CAI STRENGTH OF CFRP LAMINATES TOUGHENED WITH MULTI-WALLED CARBON NANOFIBER

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Abstract
In the present study, we suggested an alternative way to increase residual compression strength after impact of CFRP laminate by means of adding carbon nanofibers in the matrix resin. Carbon nanofiber was employed as reinforcement for matrix to decrease the delamination area which occurs when impact load acts on the CFRP laminate. For the reinforcement, multi-walled carbon nanofiber were used and twill woven fabric of carbon fiber was used as main composition materials in the present study. Impact tests using drop weight had been carried out to give the internal damage composed of delamination and transverse crack. Then, compression after impact test (CAI) were performed to evaluate the effect of carbon nanofiber to increase the residual strength of the laminates. From the experimental results, the relation between additive quantity of CNF in the matrix resin and residual compression strength was investigated in detail.

1. Introduction

Fiber reinforced plastics (FRP) have been developed as the foremost material for products in mechanical, electrical, architectural and structural engineering. Carbon fiber reinforced plastic (CFRP) has especially attained a prominent position in use as structural materials for aeronautical and space engineering. Application in this industry requires further reduction in weight to satisfy the demand for higher fuel efficiency.

Considering delamination growth in view of fracture mechanics, interlaminar fracture toughness still plays an important role in damage propagation of CFRP. Therefore, a number of experimental and analytical techniques have been proposed to estimate the fracture toughness for mode I, mode II, mixed mode and dynamic deformations[1]–[3] with several combinations of carbon fiber and matrix resin.

Previous attempts to improve the interlaminar fracture toughness of CFRP laminates has shown a variety of useful results. Namely, a certain level of toughening technique has already been achieved by inserting an interleaf (interlayer) between the CFRP prepregs[4, 5, 6]. T800H/3900-2, with a heterogeneous interlayer consisting of fine thermo plastic particles, has shown high compressive strength after impact (CAI).

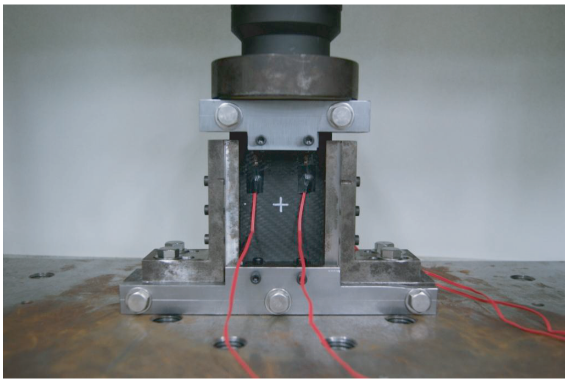

Figure 1: Apparatus of compression after impact test.

On the other hand, the author's group have been suggested the CNF interlayer for unidirectional CFRP laminates to obtain higher fracture toughness in mode I and mode II deformations[7, 8]. Since discovery of the carbon nanotube (CNT) and carbon nanofibers (CNF) [9][10] CNT and CNF have received a great deal of attention in the aeronautical, biological, electrical and mechanical sciences, and engineering fields.

Carbon nanotubes and nanofibers have been applied as the toughening filler of the structural material for resin or metal based composites. They are suitable for this application as they also have excellent mechanical properties such as elastic moduli, strength, fracture toughness, and flexibility compared with the traditional carbon fiber which are based on polyacrylonitrile (PAN).

In this study, we implemented an alternative way to increase the interlaminar fracture toughness of CFRP laminates by adding carbon nanofibers in the matrix resin of the CFRP.Carbon nanofiber was employed as reinforcement for matrix to decrease the delamination area in the CFRP laminate and inclease residual compression strength after impact testing. For the reinforcement, MWNT-7(Hodogaya Chemical Co.,LTD.) were used and the carbon fiber of twill woven fabric was used as main composition materials in the present study.

At first, transverse impact tests had been carried out by drop weight test using DYNATUP 9250HV. Then, compression after impact test (CAI) were performed to evaluate the effect of carbon nanofiber to disturb the residual strength decreasing. From the experimental results, the relation between additive quantity of CNF and residual compression strength was investigated in detail.

2. CFRP specimens

Carbon fiber twill woven fabric C06347B (TORAY) and epoxy resin DENATOOL (XNR6809 as base resin and XNH6809 as curing agent, the weight ratio of XNR6809:XNH6809 = 100:95) by Nagase Chemtex Corp. have been used as base materials for CFRP. Moreover, in order to toughen the interlayers between the woven fabric, MWNT-7 (Hodogaya Chemical Co., LTD.) have been used as nanoreinforcements.

As a first step, CNFs and the epoxy resin were mixed in a planetary centrifugal mixer (SR500, THINKY USA Inc.). The CNF volume fraction was controled as 1.2vol%, 2.5% and 0% (neat Epoxy). CNF/Epoxy slurry was spreaded on the CF woven fabric and the another woven fabric was piled up on it as the same manner up to total 18 layers. The preform was later wrapped using a sealant tape and a bagging film, and the inside was vacuumed 2 hours. Then, the laminate was cured using an electric furnace, with a primary curing cycle at 80°C (4 hours),

Table 1: Specification of CNF/CFRP specimen.

Materials	V_f(Epoxy) [%]	V_f(CF) [%]	V_f(CNF) [%]	Thickness [mm]
Base laminate	37.3	62.2	-	3.27
1.2vol%	38.6	56.1	5.3	3.63
2.5vol%	37.5	54.5	8.0	3.74

and, subsequently, a secondary curing cycle at 120°C (2 hours). The specimens for impact tests were cut out for 100mm×100mm square plates. Table 1 shows volume fraction of the epoxy, carbon fiber and carbon nanofiber on each CFRP specimens and thickness of those specimens, respectively.

