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RESEARCH ARTICLE

An investigation of the effect of structural parameters on the impact properties of sandwich-structured shock absorbers

İpek Yalçın Eniş, Hande Sezgin

Istanbul Technical University, Textile Engineering Department, Istanbul, Türkiye

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Abstract

The purpose of this study is to develop an impact absorber with a core made of sustainable textile waste as an alternative to the conventional honeycomb structure. In this case, the core structure is made of cotton fiber webs recycled from denim waste, and the outer shell is made of polypropylene plates reinforced with carbon, jute, and E-glass woven fabrics. Production of the sandwich structure is carried out using the hot press method. In addition to the fabric types and layer sequences utilized in the outer shell, the geometry of the core structure is altered, and their effect on the drop-weight impact resistance is examined. The prominent results emphasize that the use of high-performance fabrics in the outer shell facing the outer surface increases the impact resistance, and the sizes of the holes to be obtained in the core structure should be optimized in order to be effective in energy absorption. The results reveal that these developed sandwich structures can constitute a promising alternative for the automotive industry.

1. Introduction

Impact absorbers are structures that offer vital safety against collisions or fatal injuries, particularly in the automotive, high-speed rail, or aviation industries. The low resistance of vehicles to dynamic loads necessitates the use of these structures. Shock absorbers improve vehicle resistance, extend vehicle lifespan, and provide safety [1]. The fundamental notion underlying how impact absorbers work is to transform kinetic energy prior to impact into mainly plastic strain energy which leads to great deformation on the material [2].

Square tubes, circular tubes, struts, and composites (such as honeycomb structures and sandwich plates) are frequently employed in impact absorber designs [2, 3]. Among these, the most preferred sandwich structures consist of two parallel layers connected by a core of any shape [4]. As a result of effects such as explosion, cracking and impact, the plate and core combinations used in sandwich structures have a critical importance. The plates on the outer shell are expected to show high fracture resistance, and the core structure is expected to provide high energy absorption. Particularly, in sandwich structures where the panels are designed flat, the role of the core in the absorption of energy during explosion or impact is more critical. The core part can be in two different forms as foam and architectural core [5].

An impact absorber's maximum energy absorption capacity is influenced by its structure and material [6]. Aluminum and its alloys are frequently used traditional materials for impact absorbers, although fiber reinforced composites are notable alternatives with their many benefits such as light-weight and high mechanical performance [3]. Composite shock absorbers provide high impact resistance thanks to their

Correspondence Ipek Yalcin Enis ipekyalcin@itu.edu.tr

superior performance (progressive crushing behavior, higher energy absorption capacity per unit weight, etc.) compared to metallic structures [7]. Novel impact absorbers can be made of composite materials reinforced with both natural and synthetic fibers. Natural fibers have an advantage over synthetic fibers in terms of cost and weight, as well as environmental considerations [8]. Jute fiber is one of the most popular types of natural fibers used in the composite industry, due to its biodegradable structure, which makes it environmentally benign, good mechanical strength levels, and widespread use. Aside from these benefits, its pricing makes it a competitive fiber type [9]. In contrast to natural fibers, synthetic fibers have exceptionally high mechanical qualities and simple operating conditions. Due to their mechanical properties, carbon and E-glass are two of the most used synthetic fibers [10]. E-glass fiber is frequently utilized in the composite industry due to its cost advantage and good mechanical properties. High impact resistance is the main quality that E-glass fiber reinforcement material contributes to composite materials [11]. Contrarily, carbon fiber is utilized in composite materials that need to be light and strong. Although its high cost is a drawback, it is the most extensively utilized reinforcement material due to its excellent load carrying capacity [12]. Thermoplastic composites, as opposed to thermoset composites, carry the potential for providing lightweight, robust parts with improved ductility and impact resistance [13]. One of the most popular thermoplastic polymer types in terms of matrix material is polypropylene (PP). In addition to being simple to use, it has strong mechanical and thermal characteristics [14].

Textile industry poses a serious danger to the environment and is responsible for 5% of all pollutants in the world. The denims are particularly harmful to the planet both before and after they are worn out and the majority of them cannot be recycled easily. The utilization of denim wastes in composites can reduce their negative environmental effects [15]. The core layer, which assumes the task of absorbing energy in sandwich structures, can be an effective part of this type of waste group's use.

When the literature is reviewed, it is discovered that many studies [16-25] used the honeycomb model in the core layers of sandwich structures with impact absorbing properties. Unlike previous studies, this one uses perforated composite structures produced from textile waste as the core structure rather than a honeycomb structure, and the effect of different sized holes, as well as fabric type and sequences used in the outer shell design, on the impact absorbing property is investigated.

