

Effects of different roll angles on civil aircraft fuselage crashworthiness

Haolei Mou^{*}, Yuejuan Du^a and Tianchun Zou^b

*Tianjin Key Laboratory of Civil Aircraft Airworthiness and Maintenance, Civil Aviation University of China,
JinBei Rd 2898, DongLi District, TianJin, 300300, China*

(Received December 6, 2014, Revised January 11, 2015, Accepted January 12, 2015)

Abstract. Crashworthiness design and certification have been and will continue to be the main concern in aviation safety. The effects of roll angles on fuselage section crashworthiness for typical civil transport category aircrafts were investigated. A fuselage section with waved-plates under cargo floor is suggested, and the finite element model of fuselage section is developed to simulate drop test subjected to 7 m/s impact velocity under conditions of 0-deg, 5-deg, 10-deg and 15-deg roll angles, respectively. A comparative analysis of failure modes, acceleration responses, and energy absorption of fuselage section under various conditions are given. The results show that the change of roll angles will significantly affect fuselage deformation, seat peak overloads, and energy absorption. The crashworthiness capability of aircraft can be effectively improved by choosing appropriate landing way.

Keywords: crashworthiness; roll angle; failure mode; acceleration; energy absorption

1. Introduction

The crashworthiness design and certification of civil transport category airplanes are of great importance for aviation safety, occupants' survivability would be significantly increased by improving the crashworthy performance of aircraft fuselage structures, cabin layout, and internal facilities (Adams *et al.* 2001, Zou *et al.* 2012). Actually civil aircrafts often crashed under different complex environment, and the crash posture also cannot be ensured. A comprehensive evaluation of aircraft fuselage section crashworthiness can only be conducted after comparing with aircraft structural responses in various initial crash conditions and crash environment (Alan 2003).

The earliest studies of aircraft structure crashworthiness dated back to the 1960s, numerous tests of aircraft fuselage sections and full-scale aircrafts to provide reasonable and reliable test data for crashworthiness design were carried out in the United States and Europe (Damodar and Marshall 2005, Terry *et al.* 2002, Mahé *et al.* 2001). At the same time, numerous analytical researches had also been conducted to study the issues related to the crash dynamic characteristics, crash security, crash environment, and occupants' survivability during a survivable accident.

*Corresponding author, Master, E-mail: zoutianchun@126.com

^aGraduate Student, E-mail: dyjcauc@163.com

^bAssociate Professor, Ph.D., E-mail: zoutianchun@126.com

Eventually, the crashworthiness researches had been developed rapidly and had been used in the type design of civil aircraft (Beheshti and Lankarani 2006, Fasanella and Jackson 2002, Teramoto and Alves 2004, Shoji *et al.* 2007). The actual aircraft crash was not a simple vertical drop process, and it generally crashed with varying degrees of roll angle. In 1997, NASA Langley Research Center had developed a one-fifth-scale model for light aircraft fuselage section, and had conducted drop tests and simulation researches for 0-deg and 15-deg roll angles (Jackson 2001), the objectives of the research program were to limit impact forces transmitted to occupants and maintain fuselage structural integrity to ensure a minimum safe volume, while the influence of roll angle on fuselage section crashworthiness was not researched (Jackson and Fasanella 2001). The existing experimental and simulation analysis mainly focused on the crashworthiness of fuselage section subjected to vertical impact (Meng *et al.* 2009, Ren and Xiang 2011, Yu *et al.* 2011, Feng *et al.* 2013), with little regard to the effects of roll angle on civil aircraft fuselage section crashworthiness. The crashworthiness researches on roll angles were still relatively fewer, and the influence of roll angle on fuselage section crashworthiness was not clear until now, so it was necessary to research, which was also the main purpose of our researches.

