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THE DYNAMIC MODES AND NATURAL FREQUENCIES OF OVERHEAD STOWAGES IN TRANSPORT AIRCRAFT

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ABSTRACT

On 8 January 1989, a British Midland Airways Boeing, 737-400 aircraft crashed on its final approach to land. The UK Air Accidents Investigation Branch (AAIB) conducted an investigation into the accident and recommended that;

> "The certification requirements for cabin stowage bins, and other stowage items of mass, should be modified to ensure the retention of these items to fuselage structure when subjected to dynamic crash pulses substantially beyond the static load factor required."

Research has revealed that no detailed analytical investigation to provide a better understanding of the behaviour of overhead stowages in crash situations has been conducted to date. The project includes the following; 1. Simulation of tests conducted by the FAA using mathematical modelling tools to develop a methodology for estimating overhead stowage attachment dynamic pulses, 2. Simulation of overhead stowage attachment loads during the Boeing 737 accident, 3. Investigation of stowage behaviour under different crash scenarios, 4. Isolation of critical overhead stowage dynamic load cases. An F.E. Model of a Boeing 707 fuselage section has been created and is currently being validated.

INTRODUCTION

Much work has been directed at improving the human survivability of transport aircraft accidents through crash dynamics research. The main focus of all such research has been on primary structure such as the fuselage and other secondary structure such as seats.

The accident report into the Boeing 737 accident at Kegworth in Leicestershire, England in 1989, indicated the need for improvements in the capacity of overhead stowages to withstand dynamic crash pulses. No detailed analytical investigation has as yet been conducted to provide a better understanding of the behaviour of overhead stowages in crash situations.

CRASH DYNAMICS: THE 1980's

In 1984, the United States Federal Aviation Administration (FAA) published a Draft Advisory Circular, clearly stating the FAA's goal of improving structural crash dynamics analytical methodologies for transport airplanes.(1) The core of the FAA crash dynamics and engineering program centred on the following areas:

- definition of survivable transport impact environment;
- development of analytical methods to define structural and occupant responses in a survivable crash;
- establishment of performance parameters to ensure continued high level of occupant safety.

SURVIVABLE TRANSPORT IMPACT ENVIRONMENT

As a first step a review of past accident data was conducted by major aircraft manufacturers which indicated that contemporary transport aircraft possessed a commendable level of crashworthiness. Subsequent research work was therefore directed to:

i. define that safety level quantitatively;
ii. improve safety levels where necessary;
iii. ensure that the desired safety level was maintained in future transport aircraft design.

DEVELOPMENT OF ANALYTICAL METHODS

As a result, the development of analytical methods such as KRASH and SOMTA was sponsored by the FAA. Fuselage section drop tests were included in the FAA crash dynamics program for validation of the above analytical crash dynamic modelling techniques but also more specifically, to provide accurate information on the crush characteristics of the lower fuselage shell during an impact condition, on which the modelling techniques were dependent. (2)

CONTROLLED IMPACT DEMONSTRATION (CID)

In addition, as part of the overall FAA/NASA joint effort to develop improved crash dynamic analytical methodology, a full scale remotely piloted transport air-to-ground impact test was performed. The primary goal of that test, which became known as the Controlled Impact Demonstration (CID), was to acquire crash impact data and validate analytical models.(3) The Controlled Impact Demonstration test was performed on 1 December 1984, at the NASA

21st ICAS Congress
13-18 September 1998
Melbourne, Australia

Dryden dry lake bed, Edwards Air Force Base, California.

The controlled impact demonstration was an integral part of the development and validation of analytical methodologies. Other areas identified for further work included the creation of crash design envelopes by cross-plotting the results from a series of attitude versus sink speed studies.

CRASH DESIGN CRITERIA

By 1984, substantial progress had been made in the advancement of methodology for assessing aircraft structural crash dynamics behaviour and the definition of dynamic pulses associated with aircraft crashes. There was a renewed focus on:

- new seat dynamic test requirements for commercial aircraft;
- composites;
- fuel containment.

