High Energy Absorbing Structure for Rotorcraft Crashworthiness

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ABSTRACT

The present paper describes a new efficient energy absorbing structure for rotorcraft crashworthiness with "Z-anchor" technology shooting for improving out-of-plane strength of composite structures, and the research activities of aircraft crashworthiness in Mitsubishi Heavy Industries (MHI).

The efficiency of energy absorption of CFRP tubes with Z-anchor is about 1.5 times higher than the one without it. And load uniformity ratio is improved with Z-anchor. We expect that we can produce the energy-absorbing structure which has an ideal character with Z-anchor, and it can be applied to a seat, a fuselage structure, and a landing gear to improve their energy absorption capability.

INTRODUCTION

The rotorcraft always has the risk of accidents by contact with the obstacle etc. because it is often employed in mountainous area and at low altitude. It is important for rotorcraft to have crashworthiness to secure crews' survivability because it is impossible to prevent an accident completely. Until now, the effort has been made to improve a crews' survival rate in the crash, so current rotorcraft has impact energy absorbing members in the seat and landing gear. But the landing gear will not work as the energy-absorbing device when landing on the water or on soft ground surface. So recently, it becomes more important to install high energy-absorbing members in the fuselage structure without increasing in the fuselage weight.

According to the various researches, the progressive failure of the brittle composite material gives more energy absorption than the plastic deformation of the metal. So recently, many researches on composite materials as the impact energy absorbing structure are carried out. For example, it is studied that the effect of the selection of the fiber and matrix, the fiber orientation on the energy absorption capability of the composite material. But, "Z-anchor" is the way to complement those methods, and increase the amounts of energy absorbed per unit mass by 50% or more, and a load uniformity ratio approach almost 1.0, too. We expect that applying this technology to the energy absorbing structure can control its load-displacement curve.

MEASURES OF ENERGY ABSORPTION CAPABILITY

The typical load-displacement curve of the general energy absorbing structure, for example, the progressive folding crushing of the metal tube, is shown in Fig. 1. There is an initial linear-elastic response which reaches a peak load, F_{max}, before dropping. This is then followed by a series of oscillations around a mean crush level, F_{ave} in which each oscillation corresponds to the formation of one complete fold in the tube. Finally, the load rises rapidly as the tube becomes fully crushed, which is so-called "bottoming".

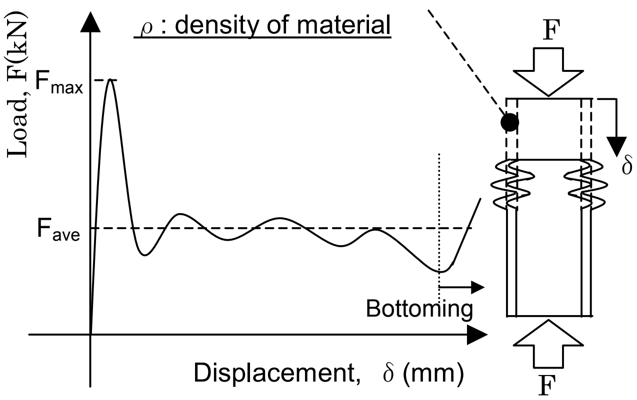


Fig. 1 Typical load-displacement curve

There are 2 indexes which show the capability of the impact energy absorbing structure. The first is efficiency, that is, the amount of the energy absorption per unit mass. Another is the load uniformity ratio as an index which shows the relation between the maximum acceleration loaded into the crews and the amount of the energy absorption.

The energy absorbed per unit mass, or specific energy absorption, E_s, is defined as the energy absorbed by crushing, E, per unit mass of deformed structure. It represents the efficiency of the energy absorption, and so it is suitable that E_s increase as much as possible. Using the notation of Fig.1, this can be written as:

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

The load uniformity ratio, $R_{L.U.}$, is defined as the ratio the max load by the average load in crushing process. It is suitable that $R_{L.U.}$ approach 1.0. In other words, it is desirable that the load-displacement curve is flat. Using the notation of Fig. 1, this can be written as:

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

The ideal load-displacement characteristic of energy absorbing structure is shown in Fig. 2.

