Application of Finite Element Dynamic Simulation to Airplane Cabin in Air Turbulence

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Abstract

This paper describes demonstration of the effect of air turbulence on belted and un-belted occupants and unsecured objects inside an aircraft cabin using finite element computer simulation. A finite element model of a fuselage section was used to simulate the aircraft cabin environment. The model contains two hybrid III dummy models and a serving cart. This is an un-validated effort, however, the simulations provide a fantastic (and credible) tool for public education, additional research in injury mechanism in air turbulence scenarios, and potential cabin safety improvements. As cases of in-flight passenger injuries due to air turbulence are amassing in the increasing air-travel environment, the immediate need for use of the safety belts and the need for public appreciation of the risks associated with in-flight turbulence incidents may be realized more easily through the use of such simulations.

Introduction

There seems to be two parallel phenomena at work in the dynamics of the accident rates and efforts to reduce fatalities. 1) The number of flights and passenger miles traveled are increasing, while the accident rate is on (or expected to) decline since the "Gore Commission recommendations"[1]. 2) Reducing fatalities have been targeted, thus there is a focused effort in reducing CFIT (Controlled Flight into Terrain) and in-flight human errors (with some significant success), while other type of accidents such as in-flight fires and explosions, runway incursions, and non-fatal (or low fatality) accidents, such as ***in-flight turbulence***, have attracted more attention. One may also argue that the increased pressures on airlines for on-time performance, sensitivity of hub and spoke operations to delayed flights may result in more pilots "braving the storms". In addition, probability of encountering "clear-air turbulence" has increased due to the significant increase in air-travel. Finally, the increasing need for use of smaller planes, turbo-props and proliferation of the commuter planes, makes passenger safety in turbulence conditions a more important issue.

According to the recent available data[2], there have been 3 fatalities and 629 injuries due to air turbulence between 1980-1997. These numbers are certain to rise in the future and airline crew injury and long-term work disability is of a grave concern. The recent efforts by ATA (Air Transport Association) which lead to the new policy of requiring or encouraging seat belt use by airplane passengers, while seated, is a significant step to address this problem. Theoretically, one may conclude that by having seat-belts worn at all times, injury in turbulence conditions should be totally alleviated. There are, however, a large number of issues that would remain. Some are listed below:

1. Rate of compliance of passengers with wearing seatbelts while seated, in or out of turbulence.
2. How well (i.e. tight) the belt is worn.
3. Overhead bin latch performance (over-stuffed bins)
4. Children wearing seatbelts (designed for adults) or those carried on laps.
5. Unsecured objects within the cabin including the serving cart.

Beyond direct passenger safety issues, one may speculate about rare, but potentially dangerous subsequences on aircraft systems during severe turbulence.

It appears that educating the public as well as the crew about the dangers of air turbulence (and taking it seriously) is a first and necessary step. As cases of in-flight passenger injuries due to air turbulence are amassing in the increasing air-travel environment, the immediate need for use of the safety belts and the need for public appreciation of the risks associated with in-flight turbulence incidents may be realized more easily through the use of dynamic simulations. This paper presents such an approach by using Finite Element (FE) dynamic modeling of a fuselage section exposed to air turbulence. Hybrid III dummy models[3] are used to simulated both restrained and unrestrained occupants and a serving cart is placed in the isle to simulate an unsecured, potentially dangerous, object in the cabin environment. Although, this is a preliminary and un-validated effort, the finite element simulations provide a credible and versatile tool for public education, additional research in injury mechanism in air turbulence scenarios and potential cabin safety improvements.

Description of the Finite Element Model

The finite element model consists of a partial airplane structure that includes seats, floor, windows, and head bins[4]. Two 50th percentile male Hybrid III dummies are placed in close proximity. Only one of the dummies is belted to the seat. The seats and the rest of the airplane structure are modeled with 23,000 rigid shell and solid elements. The two dummies are modeled with 14000 elements each[5]. Most of the dummy parts are made of rigid materials connected with joints that allow the dummy to exhibit the proper biomechanics response. The neck and head skin are modeled with viscoelastic materials that give a more realistic response of the head impact with the overhead bins. The seat belt elements are modeled with beam materials that allow only tensile forces. Seat belt material is given the characteristics of actual seat belt fabric as a force vs. deflection load curve.

