Characterization of sandwich panels for indentation and impact

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Abstract. The integrity of sandwich structures which are susceptible to impact may deteriorate significantly due to collapse of the core material and delamination of the face sheets. The integration of a thin polyurethane interlayer between the composite face sheet and foam core is known to protect the core material and substantially improve the resistance to impact. The objective of the present work is to characterize the response of sandwich panels, as well as that of the constituents to impact. In particular, the response of polyurethane and foam samples under a range of quasi-static and dynamic loading rates is determined experimentally. Furthermore, the response of sandwich panels to quasi-static indentation and low velocity impact is examined to quantify the extent of damage and how it is affected by the integration of polyurethane interlayers in their construction. This information is useful in the modelling of high velocity impact of sandwich panels; an effort which is currently underway. The results illustrate the benefit of using polyurethane interlayers within the construction of sandwich panels in enhancing their performance under quasi-static indentation and impact loads.

1. Introduction
Motivated by the desire to develop damage-tolerant composites and sandwich structures for wind turbine blades, the present paper discusses an experimental program for quantification of the performance of these structures and their constituents. Of particular interest is the behaviour of sandwich panels since they are used extensively in the designs of modern wind turbine blades. It is well known that standard sandwich designs, which consist of laminated face sheets bonded to structural foam core often exhibit collapse of the core under both quasi-static and dynamic compressive loads. Collapse of the foam is usually accompanied by delamination of the face sheet when bending moments are dominant [1].

Under lateral impact and blast loads, induced compression waves propagate through thickness of the sandwich structure and cause permanent compression of the foam core [2]. Recent work by Bahei-El-Din et al. [3-5] showed that permanent compression of the foam core can be partially suppressed if a thin membrane of a flexible material is inserted between the face sheet and the core on the loading side. Various types of materials were investigated for the proposed membrane including polyurethane, polyurea, elastomeric foam and their combinations. Massabo' [6] studied the interaction

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of multiple damage mechanisms in multilayered and sandwich structures subjected to static and
dynamic loading conditions and showed that these loadings on laminated and multilayered systems
affect crack growth characteristics and energy absorption. Abrate [7] introduced some models capable
of predicting the ballistic limit and the extent of damage in composites and sandwich structures. Gupta
and Shukla [8] studied the performance of sandwich structures subjected to high velocity impact
accompanied with varying service temperatures. Their results showed a significant decrease in flow
stress with increasing the service temperature. Gardner and Shukla [9] studied the effect of
implementing a polyurea interlayer behind the foam core and in front of the back face sheet using a
shock tube; the results obtained emphasized that implementing a polyurea sheet will reduce the back
face deflection and in-plane strain, which lead to enhancing the overall blast performance.

Review of the literature on this subject indicates that the current state of the art informs that
implementing a ductile interlayer in composite sandwich structures enhances their structural
performance. While several trials have shown that introducing polyurethane in the design of sandwich
panels leads to significant improvements, there is a lack of sufficient experimental data for sandwich
panel to quantify it. Consequently, the current work aims at investigating the properties of a modified
sandwich structure, where a flexible polyurethane (PUR) layer is introduced.

The paper examines the behaviour of sandwich panels and their constituents under quasi-static and
dynamic loading conditions, with focus on how effective the inclusion of PUR interlayers is in
enhancing the resistance to indentation and impact. The paper first describes in Section 2 the materials
involved in the present work. Section 3 discusses the experimental methods and tools involved.
Section 4 presents results obtained along with discussions, followed by conclusions in Section 5.

2. Materials
Conventionally designed sandwich plates consist of laminated fibrous composite face sheets bonded to
closed cell structural foam core, figure 1a. The modified sandwich design, on the other hand, inserts a
polyurethane (PUR) interlayer between the face sheet and the foam core on one side where the load is
expected, figure 1b.

E-glass/epoxy composites were used for fabrication of the composite face sheets of the sandwich
panels. The glass fibres were obtained from Selcom Multiaxial Technology, Italy as nonwoven fabric,
and the epoxy resin was provided by Huntsman, Switzerland. The core material used in the sandwich
panels is Divinycell P, a closed cell structural foam provided by DIAB. Axson Technologies of France
provided the polyurethane (PUR) used in modified sandwich designs, figure 1b. Table 1 lists the
material data received from respective supplier.

3. Experimental Work
3.1. Uniaxial quasi-static tests
To quantify the mechanical properties, samples of the above materials were prepared and tested under
uniaxial tensile load. Composite specimens are fabricated using both hand layup and vacuum infusion
methods. Tensile tests performed on unidirectionally reinforced specimens provided a fibre volume
fraction of 0.542 when the measured longitudinal Young’s modulus was compared to that estimated
from the Mori-Tanaka estimate [10]. This was verified by comparing the measured and calculated
overall tensile strength in the longitudinal direction and the overall density. Table 2 shows measured
and calculated elastic properties of E-glass epoxy unidirectional composites produced by the vacuum
infusion technique.

