Research on Optimization Design of Key Energy-Absorbing Structure of a Helicopter Seat Based on Human–Seat Coupling System

Xingye Wang, Yanjun Li *, Yuyuan Cao, Xudong Li, Shixuan Duan and Zejian Zhao

College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
* Correspondence: lyj@nuaa.edu.cn; Tel.: +86-13805156301

Abstract: During the process of emergency landing, the energy of the impact in the vertical direction is dissipated through the deformation of the structure. The landing load is transferred to the spine of the occupant through the landing gear, the fuselage and finally the seat. This can cause serious damage to the human body. Since the seat is in direct contact with the human body, the energy absorption capacity of the seat is the most direct manifestation of the Crashworthiness of the helicopter. The solutions proposed in the paper may reduce the impact of the seat on the spine of the occupant during the collision by optimizing the key energy-absorbing structure. Taking the seat of the H135 helicopter as a case, the mechanical model of the human–seat coupling system, which is based on the theories of energy methods and structural mechanics, is simplified. Additionally, the simulation was considered reasonable by comparing the simulation results with the results of crashworthiness tests. On the basis of the above, the optimization of the key energy-absorbing structure of the seat was completed by using Latin hypercube sampling and the kriging model. Overall, the optimization effectively enhanced the crashworthiness of this helicopter seat and provided a solution for the passive safety design of aviation seats.

Keywords: human–seat coupling system; key energy-absorbing structure of the helicopter seat; structural optimization; crashworthiness tests

1. Introduction

With the rapid development of the helicopter in recent decades, accidents due to structural failures or human factors have occurred frequently. For example, from 2006 to 2015, 211 accidents occurred in Brazil, with an average of 133 deaths per year and 63 deaths per 100 accidents [1]. According to incomplete statistics, more than 20 helicopter accidents occurred in China from 2016 to 2018, resulting in 18 fatalities [2]. All of these have brought more attention to the safety of helicopters.

For safety, helicopters are generally designed for static strength, fatigue strength, aerodynamics, stability and control performance. However, when the rotorcraft makes an emergency landing, the crash may still produce serious damage to the occupants and the structures of the helicopter. The impact beyond the maximum acceptable levels for individuals can result in significant injury or death. Additionally, there is no doubt that the broken structure could affect the escape of passengers. Generally speaking, the helicopter carries out tasks at low altitudes which makes it more difficult to escape through an ejection system than the fixed-wing aircraft. Therefore, the crashworthiness (i.e., the ability of an aircraft to withstand an impact and protect its occupants [3]) design of helicopters is increasingly becoming an important part of the design of the whole aircraft.

Currently, some major developed countries in America and Europe have considered crashworthiness design as an equally critical part that is as important as the design of the weight in the initial design of military helicopters [4,5]. FAA and NASA have conducted numerous dynamic tests, which lay the foundation for the design of the aircraft systems.
and the assessment of crashworthiness [6]. As identified in FAR 23.562 and 25.562 in 2003, FAA allowed the use of computer modelling analytical techniques validated by dynamic tests to provide pass/fail criteria [7]. In the helicopter design, crashworthiness is mainly reflected in the energy absorption capacity of the landing gear, the fuselage and the seat [8]. Compared to the landing gear and the fuselage, the seat has better adaptability in terms of the crashworthiness, mainly in the following aspects [9]. (1) The energy absorbing device can be pre-installed on the seat to make it easier and more effective to control the impact. For best results, the limiting load of the energy absorbing device can be adjusted according to the needs of users. (2) The seat is better suited to provide enough space for the deformation caused by energy absorption. The height from the floor of a helicopter to the ground is usually specified directly by the overall external dimensions. Therefore, the impact distance on the fuselage is limited by the overall requirements. (3) The energy absorption capacity of the seat can be verified easily, while the capacity of the fuselage is difficult to predict. Additionally, in the process of developing new-generation helicopters, early design stages generally do not carry out crash tests. (4) Many complex terrains (such as trees, rocks, loose soils, marshes, water and so on) may prevent the landing gear from absorbing energy. However, as long as the fuselage is not partially penetrated, the seat will be able to play its role as an energy absorbing device. In 2009, the new rule, which added stringent dynamic tests for seat certification, was implemented by FAA [10]. It was included in 14 CFR Part 25.562 and its main purpose was to improve the level of pilot’s and passenger’s safety during the crash. In summary, the optimal design of the seat is one of the most effective ways to improve the crashworthiness of helicopters.

