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Investigation on the mechanical properties of resin pin-reinforced marine sandwich composite structures under quasi-static indentation load

Yarı-statik batma yükü altında reçine pimi ile güçlendirilmiş denizel sandviç kompozit yapıların mekanik özelliklerinin incelenmesi

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Abstract

This study aims to experimentally examine the indentation behaviour of marine sandwich composites with pin-reinforced polyvinyl chloride foam core and E-glass face sheets. The effects of indenter diameter, resin pin diameter, and arrangement on force-displacement, maximum contact force, and absorbed energy values of sandwich panels were evaluated by the indentation tests. Throughout the experiments, the contact forces increased as the pin diameter increased from Ø2 mm to Ø4 mm. The contact forces decreased as the distance between pin diameters increased from 12 mm to 16 mm and 18 mm. Additionally, the values of absorbed energy increased as the diameters of the resin pin and indenter increased. Placing pins at a distance of 12 mm allows the material to absorb more energy for Ø12.7 mm and Ø20 mm indenter tips. The 8 mm diameter and 12 mm spacing holes provide significant initial resistance to penetration, despite the increase in weight in critical areas, against object contact from Ø12.7 to Ø20 mm. A visual inspection took place on the post-indentation cross-sections of the sandwich specimens to detect any damage modes. Damage modes varied depending on the size of the indenter and the hole pattern in the foam core.

Keywords: Sandwich composite, Pin reinforcement, PVC foam, Indentation

Öz

Bu çalışma, pimle güçlendirilmiş polivinil klorür köpük çekirdekli ve E-cam tabakalı denizel sandviç kompozitlerinin batma davranışını deneysel olarak incelemeyi amaçlamaktadır. Batma ucu çapı, reçine pim çapı ve diziliminin sandviç panellerin kuvvet-yer değiştirme, maksimum temas kuvveti ve emilen enerji değerleri üzerindeki etkileri batma testleri ile değerlendirilmiştir. Deneyler boyunca pim çapı Ø2 mm'den Ø4 mm'ye çıkması ile temas kuvvetleri de artmıştır Pim çapları arasındaki mesafe 12 mm'den 16 mm'ye ve 18 mm'ye artışı ile temas kuvvetleri azalmıştır. Ek olarak, reçine pimi ve batma ucu çapı arttıkça emilen enerji değerleri de artmıştır. Pimlerin 12 mm mesafeye yerleştirilmesi, malzemenin Ø12,7 mm ve Ø20 mm batma uçları için daha fazla enerji emmesine olanak tanır. 8 mm çapında ve 12 mm aralıklı delikler, kritik alanlardaki ağırlık artışına rağmen Ø12,7'den Ø20 mm'ye kadar nesne temasına karşı nüfuz etmeye karşı önemli bir başlangıç direnci sağlar. Herhangi bir hasar modunu tespit etmek için sandviç numunelerinin batma testleri sonrası kesitleri üzerinde görsel bir inceleme gerçekleştirildi. Hasar modları girintinin boyutuna ve köpük çekirdeğindeki delik düzenine bağlı olarak değişmiştir.

Anahtar kelimeler: Sandviç kompozit, Pim takviyesi, PVC köpük, Batma

1 Introduction

Polymer sandwich composites are extensively used in the maritime industry because of their excellent advantages, including high specific bending strength and stiffness, excellent corrosion resistance to the seawater environment, design and production flexibility, and low repair and replacement costs [1, 2]. They are often employed in the construction of pleasure and fishing boats and military patrol boats and are becoming more popular in the offshore oil and gas industry [3, 4]. In small boats with sandwich construction, foam materials, particularly polyvinyl chloride foam (PVC), are used for their lightweight combination with glass and carbon fibre-reinforced polymer face sheets [5].

However, composites used in marine crafts have low damage tolerances for out-of-plane contact and impact loads [6]. It is well-known that composite boats experience various risks that can lead to collisions, including crashing with other boats and docks, running aground, being struck by floating debris, and tools failing during production [7]. All these crashes involve out-of-plane impact loads and may result in severe damage, such as boats taking on water and sinking at sea.

In experimental works, costly impact equipment for recording dynamic responses data filtering owing to signal fluctuations, and the difficulty of evaluating results have all contributed to the preference for quasi-static indentation testing. Its use is increasing, particularly for low-velocity impact tests with minimal strain rate and wave propagation

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effects [8]. Furthermore, the use of quasi-static tests as a simpler and more cost-effective method has resulted in a decrease in testing costs.

