

Assessment of Low Velocity Impact Damage of Filament Wound Composite Vessels with Surface Protective Materials

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필라멘트 와인딩 복합재 압력용기의 저속충격손상 평가에 관한 연구

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Abstract This paper presents the impact damage behavior of filament wound composite vessels and the effect of surface protective materials on their impact resistance. Using an instrumented impact testing machine, a series of impact tests was performed on the base panels and the protected panels (panels with surface protective materials of rubber, kevlar/epoxy or glass/epoxy laminates) that were cut from the full scale vessel. And the impact damage parameters were used to identify the effect of protective materials on the damage resistance of composite vessels. Damage resistance of the composite vessels was considerably affected by the protective materials regardless of the shape of the indenters. Among the protective materials, glass/epoxy laminates was the most effective mean for improving the damage resistance of composite vessels.

요약 본 논문은 필라멘트 와인딩 공법으로 제조된 복합재 압력용기의 충격손상 및 이에 대한 표면 보호재료의 영향을 평가한 것이다. 낙하식 충격시험기를 이용하여 기본 패널과 보호재료(고무, kevlar/epoxy 및 glass/epoxy)가 표면에 접착되어 있는 보호 패널에 대한 저속 충격시험을 실시하였다. 복합재 압력용기의 손상 저항성에 대한 표면 보호재료의 영향을 정량화하기 위하여 충격손상 파라미터를 도입하였다. 복합재 압력용기의 손상 저항성은 충격압자의 형상과 관계없이 표면 보호재료의 영향을 크게 받았으며 이러한 표면 보호재료중 glass/epoxy가 가장 큰 보호효과를 나타내었다.

Key Words : Damage resistance, Filament wound composite vessels, Low velocity impact, Protective materials

1. Introduction

The filament winding technique manufactures products by winding reinforced fiber, wetted by resin mixture, around a revolving cylindrical mandrel. Since filament wound vessels made using composite materials are light-weight compared to conventional metal vessels but can contain gas of the same volume, they are

advantageous for long time usage [1].

An important factor determining whether the filament wound composite vessels can be used reliably in daily structures is their damage behavior during an impact event. Composite structures in general are susceptible to a wide range of damage and defects, which can occur during manufacture as well as during service [2-4] and impact damage is one of the main problems that

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composite structures face. Hence, there are needs to be a way of reducing impact damage that can deteriorate the integrity of the structure. One possible way to increase the impact damage resistance of composite vessels is by applying protective materials to the surface of the structure. Most of researches have, however, only focused on the impact response of a filament wound composite vessel [6-8]. Also, although it is expected that protective materials on vessels can enhance their resistance to low velocity impact, the impact resistance is greatly affected by constituent materials, geometry and their lay-ups, and even the shape of the indenter [9,10]. Therefore, more research is necessary to understand the impact damage behavior of composite vessels with protective materials applied to the surface.

The goals of this paper are to identify the impact damage behavior of filament wound composite vessels subjected to low velocity impact and to determine the effect of protective materials on their impact resistance. Impact damage parameters were used to evaluate the impact damage behavior of composite vessels and the effects of protective materials on damage resistance were examined.

2. Experimental Procedure

2.1 Materials and specimen

The vessel used in this study was manufactured by Hankuk Fiber Inc. by the filament wound technique, with carbon fiber of the T700 and epoxy resin of #2500. Mechanical properties of the composite materials are shown in Table 1. From the outer to the inner layers, the orientations of layers were [(90)₂₄/((±5)₈/((±75)₈/((±5)₈/((±75)₈]. The inner radius of the vessel was 345mm. The orientation was measured relative to the longitudinal direction of the vessel. The nominal volume fraction of fibers v_f was about 58%.

