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Characterization of the impact properties of three-dimensional glass fabric-reinforced vinyl ester matrix composites

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Three-dimensional glass woven fabric-reinforced composites (3-D composites) were fabricated by impregnating vinyl ester resin in a hand lay-up procedure for the honeycomb sandwich structure. Three kinds of 3-D had been investigated in terms of the impact properties as a function of the *z*-direction fiber length, i.e., 3, 4.5 and 8 mm in core structures. In this work, more precise impact behaviors were studied in the context of differentiating between initiation and propagation energies, and ductility index (DI) along with maximum force and total energy as a useful measure. As a result, the highest impact properties were reached in the case of the specimens with 3 mm length of *z*-direction fibers, but the lowest DI was observed in the same specimens with 3 mm length of ones, probably due to the effect of buckling. The damage photo analyses after impact tests were also discussed in terms of a hollowing on the front face against the load applied, and a whitening spread in the impact point on the back face of the fabric composites studied.

1. Introduction

Advanced fiber-reinforced composite materials are widely used in the applications such as aircraft, aerospace and construction industries for the purpose of stiffening and filling the parts with minimal weight penalties. In a composite processing, when the fiber-reinforced composites emerged in a resin matrix, their mechanical properties, such as high specific strength and stiffness, have been largely affirmed. However, primary interfacial factors such as the interfacial adhesion between fibers and matrix, damage tolerance and fracture toughness of the composite materials limit their real applications, since the load stress are sufficiently high, they may cause failure along the interface [1–5].

Recently, three-dimensional fabric-reinforced composites (3-D composites) have been receiving greater attention from the material community owing to the need for improvements in interlaminar shear and impact strengths of composite materials [6–8]. Among them, the 3-D glass-woven fabrics (3-D fabrics) produced two plain layers by a velvet weaving technique and at the same time connected two plain layer by the *z*-direction fibers, which can effectively reduce the extent of delamination by increasing the interlaminar shear strength and toughness, as shown in Fig. 1. These 3-D fabrics have been proved to have successful applications in the building industry, automotive industry, storage tank, and ultra-light aircraft owing to their low weight-to-ratio, high impact resistance, leak detection space and high delamination strength [9–12].

Meanwhile, it is noted that impact properties of the composites are largely related to the overall toughness or ductility of the constitutive materials which can be defined as the ability of the composites to absorb applied energy [13]. And, the compressive mechanical properties of the 3-D fabrics do not depend on the *z*-direction fiber length of core structure [14]. But it is difficult to find the correlation between the impact properties and the *z*-direction fiber length of core structure in the open media 3-D woven fabrics for the optimum casting.

The present investigation is aimed at elucidating the effect of length changes of *z*-direction fibers on the impact properties of 3-D fabrics. The ductility index (DI) derived from the maximum load and total energy as useful measures for the detailed and precise impact behaviors of 3-D fabrics are also investigated.

2. Experimental

2.1. Materials and sample preparation

Three kinds of 3-D fabric structures in the form of plain weave made from glass fibers, (supplied from Parabeam Helmond of Netherlands) produced by a velvet weaving technique have been investigated in terms of the length changes of *z*-direction fibers in core structures, as summarized in Table I.

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TABLE I Standards of 3-D glass woven fabrics

Fabric Type	A	B	C
z-direction fiber length	3	4.5	8
weight (g/m^2)	815	860	910

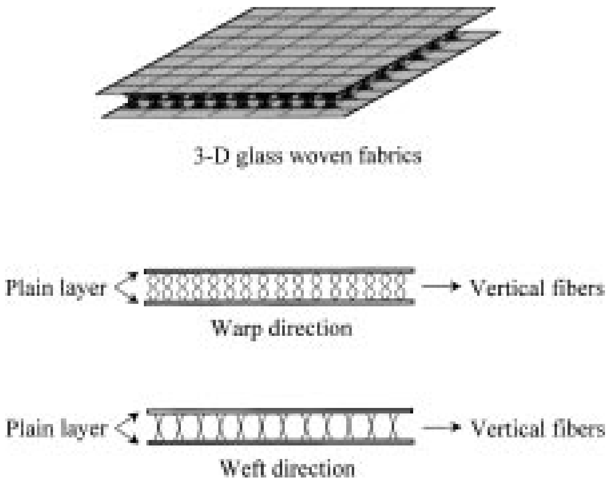

Figure 1 Structure of 3-D glass woven fabrics.

