Experimental characterization of phenolic-impregnated honeycomb sandwich structures for transportation vehicles

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Abstract

In the present paper the main outcomes of an experimental characterization on phenolic impregnated honeycomb sandwich structures are presented. The experimental investigations addressed both the static and dynamic properties of novel sandwich material, manufactured expressly for transportation industry and both the structural and impact behavior of the sandwich configuration. Moreover in order to fulfill design requirements, the prediction of the material properties and structural behaviors of sandwich structures due to environmental degradation have been assessed using accelerated aging tests. The outcomes herein presented provide information for the modification of design parameters to minimize the influences of the environmental factors and the adverse effect of in-service impact events.

Keywords:
- Phenolic sandwich structures
- Environmental degradation
- Experimental testing
- Impact behavior

1. Introduction

As designers in the transportation industry strive to reduce fuel consumption and improve safety, composite sandwich structures that provide improved stiffness-to-weight ratio, are becoming an attractive alternative to metals for mass transport applications. A reduction in structural weight of one large component usually triggers positive synergistic effects for other parts of the vehicle. For example, a reduction of the mass of a railway car body could lead to weight savings in the traction system, suspension, brakes and other subsystems. Therefore, using composite sandwich structures not only reduces weight, thereby improving fuel economy and increasing payload capacity, but also enables the design of aerodynamic, stable vehicles with a low center of gravity. Examples of sandwich composites employed in transportation vehicles can be dynamic, stable vehicles with a low center of gravity. Examples of sandwich composites employed in transportation vehicles can be found in [1,2] as structural floor and roof panels, in [3] as front structure, in [4,5] as body panels, and in [6] as nonstructural interior panels. However, problems with the fire resistance of organic matrix composites are seen by many as the most significant factor hindering their rapid expansion into a wide range of engineering applications in transport and infrastructure [7].

Among the currently available sandwich composite materials, phenolic resin-impregnated glass fiber reinforced plastics and aramid paper honeycomb (Nomex) are considered for the structural design of load carrying components of civil transportation vehicles in the present work. Phenolic resin is mainly considered for its inherently fire-retardant properties that evolve low levels of smoke and combustion products during a fire, compared to other types of resins—i.e., epoxy, polyester and vinylester—that burn and release large amounts of heat, smoke and toxic fumes that pose a risk to people, especially in the confined space of vehicles, and make it difficult for fire fighters to extinguish the fire. Despite the great interest on composite structures, only few publications contain information about mechanics and material characteristics of phenolic impregnated sandwich structures [8,9]. In particular, impact and environmental durability data for sandwich panels involving glass/phenolic skins and Nomex honeycomb core have not been reported before, to the authors’ best knowledge.

Since the mechanical properties of composite structures exposed to environmental influences such as humid air, temperature and ultraviolet radiation may be degraded with time, a decrease in performance over time can be expected. The environmental effects are, in general, peculiar to the polymeric matrix [10–12] as well as the fiber–matrix interaction and are linked to a wide variety of phenomena that can ultimately lead to swelling or even to the dissolution of the polymeric matrix of the composites. Moreover, attention should be focused on environmental degradation of the interface between core and facesheets [13,14]. As result, environmental effects must be considered during the design process. Since the degradation process of a composite sandwich structures depends on the environmental conditions, type of skins and core material, and production process, it is therefore necessary to evaluate the mechanical properties through accelerated aging tests in order to predict long-term performances of sandwich composites.

