Energy absorption structures design of civil aircraft to improve crashworthiness

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ABSTRACT

To improve the crashworthiness of civil aircraft, the design concept of energy absorption structure for civil aircraft is investigated. Two typical different design principles could be identified. The first category includes Helicopter and Light fixed-wing Aircraft (HLA), and Transport, Mid-size and Commuter type Aircraft (TMCA) are classified into the second group. Frame, strut and bottom structure are the three kinds of energy absorption structure for TMCA. The strut layout of conventional civil aircraft is studied and some energy absorption devices are adopted. High efficiency energy absorption structures such as the foam and sine-wave beam are employed as the bottom structure for both of HLA and LMCA. The finite element method is used to analyse and design energy absorption structure in aircraft crashworthiness problem. Results show that the crashworthiness of civil aircraft could be largely improved by using proper strut layout and excellent energy absorption device. The stiffness combination of frame and strut should be considered to get better global aircraft deformation. Supporting platform and failure model are the two core problems of bottom energy absorption structure design. Foam and sine-wave beam under the lifted frame could improve the crashworthiness of civil aircraft.

Paper No. 3933. Manuscript received 11 December 2012, revised version received 21 January 2014, accepted 6 February 2014.

1.0 INTRODUCTION – THE BACKGROUND OF ENERGY ABSORPTION STRUCTURE IN CIVIL AIRCRAFT CRASHWORTHINESS PROBLEM

Accidents occurring during takeoff and landing account for more than 50% although the two stages just have about 2% flight duration(1), and most accidents of the two situations are survivable. The design concept of aircraft in crash accidents could be traced back to the beginning of powered flight. The crash accident probability is not zero in spite of that there is a great development in aerospace technology, thus the absolute number of aircraft accidents is still large for the increasing flights. Consequently, the safety of occupant has drawn more and more attention. To guarantee the safety of occupant during impact accidents, Federal Aviation Administration of US (FAA), Joint Aviation Authorities of Europe (JAA) and Civil Aviation Administration of China (CAAC) have specific crashworthiness requirement in airworthiness regulations. For example, the crashworthiness requirement for civil transport given by FAA has more than 40 provisions in the part 25 of Federal Aviation Regulations (FAR). According to the design requirements, aircraft structure should provide protection for every passenger during emergency landing(2).

To satisfy the crashworthiness requirement, many countries and territories including US, EU and China have conducted extensively crashworthiness researches. From 1960s, National Aeronautics and Space Administration (NASA), National Transportation Safety Board (NTSB) and FAA in US conducted many joint impact research programs(3). Crash tests and protection system qualification tests were carried out by Impact Dynamics Research Facility (IDRF) of NASA Langley Research Center under the General Aviation (GA) crash program, Advanced General Aviation Transport Experiment (AGATE) and Controlled Impact Demonstration (CID) research program. The crashworthiness performance of several kinds of aircraft, such as B737, B707 and F-111, were investigated. From last century, EU also began their research plan under the support of several Framework Programs(4). Different from American programs, EU stressed on the composite aircraft structure. To develop aerospace industry, Chinese universities and institutes including Beihang University also initiated some crashworthiness research programs from 21st century.

Aircraft crashworthiness design is a very complex problem involving different fuselage structures and various impact conditions, etc. There are many hazard factors among which impact force suffered by the passengers and sufficient living space are two of the most important factors(5). To guarantee the safety of occupant, civil aircraft should be designed to dissipate impact kinetic energy, thus energy absorption structure is one of the most important design factors. To achieve the design goal, landing gear, fuselage and occupant seat system are the three key research aspects(6-7). Researchers put most efforts on the design of fuselage structure because energy absorption ability of landing gear and occupant seat system is limited for their size and structure. To effectively dissipate impact kinetic energy, many high-efficiency energy absorption structures, such as foam, sine-wave beam, had been used in fuselage structures within the crashworthiness program of US and EU(8-9). Their conclusions benefit the development of the energy absorption structure design of aircraft. However, energy absorption structure design is still a difficult work because different fuselage structures have different design methods, and the impact condition would influence the efficiency of energy absorption structure to some extent.

Till now, few researches are conducted on the design concept of energy absorption structure for different civil aircrafts. Consequently, the objective of this paper is to investigate the crashworthiness improvement method based on the different design methods of energy absorption structures. Firstly, the different design methods of energy absorption structure for different type of aircrafts are compared. Secondly, conventional design methods of different high-efficiency energy absorption structure including strut, bottom structure are given for HLA and TMCA. Finally, to enhance the energy absorption ability, some innovative structure concepts are proposed. The results of this research give guidance to the energy absorption structures design of civil aircraft.

