Dynamic Response of Biodynamic Model Seated on a Crashworthy Seat with Composite Absorber

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Abstract. This paper presents an energy absorber consists of an inward folding of composite tube. There is no composite debris overflow after the composites collapsing and the debris will fill in the inner of tube to increase the energy absorption. The absorber maintains integrate during crushing and then could be used in a crashworthy structure. Impact tests were conducted to explore the energy absorption performance. To investigate the application of the absorber to the shock-resistance of the seat in the helicopter, a five-degree-of-freedom nonlinear biodynamic model corresponding to 50th-percentile male occupant was setup. Simulations on the responses of the biodynamic with and without absorber were conducted, and the results present effect of the absorber on shock-resistance.

1. Introduction
Metal materials have been widely used in modern commercial aircraft fuselages. The energy generated by impact damage typically absorbed by the plastic deformation of the metal material, but the energy absorption of composite structure is relatively low if the structure was broken suddenly. The energy-absorption composite materials has attracted the attention of researchers in the automotive and aerospace industries. Extensive testing on various types of tubular structure has shown that composite materials can offer extremely high values of specific energy absorption (SEA) [1] [2]. For example, in a detailed review of energy-absorption in composite structures, Jacob et al. [3] determined that only 0.66 kg of a high-performance thermoplastic matrix composite is required to absorb the energy of a 1000 kg car travelling at 15.5 m/s (35 mph). Values for the SEA of widely-used composites, such as carbon fibre reinforced epoxy, generally range in 50–80 kJ/kg [3] [4]. So it is essential that the composite materials should be widely used and developed potential of SEA more thoroughly.

Further bumper structure design concept is to provide the bottom plate structure with foam [5] or honeycomb [6] [7]. In order to achieve the energy absorption, it is necessary to set up additional energy-absorbing device while setting up such a complex structure. The crush behaviors of thin-walled hollow square and circular tubes [8] with chamfer failure triggers were compared against those with steeple failure triggers. Results showed that steeple failure trigger for square tube was more effective than the chamfer failure trigger at maintaining a higher sustained crush load, but the opposite effect was observed for circular tubes.

The weight-specific energy absorption (SEA) of crush devices of composite materials could be superior to metallic absorbers. In the past, the characteristics of various geometrical shapes [9], fibre architectures or trigger mechanisms of the energy absorber have been investigated extensively [10] [11]. Some works shown that circular tubes can achieve high SEA values, which is much higher than any other cross-sections investigated, e.g., [9] [12] [13]. As for the trigger mechanisms, Heimbs [14] presents a solution by cutting composite tubes into strips through a special joint under axial crash, and composite materials will produce relatively complex form of damage to absorbing energy, but the
teared strips will expand outside cap in the process of implementation, spreading around and orbiting around cap. Deepak Siromani [15] conducted some experimental study on the effect of failure trigger mechanisms on the energy absorption capability of CFRP tubes under axial compression, but the load condition reveals instability because the composite tube would be split instead of being crushed. The energy absorbing structure should be completely crushed, so there is a larger space to improve the designing.

Crushing load-induced injury mitigating is an important issue in helicopter seat design. Crushing energy-absorbing crew seats have greatly enhanced helicopter crash survivability. In order to predict the biodynamic response as accurately as possible for high-amplitude vertical, frontal, rear, and side impacts, several biodynamic models representing seated human subjects have been developed. Liu et al. [16] modelled a seated occupant consisting of four main lumped body parts: pelvis, upper torso, viscera, and head, which were developed based on nonlinear mechanical. Patil et al. [17] proposed a modified 7-DOF biodynamic model, which consisted of seven mass segments with the pelvis, abdomen, diaphragm, thorax, torso, back, and head. These parts were formulated as nonlinear mechanical models comprising masses interconnected with springs with stiffness and dampers with viscous damping constants. Singh et al. [18] also developed a modified model in predicting peak magnitude, overall shape, and duration of the biodynamic transient response, with minimal phase shift. And the classic model of Liu [16] is adopted in the calculation, using the date from the test on the energy absorber. And the experimental occupant response date from a full-scale crash testing of the Sikorsky advanced composite airframe program helicopter [19]. The predicted load was used to verify the superiority of the absorber.