In addition to the aforementioned issues, in order to reliably predict the structural safety of composite sandwich structures,
understanding the adverse effect of in-service impact events (e.g. impact and penetration damage) has become important in the transportation industry. Generally, structural sandwich components have low resistance to out-of-plane impact due to the thin outer composite skins and the highly deformable cores. The common damage mechanisms in sandwich composites (e.g. matrix cracking, debonding, fiber failure) may appear individually or interact, resulting in complex skin failure modes under impact. After the fracture of the skin, the impacting object may damage and penetrate into the core. If impact speed is low, sandwich panels may respond by bending and little damage occurs if the kinetic energy of the impacting object is absorbed elastically by the panel. At higher impact velocities a critical condition is reached when local contact stress exceeds local strength, leading to laminate bending failure, core/skin interface delamination and core compression failure [15]. Core deformation and failure are therefore decisive factors for the energy absorption capability and impact behavior of sandwich panels [16]. Experimental and analytical studies have been conducted to understand the mechanical response of honeycomb sandwich structures under various loadings [17,18]. To design sandwich panels for short-term dynamic loads, it is necessary to have information about the influence of loading rate on the material properties. It is well known that in case of high loading rate an increase in material stiffness and strength compared to the static behavior may occur, which is referred to as the strain rate effect. When this effect is neglected, dynamic finite element (FE) simulations and theoretical derivations based on static material data often do not agree with experimental behavior. Consequently, design approaches using static data can be too conservative, which inhibits potential weight savings. The strain rate effect on axial behavior of both aluminum [19–22] and Nomex [23,24] honeycomb structures have been experimentally investigated through dynamic compressive tests performed with different techniques (i.e. drop weight, gas gun, and split Hopkinson bar). The results have shown that dynamic loading leads to: (i) a marginal increase of the initial stiffness and the peak compressive strength; (ii) a significant increase of the crush strength (plateau stress after the peak compressive strength).

Both experimental and numerical studies [25–28] have been presented on low-velocity impact on Nomex honeycomb sandwich structures, but only a small amount of literature concerns impact tests where complete penetration occurs [29].

The present paper describes the results of a material characterization program run on phenolic-impregnated honeycomb sandwich structure to be used in the construction of light vehicles in transportation fields. The testing program is therefore devised to investigate the role of the core and skin materials and their interaction in order to satisfy the structural safety in terms of stiffness and strength requirements, environmental influences, and in-service impact events. In particular: (i) static tests of the skin and core materials and sandwich elements are presented in order to establish the mechanical properties of the selected materials and to provide the structural response and failure modes of the impregnated sandwich structures; (ii) accelerated aging tests, involving both tensile and flexural behaviors, are presented in order to analyze long-term performances of both laminate material and sandwich elements exposed to outdoor environments; (iii) dynamic test results for the compression behavior and the impact response of sandwich panels are presented to explain the strain rate effects and damage mechanisms due to low velocity impact events.

2. Materials

The materials selected to manufacture the phenolic-impregnated sandwich structures are:

- 48 kg/m^3 hexagonal honeycomb core with a nominal cell size of 3.18 mm and made of phenolic-resin-impregnated aramid paper;
- Pre-impregnated satin-weave E-glass fiber reinforced phenolic resin skins with a cured ply thickness of 0.25 mm.

Since the skins are pre-impregnated, there is no additional adhesive used to bond the skins to the core. The materials were laminated in an autoclave at a temperature of 135 °C, a vacuum pressure of 2.5 bar and a curing time of 90 min. All the sandwich specimens considered in the following experimental activities have been assembled with the “L” direction of the honeycomb core (Fig. 1) along the primary direction.

The skin behavior can be modeled in a relatively simple manner when their properties are known, whereas the mechanical modeling of the honeycomb core material is less straightforward. The response of the core to shear loading mainly depends on the material used in the core and on the ratio of the core density to that of the solid material constituting the core. Zhang and Ashby [30] give a thorough overview of the literature on model the elastic and collapse behavior of honeycomb materials, while Aktay et al. [31] present numerical modeling of transverse crush behavior of honeycomb-impregnated materials using both detailed micromechanics and homogenized models.

3. Static tests

3.1. Laminate tests

The experiments involved both tensile and three-point bending tests to evaluate the in-plane tensile and shear properties and the interlaminar strength of the selected face sheet laminates.

Quasi-static tensile tests (Figs. 2a and b) were run on 1 × 15 × 250 mm coupons, tested in one series with the warp fibers parallel to the load and in a second series with warp fibers perpendicular to the load. These tests were performed in accordance with the ASTM D3039M standard [32]. Ultimate tensile stress and strain, elastic modulus, and Poisson’s ratio have been measured for the warp and fill directions. Due to the nearly balanced nature of the fabrics, laminates with the warp fibers perpendicular to the load are characterized by values close to those with warp fibers perpendicular to the load. Quasi-static shear tests (Fig. 2c) were run on 2 × 25 × 250 mm tensile coupons with a [+45/−45]_{25} stacking sequence in accordance with the ASTM D3518M standard [33]. Shear modulus, ultimate shear stress and strain have been derived by these tests. Three strain gauges were applied to each coupon in order to monitor the longitudinal and transversal strains and check the system alignment of coupons. Short-beam tests (Fig. 2d) in accordance with the ASTM D2344M standard [34] were run on 6 × 12 × 36 mm specimens, made by parallel laminating of prepreg.