3. Test conditions

Drop weight impact tests were carried out using Dynatup 9250HV(INSTRON). CFRP specimen size was square plate of 100mm×100mm, the mass of drop weight is 5.54kg, and the height was specified to 0.04, 0.08, 0.12, 0.16m to produce 2.17, 4.34, 6.52, 8.69J impact energies. Absorbed energy of CFRP laminate was calculated by difference between impact and after impact enegies of the drop weight.

Internal damage of CFRP laminte was observed after impact test by ultrasonic inspection equipment D-view (KJTD). Total delamination area was estimated by the observed 2D-image obtained from ultrasonic inspection, where the overlapping of the delaminations was not taken into consideration.

Compression after impact tests were carried out based on the standard JIS K7089 using material testing machine AG-IS2650kN (SHIMADZU) . The test equipment (jig) for CAI tests is shown in Fig.1. The dimension of the CFRP specimen was resized to 100mm×70 mm for CAI tests. Cross head rate of the CAI tests was specified to 1mm/min. Strain gage was put on the specimen to obtain the elastic modulus of of the “damagted”CFRP specimens.

4. Experimental results

Fig.2show the relation between jmpact energy and observed energy in the drop weight impact tests. It can be found that observed energy increases linearly as the impact energy increases. However the effect of CNF content seems to be small as shown in the figure. The relation between delamination area and impact energy was shown in Fig.3. The figure shows that the delamination area increases as the impact energy increases. It was confirmed that the delamination area of the nanomodified CFRP laminate was relatively small compared with base laminate. Furthermore, the delamination area of 2.5vol CNF/CFRP laminates is smaller than that of 1.2vol laminates. From these results, it can be confirmed that the fracture toughness and strength of the matrix phase of CFRP laminate was increased adding CNF in the matrix resin.

The relation between impact energy and elastic modulus after impact test were shown in Fig.4. From the figure, we found that the effect of CNF for the elastic modulus of “damaged”specimens was small. On the other hand, the relation between compression strength after impact test and impact energy was shown in Fig.5. The CAI strength decreases as the impact energy increases as shown in the figure. Namely, increacing of damaged area seems to be affect the decreacing of CAI strength. As shown in the Fig.5, CAI strangth can be increase by adding CNF in the matrix rasin phase. Therefore, the nanomodified treatment by adding CNF in the matrix resin is found to be valid to increase the residual compression strength after impact test.

5. Concluison

In the present study, nanomodified CFRP laminates were fabricated by adding multi-walled carbon nanofiber in the matrix resin of woven fabric based CFRP, and drop weight impact tests were carried out to evaluate damage area of the nanomodifed CFRP specimens. Furthermore, compression after impact tests were carried out to investigate the effect of carbon nanofiber for the variation of CAI strength. It can be confirmed that the nanomodified treatment by adding CNF in the matrix resin is found to be valid to increase the residual compression strength after impact test.

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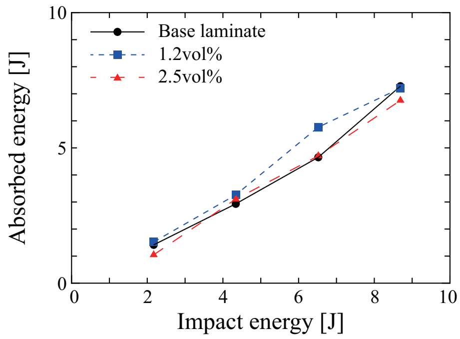

Figure 2: Relation between Impact energy and absorbed energy of CFRP laminates.

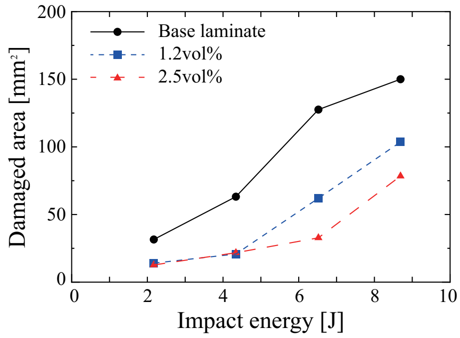

Figure 3: Relation between Impact energy and Damaged area of CFRP laminates.

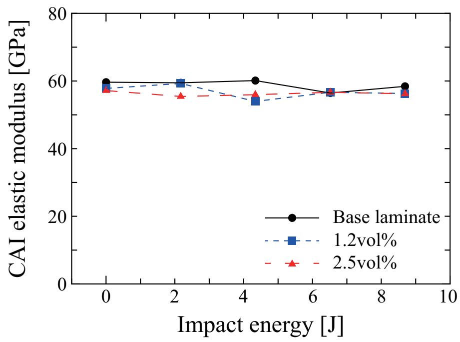

Figure 4: Relation between Impact energy and CAI elastic modulus of CFRP laminates.

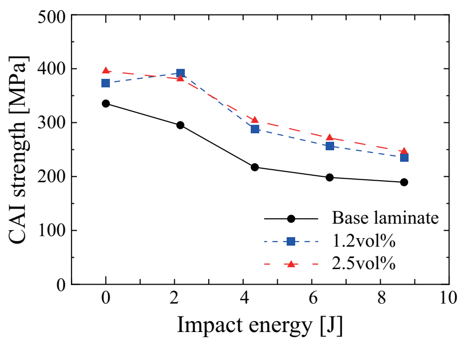

Figure 5: Relation between Impact energy and CAI strength of CFRP laminates.