Matrix used in this work was the bisphenol-A type vinyl ester supplied from Seiwon Chem. Co. of Korea. Methyl ethyl ketone peroxide (MEKP) in the presence of cobalt-octoate (supplied from Seiwon Chem. Co., of Korea) as accelerator was used as the free radical initiator for the polymerization of vinyl ester resin. Vinyl ester structure is shown in Fig. 2. From thermogravimetric analysis (TGA, Du Pont 9900) results, the thermal stability was before 300 °C in the 5 °C·min^{-1} heating rate in the presence of oxygen. The glass transition temperature (T_g) measured by thermo-mechanical analysis (TMA, Du Pont 9900) was 91 °C.

The 3-D fabric composites were made by the hand lay-up method with a mixture of vinyl ester resin, 1 phr of hardener and 0.5 phr of accelerator. During impregnation of the fabrics, 3-D fabrics were totally rolled to assure that good contact is made to the mold. The z-direction fibers between the two plain-woven fabrics stand up by themselves after rolling process. After curing at room temperature, this gives a honeycomb structure with two impregnated plain-woven fabric skin layers and z-direction core fibers.

2.2. Impact properties and microscopic analyses

The resistance to damage by high rate impact can be largely considered in application fields of the composites materials such as aerospace, aircraft, automobiles, and so on [15, 16]. In this work, the impact properties of 3-D composites studied were carried out by means of a high rate impact tester (Rheometeics Co.) with 2 m·sec^{-1} impact-rate at 20 °C. The specimens were cut from the panels using a water jet; the dimensions were about 50 mm long and 50 mm wide. The bulk fiber volume fraction in the open media of 3-D fabric composites was about 20% (±2%) for all composites. The damage shapes of the composites after impact test were observed using a scanning electron microscopy (SEM).

3. Results and discussion

3.1. Load-displacement and energy-displacement curves

As mentioned above, the impact behavior is major mechanical properties in order to evaluate the degree of toughness of composite materials. When the material is impacted, transferring load absorbs into the materials, and it affects the residual mechanical properties [17]. As shown in Fig. 3, the load-displacement curves of 3-D fabric composites are quite steep before maximum load (F_{max}) and the first major break on the load-displacement curve occurs at the onset of the failure process. And then several humps after F_{max} suggest that there exist multiple-step failures made during the impact force. The load distributed over a large portion of the composites creates more crack surfaces, reflecting a noncatastrophic failure mode. In the observation, F_{max} of Type A is the highest of all specimens studied. And F_{max} of the fabric composites studied shows a tendency to decrease in increasing the length of z-direction fibers, as seen in Fig. 3. Also, the energy-displacement curves show that the highest cumulative energy behavior is also reached in the case of the most thin specimen (Type A), and the values of cumulative impact energy gradually decrease in increasing the length of z-direction fibers

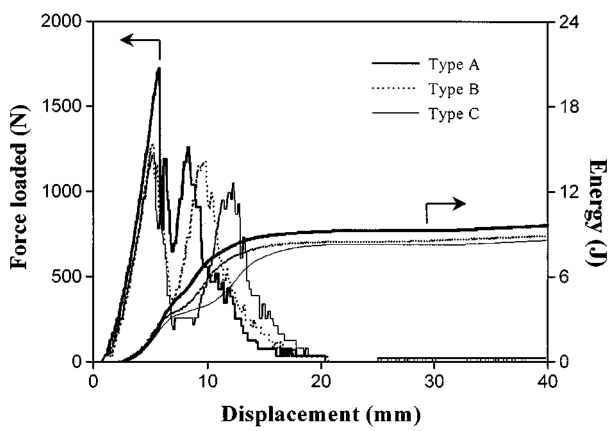

Figure 3 Load-displacement and cumulative energy-displacement curves on the length change of z-direction fibers in 3-D fabric composites.

