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A multi-body systems approach to simulate helicopter occupant protection systems

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Abstract: This paper reports on the work of computer simulations carried out at Coventry University as part of the European 6th Framework HeliSafe TA project which considered the potential improvements in occupant safety for civil helicopters. A multi-body systems approach with additional use of finite elements for critical components such as a pilot airbag and the harnesses was adopted in the computer models to simulate helicopter crash/rollover scenarios and to investigate the effectiveness of occupant protection systems deployed during helicopter crash scenarios. ADAMS and Madymo simulations of helicopter impact/rollover events were demonstrated. A cabin/cockpit model of a Bell UH-1D helicopter was developed to replicate the physical crash test setup and a parametric study for the pilot airbag and a range of harness concepts was performed. The use of validated multi-body systems based cabin/cockpit models has proved to be effective in the development of new restraint system concepts for occupant protection.

Keywords: Helicopter, Crash Simulation, Harness, Airbag, Occupant Safety

1. Introduction

The Helisafe TA project [1] was established to follow on from the original Helisafe project set up under the European 5th Framework in recognition of the fact that helicopters are important not only in military service but also in a variety of civil operations. On some occasions, a helicopter is the only effective means of transport available, having to function in bad weather conditions or search and rescue operations close to the ground or over open water. Due to the nature of these operations, and the complex manoeuvres helicopters are required to undertake, occupants require protection for scenarios that do not exist in fixed wing aircraft [2,3]. Modern helicopters are designed with advanced materials and crash worthy structures using computer aided engineering tools and test procedures that parallel those used for crash analysis in the automotive industry, albeit for different scenarios. For a helicopter, post crash risks such as fire, ditching in open water or crashing in remote

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locations were all identified in the Helisafe TA project as drivers for occupant protection systems to mitigate injuries in survivable crashes [4].

The initial simulations carried out here were performed with ADAMS and MADYMO to exploit the multi-body systems capabilities of these software systems to model the nonlinear behaviour of the landing gear systems for a generic helicopter and simulate situations such as rollover that would be difficult to recreate using a full finite element approach. The generic models developed made use of a SAMCEF data set as the basis for the model development. The approach of using a multi-body systems code such as ADAMS to carry out pre-simulation and transfer boundary conditions to a model of a vehicle interior with occupants in Madymo has precedence in the automotive industry and was investigated by the authors [5] where they looked at the problem of simulating vehicle rollover. The authors identified the strengths in ADAMS in that it is an established program for simulating ground vehicle dynamics but with a drawback in that it did not possess an embedded capability to include non-linear finite element sections of a model, validated dummy models or restraint systems and airbag modules. In their work the authors were able to simulate the evolution of the rollover event up to the point of impact in ADAMS and then pass information to Madymo to continue the simulation of the rolled vehicle and occupants. Other work has involved the combined use of ADAMS and DYTRAN. This is not co-simulation, however, and the approach was still to use ADAMS for multi-body pre-simulation and pass the boundary conditions to the explicit DYTRAN finite element program. An example of this is described in [6] where the authors used ADAMS to model the landing gears and pass the loads predicted from initial simulations to a DYTRAN model of the helicopter structure.

An early activity in the Helsafe TA project involved a study at Coventry University investigating the NTSB Aviation Accident Database [7] for helicopter crash cases to identify the significance of post-crash risk hazards with a focus on fire, smoke, crashing on open water or coming down in remote and inaccessible locations. The survey, however, also indicated that the occurrence of post-crash roll over was significant. As with automotive rollover subsequent egress from the crash structure can be compromised due to the nature of the event. The information is summarized in Table 1 where it can be seen that rollover occurred in 22% of the 92 cases surveyed.

Following the simulation work on rollover further studies involved the development of interior cabin/cockpit models of the project crash structure, a Bell UH-1D helicopter, in Madymo to replicate the crash test setup including a pilot dummy, a forward facing passenger dummy and a side seated passenger dummy. The Madymo models were validated against available sled test data from the first Helsafe project using two representative crash pulses, referred to here as HS1 and HS2. During the project an initial full-scale baseline crash test was performed at the CIRA full scale crash test facility (Figure 1) which also provided data for the ongoing validation of the computer models.

Finally a parametric study using the validated Madymo Bell cabin/cockpit models was performed to investigate a range of harness concepts and the optimum position and firing time for the pilot airbag. During this phase of the work the IrSIx (Injury Severity Index) evaluation method [1] was used to provide a qualitative objective assessment of the predicted occupant injuries and inform the selection of concepts and operational parameters for further laboratory sled tests and the final full-scale crash test. The sled tests were carried out using mock-up structures, one to represent the cabin with the instrument panel, pilot dummy and seat and similarly one

to represent the cabin area with the two seated passenger dummies. The sled tests were performed by the project partners CIDAUT for the cabin mock-up and Siemens Restraint Systems for the cockpit mock-up.

2. Full helicopter models for crash simulation and interior floor pulse prediction

For safety simulations of an aircraft or helicopter interior, there are generally two types of modelling approaches suitable. One method is the use of hybrid code models combining multi-body and finite element techniques [8]. The alternative is based on full finite element models including the vehicle structure, passenger cell, seats and safety systems. The finite element approach provides challenges in the complexity of model generation and computer simulation time while the multi-body approach offers efficiencies that can offset these. In the work presented here a modelling approach is adopted in which cockpit/cabin models are developed and then analysed using acceleration pulses representing full helicopter crash scenarios. A summary of the modelling approach used is provided schematically in Figure 2. The floor acceleration pulses are generated from crash scenarios simulated with full helicopter models and/or drop test results. The acceleration pulses are then applied to the cockpit/cabin models to carry out simulations investigating the effectiveness of occupant protection concepts.

Various modelling approaches have been used by the partners in the project. These include the use of a DRI-KRASH model of Bell UH-1D helicopter by DLR in Germany, full nonlinear finite element models at Eurocopter, and Madymo and ADAMS multi-body system models at Coventry University. The DRI-KRASH software, used at DLR, is simulation software developed specifically for crash analysis of aircraft structures. The work with this software was highly relevant for the

prediction of floor crash pulses at the cabin/cockpit seat locations and for establishing the crash pulses used in the non-destructive sled tests performed on the cabin and cockpit sled tests. The computer models developed and simulations performed with ADAMS and Madymo exploit the multi-body systems capabilities of these software systems to model the nonlinear behaviour of the landing gear systems for a generic helicopter, and the ability to simulate situations such as rollover that would be difficult to recreate using a finite element approach. The generic models developed make use of a SAMCEF data set as the basis for the model development.

For the full scale helicopter modelling work in this project the ADAMS and Madymo models were only used to simulate hard landings or rollover events resulting from situations such as the loss of anti-torque from the tail rotor (shown for the ADAMS model in Figure 3), landing on slopes with gradients that could initiate rollover, landing with a component of lateral velocity that could initiate rollover or landing on uneven surfaces that could initiate rollover (shown for the Madymo model in Figures 4 and 5). Modelling of the full scale drop test was performed in the project using the DRI-KRASH software for the full helicopter model and using Madymo for the interior cabin/cockpit and occupant models (described later in Section 3).

Using a multi-body systems approach requires that for each rigid body in the system it is necessary to include a definition of the mass, centre of mass location, and mass moments of inertia. The relative motion between different parts in the system can be constrained using joints, joint primitives, couplers, gears and user defined constraints. The next step in building the model would typically be the definition of external forces and internal force elements. The modelling of contact between bodies in ADAMS has been well catered for in recent versions of the software using a Parasolid geometry engine embedded in the software that allows automatic detection

of contact at any point on any surface of the two contacting bodies. Contact forces have been used here to model the non-linear force displacement characteristic between the tyre and wheel rim and the ground surface for both the nose landing gear and main landing gear.

The first stage in developing the ADAMS model was to build separate subsystem models of the nose landing gear and main landing gear. For both subsystems it is important to check out the correct functioning of the model kinematics before including these models in the full helicopter model to simulate crash landings or rollovers. For both the nose and main landing gears the behaviour of the damper is asymmetric with different force generation characteristics during compression (bump) and extension (rebound). During compression the damper properties are nonlinear with dependence on velocity and stroke. During extension the properties are linear and are referred to as the “release stiffness”. The nonlinear behaviour of the damper can be presented as a map or carpet plot and covers the full range of stroke to the fully closed position to allow for the severe landing cases to be simulated.

The data used to develop the fuselage body was in the form of a SAMCEF data file which used a lumped mass representation to distribute the mass through the fuselage. In the ADAMS model it was necessary to represent this as a single body with the appropriate mass, mass centre and inertial properties summed and calculated taking first and second moments of mass from the distributed SAMCEF mass data.

The roll over of a helicopter due to tail rotor failure, before or after heavy impact with the ground, results due to the reaction of the main rotors as they continue to rotate and the subsequent loss of anti-torque from the tail rotor. This mode of roll over is considered common but would be difficult to simulate using a finite element

model. An example real world case, shown in Figure 3, was used as the basis for a simulation in ADAMS using the generic helicopter data to demonstrate the capability for this scenario.

Following the initial ADAMS work rollover scenarios were developed using Madymo where the models included the ground landing surface and the helicopter systems. Compliance of the ground, for example soft soil and water, needs developing a corresponding model of the ground [9,10], which was not considered at this stage.

The models developed comprised subsystems for the nose landing gear, main landing gears and the helicopter body. Both the nose and main landing gears were modelled as systems of rigid bodies linked throughout and connected to the helicopter body by appropriate joints or/and restraints. The body of the helicopter was modelled on three levels for different simulation purposes. The total mass of the body was distributed in the body through as nodal mass elements. Finally a seat-dummy subsystem with belts and airbag integrated into the full Madymo helicopter model. A graphical representation of the model during rollover after adverse landing on an uneven surface is shown in Figure 4 and time history outputs is for the body accelerations are shown in Figure 5. For this analysis the model was simulated with a ground impact velocity of 5 m/s and a pitch angle of 5 degrees nose up. The ground terrain was modelled with a 0.25 m elevated step under the left main landing gear wheel to instigate the evolution of the rollover event.