2. Materials and methods

2.1. Materials

In this study, polypropylene (PP) chips (supplied by Yelken Plastik) are used as the matrix material, whereas E-glass (supplied by Omnis Kompozit), carbon (supplied by Spinteks), jute (supplied by Fibermak) woven fabrics and 100% cotton webs recycled from denim waste (Kucukcalik Denim) are used as reinforcement materials either in the outer shell or the core design. Technical details of the woven reinforcement materials are indicated in Table 1.

Table 1. Properties of woven reinforcement materials

Fabric type	Basis weight (g/m^2)	Weave type	Density	
			Warp (ends/cm)	Weft (picks/cm)
Jute Fabric	252	Plain	6	6
Carbon Fabric	184	Plain	4	3
E-glass Fabric	255	Plain	4	3

2.2. Methods

2.2.1. Production of sandwich structure

The production of the sandwich structure consists of four stages: i. Manufacturing of matrix plates, ii. Manufacturing of outer shells, iii. Manufacturing of core structures, iv. Design and fabrication of composite materials.

Manufacturing of matrix plates

To produce matrix plates, 100 g polypropylene chips are placed in the hot press machine between Teflon papers. The chips are allowed to melt for about 30 minutes until the temperature of the press reaches 180 ºC. Then, by applying 20 tons of pressure, the molten PP takes the form of a plate. The sample is kept under heat and pressure for 40 minutes, then the heat is turned off and the sample is left in the press for 24 hours to prevent the plate from curling.

Manufacturing of outer shells

To produce the outer shells, the prepared PP plates are placed in the hot press machine together with two selected fabrics (dual combinations of E-glass-jute and carbon-jute fabrics) to provide the PP plate/fabric/PP plate/fabric sequence. The production is carried out under 180 ºC and 20 tons, for 40 minutes as in the matrix plate production.

Manufacturing of core structures

In order to prepare the core layer, the waste denim fabrics are opened with a rag pulling machine twice (Balkan Machinery) and the shredded fibers are fed to the carding machine (Mesdan) in order to ensure homogeneity and obtain fiber webs. During carding, PP powder obtained by grinding in a blender (Retsch) is also fed to the structure as a binder, manually. Then, the fiber web containing waste cotton fibers and PP binders is placed in a hot press machine. The production is carried out at 180ºC, but this time without applying pressure to obtain a bulky structure. 0.5 cm thick metal rings are used to prevent excessive pressure on the samples. To examine the effect of core layer geometry on the energy absorption rate of the composite, holes are drilled into the samples using 2 different sizes of perforators (9 mm and 13 mm). The number of holes to be opened is calculated by keeping the total gap ratio of the sample constant. Fig. 1 shows the perforated core designs.

As a result, perforated cores with large and small holes, in addition to the imperforate cores, are prepared for use between outer shells.

Design and production of composite panels

A total of 12 samples are produced by combining different outer shells based on raw material type (E-glass or carbon) and layer sequences (inside or outside) and core structure geometries (large holes, small holes, and imperforate). The sandwich structures are once more placed into the hot press and exposed to the same production conditions to bind the outer shells by core layer. The sample codes of the produced composites can be seen in Table 2. The design of sandwich structures for a specific sample group consisting of E-glass fabric is illustrated in Fig. 2.