The FAA has sponsored extensive research and development effort (Figure 1) which is detailed in other published documents.[4]

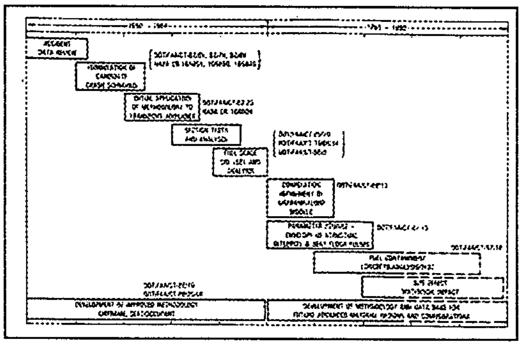

Figure 1. FAA impact dynamics program 1980 - 1989.

ON-GOING ANALYTICAL METHODOLOGY

The analysis and testing of full-scale fuselage sections continued throughout the 1980 - 1989 period to furnish the FAA with additional data.[5][6]

THE ACCIDENT TO BOEING 737-400 G-OBME

On 8 January 1989 the crew of a British Midland Airways Boeing 737-400 with registration G-OBME, engaged on a double shuttle between London Heathrow Airport and Belfast Aldegrove Airport, experienced vibration and a smell of fire. One engine was subsequently shut down and the aircraft diverted to the East Midlands Airport. Unfortunately, when the aircraft was 2.4 nautical miles from touchdown at a height of 900 feet above ground level, there was an abrupt decrease in power from the remaining engine. The aircraft crashed with a nose-high attitude on level ground just to the east of the M1 motorway. It then passed through trees and suffered a second and major impact 70 metres to the west and 10 metres lower, on the western embankment. The fuselage was extensively disrupted, and the aircraft came to rest entirely on the wooded western embankment approximately 900 metres from the threshold of East Midlands Airport runway 27 and displaced 50 metres to the north of the extended runway centreline.[7]

Of the 8 crew and 118 passengers including one infant on board, all the crew and 71 passengers survived the accident. Due to the excellent survival rate of the accident and the relatively well preserved state of the fuselage, detailed information became available for analysis of the aircraft and its response to dynamic crash pulses.

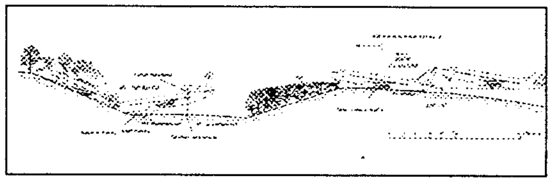

Figure 2. Impact sequence

CRASH DYNAMICS: 1990 - 1997

By the beginning of the 1990s, much effort had been invested in improving the survivability of transport aircraft accidents through aircraft crash dynamics research. The accident to the British Midland Airways Boeing 737-400 provided an additional impetus to transport aircraft crash dynamics research.

THE IMPACT OF THE KEGWORTH ACCIDENT

The Air Accidents Investigation Branch (AAIB) of the UK Department of Transport conducted an investigation into the accident and presented their findings including the following;[8]

- Although the overhead stowage bins met the appropriate Airworthiness Requirements for static loading, all but one of the 30 bins fell from their attachments, which did not withstand the dynamic loading conditions in this accident.
- Some of the doors on the overhead stowage bins opened during the last seconds of flight, demonstrating the need for some form of improved latching of the doors.

THE AAIB'S SAFETY RECOMMENDATIONS

The AAIB made safety recommendations including the following;

- The certification requirements for cabin stowage bins, and other cabin items of mass, should be modified to ensure the retention of these items to fuselage structure when subjected to dynamic crash pulses substantially beyond the static load factors currently required (Made 30 March 1990).

- The CAA consider improving the airworthiness requirements for public transport aircraft to require some form of improved latching to be fitted to overhead stowage bins and this should also apply to new stowage bins fitted to existing aircraft. (Made 30 March 1990).

Since the Kegworth accident, many of the issues identified in the inspectors report have been tackled and many more are still being addressed.

EFFECT OF AIRCRAFT SIZE ON OCCUPANT CRASH LOADS

One of the many analytical investigations conducted subsequent to the Kegworth accident included an investigation into the effect of aircraft size on the loads that occupants were subjected to in a crash situation, using the properties of the Boeing 737-400 and 747-400 aircraft.(9)

CONCLUSIONS ON EFFECT OF AIRCRAFT SIZE

In the aircraft size effect investigation, crash models were developed using the ABAQUS(10) program's non-linear structural dynamics features and validated by analysing the 737-400 accident at Kegworth (Figure 3). A 747-400 was then modelled using the same techniques.