Researchers conducted numerous studies on energy absorption during collisions and achieved certain results. According to the multibody-based methodology, researchers already established the metro vehicle frontal impact model by simplifying the structure and connections to improve the efficiency of train collision calculations effectively [11–14]. The aforementioned achievement provided a simple and efficient conceptual design method for railway safety design. Researchers have also performed equivalent calculations of the train-body structure based on various theories such as the homogenization method using strain energy equivalence [15–17], the minimum strain energy method [18] and the equivalent stiffness method [19]. The errors of these equivalent calculations satisfied requirements of the engineering. Alexander [20] created the model of a metal circular tube to predict the absorbed energy when axial compression deformation occurs. Additionally, based on the experiment, the macro cell method was put forward. It has made outstanding contributions to the research of the optimization of the mechanical models of thin-walled structures and laid the groundwork for research on the crashworthiness of structures. Wang [21] determined the structure which absorbed the energy by deformation of the body based on the analysis of the damage of the aircraft during a crash and performed optimization on the thin-walled structure. HE [22] discussed general methods for developing an aircraft finite element model under a crash environment and summarized the evaluation and filtering methods of the test data and the simulation result.

Compared to cars and trains, research on the energy absorption of aircrafts during collision has received less attention. Additionally, most of the concern is placed on the following three aspects. (1) The energy-absorbing design of the overall aircraft. (2) The energy-absorbing materials. (3) The design of thin wall structures for energy absorption. Comparatively, less research on the crashworthiness design of helicopter seats has been conducted. M. Guida et al. [23] summarized the development of the crashworthiness of aircraft seats in recent years, including a mechanism analysis of occupant injuries, accident investigations, aircraft damage, strategies of occupant protection, crashworthy design and so on. Tao Yan et al. [24] studied the method for determining the key design parameters of the energy-absorbing component through the simplified model of the X-shaped lifting seat. The article only studied the installation of the X-shaped energy-absorbing component and the formulas for describing the buffer load derived from the geometric relations. The
structure was not optimized. There is also relatively little consideration for the human–seat coupling system in cases where the helicopter makes an emergency landing.

Moreover, the aerospace industry of China suffers from a lack of experience in terms of design and the manufacturing. The research on the crashworthiness has just begun, which still lags far behind many developed countries. Three main aspects can be summarized as follows. (1) The system related to the airworthiness is incomplete. (2) Some of the key airworthiness technologies have not been mastered. (3) The relevant regulations are still inadequate. With the development and production of domestic helicopters, there is an urgent need to carry out systematic and comprehensive research on crashworthiness so as to provide technical support for crashworthiness design and airworthiness certifications.

According to the situation that the capacity of a H135 helicopter seat is not sufficient to resist shock in the vertical direction during the crashworthiness test, this paper completed the modelling of the human–seat coupling system which is based on the energy methods and the theories related to structural mechanics. The accuracy of the model will be confirmed through the dynamic simulation whose result is approximate to the result in reality. The force on the spine of the ATD (Anthropomorphic Test Device) during the vertical dynamic test of the rear-facing seat is considered as an important indicator for evaluating crashworthiness. By using the kriging model, the optimization effectively increases the capacity of the helicopter seat to absorb energy during the collision.

2. Human–Seat Coupling Modelling

This type of seat is designed for an Airbus H135 helicopter, mainly composed of several parts such as the outer frame, headrest, seat cushion, safety belt, side rails, seat basin, seat basin holder (it will be referred to as the key energy-absorbing structure of the seat in the rest of this paper), and shear pin. The 3D model of the seat is shown in Figure 1a. What is shown in Figure 1b is the simplified FEM model of a Hybrid III 50th Percentile ATD. In general, it can be effectively employed in the performance evaluation of the crashworthiness of an automotive seat. Since the margin of error between the results of the simulation, which was completed by using this FEM model, and the results of the test do not exceed 10%, it was deemed acceptable to use this model for simulation in this paper. See Section 3.3 for details. Its main components are as follows: head, neck, upper torso, lower torso, upper arm, fore arm, hands, thigh, shank and feet. The springs, which are in the spine, were used to simulate human elasticity. There is also a triaxial accelerometer in the head and a force transducer in the femur [25]. The human–seat coupling system under the restraint of the four-point seat belt systems is shown in Figure 1c.

