MECHANICAL AND IMPACT BEHAVIORS OF SANDWICH STRUCTURES USING PUR OR PERFORATED PMI FOAM CORES WITH SIMILAR BULK DENSITIES

Vasco Duarte Raposo[1], José M. C. Faria Silva[1], Albertino Arteiro[1],
Paulo Jorge R. O. Nóvoa[1, 2] and António Torres Marques[1, 2]

[1] FEUP - DEMec, R. Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal, www.fe.up.pt
[2] INEGI – UMEC, FEUP Campus, R. Dr. Roberto Frias 400, 4200-465 Porto, Portugal, www.inegi.pt
em11105@fe.up.pt, em11157@fe.up.pt, prnovoa@fe.up.pt, aarteiro@fe.up.pt, marques@fe.up.pt

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ABSTRACT

The use of polymer foams as core materials in composite sandwich structures is currently a well-established practice. Polymer foam properties in general improve with its bulk density, and it is a subject of interest to study ways by which high performance polymer foams can be modified through density reduction without significantly lowering mechanical performance.

The present investigation addresses the use of two very diverse polymer foams as core materials, both chemically and with respect to mechanical behaviour. The higher density polymethacrylimide foam was chosen as one with far superior properties to those attained by a foam material with equal density, chemically identical to the low density polyurethane resin rigid foam. The main objective was to determine how detrimental, a machining approach to match bulk densities, would be on bending, and low velocity impact performance as well as on core compression behaviour.

The sandwich structures are characterized with respect to three-point bending, four-point bending, and low velocity impact properties. Additionally, bending behaviour was modelled using the Abaqus® finite element software. The face-sheet composition used throughout the work was kept similar to those used by some of the authors in previous works. This enabled a comparison with the behaviour of the previously studied sandwich structure with non-machined polymethacrylimide foam core.

Although an effective levelling of densities was not accomplished, nevertheless, the machined foam retained far higher flexural performance. The bending behaviour modelling presents some shortcomings. With respect to low velocity impact behaviour, performance depends on criteria. It is clear that the polymethacrylimide foam based structures show higher damage onset forces and far superior ultimate impact forces. However a performance decision based solely on post-impact residual indentation clearly favours the polyurethane core structure.

1 INTRODUCTION

Composite sandwich constructions are interesting from a structural perspective as they can yield high specific strength- and stiffness-to-weight ratios. These features make them particularly attractive for applications related to the automotive, aeronautic, aerospace, marine and civil industries. The principle of a sandwich structure is the combination of a core material of low bulk density and thin stiff face sheets, which carry shear and bending loads, respectively, mimicking the I-beam principle. [1, 2]

In previous works some of the authors compared the performance of sandwich structures with different polymer foams and cork agglomerates [3, 4], and addressed the modification of the core to face-sheet adhesive layer with multiwall carbon nanotubes (MWCNT) [5, 6].

This work retains the face-sheet composition used in the aforementioned investigations, and addresses the use of two very diverse polymer foams as core materials, both chemically and with respect to mechanical behaviour.

Like in the mentioned previous works, the sandwich structures of the present work use resin infusion processed skins based on an epoxy resin system reinforced with +/-45 ºglass fibre fabric, and a polyurethane structural adhesive to join the structure elements. This work is partially based on

results of a course report [7], and focuses on the use of two polymer foams as core materials, quite distinctive both chemically and with respect to mechanical behaviour.

However, the main drive for the study was to determine how detrimental, a machining approach to match bulk densities, would be on bending, and low velocity impact performance as well as on core shear and compression behaviours. The sandwich structures are characterized with respect to three-point bending, four-point bending, and low velocity impact (LVI) properties. Additionally, the compressive and bending behaviours were modelled using the Abaqus® finite element software.

Instead of choosing two chemically identical foams - *e.g.*, based on polyurethane resin (PUR) – differing on bulk density and naturally mechanical properties, for which a levelling of bulk densities through machining would naturally lead to some degree of mechanical behaviour levelling, the higher density foam was chosen as one with far superior properties - *e.g.*, polymethacrylimide (PMI) - to those attained by an equal density foam chemically identical to the low density one.

The parameter whose influence is under evaluation is any excessive detrimental effect introduced by the perforated structure, *i.e.*, for which a straightforward explanation based simply on simply the cross-section reduction is not satisfactory.

Naturally, compression properties can be easily anticipated based solely on effective cross-section reduction, at least as far as elastic properties are concerned, *i.e.*, core modulus. However, core strength and ultimate strain may be very dependent on the selected geometry. Considering for example the use of circular holes, although it is obviously possible to obtain the same density (or effective cross-section) reduction with different radii and number of holes, the effective wall thickness between holes may be paramount for ultimate compressive properties, as very thin walls may lead to premature instability and collapse.

This study follows the recognised interest in studying the influence of core modifications on overall sandwich structure performance [8].

2 EXPERIMENTAL

Two sandwich structures were constructed using the same facing material, core thickness, and adhesive layer thickness. The materials, manufacturing, and machining processes, and test methods for structure performance evaluation, are described in detail in this section.

