2021 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
SURVIVABILITY TECHNICAL SESSION
AUGUST 10-12, 2021 - NOVI, MICHIGAN

REDUCED ORDER MODELLING METHOD (ROMM) FOR GROUND VEHICLE ROLLOVER PROTECTION M&S

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ABSTRACT

The performance of ground vehicles during a rollover event is an important safety and occupant protection requirement for military vehicles. Modeling and simulation is a very useful tool in study and investigation of vehicle rollover characteristics and countermeasure concepts.

This study presents two methods of simulating the rollover events. The first one uses Full System Method (FSM), where all the components are modelled as is and are evaluated. The second method is a reduced order modelling method (ROMM) using integration of the resulted kinematics data from FSM into the vehicle model with occupant & restraints. The FSM & ROMM methods were applied to simulate two HMMMV rollover events, and the results from both methods show that simulation and test data agreed fairly well. Computational time reduced by the ROMM was about 53% of that of the FSM. ROMM approach not only saves significant computational time but also increases robustness of the simulation.

Citation: V. Babu, J. Kang, S. Kankanalapalli, J. Sheng, M. Vunnam, S. K. Karwaczynski, C. Jessup, M. Duncan, K. Paulson, "REDUCED ORDER MODELLING METHOD (ROMM) FOR GROUND VEHICLE ROLLOVER PROTECTION M&S", In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 10-12, 2021.

1. INTRODUCTION

Automotive rollover has been widely researched over many decades by auto-industry, academia, and the Government since 1980s [1-13]. This is because about 33% of passenger vehicle occupant fatalities were in vehicles that rolled over, according to a NHTSA report [11] using the FARS and NASS GES database. The report analyzed data related to passenger vehicle rollovers, including rollover propensity and injury outcomes. The authors specifically analyzed factors that were associated with vehicle rollovers in single-vehicle crashes of passenger vehicle, and those with ejection status and varying degrees of injury severity of occupant in passenger vehicles that rolled over in single vehicle-crashes.

A vehicle is generally considered to have experienced a rollover when tires on one side of the vehicle have lost contact with the ground to the point of no return. The cause for rollover varies depending upon the operating conditions. The most commonly studied on-road rollovers occur at higher speeds and high lateral G's during maneuvers such as obstacle avoidance or J-turns [13, 14]. During these rollovers, the vehicle pivots about the outside wheels in response to high lateral G's experienced at the vehicle center of gravity (CG) where the outside wheels are laterally constrained by the cornering forces.

Extensive testing has been conducted to evaluate both the dynamic response of vehicle structures and occupant protection systems in rollover collisions through the use of Anthropomorphic Test Devices (ATDs) [15, 16]. Rollover test methods that utilize a fixture to initiate the rollover event include the SAE J2114 dolly, inverted drop tests, accelerating vehicle body buck on a decelerating sled, ramp-induced rollovers, and Controlled Rollover Impact System (CRIS) Tests. More recently, programmable steering controllers have been used with sedans, vans, pickup trucks, and SUVs to induce a rollover, primarily for studying the vehicle kinematics for accident reconstruction applications.

Robert Larson [15] conduced eight rollover research tests using the 2001 Nissan Pathfinder with a modified FMVSS 208 dolly rollover test method where the driver and right front dummy restraint system performance was analyzed. The rollover tests were initiated with the vehicle at horizontal, not at a roll angle. After the vehicle translated laterally for a short distance, a trip mechanism was introduced to overturn the vehicle. Retractor, buckle, and latch plate performance in addition to the overall seat belt performance was analyzed and evaluated in the rollover test series. Retractor pre-tensioners were activated near the rollover trip in three of the tests to provide research data on its effects. Various dummy sizes were utilized. The test series experienced incomplete data collection and a portion of the analog data was not obtained.