![Shape geometry of the hexagonal honeycomb core.](https://example.com/honeycomb.png)
All tests were run on a 10 kN universal test frame controlled by an electronic control unit which allows monitoring the applied load and the stroke of the top cross head. Strain signals were acquired by a digital data acquisition system. Tests were conducted at a constant cross head velocity of 2 mm/min for tensile and shear tests and 1 mm/min for the short-beam tests. Table 1 reports elastic properties and strength values of face sheet material calculated from the quasi-static tests.

### 3.2. Sandwich tests

The sandwich experiments involved both compressive and flexural tests to evaluate the compressive and shear core properties and to provide the bending response in terms of stiffness and failure modes of the selected phenolic sandwich laminates. Therefore indentation tests were performed in order to investigate the mechanical behavior of honeycomb sandwich structures exposed to localized point loads, for example due to interaction with attached structures.

![Graphs (a) and (b)](image1.png)

**Fig. 2.** Experimental results of laminate tests: (a) tensile tests in warp direction; (b) tensile tests in fill direction; (c) shear tests; (d) short-beam tests.

### Table 1

<table>
<thead>
<tr>
<th>Property</th>
<th>Glass/phenolic</th>
<th>C.v. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>25.5</td>
<td>warp dir.</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>325</td>
<td>warp dir.</td>
</tr>
<tr>
<td>Ultimate strain (%)</td>
<td>1.53</td>
<td>warp dir.</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>3.41</td>
<td>fill dir.</td>
</tr>
<tr>
<td>Shear strength (MPa)</td>
<td>43.3</td>
<td></td>
</tr>
<tr>
<td>Shear strain (MPa)</td>
<td>2.47</td>
<td></td>
</tr>
<tr>
<td>Interlaminar strength (MPa)</td>
<td>21.3</td>
<td></td>
</tr>
<tr>
<td>Poisson ratio (-)</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>
3.2.1. Uniaxial compressive tests

Out-of-plane crushing behavior of Nomex honeycomb has been investigated by flat-wise stabilized compressive tests according to ASTM C365M [35] standard. The tests were run on five 60 × 60 × 32.2 mm coupons bonded between two 1-mm-thick phenolic skins with a constant cross head speed of 0.5 mm/min. The specimens were laminated with external skins in order to prevent local crushing at the edges of the honeycomb cores. Specimen and test set-up details are shown in Fig. 3.

Compressive modulus, stabilized compressive strength and strain, crush strength and strain values at which densification occurs have been determined by these tests. The stress–strain relationship (Fig. 4a) consists of three stages: the elastic regime up to the stabilized compressive strength, the crushing regime at nearly constant plateau stress (crush strength), and finally the densification regime, where the cellular structure is fully compacted resulting in a steep stress increase. The mean behavior of five specimens is shown in Fig. 4a. Fig. 4b shows the three deformation stages of the honeycomb core during a flat-wise compression test.

3.2.2. Flexural tests

Nomex honeycomb core shear properties and flexural behavior of the sandwich configuration were investigated by flexural tests according to ASTM C933M [36], and ASTM D7250M [37] respectively. Both three-point and four-point bending loading configurations were used to test sandwich specimens involving different skin and core geometries as reported in Table 2. Deformation of the core in the vicinity of the loading and support points could limit the use of fundamental analyses [38,39] to interpret the experimental results. However, in the present case, local indentation of the core was avoided by using:

(i) Loading bars consisting of 25-mm-wide flat steel blocks. The bars were designed to allow free rotation of the specimen at the loading and support points, such as to have sufficient stiffness to avoid significant deflection of the bars under load.

