МАШИНОВЕДЕНИЕ, СИСТЕМЫ ПРИВОДОВ И ДЕТАЛИ МАШИН

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ И ПРИМЕНЕНИЕ В КРЕСЛЕ ПИЛОТА АМОРТИЗАТОРА, ВЫПОЛНЕННОГО ПО ПРИНЦИПУ СКЛАДЫВАЮЩЕЙСЯ ВНУТРЬ КОМПОЗИЦИОННОЙ ТРУБКИ

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В работе представлен инновационный поглотитель энергии, состоящий из композитной трубки, которая складывается внутрь: она разрезается в осевом направлении и поворачивается в свою внутреннюю часть. После того как композит разрушается и его остатки заполняют внутреннюю часть трубы, чтобы увеличить поглощение энергии, остатки композитного волокна не переполняют внутреннюю полость трубки.

Энергия главным образом поглощается посредством разрушения волокна, деламинации и трения между композитной трубой и цилиндрической стенкой крышки. Испытания ударом были проведены для того, чтобы исследовать характеристики поглощения энергии. Для исследования ударопрочности сиденья с амортизатором из композитной трубки была создана нелинейная биодинамическая модель с четырьмя степенями свободы, соответствующая 50% веса среднестатистического мужчины. Результаты моделирования дают хорошее представление об ударопрочности поглотителя энергии.

Ключевые слова: амортизатор, внутреннее сворачивание, композитный материал, кресло пилота в вертолете, биодинамическая модель.

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SHOCK ABSORBER USING INWARD-FOLDING COMPOSITE TUBE AND ITS APPLICATION TO A CREW SEAT: NUMERICAL SIMULATION

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This paper presents an innovative energy absorber consisting of an inward folding of composite tube, which is cut axially and turned into the inner of the itself. There is no excess of composite fragments after the composites' destruction, and the debris will fill in the inner part of tube to increase the energy absorption. The impact energy is absorbed mainly by the fibers' fractures, as well as delamination and friction between composite tube and the cylinder wall of the cap. Impact tests were performed to study the energy absorption performance. To study the shock absorber effect on the shock-resistance of the helicopter crew seat, a four-degree-of-freedom nonlinear biodynamic model corresponding to 50th-percentile male occupant was developed. The simulation results revealed a good shock-absorber shock-resistance performance.

Keywords: Shock Absorber, Inward-folding, Composite, Helicopter seat, Biodynamic model.

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1. Introduction

Metallic materials have been widely used in the lower-part bumper structure of conventional commercial aircraft fuselage. The energy generated by impact damage typically absorbed by the plastic deformation of the metallic material, but the stress limit of the metal material itself realizing the absorption of energy is relatively less. In recent years, the superior energy-absorption and crashworthiness properties of composite materials have attracted the attention of a range of sectors, including those associated with the automotive and aerospace industries. Extensive testing of various types of tubular structure has revealed that composite materials could offer extremely high values of specific energy absorption (SEA) [1—12]. For example, in a detailed review of energy-absorption in composite structures, Jacob et al. [13] 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 fiber reinforced epoxy, generally fall in the range 50—80 kJ/kg [14, 15]. So it is essential that the composite materials should be widelyapplied and developed potential of SEA more thoroughly.

Further bumper structure designing concept consistis in providing the bottom plate structure with foam [16] or honeycomb [17, 18]. To provide the energy absorption, it is necessary to set up additional energy-absorbing unit while setting up such a complex structure. The crush behavior of thin-walled hollow square and circular tubes [19] with chamfer failure triggers was compared to those with steeple failure triggers. The results revealed that s 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.

When it comes to the weight-specific energy absorption (SEA) of crush devices, that are also common in automotive or train applications, it has been realized that composite materials are superior to metallic absorbers. Earlier, the characteristics of various geometrical shapes [20], fiber structures or trigger mechanisms of the energy absorber have been studied extensively [13—15, 24, 25]. Several studies have shown that circular tubes could achieve high SEA values, much higher than any other cross-sections studied, e.g. [20, 23, 24]. As for the trigger mechanisms, S. Heimbs [25] 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 torn strips will expand outside the cap in the process of implementation, spreading around and orbiting around cap. Deepak Siromani [26] conducted a certain experimental study on the of failure trigger mechanisms impact on the energy absorption capability of CFRP tubes under axial compression. But the load condition reveals instability since the composite tube would be split instead of being crushed. The energy absorbing structure should be crushed completely, so there is a vast space to improve the designing.