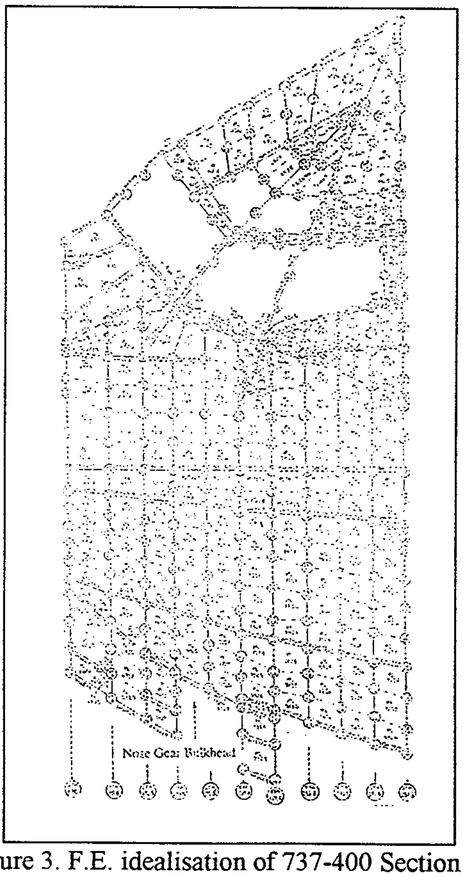

Figure 3. F.E. idealisation of 737-400 Section 41

RECOMMENDATIONS

As a result of the above investigation, several recommendations were made including the following;

- maintenance of occupant survivable volume was of particular concern and further studies of large aircraft needed to be conducted using more detailed structural models of sections of the two aircraft. The increase in detail was considered necessary to understand the structural behaviour in the presence of large deformations better.

EXAMPLES OF OTHER RESEARCH TASKS UNDERTAKEN IN THE 1990S.

Several crash dynamics research projects were undertaken in pursuit of the goal of improving aircraft crashworthiness. A sampling of typical projects undertaken are detailed below.

BEAM DESIGN FOR COMPOSITE AIRCRAFT SUBFLOORS

The focus of the study was the design and testing of subfloor structural concepts that would limit the loads transmitted to aircraft occupants to less than 20 g at crush speeds of approximately 30 feet/sec.(11)

SIMULATED CRASH RESPONSES OF COMPOSITE STRUCTURES

The KRASH and DYCAST (DYnamic Crash Analysis of STructures) codes were used to model the impact responses of composite airframe structures. Excellent correlation was obtained between the analysis and experimental data.(12)

MULTIBODY DYNAMICS OF AIRCRAFT OCCUPANTS

In this study, crash dynamics program SOM-LA/TA, incorporating a dynamic model of the human body with a finite element model of the seat structure was used to conduct a study of post-crash dynamic behaviour of victims.(13)

THE LONGITUDINAL ACCELERATION TEST

The longitudinal acceleration test of overhead stowages in a transport airframe section was one of a series of section and full-scale tests conducted in support of the Federal Aviation Administration's (FAA's) Crash Dynamics and Engineering Development Program. The test took place between June 1990 and January 1991.(14)

THE TEST OBJECTIVE

The objective of the test was to determine the interaction between and the performance of a transport aircraft fuselage section and the overhead stowage bins under simulated longitudinal impact conditions which were considered survivable. Response data from these tests would be used to determine the dynamic response characteristics of the airframe installation and to calibrate analytical computer programs such as the lumped mass model "KRASH".

THE TEST ARTICLE

The airframe test article was a ten-foot section cut from the aft fuselage of a Boeing 707 transport aircraft. The section was configured with two rows of triple passenger seats on the left side only, an auxiliary fuel tank, a 60 inch overhead stowage bin (referred to as Bin 'A') and a 20 inch, 60 inch, 20 inch (referred to as Bin 'B') series of overhead stowage bins on the left side.