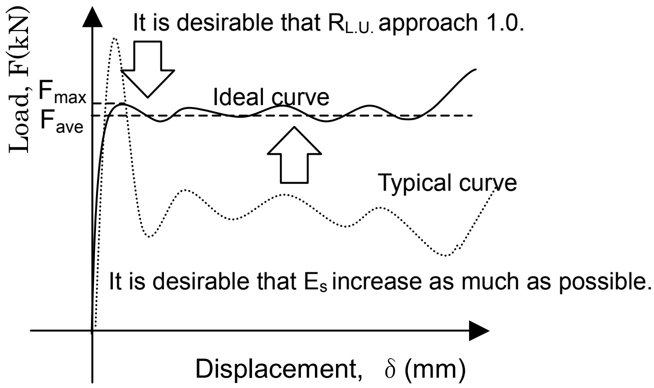
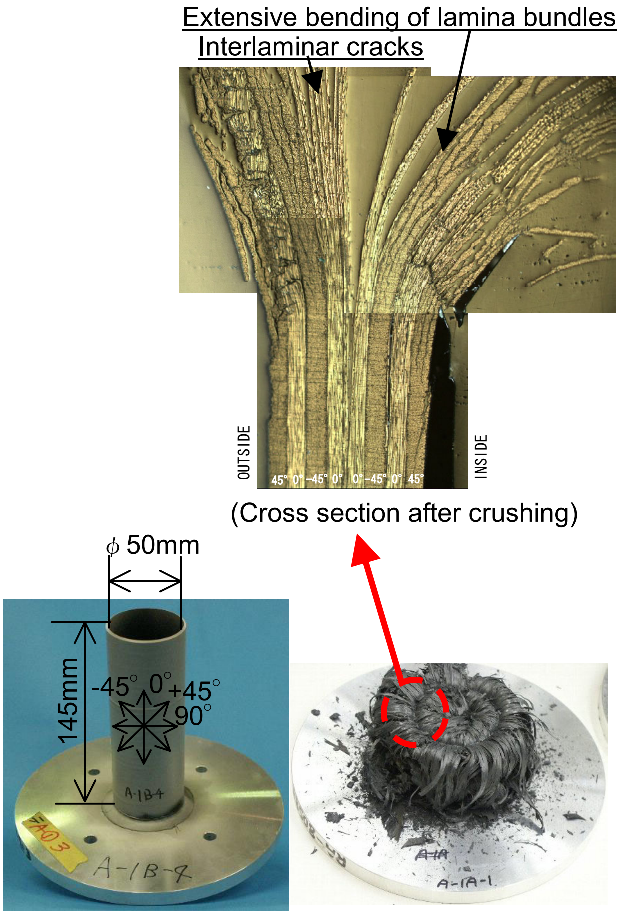


Fig. 2 Ideal load-displacement curve

EFFICIENT ENERGY ABSORPTION FAILURE MODE OF COMPOSITE MATERIAL

Crashworthiness is concerned with the absorption of energy through controlled failure mechanisms and modes that enable the maintenance of a gradual decay in the load profile during absorption. So the catastrophic failure such as Euler buckling should be avoided for the energy absorption, and the progressive failure such as concertina mode of metals is accepted.

The ductile composite materials such as AFRP(Aramid Fiber-Reinforced Plastics) crush by progressive folding mode failure which is similar to concertina mode of the metals. The brittle composite materials such as CFRP(Carbon Fiber-Reinforced Plastics) and GFRP(Glass Fiber-Reinforced Plastics) can crush by “splaying mode” which is more efficient in the energy absorption than progressive crushing of metal or AFRP if catastrophic failure is avoided（Ref. 1）. Fig. 3 shows an example of splaying mode crushing of CFRP tube tested in MHI. The lamina bundles bend extensively just like a flower blooms.



(Before crushing) (After crushing)

Material : Unidirectional graphite/epoxy prepreg

Thickness : 0.20mm / ply

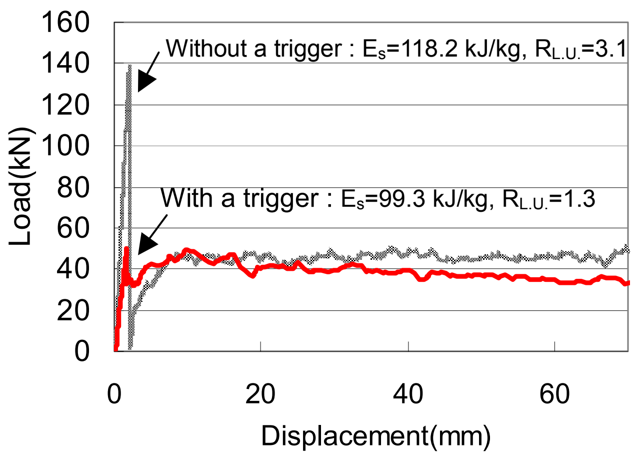
Fig. 3 Example of splaying mode crushing

The main energy absorption mechanism in splaying mode crushing is interlaminar crack growth, although energy is also absorbed through bending of the laminar bundles and by frictional effects between platen, fronds, and adjacent laminae(Ref. 2). As the result of various research, the followings enhance the energy absorption capability of the composite material in Splaying Mode（Ref. 3）.