This work presented a shock absorber with composite material, which can be used as structural parts in the normal working state. The composite tube is subjected to the axial forced only rather than bent, so the crush process is stable. A 5-DOF nonlinear biodynamic model with seat was used to demonstrate the effect of the absorber during vertical crash.

2. Design the Absorber

The absorber comprises the crush cap, flat pressing cap, the cutter and positioning sleeve (Fig. 1). The cutter is installed in the crush cap, the lower end of which is connected to the flange in the crush cap and the upper end is connected to the sleeve. The sleeve is placed in the crush cap closely contacting the inner wall, while the lower surface contacts the cutter. The crush cap, sleeve and composite tube are connected by pins. Device without cutter can also be used to absorb energy in the form of delamination by the inward-folding of composite tube. The configuration of the absorber is shown in Fig.1.

The composite tube in the absorber serves as the main bearing member to absorb the impacting energy. The steel sleeve ensures the functionality of composite strut straight towards to the upper face of the cutter. The steel cutter includes variable cross-section holes (Fig 2), reinforcing ring and guide rounded corners; The variable cross-section hole described are arranged along the circumference, forming the cutting edge blade upward, at the same time of the smaller cross section will squeeze the cut strips to absorb energy further. The cutting blades are formed by the intersection of variable cross-section hole, whose blade upward, making it convenient to cut the composite pipe moved axially.

The cutting blades were reinforced by the reinforcing ring connects with the inner face of all variable cross-section role. The guiding-corner makes the composite material torn easier to pass through the reinforcing ring when the strips turn over, which impel composite tube damaged to store in the inner cavity of tube.
The crush cap at the bottom of absorber makes the composite tube fold inward and connects external fixed structure. The cutter is fixed on the flange in the cap whose upper structure is the sleeve. When the composite tube is split by the cutter, the composite strips will reach arc at the bottom of crush cap. So the strips will flip back into the inside of composite tube, the tube will be filled with debris of composite after crush, and the bearing capacity gets a further improvement.

On the other end of the composite tube, the pressing cap connects with the external structure by the lugs. A groove inside the flat pressure cap has been fitted for flatly pressing the on the end surface of the composite materials. There are pin holes on the outer wall of the cap to fix the composite tube, so that the absorber can bear a certain degree of pull force.

Two working patterns are shown in Fig.3. When the device is subjected to axial impact, the composite tube presses the crush cap. After the failure of pins, composite tube will axially move down towards the cutter and will be cut into strips. Delamination may also appear because the strips will be squeezed through the variable diameter hole in the cutter. Meanwhile, the guide arc surface at the bottom of crush cap will promote the composite strips bending towards the inside of the composite tube. The teared strips reverse movement will be more easily under the guidance of the fillet on cutter, so the damaged composite would fill into the cavity of the tube, which makes full use of the space. When the remaining length equals the length of the rolling-over part, debris of composite reaches the flat pressing cap and be gradually compacted to absorb energy furtherly.

Another working pattern for the energy absorber as showed in Fig.3 (b). The cutter in the crush cap is removed, and the inner diameter of the cap is the same as the outer diameter of the composite tube. So the composite tube directly contacts with the inner wall of the crush cap. After the failure of pins, the composite strut moves down axially towards to the cap when absorber under the axial impact. Then the composite tube moves axially until contacting the guide arc surface at the bottom of crush cap, and the tube moves reversal in the direction into the internal cavity of tube. Delamination and fiber failure mainly occurs in this turning process. The whole debris of composite packs into the cavity after the destruction. Delamination absorbs most of the impacting energy in the process, together with the bending of the tube wall, friction and the fiber fracture.
3. Experiments

3.1. Experimental Setup
The composite tube was made from a carbon fibre/epoxy prepreg laminate with 50% uni-direction tape in 0° (axial) and 90° direction. To avoid corrosion problems with the cap supports, an outside layer of braided carbon fibres was used. All the external diameter of composite tube is 30 mm, the thickness is 1.5 mm. The tube length was 120 mm. The composite tube has the outer diameter of 30 mm with 8 unidirectional composites layers.