The behaviour of foam core sandwich composites against indentation loads has been extensively investigated in the literature. The relation between foam property and indentation resistance has been presented in several research. Zniker, Houcine, et al. [9] compared the damage response and energy absorption capacity of PVC foam sandwich composite panels and glass fibre-reinforced polymer (GFRP) laminates under repeated low-velocity impact loads and quasi-static indentation. Due to its low indentation resistance, the PVC foam does not affect the quasi-static response of the sandwich composites. Rizov, V., and Mladensky, A. [10] investigated the effect of foam core density on the indentation response of sandwich panels with glass fibre-reinforced face sheets. The results of indentation tests showed that as the density of the foam core increased, the maximum load increased. In other words, sandwich panels with denser foam cores had higher indentation resistance. This result was explained as an increase in the foam stiffness due to the increase in the elastic modulus with density. Kazemi, M. [11] examined the influence of variations in polyurethane foam core density on the quasi-static penetration process of aluminium-faced sandwich panels with constant mass and total core thickness. Increased contact force and, thus, better penetration resistance were observed by employing graded sandwich panels with decreasing foam core density. Święch, Ł. et al. [12] performed perimeter shear tests on sandwich panels with a polymethacrylimide (PMI) foam core. Authors found that increasing foam thickness increased the plateau area in force-displacement behaviour but did not increase contact forces.

The effect of indenter tip shape as a test parameter has also been widely investigated in indentation studies. Azzam, A., and Wei, L. [13] studied the effect of indenter tips on quasi-static indentation damage in foam sandwich composites. It was found that brittle behaviour and a larger peak load occurred in the quasi-static test with a hemispherical tip, but ductile behaviour and the lowest peak load took place in the cylindrical tip test. This event was explained by differences in bending forces applied to different areas of the specimens. Moreover, different types of damage were induced by hemispherical and cylindrical tips. On the compressive side, hemispherical tips cause foam crack, face wrinkling, fibre breakage, and upper face crushing, while cylindrical tips cause initial delamination, micro buckling on the face sheet, core indentation, face wrinkling, and linear crack formation. Muscat-Fenech, C.D.M et al. [14] investigated the effect of penetrating tip geometries with hemispherical, conical, square-based pyramid and cylindrical flat-faced geometry in quasi-static indentation tests of marine sandwich composites. The damage caused by various indenters was evaluated in terms of force, absorbed energy, and indentation displacement. The force-displacement plots exhibited similar trends for conical and pyramidal tips, while demonstrating different characteristics for hemispherical and cylindrical tips. The highest penetration forces were recorded with a flat-faced cylindrical tip compared to others. Garrido, M., et al. [15] performed quasi-static indentation and low-speed impact tests on sandwich composites containing polyurethane and polyethylene terephthalate foams and balsa core. Comparing the results of the quasi-static indentation and low-speed impact tests, the quasi-static test accurately predicts the initial damage load and initial stiffness at low impact velocity. The authors reported that the perforation energies of the panels were higher for impact tests than for indentation tests; these differences varied depending on the indenter tip shape. Test results showed that the increased indenter diameter required more initial peak force and perforation energy.

Research has been conducted on the utilization of resin cuts to reinforce sandwich panels with foam cores against indentation loads [16-18]. Abdi, B., et al. [16] experimentally examined the behaviour of pin reinforced sandwich panels under quasi-static indentation and flat compression tests. Although the weight of the panels increased, it was found that by strengthening the panels containing foam core with pins, the improvement in indentation and compression strengths was higher. The penetration resistance and compressive strength increased as the pin diameter increased. Furthermore, the use of polymer pin reinforcement foam core was found to be a better choice than increasing the thickness of face sheets of the sandwich panel. Eyvazian, A et al. [17] studied the indentation and bending behaviour of resin pin-reinforced composite sandwich panels made of polyvinyl chloride core and glass/epoxy face sheets. The addition of resin pins to polyvinyl chloride foam core resulted in a significant increase in the maximum indentation load as compared to foam core sandwich structures without reinforcement. Furthermore, the use of resin pins resulted in changes to the damage modes observed in the specimens. This led to an improvement in the energy absorption capacity of sandwich structures under indentation loads. Another study produced similar results, indicating that the insertion of resin reinforcements into the foam resulted in higher contact forces and higher energy absorption capacity [18].