3. Modelling and simulation of the cabin and cockpit areas

In order to create a Madymo model of the helicopter interior encompassing the cockpit and cabin areas initial CAD models were created to capture the geometry to include the pedals, control sticks, instrument panel and surrounding cabin interior

before importing this to the Hypermesh software to mesh all the surfaces. Once meshed, the surfaces were imported to Madymo where they were defined as faceted surfaces.

Figure 6 shows the Madymo layout of the helicopter interior and the installation of the crash test dummies used in the full-scale drop tests. Three state-of-the-art BK117 crashworthiness seats were adopted for the occupants to replace the original seats. All the other seats were removed from the helicopter and simulated by masses (metal plates) attached to the floor. The dummies used were a 50th%-ile HeliSafe Hybrid III dummy provided by TNO for the pilot, a 50th%-ile FAA Hybrid III dummy provided by CIRA for the forward facing passenger and a EuroSID dummy provided by Siemens Restraint Systems for the side-seated passenger.

The Madymo cabin/cockpit model combines elements of multi-body systems and finite elements to integrate the geometry of the interior, the seats represented by 40 interconnected rigid bodies, the occupants, a range of harness concepts and the pilot airbag. To accelerate the modelling process and simulation times the three occupants were simulated in isolation, as there were no interactions between them, before integration into the full model shown in Figure 6. For each of the seated occupant dummies shown in the model separate crash pulses were applied at the seat to floor locations to represent the acceleration pulses corresponding with the full-scale crash test. For the initial simulations the harness modelled was a 4-point system with a Y-connection behind the neck, and a load limiter and pre-tensioner behind the seat using Madymo switch elements to trigger and lock the pre-tensioner. Finite element models of the harness fabric were used with membrane elements representing the belt components.

For the validation of the cabin/cockpit model two crash cases were considered, referred to as the HS1 and HS2 scenarios. The HS1 scenario represents a horizontal crash with a velocity of 12.8 m/s and 10° yaw angle into a rigid obstacle. This was modelled by a triangular pulse (JAR 18.4 g) with duration of 142 ms. The HS2 scenario is equivalent to a 9.2 m/s crash with the helicopter floor horizontal, but with the flight path at 60° pitch angle to the ground. This is simulated by a triangular pulse (JAR 29.3) with duration 62 ms applied at 60° to the helicopter floor [4].

The pulses used in the simulations were based on those recorded during the actual sled tests and therefore they were not pure triangular shapes. A preliminary airbag system was incorporated in the MADYMO model. Comparisons of the simulated pilot dummy kinematics and those recorded at test are presented in Figure 7 for the HS1 scenario and Figure 8 for the HS2 scenario. Example vertical forces in the upper lumbar spine obtained from the simulation and sled test are compared in Figure 9 for the HS2 scenario.

Following the sled test simulations the cabin/cockpit model was used to simulate the full-scale drop test to recreate the CIRA test conditions for impact on hard ground with a horizontal impact velocity of 12.8 m/s, a vertical impact velocity of 7.9 m/s, and a nose up pitch angle of 8.8°. A comparison of the simulated and measured injury curves is provided in Figure 10 and the occupant kinematics are compared in Figure 11.

Overall the injury curves and kinematic movements are well matched with the test results except for the head acceleration values. From Figure 10 it can be seen that head acceleration value in the test includes a high peak value caused due to the contact of the dummy head with the wind screen during the test, occurring due to the

collapse of the frontal structure, a mechanism which was not feasible to capture in the simulation model.

4. Modelling and simulation of the harness design concepts and pilot airbag

All the initial simulations made use of a 4-point harness system. The work which followed considered six new harness systems for the front and side seated occupants as shown in Figure 12. The concepts considered were a 4/5-point harness, a triangle harness, a body-centred harness, a 3-point harness, a 3/4-point harness, and an X harness. Parameter studies were carried for all seven harness systems for the cases of side-faced and front faced passenger seats with HS1 pulse.

Each harness system was modelled in Madymo as a combination of finite element belts with membrane elements and the conventional Madymo belts. Finite elements were used to model all the belt segments that can make contact with the occupant's body, while conventional belt elements were used in the other areas. Either one or two inertia reels were used to mount a shoulder harness at the upper area of the backrest of the seat, depending on specific harness setup.

A range of simulations were performed to establish the optimum position of the airbag shown in Figure 13 before installation in the crash structure for the final full scale test. The time to fire the airbag (TTF) was also established. The Madymo simulations also indicated a major advantage in adding the pilot airbag in that the peak head acceleration occurring due to the head impact with the windscreen, not captured in the baseline model, would be avoided in the final full scale drop test.

The final configuration in terms of harness selection, the pre-tensioning force (PTF) and time to fire for each occupant was also established through simulation for the final drop test. Additional work was also carried out to investigate the introduction

of new seat cushion material to reduce the lumbar spine load. The operational parameters for the new safety concepts established through simulation are summarised in Table 2.

5. Simulation of the final full-scale drop test with the optimised safety layout

The results of the final drop test and simulations are compared below. The simulation injury curves are correlated with test result curves and compared in Figure 14. The dummy kinematics established through simulation also compare well with those recorded during the test as shown in Figure 15.

Overall there is good agreement between the simulated and measured drop test results. From the kinematics comparison it can be observed that the pilot dummy is constrained from forward motion by the deploying airbag and is protected from collision with the instrument panel and helicopter structure. For the forward facing occupant dummy forward motion relative to the seat is prevented by the new harness system. The critical injury parameters such as the neck tension force and lumbar spine force are also showing good agreement between the test results and simulation.

6. Conclusions

The work presented here has demonstrated that it is possible to develop multi-body systems based models of helicopters and simulate appropriate crash scenarios with the use of programs such as Madymo and to investigate the effectiveness of occupant protection systems deployed during helicopter crash scenarios. The modelling methodology is based on a mixed use of multi-body and finite element techniques, in which a subsystem cabin/cockpit model was used for the occupant protection studies. The use of full scale helicopter models to simulate events such as rollover following

ground impact has also been demonstrated as feasible and capable of producing boundary conditions for occupant protection systems using similar methodologies to those applicable in automotive safety studies associated with rollover. In particular the use of simulation to select safety concepts and establish operation parameters such as the time to fire airbags or harness pre-tensioners to support a programme of sled and crash tests for helicopter occupant protection has proved to be effective.

Acknowledgements

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Table 1. Survey of the NTSB Aviation Accident Database for reported helicopter crash cases

Post Crash Risk	Cases		Occupants	Fatalities		Major Injuries		Minor Injuries		No Injuries	
	No.	%		No.	%	No.	%	No.	%	No.	%
Water	5	5	22	11	50	0	0	1	5	10	45
Fire	6	7	17	9	53	1	6	5	29	2	12
Remote Location	5	5	16	5	31	2	13	1	6	8	50
Rollover	20	22	46	2	4	0	0	12	26	32	70

Table 2. TTF, PTF and load limiter values for final drop test

	Pilot	Front Facing Passenger	Side Seated Passenger
TTF of Airbag (ms)	75	-	-
Harness	4-Point	X-Harness	X-Harness
TTF of harness system (ms)	75	60	60
PTF of harness system (kN)	2	2	2
Load limiter for harness system (kN)	5	2.5	2.5

Figure 1. CIRA full scale crash test facility

Figure 2. Integration of simulation models in Helisafe TA

Figure 3. ADAMS simulation of helicopter rollover after loss of anti-torque

Figure 4. Simulation of roll-over due to uneven ground in Madymo

Figure 5. Body acceleration from the Madymo model for the roll-over due to uneven ground

Figure 6. Layout of the crash test structure for the full-scale drop test

Figure 7. Madymo simulation of the pilot dummy with airbag and sled test for the HS1 scenario
(Sled test pictures from SRS)

Figure 8. Madymo simulation of the pilot dummy with airbag and sled test for the HS2 scenario
(Sled test pictures from SRS)

Figure 9. Comparison of simulated upper lumbar spinal forces with sled test for the HS2 scenario

Figure 10(a). Comparison of baseline drop test injury curves with simulation results

Figure 10(b). Comparison of baseline drop test injury curves with simulation results

Figure 11. Comparison of dummy movements in drop test and simulation model

Figure 12. Madymo models of the simulated harness systems

Figure 13. Final positioning of the pilot airbag

Figure 14(a). Comparison of final drop test injury curves with simulation results for pilot dummy

Figure 14(b). Comparison of final drop test injury curves with simulation results for pilot dummy

Figure 15. Comparison of predicted dummy kinematics with final drop test

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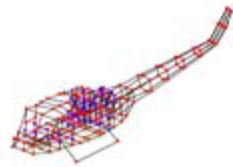
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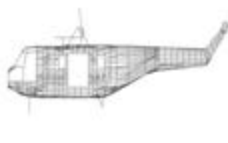
Reference Scenarios



