Sensitivity of woven textile sandwich panel faces to Charpy impact properties

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Abstract
This research work is motivated by the increased demand for high impact strength and light-weight materials for many industrial applications, including aerospace and automobiles. Impact properties of 5-harness satin-weave carbon/cyanate ester polymeric prepreg sandwich structures has not been addressed adequately, though it is ideal for many space applications subjected to high temperatures. The impact behaviour of textile sandwich panels and their damage resistance were investigated experimentally using the Charpy test under high impact energy. This includes the sample orientations and its tested face to the impact direction. The results indicated that the sample orientations and its face to the impact direction has a significant effect on impact properties and observed damage modes. The selection of textile sandwich composite panel with higher impact resistance is an effective way of improving its applicability in many potential sectors.

1. Introduction
Composite materials are highly effective in their performance when contrasted to other materials, for instance, metals. The distinct characteristics of composite materials make them ideal for a variety of purposes in the automotive, defense, and aerospace industries [1–3]. Examples of these features include the stress-free achievement of complex forms, resistance to corrosion, low weight, and excellent damping properties [4]. Engineers have to comprehend the failure and damage of composite materials to ascertain whether they will prove to be cost-effective and reliable [5]. The application of composite materials differs significantly in added value, suitable production volumes, surface quality, operating temperature, loading, complexity, and size [6]. Typically, damage to these materials could manifest as delamination, fiber fracture, matrix cracking, and so forth.

Structures are exposed to various kinds of impact situations, and such incidents are visible in manufacturing, maintenance, and operation activities. Impacts, for example, caused by foreign objects or what researchers refer to as tool drops may result in serious structural damage [7]. For instance, if birds, hailstones, or debris fall on the materials, it could cause serious structural damage. Notably, varying degrees of damage and damage types exist, and mainly, this depends on the impactor masses and impact velocity. Damage can range from non-visible outcomes to barely visible and, in some extreme cases, the overall loss of structural integrity. The barely visible and non-visible effects are crucial given that delamination, fiber fractures, and matrix cracks could occur. The described damage could promote the gradual deterioration of materials during operation, compromising strength properties, and reducing laminate stiffness [7]. Fortunately, textile composites have high damage resistance and interlaminar and intralaminar strength [8]. Briefly, this is why certain industries, for example, the aviation sector, require highly damage-tolerant materials in manufacturing and operation activities.

Research studies have attempted to address the impact behavior of various composite materials. The research by Al-Hajaj et al [9] focused on characterizing the impact of woven carbon fibers plus flax fibers in an epoxy matrix. The overall result suggested that hybrid composites might have superior performance when contrasted to pure flax fiber-reinforced epoxy composites and hence, demonstrates that hybridization using
natural and synthetic fibers can be applied successfully. Another research study by Shah et al.\textsuperscript{10} analyzed the effect of various factors on impact damage and resistance tolerance of fiber-reinforced composites. They concentrated on primary factors, including resin toughness and fabric architecture. The outcome of this research showed that TP resin has improved performance, damage tolerance, and superior impact resistance, and this is evident even under extreme conditions. Note that low-velocity impact results in internal damage and induces complicated failure mechanism, and the outcome of these activities affects the structural capabilities of composites. Damage tolerance and impact resistance of fiber-reinforced composites is affected by multiple factors, for instance, matrix/fiber hybridization, stacking sequence, extreme conditions, impactor geometry, resin toughness, and fabric architecture\textsuperscript{10}.

The study conducted by Heimbs et al.\textsuperscript{11} concentrated on understanding the mechanical performance of sandwich structures that had epoxy/carbon skins and textile-reinforced composite foldcores under shear, compression, and impact loads. Grzeschik describes foldcores as folded open cellular structures, and professionals use different manufacturing approaches to produce these structures. Carbon foldcores tended to crush after absorbing energy, while woven aramid fibers were generally ductile\textsuperscript{11}. The researchers found that the composite materials had higher weight-specific compression properties when compared to those of Nomex honeycomb cores, even when these had a similar density. The skins were responsible for absorbing energy; despite this, high stiffness resulted in localized impact damage, especially since the bending of skins was hindered. Other studies have also assessed the impact behavior of composite materials with different fiber architecture\textsuperscript{12–15}. Chen and Hodgkinson\textsuperscript{15} found that 3-dimensional woven composites had the greatest damage tolerance and resistance in the event of a low-velocity impact. However, non-crimp fabric demonstrated higher damage resistance in the event of a high-velocity impact. Clifton et al.\textsuperscript{16} conducted an in-depth methodical and technical analysis and concluded that nanocomposites have huge potential for enhancing composite materials to higher levels of high-velocity impact and structural resistance applications. Sasikumar et al.\textsuperscript{17} found that impact behavior influences two main effects on hybrid matrix composite laminates: fiber fracture and shear decoupling.