Three different types of protective materials were selected; SBR (styrene-butadiene rubber) rubber, glass/epoxy and kevlar/epoxy laminates. Here the SBR rubber with thickness of about 1mm was provided by Daeryuk Rubber Inc. The glass/epoxy and kevlar/epoxy laminates were produced by Hankuk Fiber Inc. The [0/90]₄ glass/epoxy plate was obtained from a prepreg

with a thickness of about 0.125mm (TBCarbon SGP125NS). Plates with a nominal volume fraction of fibers $v_f=50\%$ were processed in an autoclave according to the manufacturer's recommended cure cycle. Furthermore, the plain weave kevlar/epoxy plates were prepared from Kevlar-29 fibre/913 epoxy resin prepreg and produced by autoclave curing. At the end of manufacturing, the thickness of the kevlar/epoxy plate was measured as 0.95mm with a nominal volume fraction of fibers $v_f=54\%$. The mechanical properties of the three plates are given in Tables 2, 3 and 4, respectively. Here the hyperelasticity of rubber was defined by the Ogden model [11].

The plates were then bonded to the top of the vessel with an epoxy-based adhesive and the assembly was cured under ambient atmosphere for 48hours. The fabricated vessel was then cut into square panels with dimensions of 100×100mm. Consequently, four different types of panels were prepared; one base and three protected panels (panels with SBR rubber, kevlar/epoxy and glass/epoxy).

[Table 1] Mechanical properties

E_{xx} (GPa)	E_{yy} (GPa)	G_{xy} (GPa)	ν_{xy}
181.00	10.30	7.17	0.28

[Table 2] Material constants in Ogden model for SBR

μ_i	2.97641×10^{-2}	9.85415×10^{-2}
α_i	3.49264	-1.2305
d_i	0	0

[Table 3] Mechanical properties of glass/epoxy laminates

E_{11} (GPa)	E_{22} (GPa)	ν_{xy}
43.9	2.74	0.31

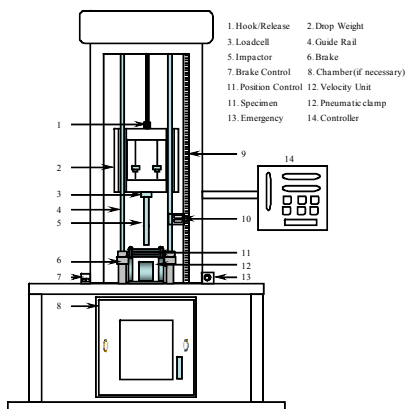
[Table 4] Mechanical properties of plain-weave kevlar /epoxy laminates

$E_{11}=E_{22}$ (GPa)	G_{12} (GPa)	ν_{xy}
27.98	1.83	0.11

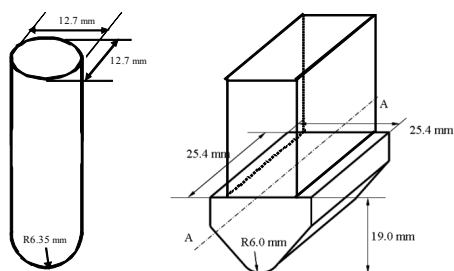
2.2 Impact test

The Dynatup 9250HV impact test machine (Fig. 1) was used for the low velocity impact tests. The tester consists of a drop tower and a variable crosshead weight arrangement, high bandwidth DSP (digital signal

processing) electronics, self-identifying load cells, and Impulse™ control and data acquisition software.



[Fig. 1] Illustration of instrumented impact testing machine



(a) Hemispherical indenter (b) Triangular indenter
[Fig. 2] Indenter type

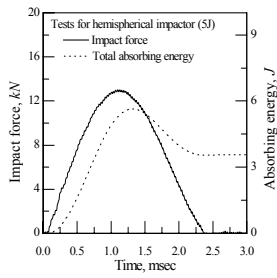
The falling impactor was dropped from predetermined target energy onto the round clamped (opening diameter 76.2mm) panels and the impactor was caught automatically after its initial rebound thereby avoiding restrikes. The impactor was 12.7mm-radius steel rods with indenters of two different shapes attached to one end. The selected indenters were a 6.35mm-radius hemispherical and a triangular indenter made of two orthogonal surfaces. The triangular was a trigonal prism and had a root radius of 6.0mm and length of 25.4mm, as shown in Fig. 2. The mass of the impactor with an indenter was 10.88kg. The triangular indenter was perpendicular to the fiber orientation of the outer layer. The target impact energies were 30J, 60J and 90J. Here, the target energy calculated by the mass and height of impactor is in error by less than 0.5% of target energy. Hence, the target impact energy will be hereafter used to denote the incident impact energy instead of applied impact energy.