In the published work, it was observed that the usage of pin-reinforced foam improved the indentation resistance of sandwich structures. In this paper, the indentation tests of sandwich panels produced with different pin diameter and diameter centre-distances were conducted to compare force-displacement graphs, contact forces, absorbed energy values, and damage modes. Furthermore, as parameters, the dimension of the hemispherical geometry indenter tip utilized in the experiments were evaluated.

2 Material and method

The face sheets were made of E-glass chopped strand mat (CSM) and E-glass bi-directional stitched non-crimp fabrics (Metyx Composites Corporation, Istanbul/Turkey). Lamination plans for the upper and lower face sheets are given in detail in Table 1. Table 2 shows the elastic and mechanical characteristics of upper and lower face sheets in the warp direction according to the standards. Sandwich panels were produced with an infusion type vinyl ester resin (Poliya, Polives702). In the core material, polyvinyl chloride foam (Airex C.70.75) [19] with a thickness of 25 mm and a density of 80 kg/m^3 was selected. To produce holes in the foam material, a CNC three-axis vertical milling machine was employed. For distances of 12 mm, 16 mm, and 18 mm between holes, 1 square meter of PVC foam sheet requires an approximate total of 80, 60, and 55 holes, respectively. These holes were filled with resin in the infusion method and took the shape of solid pins after curing. The weights of the produced sandwich panels were also compared. The square meter weights of sandwich panels with Ø4-12, Ø4-16, and Ø4-18 resin pin arrangements were measured as 15.3 kg, 14.77 kg, and 12.57 kg, respectively. The square meter weights of sandwich panels with Ø8-12, Ø8-16, and Ø8-18 resin pin arrangements were 20.7 kg, 17.7 kg, and 14.7 kg, respectively. Details of the hard resin pattern and pin-reinforced sandwich panel are presented in Figure 1a, b.

The process of vacuum-assisted resin infusion moulding (VARIM) is employed for producing sandwich panels (Figure 2). The VARIM method is given in detail in Figure 2. There was no need for peel ply cloth or flow net since holes were drilled in PVC foams. The resin flows through the mould under vacuum, wetting the E-glass fibres and filling holes in the PVC before reaching the vacuum line and resin trap. After production, the pin reinforced sandwich panels were allowed to cure for 24 hours. The panels were cut on a band saw in dimensions of 100 mm ×100 mm for indentation tests.

Table 1. Lamination plans of face sheets

Facesheet	Thickness (mm)	Stacking of fabrics	Areal weight (g/m^2)
Upper	2.4	Biaxial E-glass	850
		Biaxial E-glass	850
		Biaxial E-glass	850
Lower	4	CSM	450
		CSM	450
		Biaxial E-glass	850
		Biaxial E-glass	850
		Biaxial E-glass	850
		Biaxial E-glass	850

Table 2. Elastic properties and strength of upper and lower E-glass/vinyl ester face sheet

Skin	Elastic modulus (GPa)	Poisson ratio	Shear modulus (GPa)	Tensile strength (MPa)	Compression strength (MPa)	Shear strength (MPa)
Upper skin	20.70	0.14	4.10	355.90	226.70	51.6
Lower skin	22.50	0.17	4.40	394.10	244.20	53.5

Indentation tests were performed using the apparatus on the Zwick Roell Z250 test device. Sandwich test samples are fixed between two square steel plates with a circular hole in the centre (Figure 3). The experiments were carried out at a loading rate of 1.25 mm/minute using hemispherical indenters with diameters of 12.7 mm and 20 mm. The specimens were completely perforated in the tests. The thinner face sheets are positioned on the top section during the tests corresponding to the interior of the hull. At least three specimens from each series were tested.