2.1 Materials

A PUR foam (Polirígido, Ltd. Portugal) with 60 kg.m^{-3} nominal density and a ROHACELL® A PMI foam (Evonik, Germany) of 75 kg.m^{-3} nominal density were used respectively, as the lower and higher density core materials. The PMI foam was chosen as the better performing material to be machined down to a bulk density matching that of the PUR foam, according to a scheme to be presented below (*cf.* 2.2.1 Core preparation). The foam materials were supplied as slabs with thicknesses of 60 mm (PUR) and 25 mm (PMI).

The matrix material used in sandwich face sheets was a very low viscosity (170 mPa.s) two component Biresin® system (Sika®, Germany) based on epoxy resin CR83 and amine hardener CH83-6; the reinforcing material was Multifab® (Lintex®, PRC) E BX 600, a double biaxial (±45°) E-glass fibre fabric with areal weight of 612 g.m^{-2}, which includes the contribution from polyester yarn stitching.

A structural two-component, polyurethane assembly adhesive recommended for bonding sandwich panels − SikaForce®-7710 L100 (Sika®, Germany) − was used to bond the face sheets to the core materials. The adhesive components are a mixture of filled polyols and isocyanate derivatives, respectively, which must be mixed in a 100:19 mass ratio. This adhesive has a different colour and somewhat different properties form the one used in the previously studied sandwich structure with non-machined PMI foam [3, 4] – *i.e.*, - a fast-curing structural two-component, polyurethane with reference SikaForce®-7888 L10 (Sika®, Germany). The colour may in fact be influential throughout the visible inspection of damage. The previous adhesive was black whereas the one used in the present work was beige, resulting in less contrast.

2.2 Manufacturing

Two sandwich structures were constructed using the same facing material, core thickness, and adhesive layer thickness. The materials, manufacturing, and machining processes, and test methods for structure performance evaluation, are described in detail in this section.

2.2.1 Core preparation

Both foam materials were available as slabs with thicknesses greater than the intended core thickness (12 mm), so after cutting a piece with slightly above the planned sandwich structure area (420 × 280 mm^2), 12 mm thick pieces to be used as core parts were cut from the PMI and PUR pieces with thicknesses of 25 mm and 70 mm, respectively.

The PMI material was supplied as a 25 mm thick slab, which had to be sliced to obtain a plate with the required core thickness of 12 mm. The experimentally determined density of PMI foam slab was about 70 kg.m^{-3}, therefore, slightly differing from the expected nominal value supplied from the manufacturer.

The values given above (*cf.* 2.1 Materials) for foam bulk densities are the manufacturer nominal values. In order to work with values characteristic of the pieces used in the present study, the bulk densities of the pieces cut from thicker slabs actually used for sandwich construction, were measured obtaining their masses and linear dimensions following the method in ASTM C 271 [9] – the experimentally obtained values (*cf.* Table 1) were used for the subsequent calculations to produce the perforated PMI (p-PMI) core. Considering the foam densities difference, less than 15% of material had to be removed from the PMI foam.

Foam material	Bulk density (kg.m^{-3})	
	Nominal (manufacturer)	Measured
PUR	60	60.5
PMI	70	68.7

Table 1: Core material densities.

Using the actual measured density values, 11.94 % of volume from PMI core had to be removed. The selected scheme involved drilling normal holes on the original core. Several schemes involving different hole diameters and distances between centres were considered - 2 mm diameter holes with centres 10 mm apart were used to achieve the goal.

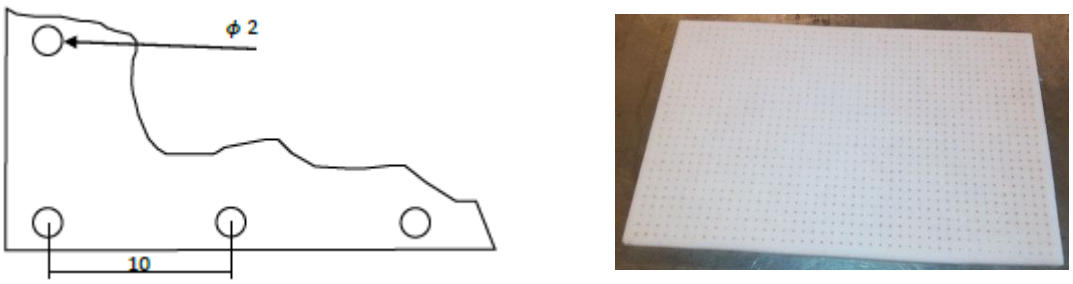

Figure 1: Perforation scheme of PMI foam (left) and actual p-PMI plate (right).

Considering the structure dimension of 420 × 280 mm^2, drilling the material using this diameter, the total area had to be reduced by 14041.44 mm^2, which required approximately 1117 holes:

$$\begin{cases} A \times B = 1117 \\ \dfrac{B}{A} = 420/280 \end{cases} \Leftrightarrow \begin{cases} A = 27 \\ B = 41 \end{cases}$$

Therefore, in total, 1107 holes (27 × 41) had to be drilled in the original PMI plate- this was accomplished with a CNC machine.

