Impact of Crash Environments on Crashworthiness of Fuselage Section

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Abstract: In order to study the crash resistance of the civil aircraft structure in different crash environments, two environmental models of soft soil and water are established to analyze the dynamic response of the fuselage section subjected to the vertical at the impact velocity of 7 m/s. Simulation results show that the soft crash environment can have a certain cushioning effect on the structure crash, but it will prolong the crash time and change the energy absorption mode. This work suggests that soft environment may not be suitable for forced landing.

Key words: crashworthiness; dynamic response; fuselage section; soft soil; water

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0 Introduction

Crashworthiness, as an important issue of aircraft safety and airworthiness certification, has received extensive attention after it was put forward. In actual environment, the occurrence of accidents makes it difficult for the aircraft to complete all flight tasks perfectly. Therefore, it is particularly important to ensure the survival of the crew in the event of an accident. In the past crashworthiness analysis, the force transmission and response characteristics of the structure are the main content of the analysis, and the impact surface is often simply treated as a rigid plane. However, aircraft accidents are unexpected. The captain often finds it difficult to find a suitable emergency landing environment. It is necessary to make an emergency landing in special environments such as farmland and lakes. This special environment is significantly different from the airport runway. Therefore, it is important to study the impact of the impact environment on the aircraft's crashworthiness.

Compared with hard ground, soft ground and water often have a larger contact surface with the fuselage skin due to their own deformation, and the force transmission path and the magnitude of the force also change accordingly. Ref.[1] compared the impact response of hard soil and soft soil of the crash-resistant composite fuselage through a drop test. As shown in Fig.1, it can be seen that for rigid terrain, the load is introduced into the hardest part of the aircraft structure, while for soft soil impact, distributed load is introduced into the fuselage skin.

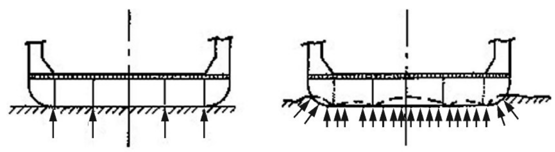

Fig.1 Force transmission mode of impact surface during forced landing

The suddenness of the crash makes it difficult for the aircraft to avoid landing on soft ground or water. Survivability in a special crash environment is already an important indicator of the crashworthiness design of many aircraft. Due to the high cost of the

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crashworthiness experiment of the fuselage section, the existing research is mainly based on simulation analysis[2-5]. In addition, the constitutive model of soft soil and water is more complicated. Therefore, this paper draws on some domestic and foreign soft modeling method of soil and water environment[6-12]. Study on the impact of environment on the crashworthiness of the fuselage section has an important guiding role for whether the aircraft can make a safe emergency landing in a special environment during an accident. It is not only helpful to analyze the deformation and force transmission characteristics of the fuselage structure during impact, and to understand the crashworthiness of the structure in a special crash environment, but also can provide a certain reference for crashworthiness experiment planning and energy-absorbing structure design. In recent years, domestic and foreign researches have been carried out on the crashworthiness of the fuselage section in special environments. Refs.[2-3] studied the impact response of structures in special environments. Through the simulation results in the paper, it can be found that the density and shear modulus of the ground have a significant impact on the impact response and the energy absorption capacity of the ground. Refs.[4-5] introduced the Euler method into the collision environment simulation, which solved the problem of large deformation when the fuselage section hits the soft ground. It can be seen that due to the deformation characteristics of the soft ground itself, the crash process of the aircraft will be different from that of the rigid ground. At present, there are still few studies on the crashworthiness of the fuselage section in different impact environments. Therefore, it is very important to study the impact of the crash environment on the crashworthiness of the fuselage section.

Based on the display nonlinear dynamics analysis software LS-DYNA, this paper uses the classical soil constitutive material and the arbitrary Lagrangian-Eulerian (ALE) fluid-solid coupling method to simulate the soil and water crash environment respectively, and analyzes the impact of the collision environment on the deformation response of the fuselage section and the energy absorption distribution. The obtained results provide a reference for the crashworthiness design of the aircraft in special environments.