2.0 THE FUNDAMENTALS OF CRASHWORTHINESS PROBLEM

Aircraft collided with the ground with a certain velocity in the impact event. The collision time is very short, and the gravitational acceleration is the necessary condition during the analysis while the aerodynamic force could be neglected. Impact problem is very complicated involving large deformation, nonlinear materials and contact problems, but the process must satisfy the fundamental dynamic equations. The basic dynamic equation is shown as Equation (1), σ_{ij}, ρ, f, $\ddot{x}_i$, $\dot{x}_i$, and are the Cauchy stress, density, body force, acceleration and velocity, respectively. Besides, the impact process should satisfy boundary, force and contact conditions.

$$\sigma_{ij,j} + \rho f_i = \rho \ddot{x}_i + \mu \dot{x}_i \qquad \ldots (1)$$

Impact process also meets with the basic energy balance equation shown in Equation (2). Kinetic energy (E_k) in the initial stage and work of the gravity force (E_g) during impact equal to the work of impact force (E_F) and total loss energy (E_{TL}). Total loss energy includes vibrational energy the energy dissipated by friction, etc.

$$E_k + E_g = \frac{1}{2} m v^2 + mgh = \int F \, \mathrm{d} s + E_{TL} \qquad \ldots (2)$$

where m, v, g, h, F, and s are the mass, impact velocity, gravitational acceleration, height, impact force and displacement, respectively. It is noted that fuselages nearly dissipate the same impact kinetic energy during the impact process although they have different design method. But the improved fuselage demonstrates better behaviour in alleviating the impact load. The internal energy absorbed by aircraft fuselage is integrated by the following equation. Theoretically, crushing distance has negative effect on the mean impact load because the impact kinetic energy nearly keeps constant for different design concept shown in the Equation (3).

$$E = \int_0^d F \, \mathrm{d} s = F_{mean} d \qquad \ldots (3)$$

Limit the impact forces transmitted to the occupant is one of the primary crashworthiness design objective. Typical and ideal force-displacement curves are demonstrated in Fig. 1 which is given by Ren[10]. Actual curve have several peak accelerations for the failure of structure during impact process, and ideal impact load curves are shown by a dashed line. Consequently, controlling the initial peak acceleration and reducing the duration of high load area are the two most important design goals for acceleration curve. In addition, necessary passenger living space would be guaranteed by controlling the failure behaviour of aircraft. In conclusion, energy absorption structure of civil aircraft should have high structural efficiency and stable impact load.

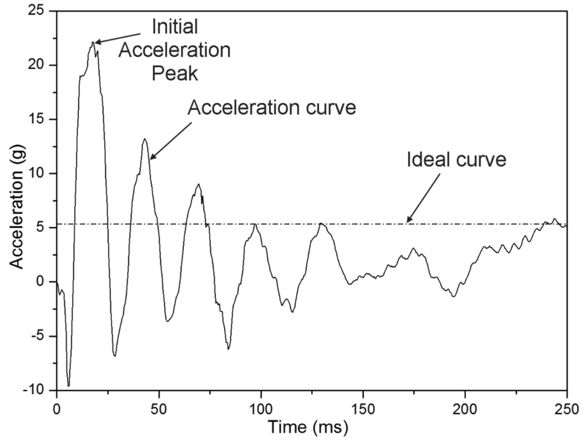

Figure 1. Force vs displacement curves.

3.0 DIFFERENT AIRCRAFT DESIGN CONCEPT AND ITS ENERGY ABSORPTION STRUCTURE DESIGN: HLA AND TMCA

Energy absorption structure design concept depends on the impact conditions, such as impact velocity and ground conditions. The survivable impact velocity is between 6ms^{-1} and 12ms^{-1}, thus impact velocity of B737, ATR42-300, A320 and YS-11aircraft during crash test are 9·14ms^{-1}, 9·14ms^{-1}, 7ms^{-1} and 6·1ms^{-1}, respectively. Vertical drop test under flat rigid floor ground condition is the most common situation, but the water and soft soil are also the common accidents[11-13]. For example, an Airbus A320-214 ditched in the Hudson River for the lost of power on 15 January 2009, and everybody is survival. Different design concepts are demonstrated between different impact conditions, and fuselage skin plays more important roles under water impact. Figure 2 indicates the impact loads under rigid floor and water conditions. Rigid floor would keep intact after impact, while the water and soft soil deform during the impact process. As a result, the concentrated load would be on the fuselage frames for rigid floor condition, and distributed load is demonstrated under water impact. However, frame structure is always the key component suffering impact load, and fuselage skin play a more important role during water impact for water pressure. A tensor skin panel is developed by Michielsen to sustain water impact as shown in Fig. 3, and it is enhanced by the sine-wave structure[14]. In any event, the energy absorption structure is the key content. Collision with rigid floor is the most dangerous and common situation, thus the design concept of aircraft in this paper is based on the rigid floor event without considering water impact. Two most important design factors for energy absorption structure are to reduce the initial peak acceleration and maintain the impact load around the mean value. Aircraft designer should consider both acceleration and living space for occupant restriction to give the best crashworthiness performance. Two typical aircraft categories including HLA and TMCA could be indentified according to their structure type and layout.

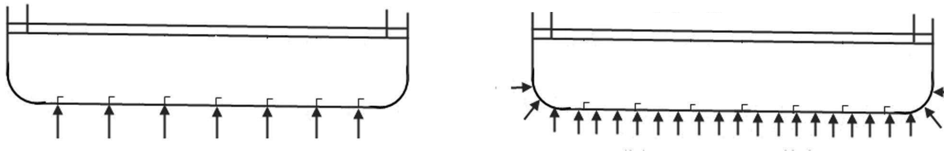

Figure 2. Impact load under rigid floor and water condition.