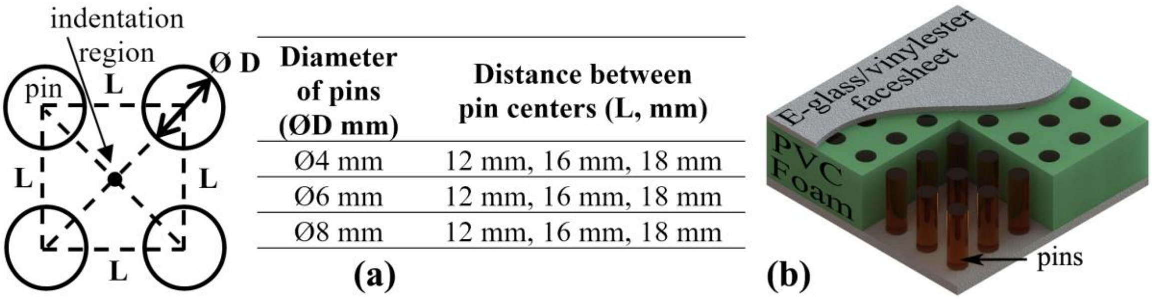

Figure 1. (a) Solid resin pin pattern and indentation zone, (b) schematic of pin- reinforced sandwich panel

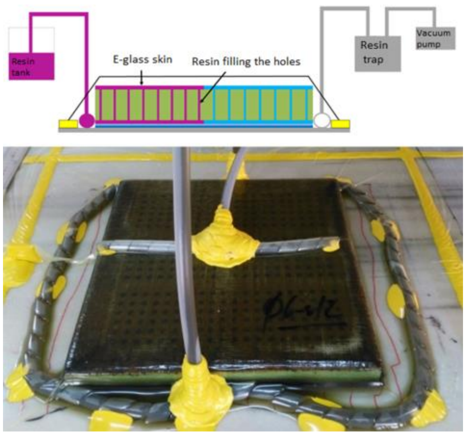

Figure 2. Production of pin reinforced sandwich panels

Figure 3. Experimental setup for indentation tests

3 Results and discussion

3.1 Force-displacement behaviour

Force-displacement curves are presented in Figure 4. The specimens showed curves consisting of two peaks and plateau region during testing. The initial peak is generated when the indenter penetrates the upper skin, followed by the second peak as it reaches the lower skin. The formation of the plateau region between the two peaks takes place as the indenter moves through the foam core material [18]. The contact load increased almost linearly in all specimen curves until it reached a maximum value, which corresponded to upper face sheet perforation and foam core crushing. In addition, the initial stiffness was higher in specimens with 12 mm distance between pin centres. As the foam core was crushed and densified in the plateau region, the contact force diminished in the curves of the specimens. As can be seen from the graphs, indenter diameter, pin diameter and pin arrangement influenced the difference between the first and second peaks. For specimens with a high first peak, it means that the initial indentation resistance is strong. During the experiments conducted using a 20 mm diameter indenter as seen Figure 4 b and d, it was found that the contact forces obtained in the plateau regions between the two peaks were higher. The increased contact forces observed in this region, particularly in specimens Ø4-12 and Ø8-12, can be attributed to the contact with the resin pins. The reason for this is that the diagonal length reduces as the distance between the square pattern hole centres opened into the foam material decreases.

3.2 Maximum contact forces

The forces resulting from contact with the upper and lower face sheets during indentation tests are shown in Figure 5. As expected, the increase in pin diameter resulted in a related increase in contact forces. The first and second peaks exhibited an increase in maximal contact forces as the diameter of the indenter was larger. Specimens Ø4-12 and Ø8-12 showed the highest peaks as seen in Figure 5. This shows that increasing the indentation resistance requires frequent pin centring. In the tests performed with a Ø12.7 mm indenter on specimens with 4 mm pins, the second peaks were higher in all of them. Tests with a Ø12.7 mm indenter on specimens with 4 mm pins resulted in higher second peaks. With the Ø20 mm indenter, the first peaks were higher at Ø4-12 mm and Ø4-16 mm specimens. The pins with a diameter of 4 mm provided less resistance to the indenter tip with a diameter of Ø12.7 mm than the bottom face sheet (Figure 5a). For the 20 mm indenter, pins at Ø4-12 mm and Ø4-16 mm increased the initial indentation resistance more than the lower face sheet (Figure 5b). Specimen Ø4-18 exhibited a decrease in initial resistance (Figure 5b). The initial resistance was higher in the Ø8-12 sample against the 12.7 mm indenter (Figure 5c). For pins with a diameter of 8 mm, the initial resistance was high in all specimens against the Ø20 mm indenter (Figure 5d). Previous studies produced similar results, and it was reported that as the diameter increased, the penetration resistance of the upper face sheet also increased [16, 17].