1 Finite Element Modeling of Fuselage Section and Special Environment

As a low-cost and high-efficiency research method, the difficulty of finite element simulation lies in whether the established model meets the requirements of the subject. Calculating a rough model may cause unreasonable structural deformation and get wrong results. Therefore, correct meshing and reasonable keywords are essential. Only by guaranteeing the accuracy of the finite element model, can the simulation serve the practical application.

1.1 Finite element model of fuselage section

In this paper, civil aircraft fuselage section structure is selected as the research object. Due to the complexity of the actual fuselage section structure, the modeling method is to accurately divide the main research objects and maintain the appearance of the secondary structural components. In the element division, simplify the processing of components with small deformation and little impact on the overall structure, and only maintain their geometric shape and connection function. According to the structure size, the grid size shall not be less than 10mm. For main deformation and force transmission structures, keep their geometric shape, and control the grid size between 5 mm and 20 mm according to the structure size.

The finite element model of the fuselage section is shown in Fig.2. The main research objects include the main deformation and force transmission structures such as the frame and struts, and the important energy absorption components such as the fuselage skin and truss. The secondary research objects include small deformation areas above the cabin floor and some small components for connection. The connection method related to the main research object in the structure is simulated by the deformable beam solder joint meshes to analyze the failure and

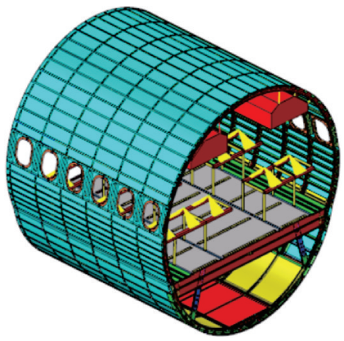

Fig.2 Finite element model of fuselage section

energy absorption effect of the fastener; for the connection method between the secondary research objects, the common node and rigid point connection are used Simplify. The finite element model consists of 7 frames and 6 sections. A reinforced beam is added at the opening for rigidity reinforcement. The total mass is 1 703.416 kg. The model also includes a simplified seat and 15 concentrated mass points that replace the dummy, each mass point giving a mass of 77 kg. These mass points are used to analyze the acceleration of the human body during the crash.

The finite element model of the fuselage section is shown in Fig.2. The main research objects include the main deformation and force transfer structures such as frames and struts, as well as important energy absorption components such as fuselage skin and trusses. The secondary research objects include small deformation areas above the cabin floor and some small components for connection. The failure and energy absorption effects of fasteners are analyzed by simulating the connection modes related to the main research objects in the deformed beam solder joint grid structure. For the connection method between the secondary research objects, the common node and rigid point connection are simplified. The finite element model consists of seven frames and six sections. A reinforced beam is added at the opening for rigidity reinforcement. The total mass is 1 703.416 kg. The model also includes a simplified seat and 15 concentrated mass points to replace the dummy, each of which has a mass of 77 kg. These mass points are used to analyze the acceleration of the human body during the crash.

The fuselage section is mainly made of aluminum alloy, so keyword "Mat3_Plastic_Kinematic" is used for simulation. When the elastic modulus, yield limit and tangent modulus are input into the material card, the stress-strain characteristics of aluminum alloy can be well reflected. Fasteners are simulated by MAT100, and the failure judgment is calculated by the failure criterion proposed in Ref.[13]. Table 1 shows the material property parameters used in the fuselage structure, including rigid ground parameters for comparison.

Table 1 Model material parameters

Material	Density/(kg·m^{-3})	Young's modulus/GPa	Yield stress/GPa	Tangent modulus/GPa	Failure strain
7075	2 769	71	0.441	0.937	0.08
7050	2 830	71	0.469	0.650	0.08
7150	2 823	71	0.538	0.679	0.07
2524	2 768	71	0.269	0.908	0.15
Fastener	2 750	71	0.165		
Rigid	750	30			

In terms of contact, the key word "contact_automatic_single_surface" is used in the finite element model, and the soft constraint formula and "ignore" are used to solve the problems of poor stiffness and penetration in structural collision. For the deformation of the main research object, the full integration calculation mode is adopted, the number of integration points in the thickness direction is increased, and the hourglass control key card is added to ensure the accuracy of simulation.