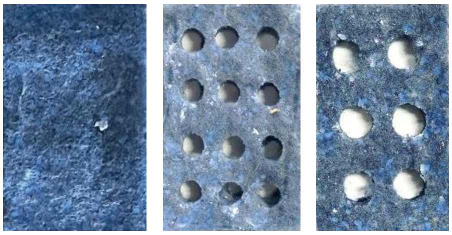

Fig. 1. Imperforate, small and large hole core structures

Table 2. Sample codes

Sample Codes	Outer Shell Design	Core Design
JC-0-CJ	binary structures including jute and carbon fabrics whereas jute fabric is placed in outer parts	imperforate core
JC-6-CJ	binary structures including jute and carbon fabrics whereas jute fabric is placed in outer parts	perforated core consisting of big holes with a diameter of 13 mm (total hole number is 6)
JC-12-CJ	binary structures including jute and carbon fabrics whereas jute fabric is placed in outer parts	perforated core consisting of small holes with a diameter of 9 mm (total hole number is 12)
CJ-0-JC	binary structures including carbon and jute fabrics whereas carbon fabric is placed in outer parts	imperforate core
CJ-6-JC	binary structures including carbon and jute fabrics whereas carbon fabric is placed in outer parts	perforated core consisting of big holes with a diameter of 13 mm (total hole number is 6)
CJ-12-JC	binary structures including carbon and jute fabrics whereas carbon fabric is placed in outer parts	perforated core consisting of small holes with a diameter of 9 mm (total hole number is 12)
GJ-0-JG	binary structures including glass and jute fabrics whereas glass fabric is placed in outer parts	imperforate core
GJ-6-JG	binary structures including glass and jute fabrics whereas glass fabric is placed in outer parts	perforated core consisting of big holes with a diameter of 13 mm (total hole number is 6)
GJ-12-JG	binary structures including glass and jute fabrics whereas glass fabric is placed in outer parts	perforated core consisting of small holes with a diameter of 9 mm (total hole number is 12)
JG-0-GJ	binary structures including jute and glass fabrics whereas jute fabric is placed in outer parts	imperforate core
JG-6-GJ	binary structures including jute and glass fabrics whereas jute fabric is placed in outer ptars	perforated core consisting of big holes with a diameter of 13 mm (total hole number is 6)
JG-12-GJ	binary structures including jute and glass fabrics whereas jute fabric is placed in outer parts	perforated core consisting of small holes with a diameter of 9 mm (total hole number is 12)

Fig. 2. An example of a sample group that belongs to a. (GJ-0-JG), b. (GJ-6-JG) c. (GJ-12-JG)

2.2.2. Performance Analysis

Physical and dimensional analyses

The samples' dimensions are measured with a digital caliper, and their weights are measured with a digital balance. The densities of the composites are calculated using the measured experimental data, and all results are given as mean values with standard deviations (SD).

Drop-weight impact resistance analysis

The impact testing machine (BESMAK) performs drop-weight impact tests on composites in accordance with the ASTM D7136 standard (sample dimensions: 89*55 mm). This method is based on the application of impact energy on the sample by dropping a weight from a predetermined height. During the test, samples are placed in a holder with an internal diameter of 100 mm and tested at a 20-Joule impact energy using a standard hemispherical head with a striker diameter of 16 mm. Results are given as average maximum load and average absorbed energy with their standard deviations. Moreover, load-deformation and energy-time graphs are plotted to interpret the deformation characteristics. Numerical results are also supported by visual deformation patterns.

3. Results

3.1. Physical and dimensional analyses test results

Thickness and the density values of the sandwich structures are listed in Table 3. While the thicknesses of the produced sandwich structures vary between 2.17-2.85 mm, their densities change in the range of 0,78-0,96 g/cm^3. Despite the fact that the productions are carried out concurrently and under the same pressure, there are minor differences in the thicknesses of some samples. The waste layer used in the core structure may be the cause of this situation. The density of E-glass fiber is 2.60g/cm^3 while the density of carbon fiber is 1.80g/cm^3 [11, 26, 27]. This supports the claim that the average density of the carbon-based samples (0.83 g/cm^3) is lower than the average density of the E-glass-based samples (0.90 g/cm^3).

Table 3. Measured thicknesses and the calculated densities of the sandwich structures.

Sample Codes	Thickness ± SD (mm)	Density ± SD (g/cm^3)
JC-0-CJ	2.82 ± 0.00	0.82 ± 0.00
JC-6-CJ	2.76 ± 0.05	0.83 ± 0.06
JC-12-CJ	2.85 ± 0.05	0.78 ± 0.03
CJ-0-JC	2.77 ± 0.07	0.84 ± 0.01
CJ-6-JC	2.60 ± 0.04	0.86 ± 0.04
CJ-12-JC	2.73 ± 0.07	0.82 ± 0.08
GJ-0-JG	2.20 ± 0.06	0.96 ± 0.04
GJ-6-JG	2.23 ± 0.07	0.97 ± 0.06
GJ-12-JG	2.19 ± 0.07	0.96 ± 0.03
JG-0-GJ	2.51 ± 0.05	0.79 ± 0.11
JG-6-GJ	2.74 ± 0.15	0.88 ± 0.03
JG-12-GJ	2.70 ± 0.05	0.84 ± 0.07

3.2. Drop-weight impact resistance test results

Table 4 shows the results of drop-weight impact resistance tests. The drop-weight impact resistance test results are evaluated separately by taking into account the type of reinforcement materials used in the outer layers, the different fabric sequences used, and finally the type of the core structure of the sandwich structures.

