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Crashworthiness Study of a Civil Aircraft Fuselage Section

Abstract

This paper studies the crashworthiness characteristics of a fuselage section and its improvement. A full-scale three-dimensional finite element model of the fuselage section is developed using a nonlinear finite element code, PAM-CRASH. The simulation is implemented to determine the structural deformation and impact response in terms of peak loads and acceleration peaks at the floor-level, deformation mode, energy absorption, and structural integrity, and then to assess the crashworthiness of the fuselage section. By partitioning the total energy dissipated, it is shown that the frames and the supports of the cargo floor play important roles in the process of energy dissipation. Based on the results, an effective approach to improve the crashworthiness of the fuselage section is presented. The paper also provides an in-depth analysis in the deformation mechanism of the fuselage section under a vertical crash, which will be helpful to effectively prevent the cabin floor from heavily damage and maintain the integrity of the fuselage section.

Keywords

Crashworthiness, fuselage section, energy absorption, acceleration peak, deformation mode

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1 INTRODUCTION

Crashworthiness is the ability of an aircraft structure and its internal systems to protect occupants from injury in an event of crash. It has been regarded as important as strength and fatigue in designing aircraft structure, especially for a civil aircraft.

Although most concepts of crash survivability were established over 50 years ago, implementation of these concepts into operational aircraft has been remarkably slow. In fact, fully integrated crashworthy designs had been limited to a few agricultural aircrafts until the U.S. Army committed itself to improving the crash survivability of its helicopters during the conflict in Southeast Asia. Many of the former studies focused on the optimal design of energy-absorbing components (Jones, 2010; Ramakrishna, 1998; Taher, 2006; Xua 2009; Xue 2009), while crashworthiness study for whole aircraft structure is limited. Considering the complexity of the aircraft structure and its experiment cost, numerical simulation has become an effective tool in studying the crashworthiness of aircraft structures. Using numerical methods, it is possible to understand the mechanism of the energy dissipation in a crash process, and to approach an optimized design. Jackson and Fasanella(Jackson, 2001; Fasanella, 2008) studied crashworthiness of a small aircraft using finite element code MSC. DYTRAN, and compared with test results of a 1/5 scale model, showing that either filling the composite round-tube under floor or using foam composite beam could effectively reduce peak impact load. Bisagni (2002) studied the energy absorption capability of a subfloor helicopter structure by crash tests, and then analyzed the structure's crashworthiness by commercialized finite element software PAM-CRASH, showing a good agreement between the experimental results and the predictions. Yang et al (2002a and 2002b) studied the energy absorption of a kneeling landing gear when helicopter crashed on the ground. Adams and Lankarani (2003) conducted an experimental study of Boeing 737 fuselage section, and demonstrated the integrity of fuel tanks under the cabin floor after a given crash condition. Then, using LS-DYNA finite element software they analyzed the crashworthiness of the fuselage section, and achieved acceptable accuracy by numerical approach. Adams and Thorbole (2012) compared the experiments of a small scale model with simulation results by LS-DYNA to evaluate the scaling method. Using genetic algorithm optimization, Zheng and Xiang (2010) investigated the crashworthiness of a typical civil aircraft fuselage structure and studied the effects of the struts, cargo floor and foam filled components. Xue and Wang (2011) investigated the performance of the struts which support the floor in a typical fuselage section and compared the energy absorption characteristics of two typical struts. The performance of the aircraft fuselage with struts of different cross sections and orientation angles were compared using PAM-CRASH software.

Although the studies on crashworthiness of the light planes or helicopters provide valuable reference, but the civil aircraft's fuselage has its own structural features. Below the cabin floor there is a relatively large space that can be designed for impact energy dissipation. The frame may contribute to a large proportion of total energy absorption. By investigating the performance of the fuselage section during an impact, and optimizing the aircraft frame, it is achievable to control its deformation mode and dissipate the impact energy, so as to reduce the peak acceleration, whilst to maintain the structural integrity..

