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Impact Damage Behavior in Filament Wound Composite Pressure Vessel

Ki-Weon Kang*, Young-Soo Kim[1], Rin Choi[1] and Mee-Hae Lee[1]

Korea Institute of Sport Science, Seoul 139-242, Korea
[1]Department of Safety Engineering, Seoul National University of Technology, Seoul 139-743, Korea

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Abstract : The goals of the paper are to understand the impact damage behavior and identify the effect of surface protective materials on impact resistance in filament wound composite pressure vessels. For these, a series of low velocity impact tests was performed on specimens cutting from the full scale pressure vessel by the instrumented impact testing machine. The specimens are classified into two types, which are with and without surface protective material. The visualization for impact damage by two different impactors is made by metallurgical microscope. Based on the impact force history and damage, the impact resistance parameters were employed and its validity in identifying the damage resistance of filament wound composite pressure vessel was reviewed. As the results, the impact resistance of the filament wound composites and its dependency on the surface protective material were evaluated quantitatively

Key words: filament wound composite pressure vessel, impact damage, impact resistance, low velocity impact, surface protective material

1. Introduction

One area in which composites have been used rather extensively is for fabricating pressure vessel. These structures can be readily manufactured by filament winding, which is, as far as composite fabrication techniques are concerned, a relatively inexpensive method for producing composite structures.[1~3] The filament winding technique manufactures products by making the reinforced fiber wetted by resin mixture wind around revolving cylindrical mandrel. As reinforced fiber used for this, carbon fiber, which has excellent strength and rigidity, is largely used with a polyester or epoxy resin. Since filament wound pressure vessels manufactured using composite materials as above are light compared to conventional metal pressure vessels but can contain gas of the same volume, and also have strong corrosion resistance, they are advantageous for long time use [2, 3].

Unfortunately, high pressure vessels manufactured applying the filament winding technique to carbon fiber have the demerit that impact damage by low velocity impact can occur easily due to the lack of through-the-thickness reinforcement [4,5]. The impact damage is difficult to be noticed with the naked eye, and even though it can be discerned using nondestructive technique, to evaluate the damage tolerance is very difficult due to the risk of leakage, etc. In particular, for the case that the thickness of pressure vessel is thin, damage occurrence mechanism by low velocity impact and its behavior have been reported [6], but there are few studies for the case that the thickness of pressure vessel is thick [4,5,7]. Accordingly, for high pressure vessels which have high possibility that the impact situation, such as falling of tool, in the process of manufacture, conveyance, storage, etc will occur, more extensive research is necessarily required to improve the impact resistance of composite structures.

In the study, to understand the impact damage behavior and identify the effect of surface protective materials on impact resistance in filament wound composite pressure vessels, a series of low velocity impact tests by two different impactors and the identification of impact damage were performed for thick specimens extracted from the high pressure vessel manufactured by the fila-

*Corresponding author: kwkang68@hanmail.net

ment wound technique. Through these procedures, the parameters for evaluating impact resistance were introduced, and also the effect of surface protective material on impact resistance was identified.

2. Experimental Proceudres

2.1. Materials and specimen

The high pressure vessel used in the study was manufactured at Hankuk Fiber Inc. by the filament wound technique, using the carbon fiber of the T700 and the epoxy resin of the #2500. The mechanical properties of the composite used are shown in Table 1. And the selected surface protective material was NBSRB rubber manufactured by Daeryuk Rubber Belt Inc. and its thickness was about 1mm. This material was then bonded to the surface of pressure vessel with epoxy type adhesive and the assembly was cured under room temperature and ambient atmosphere. From the high pressure vessel manufactured like that, specimens of square shape, which is 100 mm wide and 100 mm long, were extracted. The width and length directions of the specimen were made to coincide with the circumference and length directions of the high pressure vessel, respectively. The total thickness of the specimen was 12.7 mm.

2.2. Low velocity impact test

The low velocity impact test for extracted specimen was performed using instrumented dropweight impact testing machine (Dynatup, 9250HV). The specimen was fixed at pneumatic specimen fixture, and its opening has round shape with the diameter of 76.2 mm. The upper and lower plates which fix it the specimens were fabricated considering the curvature of the specimen extracted from cylindrical pressure vessel.