The NTSB (National Transportation Safety Board) accident reports documented from 1999 to 2011 were analyzed based on the NTSB accident database. The data and information of aircrafts crashed with different roll angles were collected from 26 accident reports. The numbers of aviation accidents and occupants injuries under different roll angles impact conditions were listed in Table 1. The aircrafts mainly crashed with roll angles between -30-deg to 30-deg, there were 17 cases of aviation accidents in all, accounting for 65.4% of the number of aviation accidents. When the aircrafts crashed with roll angles exceeding 30-deg, there were 9 cases of aviation accidents, accounting for 34.6% of the number of aviation accidents, and no one survived except for one case of aviation accident. The roll angle crashed with ground was larger, the occupants' survivability was lower, and the roll angle crashed with ground was smaller, the occupants' survivability was higher. To a certain extent, the roll angle at impact was related to the occupants' survivability.

In order to meet the safety and crashworthiness requirements at lower cost, the finite element method was used to research the crashworthy performance of fuselage section for different roll angles impact condition. A full-scale 3-dimensional finite element model of fuselage section with waved-plates under cargo floor was established by using the nonlinear finite element code LS-

Table1 Injuries chart

Roll Angle	Number of Accidents	Fatal	Serious	Minor	None
$x < -90$	0	/	/	/	/
$-90 \leq x < -60$	2	281	0	0	0
$-60 \leq x < -30$	1	8	0	0	0
$-30 \leq x < 0$	5	137	6	102	57
$x = 0$	7	300	33	3	124
$0 < x \leq 30$	5	80	11	60	74
$30 < x \leq 60$	0	/	/	/	/
$60 < x \leq 90$	3	5	3	5	0
$x > 90$	3	104	0	0	0
Total	26	915	53	170	255