![Figure 1. Three-dimensional models. (a) The seat. (b) The simplified FEM model of Hybrid III 50th Percentile ATD. (c) The human–seat coupling system.](image)

According to CCAR-27-R2 (Airworthiness Regulations for Normal Class Rotorcraft in the Chinese Civil Aviation Regulations) [26] and SAE AS 8049B (Performance Standard for Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft) [27], the defini-
tion of seat dynamic performance standards intends to reflect the survival limits during aviation accidents. The dynamic testing of the seat was used to simulate circumstances wherein the human–seat coupling system is under the impact from the forced landing of the helicopter. Compared to dynamic testing, static testing is limited to verifying the structural strength and the functionality of the seat and the restraint systems, ignoring the physical tolerance of the human. In addition to the structural strength, vertical dynamic testing and horizontal dynamic testing can also evaluate the occupant trajectory, the floor reaction loads, the HIC (head injury criteria), the spine load and the femur compressive load. Therefore, dynamic testing is irreplaceable in the process of completing the safety assessment of the human–seat coupling system.

In the vertical dynamic testing of the rear-facing seat, the seat is connected to the floor by rails and they are installed together on a sled which can only move horizontally. Velocity and acceleration are applied to the seat by means of a thrust device, which pushes the sliding table, and then the seat collides with the 77 kg ATD. The angle between the velocity direction and the helicopter floor is 60° and the region enclosed by acceleration and time in the coordinate system is an isosceles triangle. For details, see Section 3 on Simulation and Crashworthiness Testing.

2.1. The Mechanical Model Based on Energy Method

In physics, the law of conservation of energy states that the total energy of an isolated system remains constant and it is said to be conserved over time [28]. Therefore, the energy input to the human–seat coupling system can be divided into four parts after collision. The first part of the energy is absorbed through deformation and fracture of the seat structures. The second part of the energy is converted into the kinetic energy of the seat. The third part of the energy is dissipated through the work of the impact on the occupants. The fourth part is the kinetic energy of the system after the collision. Similarly, the energy absorbed by the deformation and fracture of the seat structures can also be divided into two parts. One part is the energy absorbed by the deformation of the key energy-absorbing structure, and the other part is the energy absorbed by the deformation of other structures of the seat.

\[
E_{in} = W + W^e = K_0 - W_{human} - W_{other} - E
\]

\[
E = \frac{1}{2} \int V \rho \dot{u} \ddot{u} dv
\]

In Equation (1), \(E_{in}\) is the energy absorbed by the key energy-absorbing structure of the seat. \(W\) is the energy absorbed by the elastic deformation of the key energy-absorbing structure of the seat. \(W^e\) is the energy absorbed through the plastic deformation of the key energy-absorbing structure. \(K_0\) is the total energy input to the system. Since plastic deformation is the most efficient way for ductile materials to absorb energy, the energy dissipated by viscous deformation, friction or fracture is not considered here. \(W_{human}\) is the work completed by the impact on the occupant. \(W_{other}\) is the energy absorbed by other structures of the seat except the key energy-absorbing structure during the collision. \(E\) is the kinetic energy after the collision.

Since this paper intended to study of the key energy-absorbing structure of the seat, the other structures of the seat remained unchanged. Therefore, \(W_{other}\) is considered as approximately a constant value even through the key energy-absorbing structure changes. In the equivalent simplified model which is established according to the energy dissipation condition of the human–seat coupling system, all structures of the seat except the key energy-absorbing structure are regarded as a rigid body-damping system. As is shown in Equation (3), the energy absorbed by the damping is used to represent the energy absorbed by structures of the seat except the key energy absorbing structure. The damping device works only when \(F_y\) is greater than the pre-set critical force.

\[
W_{other} = \int_{S} F_y(u) \cdot du
\]
The key energy-absorbing structure is connected to the outer frame by bolts at point C and point D. See Figure 2 for details. The structure is simplified to a V-shaped beam in the following paragraphs. Point A and point B are the front-most point and the inflection point, respectively.

![Figure 2. Partial enlargement of main structures.](image)

On the basis of the above, the mechanical model of the human–seat coupling system during collision is shown in Figure 3. The imaginary line A'B'C in the figure indicates the key energy-absorbing structure after deformation and it is only a schematic diagram. The red area is considered to be between the pelvis and the lumbar column of the ATD. F_p is resultant of the external forces on it. The arrow in the figure is only a schematic representation and does not indicate the true direction and magnitude of the force. A section view of the ATD is shown in Figure 4. The green area between the lumbar column and the pelvis is used to measure the compressive load.

