Crashworthy component design of an ultra-light helicopter with energy absorbing composite structure

Tong Yan, Jidong Wang

Abstract

The crashworthiness of aviation is a significant aspect of airworthiness, because it helps a lot in keeping crew safety and reducing economic losses. For the purpose of improving the crashworthiness performance of a kind of general aviation-type helicopter, an innovative light-weight composite energy-absorbing component has been developed in this paper. This component consists of carbon fiber woven cylindrical thin-walled tube and external triggers. The triggers let the cylindrical thin-walled tube split and break along its longitudinal axis and the energy is absorbed at the same time. In order to verify the results, a serial of test components were made and several tests were carried on. Finally, a digital simulation was carried on, whose results correspond with those of the tests.

Keywords: Crashworthiness; General aviation-type helicopter; Composites; Energy absorption structure

1. Introduction

In spite of the fact that helicopters are designed and built to operate with high level of safety, there will always be various combinations of circumstances that can, and do, result in unusually severe impacts with the ground or other objects, which may result in varying degrees of damage to the helicopter and injury or death to the occupants. The accident rate of the helicopter per flying hour is much greater than that of its fixed wing counterpart by a ratio of 2 to 1 [1]. And it has been estimated that approximately 85 percent of all aircraft crashes are potentially survivable without serious injury for occupants of these aircraft [2, 3, 4]. The design for crash survivability has become of increasing importance during the last decades, because
so many crashes have been demonstrated to be potentially survivable. Traditionally, crushable structure is made of a material with considerable capacity of plastic deformation, such as aluminum, to absorb crash energy. With the popularity of composite materials, the attention given to crashworthiness and crash energy management has been centered on composite structures. The main advantages of fiber reinforced composite materials over more conventional isotropic materials, however, are the very high specific strengths and specific stiffness which can be achieved. Besides the perspective of reduced weight, design flexibility and low fabrication costs, composite materials offer a considerable potential for light-weight energy absorbing structures.

The two primary design goals for crashworthiness are to limit the impact forces transmitted to the occupants, and to maintain the structural integrity of the fuselage to ensure a minimum safe occupant volume. To meet these goals, a crashworthiness component must be designed for high stiffness and strength to prevent structural collapse during a crash. Yet, the component design must not be so stiff that it transmits or applies high impact loads to the occupants. Ideally, the design should contain some crushable elements to help limit the loads transmitted to the occupant to survivable or non-injurious levels. In this study, an energy-absorbing component, designed to install in the landing gear of M16, has been developed. M16, shown in Fig.1, is an ultra-light helicopter developed by Beihang University. The energy-absorbing behavior of composites is not easily predicted due to the complexity of the failure mechanisms that can occur within the material such as fiber fracture, matrix cracking, fiber-matrix deboning, and delaminating [6]. Therefore a numerical simulations and experiments about the designed component are carried out. During the research program, a series of 25mm diameter, 100mm long, scale model composite components was designed, fabricated, and tested to verify structural and flight-load requirements. The experimental data from these tests were analyzed and correlated with predictions from a crash simulation developed using the nonlinear, explicit transient dynamic computer code, MSC. Dytran.

Fig.1. M16 ultra-light helicopter
2. Design Rationale

2.1. Materials

It has been proved that carbon-epoxy tubes generally absorb more energy than glass-epoxy or aramid-epoxy specimens [8, 9, 10]. Therefore the carbon-epoxy material is used to build the crashworthiness structure.

2.2. Loading

Composites absorb energy mainly by fiber breakage. It is important to break a fiber many times rather than once only [7]. To increase the capacity of energy absorption, the fiber of the crushable element should be broken as many times as possible. For composites structure, this seems possible only in a compression mode without buckling. Furthermore, to approach the square-wave type of load/displacement response, it is necessary to make sure that the compression mode is without high initial load, buckling and stability. So a trigger mechanism must be used to promote some form of progressive deformation. Traditionally, triggers are in the composite materials such as chamfers at the end of the tube. But the triggers will be rushed at the start of crashing so that they cannot continue to control the compression mode without buckling. To avoid the above disadvantage, an improved energy absorbing composite component, shown in Fig. 2, has been developed. This component consists of carbon fiber woven cylindrical thin-walled tube and two parts of triggers. The external trigger is on the top leading the composite cylinder curling. The other part is on the edge of composite cylinder. During the crash process, the cylindrical thin-walled tube is forced into a circular groove, resulting in split along its longitudinal axis and curl to absorb energy at the same time. Therefore, the failure mode of shell is preferable to be a repeating edge local buckling. Seen from top, the ideal failure mode is like the flowering process shown in Fig. 3. At the beginning, cylindrical shell detaches and feeds into stringer groove, then the longitudinal fiber buckles and breaks.