To improve HMMMV vehicle safety and soldier protection during rollover events, US Army PM-JLTV/HMMWV started an Advanced Occupant Protection Initiative. Under a CRADA agreement with the PM, Indiana Mills & Manufacturing Inc. (IMMI) conducted two baseline HMMMV rollover tests on its rollover test fixture in 2019 and 2020 [17, 18]. Four ATDs (driver, passenger, driver rear (RR) and passenger rear (PR)) were put in the HMMMV cab for both tests, one with lap belt and shoulder belt system only, and another with a 3-pt belt system and buckle end pre-tensioner for each occupant.

The performance of ground vehicles during a rollover event is an important safety requirement for military vehicles, but not emphasized till recent years. Some efforts on rollover research and development have been made in last 10 years or so, with an objective to improve the vehicle safety and soldier protection. Modeling and simulation is a very useful tool in study and investigation of vehicle rollover characteristics, development of mitigation concepts and evaluation of anti-rollover countermeasures. However, due to the relatively longer time period of a rollover event, coupled with strong occupant-kinematics/restraints interior interactions, the modeling and simulation of rollover events presents some unique challenges and should be properly addressed.

The objectives of this rollover study are to develop a HMMWV rollover model and correlate simulation results with those from IMMI tests. Furthermore, the performance of the newly-designed HMMWV restraint system and concepts is assessed in order to support the Advanced Occupant Protection Initiative for PM-JLTV /HMMWV. Rollover simulation of a full HMMWV or any military vehicle with 5^{th}%, 50^{th}% and 95^{th}% occupants inside has never been simulated numerically and this effort is the first to simulate using commercially available non-linear solver LS-DYNA [19].

2. SIMULATION MODEL DEVELOPMENT

The finite element model of a complete HMMWV rollover simulation is shown in Figure 1. The assembly consists of body-in-white (BIW) structure, seats & seat restraints systems, Occupants and roll over fixture. Underbody, suspension and wheel components were removed as they are not needed for this study. Details of the assembly components are described in the later sections. Two modelling approaches were used to simulate the rollover event: a full system model (FSM) and a Reduced Order Model Method (ROMM).

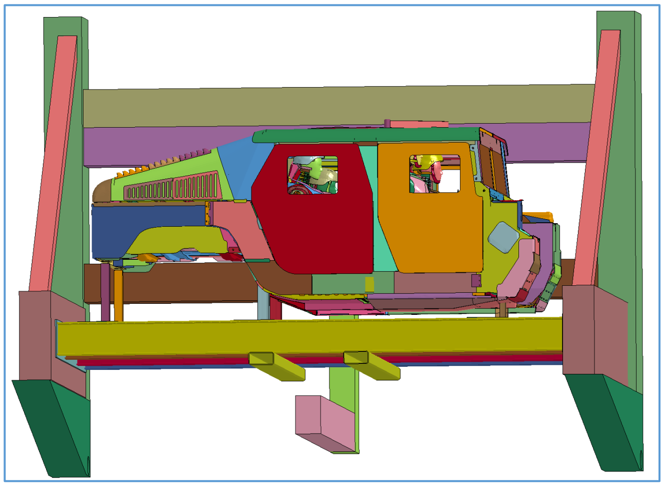

Figure 1: HMMWV M&S model for Rollover

2.1 HMMWV Cab FEA Model:

Based on a Full HMMWV Vehicle FEA model developed by Survivability and Protection M&S (SPMS) for frontal impact simulation, the model was tailored and simplified (Figure 2) to the extent required according to the IMMI rollover test set-up.

2.2 CAPE Fixture FEA Model:

The CAD model for IMMI Rollover test device (CAPE) fixture and was received and meshed by SPMS team (Figure 3).

2.3 Helmet & Vest Models:

All Helmet models and Vest models for 50th% ATD's were developed by SPMS of GVSC. Vest models for 5th% & 95th% were initially developed by University of Michigan Transportation Research Institute (UMTRI), and then re-meshed and modified extensively by SPMS team of GVSC (Figure 4).

