HIGH ENERGY ABSORBING COMPOSITE STRUCTURE FOR ROTORCRAFT CRASHWORTHINESS

Naoki Higuchi*, Ken-ichiro Abe*, Masayuki Kanemasu*
***Mitsubishi Heavy Industries, Ltd.**
10 Oye-cho, Minato-ku, Nagoya, 455-8515, Japan

Keywords: *Crashworthiness, Rotorcraft, Composite, Out-of-plane strength*

Abstract

'Zanchor' effects on energy absorption efficiencies of a composite structure have been studied for improving rotorcraft crashworthiness. Zanchor is a technology, which has been developed by Mitsubishi Heavy Industries, Ltd. (MHI) and Shikibo Ltd (Shikibo), to improve composite structure out-of-plane strength by entangled fiber. Zanchor composite tubes were crush tested under static and dynamic conditions. Results have indicated that Zanchor improves the specific energy absorption and the load uniformity ratio, since Zanchor increases the average load without changing the initial peak load. Results have also indicated that Zanchor enables the ideal load-displacement curve to be acquired by varying out-of-plane strength along the crushing direction. Therefore Zanchor is a suitable technology for crashworthy subfloor structures of rotorcraft.

1 Introduction

Rotorcrafts always have collision risks with the ground obstacle, because they are frequently employed in mountainous area and at low altitude. Providing adequate crashworthiness is important for occupants to survive in accidents. Almost all current military rotorcrafts have crashworthy seats, landing gears, and subfloor structures to attenuate acceleration. Crashworthy subfloor structures are the most important features, since landing gears will not work as an energy-absorbing device when crash on the water or soft ground surface, and when landing gears cannot extend due to low altitude flight.

Many composite researches are conducted for improving rotorcraft crashworthiness. A progressive failure mode of brittle composite materials gives more energy absorption efficiencies than a plastic deformation of ductile materials such as metal [1]. Some studies deal with reducing the initial peak load by providing triggers to prevent injurious acceleration from loading to occupants, other studies deal with increasing an amount of energy absorption. Improving out-of-plane strength is one of approaches in the latter case. Zanchor is a developed technology which improves out-of-plane strength [2]. It has been shown that Zanchor improves energy absorption efficiencies [3].

The object of this study is to investigate Zanchor effects on energy absorption efficiencies. Zanchor has improved energy absorption efficiencies, and has enabled the desirable load-displacement curve to be acquired, by varying out-of-plane strength along the crushing direction.

2 Background

2.1 Evaluation Indexes

There are two evaluation indexes which indicate energy absorption efficiencies. One is the amount of energy absorption per unit mass, or the specific energy absorption, E_s. The other is the relation between the maximum load and the average load, or the load uniformity ratio, $R_{L.U.}$.

The specific energy absorption, E_s

The specific energy absorption, E_s, is defined as energy absorbed by crushing per unit mass of deformed structure. This can be written as:

$$E_s = \frac{E}{\rho A \delta} = \frac{\int_0^{\delta} F dx}{\rho A \delta}$$

Where E is the energy absorbed by crushing, ρ is the density of material, δ is the crushing displacement, A is the cross-sectional area of the structure, and F is the crushing load. E_s is desirable to increase as much as possible, since an energy-absorbing structure size is limited in a rotorcraft. E_s can be varied with a failure mode of an energy-absorbing structure.

The load uniformity ratio, $R_{L.U.}$

The load uniformity ratio, $R_{L.U.}$, is defined as the ratio of the maximum load to the average load during crushing. This can be written as:

$$R_{L.U.} = \frac{F_{\max}}{F_{ave}}$$

Where F_{max} is the initial peak load, and F_{ave} is the average load after the initial peak load. These notations are shown in the load-displacement curve, Fig.1. $R_{L.U.}$ is desirable to approach 1.0, in other words, the load-displacement curve is desirable to be flat. $R_{L.U.}$ approaches 1.0 by providing triggers such as notches to an energy-absorbing structure which reduce the initial peak load.

