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Crashworthiness analysis of aircraft fuselage with sine-wave beam structure

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Abstract An integrated design concept for crashworthy fuselage using sine-wave beam and strut is proposed and investigated. The finite element model of aircraft fuselage is built first. The structures above cabin floor, occupant and seat are simplified as two rigid blocks. The fuselage frame is redesigned, and the sine-wave beam is arranged under the frame. The impact dynamic performance of the aircraft with bottom sine-wave beam structure is studied and compared with that of conventional type. To obtain better crashworthiness performance, different rigidity of strut is combined with the sine-wave beam bottom structure. Numerical simulation result shows that the proposed sine-wave beam bottom structure could not only dissipate more proportion of impact kinetic energy but also reduce the initial peak acceleration. The structure and rigidity of strut have great influence on the crashworthiness performance. To give a better fuselage structure, both of the strut and bottom structure should be properly integrated and designed.

1. Introduction

The crashworthiness is one of the most important structural design requirement of aircraft in airworthiness regulations, which has attracted more and more attention for the safety of occupant.[1–3] To evaluate the impact dynamic performance of fuselage, the drop test of Boeing 737-200 aircraft was conducted at FAA William J. Hughes Technical Center, and the numerical simulation of fuselage using LS-DYNA nonlinear explicit software was conducted.[4] The simulation of aircraft crashworthiness is a time-consuming process for the detailed numerical model and transient dynamic analysis. To design a crashworthy fuselage with cost-effective approach, a novel scale modeling method is proposed by Lankarani et al.[5] The progresses in experimental and numerical simulation technology guarantee the feasibility of crashworthy design for aircraft.

The crashworthy fuselage could dissipate impact kinetic energy by energy absorption structure during impact process, and the acceleration suffered by the occupant and living space should be guaranteed. A number of energy absorption

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concepts including the formable keel web with foam, sandwich, corrugated sub-floor and longitudinal cylinders for light-weight aircraft and helicopter are exhibited by Crankhite and Berry.[6] The crashworthiness design of the transport aircraft is different from that of light-weight aircraft and helicopter. The stable supporting platform and effective energy absorption structure are the two greatest challenging design concepts for the transport aircraft.[7] A hexagonal honeycomb energy absorption device is introduced into sub-floor structure with scaled model by Yang et al.[8] To make the best of Rohacell-31 polymer foam, closed-cell blocks are adopted as the sub-floor structure to enhance energy absorption ability and mitigate peak acceleration.[9] The sine-wave beam is a kind of high efficiency energy absorption structure which has great potential application prospect in the crashworthy fuselage.[10] To utilize its energy absorption ability, the sine-wave beam with triggers is adopted at the lateral position, but the prospect failure doesn't appear due to the lack of lateral support.[11,12] The sine-wave beam also could be adopted as the bottom fuselage structure, and it is used as the energy absorption structure along the longitudinal direction by David[13] and Huey[14] et al. The progressive failure is theoretically expected, but the sub-cargo beam located above the sine-wave beam ruptures due to the large impact load. The crashworthy design using the sine-wave beam is studied by Xiang et al.[15] However, the aircraft consists of many different kinds of components including the bottom structure, frame, skin, strut and stringer. The crashworthy design of fuselage is extremely difficult for the complicated impact dynamic performance of components and the coupling effect among different components during impact process. Therefore, to obtain better crashworthy fuselage structure, the integrated design concept of bottom sine-wave beam structure and other components should be further considered. The strut is the support structure under the cabin floor, and it would affect the crashworthiness performance of aircraft fuselage.[16,17] To utilize the energy absorption ability of strut, some innovative structure is adopted.[18,19] From the previous research results, both of bottom structure and strut have great influence on the crashworthiness of aircraft, but the interaction effect between the two components is not clear. Therefore, the design concepts of strut and bottom energy absorption structure are investigated here.

To improve the crashworthiness of transport aircraft, a novel aircraft fuselage with sine-wave beam is investigated and compared. In addition, to investigate the roles of strut and bottom structure during impact accident, several different kinds of strut types combined with the sine-wave beam bottom structure are studied. The finite element method is adopted because it is popular for solving the impact dynamic problem. The reliable finite element model is built, and the crashworthiness of different design concepts is compared. The numerical simulation result is given to provide guidance for aircraft design.

2. Finite element model

The geometrical model of aircraft fuselage with the sine-wave beam is exhibited in Fig. 1(a), and it is composed of cabin floor, strut, frame, cargo floor, skin, under-floor beam, sine-wave beam, stringer, etc. The occupant, seat and structure above the cabin floor have little influence on the crashworthiness of aircraft, and they are simplified as two rigid blocks symmetrically distributed on the cabin floor. The joint, stiffener and rivet are ignored for the global impact dynamic performance is paid great attention to, and their weight is allocated to the adjacent structures. The rigid floor is adopted as the impact ground.

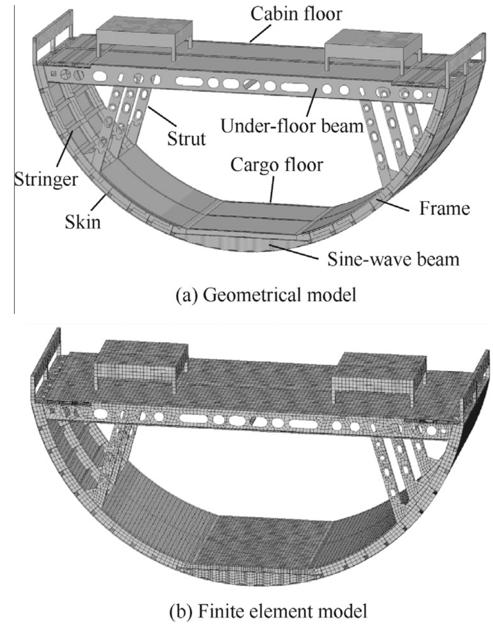

Fig. 1 Geometrical model and finite element model of aircraft fuselage.

Based on the geometrical model, the finite element model of aircraft is built (see Fig. 1(b)). The quadrilateral elements are the primary type of finite element model, and hexahedral elements are adopted to simulate occupant and seat. The elements which suffered large plastic deformation, such as the strut, frame and cargo floor, are simulated with Hughes–Liu shell theory, and other elements are based on Belytschko-Lin-Tsay shell and C0 triangular shell theory to improve computational efficiency. The contact, boundary condition and friction are properly defined to better simulate physical impact event.

The material of aircraft fuselage is Al2024 and Al7075. Al2024 is utilized as the material of skin, cargo floor and cabin floor, while other fuselage components including frame and strut are made of Al7075. The bi-linear elastic plastic material model is employed to simulate the metal structural material. The maximum plastic strain and von Mises stress are employed as the material failure criterion and yield model. The impact process is greatly influenced by the element failure, and the element would be removed if the strain reaches the maximum plastic strain for the finite element method. The yield stress is a function with respect to initial yield stress, plastic hardening modulus and effective plastic strain.

In order to guarantee the reliability and accuracy of numerical simulation result, several methods are adopted during the modeling and validation process. Firstly, the triangular element, and pentagonal and tetrahedral solids are avoided because they are too stiff. The shell element is popularly used because the thin-walled structure is the common component of aircraft. To reduce the hourglass energy, it is checked after the