The code used to run the simulations is LS-DYNA3D[6]. This code is mainly used for automotive-type crash simulations. The duration of automotive crashes is usually less than 200 milliseconds with calculation time steps in the order of microseconds. The calculation time step depends on the length of the crash event, material characteristics, and size of the model. Normally for a model similar to this turbulence simulation model, calculation time would be in the order of 10 hours per 100 milliseconds. To limit computation time, it was necessary to use only a part of the turbulence data. A 2.5 seconds clip that represents most dramatic change in vertical velocity was chosen for this simulation. The conditions right before this 2.5 seconds clip were taken from turbulence data and given to the finite element model as initial conditions.

The finite element code uses contact algorithms to prevent user-specified objects from penetrating each other. The code applies physical laws to apply the necessary forces between contacting objects and update the displacement and velocity of all elements in the model. The update rate depends on the physics of the problem. In this computer simulation, the update rate that was required for calculations and data analysis was 5 milliseconds.

The Turbulence Environment and The Input for Simulation

Generic turbulence data sample from an actual flight recorder for a commercial transport aircraft is shown in Figure 1. The length of the event, 2 minutes, makes it nearly impossible to simulate cabin environment. As stated above, a short period (2.5 seconds) containing some of the more dramatic change in the vertical acceleration was used. As Figure 1 shows the 3-axis acceleration