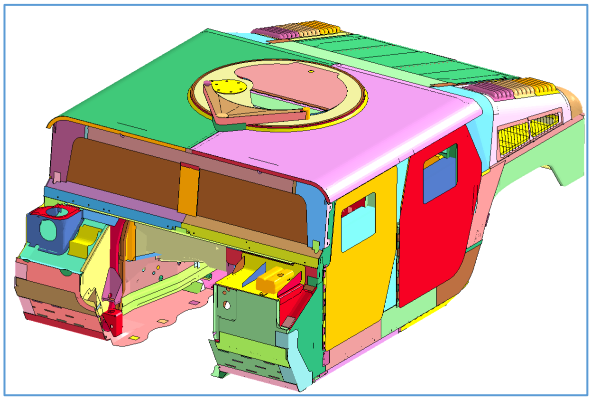

Figure 2: Simplified Model from Frontal Impact FEA Model

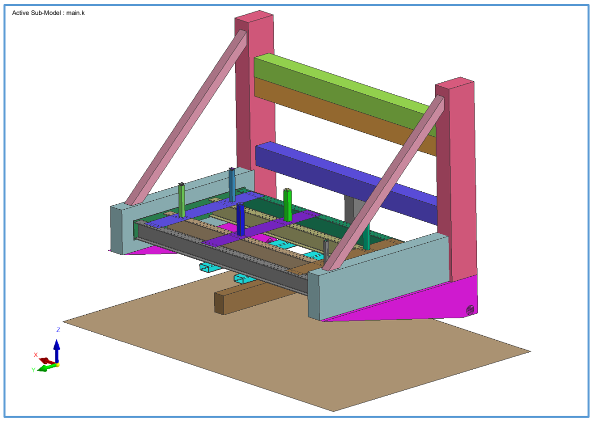

Figure 3: FEA model of CAPE fixture

2.4 ATD Models & Positioning:

Three Humanetics ATD models (Figure 5) were used in this project, all w/ personal protective equipment (PPE): HYB-III 5th% female ATD (Driver RR), HYB-III 50th% male ATD (Driver & Pass RR) & HYB-III 95th% male ATD (Passenger).

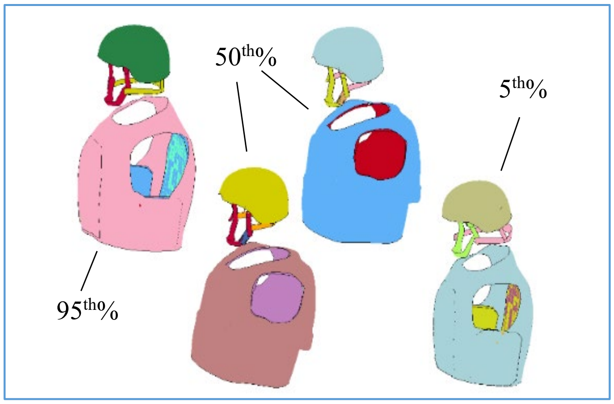

Figure 4: Helmet & Vest Models for 5th%, 50th% & 95th% ATD's

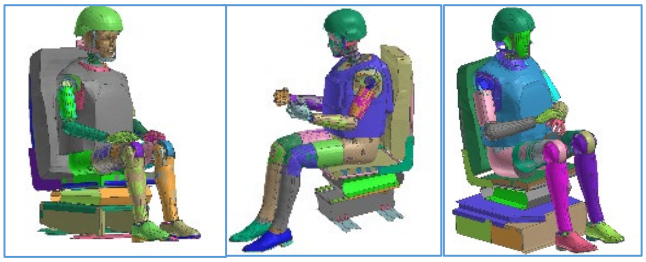

Figure 5: 5th%, 50th% & 95th% Humanetics ATD's

ATD's in vehicle: All the 4 ATD's are positioned (Figure 6) in the vehicle based on IMMI pre-test pictures. Some of the positioning required few iterations to fit the tested positions.

