CRASHWORTHINESS OF AIRFRAME BASED ON TESTS AND FINITE ELEMENT MODELLING INCLUDING PASSENGER KINEMATICS RESPONSE

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Abstract

The objective of this paper is to describe an approach adopted for investigating the crashworthiness of an airliner fuselage. It is based on a series of static and dynamic tests on a sub-floor section and supported by detailed Finite Element (FE) modelling. The detailed FE analysis was undertaken to predict the dynamic collapse mechanism of a complete fuselage ring under survivable crash conditions. A non-structural seat for occupant/seat secondary impact based on a seat configuration with nominal collapsible seat back strength and surface compliance was devised. The occupant kinematics response and the related injuries under such conditions are predicted.

1 Introduction

Most of the air crashes which are considered as possibly survivable are in and around airports during initial take-off or final landing approach. Air safety regulations such as JAR25 (Joint Airworthiness Requirements) and FAR25 (Federal Aviation Requirements) and their derivatives are becoming more stringent to improve passengers survivability (Ref. 1). In June 1988 new performance standards for transport aircraft seats were introduced by the FAA (Federal Aviation Administration). These included two dynamic tests for the assessment of the seat structural performance and the occupant restraint systems, FAR/JAR 25-561/562. The aim was to improve passive protection provided to the passengers and consequently reduce the risk of injury and fatality in emergency crash conditions.

There have been increased tendencies, as well as public demands to enhance the prospect of air passengers survivability by improving the design of airframes. However, due to the high cost of impact tests, information about the dynamic structural behaviour of commercial passenger transport aircraft in survivable crashes is limited.

Aircraft structural features are important in the consideration of crashworthiness. The Finite Element (FE) approach can model the structure in sufficient detail to enable a study to be made of the energy absorption and the collapse modes of an airframe structure under impact conditions. The evaluation and verification of analytical techniques, based on well defined limited number of tests, can be used in the design stages to improve structural crashworthiness and consequently safety, in a crash without resorting to additional costly and time consuming test programmes.

The continuous enhancement of FE modelling techniques and the increasing capabilities of supercomputers have facilitated detail modelling of the whole of the aircraft and hence eliminate expensive component and full-scale tests. Analytical verification of a dynamic test for a sub-floor component of an airframe has previously highlighted the influence of modelling techniques (Ref. 2). The methodology outlined here was specifically adapted to develop and validate non-linear dynamic FE analysis of commercial aircraft crashes through extensive analytical studies, supported by experimental work on materials, components and full-scale structures (Ref. 3).

This paper demonstrates a systematic approach taken in modelling the detailed dynamic collapse mechanism of a fuselage section. The approach was based on building a complete FE model of a fuselage section. The implementation of the FE modelling methodology which focused on the influences of various modelling factors, such as material and rivet models and data and reported in (Ref. 2), were the basis of generating a full model of an airframe ring.

Occupant injury is related to the velocity change rate which in turn depends on a chain of parameters, such as fuselage collapse, seat collapse, restraint system and furniture protective covering, the most important of which are shown in Fig. 1. If the intermediate links are not defined to be beneficial to crashworthiness, the occupant will experience a rapid velocity change resulting in an increased risk of injury.

The interaction of the occupant with the front row seats transfers the residual space into a survival space which dictates the injuries sustained by the occupant. In order to maintain a residual space in the absence of the occupant interaction with the front seats, e.g. secondary impact, it is essential that the seat floor mounting remains intact and that seat failure is limited to plastic deformation and not fracture or separation. The secondary impact provides necessary information about the injuries to head, chest or leg segments due to occupant contact with the front seat.

Modifications to the seat design or seat/floor configurations or restraint system must be related to their effects on the occupant injury levels. Various design options, within the aircraft imposed space limitations, exist to achieve improvements in this respect. They range from structural and energy absorbing seats to the effects of the seat row pitch and occupant orientations upon the injuries to the body segments (Ref. 11). Use of a 3-point lap/shoulder belt restraint system, within the seat design constraints, instead of a lap belt only, might prove to be beneficial to occupant survivability.

To investigate the secondary impact, a single rigid seat with a collapsible seat back was modelled. The interaction of the seats and the floor in the case of structural seats are through the seat attachment points. In the latter case the seats must be modelled as an integrated triple seat. This aspect was not covered in this study. This study simulated the passenger's response within the residual space in which no contact between the occupant and any other elements except the occupied seat, front seat and restraint systems takes place. The kinematics and injuries sustained by an occupant subjected to vertical forces were studied. The influence of the seat and the restraint configurations were also analysed.