2 GENERAL PRINCIPLES OF CRASHWORTHY STRUCTURE DESIGN

Cabin structure provides a protective shell for occupants. Once it collapses, it may result in collision among occupants, and hard protruding object may obstruct passages from escape. Moreover, large deformation of cabin structure in turn can lead to the distortion of the passenger floor and preventing the energy absorbing seats from effective operation.

Human body has a tolerance limit to high acceleration. The indexes widely used include GSI (Gadd Severity Index) and HIC (Head Injury Criterion). According to the requirements of FAA(Anon, 1997), the structure must be designed to give each occupant every reasonable chance of escaping serious injury in a minor crash landing when the occupant experiences inertia forces of 6.0g on downward. In order to protect the occupants from injury, therefore, the structure should be able to convert most of the input kinetic energy into inelastic energy by plastic deformation or other dissipation mechanisms. Meanwhile the peak reaction force should be kept below a threshold value during large deformation process of the structure, and also the displacement should be sufficiently long (Lu, 2003). Andthis concept is also accepted by U.S. Air Force (Desjardins, 1989).

Under these considerations, the crashworthiness of a civil aircraft's fuselage section is investigated in this study. Characteristics of overall and local deformation, impact energy absorption and the peak acceleration during a crash are studied, and the role of each component in an energy dissipating process is identified. Effect of geometric parameters is also evaluated. Based on this understanding, an approach to improve the crashworthiness of the fuselage section is presented.

3 FINITE ELEMENT MODEL

A finite element model is established as shown in Fig. 1. The finite element model contains frames, skin, stringers, cabin floor, struts, cargo floor and its supports. The mass of the seats and passengers are presented by two solid blocks. All metallic components are made of 2024 or 7075 aluminum. Because of the insensitivity to strain rate of the two materials, strain rate effects are ignored. An isotropic bi-linear elastic-plastic material model with yielding and ultimate failure strain is adopted, and the material constants, including density ρ, elastic modulus E, Poisson ratio μ, yield stress σy, hardening modulus Es and max plastic stain $\varepsilon_{p,max}$ are shown in Table 1.

Table 1Materials parameters.

Material	ρ (g/mm3)	E (Gpa)	μ	σy (MPa)	Es (GPa)	εp,max
2024	2.67	72.3	0.33	475	6.8	0.12
7075	2.8	72	0.33	406	7.2	0.08

Self-contact between the components of the fuselage sections, and a pair of master-slave surface contacts between the ground and the fuselage section are defined. The finite element model is approximately discretized as 150,000 nodes and 136,000 elements, including 2,000 solid and 134,000 shell elements. Taking the reference of the drop tests by NASA[18], the fuselage section crashes vertically to the ground at a velocity of 9 m/s. The ground is modeled by a rigid board which is totally fixed.

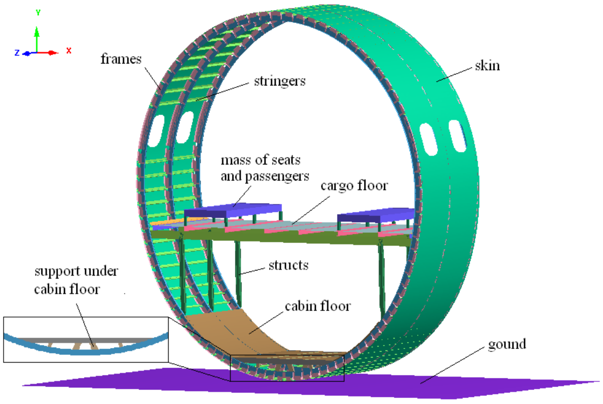


Figure 1 Geometry and numerical model of a fuselage section.

4 RESULTS

4.1 Acceleration and deformation mode

Figure 2 shows the acceleration history at the position of the passenger's seats during the impact process.