![Figure 3. Mechanical model of the human–seat coupling system during the collision.](image)

![Figure 4. The section view of the FEM model of the Hybrid III 50th Percentile Male ATD.](image)
2.2. Mechanical Model Analysis

The aerodynamic forces have little effect on the dynamic behavior of the seat and ATD throughout the crash. Therefore, the effect of aerodynamic forces on both is ignored when the FEM (Finite Element Method) is used to complete the study of the collision. The established differential equation of motion is shown in Equation (4). \( M, C, K \) are the mass matrix, the damping matrix and the stiffness matrix, respectively. \( \ddot{u}, \dot{u}, u, U \) are the acceleration, the velocity, the displacement and the position of the node in the system. The relationship among the three is shown in Equations (5) and (6).

\[
M \ddot{u} + C \dot{u} + Ku = F_e(t) \tag{4}
\]

\[
\ddot{u}(U, t) = \frac{\partial u(U, t)}{\partial t} \tag{5}
\]

\[
\dddot{u}(U, t) = \frac{\partial^2 u(U, t)}{\partial t^2} \tag{6}
\]

Equation (8) can be derived from Equations (4) and (7). \( F_e, F_i, F_r \) are the external forces, the internal forces and the remaining force, respectively.

\[
M \ddot{u} = F^e - F^i \tag{7}
\]

\[
\ddot{u} = M^{-1}(F^r) \tag{8}
\]

Equations (9) and (10) can be derived by the central difference method [29]. The value of \( u_{t+\Delta t} \) can be obtained when \( \ddot{u}, \dot{u}, u \) are known.

\[
u_{t+\Delta t} = u_t + \dot{u} \Delta t + \frac{1}{2} \ddot{u} \Delta t^2 \tag{9}\]

\[
u_{t+\Delta t} = \ddot{u}_t + \frac{1}{2} (\dddot{u}_t + \dddot{u}_{t+\Delta t}) \Delta t \tag{10}\]

In this paper, the following three principles were followed when establishing the constitutive equation [30].

1. The principle of determinacy assumes that the stress \( \sigma \) of a point in an object is determined entirely by the state and deformation process of the neighborhood of the mass point.
2. The principle of local action assumes that the influence of each other point decreases as the distance increases when calculating the stress or another physical quality of a point. In other words, the material response at a given point in the continuum is determined entirely by the values of the field variables at that point.
3. The principle of material objectivity assumes that the constitutive equation is completely determined by the nature of matter and does not change as the observer changes. In coordinate systems for relative motion, the constitutive equation of the matter has the same form.

There will be a large impact during the crash which will cause the structure to deform drastically. When the stress exceeds the yield limit of the material, the material moves from the elastic phase to the plastic phase. During the elastic phase, the relationship between the stress and the strain is linear and the elastic deformation is recoverable. During the plastic phase, the relationship between the stress and the strain is nonlinear and the plastic deformation is irreversible. When the key energy-absorbing structure of the seat absorbs energy, the energy dissipated by plastic deformation should be much larger than the energy stored by elastic deformation. In this paper, the generalized von Mises yield criterion was
selected to determine when the plastic deformation of the structure occurs. Its expression in the three-dimensional principal stress space is shown in Equation (11).

\[ F^0(\sigma_{ij}) = \frac{1}{6} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2 \right] - \frac{1}{3} \sigma_s^2 = 0 \]  

(11)

\( \sigma_{ij} \) is the stress tensor and \( \sigma_s \) is the initial yield stress of materials.

During the plastic phase, the flow rule [31] and the hardening rule [32] are used to determine how the subsequent yield surface of the material changes. The relationship between the plastic strain increment and the current stress and strain increment is established on this basis. The detail of the flow rule is shown in Equation (12). The isotropic hardening rule states that the load surface spreads uniformly outward in all directions. At the same time, the shape, the center and the position of the surface remain unchanged.

\[ \text{de}^p_{ij} = d\lambda \frac{\partial F}{\partial \sigma_{ij}} \]  

(12)

\( \text{de}^p_{ij} \) is the component of the plastic strain increment. \( d\lambda \) is a certain quantity which is associated with the hardening rule. \( F \) is the subsequent yield function. \( \frac{\partial F}{\partial \sigma_{ij}} \) is the vector whose direction is the same as the normal direction of the subsequent yield surface.

The energy absorbed by the key energy-absorbing structure through plastic deformation is shown in Equation (13).

\[ W_e = \int_V \sigma_{ij} \varepsilon_{ij} \]  

(13)

The D'Alembert principle [33], which is also known as the Lagrange–d’Alembert principle, states that if at any given moment the inertia force is added to the active forces and the reactions of the constraints acting on a particle, the resultant force system will be in equilibrium. The D’Alembert principle provides a method of solving problems of dynamics by developing equations of motion in the form of equations of equilibrium. According to the above principle, the relationship among them satisfies Equation (14).

\[ F^A_a - F^A_n = 0 \]  

(14)

The general kinetic equation of the system of the mass point can be obtained by making a vector dot product of both ends of Equation (14) and the virtual velocity of the mass and integrating the equation for each mass. See Equation (15) for details. A multibody system can be considered as a system of the mass point, which includes a system of the mass point corresponding to each rigid body in the whole system. The general kinetic equation of the multibody system is shown in Equation (16).