The study by De Almeida et al.\textsuperscript{12} identified two broad categories of failure following effects: a highly deformable behavior mode and a brittle behavior mode. Specifically, the impact of textile and laminate composites is different, and the two materials also differ based on their deflection angle and sensitivities\textsuperscript{18}. Research activities have shown that impact behavior differs based on the materials that researchers have investigated and the damage modes\textsuperscript{19, 20}. Fundamentally, individuals have to comprehend the influence of certain factors, for example, type of velocity and damage modes interaction, when attempting to predict the failure of textile composite materials. Researchers have continued to launch new investigations on the impact behavior of textile sandwich materials to determine impact resistance. Consequently, this paper aims to investigate the 5-harness satin-weave carbon/cyanate ester polymeric prepreg sandwich structures using the Charpy test under high impact energy. This includes the sample orientations and its tested face to the impact direction which has not been reported in the literature.

The present paper contributes to the existing knowledge in four important aspects. First, providing a systematic approach for the characterization of impact behavior of woven textile sandwich panel at high impact energy (750 J). This is more convenient to simulate the conditions that occur during collision, especially in space and aerospace applications. If the birds, hailstones, or debris collide on the materials, it could cause serious structural damage. Therefore, identifying dominant damage mechanisms and locations in the selected materials helps to validate its applicability in such conditions. Secondly, there are no available studies on carbon/cyanate ester prepreg sandwich panels subjected to Charpy impact. This material is of special interest to the industries due to their ease of processing and light-weight, which is ideal for many space applications exposed to high temperatures. Third, the paper analyzes the sensitivity of woven textile sandwich panel faces to Charpy impact properties. The satin fabric is not symmetrical about the middle plane. Although several studies have been conducted towards the characterization of impact, there is still lack in considering the effect of nature of the reinforcement during high impact energy test. Fourth, significant investigations must be conducted in order to obtain the required properties for the material models in the FE simulation. These material models must be correlated to the observed behavior during the material characterization tests. Hence, adding new contributions to the existing knowledge that may consider during the simulation process in the future.

2. Materials and methods

2.1. Materials

In general, thermosets are suited for high temperature applications in structural and sub-structural components, including space applications, rocket airframes, and supersonic aircraft. Epoxy, polyimide, bismaleimides (BMI), phenolic, and cyanate ester are the five main types of resins used in space applications.
However, cyanate ester resin possesses the properties of all other four resins as well as high toughness, high glass transition temperature (250 °C–290 °C), low moisture absorption, and good dielectric properties. Therefore, the carbon/cyanate ester polymeric prepreg sandwich panels are of special interest to the industries due to their ease of processing and light-weight, which is ideal for many space applications subjected to high temperatures.

The composite face sheets in this study were 5-harness satin-weave carbon/cyanate ester polymeric prepreg. Epoxy film adhesive was used to bond the honeycomb core with multilayer textile prepreg plies; four plies with [(0/90), (±45), (0/90), core], orientation were chosen. A light core material is used for the separation of the pair of thin facings, namely the Kevlar honeycomb core. The Kevlar honeycomb material is constructed from hexagonal cells with a regular pattern arrangement. The cell size was 3 mm with 46 micrometers of wall thickness and a density of 48 kg m\(^{-3}\). The core thickness was about 12 mm. The vacuum bag molding technique was used to create multilayer sandwich panel combinations. The sandwich panels underwent curing at a temperature of 121 °C for 180 min with a final thickness of 14 mm. The volume fraction of fabric plies was 50%. The sandwich panel, layup sequences, and selected samples are presented in figure 1. Please note that Ply 1—4 refers to the stacking sequence and its orientations to laminate the top and bottom factsheets of the sandwich panel, while face 1 and face 2 in each ply are correlated to the nature of the reinforcement used. The used material was a 5HS, and the satin fabric is not symmetrical about the middle plane. This implies that 80% of the fibers on one face are aligned at 0° direction and 80% of the fibers on the other face are aligned at 90° direction. When the samples were cut into warp and weft samples, the face that has 80% of the fibers in 0° direction is called face 1, and the back side face where 80% of the fibers in 90° direction is called face 2 (see figure 1).

Figure 1. Textile prepreg sandwich panels and selected samples.
2.2. Low-velocity impact test (Charpy test)

One of the primary benefits of Charpy tests is that they are capable of delivering high-energy impacts to a relatively small test specimen. This is especially advantageous for larger products such as construction beams. In this regard, Charpy tests are able to deliver higher energy impacts and damage on a smaller surface area than other low-velocity impact tests. This test is capable of simply and effectively producing valuable comparative data. To evaluate the impact damage resistance of textile composite laminate panels, a motorized pendulum impact Charpy test was utilized (see figure 2). All the Charpy experiments were carried out with an effective weight of pendulum assembly of 54.4 kg and a pendulum length of 762 mm, which resulted in an impact velocity of 5.28 m s$^{-1}$ and impact energy of 750 J. The Charpy striker attached to the pendulum head was 8 mm striker with a weight of 950 g (see figure 2(b)). All of the samples were 60 mm in length and 16 mm in width and were supported by anvils with a 40 mm support span as displayed in figure 2(c). Please note that the friction angle must be properly calibrated and checked before each series of tests. This implies that the energy absorbed field should read zero when a free swing is performed. A free swing is a complete swing of the pendulum from the latched position with no specimen in place.

