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ORIGINAL PAPER

A New Approach to Characterize the Low-Velocity Impact Behavior of Sandwich-Structured Composite Reinforced with Weft-Knitted Spacer Fabric

Fatemeh Hasanalizadeh and Hadi Dabiryan*

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Abstract- **In the present study, a new approach has been developed to characterize the low-velocity impact behavior of sandwich-structured composites reinforced by weft-knitted spacer fabric. This approach is to define various indexes to describe the impact resistance of spacer fabric composites. The experimental results of the drop-weight impact test were used to define different approaches in order to investigate different aspects of the impact behavior of sandwich composites. Novel indexes i.e. relative displacement index (RDI), energy per pile index (EPI), damaged volume index (DVI), damaged pile index (DPI), and damaged area index (DAI) were introduced to explain different features of the impact behavior of composites reinforced with 1×1 rib, 3×3 rib and 5×5 rib gaiting weft-knitted fabrics. As a conclusion, pile orientation has a significant effect on the impact resistance of sandwich composites. Rib3 sample has the maximum impact stiffness due to the low RDI value and also has the minimum value of DVI value, which describes both the area and depth of damage. In addition to the regular damage pattern of Rib3 sample, it has minimum damage based on the DPI value. Rib5 sample has the maximum impact toughness because of the maximum values of the AEI value. Also, the highest damaged area according to the DAI value belongs to the Rib5 sample.**

Keywords: **low-velocity impact, sandwich-structure, weft-knitted spacer fabric, new indexes, drop weight test, absorbed energy, damaged area**

I. INTRODUCTION

Different methods are used to evaluate the low-velocity impact behavior of materials and structures. The common methods are specifically suitable for continuum materials. Composite materials are bicomponent materials that show different impact behaviors. Sandwich-structured composites are suitable structures for impact applications. However, they need to define new indexes to analyze their impact behavior appropriately.

Some researchers have recently studied impact behavior of 3D textile composites [1-4], however a few studies have focused on the structural parameter of textiles in composites, while the structural parameters have main role in their impact characteristic. Zhang *et al.* [5] revealed the core thickness effect on the bending strength of composite sandwich. Wu *et al.* [6] examined the effective structural parameters of 3D orthogonal woven composite on the impact resistance. They claimed that the structure of layers and connecting yarn modulus of elasticity have significant effect on the impact properties according to experimental and numerical investigation. To compare the 2D and 3D composite, Miao *et al.* [7] studied the damage pattern of the same structure against low-velocity impact and reported that 3D composites had more impact strength than 2D ones. As mentioned above, a wide range of studies investigate impact properties using acceleration of impactor, damage pattern, impact stiffness and other prevalent methods to describe impact behavior of structures. Nevertheless, there are a few investigations that observe impact properties of composite with different novel approaches. In particular, it is cost and time saving to determine an accessible method for prediction of impact behavior of textile composite, which is based on the effective structural parameters. However, Kazemianfar *et al.* [8] presented new definitions to describe response and failure modes of 2D and 3D woven composites under low-velocity impact.

Previous studies have addressed the criteria that

F. Hasanalizadeh and H. Dabiryan
Textile Engineering Department, Amirkabir University of Technology, P.O. Box 15875-4413, Tehran, Iran.

Correspondence should be addressed to H. Dabiryan
e-mail: dabiryan@aut.ac.ir

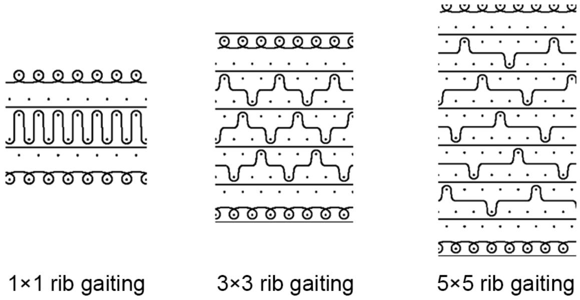

Fig. 1. Needle pattern of composite reinforcements.

have been proposed to describe the impact properties of continuum materials. The use of aforementioned criteria cannot well characterize the impact behavior of two-component materials such as textile reinforced composites. In the present study, some new indexes are introduced to analyze the impact behavior of sandwich-structured composites reinforced with weft-knitted spacer fabrics.