DRI-KRASH



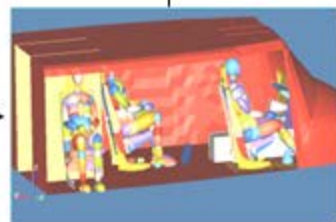
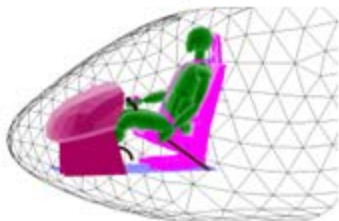
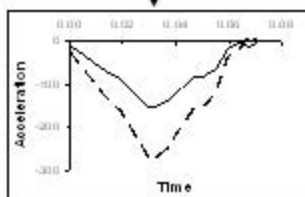
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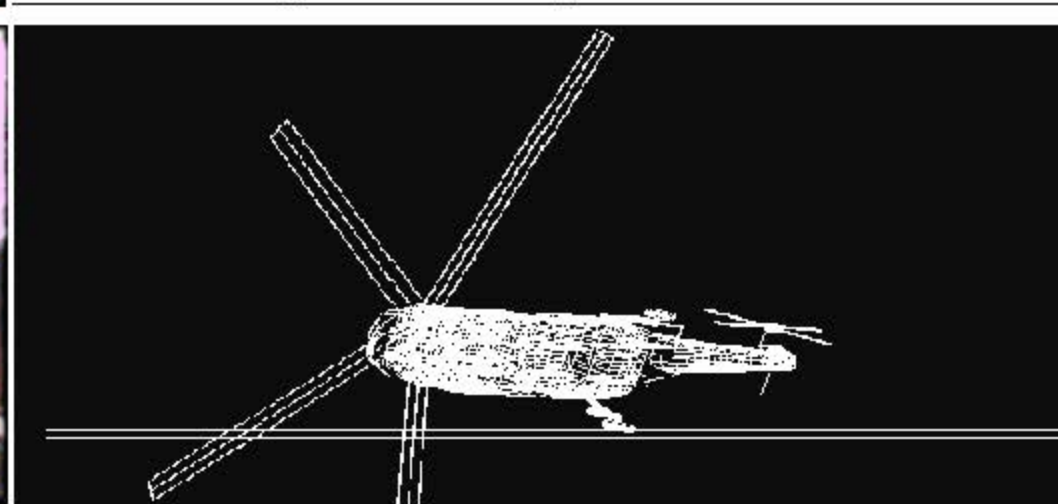
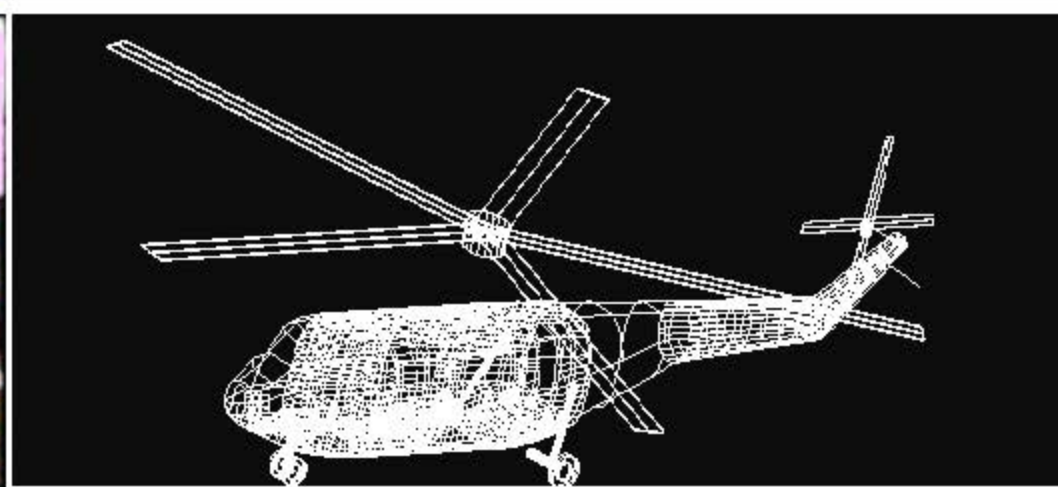
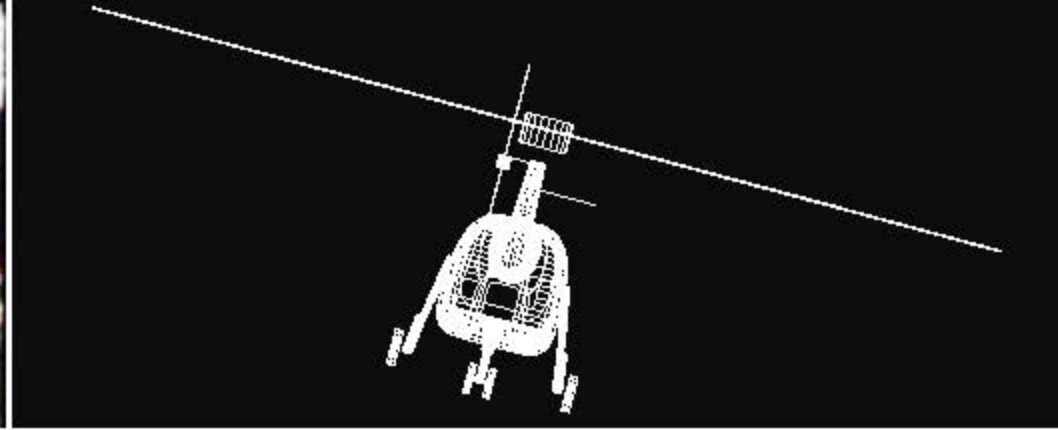