2 Dynamic Tests

A number of static and dynamic component tests were performed on various parts of a fuselage of a passenger aircraft. The test sections are shown in Figures 2 and 3. The stiffness or moment-rotation information obtained from the quasi-static component tests, shown in Figure 4, or FE analysis (modelled in Ref. 14 using RADIOSS) on sections of the A320 rear fuselage were used in hybrid modelling in KRASH Program (Ref. 13). This programme models the aircraft structure or sub-structures as a series of inter-connected beams, springs and masses. Dynamic section bending, strut-to-frame joint and cargo floor compression tests on airframe sub-floor components were performed. Reported here is one of the dynamic test. The detailed configurations for the dynamic Test 1 (mini drop test), are shown in Figures 2-3 and 5-6. The test rig used to generate the required dynamic impact conditions consisted of a trolley and an attached impacting surface. The test sections included two frames, a number of stringers, clips, shear webs, connecting parts and skin which extended to each side of both frames. The impact speed was 8 m/s which was considered to be representative of a survivable crash scenario (Ref. 7).

The pre-test set-up and post-test collapse response of the mini drop test are shown in Figures 5 and 6. The sub-structure consisted of two frames below the passenger floor. It was fully constrained at above the passenger floor cross beams. The major failures were at the cargo floor and mainly below the strut-to-frame joints. Rivet failure was observed on the skin and the frames. The main plastic hinges were between the strut to frame joints and the cargo floor cross beam. The test impact parameters were based on the pre-test simulations conducted separately. Sufficient collapse depth of 400 mm in dynamic Test 1, was obtained before the energy absorbing buffers were contacted (which dissipated the surplus impact energy). The collapsed structure exhibited some degree of recovery when the trolley was pulled back.

3 Airframe Finite Element Modelling

Two Finite Element programmes were used in this study. The fuselage structural part was analysed using PAM-CRASH (Ref. 4). In the seat/occupant study LS-DYNA (Ref. 9) software was used. In crashworthiness studies which involve large deformation of a structure over a relatively short duration, the explicit time integration method is advantageous in terms of computational efficiency. The codes used here are 3-D Lagrangian, explicit, FE programs for analysing the non-linear, large deformation, dynamic response of structures. They are specifically designed for crashworthiness analysis in the transportation industry. A main advantage of using a Lagrangian code is the ability to accurately track material boundaries and interfaces. The thin shell element used in this analysis is a bilinear, four-noded quadrilateral, which is based on Belytschko-Mindlin-Reissner plate theory (Ref. 4). This takes into account the transverse shear deformation of a plate by presuming that the lines normal to the plate mid-surface remain straight, but not necessarily normal (Refs. 4 & 5).

The models mesh generation were performed at component level where each component (frames, skin, straps, clips, shear webs, stringers and floor) of the specimen was meshed separately and then located appropriately in relation to the global reference co-ordinates.

Variations in mesh densities at different parts of the specimen allowed nominally two to three elements between adjacent rivets. Contact surfaces (‘slide lines’) were defined for all connecting parts. The accurate representation of the thickness and offsets of the components for the sliding interfaces were also taken into consideration. The impactor representing the trolley was modelled using a four-noded quadrilateral thin shell. In order to model the test loading configuration, a nodal mass point located at the centre of the thin shell was introduced.

3.1 Material and Rivet models

Material and rivet data used in this analysis were extracted from a number of separate tensile tests (Refs. 3 & 6). The material parameters were based on elastic-plastic with an isotropic hardening law (with and without material failure, respectively). Material failure was based on maximum effective plastic strain, simulated by element failure. The potential stress/strain relationship has been assumed to be described by the Ramberg-Osgood power law of the type:-

$$\sigma = \sigma_0\, \varepsilon^{m}$$

where σ = Effective yield stress
ε = Effective strain
σ_0, m = Material constants

The above law is used to define the material properties of the aluminium alloys used in the airframe.