\[ \sum_A \left( m_A \ddot{u}_A - F^A_a - F^A_n \right) \cdot \delta \dot{u}_A = 0 \]  

(15)

\[ \sum_i \left( m_i \ddot{u}_i - m_i g - F^e_i \right) \cdot \delta \dot{u}_i + \sum_i \left( J_i \cdot \dot{\omega}_i + \omega_i \times J_i \cdot \omega_i - M^e_i \right) \cdot \delta \omega_i = 0 \]  

(16)

When the generalized coordinates of the system are constrained by equations (i.e., \( \Phi(q, t) = 0 \)), Equation (16) is no longer appropriate. The kinetic equation under the restraint system is shown in Equation (17) [34].

\[ \begin{bmatrix} M & \Phi_T^T \\ \Phi_T & 0 \end{bmatrix} \begin{bmatrix} \dot{q} \\ -\lambda \end{bmatrix} = \begin{bmatrix} F \\ -\Phi_{q} q - \Phi_{I} \end{bmatrix} \]  

(17)

\( F \) is the generalized force matrix. \( \Phi_T \) is the restraint Jacobi matrix. \( \lambda \) is the Lagrange multiplier vector whose dimension is equal to the number of constraint conditions.
The expression for the work enacted by the force on the ATD during the impact, as shown in Equation (18), can be obtained. $F_p$ is the compressive load between the lumbar column and the pelvis.

$$W_{human} = \int_{s_p} F_p dq + \sum_i \int_{s_i} F_i dq$$

(18)

Finally, according to above equations (i.e., Equations (1)–(3), (13) and (18)), a link between the spine load of the ATD and the energy absorbed by the key energy-absorbing structure of the helicopter seat is established through the law of conservation of energy. Additionally, $F_p$ will change over time.

3. Simulation and Crashworthiness Testing

3.1. Simulation

Firstly, a computer-aided design software (i.e., SolidWorks) was used to establish the overall three-dimensional model of the seat. Secondly, the models of the seat and the Hybrid III 50th percentile male dummy were imported into HyperMesh, which is a finite element pre-processing software used to complete the finite element modelling and settings of simulation parameters. Thirdly the output file was imported into the LS-DYNA for solving. Fourthly, calculation results such as structural deformation, stress nephogram and other data can be viewed using Ls-Prepost.

It is necessary to simplify the seat structure appropriately and establish a reasonable and effective structural finite element model. This provides simulation results which are close to the real test results while saving on computation time. The simplifications are as follows.

1. The main force-bearing structures must be retained and the headrest, the seat cushion, the rotating device, etc., will be simplified.
2. Welded, riveted and bolted connections between components of the seat are simulated by using the rod elements connection method, the common element method and the common node method, respectively [35]. In the rod elements connection method, two parts are connected at the corresponding nodes by a mass-free rigid rod. In the common element method, two parts are connected by creating a common element. In the common node method, the element nodes of two parts are directly connected at the junction.
3. Chamfers and small holes will be ignored when their radiuses are smaller than the estimated size of the minimum element.

In the process of finite element modelling of the seat, the solid element is used to simulate the frame structures, the cushions, the rails and so on. The shell element is used to simulate the thin-walled structures such as tubes and boards. The solid element corresponds to the single point integral method and the shell element corresponds to the Gaussian integral method.

The key energy-absorbing structure and other major structures are made of 7075 aluminium alloy. The material of the seat cushion is low density polyurethane foam. The guide rails are considered to be rigid bodies with a high density to eliminate the effects of inertia of the ATD and the seat on the simulation results. Their parameters are shown in Table 1.

Table 1. Parameters of the material.

<table>
<thead>
<tr>
<th>Material</th>
<th>7075 Aluminium Alloy</th>
<th>Low Density Polyurethane Foam</th>
<th>Rigid Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density/(kg/m$^3$)</td>
<td>2810</td>
<td>51.5</td>
<td>281,000</td>
</tr>
<tr>
<td>Young's modulus (GPa)</td>
<td>71.7</td>
<td>/</td>
<td>210</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.33</td>
<td>/</td>
<td>0.28</td>
</tr>
<tr>
<td>Yield stress (GPa)</td>
<td>0.45</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Tangent modulus (GPa)</td>
<td>0.65</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>
The following initial conditions were applied to the human–seat coupling system. The guide rail rotates around local axes to simulate the deformation of the floor. The front section of left floor is raised by 10°. The right floor finishes the clockwise rotation and the angle is also 10°. The acceleration–time curve is shown in Figure 5. The area enclosed by the horizontal and vertical axes is an isosceles triangle. \( G = 30 \, g \), \( t_1 = 0.031 \, s \). The collision process lasts one second (1 s).