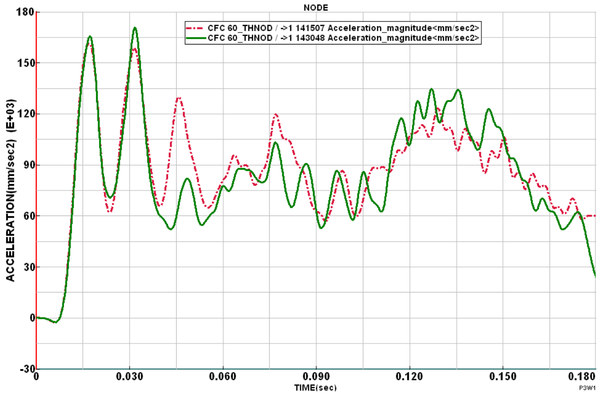


Figure 2 Acceleration history of two center nodes of seats.（filtered by CFC 60 filter)

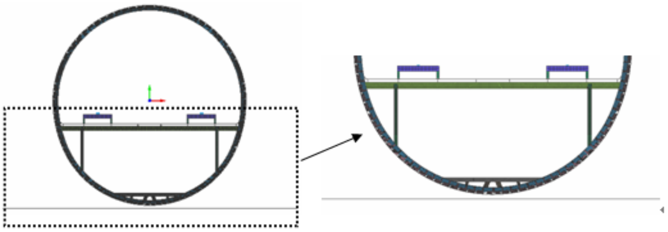
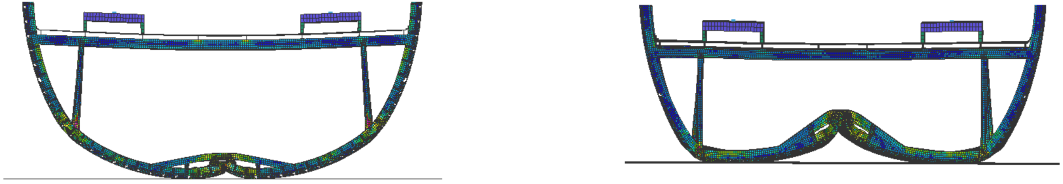


Figure 3 Fuselage section and enlarged part under cabin floor.

Considering large deformation mainly occurs below the cabin floor, the lower part of fuselage section as shown in Fig. 3 is enlarged to see the deformation clearly. Fig. 4 shows the deformed structure at different time instants. From Fig. 2, it is shown that the acceleration increases rapidly after impact. Initial acceleration peak of about 16.5g appears at 17.1ms, correspondingly the stress concentration at the junction of strut and frame is found, as shown in Fig. 4(a). At the time instant of 31.5ms, the acceleration reaches a maximum, 17g, as shown in Fig. 4(b). After 40ms, the magnitude of the acceleration remains at a low level, around 9g, whilst the structure keeps deforming, as shown in Fig. 4(c). Afterwards, at about 111ms, the segment on the frame close to the struts hits the ground and the acceleration increases again, as shown in Fig. 4(d).

(a) 17.1ms (b) 31.5ms



(c) 40ms (d) 111ms

Figure 4 Deformed structure at different time instants.

4.2 Energy absorption

When analyzing the crashworthiness of fuselage section, the partitioning of the total energy absorption is very important to identify the contribution of each component. Fig. 5 shows the energy absorbing process by each component. Frames keep on absorbing the kinetic energy effectively till about 130ms when the struts get in contact with the ground and limit the frames' further deformation. This is the reason that a second high peak of acceleration is observed. The contribution of other components to the energy absorption mainly occurs in the early stage of impact.

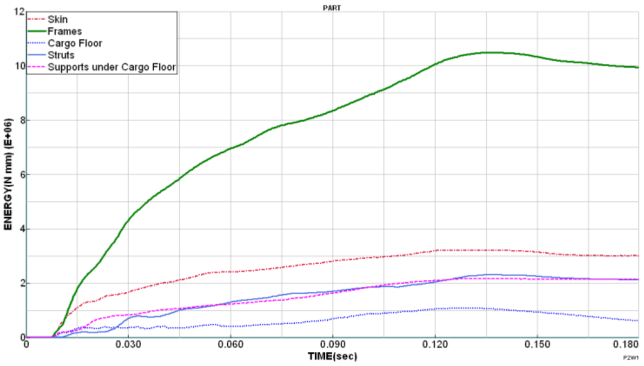


Figure 5 Energy vs. time curve of each component.