The mass of an impactor was 10.88kg, and the shapes of impactors employed were semispherical and triangular. The radius of curvature of the semispherical impactor was 6.35 mm and the radius of curvature and length of the triangular impactor were 3.175 mmm and 25.4 mm, respectively. For the triangular impactor, there exists relativity between the impactor and the fiber orientation of the surface hoop layer. Hence, to consider the worst case in the impact damage, the tests were performed for the case that the impactor is perpendicular to the fiber orientation of the hoop layer. Accordingly, the impactors can be classified into semispherical and triangular-transverse impactors. The applied impact energies were selected as 60J, considering the impact conditions of high pressure vessel.

Table 1. Mechanical properties of T700/#2500

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

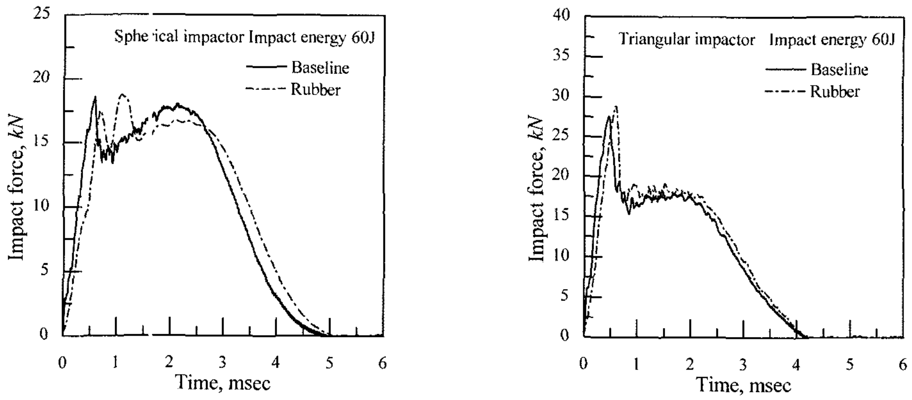
For visualization of impact damage in filament wound pressure vessel, 4 specimens representing each test condition were cut and polished in the direction parallel as well as perpendicular to the fiber orientation of the hoop layer, and then the impact damage in through-the-thickness was observed using metallurgical microscope.

3. Results and Discussion

3.1. Impact force history

When composites is subjected to impact loading, various impact damage processes, such as matrix cracking, delamination and fiber breakage, can occur [8]. These damage processes are associated with the specimen's energy absorbing capacities and impact damage behavior and can be characterized by the impact force history obtained during an instrumented dropweight impact testing machine. The energy absorbing capacity or impact damage behavior is greatly dependent on material constituents (fiber and matrix), impactor geometry, stacking sequence and boundary conditions [8] and especially for the case that the protective materials are employed on the surface and different impactors are used, these can be remarkably changed. To identify this behavior, the examples of impact force history for baseline specimen that the protective material did not employ and for protective specimen that it did employ, respectively, are shown in Fig. 1.

As shown in Fig. 1(a) which represents histories for spherical impactor, the force history for protective specimen is fairly similar to that of baseline specimen. The protective specimen has, however, the more local peaks and the delayed time-to-maximum load values. When the impact loading is applied to the protective specimen, the impactor does pass the protective material layer and reach to hoop layer. This behavior has influenced on the impact damage incipient load and energy, which has been reported that play major roles for evaluation of impact resistance. And from the Fig. 1(b), the histories exhibit the somewhat different behavior against the spherical impactor. The force history, which is the representative for energy absorbing capacity and impact damage behavior, is, therefore, affected by both the protective material and impactor geometry. Then to identify the energy absorbing capacity and impact damage behavior according to the protective material and impactor



(a) Impact force history for spherical impactor

(b) Impact force history for triangular impactor

Fig. 1. Impact force history.

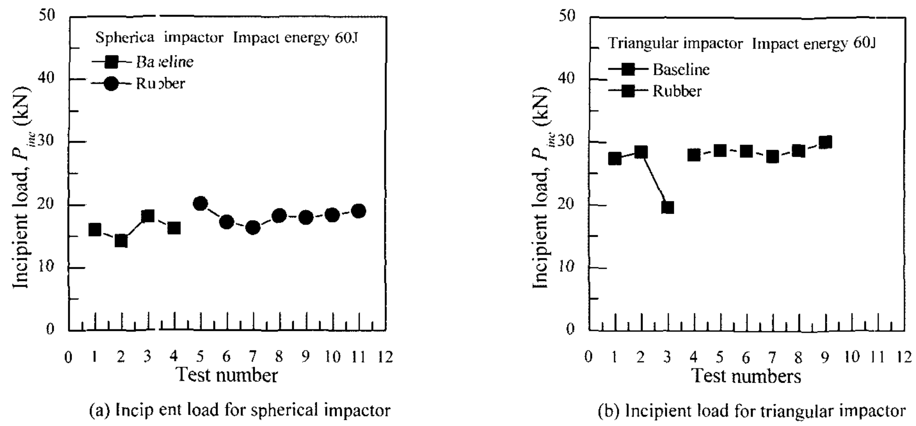
geometry, it seems to be reasonable to introduce the impact resistance parameter that is useful to identify impact resistance of composites previously reported [9, 10].