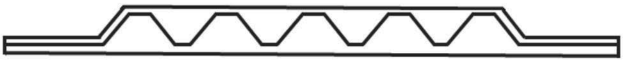

Figure 3. Improved fuselage skin structures.

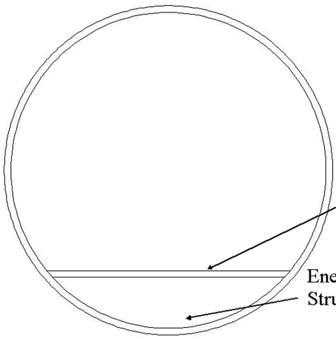

Figure 4. Crashworthiness design concept of small aircraft.

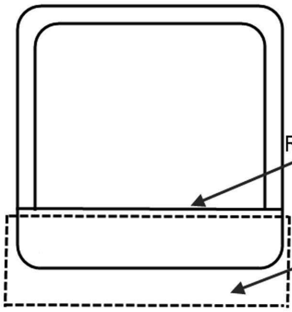

Figure 5. External energy absorption zone.

3.1 HLA

HLA including helicopter and light fixed-wing aircraft is the first category. Cronkhite *et al.* investigated the different crashworthiness design concept between helicopter, light fixed-wing aircraft, transport(15), and they are separately discussed. To better understand the energy absorption structure design concept, helicopter and light fixed-wing aircraft are classified into the same group in this paper.

The conventional fuselage consists of frame structure and cabin floor, etc. To improve the crashworthiness performance, Jackson *et al*. exhibited a crashworthiness design method for small type of aircraft(16). The design concept is shown in Fig. 4, and three structural parts including energy absorption subfloor, outer shell, stiff structure of cabin floor and upper section are demonstrated. Three design principles could be extracted from this design concept, i.e. providing a rigid protective living space for occupant, dissipating impact kinetic energy and maintaining the aerodynamic shape. The key characteristic of small aircraft is the small space under the cabin floor. As a result, it should be filled with energy absorption structure to dissipate impact kinetic energy, while the cabin floor should keep integrity to avoid the failure of cabin floor and provide a platform for seat during impact accident. In addition, the external energy absorption zone, which located outside of the fuselage structure, could be utilised as shown in Fig. 5. This energy absorption structure design concept could be expanded to HLA including helicopter and light fixed-wing aircraft. Obviously, energy absorption structure and rigid components are separately designed to satisfy their crashworthiness requirement. In conclusion, the design concepts for HLA could be given as

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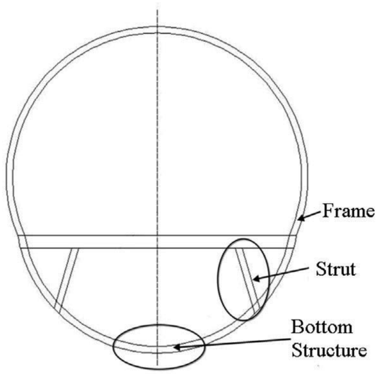

Figure 6. Improved fuselage from three ways for TMCA.

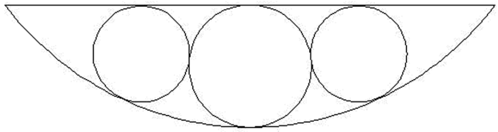

Figure 7. Cylinder shell under the cabin floor.

following. Firstly, the structure in the small space under cabin floor and external energy absorption zone are allocated to dissipate impact kinetic energy. Secondly, the cabin and its upper structure should be rigid enough to protect occupant. The core design problem of HLA is the material, type and layout of energy absorption structure under the cabin floor.

3.2 TMCA

TMCA including transport, mid-size and commuter type aircraft has a large cargo space under the cabin floor, which is a complex structure system consisting of frames, stringers and an outer skin. Longitudinal stiffeners could be ignored considering that their contribution to the stiffness of circumferential bending is very small. Aircraft skin just dissipates a small part of energy and keeps the integrity of fuselage during the impact process. Frame and strut play important roles in the crashworthiness design of TMCA. Two obvious different aspects between this type and previous one are demonstrated here, i.e. the design concept of energy absorption structure in cargo space and the role of fuselage frames and struts. The large cargo space under TMCA provides large effective crushing distance and larger structural space. However, the energy absorption structure under the cabin floor should not occupy the entire space because of enough space needed for baggage or fuel tank. Therefore, the layout of energy absorption devices is much more difficult than that of HLA. The crashworthiness of TMCA could be improved from three aspects shown in Fig. 6. Firstly, different from small aircraft, energy absorbed by the fuselage frames accounts for nearly half of internal energy of fuselage structure obtained by numerical analysis. Hence, high efficiency of energy absorption for fuselage frames could be adopted considering that it is the most important energy dissipation device. Secondly, bottom structure could improve the energy absorption characteristic of fuselage and reduce the initial peak acceleration since it would impact with ground at first, thus the efficiency energy absorption structure in fuselage bottom area should be highlighted. High efficiency energy absorption structures including foam and honeycomb are preferred in aircraft crashworthiness design. To get better performance, their configuration and layout must be stressed. Finally, for some kinds of aircraft, the strut under the cabin floor could be utilised as the energy absorption devices without employing other special devices, and it would improve the energy absorption characteristics by dissipating impact kinetic energy and altering the failure behaviour of fuselage frames.