Axial impact crushing tests were performed by using a drop hammer testing system (Fig. 4) to investigate energy absorption characteristics. The drop hammer with the mass of 62.9 kg was lifted by the pulley to a height of 3 m and then released through the trip gear to reach a velocity of 5.4 m/s. The specimens were fixed at the platform. A force sensor was mounted on the base to measure the impact force. An optical sensor was used to measure the velocity of the hammer before crushing the specimens.

3.2. Experimental Results
The curve of force time history with the debris filling the tube is shown in Fig. 5, where there is an ascending process due to the debris of composite filling the inside of tube at the end of curve. If the cutter was adopted, the energy absorption performance is more efficient under the dynamic (Fig. 6) condition. Not only the cutting by the blades, but also the squeezing of strips of composite when passing through the apertures between the blades, which contributes the energy consumption. The delamination was made more thoroughly combining with reversal radius under the crush cap.
4. Simulation of Helicopter Crew Seat

4.1. Mathematical Model
A nonlinear 5-DOF biodynamic lumped parameter model representing a 50th-percentile male exposed to high-speed vertical impacts was employed, as shown in Fig. 7. It is assumed that the human is seated in a perfect upright position and that 29% of the body weight is supported by the feet. The occupant body comprises four parts: pelvis, upper torso, viscera, and head, represented by mass $M_i$, stiffness $K_i$, and damping $C_i$, where $i = 2, 3, 4,$ and $5$, respectively. These masses were connected via nonlinear springs and dampers. The lumbar spine was represented as a stiff nonlinear spring and a damper connecting the chest to the pelvis. The occupant was assumed to undergo pure vertical displacement (i.e., $z$ direction only), and the motion in the forward direction and sideways was not considered.

The motion of this system is governed by the following equations [18]:

$$M_1 \ddot{z}_1 = -K_1(z_1 - z_0) + K_{2t}(z_2 - z_1) + C_{2t}(\dot{z}_2 - \dot{z}_1) - F_S$$  \hspace{1cm} (1)

$$M_2 \ddot{z}_2 = -K_2(z_2 - z_1) + C_2(\dot{z}_2 - \dot{z}_1) + K_3(z_3 - z_2) + C_3(\dot{z}_3 - \dot{z}_2)$$  \hspace{1cm} (2)
Converting these equations to matrix form gives:

\[\begin{bmatrix}
M_1 & \ldots & 0 \\
\vdots & \ddots & \vdots \\
0 & \ldots & M_5
\end{bmatrix}
\begin{bmatrix}
\ddot{z}_1 \\
\ddot{z}_2 \\
\vdots \\
\ddot{z}_5
\end{bmatrix}
= 
\begin{bmatrix}
-K_1 & K_1 + K_2 & -K_2 & 0 & 0 \\
0 & -K_2 & K_2 + K_3 & -K_3 & 0 \\
0 & 0 & -K_3 & K_3 + K_4 & -K_4 & -K_5 \\
0 & 0 & 0 & -K_4 & K_4 & 0 \\
0 & 0 & 0 & 0 & -K_5 & 0 & -K_1
\end{bmatrix}
\begin{bmatrix}
z_0 \\
z_1 \\
z_2 \\
z_3 \\
z_4 \\
z_5
\end{bmatrix}
\begin{bmatrix}
v_0 \\
v_0 \\
v_0 \\
v_0 \\
v_0 \\
v_0
\end{bmatrix}
\begin{bmatrix}
F_z \\
F_z \\
F_z \\
F_z \\
F_z \\
F_z
\end{bmatrix}
= 0
\]  

(6)

where

\[K_{2t} = \frac{K_2K_{2c}}{K_2 + K_{2c}}\]  

(7)

and

\[C_{2t} = \frac{C_2C_{2c}}{C_2 + C_{2c}}\]  

(8)

In the Eq. (1), \(z_0\) is the displacement of the floor. The initial conditions for this problem are \(z_i = 0\) and \(\dot{z}_i = -v_0\), where \(v_0\) is the initial vertical landing velocity of the helicopter. However, it is a fair assumption that the spinal loads are represented by the nonlinear spring and damper connecting the upper torso and pelvis. All the lumped masses are assumed to be descending at the same velocity before the impact, \(v_0 = 11.58\) m/s [19].