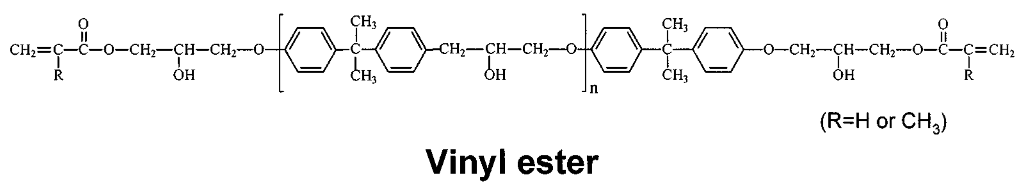

Figure 2 Chemical structure of vinyl ester.

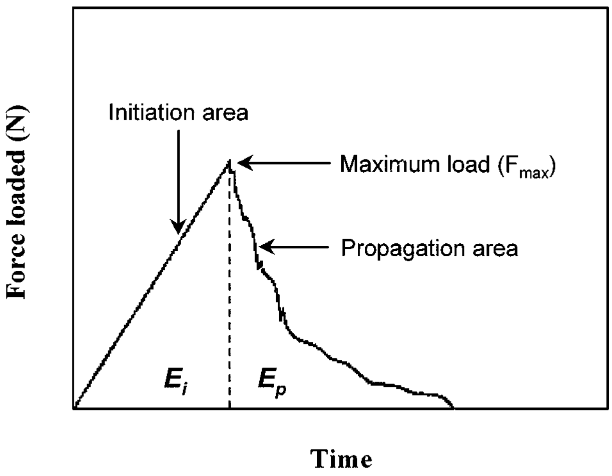

Figure 4 Schematic presentation of the load history in an impact test.

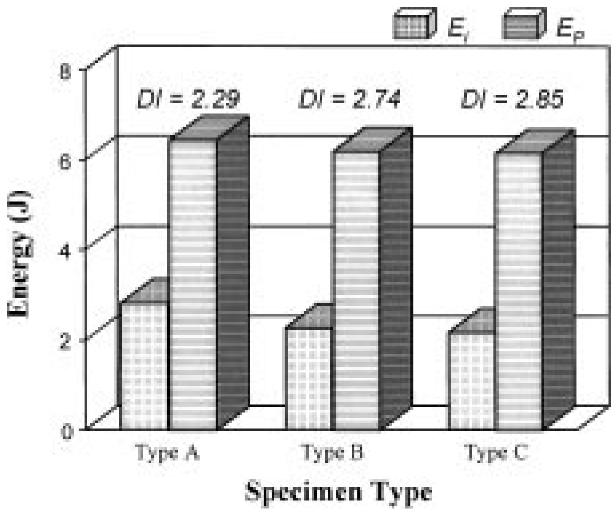

Figure 5 Initiation and propagation energies of the length change of *z*-direction fibers in 3-D fabric composites.

or the thickness of specimens, as seen in Fig. 3. This is explained by the fact that the crack growth of the 3-D fabric composites is prevented by the *z*-direction fibers when the impact force is resisted with front-plain layer and then the crack extends toward back-plain layer [7].

3.2. Initiation and propagation energies and ductility index

Fig. 4 shows a schematic representation of the load history during impact test, which is considered by the sum of two regions; initiation and propagation of the fracture.

$$E_t = \int F \, dt \tag{1}$$

$$= E_i + E_p \tag{2}$$

where E_t is the total impact energy, E_i the initiation energy before maximum load (F_{max}), and E_p the cumulative propagation energy after maximum load.

