical (CN) impactor.

4.2. Compression after impact (CAI) test results

Post-impact failure mechanisms and residual compressive strength of the sandwich panels were experimentally investigated. Column compression tests were performed through end-loading of both impacted and virgin CSS and MSS samples. The edgewise compression test results of the virgin samples were used for base compressive strength of the sandwich panels. The compression test results of virgin and damaged panels are summarized in Table 2. During the CAI tests, in-plane compression load was largely carried by the face sheets. The compressive stress in the faces of the sandwich samples, σ_f, could thus be calculated with the following equation [29]:

$$\sigma_f = P/2t_f b \quad (1)$$

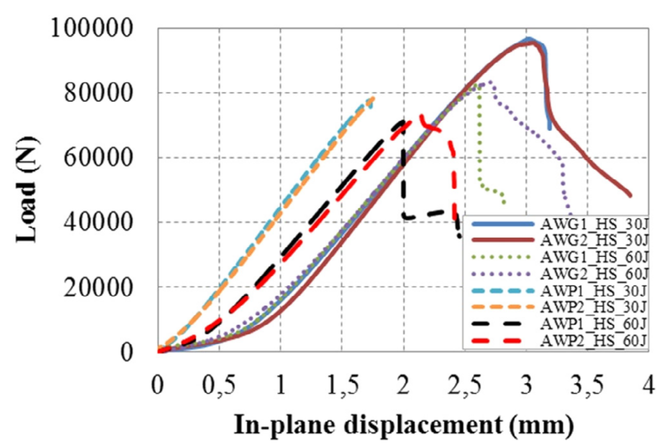

Fig. 9. Load-in plane displacement curves of damaged AWP and AWG samples.

where *tf* is the face sheet thickness and *b* is the width of the sandwich laminate.

The undamaged CSS samples failed due to column buckling and no core damage was observed. However, impacted CSS and MSS samples developed cracks in the damaged face sheet, which extended to both edges of the panels (Fig. 10a, d, f, i). The compressive load-in plane displacement curves of the CSS samples are shown in Fig. 5. Two tests were conducted for each case. The CAI strength of the CSS panel was reduced by as much as 9.3% and 15.5% with hemispherical (HS) and conical (CN) impactors at 60 J impact, respectively, in comparison to the virgin CSS sample. The reduction caused by the conical impactor can be due to the extensive delamination in the impacted face sheet. This result support the previous research [30] that as the impactor becomes blunter, the damage area increases due to the increased delamination damage. For the virgin MSS samples, compressive failure load of virgin PWP and AWP samples were found to be 3.01 and 3.13 times more than that of the virgin CSS samples, respectively. AWP samples failed at slightly higher load levels in comparison to the PWP samples as shown in Fig. 6.

Figures 7 and 8 illustrate the load-in plane displacement curves of the impacted PWP samples by hemispherical (HS) and conical (CN) impactors, respectively. As expected, the CAI strength was reduced as the impact energy increased. Moreover, the PWP samples damaged by the conical impactor at 60 J energy level showed the least CAI strength value reduced by 33.3% in comparison with the undamaged one. During the CAI tests, the PWP samples failed mainly by inward buckling. As seen in Fig. 10b–f, the intermediate pinewood layer beneath the impacted face sheet was broken under compression, and core damage was not detected.

The undamaged AWP and AWG samples failed at almost the same compression load and exhibited the highest CAI strength in all samples (Table 2). Both samples were failed by inward buckling.