When the results based on the reinforcement material differences used in the outer shells are examined, it is seen that while carbon fabric reinforced structures have higher energy absorption, E-glass reinforced structures have higher maximum loads. The impact resistance of E-glass fiber is much higher than that of carbon fiber, according to the literature [28]. This circumstance supports the outcome. Carbon fabric reinforced composite structures, on the other hand, have higher thicknesses than E-glass fabric reinforced composites. As a result, the deformation time and deformation distance of the sample are prolonged in carbon fabric reinforced composites with lower impact strength, resulting in an increase in absorbed energy. According to Srivastava and Yadav (2015), as the thickness of the composites increases, so do the impact energies [29]. These numerical results are also supported by load-deformation and energy-time graphs plotted on the basis of the outer shells' raw material (Figs. 3-4).

Table 4. Maximum load and the absorbed energy values of the sandwich structures

Sample Codes	Max Load ± SD (kN)	Absorbed energy ± SD (J)
JC-0-CJ	1.185 ± 0.000	9.215 ± 0.000
JC-6-CJ	1.174 ± 0.096	7.651 ± 0.271
JC-12-CJ	1.146 ± 0.105	7.360 ± 0.981
CJ-0-JC	1.243 ± 0.067	8.328 ± 0.233
CJ-6-JC	1.179 ± 0.355	7.547 ± 0.883
CJ-12-JC	1.183 ± 0.142	7.141 ± 0.593
GJ-0-JG	1.504 ± 0.043	7.272 ± 0.962
GJ-6-JG	1.331 ± 0.071	7.541 ± 1.474
GJ-12-JG	1.278 ± 0.028	6.984 ± 1.322
JG-0-GJ	1.485 ± 0.133	6.889 ± 0.435
JG-6-GJ	1.327 ± 0049	7.777 ± 0.590
JG-12-GJ	1.271 ± 0.153	7.247 ± 0.360

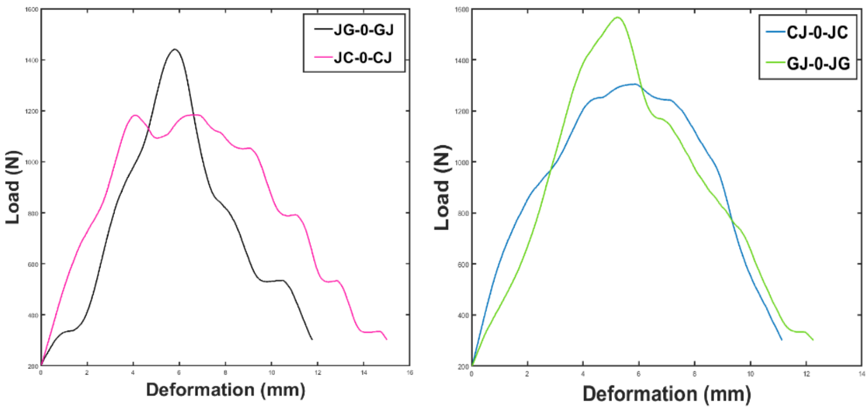

Fig. 3. Load-deformation graphs plotted based on the raw material of the outer shell (carbon/E-glass)

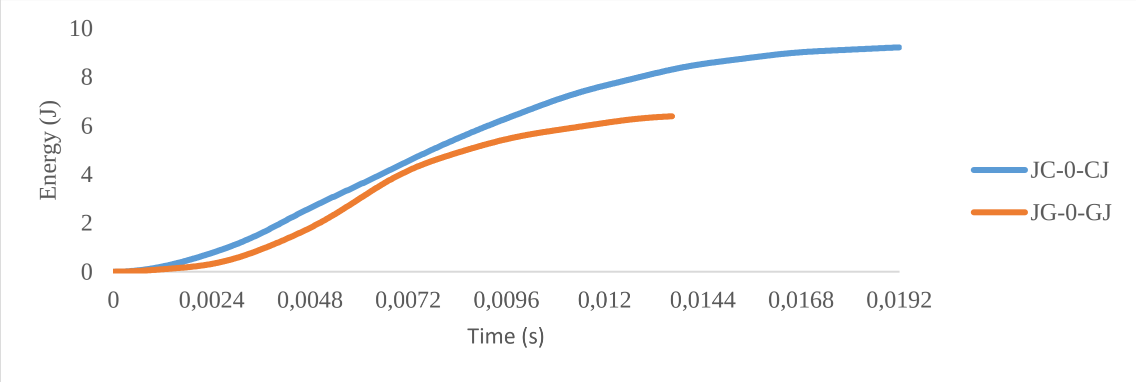

Fig. 4. Energy-time graphs plotted based on the raw material of the outer shell (carbon/E-glass)