Destructive load-induced injuries mitigation is always an important issue in helicopter seat design. Destructive energy-absorbing crew seats have greatly enhanced helicopter crash survivability. Energy absorber is the important structure in these energy-absorbing seats. To predict the biodynamic response as accurately as possible for high-amplitude vertical, frontal, rear, and side impacts, several biodynamic models representing seated human objects have been developed. Liu et al. [27] modeled a seated occupant, consisting of four main lumped body parts: pelvis, upper torso, viscera, and head, which were developed based on nonlinear mechanics. Patil et al. [28] modified the 7-DOF biodynamic lumped parameter model, 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 Mi interconnected with springs with stiffness of Ki and dampers with viscous damping constants of Ci for i = 1—7, respectively [28]. Harinder J developed also a modified model for predicting the peak magnitude, overall shape, and duration of the biodynamic transient response, with minimal phase shift [29]. The classic model of Liu [27] was adopted in the calculation, using the data from the energy absorber test. The experimental occupant response data from a full-scale crash testing of the Sikorsky helicopter advanced composite airframe program [30]. The predicted load was used to verify the absorber superiority.

This work carried out a study on the innovative device using composite material for the destructive energy absorbing. Compared to the prior works, the absorber can be employed as structural part in the normal operation state. It also has the characteristics of the full failure of composite tube, and high energy-absorption ratio. The composite tube is subjected to the axial force only rather than the bending force, so the destructive process is stable. The shock absorber remained intact during the crash, and there was no fragments excess.

2. The absorber design

2.1. Design concept

As a device that can be applied to the helicopter collision-proof seat, the bumper structure of the fuselage lower part and the bumper beam for the high efficiency vehicles, and the impact energy absorber of the introverting failure-tube from a composite material were developed. The absorber comprises the crush cap, flat pressing cap, the cutter and positioning sleeve (Fig. 1). The cutter is installed in the crush cap, which lower end is fixed to the flange in the crush cap and the upper end is fixed 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 the composite tube are fixed by the pins. The device without a cutter can also be employed to absorb the energy in the form of lamination by the composite tube folding inward. The absorber configuration is shown in Fig. 1, and its materials and functions are demonstrated as follows:

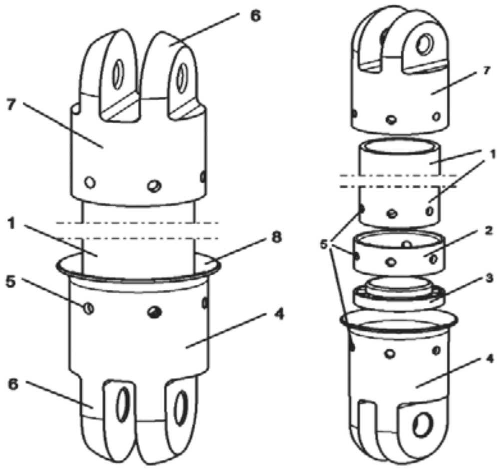

Figure 1. Outline drawing and exploded picture of absorber (1 — composite strut; 2 — sleeve; 3 — cutter; 4 — crush cap; 5 — pin hole; 6 — Lug; 7 — Flat cap; 8 — Guiding corner)

Composite strut:

The composite tube in the shock absorber serves as the main bearing member to absorb the impact energy. At the same time it functions as a supporting structure.

Various lay-outs and dimensions of the strut can be manufactured to account for the impact mechanical properties.

Sleeve:

The steel sleeve ensures the of composite strut functioning directly towards to the upper face of the cutter Chamfering and pin hole were designed, and the pin holes are directed exactly right to the pin holes on the crush cap, fixing the composite strut, the crush cap and themselves.

Cutter:

The steel cutter includes holes with variable cross-section, reinforcing ring, and rounded guide corners. The above said holes of variable cross-section described are arranged along the circumference, forming the cutting edge blade upward, at the same time the holes of the smaller cross section will squeeze the cut strips for further energy absorbing. The cutting blades are formed by the intersection of variable cross-section holes, which blades are directed upward, allowing convenient cutting of the composite pipe moved axially.