3. Results and Discussion

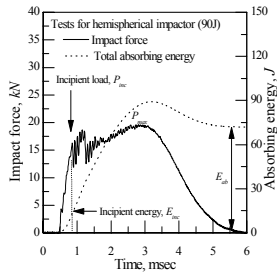
3.1 Impact Damage Behavior

Impact damage processes are associated with energy absorbing capacities and can be characterized by force and energy histories. Energy absorption can be determined by the some parameters derived from the force and energy histories [12]. To identify these behaviors, impact tests were made at the base panel center, with energy levels of about 5J and 90J and their histories are shown in Fig. 3. The history for a low-energy event was relatively smooth, and not unlike a half sine wave. For a high-energy impact, a point was reached where the load history was no longer smooth. Instead, a major load drop occurred and was followed by several small reversals. This behavior may result from an initiation or propagation of impact damage. Based on these, Poon et. al. [13] proposed some parameters to assess the damage tolerance of composite laminates. Among them, the authors have used the following six parameters: (1) load at incipient damage, P_{inc} , (2) energy absorbed at incipient damage, E_{inc} , (3) maximum load, P_{max} , (4) absorbing energy E_{ab} , (5) plastic energy absorbed by damage, E_{pl} , and (6) through-the-thickness damage.

The load at incipient damage P_{inc} means the load at which the impact damage first occurs. The loads were obtained with different indenter types and shown against the impact energy in Fig. 4. Although there was some scatter, the incipient load was almost constant for each indenter. And, the load in the hemispherical indenter was much lower than that of the triangular indenter. This may result from the concentrated load in the hemispherical indenter, as expected. Also, the impact damage incipient energy E_{inc} was pretty similar to the incipient load and was closely related to the threshold energy of the structure as shown in Fig 5. The incipient energy level of the hemispherical indenter was remarkably lower than that of the triangular indenter, same for the incipient load. Based on the results for incipient load and energy, it can be inferred that when impact energy increases above some threshold level, a critical condition is reached at which damage will initiate in a composites vessel. This level can be defined as the damage threshold energy, which is the minimum energy required to cause impact damage in structures.