When the effect of fabric sequences on drop-weight impact resistance is examined, the maximum load values of the samples with E-glass and carbon fabric on the outer layer are found to be greater than those of the samples with jute fabric on the outer layer (Table 4). Since the outer high-performance fabric absorbs the impact first in these samples, its resistance is also high. Furthermore, the elongation at break of jute fiber ranges from 1.1 to 1.5%, while E-glass has a value of 2.5% and carbon has a value of 1.4-1.8% [11]. The lower elongation at break values results in lower maximum load values. Besides, load-deformation and energy-time graphs (Figs. 5 - 6) based on outer shell sequences support this result.

Finally, when the core structure is examined, it is discovered that the imperforate yields the greatest results in carbon reinforced samples, followed by large hole and then small hole designs. When the samples containing E-glass are examined, it is observed that the best results are given by the large hole designs, followed by the imperforate and small hole designs (Fig. 7). In conclude, the small hole structure has a negative effect on the overall performance characteristics. According to the literature, the perforation resistance of the front surface in sandwich structures is higher when the core structure is soft, and a soft core structure can be obtained with large cell size and/or thin cell wall [30]. Furthermore, Zuhri et al. (2014) investigated the energy absorption properties of sandwich composite structures with square and triangular honeycomb core structures, and it was discovered that the square shaped honeycomb structure, which has a larger cell unit, absorbs more energy [31]. This can be attributed to the fact that in the study, structures with large holes construct better results.

The open curves noticeable in the load-deformation graphs (Fig. 3, 5 and 7) of the samples prove that the striker has fully penetrated the samples, that is, full penetration has occurred [32]. This full penetration can also be noticed in damage patterns shown in Fig. 8.

4. Conclusion

The goal of the study is to develop sandwich designs with a textile waste core as an alternative to traditional honeycomb shock absorbers. In the outer shell design, PP plates reinforced with carbon, E-glass, and jute woven fabrics are used and fabric types and locations are altered. The core structure is made primarily of denim waste. One of the most detrimental processes in the textile industry is the production of denim. The water and toxic fertilizers used in the production of cotton, which serves as its primary raw material, the indigo dyeing process, and other finishing procedures all indicate the harm that denim manufacture causes to the environment. Moreover, in the core design two different sizes of holes are drilled. With respect to these structural design parameters, the resulting sandwich structure's impact resistance is investigated. Below is a list of the main conclusions:

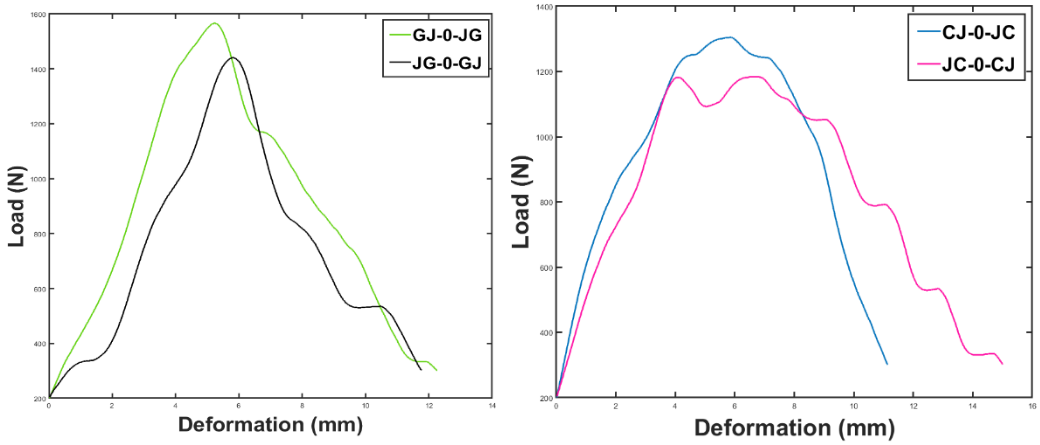

Fig. 5. Load-deformation graphs plotted based on the sequences of the outer shell components (inside/outside)