Three tests were conducted. The first test attained a peak acceleration of 5.9 g and a velocity change of 30.7 ft/sec. The second test reached 8.8 g and 37.5 ft/sec. The third test resulted in 13.2 g and 42.3 ft/sec. The input acceleration pulses were triangular in shape.

THE RESULTS

Acceleration measurements were obtained from the fuselage and the overhead stowage bins. Load measurements were obtained from the overhead stowage bin attachment links. Peak longitudinal floor acceleration levels were 6.6g in the front and 6.5g in the rear for the first test, 9.3g front and rear in the second test, and 15.0g in the front and 15.3g in the rear for the third test.

At the maximum test condition (Test 3);

- peak longitudinal accelerations measured at the fuselage floor were in the 15.0g to 15.3g range,
- peak longitudinal accelerations measured on the overhead stowage bins were 20.5g for Bin 'A' and 23.3g for Bin 'B'.

VERTICAL DROP TEST OF A NARROW-BODY FUSELAGE SECTION

In October 1993 the FAA Technical Center conducted a vertical drop test of a narrow-body fuselage section.[15] This vertical impact test was also part of the FAA's ongoing Aircraft safety research plan. Previous cabin safety research efforts had led to the definition of the survivable crash environment, the development of crash dynamic analytical modelling methodologies, and improved design standards and regulatory requirements for aircraft seats and aircraft interiors.

THE TEST OBJECTIVES

The primary objective of the test was to determine the dynamic response characteristics of the;

- overhead stowage bins and;
- auxiliary fuel tank system; as well as the
- fuselage section itself, when subjected to a potentially survivable impact.

Additional test objectives included;

- obtain test data to validate analytical predictions;
- evaluate the impact response characteristics of interior overhead bins and double wall auxiliary fuel tank systems; and,
- identify failure modes, if possible, for interior overhead bins and double-wall auxiliary fuel tank systems under dynamic impact conditions.

The test was intentionally structured to simulate a severe, but survivable, crash. Therefore, this test imposed a dynamic load condition in excess of the current design and certification requirements for the onboard items of mass.

THE TEST ARTICLE

The test article was a ten-foot tapered section of a Boeing 707. The section was equipped with six, floor mounted, triple passenger seats placed in three rows. Mannequins, anthropomorphic dummies and ballast, i.e. torso shaped wood blocks, were strapped firmly into the seats with restraint systems. A 330-gallon, double walled, cylindrical tank was mounted to the underside of the fuselage floor. The tank contained 247.5 gallons of water to simulate the weight of a full tank of fuel and was pressurised to 2.5 psi.

A 60 inch Boeing overhead stowage bin was mounted on the left side of the fuselage. A 20 inch Boeing overhead stowage bin was mounted in front of the 60 inch bin and another 20 inch bin was mounted behind the 60 inch bin. The bin was fitted with accelerometers and the support links with strain gauges. On the right side of the fuselage, a 113 inch C&D stowage bin was mounted. This bin was also fitted with accelerometers and its support attachments were strain gauged. The total weight of the test article was 8097 pounds.

THE TEST FACILITY

The FAA Technical Center Test Facility was composed of two 50-foot vertical steel towers connected at the tops by a horizontal platform. An electrically powered winch, mounted on the platform, was used to raise or lower the test article and was controlled from the base of one of the tower legs.

THE TEST

The airframe test section was levelled and then raised to the desired height of 14 feet. At that point, the aircraft section was then released and accelerated to an approximate velocity of 30 ft/sec at impact.

RESULTS OF THE VERTICAL DROP TEST

The conclusions drawn from the vertical drop test include the following;

i. At a 30-feet-per-second vertical impact velocity, the drop test of a narrow-body fuselage section resulted in a severe but survivable test that could be expected to inflict moderate injury to occupants. The average idealised triangular pulse deceleration for the fuselage was 36 G_{max}, with an approximate duration of 57 milliseconds.

ii. The Boeing bin maintained its structural integrity and remained attached to the fuselage after the test, although four links of a total of fifteen, fractured after the primary impact. The door of this bin was strapped closed for test purposes otherwise its contents would have spilled out due to the fracture of its door hinges and latching mechanism. Two of six C&D bin attachments separated. The bin exhibited an additional structural fracture, resulting in the bin breaking up and remaining only partially attached to the fuselage structure. This resulted in the spilling of the bin contents.