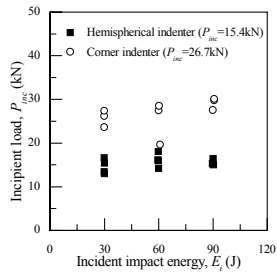


(a) Tensile strength

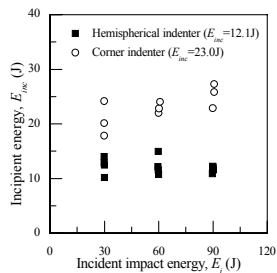


(b) Failure strain

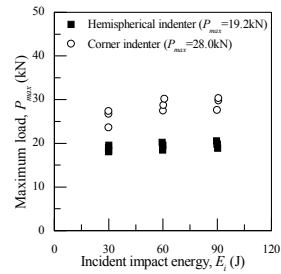
[Fig. 3] Impact force histories



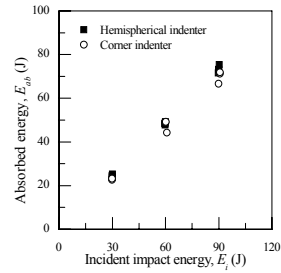
[Fig. 4] Incipient load, P_{inc}



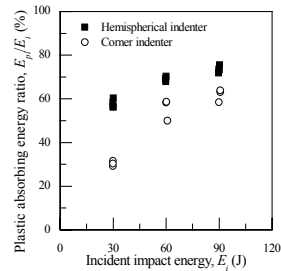
[Fig. 5] Incipient energy, E_{inc}



[Fig. 6] Maximum impact load, P_{max}



[Fig. 7] Absorbed energy, E_{ab}

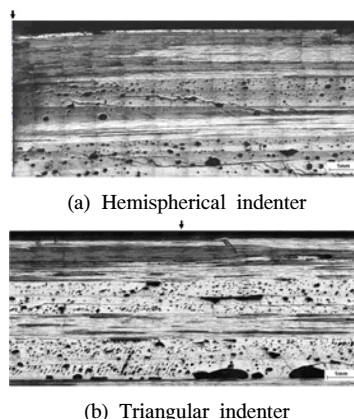


[Fig. 8] Plastic absorbing energy ratio, E_p/E_i

Maximum impact load (P_{max}) is an index related to the load carrying capacity of structures and were plotted against the impact energy in Fig. 6. The maximum impact load was nearly constant for the hemispherical indenter. However, the maximum load for the triangular indenter exhibited somewhat different behavior from the hemispherical indenter. The load showed a little initial rise with increasing impact energy before reaching a plateau of approximately 28.0kN. This indicates that the damage for the triangular indenter was not serious and consequently, had a load bearing capacity even at a higher energy.

Energy absorbed P_{ab} is often assumed to be a measure of the energy dissipated through damage mechanisms of the structure and are shown in Fig.7. They showed a linear rising trend with increasing of impact energy and an effect of the indenter was not observed. However, it should be noted that total absorbing energy consists of elastic and plastic absorbing energies. Therefore, to calculate the energy absorbed by impact damage, the elastic absorbing energy should be extracted from the total absorbing energy [10,14]. For this, additional impact tests were carried out at the damage threshold energy and then, the elastic absorbed energy was 7.1J for the hemispherical indenter and 14.0J for the triangular indenter, respectively. Figure 8 shows the plastic absorbing energy ratio, which was normalized by the impact energy. The ratio for the hemispherical indenter was much higher than that for the triangular indenter, especially at lower energy levels. This result is probably associated with the serious impact damage caused by the hemispherical indenter, as compared with the triangular indenter.

A sectioning method was used to study the impact damage in the through-the-thickness direction. A cross-sectional cut was made parallel to the outer fiber orientation for each indenter. The exposed surface was polished to remove the roughness resulting from the cutting process. Photographic records of the impact damage profiles are shown in Fig. 9. Here the arrow indicates the impact point on the panel. For the hemispherical indenter, an impact energy of 60J resulted in severe fiber and matrix fractures that extended from the impact point to the inner layer. In particular, the outer layer had almost completely collapsed near the impact point. And the coalescence of these fractures formed a large through-the-thickness crack which was accompanied by severe delamination in the interface. For the triangular indenter, the impact resulted in fiber breakage near the impact point and local indentation was noticed just below the impact point. Nevertheless, the damage was much less than that in the panel impacted by the hemispherical indenter. These results support that when the filament wound vessel is subjected to low velocity impact, a hemispherical type object is the most damaging in view of damage tolerance.



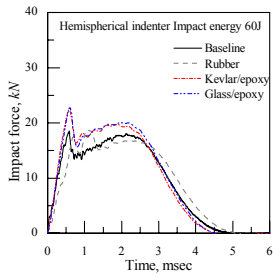
[Fig. 9] Impact damage in base panel at 60J

3.2 Effect of Protective Materials

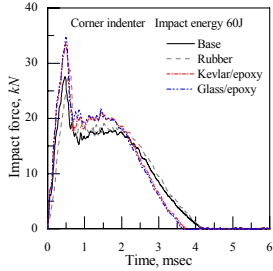
To understand the overall impact response according to indenter types and protective materials, the force histories are shown in Fig. 10. The kevlar/epoxy and glass/epoxy panels (panels with the kevlar/epoxy and glass/epoxy laminates, respectively) had higher peak loads compared with the base panel and this behavior was more remarkable for the triangular indenter. The rubber panel had more local peaks and a delayed time-to-peak load. These indicate that the protected panels had higher impact resistance, as expected.

Fig. 11 illustrates the incipient load for hemispherical and triangular indenters at 60J, normalized by that of the base panel. For the hemispherical indenter, the incipient loads were almost constant for each protected panel, and a similar behavior was observed for the triangular indenter. This trend was also observed for the base panel. However, while protective effects of the kevlar/epoxy and glass/epoxy laminates were almost identical to each other, the rubber panel had a lower incipient load for both indenters. The incipient energy ratio exhibited somewhat different behavior from the incipient load, as shown in Fig. 12. The kevlar/epoxy and glass/epoxy panels exhibited higher impact resistance for both indenters. The rubber panel had the poorest performance.