In order to identify the final contribution of each component, the partitioning of the total energy absorbed is given in Table 2. It can be seen that the frame absorbs about 59.1% of the total impact kinetic energy. The skin and stringers absorb 3.6kJ energy, being 13.59%. The deformation of the cabin floor is small and it only absorbs 2.31% of total energy. The strut absorbs only 7.96% of total energy. It should be noted that the deformation of the cargo floor is obvious and it absorbs 16.33% of the total energy, being the second after the frame. The energy absorbed by the frame is much larger than the other parts, followed by cargo floor part, skin and stringer. Therefore, crashworthiness of the fuselage can be improved by optimizing the design of the frame and the cargo floor part.

Table 2 Partitioning of the energy absorption.

Part	Internal energy (kJ)	Percentage (%)
Frames	15.667	59.08
Skin and Stringers	3.607	13.59
Cabin floor	0.614	2.31
Struts	2.112	7.96
Cargo floor and its supports	4.332	16.33

5 DISCUSSIONS

5.1 Acceleration of the fuselage section under different crashing velocities

To compare the responses such as acceleration, deformation mode to crash under different condition, three different velocities are selected, i.e. 6m/s, 9m/s, and 12m/s. The acceleration responses for the three velocities are plotted in Fig. 6. It can be seen that when the crashing velocity is 6m/s, the first acceleration peak is dominant; with the increase of the crashing velocity, the second acceleration peak becomes larger.

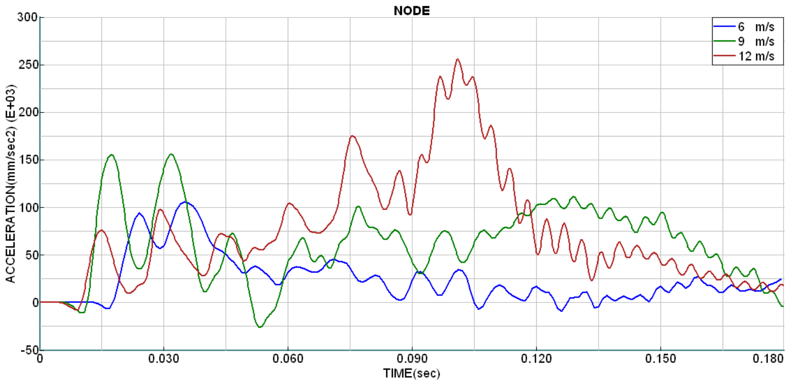


Figure 6 Acceleration history at seats of the fuselage section under different crashing velocities.

At the beginning of impact, the bottom of fuselage section crashes on the ground producing the first acceleration peak. Afterwards, the acceleration gradually decreases with the dissipation of the impact kinetic energy. The initial acceleration peak is much larger for impact velocity of 9m/s as compared to that for 6m/s, the second acceleration peak which appears within the time period from 120ms to 150ms is slightly less than the initial acceleration peak but lasts for a longer duration. It should attract attention because the acceleration peak and the duration both are important for human body's tolerance limit. If impact velocity is 12 m/s, the initial acceleration peak is lower but the second acceleration peak is much higher. This is because the plastic deformation happens earlier under high impact load resulting in a smaller initial acceleration peak, while when the struts hit the ground a higher second acceleration peak occurs with different deformation mode of the entire structure.

In general the initial acceleration peak which may contain several sub-peaks appears when the fuselage section crashes on the ground. Its magnitude could be reduced by filling foam under the cargo floor or weakening the support under the cargo floor. The second acceleration peak occurs when the struts hit the ground. With the increase of the impact velocity, the second acceleration peak increases significantly. Its magnitude can be reduced by weakening the struts, or by appropriate design of the stiffness distribution along the frame, so as to enhance the aircraft crashworthiness.

5.2 Deformation mode of the fuselage section under different impact velocities

In order to clearly demonstrate the different deformation modes of fuselage section under different impact velocities, the plastic strain distribution is depicted along the arc length of the frame as shown in Fig. 7, where 0° represents the horizontal direction, 90° the vertical direction. The frame connects to the cabin floor at about 16°, to the strut at about 44° and to the cargo floor at about 68°, respectively. The largest plastic deformation appears near the junction of the frame and the struts. Plastic deformation that appears near the junction of the frame and the cabin floor or the cargo floor is also large. Stiffness of the structure along the frame is not continuous at these connections, so the stress concentration takes place.