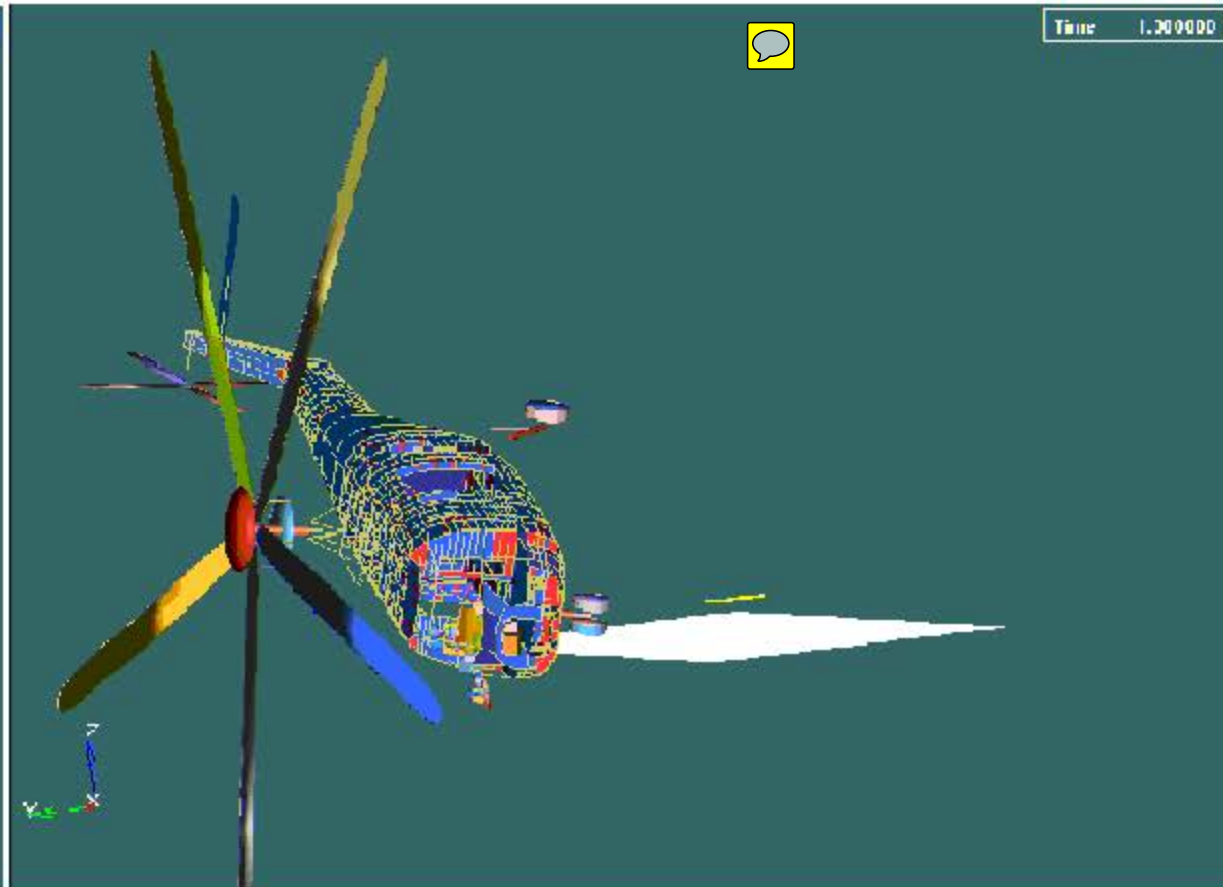
MAD YMO/ADAMS
Simulations

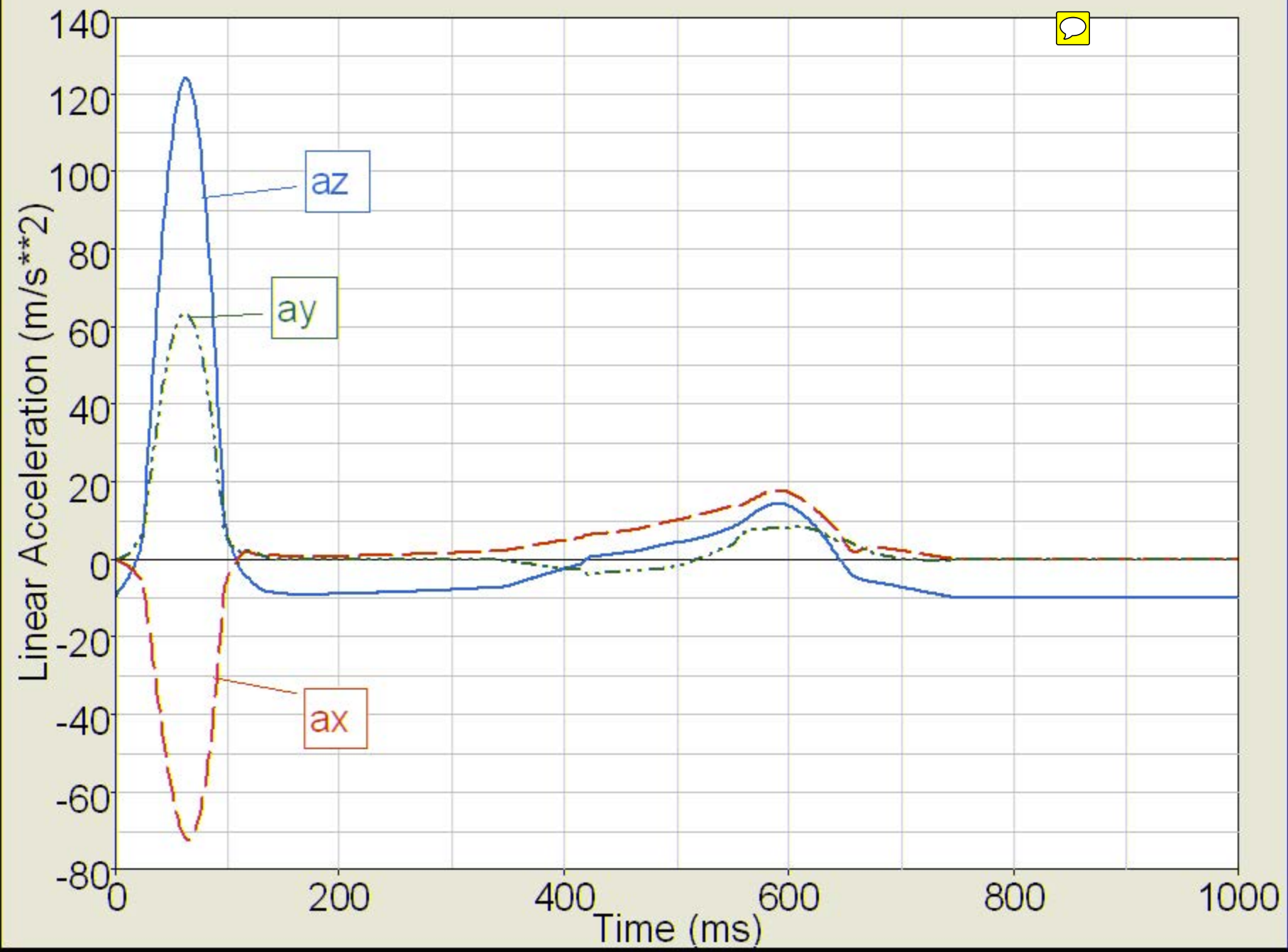


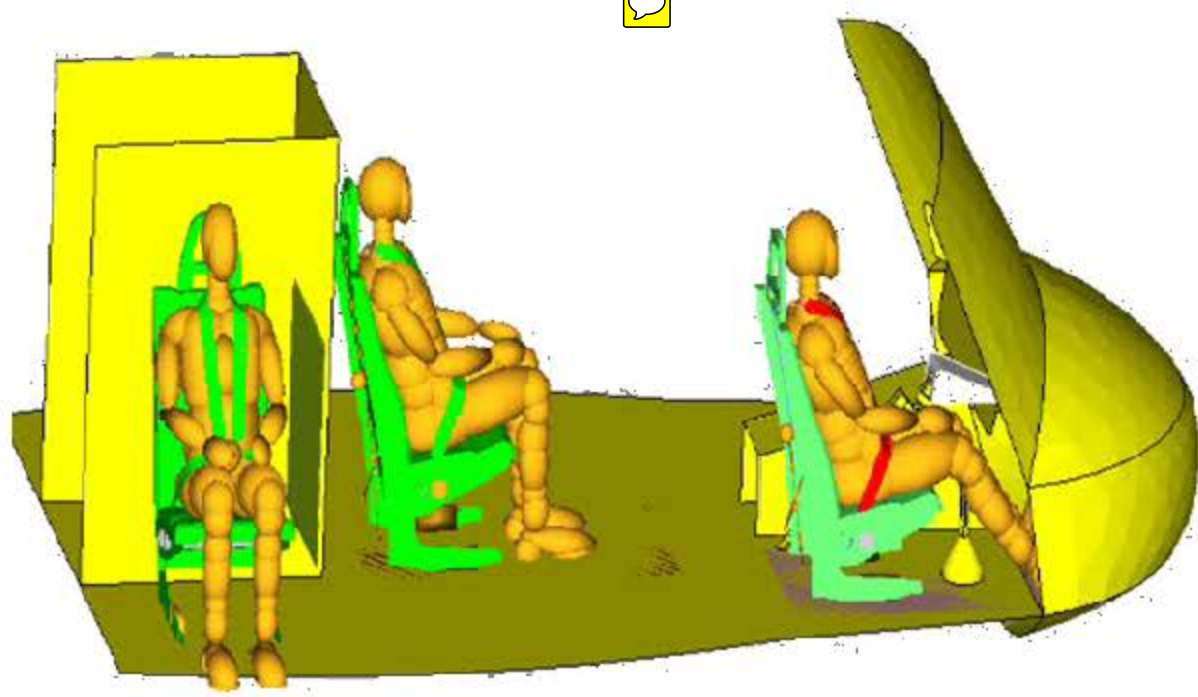
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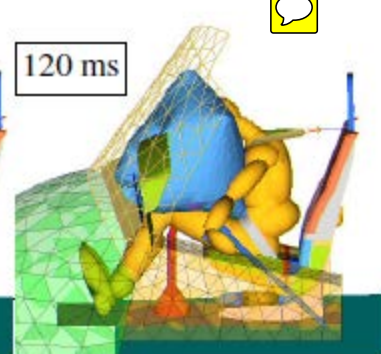
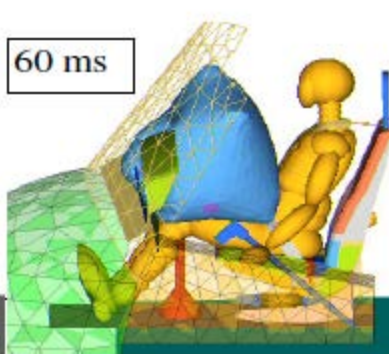
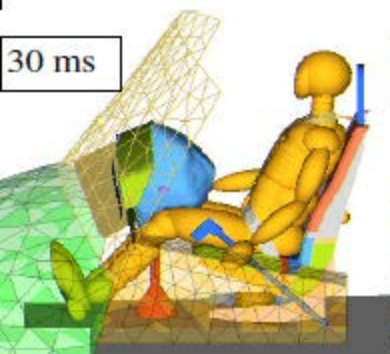
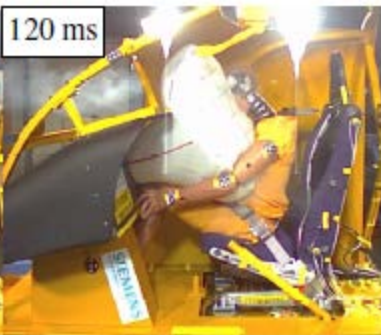
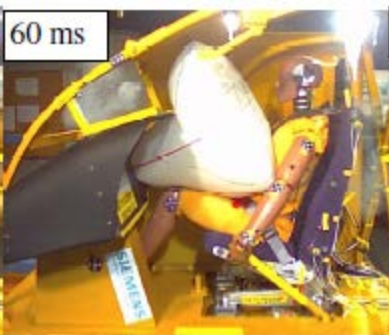