2.2.2 Sandwich construction

The sandwich structures were produced by sequentially producing the fiberglass/epoxy laminate face sheets by vacuum infusion, preparing the core, and bonding them together using the structural adhesive. Each fiberglass/epoxy facing had two layers of ±45° biaxial fabric. Two *ca.* 1 mm thick, large laminates (*ca.* 2000 × 600 mm^2) were obtained by vacuum infusion, from which 450×300 mm^2 face sheets were cut. These were bonded to the cores using the two-component polyurethane-based adhesive. After assembly, weights were uniformly distributed on the sandwich structures so that a constant pressure was applied throughout adhesive curing/bonding, and adhesive layers with nearly constant thickness resulted along each of the sandwich bonded surfaces. Both structures had a nominal thickness of 15 mm, from which specimens for impact and four point bending were cut.

2.3 Mechanical testing

Flatwise compression tests of the core materials used in the sandwich constructions were performed on a TIRATEST 2810 (TIRA® GmbH, Germany) electromechanical universal testing machine with 5 kN load cell. Three- and four-point bending tests were performed with an Instron® (MA, USA) model 4208 electromechanical universal testing machine, with a 5kN load cell. A Rosand® (USA) IFW 5 HV drop weight instrumented impact tester, was used for low velocity impact testing.

2.3.1 Flatwise compression of core material

Core material specimens with standard nominal dimensions of 30 × 30 mm^2, were tested in accordance with ASTM Standard C365/C365M [10], between two steel platens, at a cross-head speed of 0.5 $mm.min^{-1}$. The standard test speed was kept up to 35% deformation, which far exceed the range required to determine foam moduli and yield strengths. Beyond 35% deformation the speed was increased to 5 $mm.min^{-1}$. This was done to observe the foam compressive behaviours up to 75% deformation, while maintaining reasonable test duration.

2.3.2 Flexural Testing

The three- and four-point bending tests were carried out according to methods described in ASTM C 393-00 [11].

2.3.2.1 Three-point bending

Sandwich specimens with standard nominal dimensions of 200 × 75 mm^2 (length × width), were tested using a third-point loading configuration. The span length was set to 150 mm. Loading was applied at a constant speed of 5 $mm.min^{-1}$, and a loading roller and supports, with 30 mm and 20 mm diameter respectively, were used.

2.3.2.2 Four-point bending

Sandwich specimens with nominal dimensions of 350 × 30 mm^2 (length × width), were tested using a third-point loading configuration. The span length was set to 300 mm. Loading was applied at a constant speed of 5 $mm.min^{-1}$, and both loading and supporting rollers with 20 mm diameter were used.

2.3.3 Impact Testing

Sandwich structure specimens with nominal dimensions of 60 × 60 mm^2 (length × width), were used for low velocity impact tests, following procedures described in standards ASTM D7136/D7136M–05 [12] and ASTM D7766/D7766M-11 [13]. Considering the sandwich face-

sheet thickness of *ca.* 1 mm, tests were carried at the recommend impact energy of 6.7 J (two specimens), and additionally tests were carried at impact energies of 10 J (two specimens), 15 J (two specimens), 20 J, 30 J and 40 J, using a 5,774 kg mass impactor with a 16 mm diameter hemispherical tip. The impact energy was obtained changing the drop height, as summarized in Table 2.

Each specimen was held in place by a pneumatic lever arm with a reversible ring, at a clamping pressure of 0.5 bar - a higher clamping pressure would be excessive for the low compressive strength of the structure with low density PUR core. Sampling was 1000 points in 20 to 30 ms. The impactor was captured after rebound to prevent multiple striking.

Impact energy	[J]	6.7	10	15	20	30	40
Impact height	[m]	0.118	0.177	0.265	0.353	0.530	0.706
Impact velocity	[$m.s^{-1}$]	1.523	1.861	2.279	2.632	3.224	3.722

Table 2: Impact conditions for low velocity impact testing.

2.3.3.1 Impact damage evaluation

Damage resistance was evaluated by inspection of the impact event history plots. After impact testing, specimens were visually inspected, supported by micrographs, to qualitatively assess externally visible damage.

Additionally, damage resistance was also quantitatively evaluated by measuring the long-lasting indentation at the point of impact more than 60 days after testing. The method consisted in using a dial gage to measure at least three z-coordinate values not more than 5 mm inwards from the specimen edge to define the z-coordinate of un-indented specimen face-sheet plane, and measuring the z-coordinate value coinciding with the point of impact close to the specimens' centre – the difference was considered a permanent indentation. The complete information concerning material properties and modelling details criteria is found in ref. [7].

2.3 Sandwich bending modelling

The chosen tool to predict specimens' behaviour was Abaqus® computer software (Systems, ABAQUS CAE). The structural adhesive that links the skins with the core wasn't considered modelling, instead, a mechanical interaction between core and skins was considered. For purpose of modelling the perforated structure was not considered, instead both cores were considered continuous. The face-sheets were assigned continuum shell elements, and the core with 3D stress elements.

On both bending test modes, a boundary condition was used to simulate the support members and another to simulate the loading member/s during 3/4 -point bending. The foam cores were defined with linear elastic behaviour, and glass fibre reinforced face-sheets initially with linear elastic behaviour followed by Hashin damage.