(ii) A size of specimen that satisfies the following relation [36]:

\[
F_c \geq \frac{2(c + t) \sigma t}{(S - L) l_{pad}}
\]  

where \(F_c\) is the core compression strength; \(S\) is the support span length; \(L\) is the loading span length, \((L = 0\) for 3-point loading); \(\sigma\) is the expected facing ultimate strength; \(t\) is the facing thickness; \(c\) is the core thickness; \(l_{pad}\) is the dimension of loading pad in the lengthwise direction of the specimen.

In the three-point bending tests (Fig. 5), skin deformations were monitored by three longitudinally-oriented electrical resistance strain gauges—one at the mid-span of the bottom skin and one at a 25-mm distance from the mid-span on the top and bottom skins. In the four-point bending tests, skin deformations were monitored by four longitudinally-oriented electrical resistance strain gauges—two at the mid-span of the bottom skin and two at the mid-span of the top skin. The displacement of the mid-span was monitored using a LVDT for both loading configurations. All the flexural tests were conducted in stroke control with a cross-head speed of 6 mm/min.

In order to compare the results of the different specimen geometries and loading configurations, the flexural response of the selected sandwich panels has been reported in terms of bending moment–curvature curves, as shown in Fig. 6a where each curve is the mean data of the three replicate specimens. The sandwich curvatures have been calculated by the strain signals of the top and bottom skins at the mid-span and at a 25-mm distance from the mid-span for the four-point and three-point bending tests, respectively. Fig. 6a allows comparing the flexural stiffness (slope of the curves) of the sandwich elements obtained by varying the core and/or skin thicknesses. As expected, a higher increase in the sandwich stiffness can be obtained by increasing the core thickness (from GN_1/GN_3 to GN_2/GN_4) as opposed to the skin thickness (from GN_1/GN_3 to GN_1/GN_2/GN_4).

Based on the measured sandwich skin properties, the sandwich transverse shear rigidity and the Nomex honeycomb shear modulus were calculated as functions of midspan deflections and applied forces in flexural tests of sandwich beams. First, the flexural stiffness, \(D\), of the sandwich configuration is found as:

\[
D = \frac{E(d^3 - c^3)b}{12}
\]  

Fig. 3. Static flat-wise stabilized compression tests: (a) test set-up; (b) specimen geometry.
core shear modulus, $G$, for at least ten sets of applied forces and deflections were found as:

$$U = \frac{P(S - L)b}{4A} \left[ \frac{P^2}{P^2 - 3S^2 - L^2} \right]$$  \hspace{1cm} (3)

$$G = \frac{U(d - 2t)}{(d - t)^3b}$$  \hspace{1cm} (4)

where $A$ is the beam mid-span deflection corresponding to the force level $P$. The shear rigidity and core shear modulus are finally evaluated as the average of the values calculated at each force level for each specimen.

Since all specimens failed by transverse shear in the core, the shear strength of the selected Nomex honeycomb core has also been calculated from the results of the flexural tests. Table 3 reports the mechanical properties of the core material derived from the quasi-static tests.

Closed-form analytical and numerical tools are able to capture the experimental behavior both in terms of stiffness and in regard to failure modes. Fig. 6b shows load displacement curves derived for the GN_3a and GN_3b specimens and the comparison with results of simulations based on both higher-order sandwich beam theory (HOSBT) \[41,42\] and on the finite element approach. The FE analysis has been performed on 3D-models (Fig. 7) using Nastran\textsuperscript{®} finite element codes \[43\]. The skins were meshed using 4-node shell elements, while the core was meshed using 8-node solid elements. A 2D-orthotropic material was used to define the composite fabric prepreg, and the composite function was used to create the stacking sequence of the face sheets. On the other hand, 3D-orthotropic material elements were used to define the honeycomb core. Skins and core material properties are defined only in the linear elastic range. Tied constraints were applied to obtain a full bond between the skins and the core.
Fig. 8 shows the “failure mode map” concept [44–46] applied to the phenolic-impregnated honeycomb sandwich elements under three-point bending loading configurations. The failure mode map was generated analytically using ordinary sandwich beam theory. The map shows the dependence of failure mode upon the sandwich geometry and the relative-core density and is able to capture the actual experimental failure mode. The relative core density is defined as the ratio of honeycomb core’s density to the honeycomb constituent material’s density.