3. Results and discussion

3.1. Absorbed impact energy

As previously shown in figure 1, both the warp and weft samples were included in the analysis to investigate the effect of weave structures on impact properties. When the Charpy striker was applied perpendicularly to the warp direction tows, the selected samples were known as the warp samples. On the contrary, the weft samples were considered when the weft direction tows were perpendicular to the Charpy striker during the impact test. Note that Face 1 for both the warp and weft samples is also shown in figure 1. In 5-harness woven fabric, 80% of fiber tows on one face were in the strip-long direction, though 80% of fiber tows on the other face were perpendicular to that direction [21, 22]. Therefore, the impact properties may be sensitive depending on which face is tested. During the warp face 1 sample tests, 80% of fiber tows were aligned to the warp direction, whereas, in the weft face 1 samples, 80% of fiber tows were perpendicular to the weft direction (see figure 1). Other faces (back faces) were indicated by warp face 2 and weft face 2 samples, respectively.

The absorbed impact energy for 5HS sandwich panel (warp) and (weft) samples tested at room temperature with an impact speed of 5.28 m s$^{-1}$ is presented in figure 3. The average absorbed impact energy of the three test experiments in the warp direction (face 1) was 7.15 (J), versus 6.28 (J) in the weft direction (face 1). The results show that the absorbed impact energy in the warp direction was almost 14% higher than the absorbed energy in the weft direction. This difference may be attributed to the fact that the warp direction has a smaller number of crimps and more fabric density compared to the weft direction. In addition, the variation between face 1 and face 2 for both directions is depicted in figure 3. The face 1/face 2 variation is likely to have as much influence on the results as the variation between the warp and weft samples. However, the distribution of resin in the prepreg materials may have played a role in this distinction.
3.2. Observed damage modes

The damage behaviours and penetrations were investigated by analyzing the cross-section pictures of impacted samples. Figure 4 shows the damage and failure modes of 5HS sandwich panel for warp direction face 1/face 2 and weft direction face 1/face 2 samples. Although the damage modes are complicated for the woven textile sandwich panel, the results of three tests conducted for each sample show a minor difference between them in terms of the observed damages. As seen in figure 4, a complete penetration has not occurred for all the cases. However, the failure modes, such as fiber fracture, de-bonding, delamination, and core damage, were different between the four selected samples. In warp sample face 1, the fiber fracture occurred on the impacted side, and ply delamination could be observed on the other side within the same sample. The delamination damage was limited in the woven fabric plies because the propagation of delamination is limited by the chaotic interface of any two plies [12]. However, it was considered to be a significant failure mode in unidirectional (UD) laminates [12]. The fiber fracture for both sides and core damage were obviously dominant in the weft sample face 1. Debonding of the face sheet and core and fiber fracture occurred only in the impacted side of warp sample face 2. The last sample (weft face 2) showed fiber fracture and severe damage of core materials. In all the samples, dominant fiber fracture had occurred, especially on the impacted sides.

The amount of energy absorbed by a structure offers valuable data about the crash performance of selected materials. Overall, the damage modes and failure behaviours are in accordance with the absorbed energy investigated in the aforementioned results. This implies that higher absorbed energies show lower occurred damage modes. Note that this depends on many other factors, such as weave patterns and stacking sequences [12]. Moreover, core materials play an important role in terms of observed damage modes as described in [23]. In this regard, it should be noted that core material content by weight within cut samples contributes to different failure modes. The friction between the samples and anvils may also play a role in this regard. These findings suggest that sample orientations and its face to the direction of impact have a significant effect on impact properties and observed damage modes. However, different stacking sequences should be tested to confirm this conclusion. This will be a part of future research.

4. Conclusions

In the current study, the impact properties of 5-harness satin-weave carbon/cyanate ester polymeric prepreg sandwich structures and their damage resistance was investigated experimentally using the Charpy test under high impact energy. Based on the obtained results, the results show that the absorbed impact energy in the warp direction was almost 14% higher than the absorbed energy in the weft direction. This difference may be attributed to the fact that the warp direction has a smaller number of crimps and more fabric density compared to the weft direction. The sample orientations and its face to the impact direction had a significant effect on impact properties and observed damage modes. Therefore, the impact properties are sensitive to which face of textile fabric is tested. The influence of woven structures could be considered as key factors controlling the
damage mode of the selected materials. Hence, this factor should be taken into account during the simulation process in the future. Moreover, SEM analysis of the sample before and after testing must be carried out in order to investigate microscopic observations, including matrix cracks, fracture surfaces, and fiber surface.

Figure 4. Observations of damage behaviours on 5HS sandwich panel for warp direction face 1/face 2 and weft direction face 1/face 2 samples; (a) test 1, (b) test 2, and (c) test 3.
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of Interest

The authors declare that they have no conflict of interest.

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