Rivets are the principal connecting member in an aircraft structure. In a crash situation, the behaviour of the structure will be dominated by rivet strength. Consequently, modelling of rivet strength and failure characteristics is fundamental to a detailed impact model of an aircraft structure. In representing rivets in PAM-CRASH, depending on the number of nodal points associated with a rivet, these were modelled as either rigid bodies or nodal constraints or as contact tiebreak nodes to surface by a number of nodes which were allowed to rotate and translate. Two-noded rivets were modelled as rigid bodies, whereas nodal constraints were applied to rivets going through three layers of contact surfaces. They were modelled in areas of fine mesh density where plastic failure (‘plastic hinges’) is expected to occur. Rivet failure can occur upon the violation of the failure criterion is defined as, (Ref. 4):-

$$\left(\frac{NormalForce}{AFAILN}\right)^{a1} + \left(\frac{ShearForce}{AFAILS}\right)^{a2} \leq 1.0$$

where ‘a1’ and ‘a2’ are coefficients and ‘AFAILN’ and ‘AFAILS’ are the normal and shear failure loads in a rivet, respectively.

In modelling rivets in PAM-CRASH, rivet failure can occur prematurely because the above failure criteria does not account for the length of time the rivets can withstand the load prior to failure. A number of rivets failed in the simulation of the complete fuselage ring shown in Figure 7.

3.2 Modelling Methodology

Some of the influencing FE modelling factors which were implemented at component level (for a relatively small size problem) and investigated in the simulation of dynamic Test 4, shown in Figure 3, are highlighted in Table 1, (Refs. 2, 8). A number of simulations were performed in the case of dynamic Test 4 model (Ref. 2). The methodology examined the following points:-

a) Variations in the material failure strains used to rupture elements. Elements were eliminated once their plastic strains exceeded the specified limits.
b) Introduction of damage and failure in the material laws (elastic-plastic material law with isotropic hardening).
c) Rivet failure both in tension and shear. (Failure was modelled accurately in the areas where plastic hinges were likely to occur. No sensitivity study regarding rivet failure criteria was performed).

General Modelling Problems	Behaviour Problems	Analysis Methods
Mesh generation	Material Failure	Element Formulation
Contact Definitions	Rivet Failure	Material Models
Boundary Conditions	Plastification	Rivet Models
Loading Conditions	Stability	Friction Models
Material Data		Contact Treatment
Friction Data		

Table 1 - Finite element modelling factors (Ref. 8)

The modelling methodology was then used in simulation of the extension of dynamic Test 1 in which the whole frame of a fuselage ‘ring’ was modelled. In modelling the whole ring, as shown in Figure 7, the constraints associated with the passenger floor, as was the case in the dynamic Test 1, were removed. The floor with the added lump masses representing weight at passenger floor level was then allowed to deform.

4 Seat/Occupant Modelling

The occupant model is the standard Oasys LS-DYNA 50th percentile Hybrid III dummy model. The standard model was modified in the femur to allow measurement of the femur loads. Each femur was divided into two segments and a longitudinal spring was introduced between the knee and the pelvic joints.

The seat model is based on the A320 airliner seat type. Since the design of the seat and its interaction with the occupant were of prime consideration, only two rows of a single seat were considered. This represented one of the extreme occupant/seat impact scenarios due to the interaction of the occupant with the front row seat back. A collapsible seat back, using the data for the break-over moment, was incorporated in the model. The interaction between the seats and the floor, referred to as structural seats, through the attachment points was not considered.

The interaction between seat and occupant for secondary impact were modelled by dividing the back of the front seat into several contact surfaces, e.g. seat tray, with varying degrees of compliance. The analysis was confined to models with one occupant positioned on the rear seat.

Both lap and shoulder belt models with a sufficient number of segments for contact definitions were defined. Since the belt to body segment interaction was defined as node-to-surface, insufficient choice of the belt segments would not allow the contact between the belt and the body segments to be maintained. The belts were allowed some degree of slackness (8% web extension).

5 Results

The principal aim was to model the collapse behaviour of a complete section of a fuselage ring subjected to a dynamic crash load and compare the results with the dynamic test. Comparisons were made in terms of:-

a) correlation between the magnitude of applied load and the displacement measured at the interface between the impactor and the specimen.
b) correlation between the predicted and observed mode of collapse mechanism and location of the plastic hinges.

The kinematics of the complete fuselage ring at 50 and 150 msec are depicted in Figure 7. The measured and simulated loads at the structure/impactor interface for the dynamic Test 1 and the complete fuselage ring are shown in Figure 8. Despite the absence of the constraints at the passenger floor, as compared with the dynamic Test 1, Figures 5 and 6, the simulated collapse mechanisms below the floor were not dissimilar to the test. The damage above the floor was minimal. This was indicative of a possible re-definition of the mesh density in this region in order to reduce the model size.

In the structural analysis of the airframe, elements were eliminated from the simulation as soon as either the smallest value of the equivalent plastic strain over the element thickness integration point reached the equivalent strain limit, or the calculated stable time step dropped below the minimum allowed time step. Analysis results indicated that the former criterion applied.