Note: Roll to left is negative, roll to right is positive

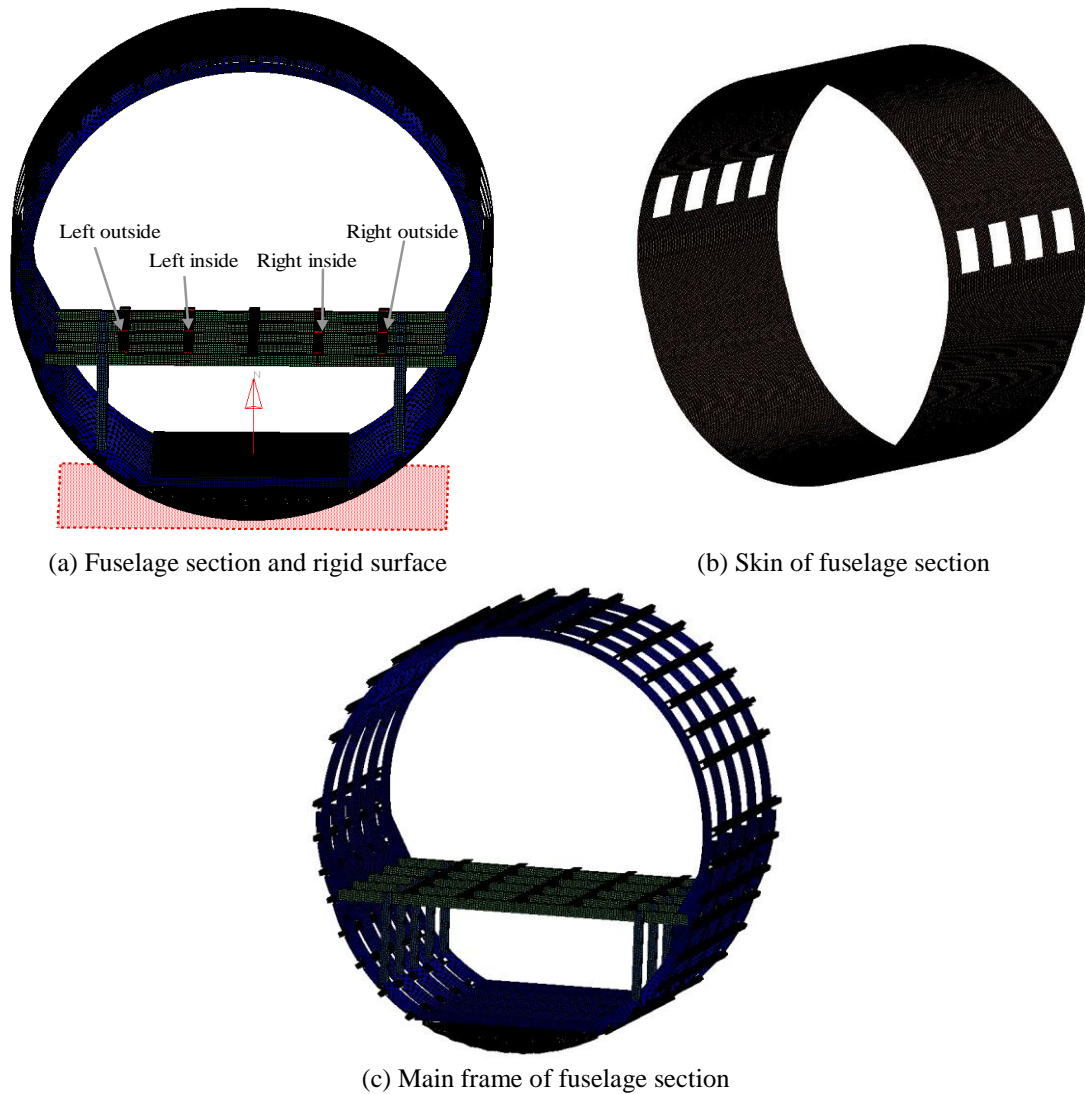


Fig. 1 Finite element model of fuselage section

DYNA. The failure modes, acceleration responses, and energy absorption of fuselage section under the conditions of 0-deg, 5-deg, 10-deg and 15-deg roll angles, respectively, were obtained and analyzed, and the results revealed some useful tips about dealing with aircraft emergency landing.

2. Finite element model of fuselage section

A typical five-frame, four-span fuselage section with waved-plates under the cargo floor was modeled for typical civil aircraft fuselage section. The FE model of fuselage section (including

skin, fuselage frames, long stringers, oblique struts, floor beams, cargo floor and waved-plates) was constructed, the chamfer of fuselage frames, long stringers, oblique struts and floor beams were ignored, and they were simplified as regular cross-sectional shape. The length of fuselage section is 2200 mm; the radii of cabin and cargo are 1700 mm and 1600 mm, respectively. The FE model of fuselage section consists of 609367 nodes and 616625 shell elements. Fig. 1 shows the FE model of fuselage section.

In order to keep the finite element model as simple as possible and improve the computational efficiency, the joints, rivets, fasteners, other connection pieces and cargo doors were neglected during the modeling process of fuselage section based on the simplified principles described by Adams and Lankarani (2003), Kumakura *et al* (2000), Jackson and Fasanella (2005). The adjacent parts which did not share common border or nodes were connected by using spot welds.

The occupant-seat system was considered a concentrated mass distributed on cabin floor. The fuselage section had 12 concentrated masses, and each concentrated mass was defined to 88 kg according to the Federal Airworthiness Regulation 25.562(b). Considering the constraint of the 1st and 3rd row seats, only 4 seat reference points in the 2nd row were given, shown in Fig. 1(a). The shell element formulation was selected to Belytschko-Tsay because it could simulate buckling accurately, as well as calculate internal energy absorption accurately, and the shell thickness of finite element model was adjusted to keep consistent with physical model.

3. Finite element model simulation results and discussion

3.1 Failure modes

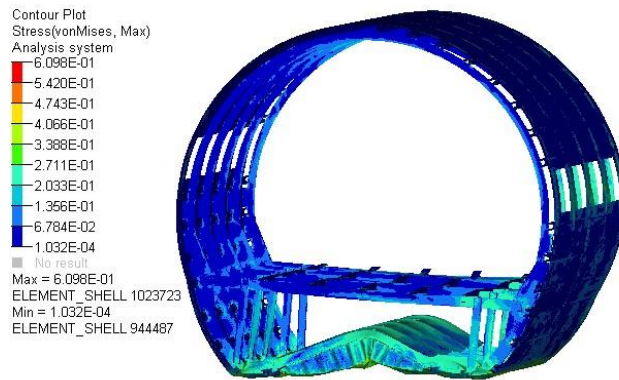
The impact responses transmitted to cabin floor can be generally determined by the failure modes of aircraft subfloor structures. Consequently, a comprehensive understanding of failure modes would be helpful in crashworthiness design of civil aircraft. The failure modes of fuselage sections at 100 ms under different conditions were shown in Fig. 2.