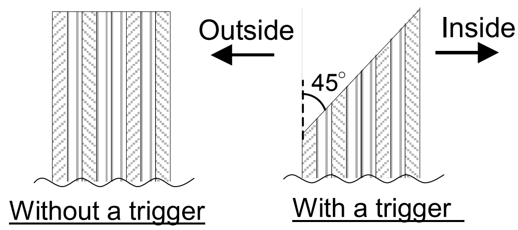
(1) Increase the strain to failure of the fiber.
(2) Increase interlaminar fracture toughness, G_{IC}, of matrix material.
(3) Increase matrix failure strain.
(4) Increase the axial stiffness of the composite material with respect to fiber orientation.
(5) Increase the lateral support to the axial fibers with respect to fiber orientation.

Progressive crushing of composite material can be achieved by providing a trigger at one end of the tube. A trigger is a stress concentrator that causes failure to initiate at a specific location within the structure. A trigger reduces the initial load peak that accompanies failure initiation followed by stable collapse. The most widely used method of triggering is to chamfer one end of the tube.

Fig. 4 shows examples of an effect of a trigger in splaying mode crushing tested in MHI.



(Load-displacement curve)



(Cross section of one end of the tube)

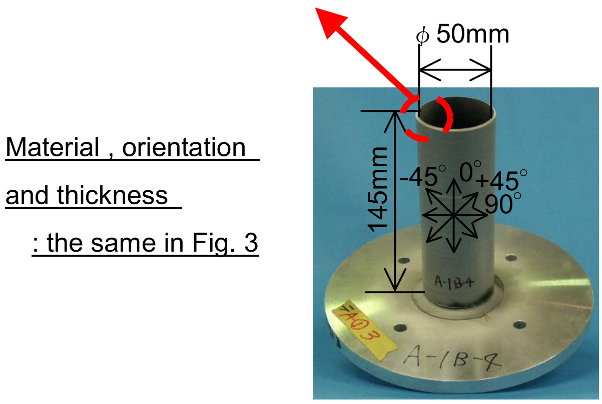


Fig. 4 Example of an effect of a trigger

THE EFFECT OF “Z-ANCHOR” TECHNOLOGY ON ENERGY ABSORPTION CAPABILITY

Z-anchor Technology

MHI and Shikibo developed a new technology “Z-anchor” aiming for improving out-of-plane strength of composite structures. This technology can be applied to the composite structure made of the liquid composite molding process, such as RTM(Resin Transfer Molding), RFI(Resin Film Infusion) and VaRTM(Vacuum-Assisted Resin Transfer Molding). Schematic of this technique is shown in Fig. 5. Strength improvement is shown in Fig. 6(Ref. 4) . As above-mentioned, the energy absorption capability of CFRP depends on the interlaminar strength. So, we try to apply Z-anchor technology which improve the interlaminar strength to CFRP tube and investigate the effect of Z-anchor on the energy absorption capability of CFRP.

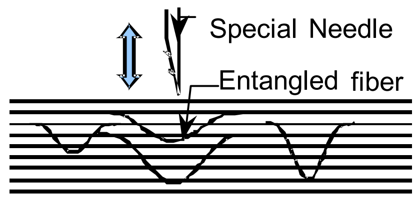


Fig. 5 Schematic of Z-anchor

	Z-anchor effect
CAI	35% up
G1c	144% up
Flatwise Tension	35% up
Non Hole Tension	9% up
Non Hole Compression	5% down

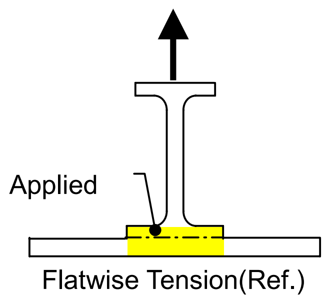


Fig. 6 Strength improvement effect on Z-anchor

Specimens and Methods

Test specimen description is shown in Fig. 7.