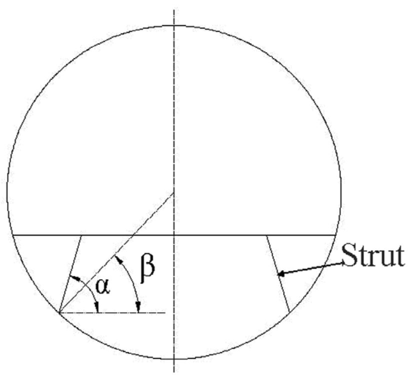

Figure 8. Conventional strut layout of aircraft.

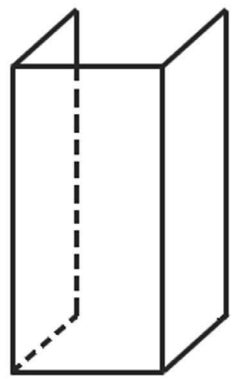

Figure 9. Open shell of strut.

3.3 Energy absorption structure in aircraft crashworthiness design

High efficiency energy absorption structure, such as foam, corrugated beam and shell, could be adopted in aircraft structures according to their requirement. Their structure configuration and layout have great influence on the crashworthiness performance. Foam and sine-wave beam structures are mainly applied in HLA, because ground and rigid floor provide supporting platform for their crush. However, it is a very difficult work to apply them in TMCA. Except foam and sine-wave beam, honeycomb and thin-walled structures also are the important high efficiency energy absorption structures(17). Among them, thin-walled structures including circular and square tube have various failure behaviours. Several typical failure modes such as axial symmetric folding, non-axial symmetric folding, crimping crack and transverse impact of shells could be adopted to dissipate impact kinetic energy. Based on the crimping crack model, Taher *et al.* purposed a new composite absorbing system for the sub-structure of helicopter. To enhance its energy absorption efficiency, the composite web is adopted(18). Using transverse failure mode, cylinder shell was arranged under the cabin floor indicated in Fig. 7(9). Although the axial progressive failure is the common failure type in crashworthiness design, the transverse impact is also perfect and the transverse failure process of tubes are more stable than that of axial impact.

It could be easily understand that both foam and sine-wave could be used in the crashworthiness design of all kind of aircraft, but different design concept should be adopted for different type of aircraft to improve the energy absorption efficiency. The design concept of energy absorption structure of HLA is relatively simpler than that of TMCA. Energy absorption structure could be easily adopted in HLA because the space is relatively small and rigid floor provide reliable crush platform. The construction of supporting structure and failure model of energy absorption structure are the two key design factors for TMCA. In addition, the stiffness combination of different components is a very important factor involving the efficiency of energy absorption structure. The application of energy absorption structure design in TMCA is the main discussion of this paper. Strut, frame and bottom structure are investigated to give better impact dynamic performance.

4.0 ENERGY ABSORPTION STRUCTURES DESIGN OF STRUT AND FRAME

4.1 Preliminary strut design

Strut is the structure support the cabin floor locating between the floor beams and lower fuselage frames, and it is used in the TMCA. It not only could be adopted as the energy absorption device but also would influence the impact dynamics of the entire aircraft. Conventional strut design is shown in Fig. 8, there are two struts under the cabin floor for each fuselage frames. Open shell as shown in Fig. 9 is a general strut structure in aircraft, but the energy absorption ability is limited for its asymmetric cross-section[19]. A possible strut design for aircraft is demonstrated in Fig. 10, there are two series symmetrical struts for each frame having good crashworthiness performance compared with the previous traditional structure in some cases[20]. However, two series of strut would sacrifice more cargo space than that of previous one.

Two strut ends are fixed connection with under-floor beam and frame in the above strut design method, respectively. Unfortunately, it is a very difficult work to get progressive failure behaviour for strut because of the rotation of frames about plastic hinges. Consequently, the energy absorption ability is limited for the fixed connection. Plastic deformation is the normally energy absorbing manner for metallic strut, while the composite strut would fail in a different way. It could reduce the structure weight and get better crashworthiness performance than that with metal structures. Therefore, composite materials may be the better choice for strut instead of metal material to enhance their energy absorption ability. A new articulated connection was given by Heimbs *et al*., and shear failure behaviour of composite tube was adopted as shown in Fig. 11[21]. It is a new attempt to get better structure having important significance to the development of crashworthiness design. However, the influence of layout and structural stiffness on the crashworthiness is not clear, and energy absorption structure design needs more investigation.

Strut design could improve the crashworthiness of aircraft without altering the original fuselage structure. Consequently, struts are one of the best design considerations to improve energy absorption ability.