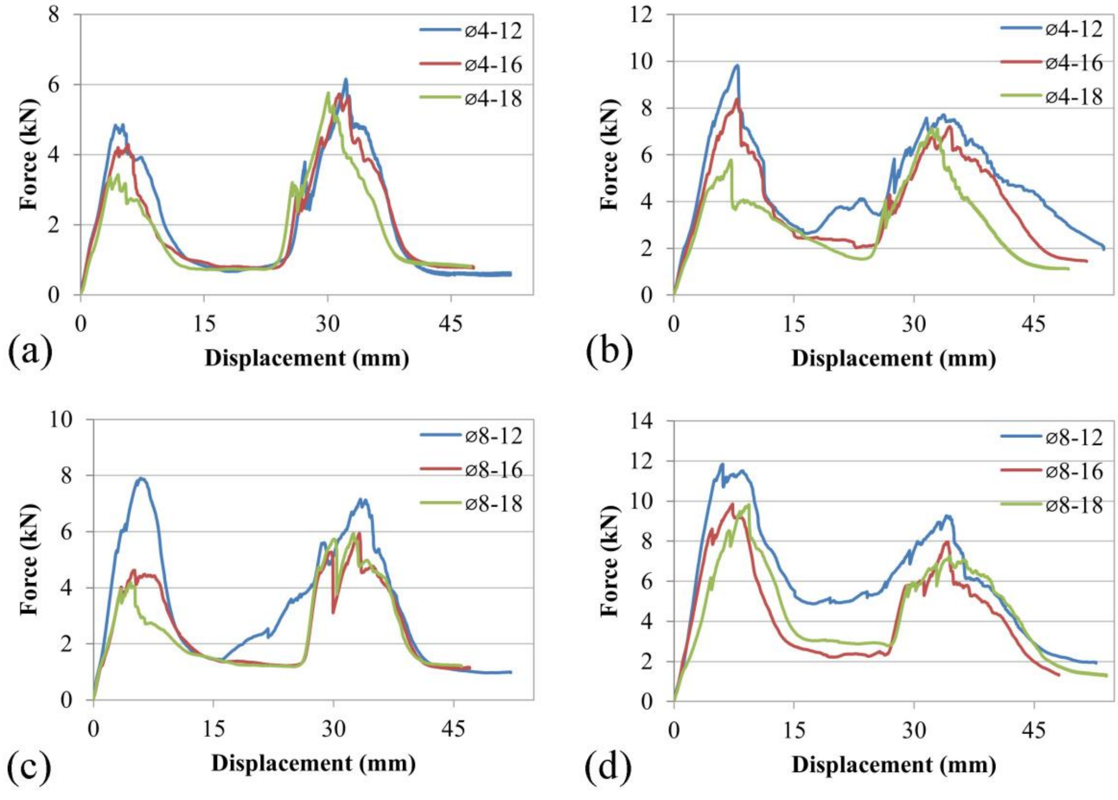

Figure 4. Force-displacement graphs of sandwich specimens, with Ø4 mm diameter pins tested with (a) Ø12.7 mm and (b) Ø20 mm indenters, with Ø8 mm diameter pins tested with (c) Ø12.7 mm and (d) Ø20 mm indenters