The failure modes and stress distribution of fuselage sections were different by comparing the figures, but the structural integrity of cabin floor was basically maintained during the crash. The larger initial in-plane loads resulted in fuselage frames and skin fracturing and moving towards cabin floor when fuselage sections crashed the rigid ground with 0-deg, 5-deg and 10-deg roll angles, and the waved-plates bent and deformed. The fractured frames had three plastic hinges. On both sides, the triangular region formed by the fuselage frames, floor beams and oblique struts had one plastic hinge. The third plastic hinge was at the bottom of fuselage frame. The oblique struts yielded, and floor beams were not penetrated by oblique struts, and the occupant-seat systems were effectively supported. And more important, the occupant survival space is not less than 85% of original space after the crash. The fuselage section tilted right with the increasing of right roll angle, the waved-plates were bent offset from center to right position, and the deformation of right oblique struts were more and more serious. The rare bending occurred to waved-plates when fuselage section crashed with 15-deg roll angle, there were also three plastic hinges in the frames, and the fuselage section tilted right seriously.

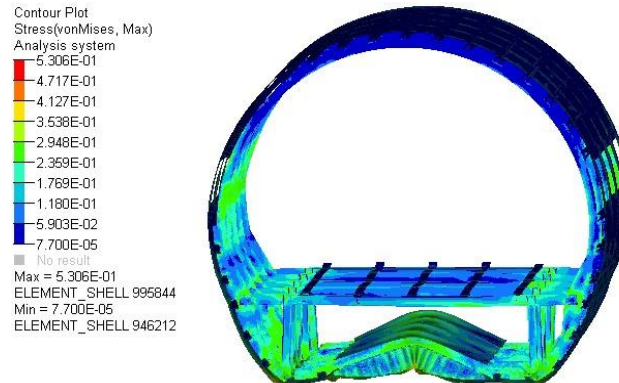
The energy absorbed by deformed waved-plates was reduced, which resulted from the reduction of waved-plates effective energy-absorbing areas, due to the increasing of roll angles. Hence, the energy dissipated to main fuselage structure increased, and the deformation of fuselage frames became more and more serious.

3.2 Acceleration responses

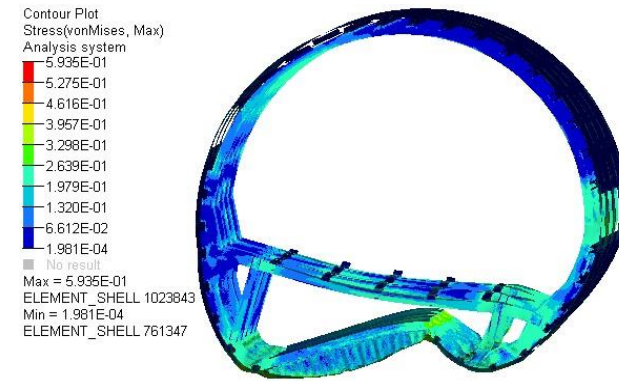
The acceleration characteristic is one of the important factors for occupants' safety and can be evaluated with the acceleration at the junctions between seats and floor. Owing to the symmetry of fuselage section, the acceleration responses of right outside/left outside seats were considered in