The cutting blades were reinforced since the reinforcing ring is connected with the inner face of all holes of variable cross-section. The guiding-corner makes the composite material torn easier to pass through the reinforcing ring when the strips turn over, which impels the damaged composite tube staying in the inner cavity of the tube.

Crush cap:

The crush cap at the bottom of shock absorber makes the composite tube fold inward and connects the external fixed structure The cutter is fixed on the flange in the cap which upper structure presents the sleeve. When the composite tube is split by the cutter, the composite strips will form an arc at the bottom of crush cap So the strips will flip back into the inside of the composite tube, and the tube will be filled with composite fragments after crush. Its bearing capacity will be improved further.

Flat pressing cap:

On the other end of the composite tube, the flat pressing cap connects with the external structure by the lugs. A groove inside the flat pressure cap has been fitted to be aflat press fitted on the end surface of the composite materials. There are pinholes 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 modes are shown in Fig. 2. When the unit is subjected to axial impact, the composite tube presses the crush cap. After the pins failure, the composite tube will axially move down towards the cutter and will be cut into strips. Delamination may also appear since 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 contribute to the composite strips bending towards the inside of the composite tube. The torn strips reverse movement will be much easier under the guidance of the cutter fillet, so the damaged composite would fill into the cavity of the tube, which allows the full usage of the space. When the remaining length equals the length of the rolling-over part, the composite fragments reach the flat pressing cap and gradually compacted for further energy absorbing. After destruction the composite's fragments will not effect the surrounding environment or the structure.

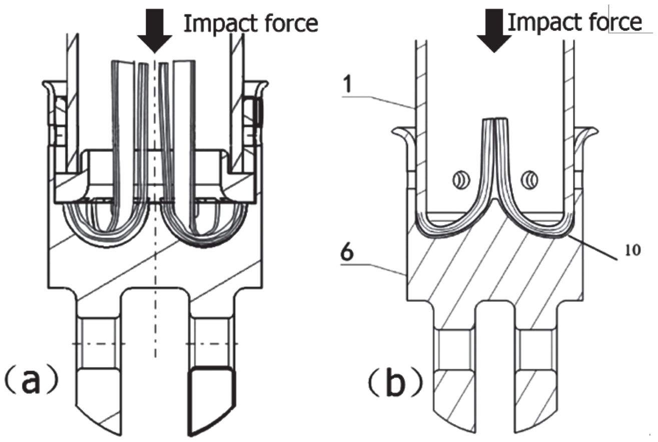

Figure 2. Working mpdes of the energy absorber: with the cutter (a) and without the cutter (b)
(1 — composite strut; 6 — Crush cap; 10 — Inward-folding composite tube)

Another working pattern for the energy absorber is shown in Fig. 2b. 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 pins failure, the composite strut moves down axially towards to the cap, while the absorber is under the axial impact. Then the composite tube moves axially until it contacts with the guide arc surface at the bottom of crush cap, and the tube moves reversely in the direction to its internal cavity. Delamination and fiber failure occurs mainly while this turning process. After destruction, all fragments of the composite pack up into the cavity. During this process, delamination absorbs most of the impacting energy with account for the tube wall bending, friction and the process of fiber fracture. This scheme is simpler, more reliable, and still has a higher energy absorption ratio

3. Experimental procedure

3.1. Composite tube

The composite tube was made of a carbon fiber/epoxy prepreg laminate with 50% unidirectional tape in 0° (axial) and 90° direction. To avoid corrosion problems of the cap supports, an external layer of braided carbon fibers was used. The composite tube overall external diameter is of 30 mm, and the thickness is of 2.0 mm.

The tube length was of 120 mm for quasi-static and dynamic testing. The composite tube has the outer diameter of 30 mm with 12 unidirectional composites layers.

3.2. Dynamic experimental setup

To study energy absorption characteristics, axial impact crushing tests were performed using a drop hammer testing system (Fig. 3). 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 samples were located at the centre of the base of the drop hammer testing system. A force sensor was mounted on the base to measure the impact force. A force sensor was mounted on the base to measure the impact force. An optical sensor was fixed near the sample to catch the passing time of the sheet of a known width, placed on the hammer, through the sensor. Due to the small width of the sheet, the velocity of the hammer before crushing the specimen was calculated by dividing the sheet width by the time of sheet passing through the optical sensor. The crushing energy could be more calculated accurately by the usage of the stroke velocity.