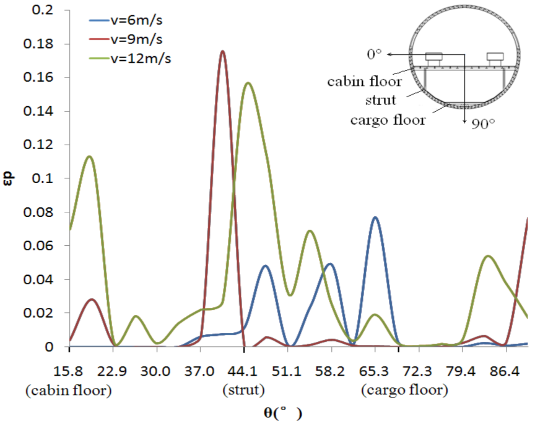


Figure 7 Plastic strain distributions in arc coordinate of fuselage section under different impact velocities.

If the lower part of fuselage section is divided into four partitions I to IV, as shown in Fig. 8, the closed partitions I, II, and III, geometrically similar to a triangle shape, are consists of floor, frames and struts, having large overall stiffness and stability. As compared to partitions I to III, partition IV is easy to deform, especially within the arc segments between two close partitions. Therefore, the large plastic deformation mainly occurs in this area.

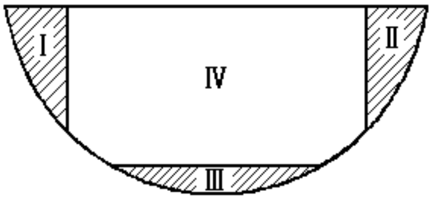
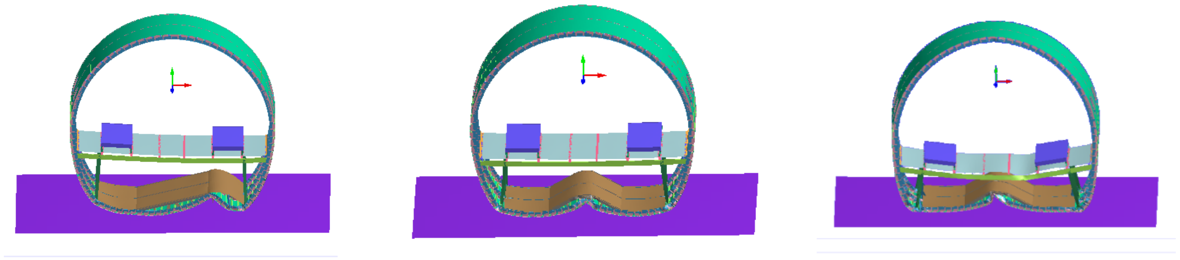


Figure 8 Partition of fuselage section under the cabin floor.



(a) V=6 m/s (b) V=9 m/s (c) V=12 m/s

Figure 9 Final deformation configurations under different impact velocities.

It can be seen from Fig. 7 and Fig. 9 that the distribution of the plastic deformation and the deformation modes of the frame are different under different impact velocities. When the impact velocity is 6m/s and impact load is relatively small, the closed partition III is undestroyed, resulting in the asymmetric deformation mode. When the impact velocity increases to 9m/s and impact load becomes larger, the closed partition III is destroyed, whilst three plastic hinges occur at the bottom of the frame and the region near struts. The deformed structure is symmetric with the bottom turning upwards. As the impact velocity increases to 12m/s, the deformation mode is similar but the cabin floor and beam structure both deform significantly.