The peak load showed different behavior from the incipient load and energy as plotted in Fig. 13. The rubber panel had almost the same peak load for both the hemispherical and the triangular indenters. This may result from that the protective materials can absorb only the initial part of the impact energy during an impact event.

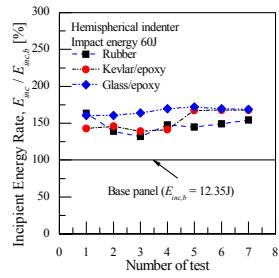


(a) Hemispherical indenter

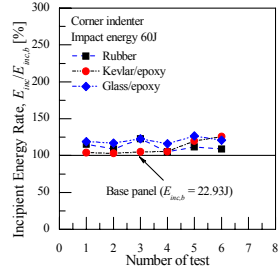


(b) Triangular indenter

[Fig. 10] Impact force histories with protective materials

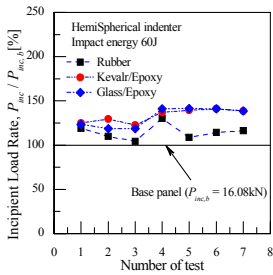


(a) Hemispherical indenter

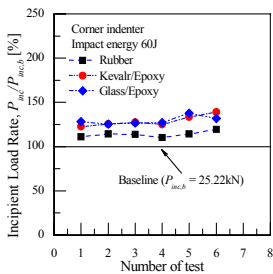


(b) Triangular indenter

[Fig. 12] Incipient energy with protective materials

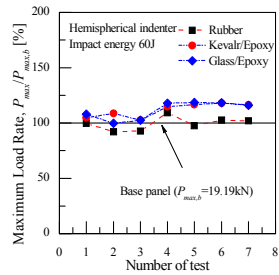


(a) Hemispherical indenter

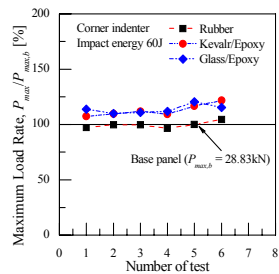


(b) Triangular indenter

[Fig. 11] Incipient load with protective materials

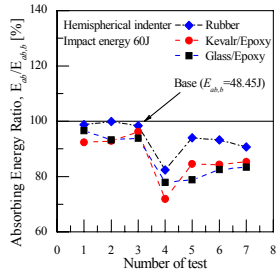


(a) Hemispherical indenter

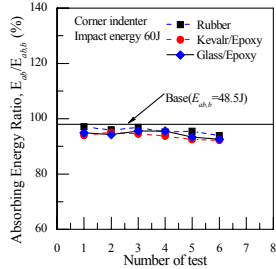


(b) Triangular indenter

[Fig. 13] Maximum impact force with protective materials

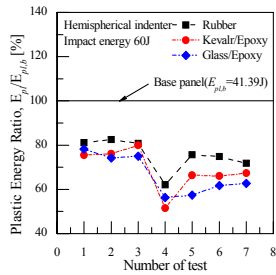


(a) Hemispherical indenter

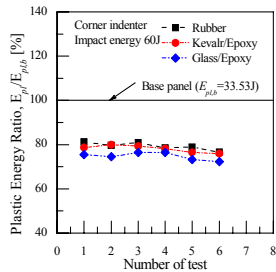


(b) Triangular indenter

[Fig. 14] Absorbing energy ratio with protective materials



(a) Hemispherical indenter



(b) Triangular indenter

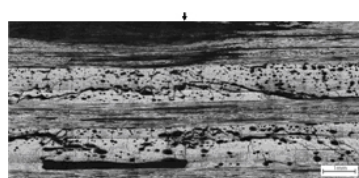
[Fig. 15] Plastic absorbing energy ratio with protective materials