3 RESULTS AND DISCUSSION

The results for quasi-static core compression and sandwich structure flexural behaviours, low velocity impact performance, and flexural modelling, are presented in detail in the present section.

3.1 Flatwise compression of core material

The core compression test curves are shown in Fig. 2. It is clearly observed that the perforation scheme while resulting in a yield strength lower than that indicated by the manufacturer for the original material (1.5 MPa), is still significantly higher than that of the PUR foam. The graph also shows that the compressive modulus still favours p-PMI over the PUR foam.

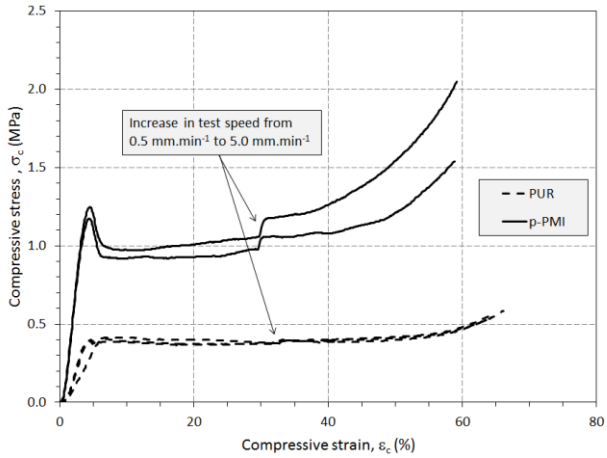

Figure 2: Compression behavior of core foam materials.

Core Material	Yield stress (MPa)	Yield strain (%)
PUR	0.40	5.43
p-PMI	1.21	4.45

Table 3: Core material compressive properties.

3.2 Flexural Testing

Concerning the flexural behavior of the sandwich constructions, the properties retained by the PMI material after perforation result in a better performing structure than the one based on PUR core. This can clearly be observed in the flexural test curves and Table 4. Also presented, are a curve and respective results for the 4-point bending behavior of a similarly constructed PMI core structure (*i.e.*, non-perforated), obtained by Arteiro *et al.* [3, 4], showing that perforation resulted in a lower sandwich resistance, but flexural stiffness remained relatively unaffected as it is mainly determined by the face-sheet material. Considering that core shear failure was responsible for structure collapse, perforation can be considered the cause for the reduced core shear strength between both PMI based structures.

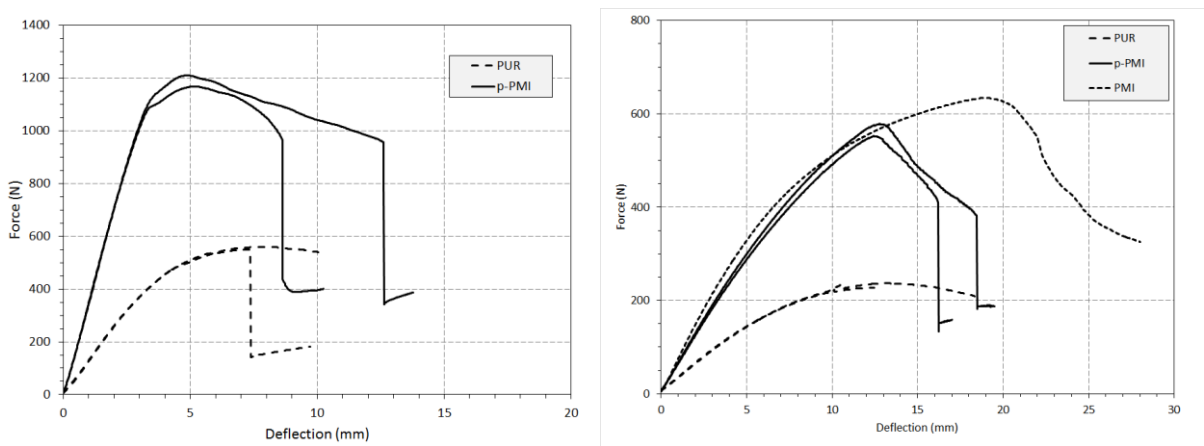

Figure 3: Flexural behavior of PUR and p-PMI core sandwich structures in 3–point (left) and 4-point bending (right).

Test geometry	Core material	Max. load (N)	Max. load displacement (mm)	Break load (N)	Break displacement (mm)
3-point bending	PUR foam	554	7.51	543	8.78
	p-PMI foam	1189	5.06	960	10.6
4-point bending	PUR foam	232	12.8	-	-
	p-PMI foam	565	12.6	395	17.3
	PMI foam [3, 4]	634	19.0	-	-

Table 4: Sandwich structure flexural testing results.

3.3 Impact Testing

The impact force-time plot histories of both types of sandwich specimens for all tested energy levels, are shown in Fig. 4. The force- time-plot histories for the neat PMI core are not included for clarity of the graphics and discussion, as they would to a great extent overlap the p-PMI related plots. The discussion with reference to the neat PMI structures shall be limited to the analysis of post-impact specimen features. The low velocity resistance test results are presented in Table 2.