The tests are carried out by Instron 4400R servo-hydraulic test machine, the capacity of which is 500kN. The testing speed is 0.5mm/min until the crushing displacement of the specimen reaches about 4mm. After then, the speed is accelerated up to 10mm/min.

The test parameter is Z-anchor level, “z”. The more “z” value is, the more Z-anchor is applied to the specimens. 0(z) represent no Z-anchor.

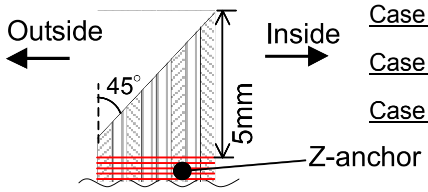
The crushing load and displacement of specimens is measured during the tests and take pictures of specimens after crushing.

Z-anchor level

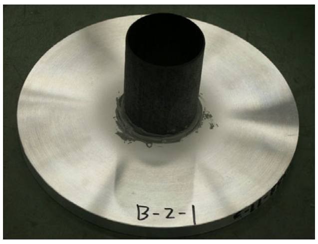
Case 1 : 0 (z)

Case 2 : 1 (z)

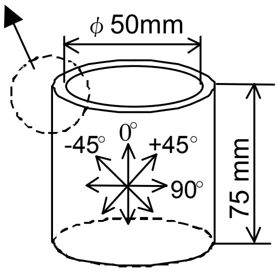
Case 3 : 2(z)



(Cross section of one end of the tube)



(Photo of a specimen)



Material : graphite cloth / epoxy

Thickness : 0.15mm / ply

Process : VaRTM(Vacuum-Assisted Resin Transfer Molding)

Fig 7 Description of test specimen

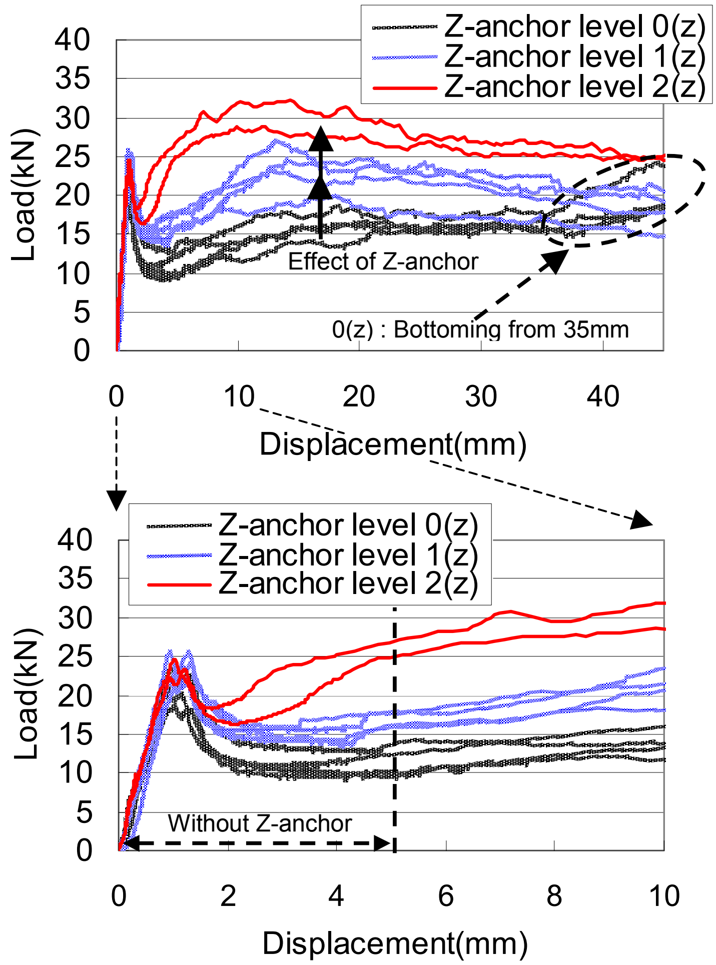


Fig 8 Load-displacement curve

Test Results

The load-displacement curve is shown in Fig. 8. An initial peak load becomes almost equivalent values regardless of Z-anchor level of the specimens because Z-anchor didn't apply until 5mm from one end of the tubes.

The effect of Z-anchor is the followings:

(1) Z-anchor increases the crushing load of CFRP tube.