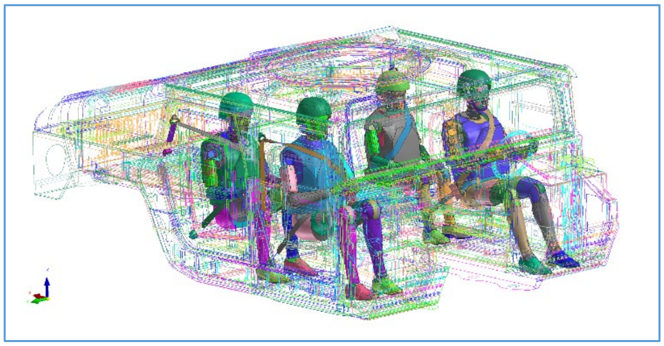

Figure 6: ATD's positioned in HMMWV Cab

2.5 Seat Restraints Modeling

The two tests done at IMMI were 3-pt belt system without pre-tensioners & with pre-tensioners. Once the simulation-test correlation was done, there has been a study on restraint systems such as dual pre-tensioners, 5-pt belt system & pull-down seats. It is important to explain the belt modeling and routing in detail which is the critical path for rollover event.

Belt modelling and routing is very complex especially in military vehicles for occupants with soldier gears such as armored vests. In LS-DYNA Version 970 R9.0 or higher, there are two ways to model the belts, the first one is a one degree (1d) beam elements with force displacement curves defined to represent the behavior of the belts. This method is mostly used in frontal crash and rear impact simulation where the belts are in full tension, but may or may not work in rollover events due to belt slipping. MAT_SEATBELT is used to represent the seatbelt materials in LS-DYNA, requiring user to input mass/unit length (MPUL) value. This is calculated by dividing the total weight of the belt by the total length of belt in the spool. Advantages is that, it is easier to model and route, and to calculate belt forces which are captured in DATABASE_SBTOUT. Also, 1d belts are very user friendly and easy to model retractors and pre-tensioners. Contact between 1d beam elements and the dummy surfaces are bit challenging especially in simulating rollover where the kinematics of the whole event becomes aggressive after the roll stops and inertia forces of dummy starts to stretch the belts.

The second approach is to use combination of shell elements using fabric either as an orthotropic material or as an isotropic material and a limited 1d belt near the anchor points and to model retractors and pre-tensioners. During the initial simulations, the model encountered a couple numerical instabilities associated with the seatbelts, such as belt slipping or too much retractor pull-in, which resulted in belt segments causing early termination of the calculation. To eliminate these numerical difficulties, a component model was set up with the seat, occupant, and seat belt systems as shown in Figure 12, and eventually a robust seat belt restraint system model was developed. One has to pay lot of attention to details in modeling the seatbelt system, otherwise it will lead to numerical instabilities and inaccurate responses. For example, the MPUL value from all 1d belts cannot be used in a shell/1d combination belt system because the 1d belt segments will be significantly less in this hybrid approach and the total weight of the 1d belt will be less. The user needs to recalculate the MPUL value only for the 1d segments used in this hybrid model and cannot use the value as standard input. Some of these changes are easier to implement in a component model and to eliminate complexities in full system model simulation. It took several iterations to develop a robust Supplemental Restraint System (SRS) model. Since the HMMWV rollover model has four different occupant positions, it requires four different sets of belt routing for all occupants. In addition to that there are four different seat restraint systems which make it a very challenging system to develop and successfully simulate the rollover events. In all the cases, seatbelts were routed very close to that of the test set-up.

2.6 Full System Model (FSM)

The HMMWV Cab model along with all the sub-systems such as Fixture, ATD's, and belt systems were integrated (Figure 1). Total mass of the test asset was 41500 kg and simulation model was 41680. In order to match the test mass, distributed mass was used in the M&S model. Fixture weighed 33,568 kg and the structure weighed 3340 kg.