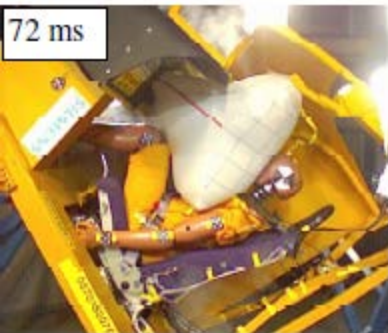




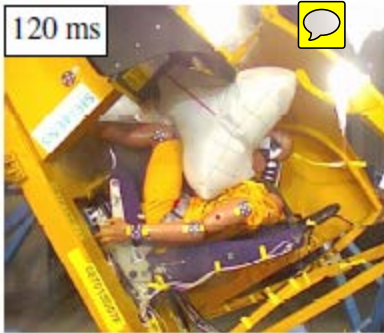




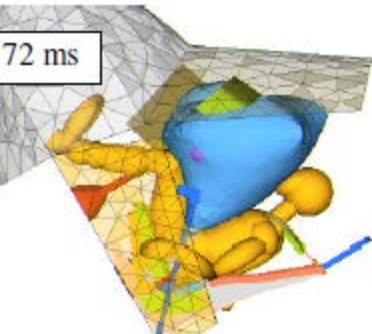
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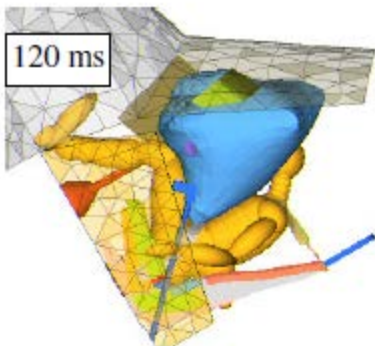
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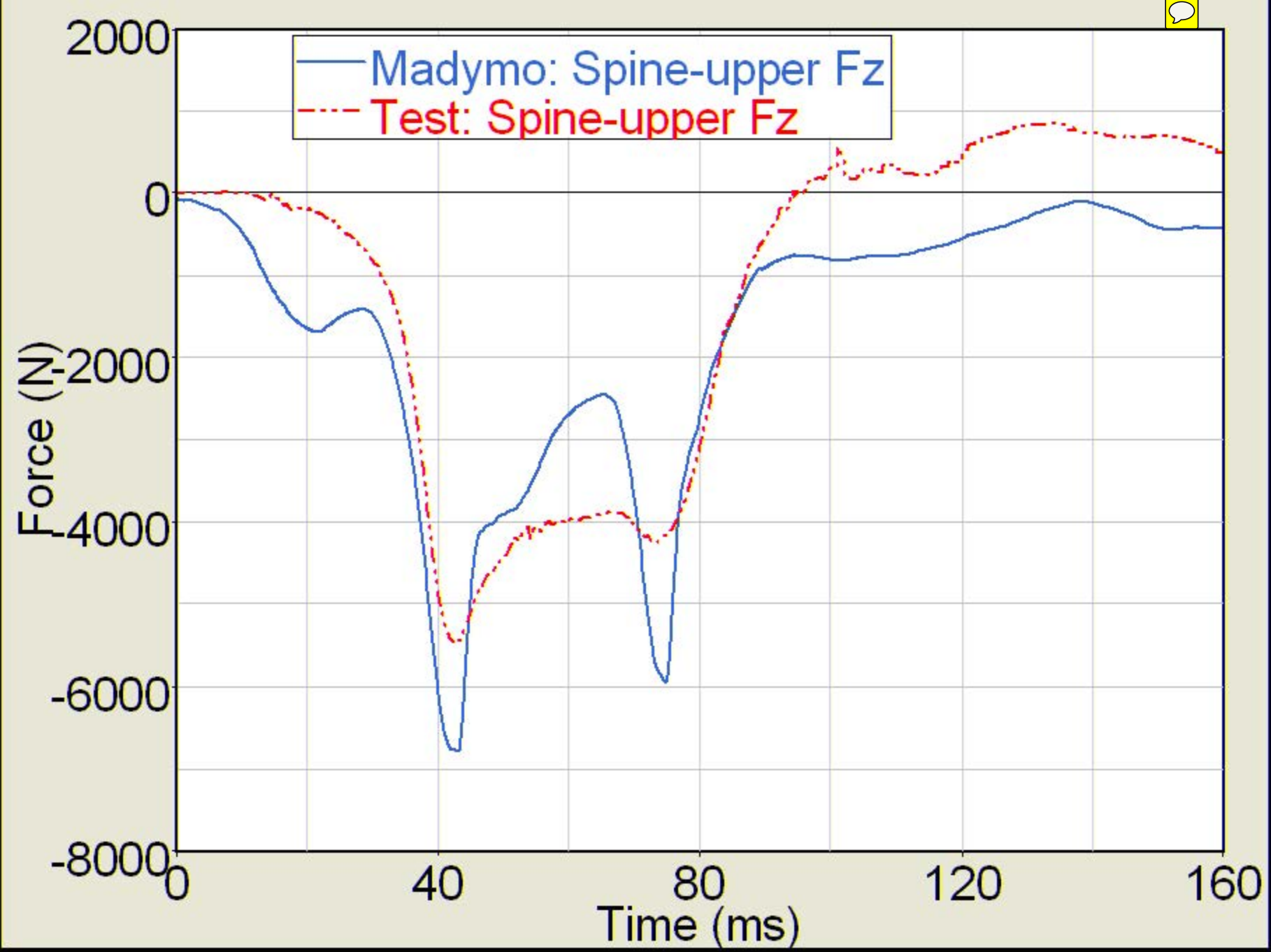


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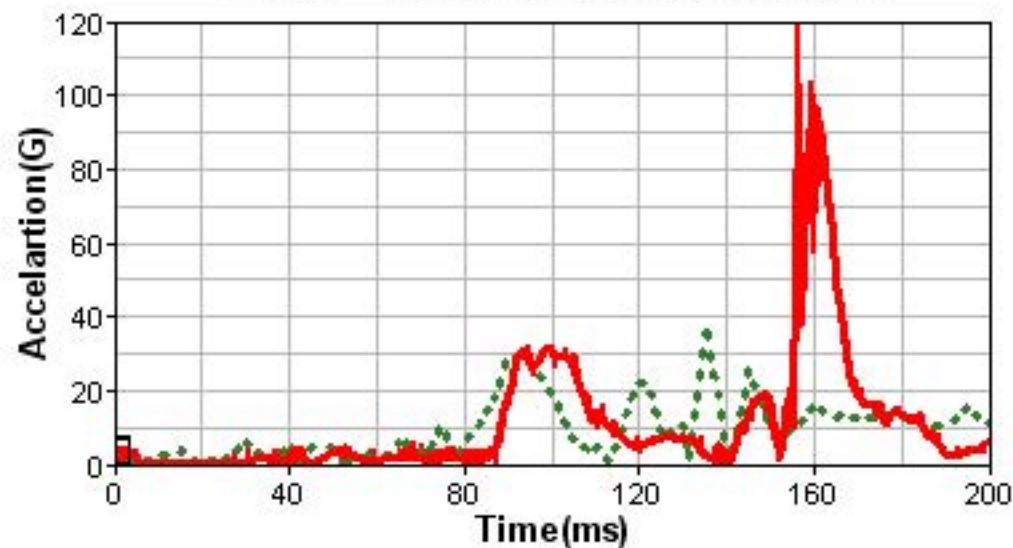