(2) Z-anchor delays the start displacement of bottoming.

The photos of specimens after crushing are shown in Fig. 9. In crushing, the flower bloom of lamina bundle of CFRP tube with Z-anchor is more extensive than the one without Z-anchor. The reason why Z-anchor delays the start displacement of bottoming is the following:

(1) Without Z-anchor, the lamina bundles going into the tube work as a prop.

(2) With Z-anchor, the lamina bundles don't work as a prop because they bend extensively.

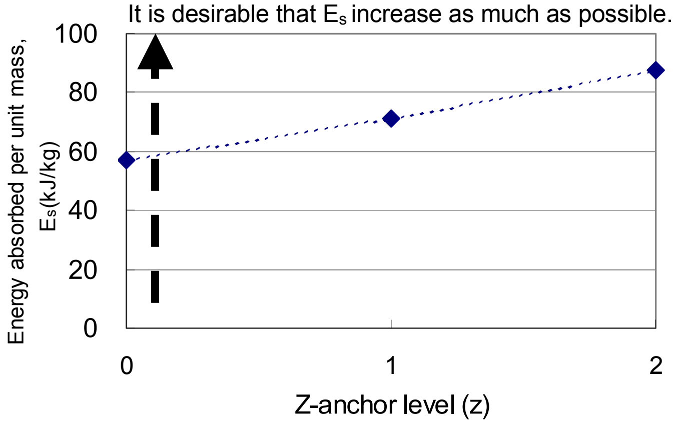
Z-anchor level 0(z)

Z-anchor level 1(z)

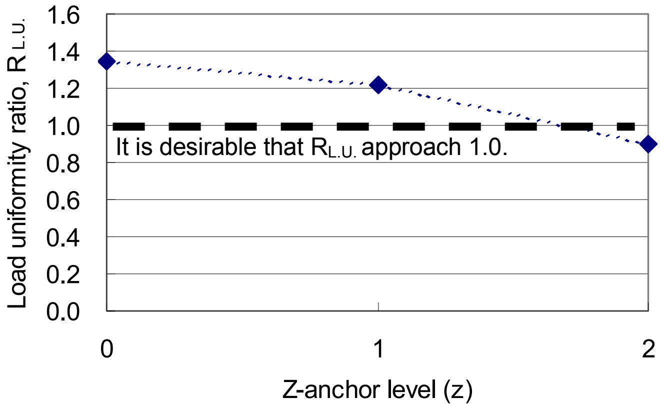
Z-anchor level 2(z)

Fig 9 Photos of the specimens after crushing

The comparison between Z-anchor level and the energy absorption capability indexes is shown in Fig. 10. Z-anchor increases the energy absorbed per unit mass of CFRP tube, and the efficiency of energy absorption of with Z-anchor, 2(z), is about 1.5 times higher than the one without Z-anchor, 0(z). And Z-anchor improves the load uniformity ratio, the load uniformity ratio with Z-anchor, 2(z), is 0.9. It indicates that Z-anchor improve the energy absorption capability of CFRP without any changes of fiber and matrix, and fiber orientation. Moreover, we can produce the energy absorbing structure having the ideal load-displacement curve by adopting Z-anchor level.



(Energy absorbed per unit mass)



(Load uniformity ratio)

Fig 10 Effect of Z-anchor on the energy absorption capability

FUTURE CRASHWORTHINESS RESEARCH PROGRAM IN MHI

In MHI, various researches on the aircraft crashworthiness are planned now. It is the followings :

1. Effect of Z-anchor on the energy absorption capability

   To produce the energy absorbing structure having the ideal load-displacement curve, we will investigate the following factors :

   (1)The effect of testing speed

   (2)The effect of processing

   (3)The limit of Z-anchor level

   (4)The effect of geometry of the specimen

   (5)To make the CFRP tube having Ideal load-displacement curve by Z-anchor

   (6) Development of numerical tools for the crush prediction of CFRP including Z-anchor

2. Application to the actual fuselage structure

   (1)A beam shape energy absorbing structure

3. Development of the numerical tools for the prediction of rotorcraft behavior in crash

   (1)Full-scale rotorcraft drop test

CONCLUSION

We have reached the following conclusions.

(1)Z-anchor can increase the energy absorbed per unit mass of CFRP tube.

(2Z-anchor can improve the load uniformity ratio of CFRP tube.

(3)Z-anchor can delay the start displacement of bottoming.

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