(a) 0-deg roll angle

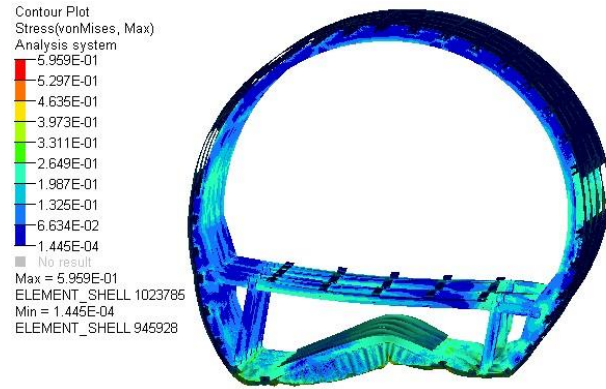


(b) 5-deg roll angle



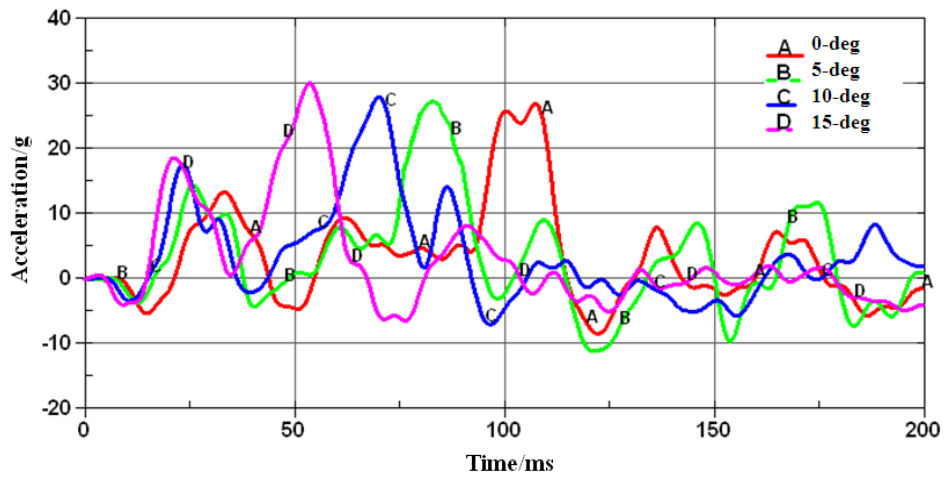
(c) 10-deg roll angle

Fig. 2 Deformation and stress cloud of fuselage section at 100 ms

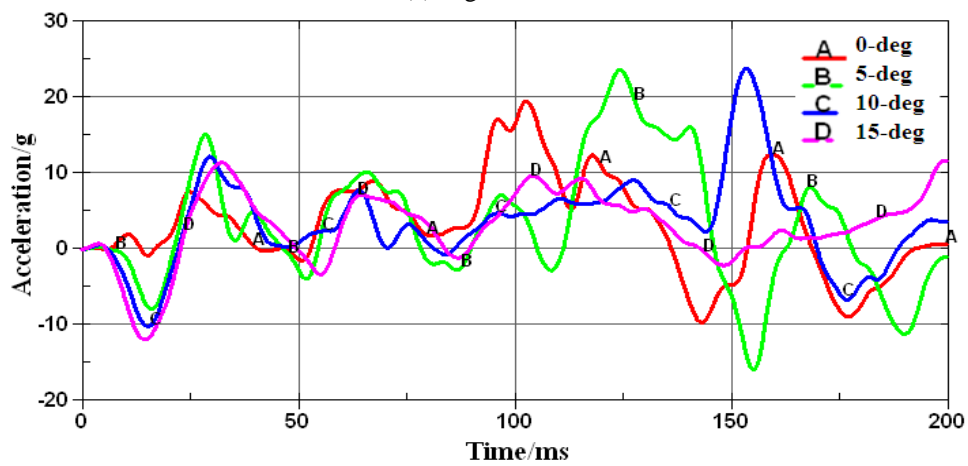


(d) 15-deg roll angle

Fig. 2 Continued



(a) Right outside



(b) Left outside

Fig. 3 Acceleration responses of junctions between seats and floor with different roll angles

Table 3 Maximum peak acceleration and corresponding time

Roll angle	Right outside		Left outside	
	Maximum peak acceleration	Time	Maximum peak acceleration	Time
0-deg	26g	110ms	19.5g	105ms
5-deg	27g	80ms	25g	125ms
10-deg	29g	70ms	25g	160ms
15-deg	32g	52ms	12g	200ms