![Figure 5. Curve of the acceleration applied to the seat over time.](image)

**Figure 5.** Curve of the acceleration applied to the seat over time.

### 3.2. Crashworthiness Testing

The arrangement of the seat and ATD and the deformation simulation of floors were completed according to the regulations. A load cell, which fits the ATD, was placed between the pelvis and the lumbar column to measure the maximum compressive load, which was used to determine the probability of a spinal injury according to aviation regulations. The image of the seat during the vertical impact captured by a high-speed camera, whose sample rate is 1000 Hz, is shown in Figure 6.

![Figure 6. A frame during the process of the test.](image)

**Figure 6.** A frame during the process of the test.

### 3.3. Results Comparison

The comparisons between testing and simulation in terms of acceleration and velocity at the marker point are shown in Figure 7. The marker point is located at the pelvis. The margin of error between the results of the simulation and the testing is no more than 10%.

With the time on the horizontal axis and the spine load on the vertical axis, the line graph illustrates the trend of the spine load of the ATD as the change of time during the crash. The orange curve indicates the simulation result and the blue curve indicates the test result. As is shown in Figure 8, the initial motion conditions are applied to the seat at the moment \( t = 0 \), and the collision between the seat and the ATD begins after 65 ms. After approximately 28 ms, the spine load rapidly increases to a peak and then decreases to a
smaller value which is nearly zero. During the simulation, when \( t = 88.3 \text{ ms} \), the peak spine load (i.e., 8578 N) appears. In the test, the maximum value of the spine load (i.e., 8387 N) occurs at \( t = 93.1 \text{ ms} \). Like the trend of the acceleration applied to the human–seat coupling system with time, the region enclosed by the spine load and time was also approximated using an isosceles triangle. With the restraint of the seat belt, the spine load fluctuates in a small range from \( t = 130 \text{ ms} \) to \( t = 330 \text{ ms} \). After 130 ms, the seat is no longer pushed and there is no excessive spine load, so the process after that has no reference value.

![Figure 7](image7)

Figure 7. Comparison in terms of acceleration and velocity between the testing and the simulation. (a) the comparison of acceleration (b) the comparison of velocity.

![Figure 8](image8)

Figure 8. Spine load–time curve during the crash. The arrow indicates the change of the spine load during a short time when the peaks of the test and the simulation occur, respectively.

Overall, the margin of error between the results of the simulation and the testing is no more than 10%. Thus, the simulation result is considered to be basically in accordance with the actual situation and acceptable.

4. Structural Design Optimization

In order to optimize the key energy-absorbing structure, the parametric model of the seat was developed. The length of the projection of the AB in the horizontal direction is \( l_1 \). The length of the projection of the BD in the horizontal direction is \( l_2 \). The length of the CD is \( l_3 \). The angle between the AB and the horizontal plane is \( \alpha \). The angle between the BD and the horizontal plane is \( \beta \). See Figure 9 for details.
As mentioned in Section 2 of this paper, the value of \( F_p \) varies with time and peaks at one point when the above four structural parameters are determined. The change in each of the four structural parameters may affect the energy absorption capacity of the key energy-absorbing structure, which can thereby affect its peak. When the combination of the four parameters minimizes the peak, the seat has the best protection for the human body during the crash. The mathematical model for the optimization of the key energy-absorbing structure of the seat is shown in Equation (19).

\[
\begin{align*}
\text{min} & \quad F_{p\text{-max}}(x) \\
s.t. & \quad x^l \leq x \leq x^u (x \in \mathbb{R}^n) \\
& \quad g_u(x) \geq 0, \quad u = 1, 2, \ldots, p \\
& \quad h_v(x) = 0, \quad v = 1, 2, \ldots, q
\end{align*}
\]  

\[x = \{a, \beta, l_1, l_3\} \]  

\[F_{p\text{-max}}(x) \] is the objective function which is expected to be minimized in the optimization process. It is a function based on the connection between the parameters and the maximum value of \( F_p \). \( a, \beta, l_1 \) and \( l_3 \) are the four variables of the objective function, respectively. See Equation (20) for details. \( x^l \) and \( x^u \), which are two column vectors, are the upper and lower limits of the variables, respectively. \( g_u(x) \geq 0 \) are inequality constraints and \( h_v(x) = 0 \) are equation constraints.