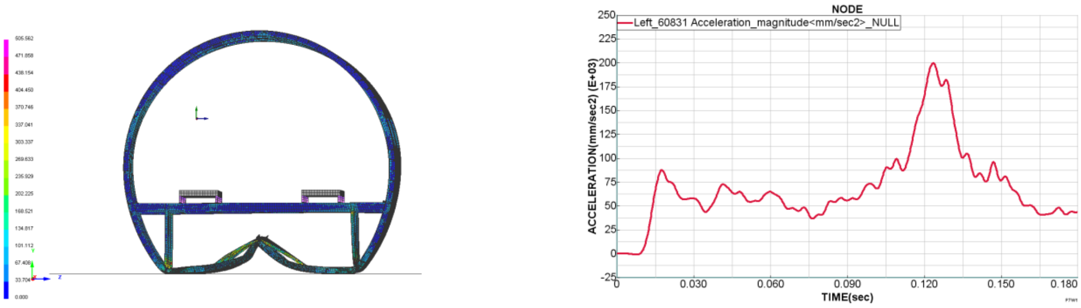
To meet the crashworthiness requirement, the fuselage section, especially the upper part of cabin floor, should keep its structural integrity, while limiting the peak acceleration on the passenger seat position. From above analysis, it is obvious that the closed triangular partitions I and II play a very important role in providing sufficient space and maintaining upper structural integrity during an impact event.

5.3 Influence of the support under cargo floor on the crashworthiness of fuselage section

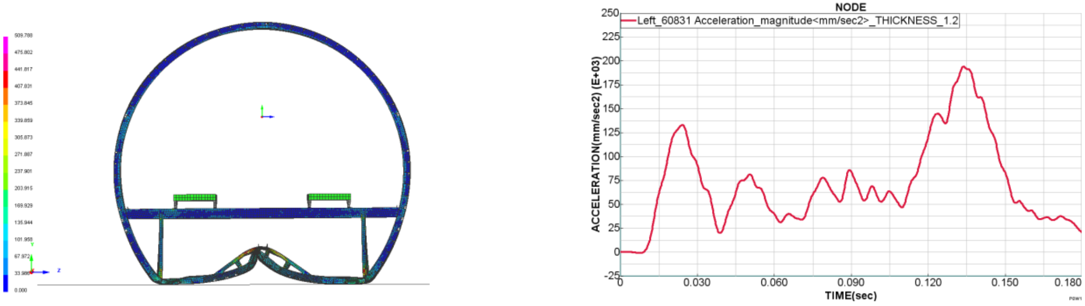
From the above analysis, it is clear that the stiffness of the support under cargo floor has a great effect on the initial acceleration peak and the deformation mode of the whole frame, though the cargo floor support, itself is not a main energy absorbing component. Therefore, the influence of the support under cargo floor on the structural response is also investigated. The following cases will be compared with the original case which the thickness of the support is 1.6mm, i.e. with and without support under cargo floor; and the thickness of the support under cargo floor is varied as 1.2mm, and 2.0mm, respectively.

The simulated acceleration variation and the deformation of fuselage section under impact velocity of 9m/s are plotted in Fig. 10. Absence of the support under cargo floor leads to large bending deformation of cargo floor. Three plastic hinges occur on frame, and two of them at the junctions of struts, as shown in Fig. 10(a). The initial acceleration peak is only 8.3g, but the second acceleration peak is as high as 17.4g. When the thickness of strut increases to 1.2 mm, three plastic hinges appear at the bottom and the junctions, too, as shown in Fig. 10(b). With the further increase in the thickness of the support under cargo floor to 1.6mm, the initial acceleration peak increases while the second acceleration peak decreases, as shown in Fig. 10(c).