The stiffness of the upper torso is also nonlinear:

\[K_3 = \begin{cases} 
3780 & (Z_2 - Z_3) < 0 \\
3.78e3 + 1.09e7(Z_2 - Z_3) - 2.69e7(Z_2 - Z_3)^2, & 0 \leq (Z_2 - Z_3) \leq 0.04 \\
77043, & (Z_2 - Z_3) > 0.04 
\end{cases}\]  

(9)

The initial conditions given as

\[z_i(0) = 0; \dot{z}_i(0) = -v_0; \forall i = [0 - 5]\]  

(10)

The damping \(C_i\) is given by

\[C_i = 2\xi_i\sqrt{M_iK_i} \quad i = 2,3,4,5\]  

(11)

For \(K_2\) and \(K_3\) are nonlinear functions, \(C_2\) and \(C_3\) are also nonlinear. The parameters of the systematic seat model used for this study are specified in Table 1 [16].
Table 1. Parameters of the systematic seat model

| Quantity                      | Symbol | Value | Units |
|-------------------------------|--------|-------|-------|
| Mass of seat                  | $M_1$  | 11.5  | kg    |
| Mass of pelvis                | $M_2$  | 29    | kg    |
| Mass of upper torso           | $M_3$  | 21.8  | kg    |
| Mass of viscera               | $M_4$  | 6.8   | kg    |
| Mass of head                  | $M_5$  | 5.5   | kg    |
| Stiffness of coil spring      | $K_1$  | 25500 | kN/m  |
| Stiffness of soft seat cushion| $K_{2c}$ | 37.7  | kN/m  |
| Stiffness of viscera          | $K_4$  | 2.84  | kN/m  |
| Stiffness of head             | $K_5$  | 202.3 | kN/m  |
| Cushion damping               | $C_{2c}$ | 159   | N.s/m |
| Pelvis damping                | $\zeta_2$ | 0.25  | —     |
| Torso damping                 | $\zeta_3$ | 0.11  | —     |
| Viscera damping               | $\zeta_4$ | 0.5   | —     |
| Head damping                  | $\zeta_5$ | 0.1   | —     |

4.2. Results and Discussion

From the figures 5 and 6, the impacting force for composite remains stable for a considerable length of time. So that, in order to simplify the calculation, the reaction force of the energy absorber is considered as a constant. The stroke is assumed to be 0.8 m, and then $F_s$ was optimized as 5000 N.

Figure 8 to figure 11 show the comparison of acceleration of each part of the biodynamic model, with and without absorber. The decrease of acceleration on pelvis and viscera is significant. There is merely change on the acceleration of head and upper torso. So additional control method should be applied for the seat.

![Figure 8. Acceleration of pelvis](image)

![Figure 9. Acceleration of upper torso](image)
5. Conclusions
In the study, an energy absorber based on composite tube was proposed, the design concept and the detailed structure of the absorber had been presented. The corresponding experiments were conducted to explore the performance of the absorber in the energy absorption. This absorber had been used in the nonlinear 5-DOF biodynamic lumped parameter model to test the absorber in practical application. The following conclusions were drawn:

1) The crushing-energy absorber contains high energy absorption efficiency, it is very suitable for lightweight crashworthiness design in terms of decreasing the initial peak load, and the SEA of absorber still maintains at a high level.

2) The simulation results show that the absorber affect the acceleration of pelvis and viscera significantly. But the acceleration of head and upper torso decreased a little.

6. References
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