According to the H135 flight manual [36], the minimum distance inside the cabin from the floor to the top is 1150 mm and the distance between the two seat cushions placed in the opposite direction is 1342 mm. The seated height of the Hybrid III 50th Percentile ATD is 884 mm. The distance from the hip to the outside of the knee is 592 mm and the thickness of the knee is about 119 mm. The thickness of the cushion is 39 mm. On the basis of the above, the scope of variables as well as equality or inequality constraints can be determined by considering the comfort level of the occupant. See Equation (21) for details.

\[
\begin{align*}
0^\circ & < a \leq 90^\circ \\
0^\circ & < \beta \leq 90^\circ \\
0 & \leq l_1 \leq l = l_1 + l_2 = 434 \text{ mm} \\
l_3 & \leq l_2 \cdot \sec \beta \\
l_1 \cdot \tan \alpha & \leq 202 \text{ mm} \\
l_1 \cdot \tan \alpha & < l_2 \cdot \tan \beta \leq 227 \text{ mm}
\end{align*}
\]  

Additionally, in this way, the optimal solution which minimizes the peak spine load during the crash can be obtained and the structure can be optimized.

4.1. Optimization Algorithm

In this paper, iSIGHT was used to optimize the key energy-absorbing structure so as to reduce the impact on occupants during the crash.

During the process of building the response surface model, sample points have a great influence on the response surface. The true response cannot be reflected by just a few sample points. However, too many sample points require more time which is also
unreasonable. Here, Latin hypercube sampling [37] was selected to complete the sampling and the kriging model [38] was used to construct response surface functions.

During Latin hypercube sampling, each factor was equally divided which resulted in the same number of levels for each factor. A matrix which contains n design points can be obtained by combination according to the probability. See Equation (22) for details.

\[ X = \{ x_1, x_2, \ldots, x_n \}^T \]  

The response surface function based on the kriging model is shown in Equation (23). \( \mu \) is the multinomial coefficient. \( r \) is the covariance matrix between the prediction points and the data points. \( R \) is the covariance matrix between the data points. \( Y \) is the response value of the approximating function. \( l \) is the matrix consisting of the primary functions of the regression functions at each sampling point.

\[ \hat{y} = \mu + r^T R^{-1} (Y - l\mu) \]  

\[ \mu = \left( l^T R^{-1} l \right)^{-1} l^T R^{-1} Y \]  

The estimated value of the kriging model at the prediction point has high uncertainty. It is necessary to use mean squared error to evaluate the accuracy of the response surface function. See Equation (25) for details. The smaller the value of the \( s^2 \), the smaller the error between the estimated value and the true response. Too large a value indicates that the accuracy is not sufficient. According to the infill sampling criteria [39], the estimated point of the maximum value should be taken as the new sample point to reconstruct a new response surface function.

\[ s^2 = \gamma^2 \left[ 1 - r^T R^{-1} r + \frac{(1 - l^T R^{-1} r)^2}{l^T R^{-1} l} \right] \]  

\[ \gamma^2 = \frac{(Y - l\mu)^T R^{-1} (Y - l\mu)}{n} \]  

4.2. Optimized Process

1. Complete sampling by using Latin hypercube sampling and determine the initial sampling point.
2. Calculate the response by using finite element software.
3. Construct response surface functions for the objective and constraint functions by using the kriging model.
4. Find the minimum \( F_{p_{-\text{max}}} (x) \) by performing the analysis.
5. Judge the convergence: if the result converges, the optimization will be terminated. If the result does not converge, skip to the step (6).
6. Take the estimated point where \( F_{p_{-\text{max}}} (x) \) is maximum value as the new sampling point and skip to step (2).

4.3. Example Verification

The four variables which were optimized simultaneously were \( \alpha \), \( \beta \), \( l_1 \) and \( l_3 \). Additionally, the optimization results are shown in Table 2. At the same time, each of the four variables were individually optimized according to the results. The errors of the spine load of all five optimizations between the test and the simulation did not exceed 10%. Thus, the simulation result is acceptable. Before the improvement, the peak spine load during the crash was 8578 N. After optimizing the variable \( \alpha \) independently, the maximum load at the spine of the ATD was 6948 N (see Figure 10a for the comparison). The optimization of the variable \( \beta \) changed the peak spine load from 8578 N to 7850 N (see Figure 10b). If the opti-
mized variable was $l_1$, the load would be reduced from 8578 N to 7615 N (see Figure 10c). Optimizing $l_3$ independently made the maximum load 8180 N (see Figure 10d). Compared with the previous four cases, optimizing all four parameters at the same time had the best effect and the peak spine load was 6292 N (see Figure 10e). The corresponding peak spine load for the above five cases decreased by 19%, 8.5%, 11.2%, 4.6% and 26.6%, respectively.