Samples of polyurethane (PUR) are prepared from two parts, which are mixed and cast in moulds
prepared to provide the net shape of the samples. The latter are cylindrical samples with a diameter of
38 mm and height of 6 mm. The compression tests are performed at various strain rates for two sets of
boundary conditions, unconfined and laterally confined. In addition, the friction between the loading
platens and the PUR samples is reduced in one group of samples by means of a lubricant. Foam
samples having a diameter of 50 mm and thickness of 20 mm are cored from Divinycell P150
structural foam sheets and tested at different strain rates under the quasi-static regime.
Figure 1. Sandwich construction, (a) Conventional design, (b) Modified design.

Table 1. Material data

| Fabric Arrangement | UNIE1050M50 | ETXL 1200 – SBIL | ETXL 900 |
|--------------------|-------------|------------------|----------|
| 0° (1005)          | 0° (595)    | +45° (224)       |
| 90° (50)           | +45° (303)  | 90° (452)        |
| Random (50)        | -45° (303)  | -45° (224)       |

| Designation         | Density (kg/m³) | Compressive Strength (MPa) | Compressive Modulus (MPa) |
|---------------------|-----------------|-----------------------------|---------------------------|
| Divinycell P Structural Foam | 150             | 9.4                         | 152                       |

| Designation         | Hardness (Shore A1) | Tensile Strength (MPa) | Elongation at Break (%) |
|---------------------|---------------------|------------------------|-------------------------|
| Polyurethane Casting Elastomer UR5801 /UR5850 | 50                 | 5                       | 1100                     |

Table 2. Elastic properties of E-glass/epoxy unidirectional composites

| \( \rho \) (kg/m³) | \( E_1 \) (GPa) | \( E_2 = E_3 \) (GPa) | \( G_{12} = G_{13} \) (GPa) | \( G_{23} \) (GPa) | \( v_{12} = v_{13} \) | \( v_{23} \) |
|-------------------|-----------------|-----------------------|-----------------------------|-----------------|------------------|-----------------|
| 1848              | 42              | 10.33                 | 4.31                        | 3.77            | 0.238            | 0.37            |

* measured

3.2. Split Hopkinson Pressure Bar Tests
The Split Hopkinson Pressure Bar (SHPB) apparatus used in the present work consists of an operated gas gun, a striker, an incident bar and a transmitted bar made of aluminium alloy. A data acquisition system consisting of a 120 ohm Wheatstone bridge connected to an amplifier and a PC-Based oscilloscope is employed in the present work. However, testing of soft materials presents a challenge to the conventional SHPB. Chen et al. [11] have investigated techniques for dynamic testing of soft materials and suggested modifications to be made to the conventional split Hopkinson pressure bar in order to test low-strength, low-impedance materials. A hollow transmission bar made of aluminum alloy together with a pulse shaper are used to measure the dynamic mechanical responses of soft materials such as PUR and foam tested in the present work. In addition, one dimensional wave analysis of signals recorded, i.e. incident, reflected and transmitted, is modified to account for the new arrangement. Foam cylindrical specimens, which are 10 mm long and 18 mm in diameter are tested at different levels of strain rates. Samples of PUR having a diameter of 5 mm and 1 mm or 2 mm thickness are cored from sheets of the same thickness. All tests are carried out using copper pulse shaper and grease between the surfaces of the specimen and the ends of the bars.
3.3 Indentation Tests

Indentation tests are performed according to ASTM D6264–98 on sandwich panels. The purpose of the experiments is to measure the resistance to damage under the effect of a concentrated load applied at the centre of the specimens by means of an indenter with a hemispherical tip. The rate of loading is slow enough to qualify for quasi-static loading conditions.

Square specimens with a side length of 152 mm are cut from larger panels which were fabricated by both hand layup and vacuum infusion. One set of specimens contained sandwich construction with PUR interlayers on the indentation side, figure 1b. In this case and to insure flow of the resin through the specimen thickness during vacuum infusion, a network of small holes was introduced in the PUR interlayer. Experiments are conducted for both simply supported and fully clamped boundary conditions. A universal testing machine was used to apply the load in displacement control mode at 2 mm/min. The diameter of the hemispherical tip of the indenter is 20 mm.

Low velocity impact is performed using a drop tower facility in which the indenter resembles that used in the quasi-static indentation tests. Three test specimens of each sandwich construction are impacted with equivalent impact energy of 67 Joule induced by a mass of 3.4 Kg dropped from a height of two meters. Specimens are securely clamped between two steel plates.

4. Results and discussion

Figure 2 shows the stress-strain behaviour of PUR under quasi-static compression. The loading branch of the stress-strain curves is slightly nonlinear. On unloading, the stress-strain response of the specimens with no lubrication on the surfaces which support the load is nonlinear with a large hysteresis forming before the specimens are fully unloaded, figure 2a. This is attributed to friction between the compression platen and the specimen, which tend to retard the lateral deformation and hence affect the axial displacement. The hysteresis however disappears for the specimens where lubrication was applied at the loaded surfaces, figure 2b. The material exhibits moderate increase in strain hardening as the strain rate increases by one order of magnitude. As expected, lateral confinement of the PUR specimens enhances its

Figure 2. Measured response of PUR under uniaxial compression, (a) Unconfined and unlubricated, (b) Unconfined and lubricated, and (c) Confined.
load carrying capacity, figure 2c. The
dynamic response of PUR on the other hand
shows extremely high dependency on the
strain rate, figure 3. For example, the flow
stress at the highest strain rate of 8800 s\(^{-1}\) is
almost 35 times that found at a quasi-static
rate of 1.0 s\(^{-1}\) and a strain of 0.25.