II. EXPERIMENTAL

A. Materials and Methods

A.1. Composites Fabrication

Three types of spacer fabric were knitted by a STOLL flat knitting machine (CMS330TC) with different pile yarn orientations. Fig. 1 describes the needle pattern of spacer fabrics. C-glass yarn count of 100 tex was used to produce top and bottom layers of rib gaiting structures. Table I shows properties of C-glass fiber and Table II reports epoxy resin properties.

In order to fabricate composites, epoxy resin type of PC105 was used and the samples were impregnated with the mixture of resin and hardener. Reinforcements were impregnated with resin using a brush. Thereafter, extra resin was removed from the structure of reinforcements

TABLE I
C-GLASS FIBER PROPERTIES [8]

Density (g/cm^3)	2.52-2.56
Tensile strength (MPa)	3300
Elastic modulus (GPa)	69
Shear modulus (GPa)	27.0
Elongation-at-break (%)	4.8
Poisson’s ratio	0.276

TABLE II
EPOXY RESIN PROPERTIES

Density (g/cm^3)	1.0
Viscosity (MPa.s)	1000
Tensile modulus (MPa)	3700
Tensile strength (MPa)	73
Flexural modulus (MPa)	3000
Flexural strength (MPa)	126
Elongation-at-break (%)	3

using a rigid roller. Fig. 2 shows side view of Rib3 sample as a typical sample.

Table III reports the structural parameters of composites after room-temperature curing.

A.2. Drop Weight Test

A cylindrical stainless steel impactor was applied to carry out the low-velocity impact test on the composites using drop weight tester available in mechanical engineering department of Amirkabir University of Technology. The mass of impactor was 2.7 kg and its diameter was 16 mm. The fall height was 24.4 cm and initial velocity before impact was 2.19 m/s. Samples were placed on the simply supported resting. Fig. 3 shows the schematic of impact test condition. As shown, the sample was laid on a rigid plate and clamped at four sides.

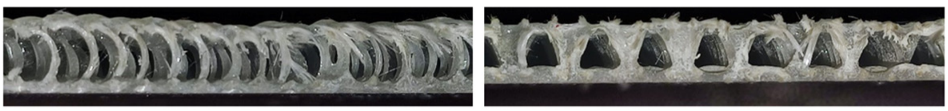

Fig. 2. Side view of sandwich composites.

TABLE III
GEOMETRICAL PROPERTIES OF COMPOSITE REINFORCEMENTS

Pattern	Thickness (mm)	W.P.C[1]	C.P.C[2]	S.D[3]	P.S.C[4]	FVF[5] (%)
Rib1	2.43	2.75	7.2	19.8	6	16.32
Rib3	3.18	3	7.5	22.5	6	16.15
Rib5	2.22	2	8	16	6	16.67

[1]Wale per centimeter [2]Course per centimeter [3]Stitch density [4]Pile per square centimeter [5]Fiber volume

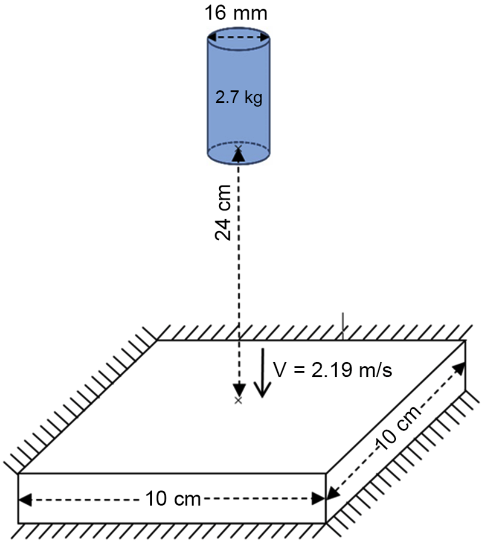

Fig. 3. Schematic of impact test condition.