Impact parameter	Sandwich structure core material	Impact energy (J) 6.7	10	15	20	30	40
Maximum force (kN)	PUR foam	1.47	1.83	2.45	3.38	4.68	5.33
	p-PMI foam	2.82	2.99	3.05	3.51	3.70	4.56
Distance at maximum force (mm)	PUR foam	4.54	9.64	11.95	13.50	15.13	16.42
	p-PMI foam	4.66	5.27	4.89	6.11	12.33	14.67

Table 5: Sandwich structure LVI results.

In Fig. 5, characteristic impacted specimens for all energy levels, including specimens from the work of Arteiro *et al.* [3, 4], are shown, and core fracture locations are highlighted, as they may be difficult to spot in the lateral view photographs. Quite distinctive impact event histories result from the curves for structures with PUR and p-PMI cores. An expected feature is the lower dynamic stiffness of the PUR structure, considering the known elastic properties of both materials. The p-PMI structure appears to withstand the lowest studied energy level without damage. In the case of PUR, the force reaches a plateau but no severe force pulse is observed, which may indicate damage associated with collapse of core cells. At energies of 10 J and beyond, force drops indicative of damage phenomena become apparent in the p-PMI structure, but the lower stiffness of PUR seems to accommodate the excess energy mainly through internal cell collapse, and no significate damage is observed on the structure face-sheet. Core cracks however become externally visible in PUR already at 10 J, whereas the onset of visible core fracture is delayed to 15 J and 20 J, in the case of p-PMI, and PMI, respectively. Additionally, the core fracture seems to progress more easily through PUR foam, as at 30 J cracks extend from top to bottom of the specimen, whereas that is not observed for both p-PMI and PMI even at the highest tested energy level (40 J). Conversely, with regard to face-sheet fracture, for the PUR structure, such feature only becomes slightly apparent at 20 J, whereas it is clear at 15 J and 20 J, for p-PMI and PMI, respectively.

In order to address the issue of damage associated with an impact event in relation to the resulting permanent indentation it is helpful to have an estimate of the maximum compressive deformation attained during the event. The force-displacement curves for all tested energy levels and specimens for PUR and p-PMI structures are depicted in In Fig. 6. The results for PMI specimens are not presented as the following analysis is concerned with permanent indentation, which was not addressed in the works of Arteiro *et al.* [3, 4], nor were the specimens available for further testing.