Table 2. Optimization results.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before the Optimization</th>
<th>After the Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>14°</td>
<td>31°</td>
</tr>
<tr>
<td>$\beta$</td>
<td>57°</td>
<td>64°</td>
</tr>
<tr>
<td>$l_1$</td>
<td>303 mm</td>
<td>335 mm</td>
</tr>
<tr>
<td>$l_3$</td>
<td>103 mm</td>
<td>122 mm</td>
</tr>
</tbody>
</table>

| The peak spine load of the ATD | 8578 N | 6292 N |
| The mass of the system         | 90.9 kg | 91.3 kg |

Figure 10. Comparison of the spine load before and after the optimization. (a) The optimized variable is $\alpha$. (b) The optimized variable is $\beta$. (c) The optimized variable is $l_1$. (d) The optimized variable is $l_3$. (e) The optimized variables are $\alpha$, $\beta$, $l_1$ and $l_3$. 
According to the description of the results provided above, the four structural parameters of the key energy-absorbing structure of the seat ($\alpha$, $\beta$, $l_1$ and $l_3$) have a significant impact on the ability to absorb energy when the rear-facing seat is tested for vertical impact. Compared with the other three variables, the change of the single variable $\alpha$ plays a more important role in the energy absorption improvement under the constraints. When the four variables were simultaneously changed, the structure of this helicopter seat was greatly optimized. In the human–seat coupling system, the optimized seat can effectively reduce its impact on the spine of the occupant during collision and it also improves the crashworthiness of the helicopter. According to the AIS (Abbreviated Injury Scale), which was proposed by AAAM (Association for the Advancement of Automotive Medicine) in 1969, the condition is severe but the passenger can be saved from death. This condition corresponds to AIS level 4 [40]. At the same time, the result meets the following regulations of the CCAR-27-R2 on the dynamics of landing.

1. The seating system must withstand the intended separation, while the rest of the system must remain intact.
2. The connection within the main structures of the seating system must not be destroyed, even though the load on the seating system may have exceeded its limit.
3. The peak spine load of the ATD should be less than 6668 N (1500 pounds).

5. Conclusions

This paper studied the optimization of the key energy-absorbing structure of the helicopter seat based on the human–seat coupling system. The optimized key energy-absorbing structure significantly improved the energy absorption capacity and the crashworthiness of the helicopter seat. Additionally, the whole process provided a solution for the crashworthiness design of helicopter seats.

1. Based on the aerospace standards, i.e., SAE AS8049B and CCAR-27-R2, this paper determined the conditions required for the H135 helicopter seat to complete the crashworthiness test. It also studied the estimation methods of the maximum tolerance limit of the human body and the minimum performance standard of the helicopter seat. This provides a reference for the crashworthiness evaluation of a helicopter.

2. According to the energy methods and the theories of structural mechanics, the simplified mechanical model of the human–seat coupling system of this helicopter during collision was established. The simulation results basically coincide with the results of the crashworthiness test. This shows that the crashworthiness assessment and analysis method established in this paper are reasonably effective, as they can analyze the structural characteristics of the seat and the dynamic response of the ATD during the crash more accurately.

3. The optimization design of energy-absorbing structures for crashworthiness represents a research hotspot in the engineering community. In this paper, the link between the design variables and the objective function was established to complete the optimization process by using Latin hypercube sampling, the kriging model and nonlinear transient finite element analysis techniques. After optimization, the crashworthiness of the helicopter was improved greatly and the result met the regulatory requirements. This optimization method can be easily extended to other complex structures for optimization design.

4. By comparing the previous results with the optimized results, we found that the height of the front end of the key energy-absorbing structure and the horizontal length have important effects on the energy-absorbing capacity of the structure. These two should be prioritized in the structural design process.

5. In this paper, the spine load was the only optimal object. More aspects should be given attention in the next step such as head injury, chest injury, femur injury and so on. In addition to the seat basin holder, the optimization of the round tubes in human–seat coupling can also improve the crashworthiness of helicopter seats.
Author Contributions: Conceptualization, Y.L.; methodology, X.W.; software, X.L. and Z.Z.; validation, Y.C.; formal analysis, S.D.; writing—review and editing, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (50705097) and Open Fund of the Postgraduate Innovation Base (Laboratory) of Nanjing University of Aeronautics and Astronautics (kjj20200725). The funder of both of them is Yanjun Li.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to commercial reasons.

Acknowledgments: The authors would like to thank Editor-in-Chief, Editor and anonymous Reviewers for their valuable reviews.

Conflicts of Interest: The authors declare no conflict of interest.

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