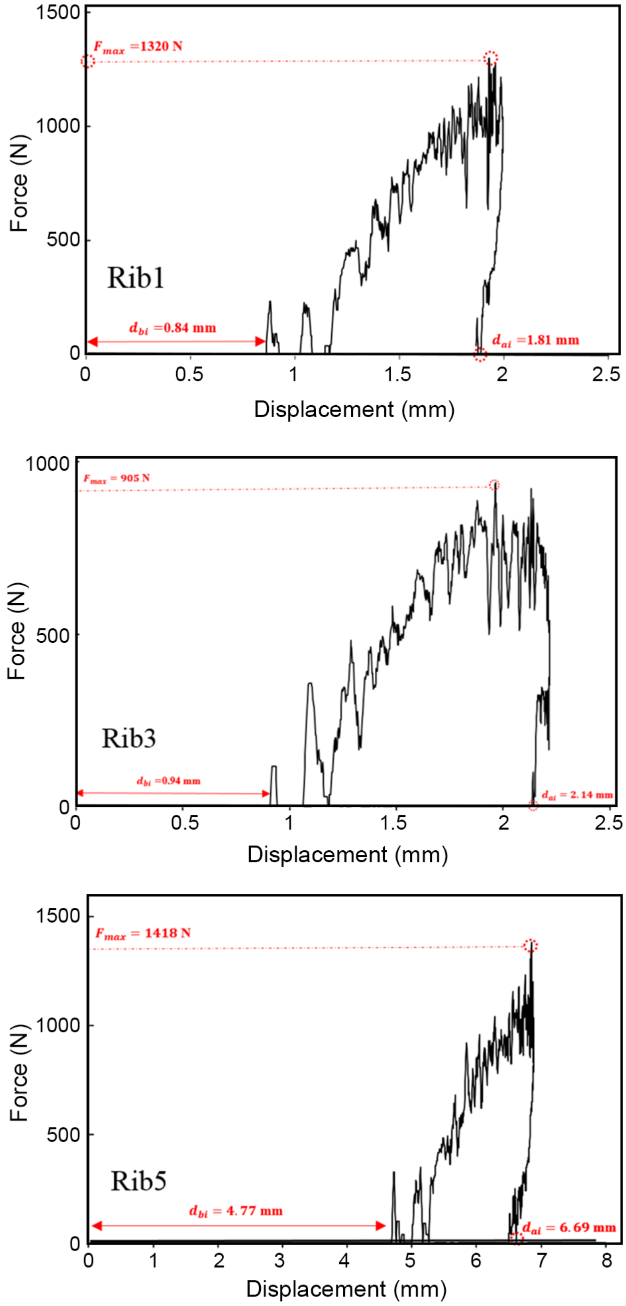

Fig. 4. Force-displacement curve of impactor.

III. RESULTS AND DISCUSSION

The results of the impact test have been demonstrated in Fig. 4 as force-displacement diagram of impactor on different targets (Rib1, Rib2, and Rib3 samples). An accelarator recorded the acceleration of impactor every thirthy microseconds. Finally, impactor displacement was calculated by two times integration of accelaration-time data. Also, contact force value was calculated by Newton's law of motion (F=ma).

As aforementioned above, force-displacement diagram of impactor was plotted for different samples according to the drop-weight test. Different parameters such as maximum force, distance from the targets (d_{bi}) and total displacement of impactor (d_{ai}) were extracted from the force-displacement diagrams. As shown in Fig. 4, the maximum force of 1300, 1000, and 1400 N has been recorded for Rib1, Rib3, and Rib5, respectively. Different values of maximum force are attributed to the orientation of pile yarns in the structure of reinforcements.

As demonstrated in Fig. 5, the pile yarns in Rib3 sample have a sharp angles that increase their angle with the horizon.

This leads to an increase in the Rib3 composite resistance against impact load compared to oblique pile yarns in Rib1 and Rib5 samples.