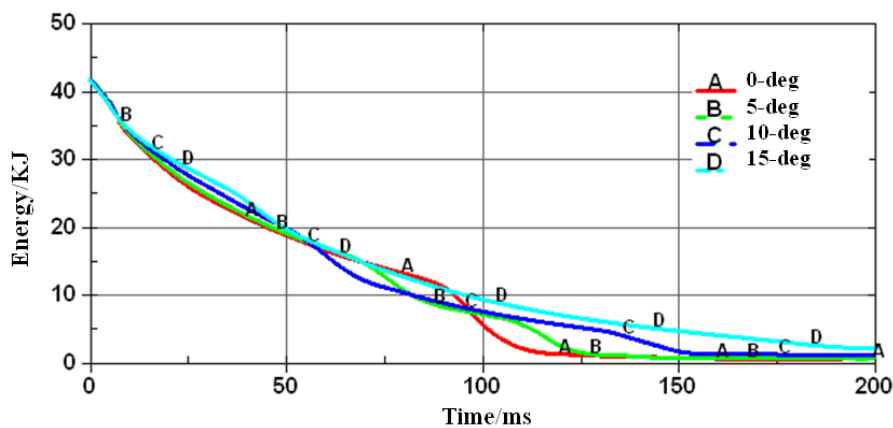


Fig. 4 Kinetic energy histories of fuselage section with different roll angles

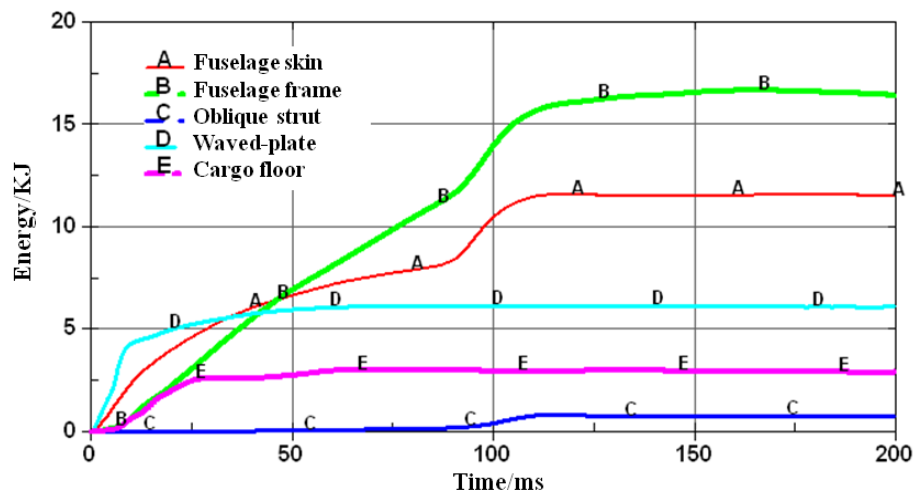
our work. The sampling frequency was set as 100 Hz. Fig. 3 showed the acceleration responses of fuselage sections with different roll angles, corresponding to 0-deg, 5-deg, 10-deg and 15-deg roll angles, respectively.

The results presented in Fig. 3 and Table 3 illustrated the influence of roll angle on acceleration pulses for the left and right seat tracks. The right roll angle led to an increase in the magnitude of peak acceleration response in the right side, and a decrease in the left side. The time of acceleration pulse also changed, the right side pulses occurring earlier with the roll angle increasing, and the left side pulses delaying. This changes in peak acceleration would also affect the behavior of seats, and would likely lead to the collapse of right side seats. Take Fig. 3(a) for example, when the fuselage section crashed with 0-deg roll angle, the corresponding 26 g maximum peak acceleration appeared in 110 ms; when the roll angles were 5-deg and 10-deg, the corresponding 27 g and 29 g maximum peak acceleration appeared in 80ms and 70 ms, respectively; when the fuselage section crashed with 15-deg roll angle, the corresponding 32 g maximum peak acceleration appeared in 52 ms. It was obvious that the initial, the second and the maximum peak accelerations were increased with the roll angle increased, and the resulting acceleration pulse arrived earlier. The large acceleration response appeared in short time would cause certain injuries to occupants.