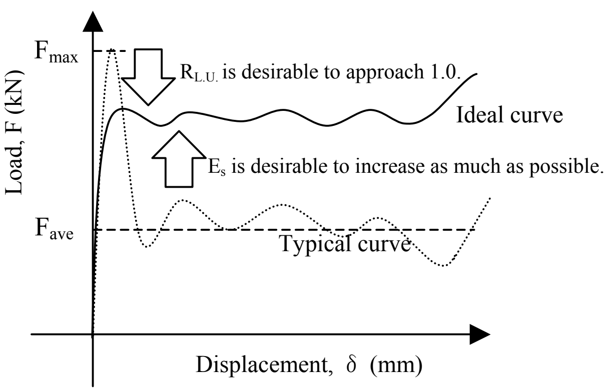

Fig. 1 Typical and ideal load-displacement curves

2.2 Failure modes of composite materials

E_s is concerned with a failure mode of an energy-absorbing structure, as mentioned above. An energy-absorbing structure should have a failure mode which enables the maintenance of a gradual decay in the crushing load profile. Catastrophic failure modes such as Euler buckling should be avoided.

Ductile composites such as Aramid Fiber-Reinforced Plastics (AFRP) crush in a progressive folding failure mode. This is similar to a concertina mode of metals. Brittle composites such as Carbon Fiber-Reinforced Plastics (CFRP) and Glass Fiber-Reinforced Plastics (GFRP) can crush in a splaying mode. This is more efficient for energy absorption than a progressive folding mode of ductile materials, assuming that other failure modes can be avoided [1]. An example of CFRP tube crushed in a splaying mode is shown in Fig. 2. This indicates that the lamina bundles bend extensively just like a flower blooms.

An energy absorption mechanism in a splaying mode is mainly concerned with an interlaminar crack growth, although the energy is also absorbed through of the laminar bundles bending and by frictional effects between platen, fronds, and adjacent laminas [4]. Previous researches have revealed that the followings approaches improve CFRP tube energy absorption efficiencies in a splaying mode [5].

- Increase the strain to failure of fiber.

Fig.2 An example of splaying mode

- Increase interlaminar fracture toughness, G_{IC}, of matrix material.
- Increase matrix failure strain.
- Increase an axial stiffness of CFRP materials with respect to fiber orientation.
- Increase the lateral support to the axial fibers with respect to fiber orientation.

Providing trigger to one end of CFRP tube can achieve a splaying failure mode. Trigger plays the role of a stress concentrator which causes failure at a specific location within the structure.

3 Zanchor technology

MHI and Shikibo have developed Zanchor technology which was intended to improve CFRP out-of-plane strength. Zanchor can be applied to the CFRP structure made of the liquid composite molding process, such as Resin Film Infusion (RFI) and Vacuum-Assisted Resin Transfer Molding (VaRTM).

A Schematic of this technology is shown in Fig. 3. Special needle entangles fiber, which improves out-of-plane strength. The CFRP structure cross-sections are shown in Fig.4. These show fiber was entangled in the Zanchor level 1 CFRP structure. Zanchor level is defined as an amount of entangled fiber. Zanchor level 0 means no Zanchor. Therefore out-of-plane strength improves with increasing Zanchor level. Strength improvements are shown in Fig. 5 [2]. Zanchor can easily vary out-of-plane strength along the crushing direction, by varying its level.

Zanchor was applied to CFRP tubes which were crush tested, to investigate Zanchor effects on energy absorption efficiencies.

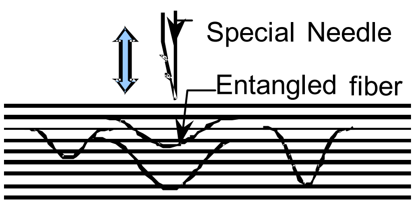

Fig.3 A schematic of Zanchor technology [2]

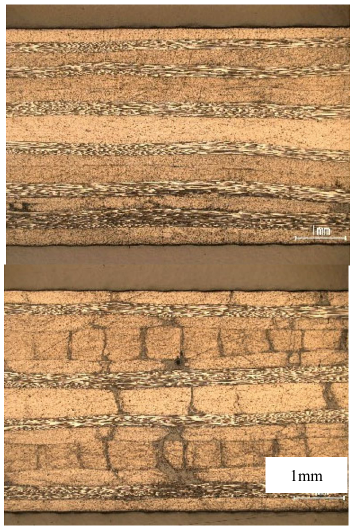

Fig.4 Photo of cross-sections

	Zanchor effect
CAI	35% up
G1c	144% up
Flatwise Tension	35% up
Non Hole Tension	9% up
Non Hole Compression	5% down