For the absorbing energy ratio ($E_{ab}/E_{ab,b}$) as shown in Fig. 14. There was a large amount of scatter in data, especially for the hemispherical indenter. However, the protected panels had a slightly lower ratio than that of the base panel. To further understand energy absorbing behavior when using protective materials, the energy absorbed plastically was normalized by the plastic energy of the base panel and their ratio were plotted in Fig. 15. To calculate the plastic absorbing energy, the elastic absorbing energies were obtained and summarized in Table 5. For the hemispherical indenter in Fig. 15(a), the ratio had a considerable amount of scatter and were much lower than for the base panel regardless of protective materials. Among these protective panels, the rubber panel had an inferior protective effect. For the triangular indenter in Fig. 15(b), the glass/epoxy panel had a superior protective effect.

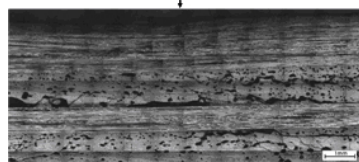
Figures 16 and 17 illustrate impact damage according to protective materials for the hemispherical and the triangular indenter, respectively. Damage modes in the panels were similar to that of the base panel in Fig. 9. However, the severity of damage in the protected panels was remarkably reduced compared with the base panel. For the hemispherical indenter in Fig. 16, it appears that damage in the rubber panel was more serious than damage in the kevlar/epoxy and glass/epoxy panels. This is consistent with the inferior protective effect of the rubber panel, as aforementioned. A similar behavior was observed in the panels impacted by the triangular indenter, as shown in Fig. 17. Also, the damage states in these panels were much less severe than those in the panels impacted by the hemispherical indenter, as expected.

[Table 5] Elastic absorbed energy at threshold energy

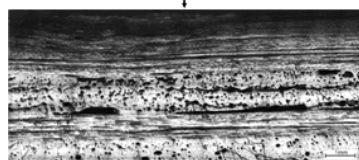
Indenter	Panel with rubber	Panel with kevlar/epoxy	Panel with glass/epoxy
Hemispherical	14.26J	13.70J	14.44J
Corner	19.83	19.24J	21.09J



(a) Panel with rubber

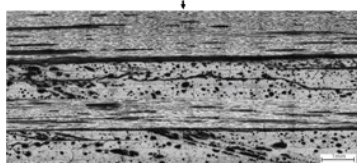


(b) Panel with kevlar laminates

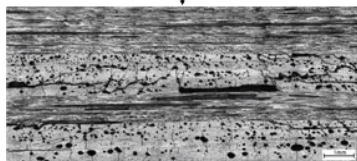


(c) Panel with glass/epoxy laminates

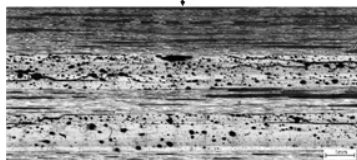
[Fig. 16] Damage in panels impacted by hemispherical indenter at 60J



(a) Panel with rubber



(b) Panel with kevlar/epoxy laminates



(c) Panel with glass/epoxy laminates

[Fig. 17] Damage in panels impacted by triangular indenter at 60J

4. CONCLUSIONS

To understand the impact damage behavior and effect

of protective materials on impact resistance in filament wound composite vessels, a series of low velocity impact tests using two different indenters were performed on panels with three types of protective materials. Impact damage parameters were introduced to evaluate the impact damage behavior of filament wound composites vessels. The effect of protective materials on impact resistance was identified. The following conclusions were obtained.

(1) To identify the protective effect of surface protective materials in a filament wound composite vessel subjected to a low velocity impact, impact resistance parameters were introduced. These were largely classified into (a) force history-based parameters and (b) impact damage-based parameters.

(2) Based on the results for impact resistance according to indenter type, when the filament wound composites vessels were subjected to a low velocity impact, the hemispherical type object was most damaging in view of damage tolerance.

(3) The protective materials considerably improve impact resistance regardless of indenter type. Among the protective materials, the glass/epoxy laminates had superior protective effects while the rubber plate had inferior effect.

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<Research Interest>

Structural and fatigue analysis for composite materials

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<Research Interest>

Wind energy conversion system, Aerodynamic design