4.2 Application strut on aircraft

To enhance the strut's energy absorption ability, metal strut under conventional layout are extensively studied[10,22]. However, design concept of the conventional strut energy absorption structure is still

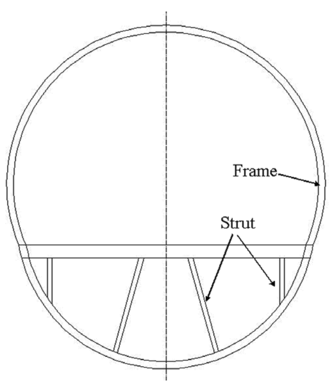

Figure 10. A innovative strut design method.

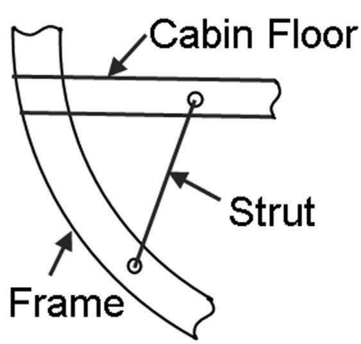

Figure 11. Strut with rivet connection.

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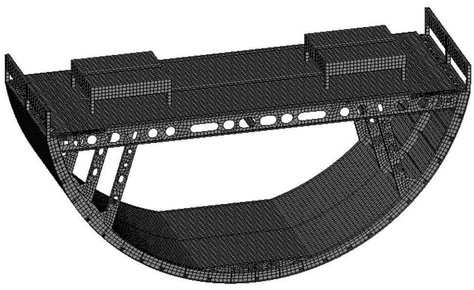

Figure 12. Finite element model for numerical simulation.

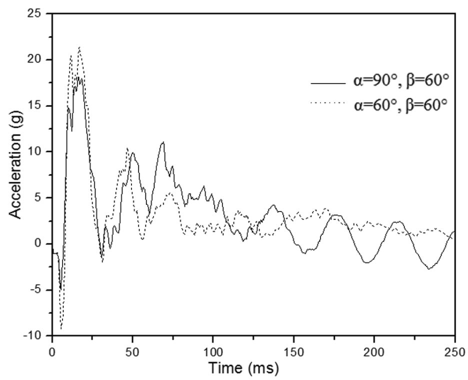

Figure 13. Acceleration characteristics with different α.

not clear, although many kinds of strut type are proposed. In addition, there is a great difference of boundary conditions between single test and entire aircraft impact environment. To better understand the failure behaviour of strut, it is necessary to verify the energy absorption characteristics and its influence on the failure behaviour of frame. A finite element model consisting of about 32,000 shells, beams and solids was built based on a typical civil aircraft geometrical model as shown in Fig. 12. Just the structure under the cabin floor is considered, and occupant and seats are simplified as solids. Al-2024 and Al-7075 are the typical aircraft metal materials, and they are simulated with bilinear elastic-plastic material model with Von-misses stress model. Shells and their internal energy would be deleted from system once the maximum plastic strain is satisfied, and beam failure is not taken into account. The influence of strain rate on the Aluminium could be neglected. The contact of finite element model is sound set, and the impact velocity is $7ms^{-1}$ in this numerical simulation. In addition, the gravity centre and mass of finite element model is checked to coincide with geometrical model.

To comprehensive understand the failure behaviour of strut, both of open shells and quadrangular tubes are considered here. Also, the layout of different strut type is investigated, and it is expressed as two angles as shown in Fig. 8. The acceleration characteristics of civil aircraft's seat with open shells are revealed as Figs 13 and 14(10). Obviously, the civil aircraft when α and β equal to 60°, 60° is best one. The number of peak acceleration decreases although the initial peak acceleration increase with respect to α. Both of the number of peak acceleration and initial one are the decreasing function with β. Consequently, the civil aircraft has the best acceleration performance if both of α and β are 60°. Maybe the moderate layout is preferred considering that this kind of strut layout would sacrifice much more cargo space. The fuselage frame would be divided into several segments by plastic hinges, and it will rotate with these hinges. Torsional deformation is the failure behaviour of strut as shown in Fig. 15(22). Quadrangular tubes, as a kind of closed-section shells, could improve the energy absorption ability of strut because they have higher energy absorption efficiency than that of open shells.

4.3 Integrated design of frame and strut

Frame absorbing half of impact kinetic energy are the most important component of TMCA. It also plays the key role in the impact process of aircraft, and the failure behaviour of entire aircraft is determined by frame. Consequently, controlled failure behaviour of frame is very important.

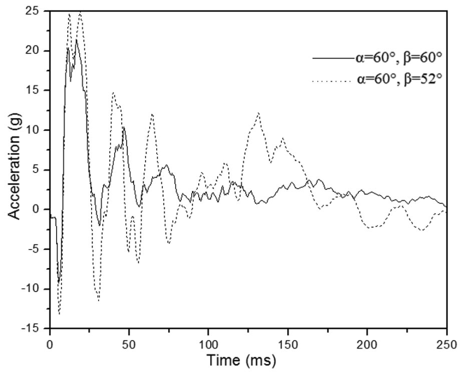

Figure 14. Acceleration characteristics with different β.