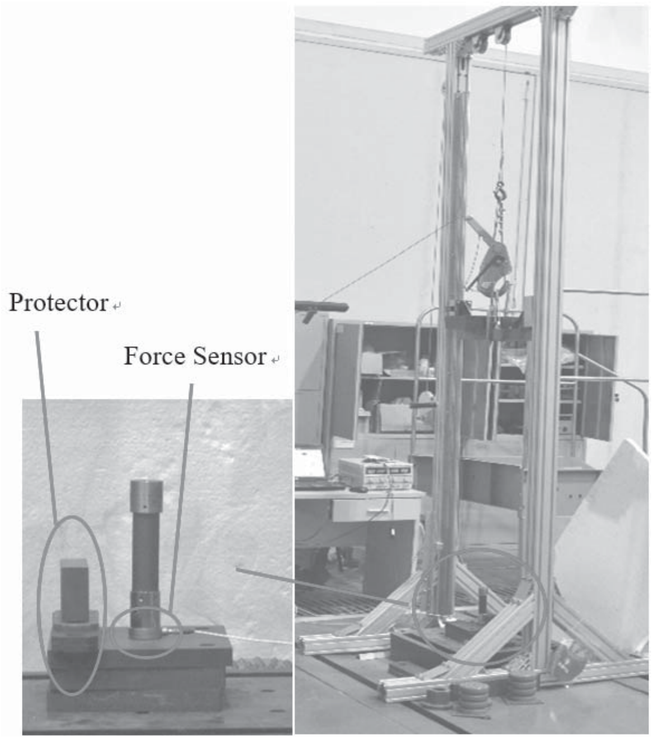

Figure 3. Impact test equipment

3.3. Experimental results and discussion

According to the laser displacemnt sensor data, we can get the velocity of drop hammer prior to impacting the sample. The relationship between the impact force and the composite tube was recorded by the data acquisition system. The force curve with the fragments filling the tube is shown in Fig. 4. At the end of the figure 4, we can observe an ascending process due to the composite's fragments filling the inside of the tube, and the load capacity herewith will increase. Thus, the innovative energy absorber is very suitable for lightweight crashworthiness designing in terms of decreasing the initial peak load, and the absorber's SEA is still maintained at a high level.

In Fig. 5 and 6, the stationary stages of the impact process were partially zoomed in for the comparison. The

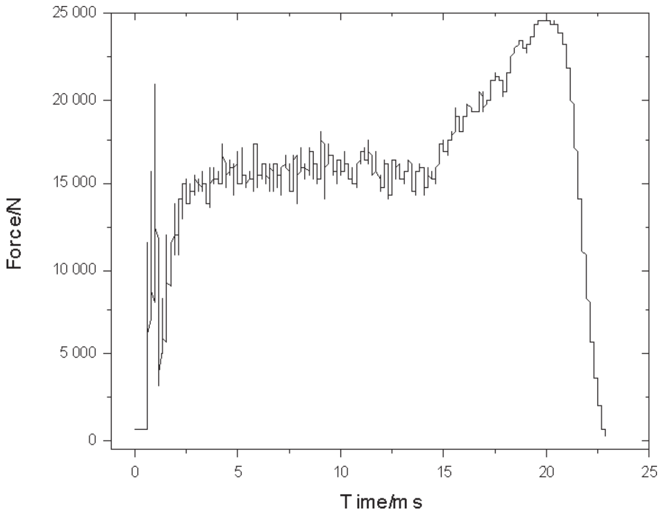

Figure 4. Force-time curve under dynamic test with the fragments filling the tube