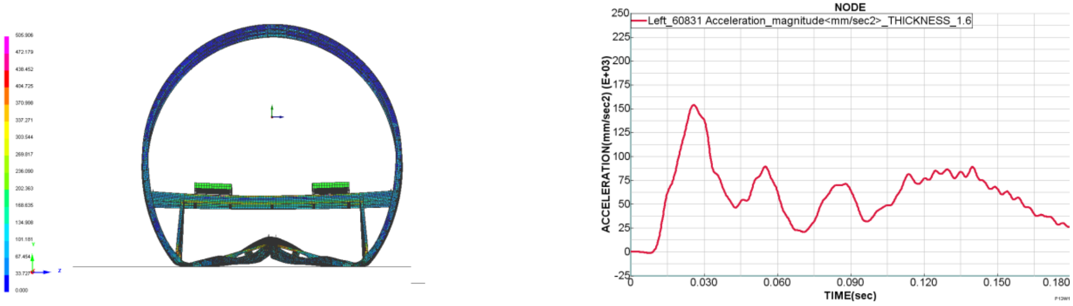
If the thickness is taken as 2.0mm, a serious asymmetry deformation of the fuselage section appears, as shown in Fig. 10(d), because of the high stiffness of the supports. There is no obvious plastic hinge appearing at the bottom of the frame, and the entire cargo floor remains almost undeformed. Plastic hinges, asymmetrically, are located outside the cargo floor. Two obvious acceleration peaks can be seen; the initial acceleration peak reaches 16g and the second acceleration peak is as high as 18g-20g.



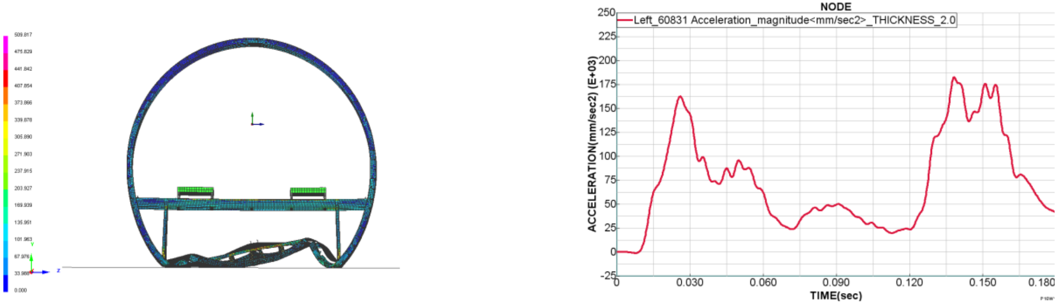
(a) Without support under cargo floor



(b) Thickness of support being 1.2 mm



(c) Thickness of support being 1.6mm



(d) Thickness of support being 2.0 mm

Figure 10 Structural deformation and acceleration history with different thickness of the support under cabin floor.

The acceleration peaks with varied thickness of support under cargo floor are shown in Fig. 11 where the zero thickness represents the case without the support. It is obvious that when the support under cargo floor is weaker, a symmetric deformation of the structure appears. The initial acceleration peak is low and the second acceleration peak is relatively higher. When the support under cargo floor is more rigid and stronger, asymmetric deformation of the structure appears. In this case, the initial acceleration peak is higher, whilst the second acceleration peak is relatively low, as shown in Fig. 11. However, if the support is too rigid (e.g. the thickness being 2.0mm), an asymmetric deformation of the structure appears, but both the initial and the second acceleration peaks are high. Therefore, the thickness of support under cargo floor can limit the magnitude of the initial and second acceleration peaks. When the thickness of support under cargo floor is 1.2mm, the maximum acceleration peaks are the lowest. And the duration time of acceleration peaks with varying thickness of support under cargo floor are shown in Fig. 12. When the thickness of support under cargo floor is 1.2mm, the peak duration time is the longest. It also indicates that the energy is absorbed effectively in this case. It can significantly improve the crashworthiness of the fuselage section.