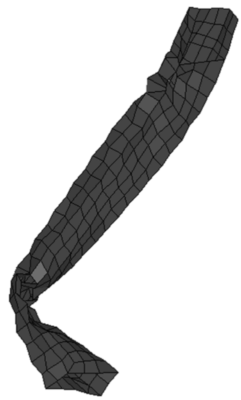

Figure 15. Failure behaviour of quadrangular tube.

Although the impact dynamics characteristic is very complicated, a strong similarity is shown between static and dynamic mode by the research of some general trends in the failure behaviour of fuselage[23]. Material, floor location and cargo containers etc. have great influence on the failure model of frame[24-26]. It is a very difficult job to analyse the impact process of complicated civil aircraft from theoretical point, and frame provides the most effective method to reveal failure behaviour. Some theories such as Vlasov-type curved bar are given to simulate the crash of frames by some researchers[27-28]. There is a strut connecting with under-floor beam and stiffed frame in TMCA, and strut and frame would influence each other. Two design aspects could be utilised including enhancing strut's energy absorption ability and improving the impact dynamics of frame. There is an optimal rigidity combination between frame and strut, although frame and strut are separately discussed in most research. Consequently, the influence of strut should be considered to analyse the impact dynamic performance of frame.

Plastic hinges of frame are chosen to measure the strut's influence because metal aircraft frame dissipates impact kinetic energy by them. Two obvious categories could be obtained by the deformation of fuselage shown in Fig. 16, and both of them have two common symmetrical plastic hinges located near the bottom of strut, which is on the right or left side of strut depending on the stiffness and location of strut. Two types of failure model have one or two plastic hinges in the bottom area according to the stiffness of bottom structure. The typical failure mode of the first kind of aircraft frame is indicated in Fig. 17, and frame has three plastic hinges to dissipate impact kinetic energy, the bottom plastic hinges would move upward after the failure of bottom structure. Cargo floor between two plastic hinges of second failure model type would be lifted up, and lateral tilt may appear due to the asymmetric failure of the two plastic hinges. In conclusion, the plastic hinges would be forced to move from bottom to its adjacent area because of the reinforcement of bottom structure. To absorb more impact kinetic energy, more material must be forced to deform, thus travelling plastic hinge is the preferred deformation way. However, it is difficult to form travelling plastic hinge. In addition, the location of plastic hinges may be altered by strut. The hinge's position without strut may lie on the left side of strut shown in Fig. 18, and they would move from A to B when the strut is stiffness enough. This shows that controlled failure model of frames could be obtained not only the design of frame but also the reasonable stiffness combination of strut and frame depended on the detailed civil aircraft structure.

5.0 BOTTOM ENERGY ABSORPTION STRUCTURE DESIGN

5.1 Available bottom structure design

Bottom structure is taken into account to reduce initial peak acceleration and absorb impact kinetic energy, while conventional structure has poor impact performance. High energy absorption structures such as foam, sine-wave beam and honeycomb are popular in crashworthiness design, and some typical bottom structure design methods are shown as following.

Foam consisting of array of cellular structures is a kind of lightweight structure, and it could be used as the energy absorption structure in crashworthiness design. There is a variety of foam materials used in the crashworthiness design, while great application potential of Rohacell polymethacrylimide series foams in aircraft structure design is shown by many researches. Under the support of 'CRASURV Design for Crash Survivability of Commercial Aircraft', Li *et al.* studied various mechanical behaviours of Rohacell-51WF foam for its crashworthiness application aircraft design[(29)]. Foam has been used as the energy absorption to reduce the initial peak acceleration and dissipate impact kinetic energy. The results demonstrate that it has excellence performance in impact characteristics in some cases. For example, Jackson purposed a kind of crushable foam under the rigid cabin floor of small aircraft[(16)]. To reduce the initial peak acceleration and the number of peak acceleration, foam is designed as uniformly spaced individual blocks in the subfloor. The rigid cabin floor and ground could provide the crush platform for its crush which makes sure that foam could absorb impact energy during impact process. However, little research is about the application of foam structure in TMCA because it is much more difficult than that of small aircraft.

Sine-wave beams also exhibit excellence crashworthiness performance as foam structure, and it has been got enough attention from the beginning of crashworthiness design. Composite is extensively used in sine-wave beams and aircraft structure for its impact performance. To investigate the fundamental mechanical performance, Kermanidis *et al*. studied the vertical compression of sine-wave beams under the CRASURV project[(30)]. After that, many new aircraft fuselage design methods were purposed considering its better impact characteristics. The same as foam structure, sine-wave beams in crashworthiness design of HLA have been implemented, and they locate under the cabin floor to absorb impact kinetic with the support of rigid floor and ground. However, the configuration and layout design of sine-wave beam is still a very challenging work in aircraft design. To develop composite frames with good energy absorption ability, Wiggenarrd *et al*. placed sine-wave beam on the location of strut, and it was arranged at

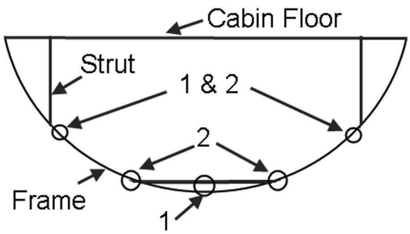

Figure 16. Plastic hinges of fuselage (1 and 2 represent the two types of failure mode).