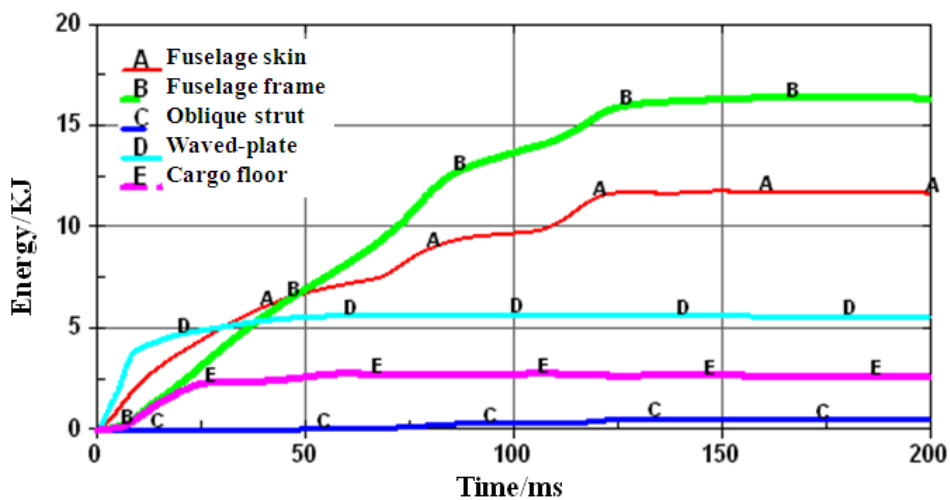
3.3 Energy absorption

Fig. 4 showed the kinetic energy histories of fuselage section under the different conditions of 0-deg, 5-deg, 10-deg and 15-deg roll angles. The initial total kinetic energy of the fuselage

sections were the same, i.e., 42KJ, when the fuselage sections crashed rigid ground with different roll angles. The processes of kinetic energy reduction were more consistent and smoother before 60ms for the four cases, while the processes were different after 60 ms. The kinetic energy of fuselage section decayed quickly at 90ms, and decreased to the lowest at 110 ms when the fuselage section crashed rigid ground with 0-deg roll angle; the kinetic energy of fuselage section decayed quickly at 70 ms, and decreased to the lowest at 125 ms when the fuselage section crashed rigid ground with 5-deg roll angle; the kinetic energy of fuselage section decayed smoothly, but had not yet decrease to the lowest at 200 ms when the fuselage section crashed rigid ground with 15-deg roll angle. It was obvious that the times of kinetic energy decreased to the lowest were getting longer and longer with the roll angles increased, and impact energy was absorbed slowly during a crash which caused certain injuries to occupants.