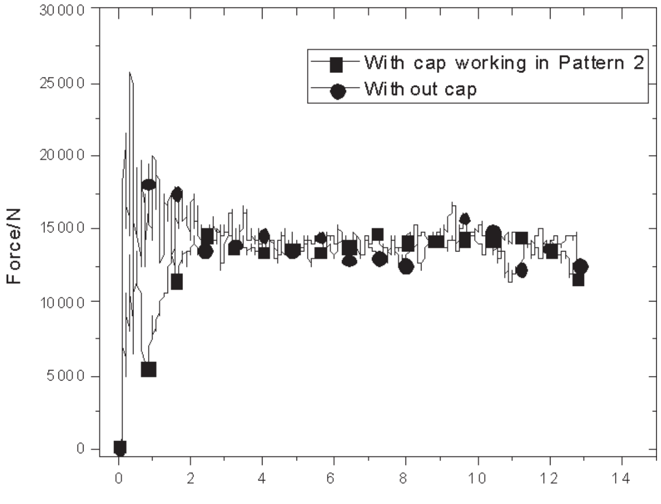

Figure 5. Force-time curve under dynamic test with the cap and without the cap

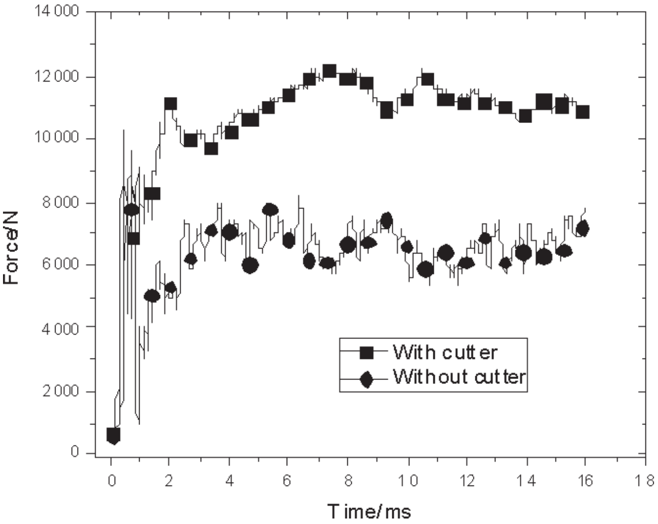

Figure 6. Force-time curve under dynamic test, with the cutter and without the cutter

initial peak value does not exceed the stationary level of the force after the crash cap usage. With the cutter employing, the energy absorption performance is more efficient under the dynamic (Fig. 6) condition. Both the cutting by the blades, and the squeezing of strips of the composite when passing through the apertures between the blades, will contribute the energy absorption. The lamination will proceed more thoroughly if combined with reversal radius under the crush cap

4. Experimental results and discussion

4.1. Crushing morphology

Since the crushing process in this innovative absorber is very complex, a fundamental understanding of the physical morphology of the composite crushing phenomena is necessary before any model developing In this context, the energy absorbing factors can be separated according to the efforts of previous researchers. Besides the in-plane failure under bending, two degradation modes are dominating in this energy absorption process: fragmentation and delamination [31]. All degradation modes consist of the total energy absorbed by the proposed absorber.

Fragmentation, which means the crushing of a material into small pieces, can be considered as the important part of degradation The crucial failure finally develops due to the fiber bending sharp increase and stiffness drop The cross-sectional view of the tubes crushed under the impact is shown on Fig. 7, the fragments fill the inside of the tube. Still, the challenge of the crush damage modes remains.

Figure 7. Cross-sectional views of crushed tubes under dynamic condition

5. Simulation of a helicopter crew seat

5.1 Mathematical Model

A nonlinear 4-DOF biodynamic lumped parameter model corresponding to a 50th-percentile male exposed to the high-speed vertical impacts was employed, as shown in Fig. 8.

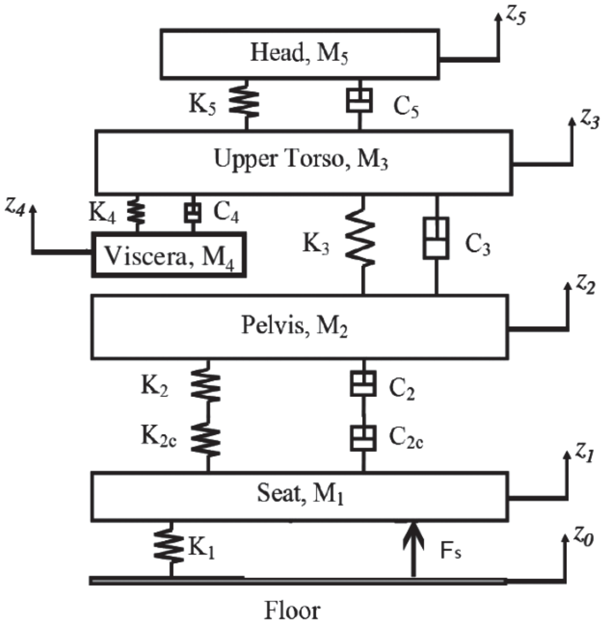

Figure 8. Proposed 4-DOF biodynamic model of a seated occupant [32]