120 ms

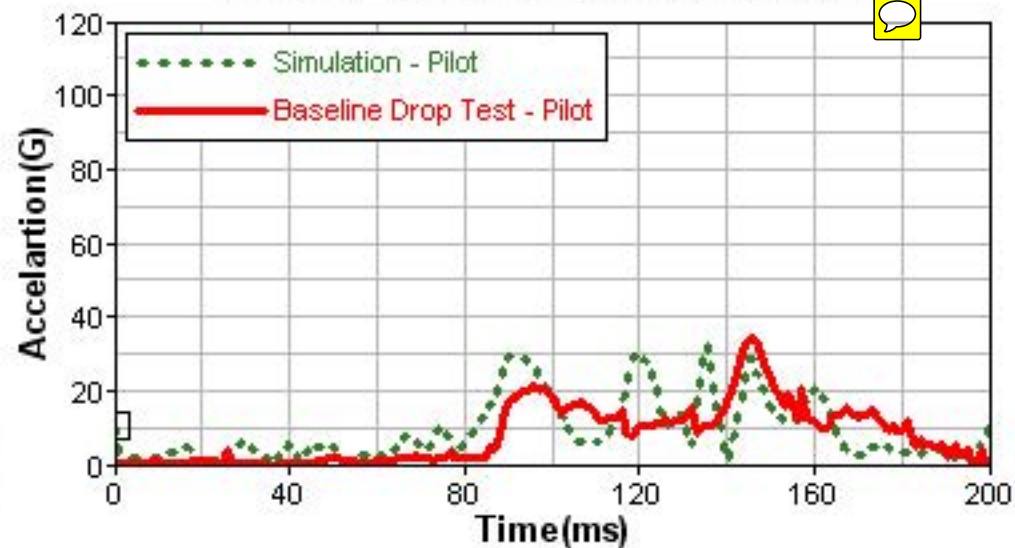




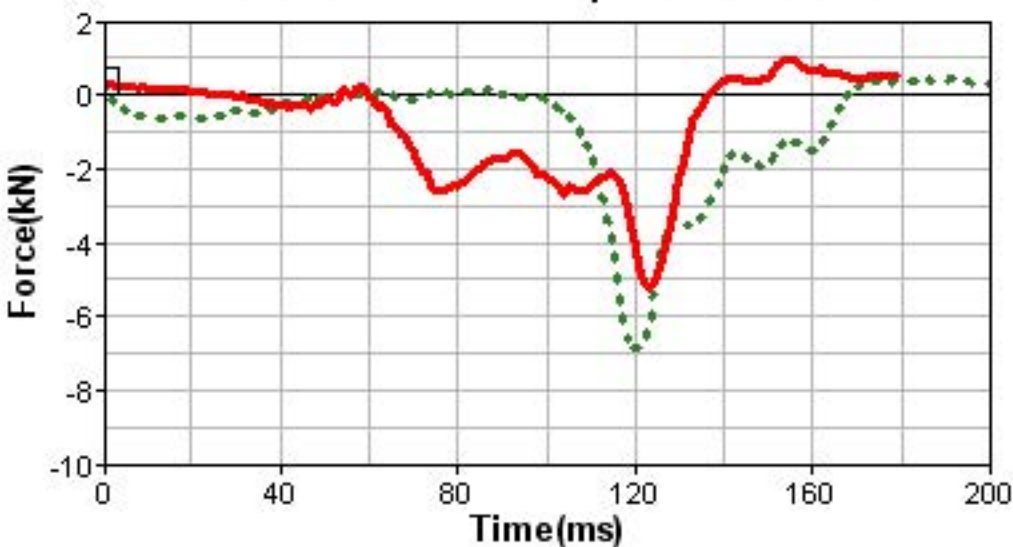
Head - Resultant Acceleration



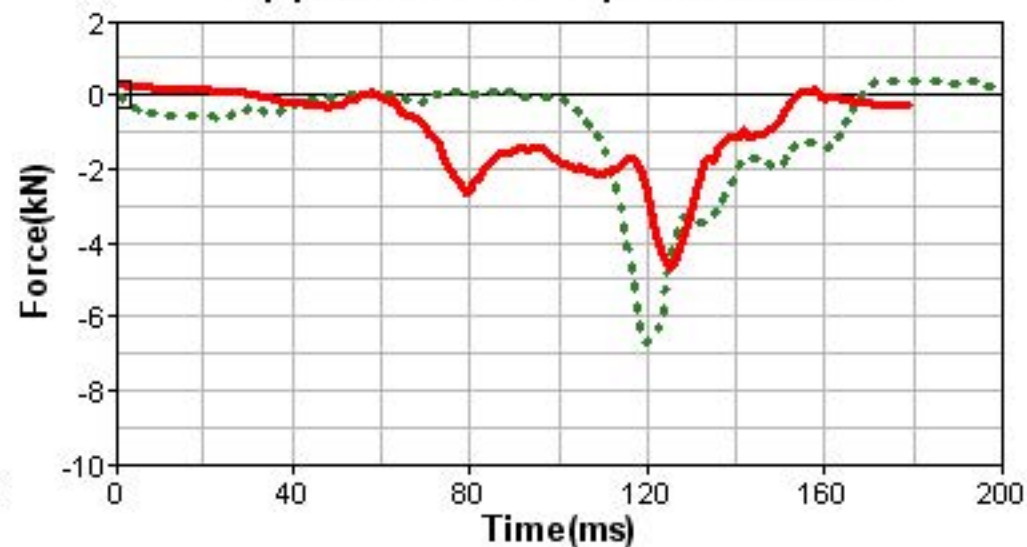
Chest- Resultant Acceleration



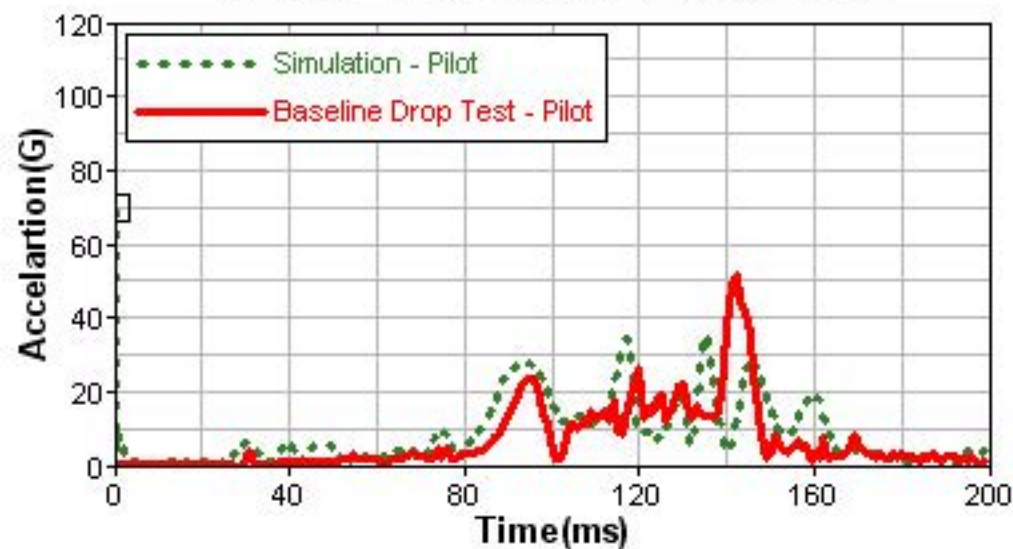
Lower-Lumbar Spine-Z Force



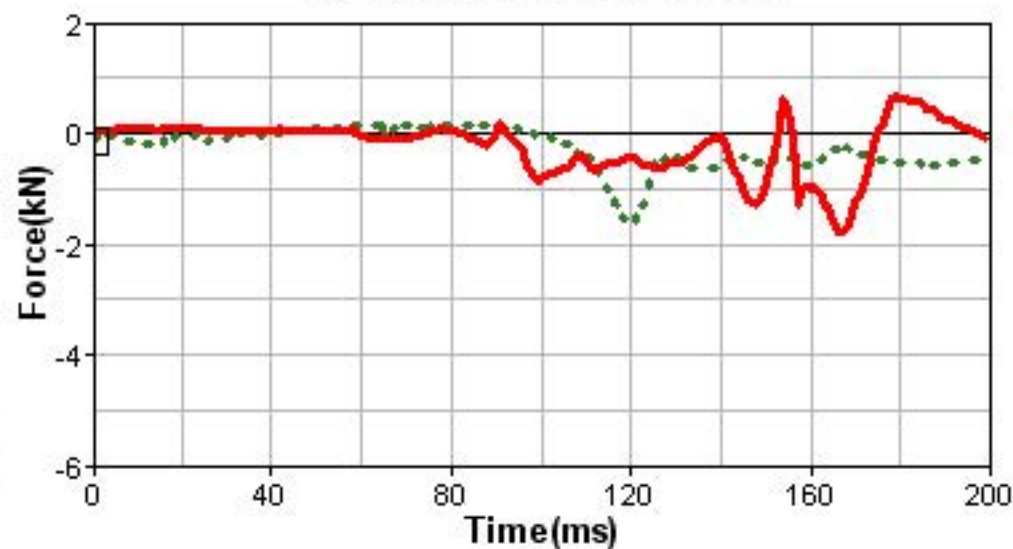
Upper-Lumbar Spine-Z Force



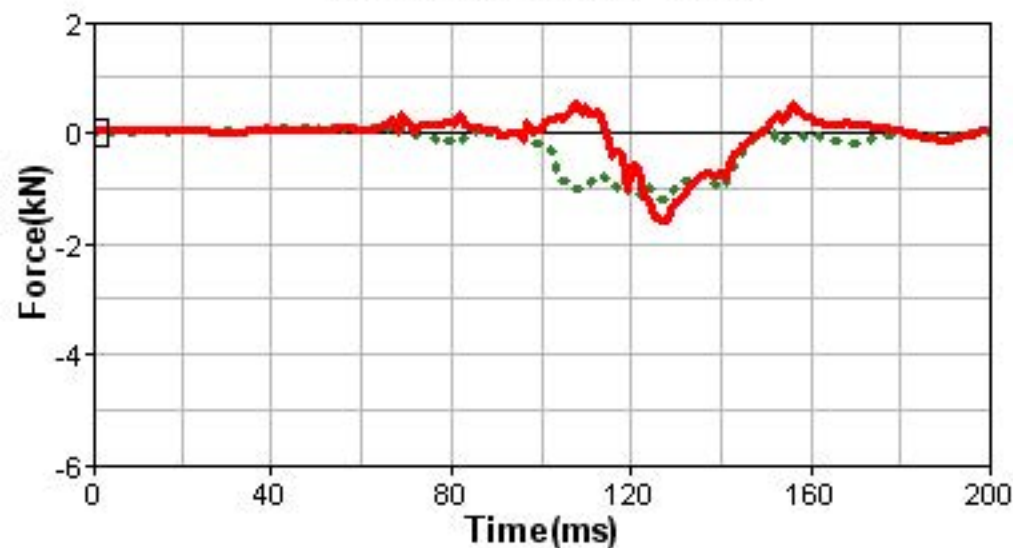
Pelvis - Resultant Acceleration



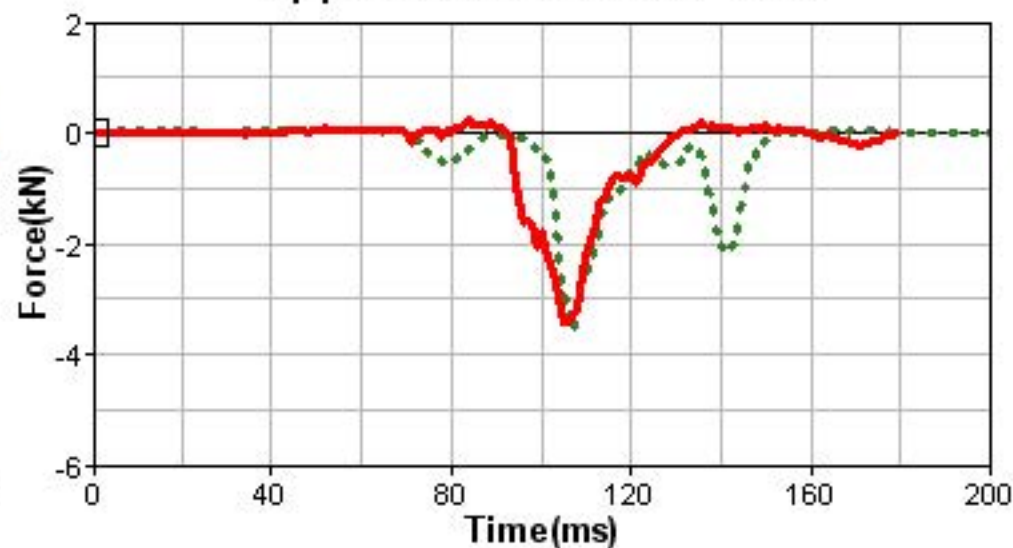
Lower-Neck-Z Force