![Fig.2. Structure of the component](image-url)
3. Experimental program

3.1. Fabrication

Angle-ply tubes with fibers at $[0/90]_2s$ relative to the longitudinal axis were manufactured in-house. The wall thickness was 2mm in all angle-ply tubes. The carbon-epoxy material is 1400g/m3 with approximately 0.2mm thick each ply. Four test specimens, of 25mm diameter and 100mm long, are made and three of them have six notches on the top, shown in Fig.4. The external triggers with different evertting radius, shown in Fig.5, are made of steel which has high hardness in order to prevent surface damage.
Fig. 5. Steel flanges

3.2. Test instrumentation

Because the scale models are used to test the failure mechanism and absorption capability, the tests are conducted on a standard testing machine JSL-3000 (Fig. 6) with 70kg weight crashing down at some special height to create initial velocity. The measurements were intended to support the analysis of the structural behavior and to estimate the structural energy absorption. In order to take the absorption capacity due to the guidance system into account, various tests were performed.

Fig. 6. Testing machine JSL-3000
4. Experimental results and discussion

4.1. Test 1 Specimens with R5 trigger and notches

In this test, initial impact velocity is 2.45m/s achieved by 70kg weight dropped from 0.3m height. The load-displacement curve for the tube is shown in fig.7. As we can see, the curve is generally a square-wave type of load/displacement response. For this type of specimen the average load of 6150N is recorded. Fig.8 shows the specimen after crush testing. The specimen splits into strips and the circumferential fiber breaks, which absorbs all of the impact energy about 215J.

First region describes the pre-crush stage in which the crush load rises at a steady rate to a peak value. Immediately after this point is the beginning of the second stage. At the end of crashing, the force increases, which is because the composite debris accumulation reinforces the structure.

![Fig.7. Load-displacement curves for test 1](image)

![Fig.8. (a) specimen 1(R5) after crush testing; (b) specimen 1(R5) after crush testing on the test machine](image)
4.2. Test 2 specimen with R10 trigger and notches

Test 2 changes the external trigger with a bigger one (R10) to estimate the effect of different trigger radius. The load-displacement curve is showed in Fig 9. We can see from the fig 9 that the load curve is more stable. However, the average force which is 5531N is lower than that of test 1, so this specimen cannot absorb energy as much as specimen 1. Fig 10 shows the failure modes of specimen 2 is same with first specimen.

![Fig.9. Load-displacement curves for test 2](image1)

![Fig.10. (a) specimen 2(R10) after crush testing; (b) specimen 2(R10) after crush testing on the test machine](image2)
4.3. Test 3 specimen with R5 trigger without notches

The notch is designed to control initial split of the tube. This test wants to identify whether notches increase the energy-absorption capability or not. Fig.11 shows that without notches the first region of the curve is not stable as specimen 1. However, the average force is 6296N, slightly bigger than specimen 1. Therefore this specimen absorbs 330J. What’s more from the Fig.12 we hardly tell any different from Fig.8. This shows that the notches in this structure do not lead a special failure mode.

![Load-displacement curves for test 3](image1)

Fig.11. Load-displacement curves for test 3

![Crushed specimens](image2)

Fig.12. (a) specimen 3(R5 without notches) after crush testing on the test machine; (b) specimen 3(R5 without notches) after crush testing
4.4. Test 4. Specimen with double side trigger and notches

This specimen is assembled with two external triggers; the one R5 is on the top of the tube and the other one R10 is at the bottom of the tube (Fig. 13). The top side has six notches while the bottom is just a smooth end. The load-displacement response of the specimen 4 is shown in Fig. 14. For this type of specimen an average load of 5703N is found. Fig. 15 shows the specimen 4 after crashing. From the figure, we can see that the top end is hardly broken while the bottom of tube is totally splitting.

Fig. 13. specimen 4 before crush testing

Fig. 14. Load-displacement curves for test 3
5. Results discussion

As all load-displacement curves shown, owning to new trigger the reaction force of this kind of structure is quite stable. The load has neither high initial load nor intense change. Therefore, this new trigger could lead a stability failure mode without high initial load, buckling.

Table 1 comparison between all specimens

| Specimen No.                  | Average Force/N | Maximum Force/N | Absorbed Energy/J     |
|-------------------------------|-----------------|-----------------|-----------------------|
| 1(R5 with notches)            | 6150            | 7886            | 215.25J (all of impact energy) |
| 2(R10 with notches)           | 5531            | 7110            | 280.31J               |
| 3(R5 without notches)         | 6296            | 7283            | 330.18J               |
| 4(R5 with notches+ R10 without notches) | 5003            | 5560            | 252.81J               |

Table 1 shows that the specimen 1 with R5 trigger could provide larger average force than specimen 2. So the specimen with R5 could absorb more energy than that with R10. In theory, with the radius increase, the failure mode changes from compression mode to split mode. Whereas the compression mode is the most efficient mode for composite material to absorb energy, it can conclude that big radius leads weak component. Also the maximum force of specimen increases when the radius of trigger is decreasing.