3.2. Evaluation of impact resistance

3.2.1 Impact damage incipient load

If impact loading is applied to composite structures, the impact damage, such as matrix cracking, delamination and fiber breakage, occur and then this cause the local vibration and load drops in force history:

This behavior has been reported to be due to the fact that impact damage occurs seriously and load bearing capacity in the region of the surface disappear, and then load decreases rapidly and the lower region of the surface bears loading [9, 10]. Accordingly, the load that the impact damage first occurs, that is, the impact damage incipient load (P_{inc}) is closely related to the impact resistance of structure. To identify clearly the behavior of the impact damage incipient load, the loads are obtained with impactor geometry and protective materials are shown in Fig. 2. As shown in Fig. 2, though there are scatter in the incipient load, the incipient load of composite structure is maintained constantly for the impactor types. This tendency coincides with the concept that since impact damage always occur if energy above threshold energy, under which impact damage does not occur, is applied, the occurrence of impact damage begins at a constant load. However, to some extent of scatter, for the spherical impactor, the loads are 14.7kN and 18.4kN for baseline and protective specimens, respectively, while the loads are identified as about 25.2kN and 28.7kN, respectively. This behavior is attributed to the protective effect of surface material on damage. Also, there is significant difference in incipient load according to impactor geometry: the reason of the difference is that since for the spherical impactor more concentrated load, due to its geometry, can be applied to the structure, the occurrence of damage occurs easily compared to other impactors. Accordingly, the impact damage incipient load can be considered to be the maximum bearing load of the surface layer of the composite



(a) Incipient load for spherical impactor

(b) Incipient load for triangular impactor

Fig. 2. Impact damage incipient load, P_{inc}

structure treated in the study.

3.2.2 Impact damage incipient energy

The impact damage incipient energy (E_{inc}) is pretty similar to the impact damage incipient load conceptually, is closely related to the threshold energy of structure, and is obtained by taking the energy value of the impact damage incipient load. To examine clearly the behavior of the impact damage incipient energy, the impact damage incipient energies are obtained and shown in Fig. 3.

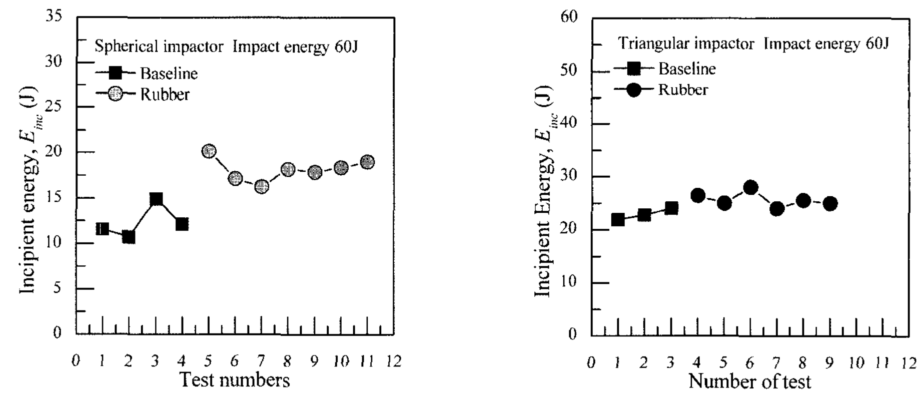
From figure, the impact damage incipient energy is maintained constantly and this tendency appears for impactor and specimen types. This phenomenon coincide with the above descriptions that the impact damage incipient load is maintained constantly regardless of incident impact energy. Also, for the spherical impactor, the energies are 12.7J and 18.1J for baseline and protective specimens, respectively, while the energies are identified as about 22.9J and 25.7J, respectively. It is concluded that the surface protective rubber material brings about a considerable improvement of impact resistance in filament wound pressure vessel regardless of impactor types.