3.2.3. Indentation tests

In order to investigate the crushing behavior of sandwich structures subjected to localized point loading, indentation tests were performed on 50 × 250 mm sandwich specimens manufactured by laminating 32.2-mm-thick Nomex core between two 1-mm-thick glass/phenolic skins. The sandwich beams were supported by a steel substrate. Thus, overall bending of the specimen was avoided. The tests were carried out under displacement control at a cross-head speed of 2 mm/min. The indentation load was applied through a steel cylinder (20 mm in diameter) across the whole width of the beam cross-section (Fig. 9). The test was conducted on three replicate specimens for each of four different displacement levels. Afterwards the load was released at a cross-head speed of 20 mm/min. During unloading, the face sheet flexed back but did not recover completely its undeformed shape: thus, a residual facesheet dent remained.

During the indentation tests, the load-indentation curve was recorded for both loading and unloading steps. A typical load-indentation curve for a Nomex honeycomb sandwich specimen is shown in Fig. 10. The curve shows a linear behavior up till the peak load. The emission of a noise (cracking sound) at the end of the linear domain is believed to be associated with the onset of core crushing. From an analytical point of view, if the back face of a sandwich beam is supported by a rigid plate, the upper facing can be considered as a beam of rigidity $EI$, supported by a foundation which provides a reaction $r(x)$ per unit length. The equilibrium of the beam is governed by the equation:

$$EI \frac{d^4w}{dx^4} + r(x) = 0$$

where $w$ is the transverse displacement. When the transverse normal stress remain low, the core behaves elastically and the reaction of the foundation is proportional to the transverse displacement.
In that case, the equilibrium of the top facing is governed by the equation for a beam on linear elastic foundation:

\[ \frac{d^4w}{dx^4} + \frac{k}{EI}w = 0 \]  

The stiffness of the foundation \( k \) is related to modulus of the core in the transverse direction \( E_c \), the width of the beam \( b \), and the thickness of the core \( c \) by:

\[ k = \frac{E_c b}{c} \]  

The foundation behaves elastically as long as the compressive stress in the core does not exceed the value \( F_c \) (core compression strength). That is, when the contact force reaches the value:

\[ P = \frac{2bF_c}{\lambda} \]  

where

\[ \lambda = \sqrt{\frac{k}{4EI}} \]  

In the present case, the peak indentation force derived by Eq. (8) is equal to 1.51 kN, whose value is very close to the experimental one 1.54 kN (C.V. = 8.16%).

After the peak indentation force, the force–displacement curve became nonlinear with a decrease in the stiffness. The nonlinear behavior was due to the progressive honeycomb crushing in the area under the indentor. Fig. 10b shows the residual dent magnitude and the length of damaged area as function of the imposed indentation. Each data point reported in Fig. 10b is the average of three tests. The results of the residual dent measurements are very sensitive to the time passed after indentation test. In this study, the measurement of the residual dent, equal to the displacement when the load dropped to zero, was performed directly in the test machine and immediately after unloading to the zero load level, thus, characterizing the instantaneous residual dent magnitude. The residual dent magnitude and length can be theoretically found applying the principle of minimum total energy. Energy methods based on assumed displacement functions, such as that used in the analysis of unloading, provide powerful tools for solving complex problems but do not in general lead to exact solutions as the conditions of equilibrium are only approximately satisfied [47]. For this reason, in Fig. 10b the residual dent magnitude and length have been interpolated by third order polynomials as functions of maximum indentation displacement.

4. Accelerated aging tests

In the present section, accelerated aging tests have been presented to analyze long-term performances of both laminate material and sandwich elements exposed to outdoor environmental conditions. The expected service life of the composite materials used in transportation fields is approximately between 20 and 30 years—a long period of exposure for polymer materials. Generally, damage by aging or weathering—environmental degradation of structural components of vehicle—can be due to a combination of processes.
The main factors that can affect long term properties in the railway field [48], considered in accelerated aging tests, are:

- Hygrothermal conditioning.
- Thermal cycles.
- Ultraviolet radiation.
- Chemical attacks.