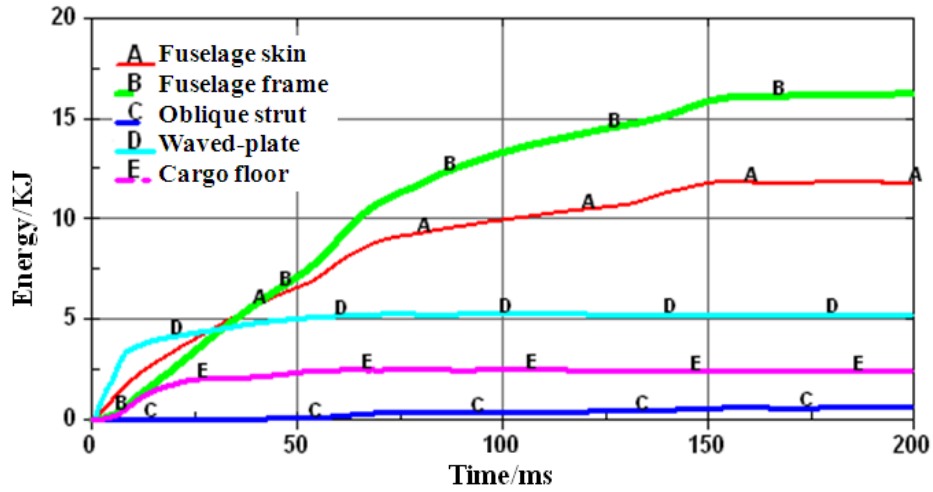


(a) 0-deg roll angle

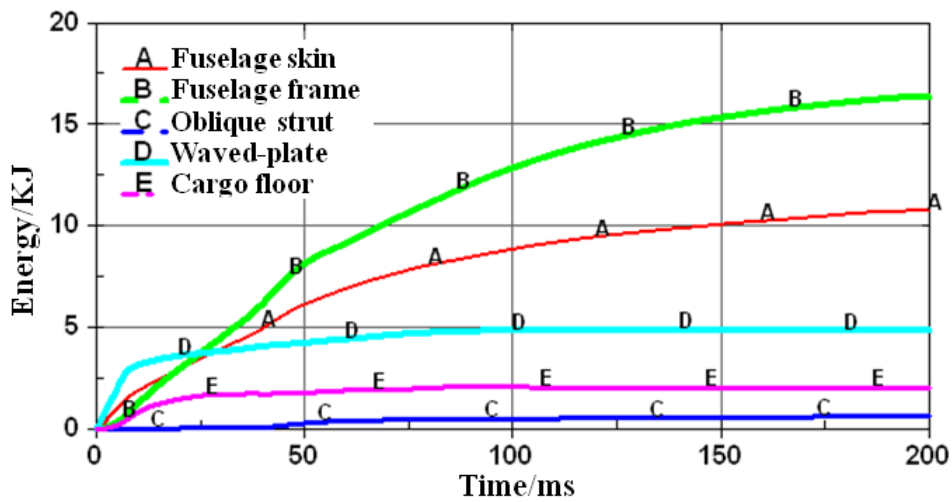


(b) 5-deg roll angle

Fig. 5 Energy absorption of main structures of fuselage section with different roll angles



(c) 10-deg roll angle



(d) 15-deg roll angle

Fig. 5 Continued

Table 4 Time of steady state and energy absorbed by waved-plates

Roll angle	Time of steady state	Energy absorbed by waved-plates
0-deg	110ms	6.3KJ
5-deg	130ms	6KJ
10-deg	150ms	5.2KJ
15-deg	200ms	5KJ

The impact energy was mainly dissipated by large plastic deformations of fuselage structures during impact accidents, but the energy-absorbing abilities of main fuselage structures were different. The energy vs time curves of different fuselage structures were shown in Fig. 5, the time of steady state and the energy absorbed by waved-plates were listed in Table 4 for the four

different cases. As can be seen from Fig. 5 and Table 4, the waved-plates and skin were the main energy-absorbing structures during the initial stages of impact, and fuselage frames soon became the main energy-absorbing structures because of the unique design features of fuselage section. The energy absorption of components could basically reach a steady state around 110 ms for the case of 0-deg roll angle, while that of the case of 5-deg roll angle, it was around 130 ms; The energy absorption of components could basically reach a steady state around 150 ms for the case of 10-deg roll angle, while that of the case of 15-deg roll angle, it was around 200 ms. It was obvious that the energy absorbed by waved-plates gradually reduced with the roll angles increased, and the time of internal energy of each component basically achieved stable was getting longer and longer, which indicated that the deformation of fuselage section reached stable later and later during the crash.

5. Conclusions

The influence of different roll angles on crashworthiness of fuselage section was studied in the paper. The main conclusions could be listed as follows:

- The failure modes, deformation, stress distribution, acceleration responses and energy absorption of the fuselage section were significantly different when the roll angles changed during the crash.
- The aircraft fuselage section tilted right seriously with the increasing of right roll angles, the waved-plates were bent offset from center to right position, and the deformation of right oblique struts were more and more severe.
- The maximum and initial peak accelerations of junctions between seats and floor gradually increased and appeared earlier with the right roll angles increased, the large acceleration response appeared in short time would cause certain injuries to occupants sitting on the right side.
- The energy absorbed by waved-plates gradually reduced and the fuselage section reached steady state later during the crash. When the aircraft crashed rigid ground with big roll angle, the energy absorbed by waved-plates was less, and the deformation of fuselage section was more severe, which would cause serious damage to occupants.

Acknowledgments

The research described in this paper was financially supported by the Science and Technology Item from Civil Aviation Administration of China (NO. MHRD20140207), the Fundamental Research Funds for Central Universities (NO. ZXH2012B004), and the Fund of Tianjin Key Laboratory of Civil Aircraft Airworthiness and Maintenance in CAUC (Civil Aviation University of China).

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