iii. A comparison of the calculated loads and the measured loads for the upper attachment links of the Boeing bin showed good correlation with minimal dynamic amplification. A comparison of the calculated loads and the measured loads, up to the point of failure, for the upper brackets of the C&D bin also showed good correlation with minimal dynamic amplification. The measured and analytical data may be used to evaluate current regulatory requirements and analytical load predictive methodologies.

iv. The passenger service units (PSU) attached to the Boeing bin came loose primarily due to the relative motion between the bin and the fuselage. The PSUs were attached to both the bin and the fuselage side wall.

STATUS OF CRASH DYNAMICS RESEARCH IN 1997

Additional tests and analyses have been planned and executed since those outlined in the preceding subsections. The FAA's crash dynamics research program is on-going and will continue for some time to come.

ON-GOING AND PLANNED RESEARCH

One major development in aircraft cabin safety research in general, and crash dynamics research in particular in the 1990s has been the development of the "Cabin Safety Research Program", by the North American and European airworthiness authorities.[16] Crash dynamics research forms an integral part of this programme.

THE CONFERENCE

An international conference on cabin safety research was held in Atlantic City New Jersey in November 14-16 1995. The main objectives of the conference were to:

i. present the FAA Cabin Safety Research Programme to the public;
ii. get input from the industry and users on the direction that future research should take;
iii. provide a frame of reference to the public.

OBJECTIVES OF THE CABIN SAFETY RESEARCH PROGRAMME

The objective of the cabin research programme is to enhance the effectiveness and timeliness of cabin safety research to achieve improved and more consistent rules/standards. The programme addresses two aspects of cabin safety illustrated by Figure 4, namely:

i. post crash survivability, which includes, physical protection from the crash, egress (evacuation/fire protection) and water/environmental survival, and,
ii. in-flight safety which covers turbulence, decompression, fire protection and medical considerations.

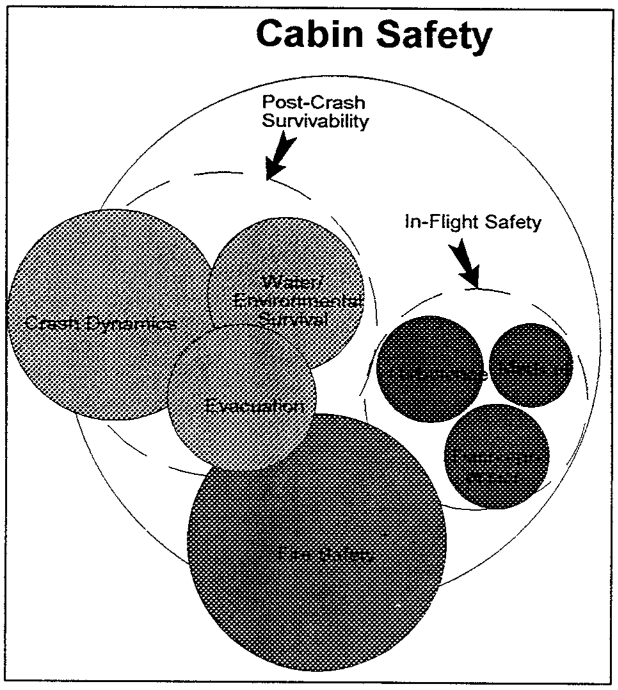

Figure 4. Aspects of cabin safety

JUSTIFICATION FOR THE CO-ORDINATED PROGRAMME

One justification for the co-ordinated programme is that, industry deserves and has a vested interest in having "good" and consistent standards and regulations, i.e. standards that can be realistically achieved. Air traffic is expected to double within the next ten to fifteen years.[17] This increase will render the present accident rate unacceptable.

CABIN SAFETY RESEARCH IN EUROPE

In parallel with the cabin safety research efforts in North-America, a considerable amount of work has been and is being undertaken in Europe.