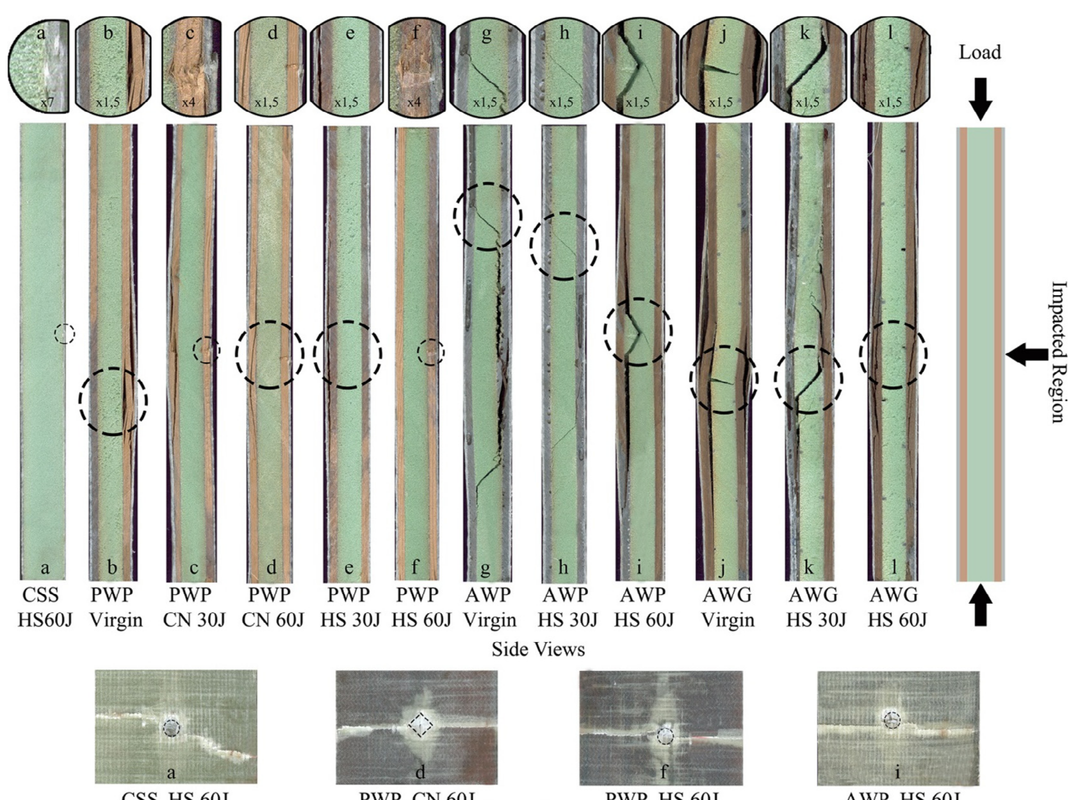

Fig. 10. Photographs of damaged CSS, PWP, AWP and AWG sandwich panels after CAI tests.

This result showed that using grooved PVC foam did not alter the compressive strength significantly for undamaged AWG samples compared to the virgin AWP ones. Figure 9 illustrates the load-in plane displacement curves of the impacted AWP and AWG samples by hemispherical (HS) impactors. Using the grooved core structure delayed shear crack propagation and buckling. CAI strength of AWP samples following the 30 J and 60 J impacts with hemispherical impactor was reduced by 15.6% and 22.3%, respectively, in comparison with the virgin samples. Furthermore, 30 J and 60 J impact loads conducted with conical impactor did not affect the CAI performance of the AWP and AWG samples. These samples were referred to as "unaffected" as seen in Table 2. Similarly, impact-induced damage by hemispherical impactor at 30 J energy level had a little effect on the CAI strength of the AWG panels. The impacted ashwood layers showed better compression strength than the pinewood counter parts (Table 2). In terms of failure mode, shear buckling and collapsing of the intermediate layers due to compressive loading were observed for the ashwood reinforced specimens as illustrated in Fig. 10g–l.

Considering the overall CAI data, the AWG samples showed better CAI performance than the PWP and AWP ones. No separation was observed between the foam core and wooden layers of virgin and damaged AWP, PWP and AWG panels during the CAI tests as seen in Fig. 10.

5. Conclusions

Multilayered sandwich panels were developed by introducing pinewood and ashwood intermediate layers within the thin fibrous laminates and foam core in order to minimize the impact damage size and improve post-impact behavior of the conventional sandwich structures. Using the wooden intermediate layers with the grain direction parallel to the compressive load direction improved the compressive strength of multilayered sandwich panels in comparison to the CSS samples. Overall, AWP, PWP, and AWG samples showed a good performance under in-plane compressive loading, and may have a potential to be used in sandwich deck and partial bulkhead panel's interior applications in boat construction industry. While this research confirmed the feasibility of the proposed multilayered composite structure, the effect of thickness of heat-treated wooden layer on the mechanical performance of the sandwich panels should be investigated in more detail.

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