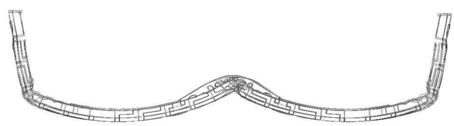

Figure 17. Failure behaviour of fuselage frame.

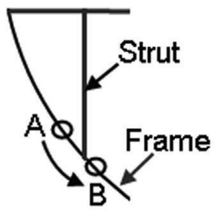

Figure 18. Plastic hinges caused by strut.

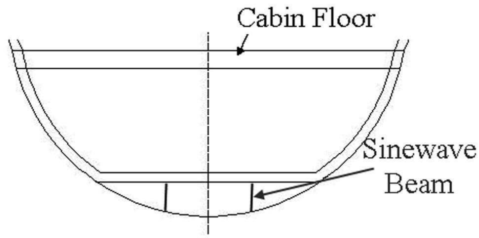

Figure 19. Sine-wave beams under the fuselage frame.

a slight angle considering the rotation of the frames[31]. Unexpected, sine-wave beam becomes unstable after the failure of trigger because frames rotate around the hinges for the failure of bottom structure. To obtain better failure behaviour, it needs adjacent supporting components to maintain its stability. Under the same program, David *et al.* proposed a new composite sine-wave beam crash design method which lay under the fuselage frames exhibited in Fig. 19[32]. To provide rigid platform for sine-wave beam, bottom fuselage frames are lifted, while frames and bottom skin are redesigned. The progressive failure of it is theoretically expected, but the results showed that sine-wave beam fail in an unexpected manner instead of progressive failure. The sine-wave beam is lack of rigid support for crash deformation because fuselage frames above the sine-wave beam rupture. In conclusion, the application of foam and sine-wave on the TMCA is a very difficult work for the absence of supporting structure to allow the crushing of energy absorption structure. Besides, a new bottom structure with honeycomb exhibits excellent impact performance as shown in Fig. 20[17]. It has better impact dynamic performance than that of original structure.

5.2 Improved design concept

It can be obtained that ideal failure behaviour of energy absorption structure in civil aircraft is inaccessible for the complex impact conditions. Rigid cabin floor and ground provide crushing stable platform for the energy absorption structure in HLA, but it meets a great challenge in TMCA. The two key problems of bottom structure are constructing a supporting crushing platform and developing structure for complex impact environment. Consequently, a new design method for TMCA is developed considering that there is no supporting structure in traditional frame

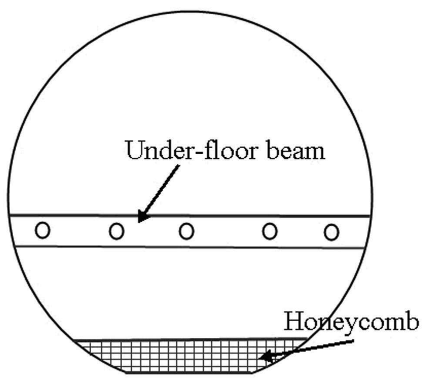

Figure 20. Honeycomb structure of the bottom area.

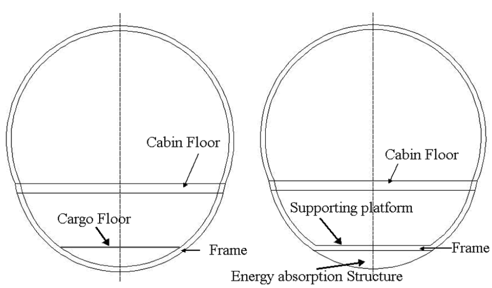

Figure 21. A new crashworthiness design concept.

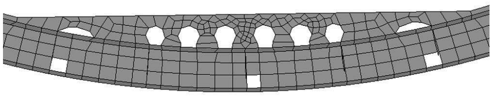

Figure 22. Conventional bottom structures.

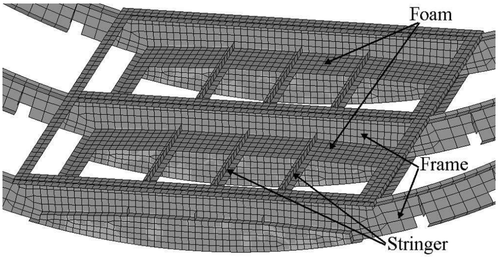

Figure 23. Foam structure under the frames.

structure[33]. Fig. 21 shows that bottom frame is lifted as a supporting platform to allow the crush of structure under the frame. Reducing initial peak acceleration is also achieved by using flexible material under the bottom frame. Conventional bottom structure is shown in Fig. 22, and frame with reinforcement is the typical structure. Innovation bottom structures with foam and sine-wave beam are proposed, and both of them are arranged blow the bottom frame. Reduced initial peak acceleration is expected because foam and sine-wave beam would collide with rigid floor at first instead of frame. Besides, they also could dissipate a part of impact kinetic energy. Finite element method is used to verify the proposed structure design concept, and civil aircraft model keep in consistent with Fig. 12. The foam block structure locates below the frame as shown in Fig. 23. Skin and stringer are adopted to keep the intact of foam. Bilinear elastic-plastic metal material is employed as the foam material model, and foam is a continuous structure along the transverse direction. Total mass of civil aircraft increases just a little due to the small density of foam. The failure behaviour of foam is revealed as Fig. 24, bending deformation of foam is guaranteed by its continuous transverse structure. The comparison of acceleration characteristics is indicated as Fig. 25. Initial peak acceleration of the improved structure is 15% lower than that of original one, and the number of peak acceleration is also reduced. The result shows that foam structure could dissipate nearly 10% impact kinetic energy. There is a significant improvement of the civil aircraft crashworthiness by using foam structure.