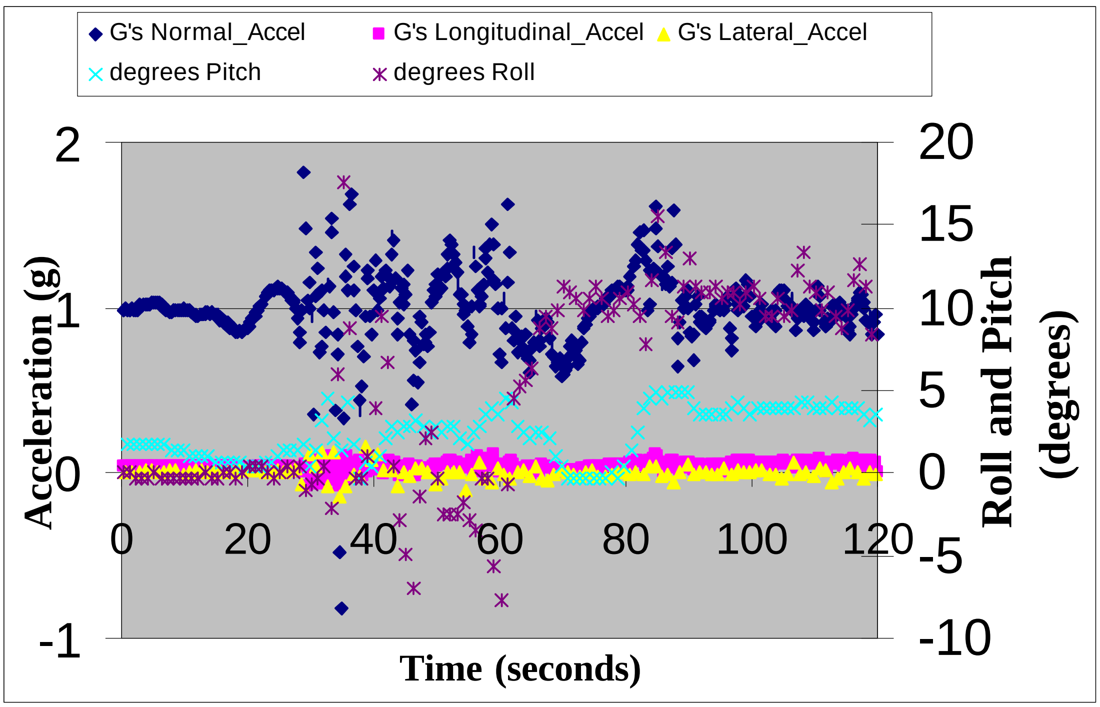

Figure 1 - Turbulence raw data

in addition to pitch and roll which were used as input for the simulation. Given the head clearance in aircraft cabin, which is in the order of 0.5 m for an average height adult occupant, a simple calculation shows that a rapid change in acceleration vector (upward followed with downward) in about 100 milliseconds can result in an unbelted occupant impacting the overhead bin. The problem may be exaggerated due to pitch and roll of the aircraft. It is clear that if an average occupant can be thrown about the cabin in conditions described above, the risk to infants (being held by adults and not in a child safety seat) and children may be far greater. Lack of data for children and infants, traveling on lap, may be partly due to the much lower frequency (passenger miles traveled) for this class of passengers. It should be also noted that lap belts which have been designed for adults, may not provide adequate protection to small children due to belt slippage in a severe turbulence. In addition, loose objects in the cabin, particularly laptop computers, books and similar material would pose potential hazard to all occupants in these turbulence environments even when turbulence warning has been issued and all passengers have been belted. Finally, the very difficult issue of serving cart dislodgment and potential for overhead bin opening in severe turbulence remains a contentious matter.

Results and Limitations

The primary result of the modeling work is the dynamic simulation of the aircraft cabin. The initial state, prior to imposing the motion and acceleration, is shown in Figure 2a. The dummy seated in the left is belted, although the belt is not shown here. The serving cart is approximately 35 kg and is initially at rest. The other state, shown in Figure 2b, is at the time of impact of the un-belted dummy. These figures show the dramatic variations in the cabin environment after a short, approximately 2 seconds, time period. The unbelted dummy is thrown and rotated due to the sudden change in velocity and roll of the aircraft. The impact on the head and neck of the dummy is the greatest concern from injury point of view. The cart is falling back after impacting the overhead bin and roof lining. The potential damage to the roof and fuselage is not being modeled here, although the modeling approach is quite capable of predicting the damage. In order to fully model such interactions, the details of the structure and material properties have to be included. In such a scenario (i.e. cart impacting the roof lining) the potential damage to wiring, control lines and other systems located behind the lining as well as the possible damage to the fuselage itself can be modeled.

The finite element modeling also allows the more detailed time-dependent examination of multitude of parameters including forces, acceleration, velocity and deformations. Figures 3-5 show a selective display of these parameters.

Figures 3 and 4 show the reaction of the belted and unbelted dummies to sudden change in cabin vertical speed. The belted dummy is constrained to the seat and follows a relatively smooth velocity change that translates into a minor acceleration. The unbelted dummy, however, leaves the seat and gets stopped by the head bin (vertical solid line in Figure 3). The impact with the head bin produced the high acceleration (18 g) as shown in Figure 4. The high acceleration that the unbelted dummy experienced, combined with the total weight of the dummy, produced very high impact forces on the head as shown in Figure 5. This impact force of over 8 KN can cause skull fracture in addition to severe neck injury. It is customary to use the Head Injury Criterion (HIC) number as an index for such impacts. The interpretation of HIC number may be controversial at times. In this particular case, it may be less relevant, but is discussed for completeness. The acceleration pulse in Figure 4 produces a relatively low HIC number (which is a normalized integration of acceleration in time). However, it is the difference between the impact process (weight of the dummy being transferred through the neck to the head) in this case, vs. automotive accidents (where HIC number was defined for) that is the concern.