The comparison in table 1 between specimen 1 and 3 illustrates that the notches lower the energy absorption capacity of specimen slightly, smoothing the load state. So they should be reduced or even removed from this component to achieve greater energy absorption capacity.

The comparison shows that the specimen 4 is the weakest component of all four types. These double sides’ triggers influence each other so that provide the poor results.

Although the load of crash is stable, the capacity of energy-absorption is less than the goal. It is mainly because a small amount of axial fiber is broken. Seen the after crashing specimen in the fig.8, we believe there are two reasons leading to this result. First, the strength of the 90° direction is insufficient. After 90° direction al fiber breaking, the axial fibers are no longer restricted in the trigger which avoids them to be broken. Second, the trigger radius is too large for these fibers to break. At the initial part of the splitting, the laminate will delaminate because each ply travels different distances. So the plies bent as thin layers not a whole one. Therefore to increase Energy absorption capability of this component, designers should
focus on smaller radius of trigger or adding some circumferential fiber to reinforce the strength of circumferential direction.

6. Finite Element Model

MSC.Dytran, a general-purpose explicit nonlinear transient dynamic finite element code, was used to model the composite tube section and steel external triggers. A picture of the integrated MSC.Dytran model of the composite crushable tube with an external trigger is shown in Fig.16a. The MSC.Dytran model of the composite crushable tube with an external trigger is shown in Fig.16a. The MSC.Dytran model of the steel external trigger, shown in Fig.16b using MSC.Patran’s 3-D visualization, were modeled with shell elements, which were defined with rigid material properties to provide the correct body contour needed for contact calculations. The mass of the steel was 70kg and the initial velocity was set to 2.5m/s at -z direction to simulate test 1. The R5 trigger consisted of 1950 nodes and 2000 elements. The material properties of the carbon-epoxy fabric material are modeled using a DMATEP material model. The elasticity modulus and strength of the material is calculated by classical laminated plate theory. In order to simulate composite delamination some elements of the composite tube are defined as spotweld.

Fig.16. (a). Model of the whole structure; Fig. 16. (b). External trigger
A master-surface to slave-surface contact is defined between the composite tube and the external trigger, which is modeled as a thick plate. A self-adaptive contact is defined on the tube itself. After all, a rigid wall has been created to simulate ground. The model was run on 8 processor of an Intel Windows 8-processor, 2.2 GHz laptop. To simulate 0.06 seconds required about 3.5 CPU hours.

Comparison between test 1 and analysis will be made with load responses measured on time (Fig.17). The test 1 exhibits a peak of 7886N after 0.004s, then the load decreases sharply. The first peak of simulation response occurs in 0.0028s at 7521N then the load drop sharply just like what happened in the test curve. In this case, the model predicts the peak load well, but make the pulse duration ahead of time. Just as what is shown in the experiment, after the first peak, analysis load response change near 5500N. This analysis anticipates the trend of load response. Comparison of peak and average force between experiment and simulation is shown in table.2. It is obvious that the simulation successful predicts the load response of the test.

Fig. 18a to d shows the crushing process of the tube model simulated by MSC.Dytran.

![Comparison of test 1 and simulation](image)

**Table.2. Comparison of load between experiment and analysis**

|        | Peak load/N | %change | Average load/N | %change |
|--------|-------------|---------|----------------|---------|
| Experiment | 7886       |         | 6150           |         |
| Analysis  | 7521       | -4.63   | 5732           | -6.8    |
Fig.18. (a) Crushing process 1 of tube model; Fig.18. (b) Crushing process 2 of tube model

Fig.18. (c) Crushing process 3 of tube model; Fig.18. (d) Crushing process 4 of tube model
7. Conclusion

Based on the axial crushing test results and the numerical simulation the following conclusions can be made:

1. Increasing the R tends to decrease the initial crush load and average crush load due to the changing of crushing mode.
2. Notches in this kind of energy-absorption composite structure lower the energy absorption capacity and help little on the compression stability. The longitude split could be excited by external trigger, so the notches could be reduced or removed.
3. Although this component is designed to break axial(0° direction) fibers repeatedly, the 90° direction fibers are very important because they not only absorb energy by breaking up but also hold the axial fibers in position to guarantee the axial fibers breaking step by step.
4. The R of the external trigger should be made smaller to make sure the axial fiber being broken. In addition, lengthening the outside of external trigger to prevent axial fibers slipping out.
5. The no notches component with R5 trigger has the highest value of 15kJ/kg for specific absorption.
6. Since seldom axial fibers of the component had been broken in the tests, the energy absorption capacity will increase dramatically if successfully chose the R and horizon strength.
7. The DMATEP material in MSC.Dytran could be used to predict composite crashing process. The results are reliable.

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