It is assumed that the human is seated in a perfect upright position and 29% of the body weight is supported by the feet. The occupant body is divided into four parts: pelvis, upper torso, viscera, and head, represented by mass of M_i, stiffness of K_i, and damping of C_i, where

$i = 2, 3, 4$, and 5, respectively. These rigid 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 a 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 [30]:

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

$$\begin{aligned} M_2\ddot{z}_2 = {} & -K_2(z_2 - z_1) + C_2(\dot{Z}_2 - \dot{Z}_1) + \\ & + K_3(z_3 - z_2) + C_3(\dot{Z}_3 - \dot{Z}_2) \end{aligned} \quad (2)$$

$$\begin{aligned} M_3\ddot{z}_3 = {} & -K_3(z_3 - z_2) + C_3(\dot{Z}_3 - \dot{Z}_2) - K_4(z_3 - z_4) - \\ & - C_4(\dot{Z}_3 - \dot{Z}_4) + K_5(z_5 - z_3) + C_5(\dot{Z}_5 - \dot{Z}_3) \end{aligned} \quad (3)$$

$$M_4\ddot{z}_4 = K_4(z_3 - z_4) + C_4(\dot{Z}_3 - \dot{Z}_4) \quad (4)$$

$$M_5\ddot{z}_5 = -K_5(z_5 - z_3) - C_5(\dot{Z}_5 - \dot{Z}_3) \quad (5)$$

Converting these equations to matrix form gives:

$$\begin{bmatrix} M_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & M_5 \end{bmatrix} \begin{bmatrix} \ddot{z}_1 \\ \ddot{z}_2 \\ \ddot{z}_3 \\ \ddot{z}_4 \\ \ddot{z}_5 \end{bmatrix} +$$

$$+ \begin{bmatrix} -K_1 & K_1 + K_2 & -K_2 & 0 & 0 & 0 \\ 0 & -K_2 & K_2 + K_3 & -K_3 & 0 & 0 \\ 0 & 0 & -K_3 & K_3 + K_4 + K_5 & -K_4 & -K_5 \\ 0 & 0 & 0 & -K_4 & K_4 & 0 \\ 0 & 0 & 0 & -K_5 & 0 & -K_5 \end{bmatrix} \begin{bmatrix} z_0 \\ z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{bmatrix} +$$

$$+ \begin{bmatrix} C_2 & -C_2 & 0 & 0 & 0 \\ -C_2 & C_3 + C_2 & -C_3 & 0 & 0 \\ 0 & -C_3 & C_3 + C_4 + C_5 & -C_4 & -C_5 \\ 0 & 0 & -C_4 & C_4 & 0 \\ 0 & 0 & -C_5 & 0 & C_5 \end{bmatrix} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \\ \dot{z}_5 \end{bmatrix} + \begin{bmatrix} F_s \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = 0 \quad (6)$$

where

$$K_{2t} = \frac{K_2 K_{2c}}{K_2 + K_{2c}} \quad (7)$$

and

$$C_{2t} = \frac{C_2 C_{2c}}{C_2 + C_{2c}} \quad (8)$$

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 $i = 0, 1, 2, 3, 4$ and 5, and v_0 is the helicopter initial vertical landing velocity. 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 [30].

The stiffness of the pelvis K_2 is modeled by the nonlinear function [27]:

$$K_2 = 8.1075e7(Z_2 - Z_1)^2 \quad (9)$$

The stiffness of the upper torso is also nonlinear:

$$K_3 = \begin{cases} 3.78e6 + 1.09e7(Z_2 - Z_3) - 2.69e7(Z_2 - Z_3)^2, \\ \qquad (Z_2 - Z_3) \geq 0.04 \\ 77044, \ (Z_2 - Z_3) < 0.04 \end{cases} \quad (10)$$

And the initial conditions are given as

$$z_i(0) = 0;\ \dot{z}_i = -v_0;\ \forall i = [0 - 5] \quad (11)$$

The damping C_i is given by

$$C_i = 2\zeta_i\sqrt{M_i K_i},\ i = 2,3,4,5 \quad (12)$$

where ζ_i is the damping ratio of each part of the human body.