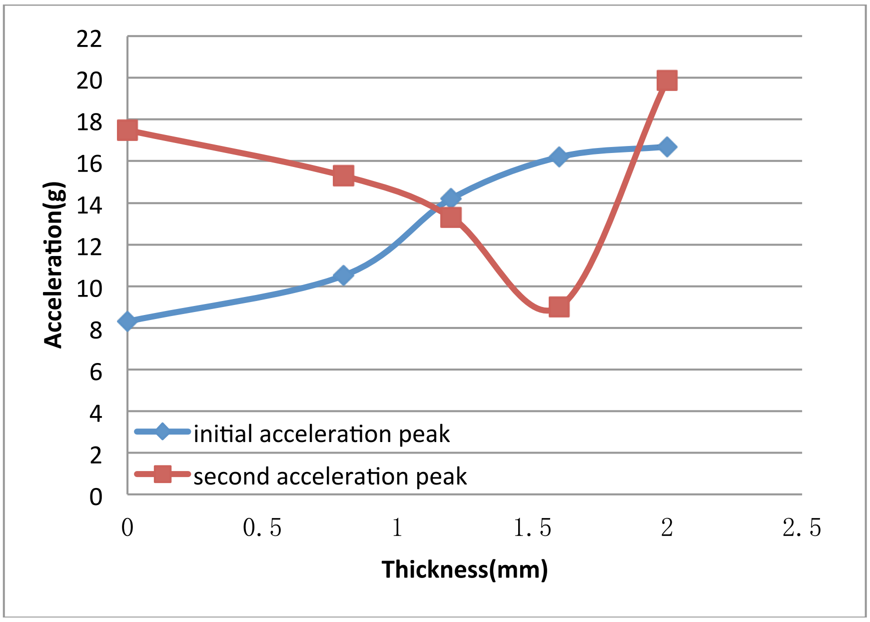


Figure 11 Acceleration peaks with varying thickness of support under cargo floor.

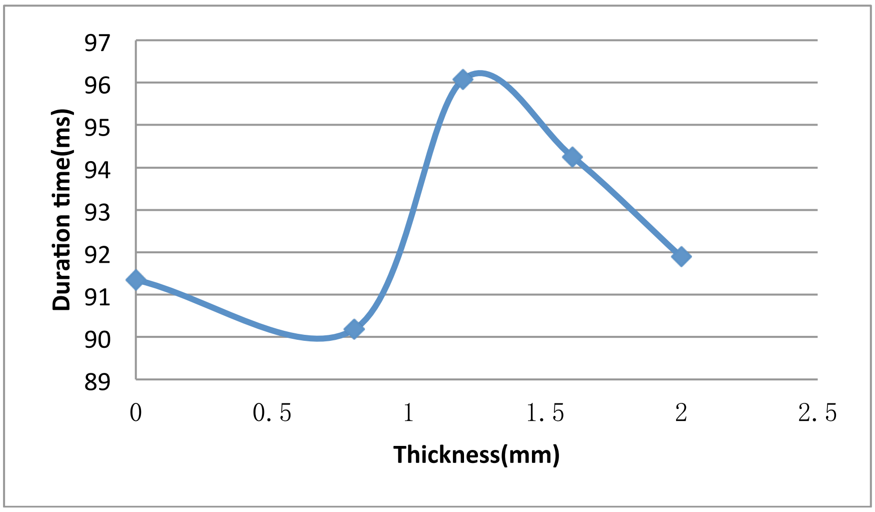


Figure 12 Duration time of acceleration peaks with varying thickness of support under cargo floor.

6 CONCLUSIONS

In this study, the crashworthiness of a typical fuselage section is characterized numerically in terms of peak loads, acceleration peaks, deformation mode and mechanisms, energy absorption, and structural integrity. The roles of each component in an energy dissipation process are identified, and improvement in the fuselage section for crashworthiness is proposed. The conclusions drawn from this study are as follows.

Frames of the fuselage section absorb the most of the total impact kinetic energy by large plastic deformation occurring under the cabin floor; the cargo floor is the next among all components.

The closed triangular partitions can effectively prevent the cabin floor from heavy damage and play a very important role in maintaining the integrity of the upper structure of the fuselage and provide a survival space for passengers.

The initial acceleration peak appears when the fuselage section crashes on the ground. While the second acceleration peak appears when the strut hits the ground. When the impact velocity is low, asymmetric deformation appears after crash. With the increase of the impact velocity, symmetrical deformation mode appears, however, the second acceleration peak becomes larger, threatening the survival of passengers.

The local stiffness and strength of the supports under cargo floor has significant influence on both the initial and second acceleration peaks. With the increase of the thickness of the support, the initial acceleration peak increases, but the second acceleration peak does not vary monotonously. A critical thickness of support under cargo floor can restrict the magnitude of both the acceleration peaks, and prolong the peak duration time so as to greatly increase the probability of survival of the passenger.

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