THE FOURTH FRAMEWORK PROGRAMME

In its fourth framework programme scheduled to run from 1996 through to 1998, the EU Transport Directorate has identified certain areas in which it is willing to support cabin safety research in addition to many other ongoing research tasks including; enhanced passenger crash protection through improved integrity of seat attachments, seat design, passenger restraint systems, stowage bin and galley integrity for a range of typical aircraft crash loading scenarios.[18]

OTHER RESEARCH TASKS

Other cabin safety research tasks conducted in Europe include;

Research to determine the least damaging brace positions.[19] Following the Boeing 737 accident at Kegworth in Leicestershire, research has been conducted to determine the brace position most likely to result in the lowest risk of injury. The recommended position illustrated in Figure 5 is described as follows;

> "Adopt a crouched position like a ball, with hands clasped firmly on top of head, elbows tucked outside knees and head resting against the structure in front if possible. Legs should be positioned with feet together slightly behind knee."

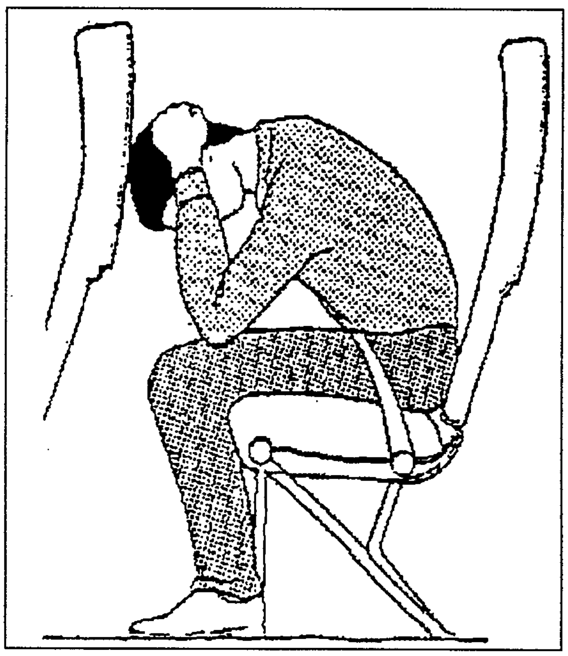

Figure 5. Recommended brace position

The development of hybrid tools such as the Air Accident Investigation Tool (AAIT) developed by the Cranfield Impact Centre, which has helped in the understanding of crashes. It allows investigators to associate aircraft kinematics with forces, failure mechanisms and time histories. This enables the causes of injury to be established through parametric studies and the means of reducing/eliminating the cause can then be identified.[20]

The planning, development and construction of the Italian crash test facility for large aerospace structures LISA which is still ongoing.

The Falcon 10 test programme[21] sponsored by the French Civil Aviation Authority (DGAC) to:

- validate a crash computational model for small FAR/JAR 25 aircraft;
- evaluate the adequacy of required dynamic test landing standards; and,
- propose rulemaking adapted to business jet size aircraft.

The crash test was performed at CEAT (The Toulouse Aeronautical Test Centre) in 1993 and the results published in 1995. The simulated crash scenario was an emergency landing after take-off. The aircraft weighed 8000kg (17600lbs) and was subjected to a swing test from a height of 14.6m (48ft). It achieved vertical and horizontal speeds of 6.9m/s (22.6ft/sec) and 14.7m/s (48.2ft/sec) respectively.

It was the first swing test undertaken in Europe and provided valuable information to the French research programme for the reduction of certification compliance costs and the improvement of safety through a risk/benefit analysis.

FUTURE CRASH DYNAMICS RESEARCH TOPICS

In his paper to the international conference on cabin safety research, Mr Stephen Soltis, the National Crash Dynamics Resource Specialist of the US Federal Aviation Administration identified areas in crash dynamics research where there was scope for future work including;[22]

INTERIOR FURNISHINGS

Interior furnishings require further research since separation in an accident may cause occupant injury and impediments to emergency evacuation.

The identified items include:

- overheads stowage bins;
- passenger service units (PSUs); and
- other impediments.

THE DYNAMIC MODES AND NATURAL FREQUENCIES OF OVERHEAD STOWAGES IN TRANSPORT AIRCRAFT

This research project which is still on-going was proposed to address the recommendations made by the UK Air Accidents Investigations Branch of the Department of Transport.