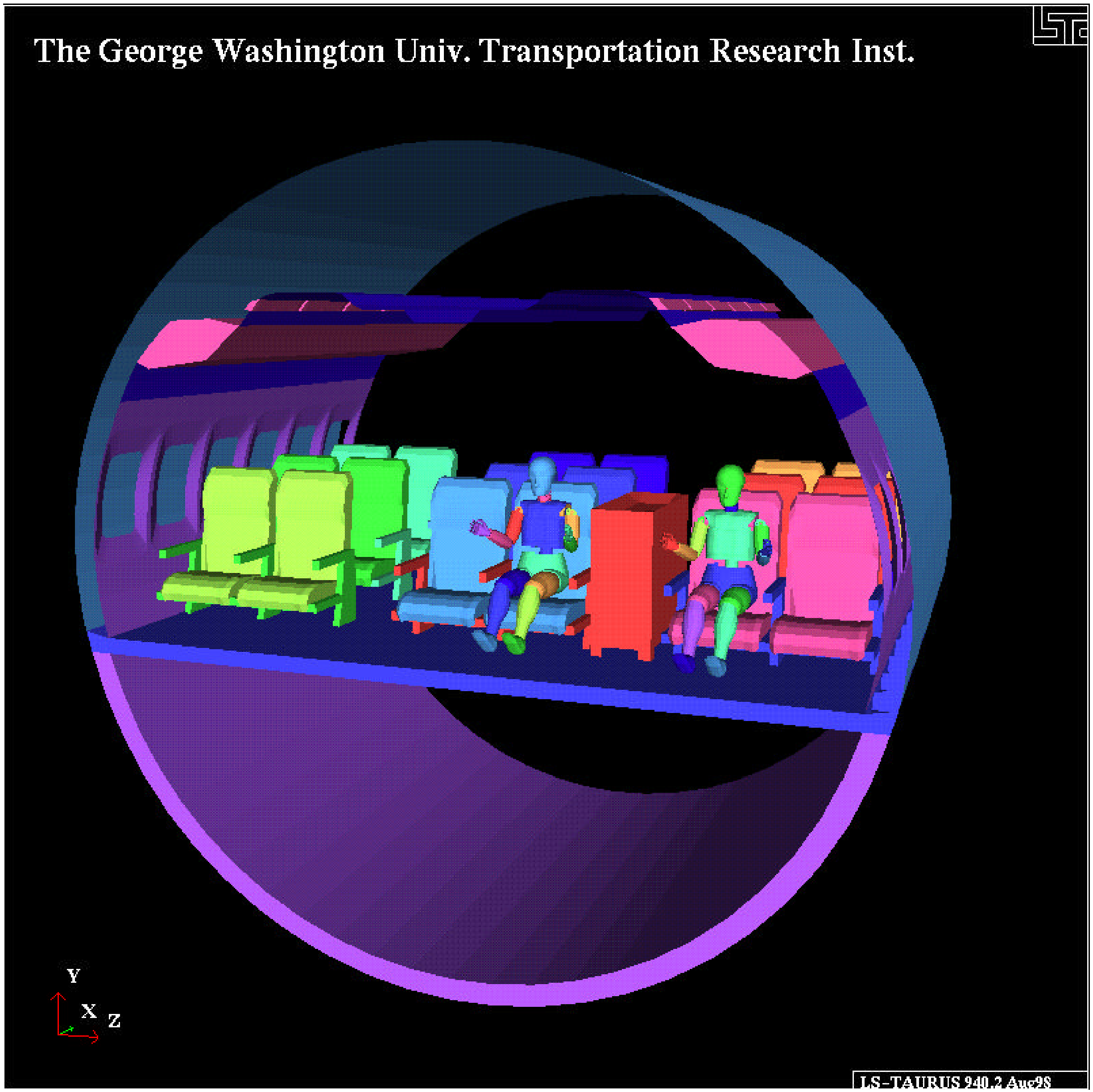

Figure 2a -Finite Element Model of the Fuselage Section, Initial State

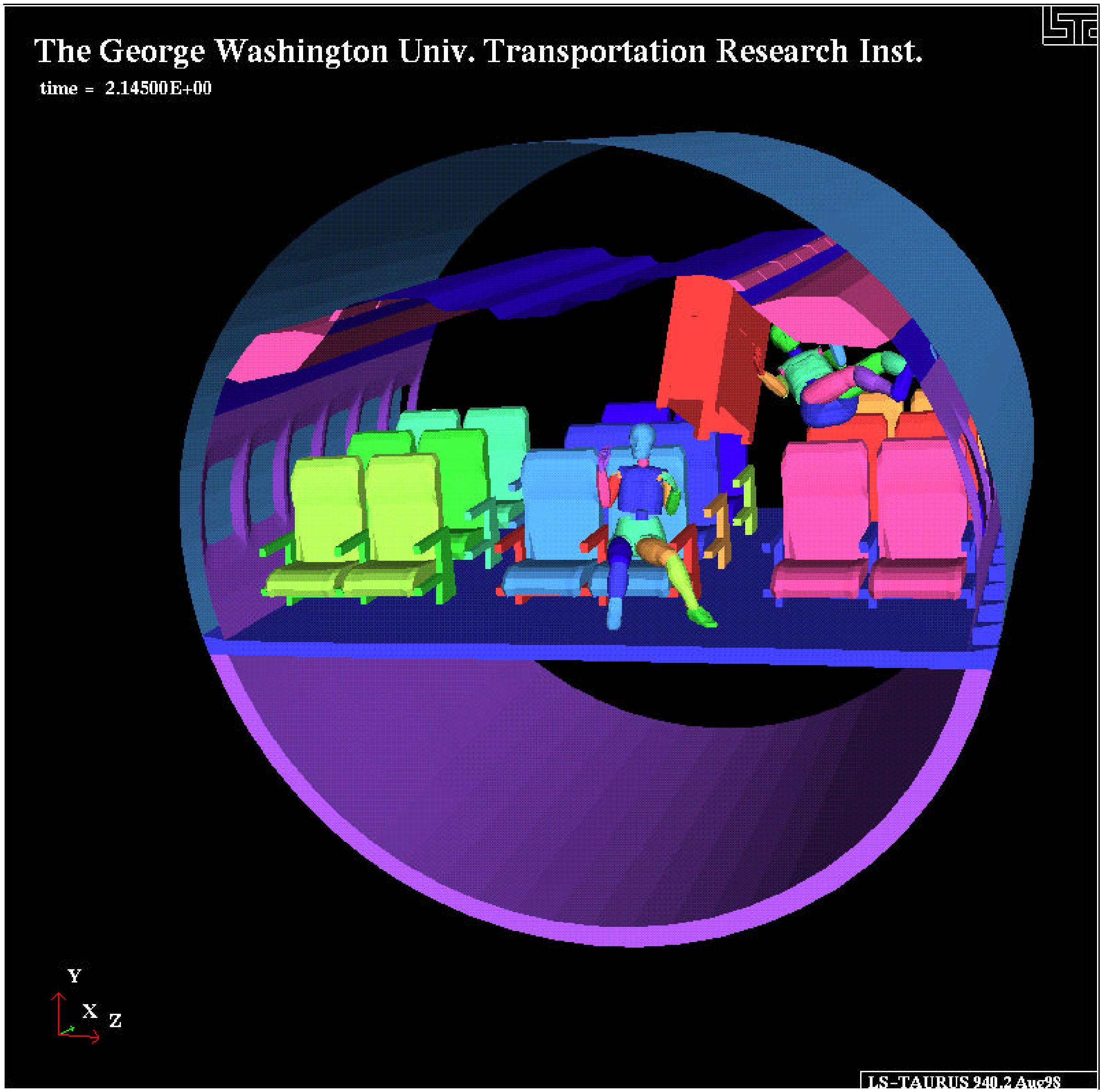

Figure 2b -Finite Element Model of the Fuselage Section, Impact State

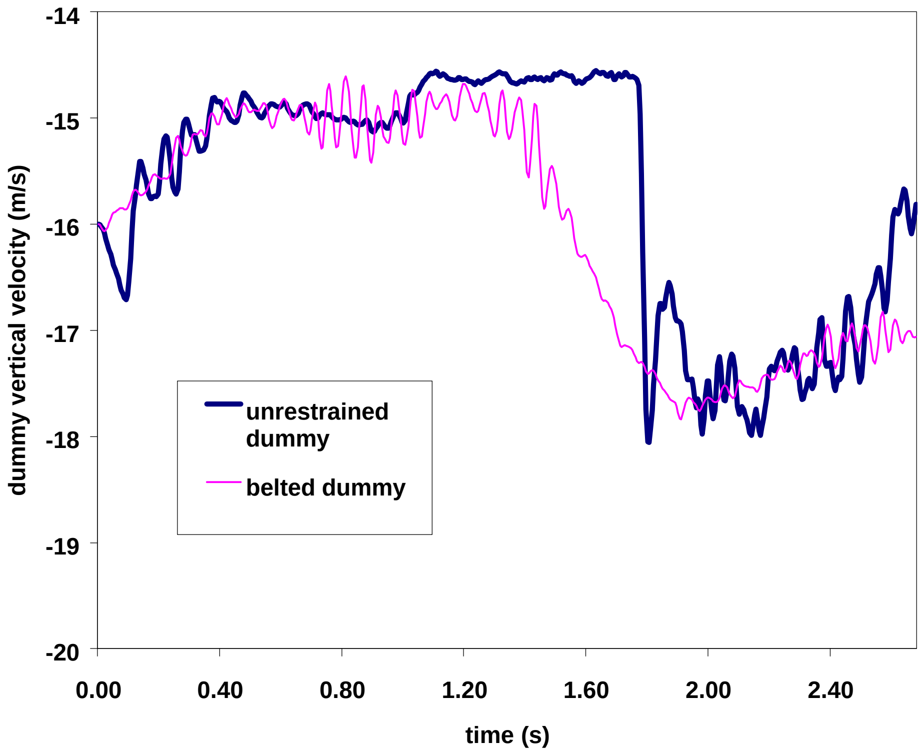

Figure 3 – Comparison of belted vs. unbelted dummy in the turbulent environment

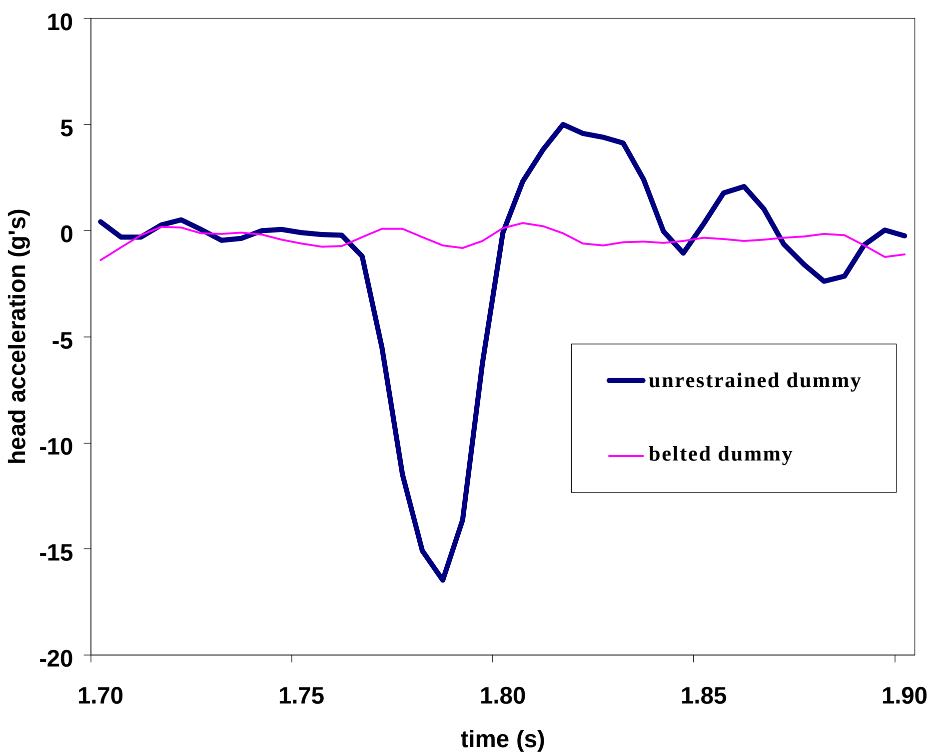

Figure 4 – Normalized head acceleration for belted and unbelted dummies.