The natural process of absorption of moisture in many composite materials is usually very slow. To accelerate the effects of moisture, specimens have been conditioned at 80 °C and 85% RH (hot-wet conditioning), and 80 °C and 0% RH (hot-dry conditioning) for 60 days. To assess the influence of freeze–thaw cycles, specimens have been subjected to an alternating decrease of temperature from 4 to −18 °C and increase from −18 to 4 °C in not less than 2 h and not more than 5 h. All the specimens have been subjected to 250 cycles. The UV environment was reproduced by sub-jecting the specimens to Cycle C, continuous UV with uninsulated black panel temperature at 50 °C, as described in the standard ASTM D 5208 [49]. For the analysis of the degradation due to alkali and acid attack, specimens were submerged in alkaline (NaOH 1 M sodium hydroxide solution) and acid (HCl 1 M hydrochloric acid) solutions, respectively, for 20 and 40 days at a temperature of 60 °C.

After environmental conditioning, the specimens were tested in order to evaluate in-plane tensile properties of the skin, core shear properties and flexural behavior of the entire sandwich configuration. The test matrix of accelerated aging tests is summarized in Table 4.

4.1. Laminate tests

Static tensile tests were run on 1 × 15 × 250 mm conditioned coupons with the warp fibers parallel to the load. These tests were performed as described in the static section. Elastic modulus, ultimate strain and stress have been determined by tensile tests for each specimen. It is underlined that coupons dipped into the alkaline solution were completely deteriorated (Fig. 11a) and could therefore not be mechanically tested. Experimental results are presented in Fig. 11b in terms of degree of degradation of tensile properties for each environmental conditioning. The obtained values show considerable reductions in ultimate strain and stress for the hot-wet and acid conditionings.

The degradation due to hygrothermal conditioning is related to the diffusion of water molecules in a polymer structure that causes an expansion and swelling of the structure: the increasing in distance between the macromolecular chains involves a weakening of the secondary intermolecular forces so that material becomes soft and more ductile. The chemical environment influences both the glass fibers and the polymeric resin. In particular, the acid conditioning causes the cleavage of the macromolecular chains, while the effects of the alkaline conditioning include both the disintegration of the matrix and the corrosion of the E-glass fibers.

4.2. Sandwich tests

Three point bending tests were run on 16.5 × 100 × 235 sandwich panels (GN_4 specimen code) with equal laminated E-glass/phenolic composite face sheets, each consisting of eight 0/90 woven plies (2 mm total thickness) stacked in the [0/90]_2s arrangements, bonded to 10.5 mm honeycomb Nomex core. Each type of sandwich structure was tested with two different support spans: S = 170 mm and S = 150 mm. The test procedure is the same as that described previously for unconditioned specimens. Two replicate specimens are tested for each configuration.

Figs. 12 and 13 shows the average load–displacement curves measured for each conditioned specimen families loaded in flex-ure. No premature failures (i.e., debonding) occurred during these tests. All specimens failed due to shear in the core. Therefore, the core shear ultimate strength has been obtained as a function of the maximum load. The experimental results show a reduction in the core shear ultimate strength of about 20% for hygrothermal, freeze–thaw and acid conditionings, while no reduction is ob-served for UV and hot-dry conditionings. The experimental results show a reduction in the sandwich flexural stiffness of less than 15%. As expected, the flexural stiffness reduction is due to the modulus reduction observed in the facesheets in each environmental conditioning. There are no reductions in terms of core shear modulus and sandwich transverse rigidity.

5. Dynamic tests

Dynamic tests at different loading were conducted using a drop weight tower apparatus that is controlled by an electronic control unit which allows monitoring displacement measurements with a laser measurement system (Fig. 14a). The experimental investiga-
tions addressed the dynamic compression behavior and the impact response of the sandwich panels. The compression tests were designed to provide the strain rate effect of the core behavior, whereas the impact tests assess the damage mechanisms occurring in the phenolic skins.