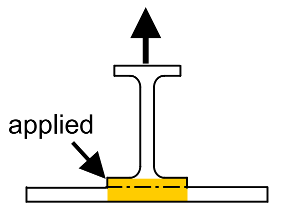

Fig.5 Zanchor effects on strength improvements [2]

4 Experimental

4.1 Materials and fabrication

CFRP tubes were fabricated as crushing test specimens. All specimens have the same laminate configuration [45/0/-45/0/0/-45/0/45], the 45° chamfer at the end of specimens as a trigger, and the same diameter 50mm. These were fabricated of T700/#172 (carbon/epoxy) preform/resin material in VaRTM process. A rough description of specimen is shown in Fig.6.

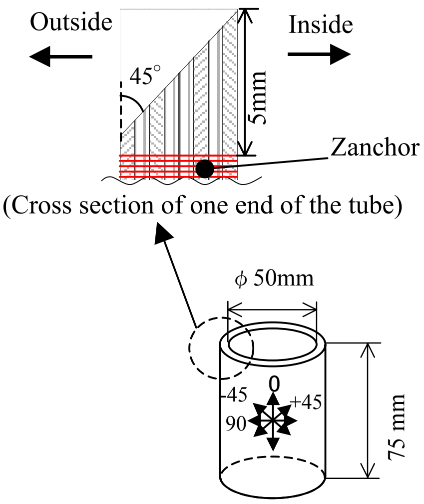

Fig. 6 A description of test specimens

Test parameters were Zanchor level and the strain rate. Zanchor level were from 0 to 4. Tests were conducted under two conditions to investigate the strain rate effects. One is a static test, the other is a dynamic test. Most of tests were carried out under static conditions for simplicity.

Specimens which have varied Zanchor level along the crushing direction were also fabricated. These were prepared for investigating that Zanchor can control the crushing load. Zanchor level of these is shown in Fig.7, which was based on the results from uniform Zanchor level specimen tests.

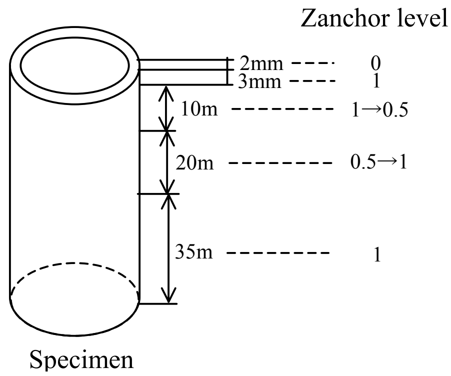

Fig. 7 A distribution of Zanchor level

All specimen tests in this study are summarized in table 1.

Table 1 The variety of specimens

No.	Material	Height (mm)	Zanchor Level	Test type	
				Static	Dynamic
1	T700 /#172	75	0	○	-
2			0.5	○	○
3			1	○	-
4			2	○	-
5			4	○	-
6			Varied	○	○

○: test, -: no test

4.2 Test method

Crushing tests were conducted in two speeds to investigate the strain rate effects, as mentioned above. In both tests, the crushing load and the crushing displacement of each specimen was measured during crushing.

Static tests were carried out by Instron 4400R servo-hydraulic test machine, the capacity of which is 500kN. Testing speed was 0.5mm/min until a crushing displacement of each specimen reached about 4mm, after then speed was accelerated up to 10mm/min.

Dynamic tests were carried out by the dynamic test equipment. This equipment has rails and a drop weight. A drop weight drops along rails, and crushes a specimen. Maximum height of a weight is 5m. Weight range of a drop weight is from 50 to 100kg. The testing speed was set from 7.0 to 8.5 m/s in this work.

5 Results and discussion

5.1 Zanchor level effects

Examples of specimens after crushing are shown in Fig. 8. These indicate that all specimens crushed in a splaying mode, regardless of Zanchor level.