3.2.3 Maximum impact load

The maximum impact load (P_{max}), which is the maximum value of impact load to which the composite structure is subjected, is a parameter closely related to the bending rigidity, contact rigidity and impact damage of structure. To identify clearly the behavior of the maximum impact load, the maximum impact loads are obtained and shown in Fig. 4. From figure, for the both the impactors, the maximum impact load is nearly constant regardless of specimen types. This tendency is considered to be due to that the impact damage occurs very seriously even for the surface protective specimen, and that more than the load can not be born.

3.2.4 Plastic absorbing energy

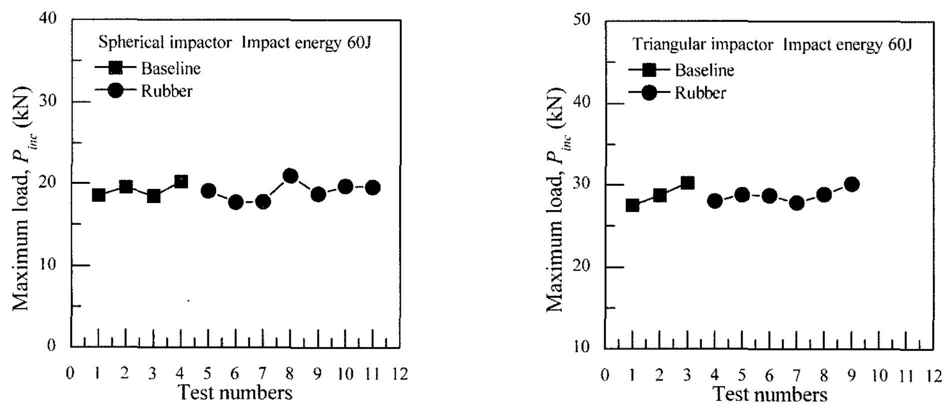
The plastic absorbing energy (E_{pl}) is the energy absorbed by impact damage and can be obtained by



(a) Incipient energy for spherical impactor

(b) Incipient energy for triangular impactor

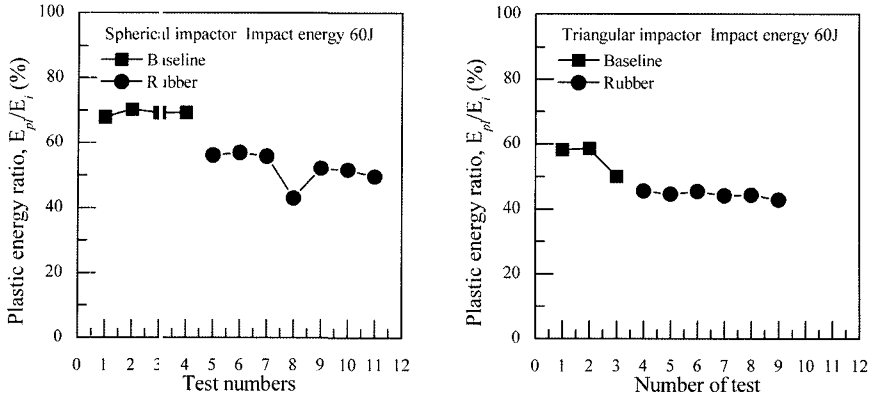
Fig. 3. Impact damage incipient energy, E_{inc}



(a) Maximum load for spherical impactor

(b) Maximum load for triangular impactor

Fig. 4. Maximum impact load, P_{max}



(a) Plastic absorbing energy for spherical impactor (b) Plastic absorbing energy for triangular impactor

Fig. 5. Plastic absorbing energy, E_{ol}

subtracting the elastic absorbing energy (E_{el}) by the vibration, deflection, etc of structure from the total absorbing energy. For this, the elastic absorbing energy was obtained by performing in three addition tests at the impact damage incipient energy evaluated for each test conditions. These elastic absorbing energies were identified as about 7.1J, 14.3J, 14.6J and 19.8J for spherical-baseline, spherical-protective, triangular-baseline and triangular-protective specimens, respectively.

Fig. 5 represents plastic absorbing energy ratio (the ratio of plastic absorbing energy to incident impact energy), which were obtained using the above method. From figure, the ratio for protective specimen is much lower than for baseline specimen regardless of the impactor types. This means that impact damage is serious by absorbing much energy by the plastic behavior of the baseline specimen, that is, the impact damage for protective specimen is slight due to protective effect of surface rubber material, compared with the baseline specimen.