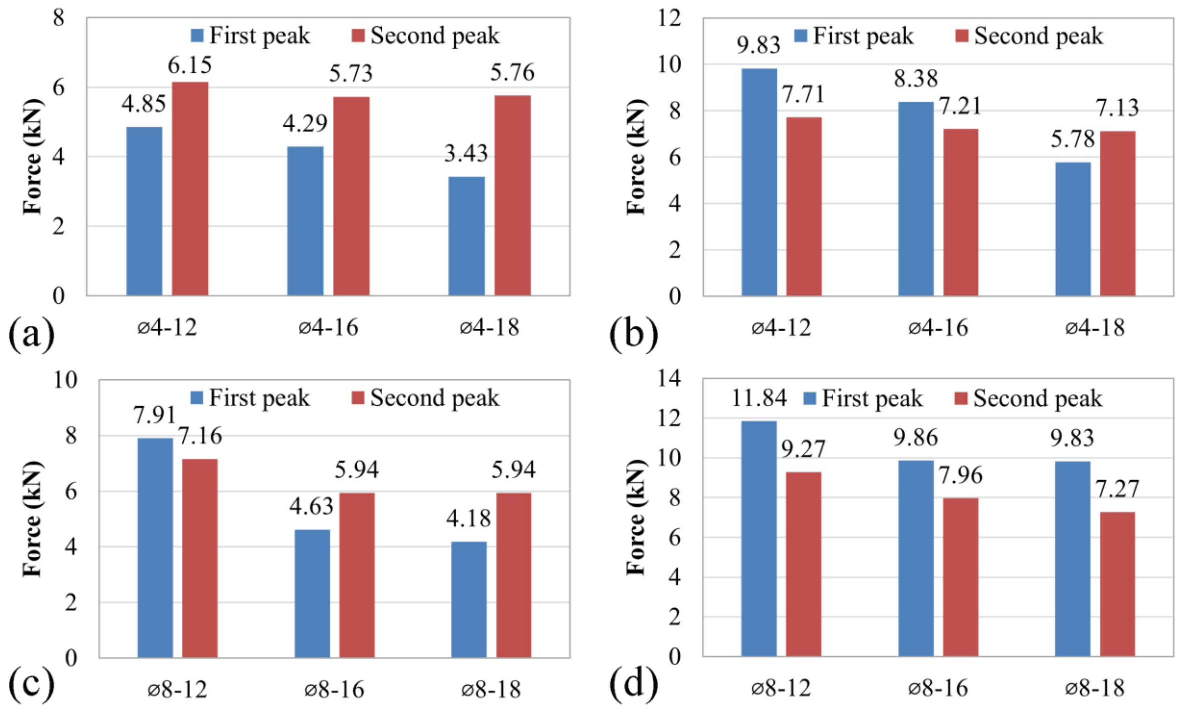

Figure 5. Contact forces of sandwich specimens, with Ø4 mm diameter pins tested with (a) Ø12.7 mm and (b) Ø20 mm indenters, with Ø8 mm diameter pins tested with (c) Ø12.7 mm and (d) Ø20 mm indenters

3.3 Absorbed energy of the pin reinforced sandwich panels

The area under the force-displacement graphs gives the absorbed energy values of the sandwich specimens. As seen in Figure 6, the highest absorbed energy values were obtained at Ø4-12 and Ø8-12 for both types of penetrating tips.

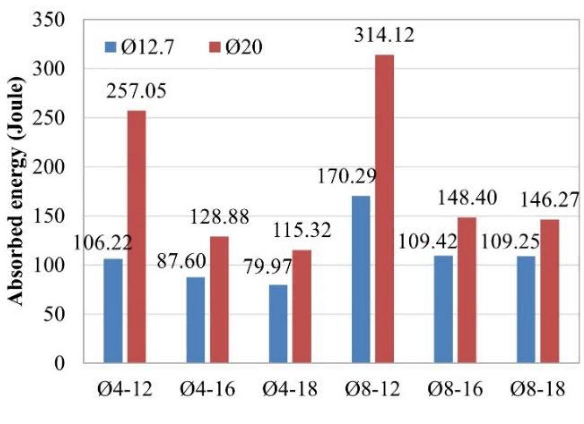

Figure 6. Absorbed energy values of sandwich specimens

This result confirms the literature, which states that foam cores with more closely spaced hole patterns absorb a larger amount of energy [17]. Additionally, energy absorption values increased with the increase in resin pin diameter [16]. In the tests performed using a 12.7 mm indenter tip, Ø4-12 specimen absorbed 21% and 33% more energy than Ø4-16 and Ø4-18 specimens, respectively. Applying the Ø20mm indenter tip resulted in higher values of 99.4% and 123% in comparison with Ø4-16 and Ø4-18 specimens. In the tests with the 12.7mm indenter tip, the amount of energy absorbed by the Ø8-12 specimen was approximately 55.8 times higher than the Ø8-16 and Ø8-18 specimens. In testing with Ø20 mm indenter, the Ø8-12 specimen absorbed 112% and 115% more energy than the Ø8-16 and Ø8-18 specimens. The Ø8-16 and Ø8-18 specimens absorbed similar energy levels at both indenter tips.