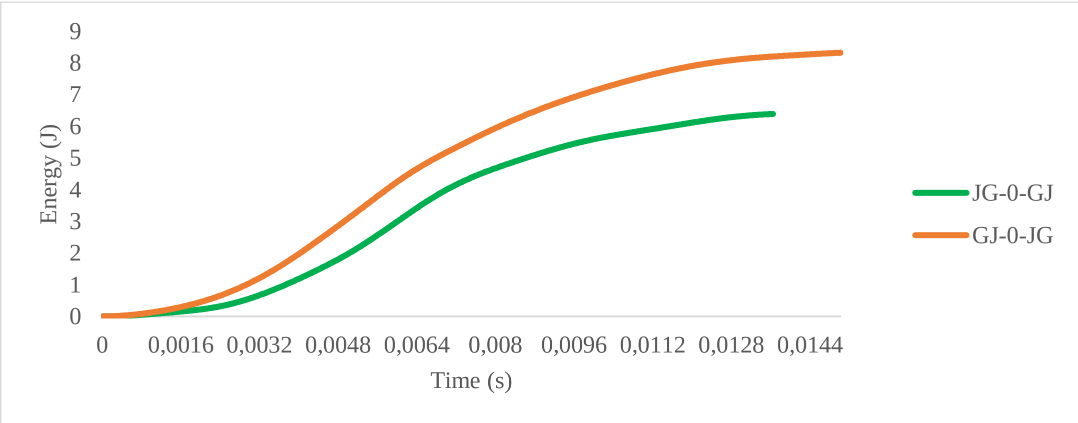

Fig. 6. Energy-time graph plotted based on the sequences of the outer shell components (inside/outside) that belong to the sample group consisting of E-glass fabric

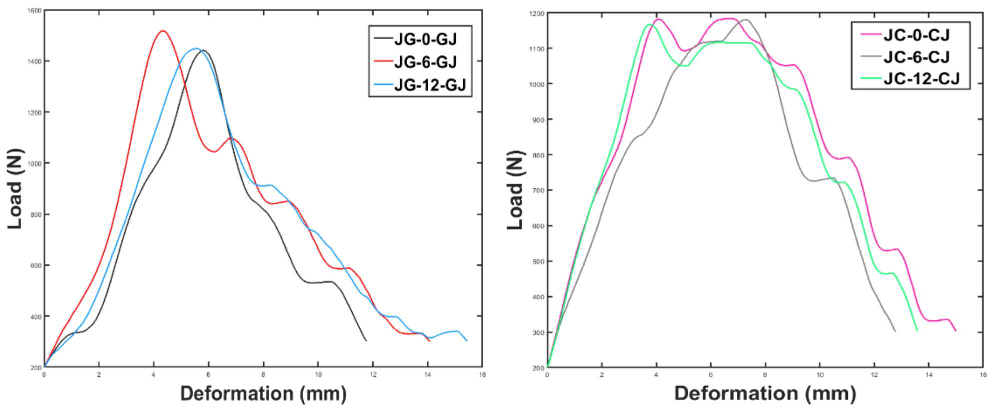

Fig. 7. Load-deformation graphs plotted based on core designs (small hole, large hole, and imperforate)

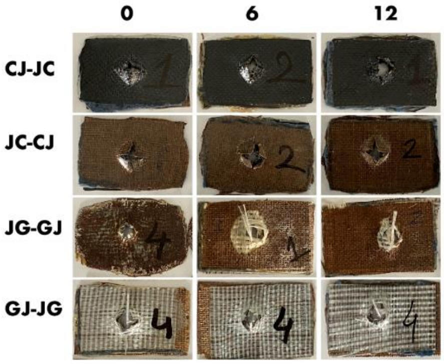

Fig. 8. Damage patterns of samples after drop-weight impact test

- Sandwich structures are produced successfully in thicknesses between 2.17 and 2.85 mm and densities between 0.78 and 0.96 g/cm^3.
- Considering the fabric sequences, sandwich structures in which high-performance E-glass and carbon fabrics are located on the outer surface of the composite exhibit higher impact resistance.
- The impact strength is negatively influenced by the small hole structure, while large holes or imperforated surfaces display the intended effect when the core design is taken into account.
- The load deformation plots of the samples show open curves indicating complete penetration of the samples by the striker, while the damage patterns confirm these results.

According to the results, it can be concluded that recycled textile wastes can be utilized in the sandwich structures' core layer, and that the geometry of these structures can be altered to produce a honeycomb effect. These structures can thus serve as an alternative to conventional honeycomb structures when used with an ideal design. The automotive sector can be considered as a potential area of use for these structures, which attract attention with their contribution to solid waste management and creating an environmentally friendly material alternative.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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