The load-displacement curves are shown in Fig. 9. The initial peak load became almost the same values regardless of Zanchor level, since Zanchor was not applied 5mm of tubes top end (area A of Fig.9). The crushing load increased with increasing Zanchor level (area B of Fig.9).

The comparisons between Zanchor level and energy absorption efficiencies are shown in Fig. 10. Zanchor improved $R_{L.U.}$, since Zanchor increased the average load without changing the initial peak load. E_s of Zanchor level 1 was about 1.5 times as high as E_s of Zanchor level 0. E_s increased with increasing Zanchor level, although the rate of increase of E_s became small above level 2.

They indicated that Zanchor improved energy absorption efficiencies in the same fiber, matrix, and laminate configuration.

Fig. 8 Specimens after crushing

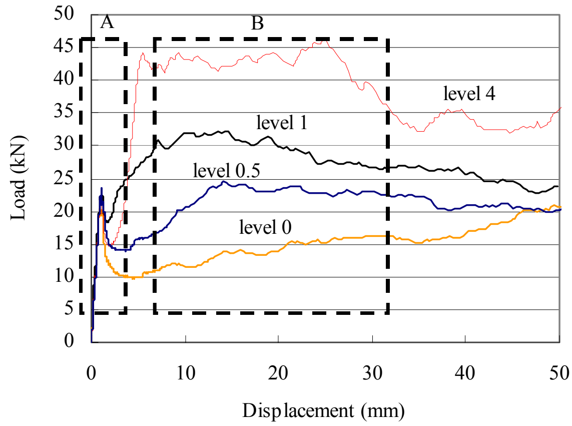

Fig.9 Zanchor effects on the load-displacement curve

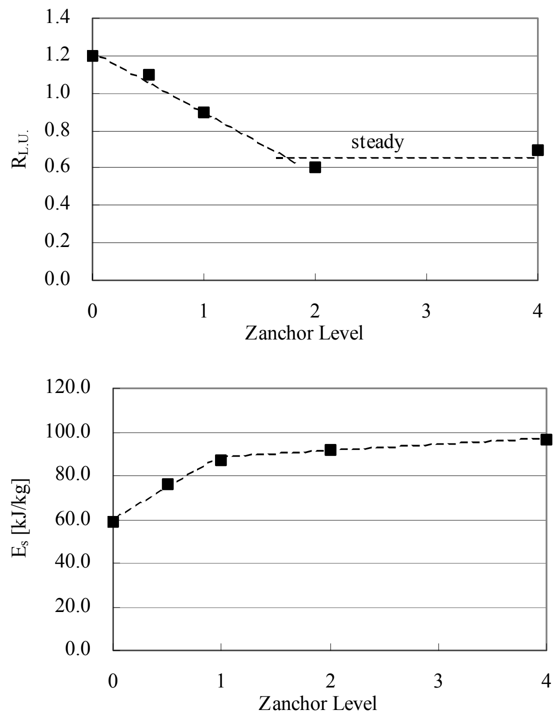

Fig. 10 Zanchor effects on energy absorption efficiencies

5.2 The strain rate effects

Examples of the load-displacement curves, which indicate the strain rate effects, are shown in Fig.11. The crushing load under dynamic test was higher than under static test. E_s are summarized in table 2. E_s under dynamic test was about 10% higher than under static test. These differences occurred due to the fact that mechanical properties of matrix material were affected by the strain rate.

5.3 The crushing load control

The load-displacement curves of varied Zanchor level specimens are shown in Fig.12. The target loads under both static and dynamic tests are shown too. These loads were based on results from uniform Zanchor level specimens. The target load under dynamic test was higher than under static test, since the crushing load under dynamic test were higher than under static test.

In both tests, the load-displacement curves closed to targets. These indicated that Zanchor could control the crushing load, and the desirable load-displacement curves were acquired by varying Zanchor level along the crushing direction.