In addition, the orientation of the pile yarns in the Rib3 sample leads to an increase in the thickness of the composites. It is obvious that as the thickness of the Rib3

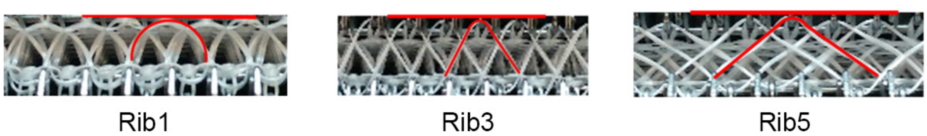

Fig. 5. Pile structure in composites.

TABLE IV
DETAILS OF IMPACTOR DISPLACEMENT

	d_{bi} (mm)	d_{ai} (mm)	Δ (mm)	Δ/t
Rib1	0.84	1.81	0.97	0.40
Rib3	0.94	2.14	1.2	0.38
Rib5	4.77	6.69	1.92	0.87

sample increases, the distance of the sample to the drop point of the impactor decreases. Hence, the impact force is reduced at the moment of impact.

In order to find the role of reinforcement structure on the impact behavior of sandwich-structured composites and characterize their impact properties, different indexes were defined using derived parameters. The defined indexes are as follow:

A. Relative Displacement Index (RDI)

As shown in Fig. 4, there are two key values on the force-displacement curve of samples:

- Distance of impactor drop-point from the target (d_{bi}) and
- Total displacement of impactor (d_{ai}).

It is well known that the difference between d_{bi} and d_{ai} (Δ) is the distance the impactor has moved through the thickness of sandwich composites. Obviously, the higher value of the Δ, the lower the resistance of the samples. In order to compare the results accurately, this value is normalized to the thickness (Δ/t) and the result is reported in Table IV. RDI is a dimensionless value which may be used to describe impact resistance of composite. According to Table IV, the minimum value of RDI (Δ/t) belongs to the Rib3 sample that is attributed to the role of both the pile orientation and the stiffness of top surface of composites, simultaneously. As pointed out, the pile orientation determines the angle of pile yarns with the horizon. Also, the role of top surface is determined by the values of S.D. Based on the values of Stitch Density (S.D.) in Table I, the highest S.D. belongs to the Rib3 sample (22.5), which means that there are more loops in the contact area to resist the impact force.

B. Absorbed Energy Index (AEI)

Absorbed energy index (AEI) is an index to find out the capability of sandwich composites to absorb impact energy of sandwich-structured composites. It is calculated by integration of force-displacement curve. Table V reports the AEI of different samples.

TABLE V
ABSORBED ENERGY OF COMPOSITES

Sample's code	AEI (J)	EPI (J)
Rib1	5.94	0.296
Rib3	6.18	0.407
Rib5	5.85	0.158

Since the pile yarns have the main role in the impact behavior of composites reinforced with spacer fabric, the energy per pile should be considered. In order to obtain the energy per pile, the values of total absorbed energy were divided to the number of pile yarns in the contact area. These values are presented in Table V to show that how much energy is absorbed individually by a pile yarn in the contact zone. It is worth noting that for a constant contact area, the absorbed energy trend depends on the number of pile in the contact area. The maximum value of EPI (0.407 J) belongs to the Rib3 sample and the minimum value of EPI (0.158 J) belongs to the Rib5 samples. This fact is confirmed by force-displacement results. Indeed, the pile capacity to absorb energy in Rib3 is more than that in Rib1 and Rib5 and it is reasonable according to the peak force and total displacement of impactor trend.

C. Damaged Volume Index (DVI)

Damaged volume index (DVI) is another dimensionless index which is defined to describe the impact behavior of composite. DVI describes both the area and depth of damage caused by an impact load. The main advantage of DVI is to show the role of both the pile yarns and top face properties.

In order to measure the damaged area, a 36 cm^2 square frame is circumscribed around the damaged area. Then the damaged area is calculated by dividing the number of pixel of binary damaged area to the number of pixel of square frame. Since the damaged area is not the same in different samples, the resolution and thus the number of pixels in the pictures are different.