A typical transport aircraft overhead stowage and its location is illustrated by Figure 6.

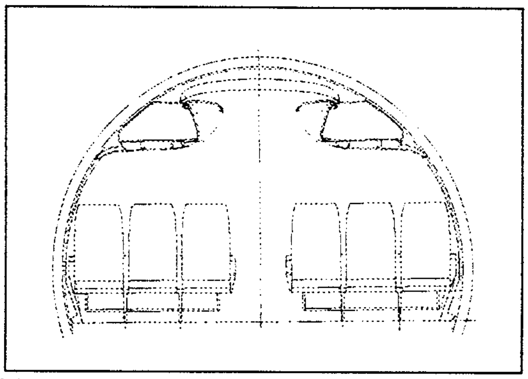

Figure 6 Typical overhead stowage and location.

An investigation into the dynamic modes and natural frequencies of overhead stowages would facilitate better understanding of the behaviour of overhead stowages in crash situations.

To provide this understanding, the research project includes the following features;

1. Simulation of vertical drop and horizontal acceleration tests of Boeing 707 fuselage sections conducted by the FAA using mathematical modelling tools such as MSC/NASTRAN and MSC/DYTRAN to develop a methodology for estimating overhead stowage attachment dynamic pulses,
2. Simulation of overhead stowage attachment loads during Boeing 737 accident at Kegworth, Leicestershire,
3. Investigation of stowage behaviour under different crash scenarios,
4. Isolation of critical overhead stowage dynamic load cases.

The current status of the work is as follows:

A coarse mesh of a Boeing 707 fuselage section between frames 1120 and 1240 has been created and an initial static run performed to validate the model.

It is intended that the two crash tests conducted by the FAA be simulated using;

a coarse mesh for initial predictions of fuselage response and,

a refined mesh in the region of stowage attachments for predictions of stowage responses.

This simulation would then in turn facilitate the development of a methodology to simulate the Kegworth accident and investigate the dynamic modes and natural frequencies of overhead stowages under different crash scenarios.

Given the recent Japan Airlines experience of overhead stowage detachment in severe turbulence leading to one fatality and injury to passengers, it would appear that such an investigation would be timely.

CREATION OF MODEL

Due to difficulties in obtaining drawings, actual measurements were made of a Boeing 707 fuselage section. Using this geometry, a preliminary model was created. In this model, all fuselage frames, stringers, floor beams and seat tracks were modelled as bar elements which are simple one dimensional beam elements defined by two grid points in the model, cross-sectional area, area moments of inertia, torsional constant and material properties. All skin and floor panels were modelled as quad4 quadrilateral shell elements defined by four grid points in the model, thickness, material properties and material property orientation. The preliminary model is shown in Figure 7.

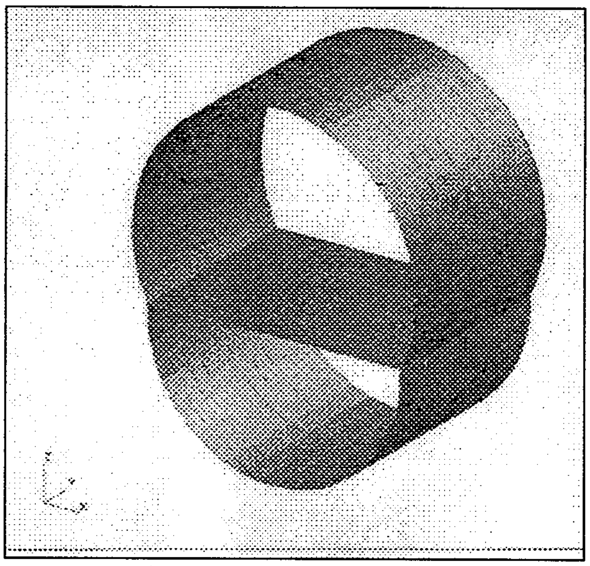

Figure 7 Preliminary FE model.

At the time of writing this report, the model is nearing completion for validation using static loads.

CONCLUSION

It has been shown that given the forecast increase in air travel in the next decade, there is scope for such a project and that such work would be timely.

It is hoped that the results of this research would be a methodology that would make a significant contribution to safety in air travel.

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