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 [30].

5.2. Results and discussion

From the figures 5 and 6, the impacting force for composite remains stable for a considerable length of time. Thus, to simplify the calculation and increase the running speed, the role of the energy absorber is considered as a constant. The occupant in helicopter can typically bear an acceleration of

Table 1

Parameters of the systematic seat model

Quantity	Symbol	Value	Units
Seat mass	M_1	11.5	kg
Pelvis mass	M_2	29	kg
Upper torso mass	M_3	21.8	kg
Viscera mass	M_4	6.8	kg
Head mass	M_5	5.5	kg
Stiffness of coil spring	K_1	0.0	kN/m
Soft seat cushion stiffness	K_{2c}	37.7	kN/m
Viscera stiffness	K_4	2.84	kN/m
Head stiffness	K_5	202.3	kN/m
Cushion damping	C_{2c}	159	N.s/m
Pelvis damping	ζ_2	0.25	—
Torso damping	ζ_3	0.11	—
Viscera damping	ζ_4	0.5	—
Head damping	ζ_5	0.1	—

14.5 *g*, with a proper motion space during a crush event [30]. The movement is assumed to be 0.8 m, and then F_s was optimized to 6000 N.

To fit the experimental data better and get more accurate simulation result, a function of F_s was developed, as shown in equation

$$F_s = \begin{cases} 0 & x_1 \le x_a \\ \dfrac{F_{se}}{s_t}(x_a - x_1) & x_1 \ge x_a \\ F_{se} & F_s \ge F_{se} \end{cases} \qquad (13)$$

Where:

F_{se} is the stability values of the absorber

x_1 is the displacement of seat

x_a is the crush distance of energy absorber

s_t is the displacement of seat reached F_{se}

The constitutive relation of the absorber is represented with a nonlinear spring, which exerts the impacting force according to the displacement of the composite tube. When $z_1 < 0$, the model of the absorber will exert the activation force, otherwise its value is 0. The composite tube will crush when the force reaches a crush value. If the exerted force exceeds the crush force, it will be set to a fixed value. The slope of function F_s in the initial stage is related to the stiffness of the composite tube.

While calculation, F_{se} is set to 6000 N and S_t is set to 0.01 m according to the experimental data.

Figures 9—12 show acceleration of each part of the biodynamic model. The peak of head and upper torso acceleration is close to 14 *g*, and those of pelvis and viscera are relatively lower. So, it is feasible to mitigate the shock by using such an absorber.