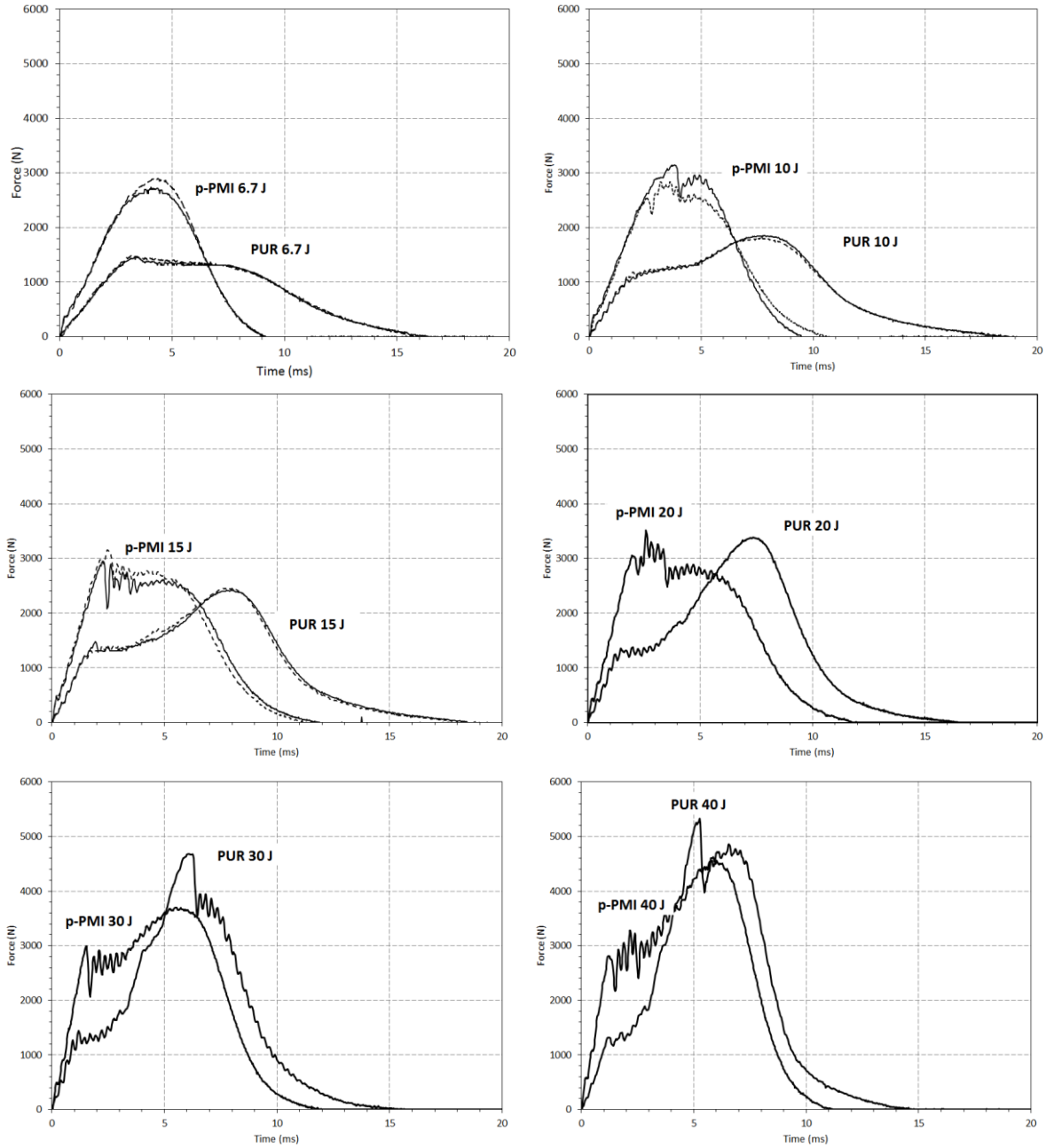

Figure 4: Force-time plot histories of low velocity impacts for all energy levels, of sandwich specimens with PUR and p-PMI core materials.

The results for permanent indentation are presented in Figure 7 as a function of impact energy. The results are interesting as they reveal that although the stiffer p-PMI core withstands consistently lower displacements during equal energy impacts (*cf.* Table 5, Fig. 6), the resulting permanent indentation values are always higher than those measured for the PUR core specimens.

Also interesting is the fact that permanent indentation correlates well with impact energy, and a quadratic function results for both core materials. During curve fitting the function was forced to reach the graph origin. One point, corresponding to the 6.7 J impact energy - identified as PUR* in the graph - was discarded in the curve fitting analysis. These tests were performed with an excessive clamping pressure for the low density PUR foam. The fact that the measured result of permanent indentation for 6.7 J was higher than the one for 10 J may be associated with the different testing conditions, and although it wouldn't change the overall conclusion, it would deteriorate correlation, which is otherwise remarkable.