As shown in Fig. 6, the ratio of the damaged volume to the volume of hypothetical cylinder is calculated as follows:

TABLE VI
DAMAGED AREA

Sample's code	Pixel of damaged area	Pixel of circumscribed square	Damaged area (mm^2)
Rib1	457800	504654	3.34
Rib3	21198	301948	2.53
Rib5	84336	492046	6.17

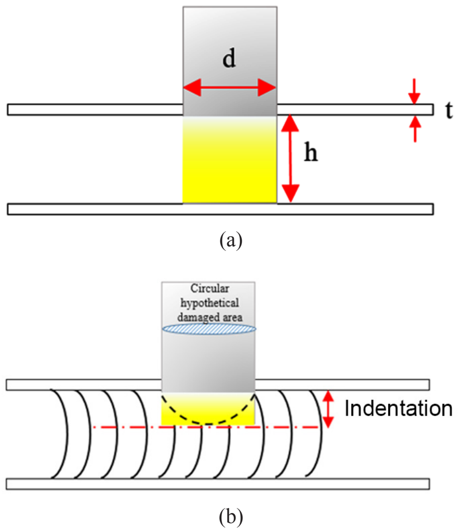

Fig. 6. Schematic of DVI Index identification: (a) structural parameters and (b) impactor parameters.

$$\mathrm{DVI} = \frac{\text{Damaged volume}}{\text{Volume of hypothetical cylinder}} = \frac{(\pi.r^2).h}{(\pi.R^2).t}$$

where r is radius of damaged area, h is depth of penetration, R is radius of impactor, and t is thickness of the sample.

The radius of the damaged area (r) is the hypothetical radius of this area, when it is assumed to be circular. The less value of DVI means that the damaged area is small and the sample is strong. According to Table VII, minimum DVI value (0.88) has been recorded for Rib3 and maximum value (9.52) has been recorded for Rib5. This confirms the strength of Rib3 against impact as in previous indexes.

D. Damaged Pile Index (DPI)

Damaged pile index (DPI) is defined to determine the ratio of number of damaged piles to the number of piles in the contact area. DPI is a dimensionless relative index which shows the effect of pile number on the impact behavior of spacer fabric-reinforced composites. Obviously, a higher DPI is likely to result in sample failure. According to Table VII, the lowest DPI (1.259) is about Rib3 and the highest value (3.070) is about Rib5. Therefore, the DPI index to describe the impact behavior of the composite shows a trend similar to the previous indices.

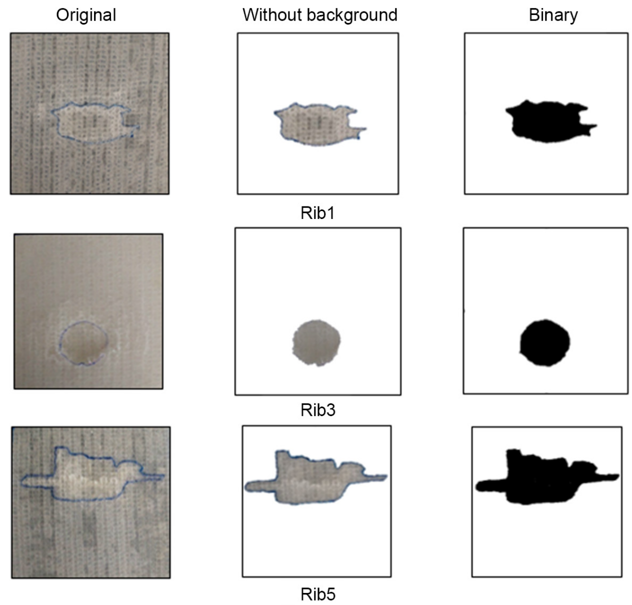

Fig. 7. Damaged area of sandwich composites.