Samples of structural foam are tested
under compression. The measured quasi-
static behaviour is given in figure 4. The
response shows a linearly elastic behaviour
with Young’s modulus of 150 MPa up to a
yield stress of 2.0 MPa. This is followed by
perfectly plastic response up to about 50% strain, which is caused by collapse of the
foam interior cells. Increasing the strain
beyond this magnitude initiates locking of
the foam closed cells, which causes a sharp
increase in the compression load. Full
densification of the foam is reached at strain
of about 85%.

The experiments reveal that behaviour of the structural foam is independent of the rate of loading
at the quasi-static regime. Under dynamic loading, however, there is a remarkable dependency on the
strain rate as shown in figure 5. At low and intermediate strain rates up to 2800 s\(^{-1}\), the foam samples
show a weaker behaviour as compared to the quasi-static response. At higher strain rates on the other
hand, the foam exhibits much larger stiffness under the applied load in comparison with loading at
quasi-static conditions. This discrepancy in behaviour could be attributed to the rate and sequence of
collapse of the foam cells.

Figure 3. Stress-strain response of PUR.

Figure 4. Response of cellular foam under
uniaxial, quasi-static compression

Figure 5. Dynamic response of cellular foam
under uniaxial compression
Energy absorption during quasi-static indentation up to complete perforation for different layups and manufacturing techniques is shown in figure 6. It is seen that energy absorption in the specimens fabricated by vacuum infusion is slightly higher than that found in the specimens fabricated by hand layup. This is attributed to the fully consolidated specimens produced by vacuum infusion. Moreover, the addition of PUR interlayer in the sandwich panels led to enhancement of the performance under penetration. It should be noted that, although the clamped specimens are expected to give higher energy absorption as compared to the simply supported specimens, the load-stroke curves for both experiments are very close as shown in figure 7. The short span and the fact that the deformation process is dominated by face sheet perforation lead to almost identical behaviour.

In low velocity impact experiments, the effect of introducing PUR interlayers to the sandwich panels can be quantified by measuring the depth of indentation and observing failure. The tests are conducted on different and multiple specimens and the depth of indentations are recorded and averaged. Sample results for the drop tower tests are given in figure 8. It is seen that inserting thin PUR layer between the face sheet and the foam core improves the resistance to impact substantially. For a 1 mm thick PUR layer, the impact resistance increased by 30% for specimens made by vacuum infusion and by 20% for specimens made by hand layup. The impact resistance was increased favourably by 60% for both hand layup and vacuum infusion specimens when a 2mm thick PUR layer is incorporated in the sandwich construction.

Figure 6. Comparison of measured specific energy for simply supported and fully clamped sandwich specimens subjected to quasi-static indentation, (a) Hand layup, (b) Vacuum infusion.
Figure 7. Representative load-stroke curves for simply supported and fully clamped sandwich specimens subjected to quasi-static indentation for [(0/±45)/(-45/90/45)/(20mm Foam)/(45/90/-45)/(±45/0)] specimens produced by vacuum infusion.

Figure 8. Depth of indentation caused in sandwich plates by low velocity impact at 67 Joule.

5. Conclusions
The present research measured experimentally the response of the constituents of composite sandwich panels under quasi-static and dynamic loading ranges. It also investigated the effect of modifying conventional sandwich designs by adding polyurethane (PUR) interlayers on resistance to indentation.
The following salient results summarize our findings:

1. PUR shows significant dependency on test conditions and loading rate, including quasi-static and dynamic rates, with the maximum resistance to deformation exhibited at high strain rates.
2. Cellular foam samples show distinct behaviours under quasi-static and dynamic loading rates.
3. Specimens fabricated by vacuum infusion exhibit enhanced resistance to indentation over specimens fabricated by hand layup.
4. The energy dissipated due to progressive damage and perforation of sandwich panels show an increase of about 20% for specimens produced by vacuum infusion over those produced by hand layup.
5. The energy dissipated by progressive damage and perforation under indentation is enhanced by the addition of PUR interlayers to sandwich designs. This increase in energy dissipation amounts to about 10-15% for thin PUR sheets on the order of 1-2 mm thick.
6. Under velocity impact, a 1 mm thick PUR layer, increases the impact resistance by 30% for specimens made by vacuum infusion and by 20% for specimens made by hand layup. The impact resistance is increased favourably by 60% for both hand layup and vacuum infusion specimens when a 2 mm thick PUR layer is incorporated in the sandwich construction.

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