1. 2 Finite element model of soft soil

For the constitutive model of soft soil, LS-DYNA provides Mat5 _Soil_and_Foam material card for soil simulation. This paper refers to the soil parameters given in Ref.[14], and the specific parameters are shown in Table 2, where p_c is the pressure cutoff for tensile fracture.

In addition, the pressure stress curve must be provided, and the curve formula is

Table 2 Soft soil parameters

Density/ $(kg·m^{-3})$	Shear modulus/ GPa	Bulk modulus/ GPa	a_0/ GPa	a_1/ GPa	a_2/ GPa	p_c/ GPa
1 290	0.031 7	0.168	6.18e−12	5.143e−6	1.068	0

$$\sigma_y=\left[3\left(a_0+a_1 p+a_2 p^2\right)\right]^{\frac{1}{2}} \tag{1}$$

where a_0, a_1, a_2 are the yield function constants of plastic yield function. p is the pressure.

Different from the rigid ground, the soil material can only be assigned in the 3-D meshes. Since the material does not provide the freedom constraint option, it is necessary to use Boundary_Spc to constrain the freedom of the bottom of the soil model.

1.3 Finite element model of water

The element modeling of water is the same as that of soil, but due to the great deformation of water in the calculation, the Lagrangian meshes will have the hourglass phenomenon caused by large deformation, so it is necessary to use the ALE method to simulate the water. Considering that the simulation of water splashing during the collision requires the material to flow outside water meshes, air meshes are added on the water surface, air and water meshes are connected by node merging.

In this paper, the fuselage section is coupled with the air and water which is a structure-liquid coupling problem. The state equation uses the parameters recommended by the keyword manual. The coupling method uses the keyword "Constrained_Lagrange_in_Solid" for modeling. The water mesh uses the same size as the fuselage skin mesh. This modeling method can increase the calculation cost, but the results have good stability. In addition, since the Euler mesh will not deform during the calculation process, and the fuselage section mesh will pass through the area of the Euler mesh, the Euler mesh needs to be set as a multi-material grid to prevent errors.

2 Deformation Analysis of Fuselage Section

The initial crash velocity is set to be 7 m/s to study the deformation difference of the fuselage section in a vertical crash on soil, water and rigid ground.

2.1 Maximum deformation in rigid ground environment

In order to compare the crashworthiness of the fuselage part in different crash environments, the rigid ground conditions are selected to analyze the deformation of the fuselage part at 7 m/s.

It can be seen from Fig.3 that when the fuselage section collides with the rigid ground, the bottom structure receives a huge impact, the fuselage frame breaks, the cargo hold structure deforms upwards and hits the cabin floor beam. The deformation of the fuselage section during the whole collision process in the rigid ground environment is very severe.

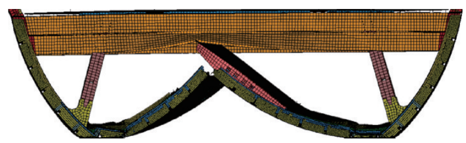

Fig.3 Maximum deformation diagram of cargo hold area impacted on rigid ground

2.2 Maximum deformation in soft soil environment

Fig.4 shows the maximum deformation of the fuselage structure when the fuselage section hits soft soil at an initial velocity of 7 m/s. It can be seen that compared with the rigid ground, the deformation of the cargo hold structure is significantly reduced. The cargo hold structure tilts with the fracture of the fuselage frame, but does not hit the cabin floor beam. Meanwhile, the fuselage frame is broken and forms plastic hinge, and the frame participates in energy absorption more than in the rigid ground environment, as shown in Table 3. The deformation of the soft soil is shown in Fig.5. The deformation of the soil increases the contact area between the ground and the fuselage components, thus increasing the

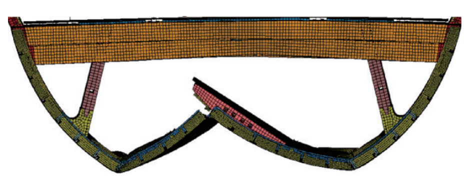

Fig.4 Maximum deformation diagram of cargo hold area impacted on soft soil

Table 3 Energy absorption proportion of main components %

Crash environment	Fuselage frame	Shear corner	Fuselage skin	Fastener
Rigid	22.22	15.13	10.52	19.76
Soft soil	24.38	6.78	12.28	24.30
Water	15.90	11.46	21.11	27.38