3.4 Visual observation of indentation damage

Sandwich test samples were cut using a band saw to evaluate the damage in the cross-sections after the testing. All samples exhibited failure modes such as fibre breakage, delamination, and fibre pull-out on the upper face sheets. The bottom face sheets suffered damage from delamination and fibre breaking in the form of petalling. In the tests performed with a Ø12.7 mm indenter tip in the core section, no resin pin breakage and foam crack damage occurred in Ø4 mm reinforced foams (Figure 7a). In the Ø20 mm indenter tests, bottom face-foam core debonding occurred in the Ø4-12 specimen (Figure 7b). As seen in Figure 7b, foam cracking, and resin pin breakage damages were observed in Ø4-12 and Ø4-16 specimens with the increase in diameter of the indenter tip. The Ø4-18 specimen did not suffer any fracture of the resin pin. For specimens with 8 mm pins, the Ø12.7 mm indenter tip broke the resin pins in the Ø8-12 specimens (Figure 7c). This resulted in the highest initial peak for the Ø8-12 specimen. It has been found in the literature that the indenter tip contact with resin pins causes an increase in initial peak load [17]. Bottom face-foam core debonding and foam cracking damages became dominant in the 8 mm pin specimens tested with an indenter tip diameter Ø20 mm (Figure 7d).

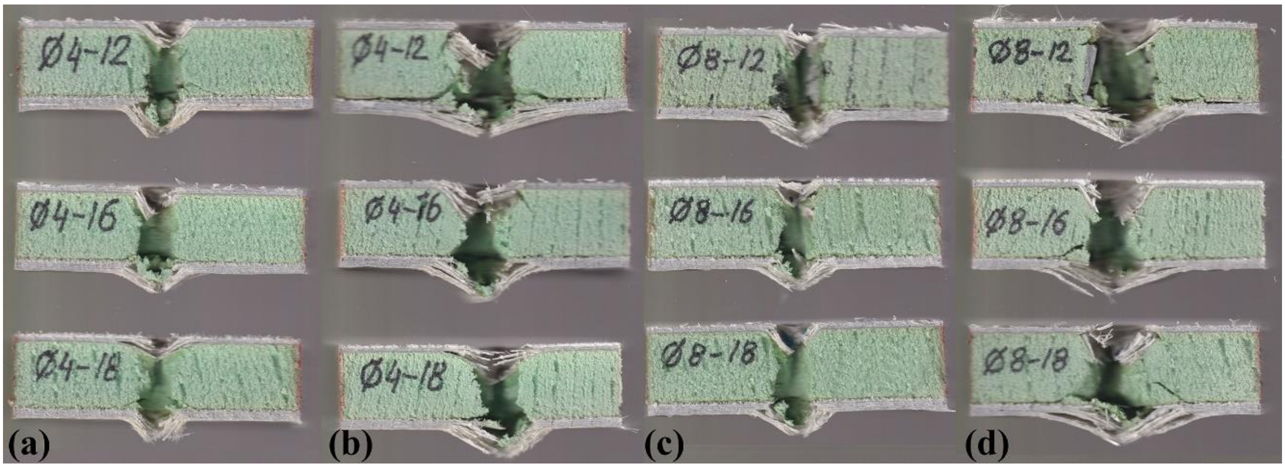

Figure 7. Cross-sectional images of damaged sandwich specimens

4 Conclusions

The present work performed experimental studies to evaluate the effect of resin pin-reinforced PVC foam on the indentation behaviour of marine sandwich composites.

- To enhance the resistance to indentation load, it is necessary to either increase the diameter of the pin reinforcements or drill holes into the foam material with closer centres.
- Frequent drilling of holes and increase in pin diameter will cause an increase in the weight of the structure.
- Small pin diameters do not provide enough resistance for small indenter tips.
- The size of the indentation object influences the initial resistance to indentation load.
- By drilling more frequent holes between the centres, the energy absorbed during indentation loading increases.
- The damage modes varied depending on the size of the indenter object in contact. A significant increase in initial force and perforation energy was achieved in case of contact between the resin pins and the indenter tip.
- An enhancement in the resistance of marine sandwich composites to indentation loads can be achieved through the application of pin reinforcement to the foam. However, applying this technique only in critical areas to prevent excessive weight gain in marine structures can provide beneficial results.

Conflict of interest

The authors declare that there is no conflict of interest.

Similarity rate (iThenticate): 9 %

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