According to Equation 2, we believe that the division of E_t can provide more detailed and precise information on the fracture behavior of a material. For example, brittle and high strength material will have a large E_i and small E_p. Also, the ratio of E_p to E_i may be considered as ductility index, DI, for evaluating the impact toughness or total absorbed energy of a material, as follows [17, 18]:

$$\mathrm{DI} = \frac{E_p}{E_i} \tag{3}$$

The results of the E_p, E_i and DI of the specimens are shown in Fig. 5. As a result, the E_p and E_i of Type A are the highest of all specimens studied. Also, E_p and E_i tends to a decrease in increasing the length of *z*-direction fibers. According to Jang [7], it is noted that the existence of *z*-direction fibers in composites should increase the interlaminar shear strength and, therefore, increase the resistance to crack initiation.

In this work, increasing of length of *z*-direction fibers in 3-D composites leads to more easily initiated fracture and propagated crack on the *z*-direction fibers when load stress transferred from the matrix to the fiber under the impact test. However, a surprising result also makes

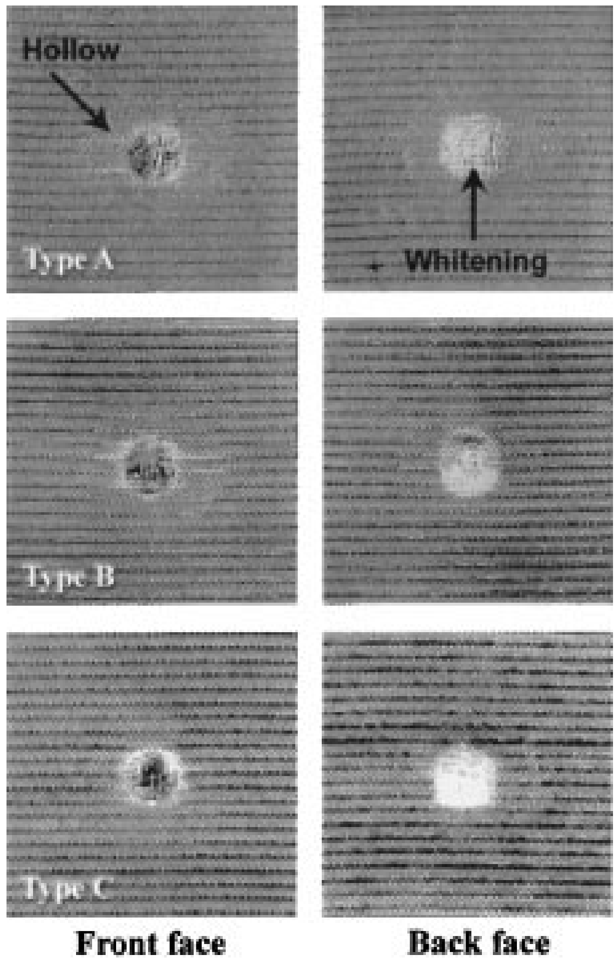

Figure 6 Damage shapes of the length change of *z*-direction fibers in 3-D fabric composites.

that the DI of Type C is the highest of all specimens studied. This seems to be a consequence of the bucking effect based on the Euler's proposition [19] in increasing the length of *z*-direction fibers in the fabric composites.

3.3. Damage analysis

Fig. 6 shows the damage shapes of the 3-D fabrics after impact test. As expected, a hollowing occur at the impact point on the front face against the load applied, also both the fiber breakage and the whitening spread in the impact point on the back face.

As a result, the impact damage areas on the front face and the whitening on the back face somewhat increase in increasing the length of z-direction fibers. It is clear that Type C has more ductile properties than Type A, resulting in larger whitening area by well-impact energy absorbed than that of Type A [20].

4. Conclusion

In this work, three kinds of 3-D glass-woven fabric composites as function of the length of z-direction fibers have been investigated in terms of impact properties, for evaluating E_i, E_p and DI of the composites studied. The highest impact properties are reached in the case of the Type A, but the lowest DI of the specimens in observed in the same Type A specimen. It has been clearly demonstrated that the length change of z-direction fibers make an important role in the impact properties of the fabric composites, including ductile index properties, even though the compressive mechanical properties of the 3-D fabrics are not affected by a z-direction fiber proportion.

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