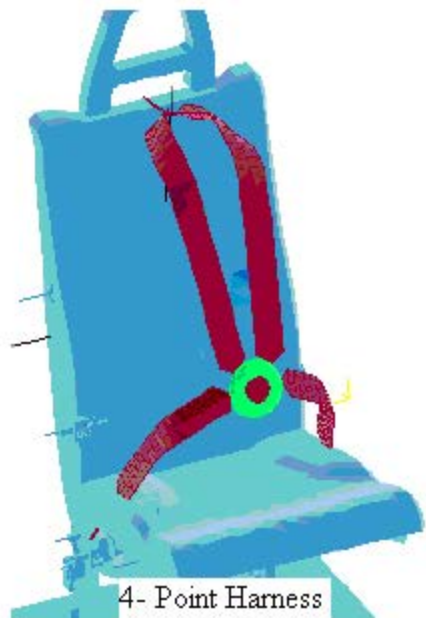
Left Femur-Z Force



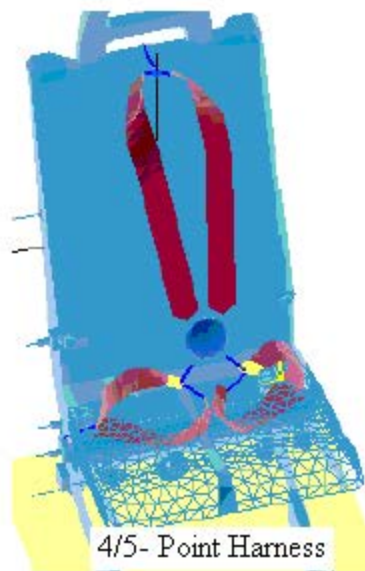
Upper Tibia Left -Z Force







4- Point Harness



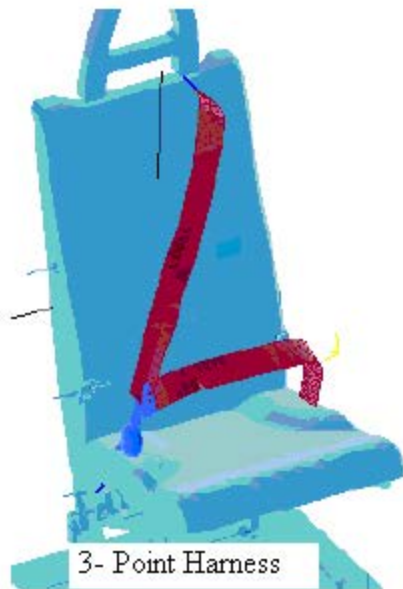
4/5- Point Harness



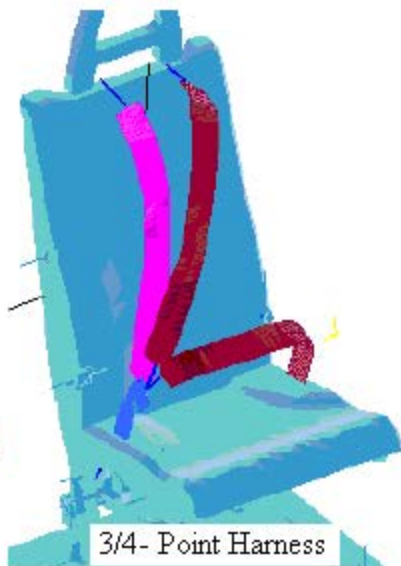
Triangle Harness



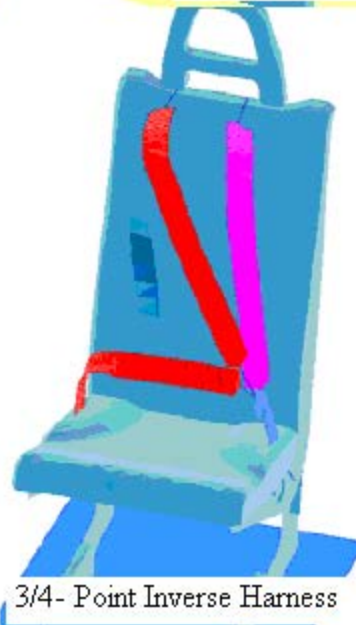
Body Centred Harness



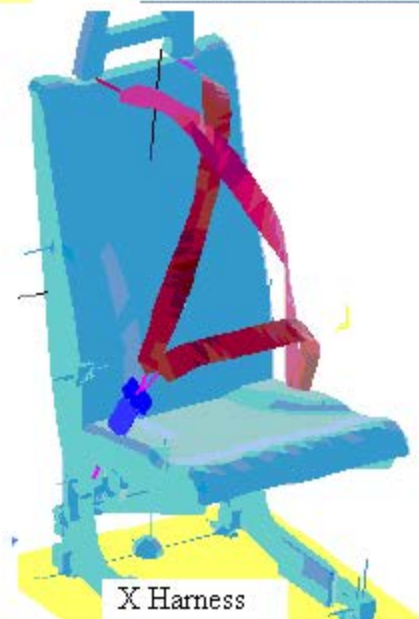
3- Point Harness



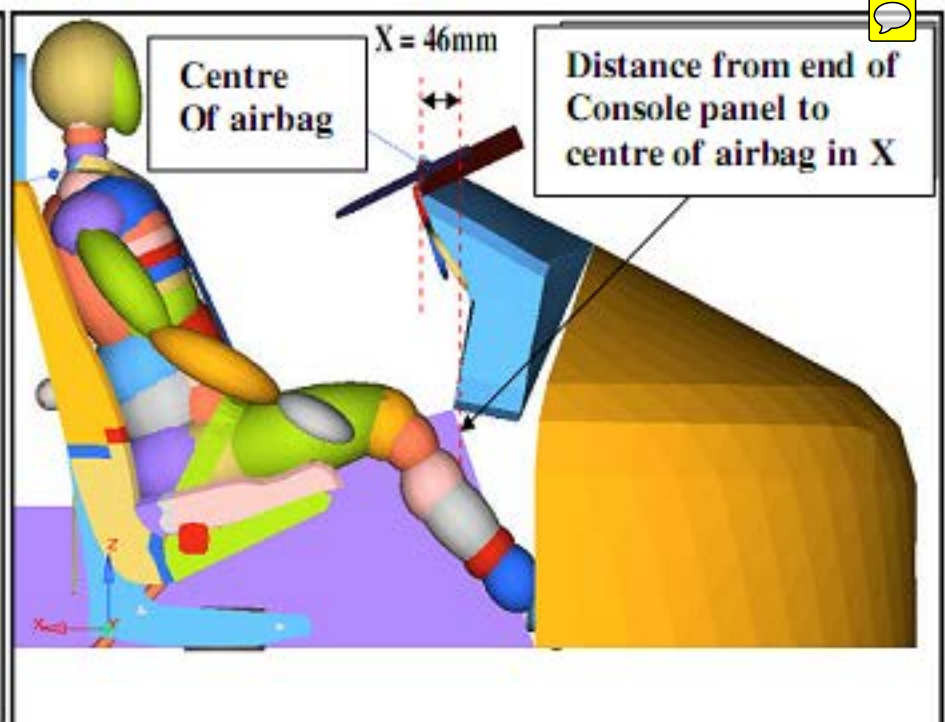
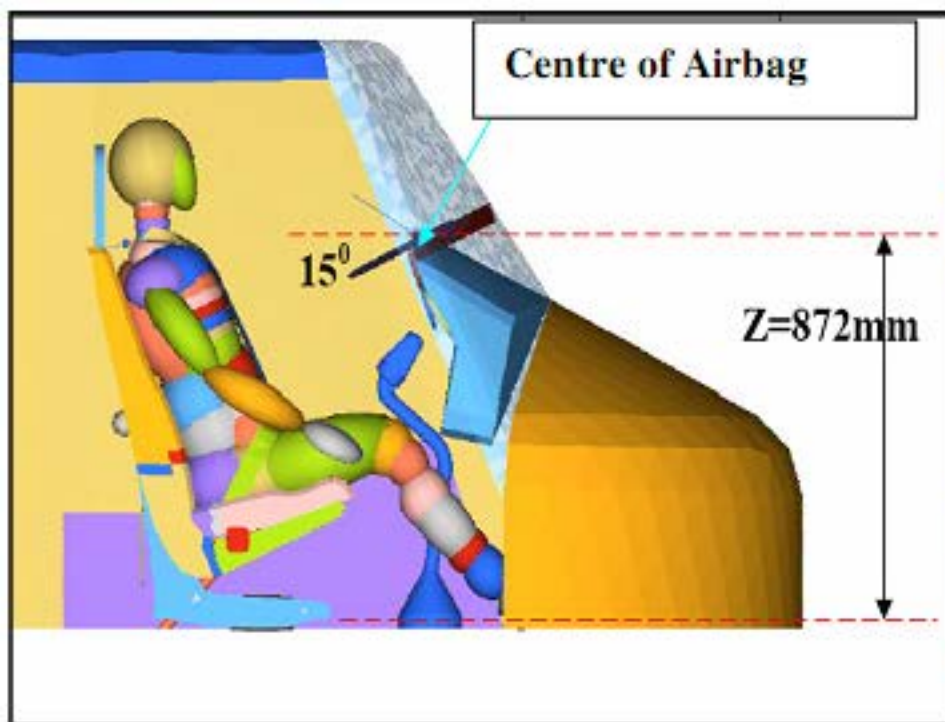
3/4- Point Harness