Since a drop weight tower cannot guarantee a constant strain rate during the all the tests, various techniques have been used in the literature to determine the strain rate. In particular Hsiao and Daniel [50] used falling weight impact system for dynamic characterization of composite materials in compression at strain...
rates up to several hundred per second. The strain rate seemed to reach a nearly constant value at a strain level of approximately 10%–20% of the ultimate strain in all cases. The authors measured strain rate by differentiating the strain–time curve at strain readings above 20% of the ultimate strain. Brown et al. [51] used a modified instrumented falling weight drop tower for dynamic characterization to analyze the effect of strain rate on the tensile, shear and compression behavior of a E-glass/polypropylene woven fabric composite over a strain rate range of $10^{-3}$–$10^2$ s$^{-1}$. The strain rate during the tests was derived from the gradient of the strain–time history data. Baker et al. [21] used gas gun dynamic tests to determine the energy absorption properties of aluminum honeycomb core. Since the impactor velocity was a nearly constant value until the core reached its compressive strength, the strain rate was computed based on the initial velocity of the impactor.

In the present experiments, it was observed that the impactor velocity holds a nearly constant value until the core reaches its compressive strength value. After that, the velocity decreased. However the gradient of the velocity curve is very low in the crushing regime, whereas it steepens in the densification regime. Based on the mentioned observation, the strain rate value was calculated based on the initial impactor velocity.

5.1. Uniaxial Compressive tests

Out-of-plane compressive tests were conducted on the drop tower facility at three different strain rates ($60$ s$^{-1}$, $120$ s$^{-1}$ and $200$ s$^{-1}$) on cylindrical specimens of 45 mm diameter and either 32.2 mm or 10.5 mm thickness (Fig. 14b). The smaller thickness was considered to achieve higher strain rates. In order to prevent

![Fig. 13. Load–displacement curves derived by bending tests for conditioned specimens: (a) support span of 150 mm; (b) support span of 170 mm.](image)

![Fig. 14. Dynamic tests: (a) drop weight tower apparatus; (b) specimen details for flat-wise stabilized compression tests.](image)
local crushing at the edge of the honeycomb structure, the core was bonded to 1-mm-thick glass/phenolic skins. A fourth order Butterworth low-pass filter was used in order to filter out superposed high frequency oscillations associated with dynamic loads (Fig. 15a). In this way, comparisons of dynamic and static test data can be made. Fig. 15b shows the stress–strain-diagrams at the investigated strain rates. Each shown curve represents the mean data of five replicate specimens for each specimen family. It can be seen that dynamic loading leads to a significant increase of both compressive and crush strength; in particular the compressive strength presents a DIF (Dynamic Increase Factor, ratio of the dynamic value over the static one) of 1.20 (at 200 s$^{-1}$), whereas the crush strength presents a DIF of 1.10 (at 200 s$^{-1}$).

The influence of dynamic loading on the densification point has been also observed: the dynamic strain value is about 10% lower than the quasi-static one. On the contrary, no influence on the initial stiffness has been observed. For aluminum honeycomb structures the DIF for crush strength was observed to be about 1.33 (gas gun test, 100 s$^{-1}$) [21], 1.40 (split Hopkinson pressure bar, 800 s$^{-1}$) [22] and 1.50 (gas gun test, 2000 s$^{-1}$) [23] above the quasi-static value. For Nomex honeycomb structures the DIF for the crush strength was observed to be about 1.00–1.30 in the strain rate domain from 50 s$^{-1}$ to 300 s$^{-1}$ [24].

5.2. Impact tests

Impact tests were performed on specimens prepared with 11-mm-thick Nomex honeycomb sandwiched between either 1-mm or 2-mm glass/phenolic skins consisting four or eight fabric plies, respectively. The specimens were clamped using cylindrical rings and impacted with a 16.8-kg mass at three different energy levels, achieved with three different velocities ($v=1$ m/s, $v=4$ m/s and $v=8$ m/s). Tests at different impact velocities were performed to provide top skin damage ($v=1$ m/s) and complete penetration ($v=4$ m/s and $v=8$ m/s). Two different hemispherical tip diameters (12.7 mm and 20 mm) were adopted to provide their
The main objective was to assess the influence of skin thickness, impactor diameter, impact energy and impact velocity on the main outcomes of the impact tests—i.e. the impact damage (damaged area and through-thickness damage), the force history, and the energy absorption.