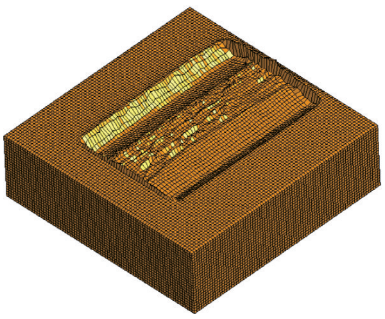

Fig.5 Maximum deformation diagram of soft soil

range of impact force transmission. The soft soil itself absorbs part of the impact energy and has a certain cushioning effect on the deformation of the fuselage structure.

2.3 Maximum deformation in water environment

Compared with soft soil, the fuselage skin has a larger contact surface with water during a crash in the water environment, so the distribution of the contact force on the impact surface is also more dispersed. It can be seen from Fig.6 that after the fuselage collides with the water, the contact surface involves the entire cargo area, which does not occur in the first two cases. As the collision progresses, the skin of the fuselage deforms and transmits a certain impact force to the energy absorbing structure, such as the fuselage frame. Because the impact force distribution is relatively scattered, no major deformation occurs in the cargo area, and the bottom structure remains relatively intact. The strength of the fuselage structure is enough to withstand the impact of falling into the water, but the large deformation of the water area shown in Fig.7 shows that the continuous sinking of the fuselage structure is the main issue that needs to be considered when the aircraft falls into the water.

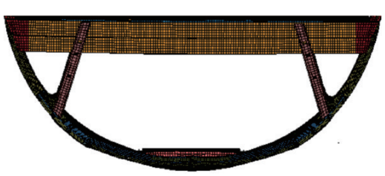

Fig.6 Maximum deformation diagram of cargo hold area impacted on water

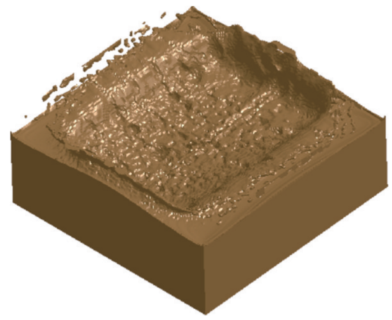

Fig.7 Maximum deformation diagram of water

3 Impact of Crash Environment on Crashworthiness

3.1 Research on impact of structure response by crash environment

The deformation of the fuselage section reflects the overall safety performance of the aircraft during a crash. In addition, since the safety of passengers is the main consideration for crashworthiness, it is essential to study the dynamic response of the cabin area. The response curve of the cabin area can reflect the dynamic changes of the passengers' survival environment over time, and further help analyze the safety of the passengers during the collision.

Fig.8 shows the vertical velocity curves of cabin seats in different crash environments. It can be seen that the 20 ms speed change of crash under different environments is basically similar, after that there is a certain difference. As the impact environment becomes softer, the vertical velocity decreases faster. Therefore, the soft impact environment has a certain cushioning effect on the crash process of the fuselage section. But after 100 ms, only in the rigid ground environment can the vertical velocity reach zero, and the crash time of the structure in the other two environments will be greatly extended.

Fig.9 shows the vertical acceleration curves of cabin seats in different crash environments. It can be seen that the first peak acceleration formed by the fu-

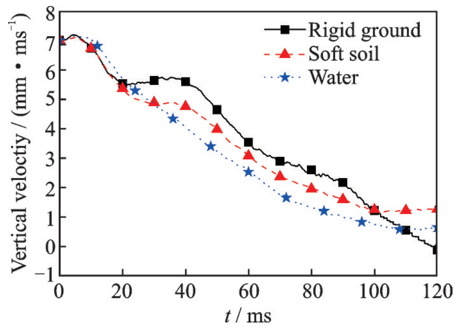

Fig.8 Vertical speed curves of passenger seat

selage crashing the ground is less affected by the environment. The time to reach the peak acceleration in soft soil and water environment is slightly delayed, and the peak acceleration is slightly increased. After the acceleration reaches the peak value, the acceleration curves in each environment are different. The softer the environment, the slower the peak acceleration will drop and the curve will be smoother. The soft impact environment creates a larger impact surface, weakens the force transmission efficiency of the fuselage structure, makes the impact of the collision on the cabin occupants more concentrated in the first 80 ms, and the subsequent acceleration is at a very low level.