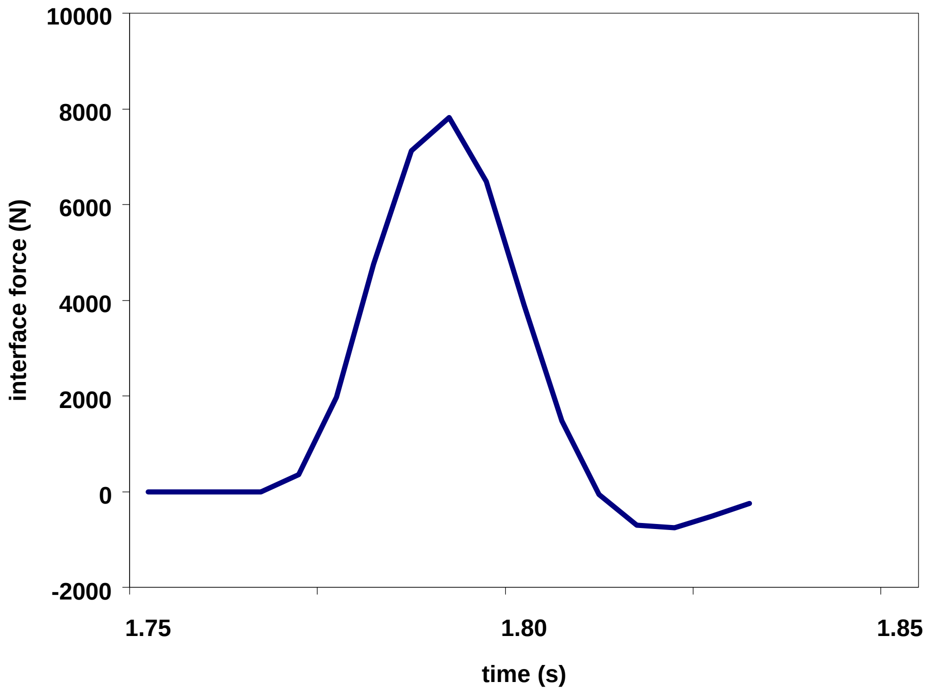

Figure 5 – Unbelted Dummy Head Impact Force,

Potential uses of Finite Element Simulation of Aircraft Cabin Safety

Use of finite element dynamic simulation provides a versatile tool and many opportunities to address cabin safety issues. This approach has to be validated by comparison with fuselage drop tests, actual incident data (to the extent possible), specific test programs as well sub-system and component testing. Several potential areas that can benefit from finite element simulation work is highlighted below:

- Structural Evaluation of overhead bins during severe turbulence and dynamic impact
- Evaluation of interior panel integrity
- Evaluation of Bulk-head occupant injury reduction approaches
- Occupant safety issues (falling luggage, child safety, seat design, etc.)

The above noted areas pose many interesting challenges. However, a more *futuristic* goal that can be characterize as a *grand challenge problem* is to simulate a survivable wide-body aircraft crash followed by a fire. This problem will encompass fluid-structure interaction in some of the most challenging ways coupled with combustion, heat transfer (all modes), smoke dispersion, human response modeling and evacuation.

Acknowledgments

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