Load–displacement and energy–displacement curves are plotted in Figs. 16–18 for impact events which produce respectively visible damage of the top skin \( (v = 1\, \text{m/s}) \) and complete penetration \( (v = 4\, \text{m/s} \text{ and } v = 8\, \text{m/s}) \) of the sandwich specimens. Each curve is the mean of the three replicate specimens. All the results in terms of energy absorption and peak force have been summarized in Table 5.

At lower level of energy \( (v = 1\, \text{m/s}) \), the load curves grow up to a peak level which is due to the penetration of the impactor through...
the top skin. Furthermore, it can be observed that, before the penetration occurs, the curves present a change of slope due to the crushing of the Nomex honeycomb structures that happens when the Nomex attains the compressive strength.

At higher level of energy ($v = 4 \text{ m/s}$ and $v = 8 \text{ m/s}$), after the first peak the load curves present a low-loading plateau, characterizing the penetration of the honeycomb core, and a second sharp peak level due to the failure of the bottom skin. The absorbed impact energy displays a constant initial slope up till a penetration of the top skin is achieved. The gradient of the curve reduces when the core is penetrated and increases again when the weight impacts on the bottom skin.

The experimental trends show that, in higher-energy impacts, penetration resistance and absorbed energy are governed by the overall rigidity of the target and the resistance of the facing to perforation [52,53]. However, the energy absorbed by each skin is almost constant and increases proportionally to the skin thickness. The absorbed energy of the honeycomb core, related to the plastic strain of the walls, is very low in relation the energy absorbed by the skins. Therefore, the strain rate effects observed in the core are not evident in the sandwich composite under ballistic impacts.

In case of 1-mm skin thickness, no significant strain rate effects are observed for the peak forces and absorbed energies, whereas in case of 2-mm skin thickness a slight increase of the peak forces is observed (18% for top skin from 1 to 8 m/s, 12% for bottom skin from 4 to 8 m/s). In any case the energy absorbed by the facesheets and honeycomb increases with impactor diameter. In order to further understand the damage mechanism involved in impact events, the influence of skin thickness and impactor size on the failure modes are presented in Figs. 19–21. The main failure mode in the composite

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Fig. 19. Pictures of the impact face and cross-sectional view of sandwich specimens: (a) 1 m/s velocity, 1 mm skin thickness and 12.7 mm impactor; (b) 1 m/s velocity, 2 mm skin thickness and 12.7 mm impactor.

Fig. 20. Pictures of the impact face and cross-sectional view of sandwich specimens: (a) 4 m/s velocity, 1 mm skin thickness and 12.7 mm impactor; (b) 4 m/s velocity, 2 mm skin thickness and 12.7 mm impactor.
skin thickness and 20 mm impactor. In impact tests, in case of thicker skins, delamination occurs at the bottom skin.

6. Conclusions

The experimental activities presented in this paper provide mechanical data of novel phenolic sandwich materials and validate the manufacturing process and the mechanical behavior. The quasi-static study, in particular, underlines the capability of analytical and numerical models to capture the elastic flexural stiffness of sandwich structures. In order to evaluate the structural performances of phenolic sandwich structures subjected to environmental effects, the selected phenolic sandwich materials were exposed to accelerated aging conditions including temperature, moisture, chemical attacks and ultraviolet radiation. In the evaluation of the degradation of the sandwich materials, the following main outcomes have been obtained: (i) the E-glass/phenolic composite shows a considerable reductions in ultimate strain and stress for the hot-wet and acid conditionings; (ii) the E-glass/phenolic composite shows a reduction in elastic modulus of less than 15% for each environmental conditionings; (iii) the Nomex honeycomb core shows a reduction in shear ultimate strength of about 20% forhygrothermal, freeze-thaw and acid conditionings.

Moreover, the influence of the skin thickness, the material strain rate, the diameter of the impacting projectile and the impact velocity on the dynamic behavior of the sandwich composite material have been experimentally derived in order to understand the response of the sandwich material and the damage mechanisms involved in an impact event on a sandwich structure. The dynamic impact tests reveal that the global behavior and energy absorption are mainly due to the contribution of the skins. As it was expected, in impact tests, in case of thicker skins, delamination occurs at the bottom skin.

References