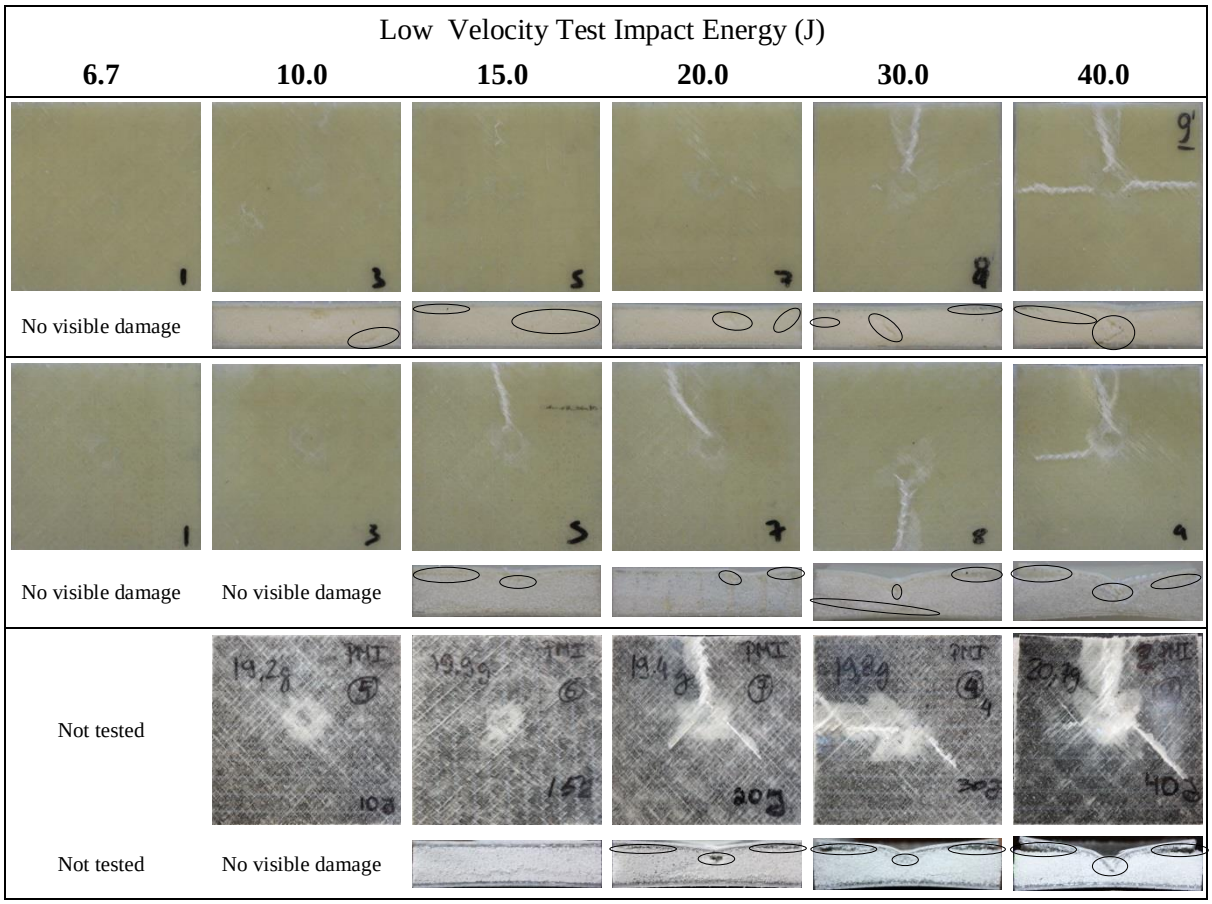

Figure 5: Post-test appearance of impacted face-sheets and core outer side views, for PUR (top), p-PMI (middle), and PMI (bottom) sandwich structure specimens.

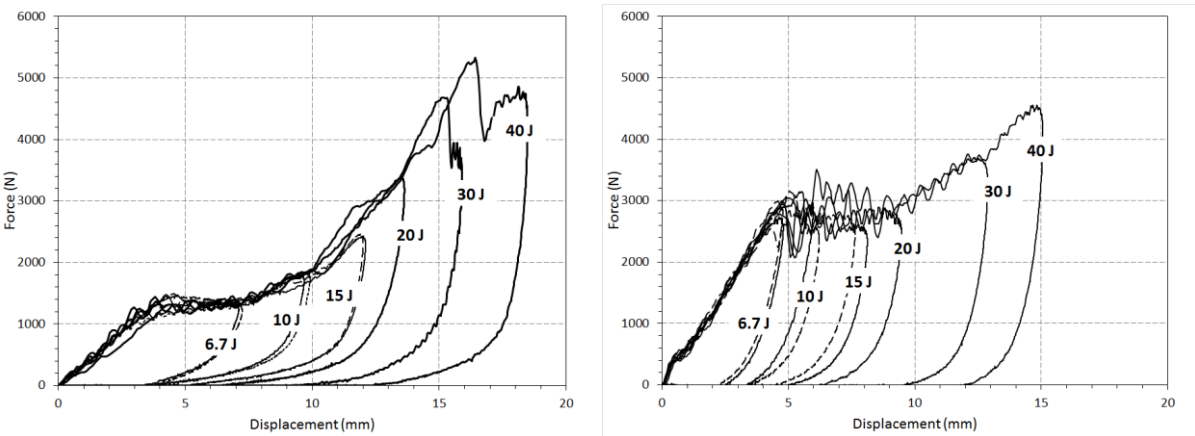

Figure 6: Force-displacement plots of low velocity impact events for all energy levels, of sandwich specimens with PUR (left) and p-PMI (right) core materials

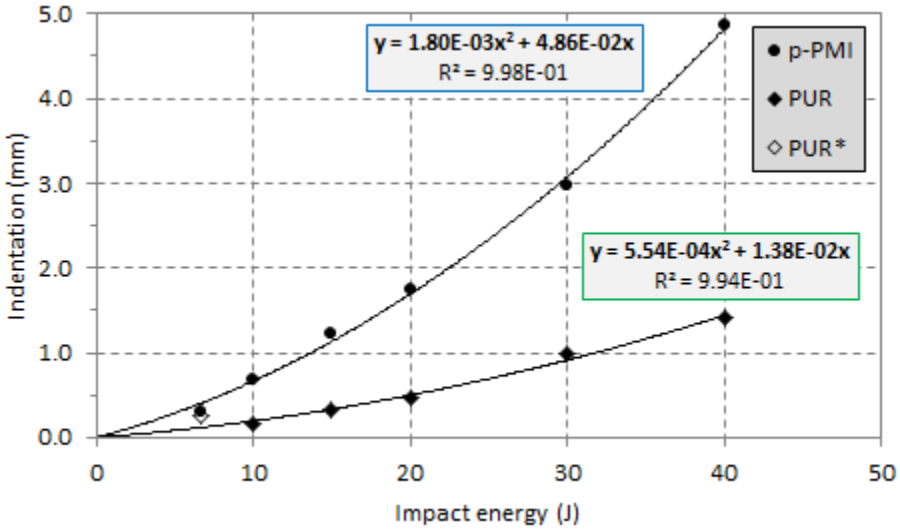

Figure 7: Permanent indentation of impacted specimens for PUR and p-PMI sandwich structure specimens.

3.4 Sandwich bending modelling

The results for sandwich failure from the modelling studies of 3-point and 4-point bending tests are presented in Figs. 8-9, and Table 6. One major discrepancy results from the predicted failure modes which fail to agree with the experimentally observed core shear failure. This results from the very simplified core behavior modelling used throughout the simulations.