E. Damaged Area Index (DAI)

The damaged area (DAI) was considered as an important criterion in the impact behavior of sandwich composites. This dimensionless index defines as the ratio of damaged area to the 36 cm^2 square frame circumscribed around it. Fig. 7 shows the observed damaged area under impact on the upper layers. The original images were processed using MATLAB R2018b. The original images were turned into a gray image after removing their background. Binary images were created using MATLAB software, and the damaged area (black area) was calculated as the number of black pixels

The DAI values are presented in Table VIII. As can be seen, the minimum DAI value belongs to the Rib3, which shows good resistance to impact loads. It is well known that the damage of the upper layer is related to the buckling of Z-fibers. Previously, it was shown that the minimum displacements of impactor occur in Rib3 samples, which was attributed to the approximately vertical direction of Z-fibers. Another reason for the minimal DAI value of Rib3 is the higher value of S.D. Due to the higher density of reinforcement in the upper layer of Rib3 sample, the crack propagation is limited during impact loading. Since

TABLE VII
DVI AND DPI VALUES

Sample's code	r (mm)	h (mm)	DVI	DPI
Rib1	1.03	1.99	1.36	1.662
Rib3	0.90	2.22	0.88	1.259
Rib5	1.40	6.88	9.52	3.070

TABLE VIII
AMOUNT OF DAMAGED AREA

Pattern	DAI
Rib1	0.09
Rib3	0.07
Rib5	0.17

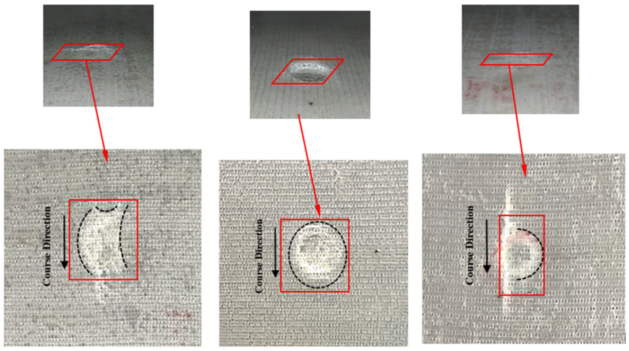

Fig. 8. Damaged pattern of composites.

the crack starts first in the matrix, the presence of thread in the vicinity of the crack prevents its propagation.

F. Damaged Pattern Index (DPI)

Fig. 8 shows the contact zone of the sandwiches after impact. The contact area pattern after impact in Rib3 is similar to the impactor cross-section shape, but it is very different from the shape of the impactor in Rib1 and Rib5. This fact can be attributed to the composite fabrication and the role of the matrix. In the other words, Rib3 is fabricated even more evenly than Rib5 and Rib1 due to the difference in their thickness. The greater thickness of Rib3 results in a good 3D composite that can be impregnated with resin. While the pattern of contact zone in Rib1 and Rib5 is not circular. This fact can be attributed to the pile yarn orientation. The interlacing of pile yarns in Rib1 and Rib5 is more than that in Rib3. So that, when a pile yarn is buckled, it affects many neighboring pile yarns, and tension transverse in the course direction.

IV. CONCLUSION

The low-velocity impact behavior of sandwich-structured composites was studied. A new approach was developed to analyze impact properties of sandwich composites, and new indexes were introduced. Various indices, namely relative displacement index (RDI), energy per pile index (EPI), damaged volume index (DVI), damaged pile index (DPI), and damaged area index (DAI) were used to describe the impact behavior of sandwich structure composite reinforced by spacer fabrics. The results show that:

- The pile orientation of reinforcement significantly influenced the impact behavior of sandwich-structured composites.
- The Rib3 sample has the maximum impact stiffness due to the low relative displacement index (RDI) value.
- The Rib5 sample has the maximum impact toughness because of maximum values of AEI and EPI.
- The highest damaged area belongs to Rib5 sample based on the damaged area index (DAI) values.
- The minimum value of damaged volume index (DVI), which describes both the area and depth of damage, corresponds to the Rib3 sample.
- Piles in the structure of Rib3 sample undergo the minimum damage based on the values of damaged pile index (DPI).
- Unlike the Rib1 and Rib5 samples, the Rib3 samples show a regular damage pattern, which is attributed to the role of pile orientation.

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