Two sets of simulations were carried out to determine the occupant response for a given seat (known compliant surfaces and break-over strength, Ref. 15) and with both 2 and 3 point restraint systems. The seat pitch in the aircraft ranges from 28 to 38 inches with the seat rows next to the overhanging emergency exits having the highest pitch. No sensitivity study concerning influence of the seat pitch was performed. The simulations were conducted with a seat pitch of 32 inches. The results presented are the kinematics of the occupant and the injury parameters representative of the dynamic Test 1.

In Table 2 selected results of the analyses in relation to the occupant injury indices are tabulated. A detailed account of the injury tolerance levels for human cadaver and Hybrid III is given in (Ref. 10). The absolute values of the injury parameters can be indicative of the level of the injuries sustained during an impact. The kinematics response of the occupant in conjunction with these values can represent the nature of the injuries sustained.

Model	Neck – U. Torso Max Moment (N m) (about x,y,z)	Neck – Head Max Moment (N m) (about x,y,z)	Acceleration (G) (max)			HIC
			Pelvis	Chest	Head	
Lap Belted	14.8 125 1.3	5.9 27 1.4	18.4	47.5	55.4	74
Lap/Shoulder Belted	23.6 61 7	9.4 24 5.8	18.7	33.2	59.2	68

Table 2 - Predicted Injury Indices

The stiffness of the seat tray or seat back, critical in the control of the kinematics of the occupant, influences the injury sustained and, in particular the value of HIC (Head Injury Criteria), set to a tolerable value of 1000, as defined in Ref. 12. Apart from the head, the current airworthiness requirements in addressing the seat design, JAR 25.785 (Ref. 11), does not specify parameters such as seat back stiffness which the occupant simulations identify as critical within the survival space due to secondary impact. The low values of the HIC in Table 2 were due to the absence of the head impact with the front seat back. These values were representative of the head experiencing the whiplash effects.

The neck rotational characteristics are generally expressed at two joints, C1 of the cervical spine and T1 of the thoracic spine. The analysis indicated that the neck loads in the median plane (mid-sagittal) in both models did not exceeded the threshold for the onset of the ligamentous damages (i.e. flexion 163 Nm, extension 54 Nm, Refs. 16 and 17) when compared with the performance envelopes of the mechanical necks for extension and flexion modes, Table 2, Figure 12. These envelopes are based on tests carried out on the dynamic response of the human head neck, using human volunteers and cadavers to produce non-injurious neck response (Ref. 16).

A 3-point lap/shoulder belt would require a seat with elevated seat back break-over properties in order to support the transfer of the upper torso forces from the seat pan to the seat back. This in turn would result in the generation of higher moments through the seat structure. The occupant can be relatively better off in terms of the head injury parameter. In reality, however, the implementation of such a restraint system requires significant fortification of the seat and floor to accommodate the extra loads generated.

The contact between the lower legs and the occupied seat, and the front seat were minimal in the cases studied. The dynamic response of the occupant and the forward flailing motion of the tibia under some impact scenarios would result in an increased contact load when the tibia impacts the rear spar of the front seat. Although leg and arm injuries may not be as serious as head or chest injuries, excessive loading may cause fracture and prevent escape from a stricken vehicle. This would in turn hamper evacuation with a possible exposure to the risk of post-crash fire.

6 Conclusions

Based on various modelling techniques previously adopted in modelling airframe sub-structures at component level, the approach was extended to predicting the failure mechanisms of an underfloor component of an aircraft structure under controlled impact conditions. The modelling technique was effectively used to evaluate a complete fuselage ring and consequently full-scale FE modelling of aircraft crash simulations. The study showed that:-

a) Rivets close to the failure regions should be accurately modelled.
b) Although most of the structure can be modelled without resorting to a fine mesh, i.e. fuselage skin away from the frames, the regions of localized failure must be modelled with a fine mesh in order to capture the failure mechanism.

In departing from relatively small FE to larger models, the knowledge of the influencing modelling factors highlighted here are important. This combined with the engineering judgement regarding failure mechanisms can allow model size and complexity to be reduced without compromising the accuracy of the results.

The behaviour of the modelled Finite Element seat(s) which included the interaction between the seat and the occupant was investigated in relation to the predicted injuries. Both safety-engineered seat and more compliant seat back contact surfaces can significantly alter the kinematics of the occupant and the related injuries occurring in the survivable space as a result of the occupant secondary impact.

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