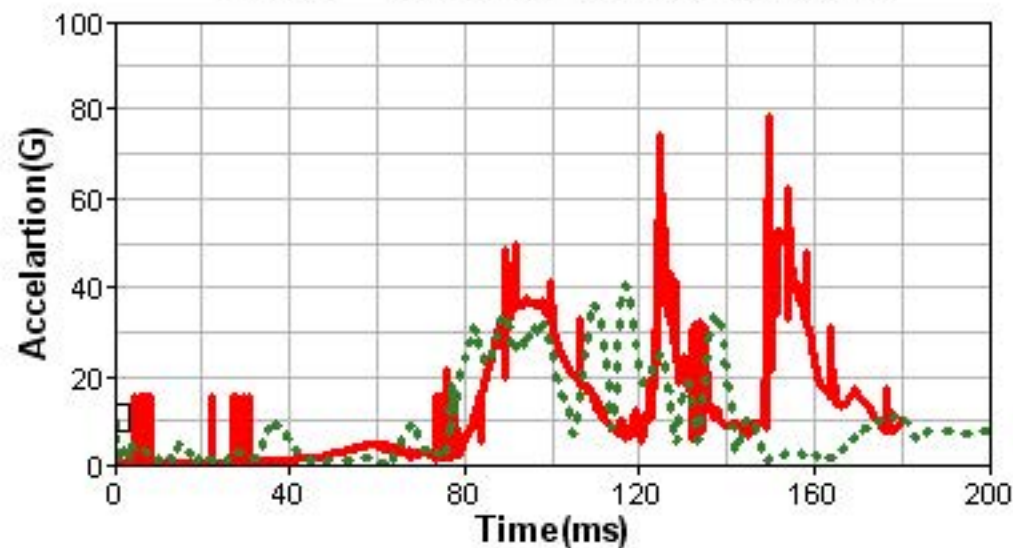
3/4- Point Inverse Harness



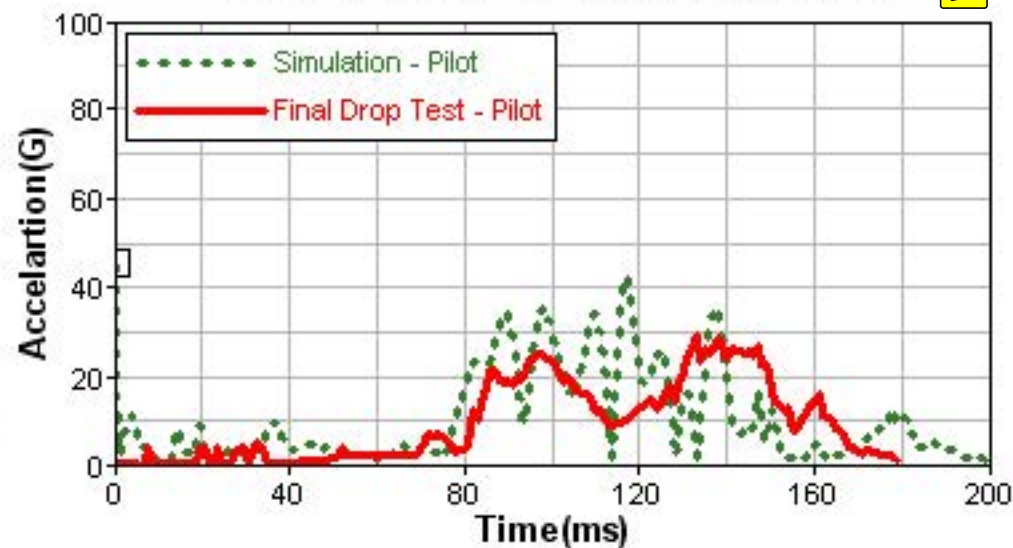
X Harness



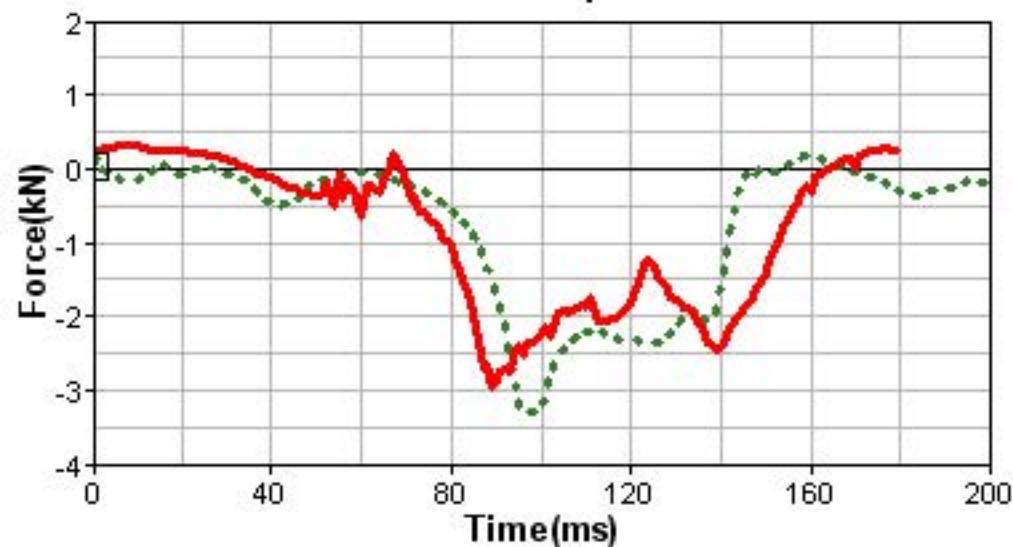
Head - Resultant Acceleration



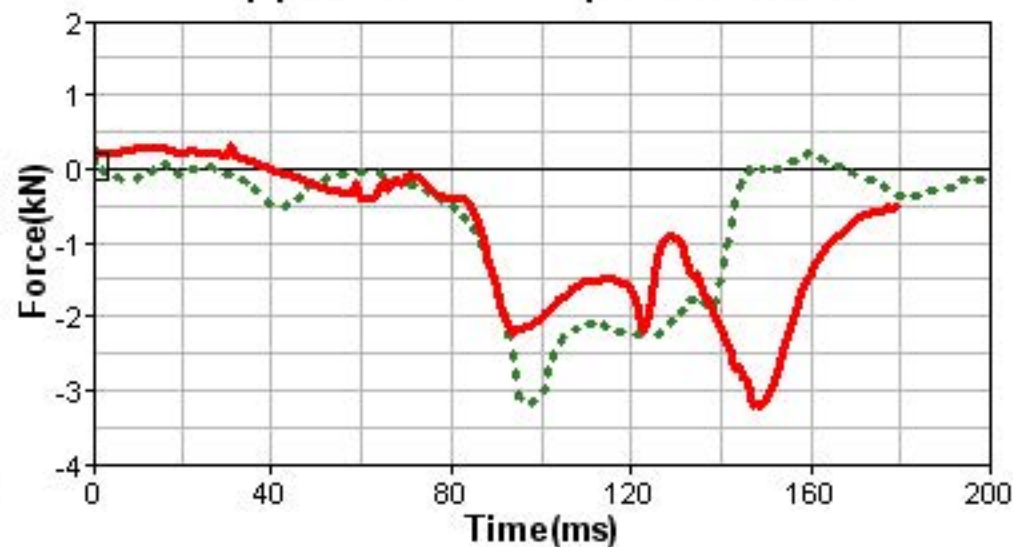
Chest- Resultant Acceleration



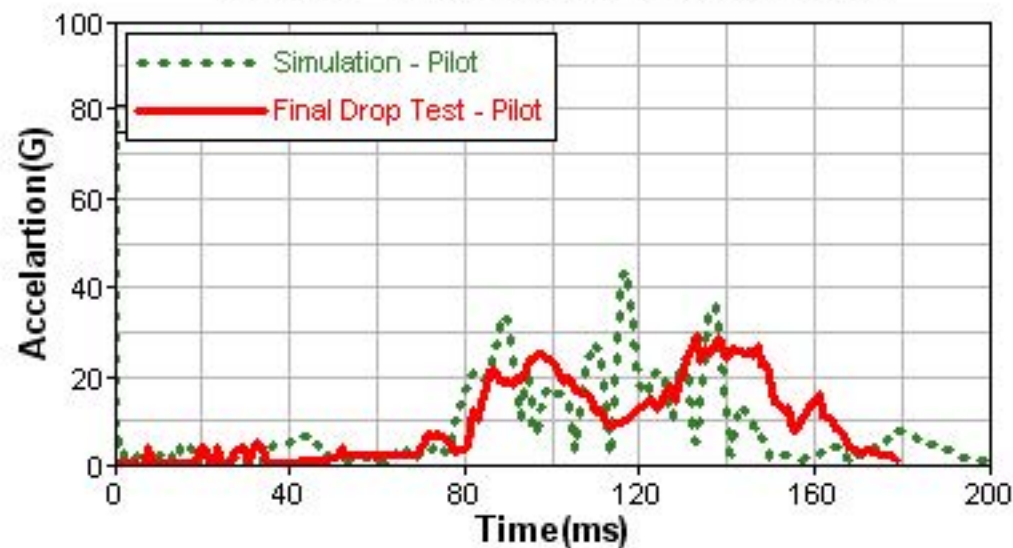
Lower-Lumbar Spine-Z Force



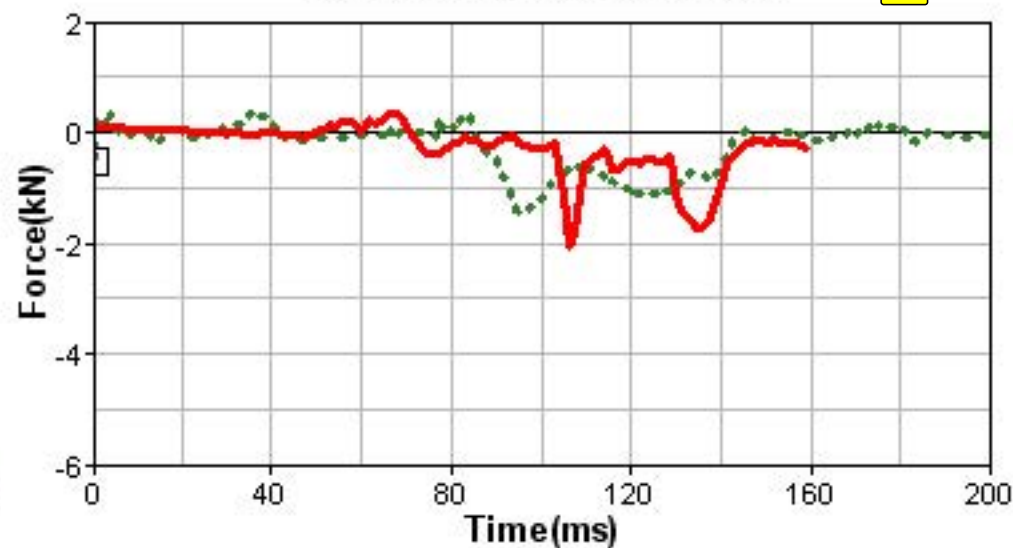
Upper-Lumbar Spine-Z Force



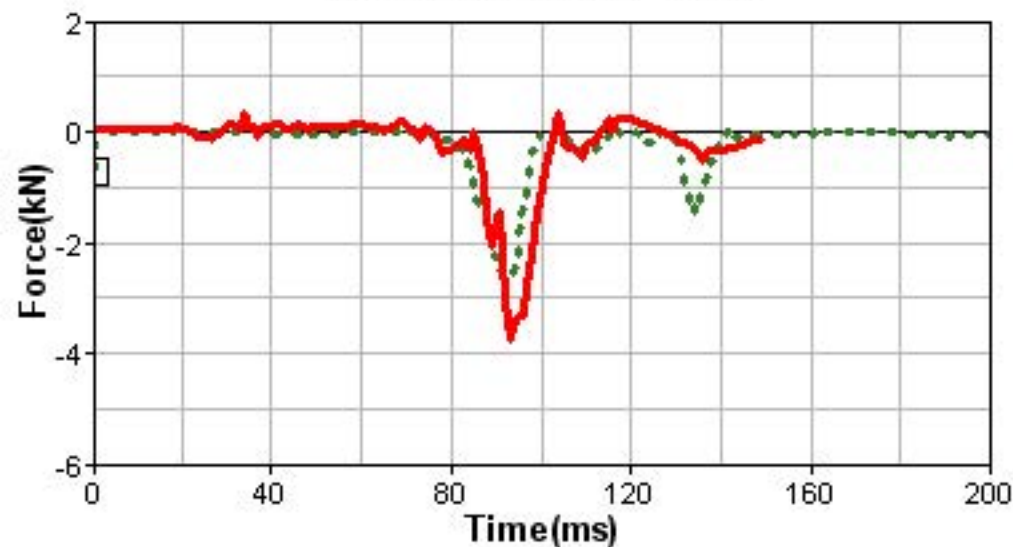
Pelvis - Resultant Acceleration



Lower-Neck-Z Force



Left Femur-Z Force



Upper Tibia Left -Z Force