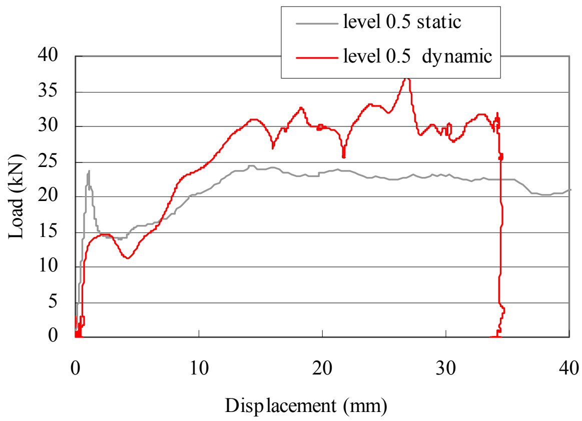

Fig. 11 The strain rate effects on the load-displacement curve

Table 2 Comparison of E_s [kJ/kg]

	Static	Dynamic	Ratio (Dynamic/Static)
T700/#172 (level 0.5)	76.1	85.6	1.12

6 Conclusion

In the present work, Zanchor effects on energy absorption efficiencies have been studied. Zanchor has improves $R_{L.U.}$, since Zanchor has increased the average load without changing the initial peak load. E_s of Zanchor level 1 was about 1.5 times as high as E_s of Zanchor level 0. E_s has increased with increasing Zanchor level, although the rate of increase of it has become small. Zanchor has enabled the ideal load-displacement curve to be acquired, since Zanchor can easily vary out-of-plane strength along the crushing direction.

It is expected that resin system which can be used in molding processes and which gives high crashworthiness will be developed for composite matrix in the near future, since these processes are still developing now.

Zanchor improves energy absorption efficiencies and enables an energy-absorbing structure to have the ideal load-displacement curve, in the same material and laminate configuration. We expect that Zanchor can be applied to energy-absorbing landing gears, the legs of seats as well as the crashworthy subfloor structure for rotorcraft.

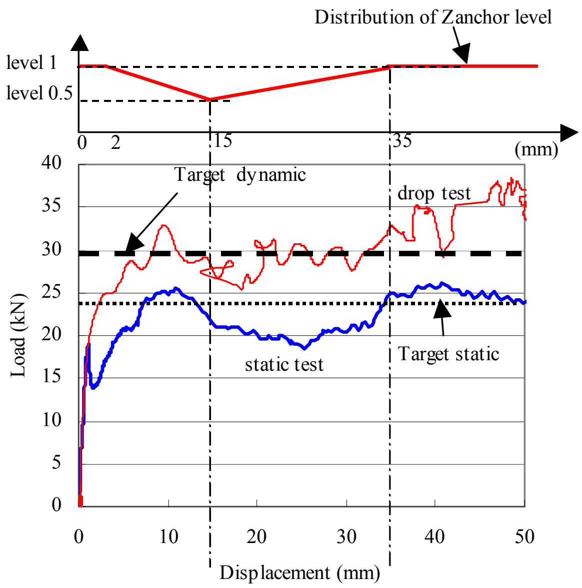

Fig.12 The load-displacement curve of varied Zanchor level specimens

7 Acknowledgement

Shikibo supported the preforming technology in this work. The author would like to thank their efforts.

8 References

[1] D.Hull. A Unified Approach to Progressive Crushing of Fibre-reinforced Composite Tubes. *Composites Sci. Tech.*, Vol.40, pp.377-421(1991).

[2] T.Abe, K.Hayashi, T.Sato, S.Yamane, T.Hirokawa. A-VaRTM Process and Zanchor Technology for Primary Aircraft Structures. *SAMPE Europe Coference 2003*.

[3] K. Abe, M Toyama. High Energy Absorbing Structure for Rotorcraft Crashworthiness. *29th European Rotorcraft Forum*.

[4] J.J.Carruthers, A.P.Kettle, A.M.Robinson. Energy Absorption Capability and Crashworthiness of Composite Material Structures: A Review. *Appl. Mech. Rev.*, Vol.51, No.10 (1998).

[5] G.C.Jacob, J.F.Fellers, S.Simunovic, J.M.Starbuck. Energy Absorption in Polymer Composites for Automotive Crashworthiness. *Journal of Composite Materials*, Vol.36, No.7 (2002).