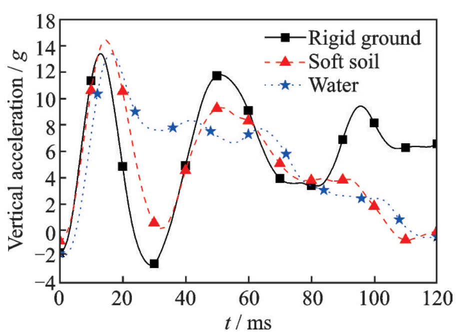

Fig.9 Vertical acceleration curves of passenger seat

3.2 Impact of energy absorption and distribution by crash environment

As an important basis for evaluating the effect of energy absorbing elements in the lower structure of the fuselage and the rationality of energy distribution, the energy absorption ratio of each structural component is an important part of the crashworthiness analysis. Whether the main energy-absorbing components can play a protective role directly affects the safety performance of the aircraft in a crash.

Table 3 shows the proportion of energy absorbed by the main energy-absorbing elements of the fuselage in three crash environments. These four structures account for about 70% of the energy absorbed during the entire crash process and bear most of the impact. It can be seen from Table 3 that as the crash environment becomes softer, the proportion of energy absorbed by the fuselage frame and the shear corners has decreased. Part of the reason is that the increase in the impact surface leads to an increase of the proportion of energy absorbed by the fuselage skin. Part of the reason is that the overall structure is less deformed due to the buffering of the soft collision environment. The energy absorption effect of the two structures is mainly due to deformation and energy absorption. Due to the increase of the impact surface, the energy absorption of the fuselage skin is significantly increased. In the water environment, the large-area contact and the transmission of uniform force make the energy absorption of the fuselage skin more than 20%. Fasteners, as connectors widely used in the fuselage, mainly absorb energy in the form of fracture failure. As the impact surface grows, the fuselage frame and the shear angle absorb less energy, and the proportion of fasteners' energy absorption also increases accordingly.

4 Conclusions

Based on the display nonlinear dynamics analysis software LS-DYNA, the simulation analysis of the crash process of the fuselage section in three crash environments is carried out, and the crashworthiness of the aircraft in different collision environments is studied. The conclusions are as follows:

As a soft ground environment, the soft soil and water play a cushioning role in the entire crash process, but the crash time increases significantly.

The time of the first peak acceleration in soft soil and water environment is slightly delayed, and the response will be more stronger. The curve changes smoothly after that, and the subsequent impact on the occupants will be small.

With the decrease in the hardness of the impact surface, the deformation of the fuselage structure will be smaller, the energy absorption effect of the fuselage frame and the shear angle will be worse, and the fuselage skin and fasteners will bear more energy absorption pressure. If the aircraft is forced to land with a greater crash speed in the soil and water environment, the impact resistance of the fuselage skin will be a huge test.

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Author contributions Mr. **TANG Huan** was responsible

for the establishment, simulation and calculation of the finite element model. Dr. **ZHU Shuhua** guided and corrected finite element modeling, calculation and analysis methods. Mr. **LIU Xiaochuan** was responsible for the establishment and planning of the whole project. Mr. **XI Xulong** participated in the research and provided technical guidance. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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坠撞环境对机身结构适坠性的影响

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摘要:为研究民用飞机机身段在不同碰撞环境下的适坠性,建立了软土和水两种环境模型,分析了机身段在7 m/s 垂直冲击速度作用下的动力学响应。仿真结果表明,较软的碰撞环境对结构的碰撞过程具有一定的缓冲作用,但会延长碰撞时间,改变结构的能量吸收方式。

关键词:耐撞性;动力学响应;机身段;软土;水