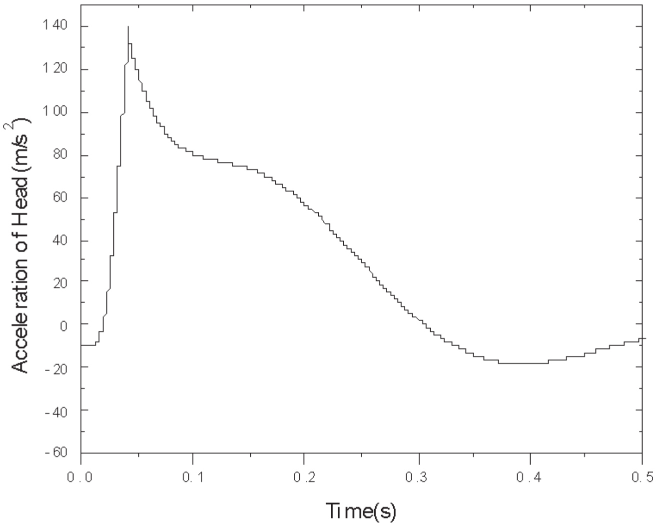

Figure 9. Head acceleration

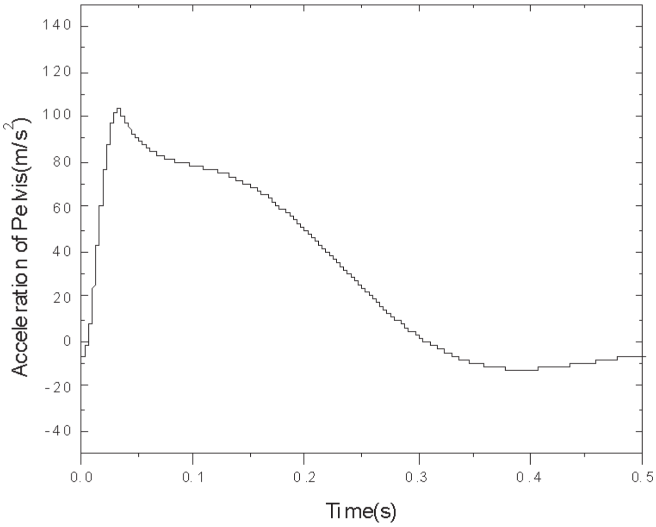

Figure 10. Pelvis acceleration

6. Conclusions

The study proposes an innovative crushing energy absorber based on a composite tube, and presents the design concept and the detailed structure of the absorber. The corresponding experiments were conducted to study the performance of the absorber in the energy absorption. At last, this absorber had been used in the nonlinear 4-DOF biodynamic lumped parameter model to test the absorber in practical application. The results presented

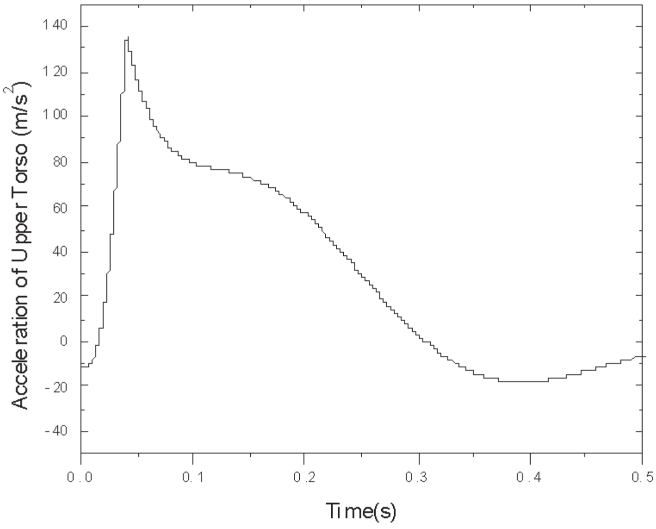

Figure 11. Upper Torso acceleration

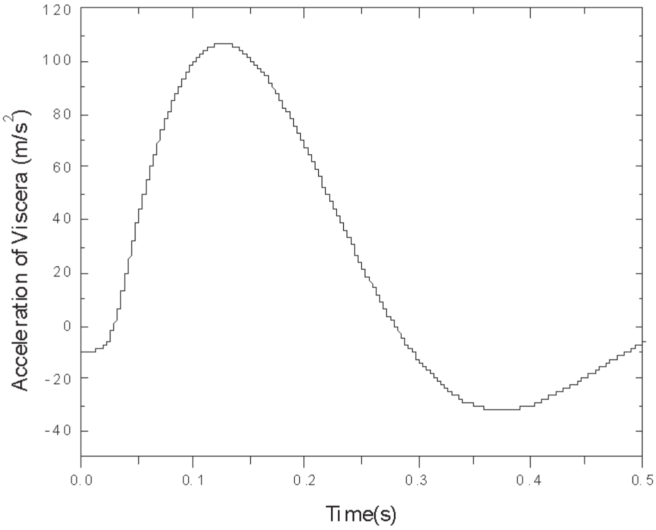

Figure 12. Viscera acceleration

in this article enable the following conclusions to be drawn:

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

(2) This absorber is the multi-functional. In addition to the supporting structure function, the composite tube fragments will be totally stored inside the composite tube without any leakage. When the impacting process proceeds to the second half, the load-carrying capacity of the absorber will be further enhanced. This characteristic was presented both in the static and dynamic test. The experimental result with the cutter in the crush cap revealed the better energy absorption performance.

(3) A nonlinear model of the absorber was developed based on the experiment data, which could be successfully applied to the biodynamic model. The simulation results demonstrate the applicability and efficiency of ensuring the occupants' safety.

The real physical fragmentation phenomena is rather sophisticated. To simulate the failure process better, an analytic method should be established to predict the value of crushing energy as accurate as possible when a certain absorber design parameter changes.

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