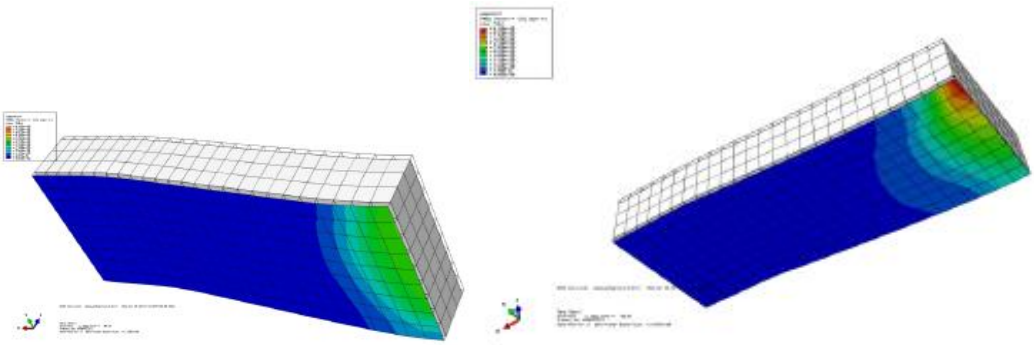

Figure 8: Three-point bending tensile failure for PUR(left) and p-PMI (right) core structures.

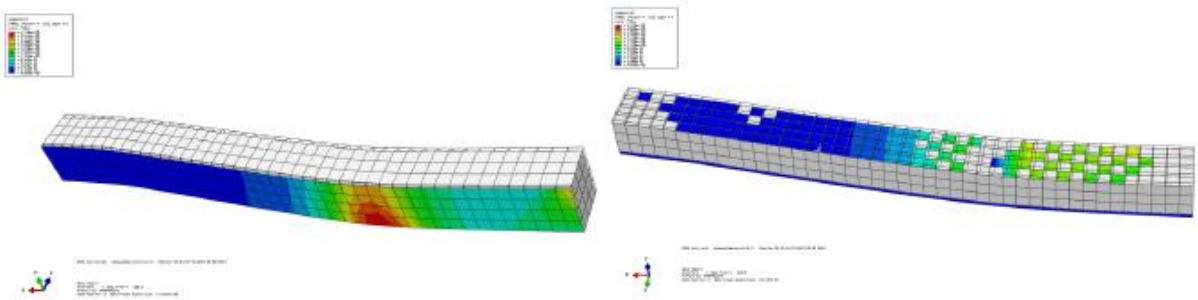

Figure 9: Four-point bending tensile failure for PUR(left) and compressive failure for p-PMI (right) core structures.

Nevertheless, in the case of the PUR core structure, the maximum force and associated displacements are not far from the experimental values (*cf.* Table 5). In the case of p-PMI core structures the simulation of 3-point bending predicts failure at force value close to only 50% of the experimentally observed load. Still, the displacements are close which indicates the face-sheet material properties may have to be reassessed. In the case of 4-point bending, the predicted failure load is closer to the observed failure load, but the predicted failure deflection is almost 60% higher than observed. This can probably be associated with the fact that a core compressive failure is predicted when in fact shear failure was observed.

Test geometry	Core material	Max. load (N)	Max. load / Failure displacement (mm)
3-point bending	PUR foam	400	7.52
	p-PMI foam	633	5.06
4-point bending	PUR foam	206	16.8
	p-PMI foam	518	20.1

Table 6: Sandwich structure flexural modelling results.

4 CONCLUSIONS

This work was initiated as a short-duration project performed within the objectives of Composite Systems course project for the Masters graduation in mechanical Engineering. The influence of machining a higher modulus and higher density PMI foam through a perforation scheme, to approach the density of a lower density lower modulus PUR foam was investigated. The study addressed foam compression behavior, and foam core sandwich structures performance in three/four-point bending and under low velocity impact. The following main conclusions resulted:

− The perforation scheme lowered, as expected, the original material compressive properties but they remained far superior to those of the PUR foam;

− The properties retained by the PMI material after perforation result in a far better performing sandwich structure than the one based on PUR core, under both 3-point and 4-point bending;

− Perforation, nevertheless resulted in a sandwich structure with lower resistance than one based on neat PMI foam, but with no noticeable decrease in overall sandwich stiffness;

− Very different impact event force-time plots result for structures with PUR and perforated PMI, and the later structure shows, as expected, higher stiffness;

− Structure damaging phenomena are observed in the face-sheet of the perforated PMI structure only at 10 J and beyond, and externally visible core fracture begins at 15 J impacts;

− The lower stiffness of the PUR core diverts energy absorption to extensive core cell collapsing, and face-sheet damage is only visible at 15 J and beyond. Core fracture becomes externally visible at 10 J impact;

− The permanent indentation values are consistently lower for the PUR core structure after impacts of equal energy, even though the PUR core structure is subject to higher displacements during the impact events;

− Permanent indentation correlates well with impact energy and a quadratic function results for structures based on both core materials;

− The sandwich flexural behavior modelling studies failed to predict the observed shear failure mode which is attributed to an over-simplified core behavior modelling;

− The simulations did however produce reasonable predictions of maximum loads and maximum load displacements for the PUR core sandwich both in three-point and four-point bending;

− Modelling of the perforated PMI core sandwich only produced an acceptable prediction of maximum load in four-point bending;

Future work shall address improving modelling assumptions with regard to core material properties, adhesive layer inclusion and face-sheet properties. The study of different perforation schemes and their influence on core and sandwich behaviours is also planned.

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