3.2.5 Through-the-thickness impact damage

To evaluate the configuration and distribution of the impact damage in thickness according to the protective material, the specimen in which impact damage occurred was cut in the directions parallel and perpendicular to the fiber orientation of the surface and their sections were polished, and observed by a metallurgical microscope. Among impact damages observed like that, Fig. 6 represents the section parallel to the fiber orientation of surface. In figures, the vertical arrow represents the central point of impact.

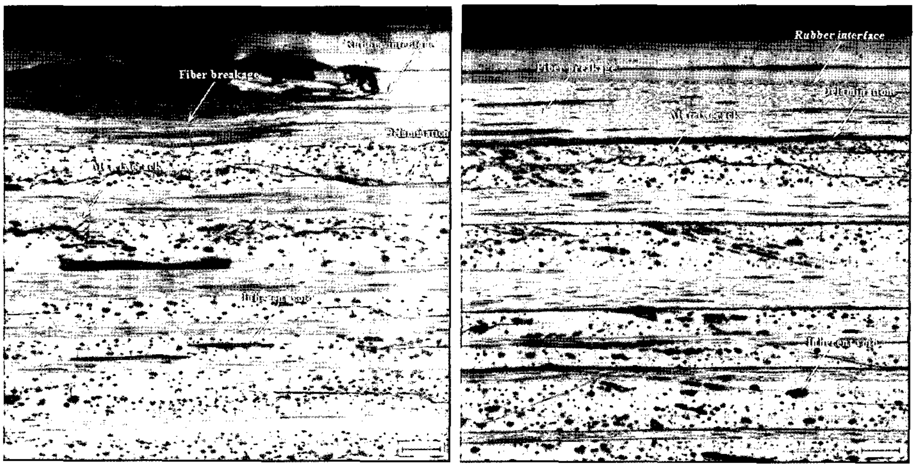
The authors have already reported the impact damage in baseline specimens for spherical and triangular impactor [10]. According to previous study, due to the spherical impactor, the hoop layer in the top was completely broken, and it was shown that it is meaningless to classify the impact damage into fiber breakage, delamination or matrix cracking. In particular, it was shown that the fiber in the part at specific distance from the impact point was completely broken. Compared with the damage by baseline-spherical impactor, the damage in protective specimen by the spherical impactor as shown in Fig. 6(a), the hoop layer is partially collapsed, and the local fiber breakage is appeared. It can be, therefore, concluded that the protective specimen by the spherical impactor has considerable amount of load bearing capacity, compared to the case of the baseline-spherical impactor.

Also, in the case of the impact damage by the triangular impactor as reported in previous study [10], the fiber breakage and the breakage of the hoop layer in the vicinity of the impact point have appeared. Also, it was shown that the impact damage which occurred in the lower part of the impact point developed in the diagonal direction and was connected to the delamination of the interface between the hoop layer and the lower layer. However, Fig. 6(b), which represents the damage by the triangular impactor in protective specimen, shows that the collapse or breakage of the hoop layer is not observed; only there are local fiber breakage, delamination and matrix crack in each layer.

It is concluded that the protective surface material gives a considerable improvement of protective effect in impact resistance on filament wound pressure vessel, regardless of impactor types.

4. Conclusions

In the study, to understand the impact damage behavior and identify the effect of surface protective materials on impact resistance in filament wound composite pressure vessels, a series of low velocity impact tests by



(a) Through-the-thickness damage for spherical impactor (b) Through-the-thickness damage for triangular impactor

Fig. 6. Through-the-thickness impact damage

two different impactors and the visualization of impact damage were performed for thick specimens extracted from the high pressure vessel manufactured by the filament wound technique. Through these procedures, the parameters for evaluating impact resistance were introduced, and also the effect of surface protective material on impact resistance was identified and the following conclusions were obtained.

1. To identify the protective effect of surface rubber material in the filament wound pressure vessel subjected to low velocity impact, the impact resistance parameters were introduced. These were classified largely into (1) impact force history based parameters and (2) impact damage based parameters.

2. Through the evaluation the protective effect of surface material on impact damage by the above impact resistance parameters, it was found that impact resistance parameters selected in the study can quantify the impact resistance of composite structure.

3. Based on the results for impact damage resistance with the protective material and impactor geometry, it was found that the protective material does give a considerable improvement of impact resistance regardless of impact types

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