A kind of longitudinal sine-wave beam is proposed by Kindervater, but the energy absorption ability is restricted by the failure of bottom frame[7]. Bottom structure with transverse direction sine-wave beam is proposed as shown in Fig. 26. Aluminium is the material of sine-wave beam,

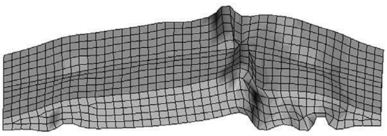

Figure 24. Failure behaviour of foam structure.

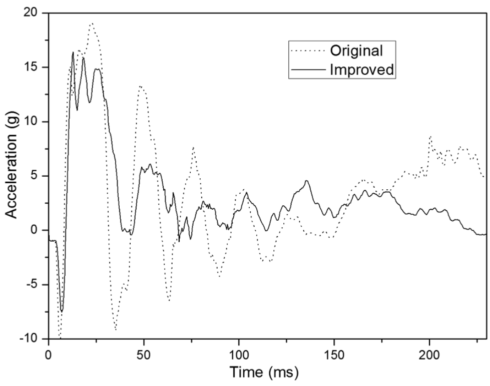

Figure 25. Comparison of acceleration curves with or without foam.

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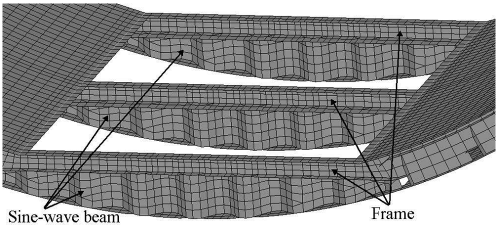

Figure 26. A new Sine-wave beam layout.

Figure 27. Failure behaviour of sine-wave beam.

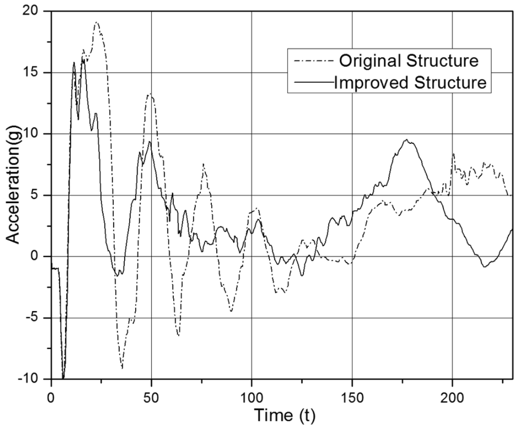

Figure 28. Acceleration after using sine-wave beam.

and failure of element is considered. The foam structure of civil aircraft model is replaced with sine-wave beam here. The result shows that the failure behaviour is also bending deformation given by Fig. 27, and its energy absorption ability is less than that of foam. The peak acceleration appeared after 150ms is little higher than original one, but improved structure's initial peak acceleration is nearly 10% lower than that of original structure, and that the following second and third peak acceleration is significantly reduced as shown in Fig. 28. Consequently, the layout of sine-wave beam could improve the crash response.

6.0 CONCLUSIONS

Design concept of energy absorption structure for all kind of aircraft is presented here. Some conclusions about the design concepts of aircraft and energy absorption structures are given as following to guide the design of aircraft.

Different crashworthiness design concepts for different aircrafts are demonstrated. Bottom structure is the key energy absorption structure of HLA, and the crashworthiness of TMCA could be improved from three aspects including frames, struts and bottom structures.

Two impact crashworthiness design considerations including frame and strut could be utilised for TMCA. Frames dissipating near half of impact kinetic energy are the most important energy dissipated devices. Strut type and layout would largely improve the crashworthiness of TMCA without employing other energy absorption devices. TMCA with moderate strut layout is preferred. In addition, the stiffness combination of strut and frame must be considered to get better failure behaviour.

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Foam and sine-wave beam could be used in the energy absorption structure design of all kind of aircraft, and they have great influence on their impact characteristics. The efficiency of energy absorption structure could be guaranteed in HLA because rigid cabin floor provide support for energy absorption structure to dissipate impact kinetic energy. However, they meet much challenge in the design of TMCA considering that their necessary supporting platform is absence. A innovate structure design concept is proposed, and the new foam and sine-wave beam structure could improve impact characteristics of TMCA.

ACKNOWLEDGEMENTS

The author would like to thank the financial support of the China Postdoctoral Science Foundation (Grant No. 2012M510306, 2013T60054).

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