The vehicle structure was attached to the fixture at 6 mount locations as shown in Figure 1 & Figure 3. The roll angle rate from the test data was input into the model along the longitudinal axis (X). Roll angle ~ time history used in the simulation is shown in Figure 7.

Defense Supercomputing Resource Center (DSRC)'s HPC system was used with 20 CPU's each for the simulation models. The full rollover event takes 2.5 seconds, but most of the occupant injuries will peak around 1.6 seconds. To account for all the occupant injury criteria, termination time for the rollover simulation was set at 2 seconds. Most of the occupant injuries will occur between 1.5 to 1.7 seconds time frame once the vehicle roll stops. Computational time required to simulation a full system model with 20 cpu's is 79 hours. Table 1 summarizes the full system model details.

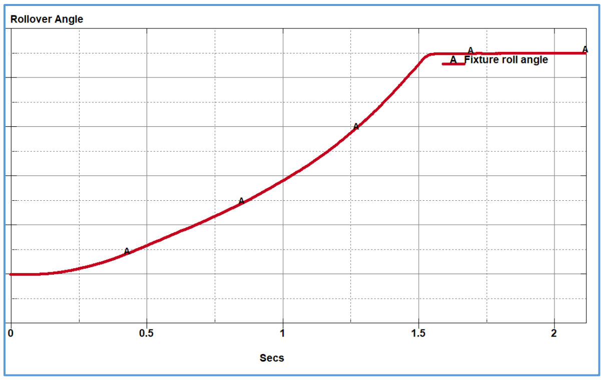

Figure 7: Roll Angle for simulation input

Table 1: Full System Model Details

Total no. of parts	2230
Total no. of elements	1,434,312
No. of CPU's	20
Termination time	2 seconds
Completion time	79 hours

Due to the complex nature of interactions between hard metallic parts and soft seat belt and occupant, numerical instabilities were encountered during the initial development. Most of these instabilities would occur once the roll stops and occupant's relative kinetic energy starts to pick up, and seat belt restraints systems energy starts to absorb the energies. To determine the root cause of these instabilities in a full system model would be time consuming and prolong the Analysis of Alternatives (AOA) phase. Reduced order modelling method (ROMM) will help to speed the analysis and AOA.

The following pictures in Figures 8-10 show the M&S occupant position compared to the test setup. Occupants are articulated and seat belts are routed to the best fit and as close to the test as possible.

2.7 Reduced order Modelling Method (ROMM)

As explained in the previous section, ROMM was developed to eliminate the long run times associated with FSM and create fast running models. LS-DYNA has a unique feature called Interface Component Analysis, which helps to speed the analysis of alternative designs of non-structural components for a given structural motion. In the case of a rollover event, rotation and kinetic energy of the structure remain constant and the non-structural masses and components' motion varies (such as in the case of the occupants or seatbelts).

Figure 8: M&S and Test Driver position

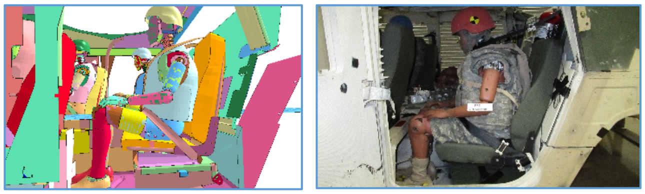

Figure 9: M&S and Test Driver rear position

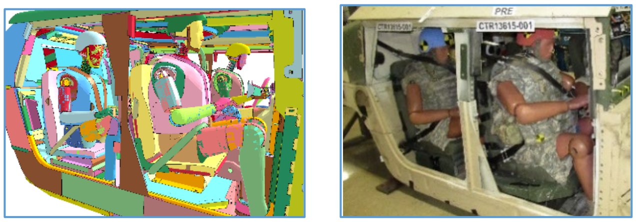

Figure 10: M&S and Test Passenger side positions

Interface component analysis involves two steps. In the first step, most of the structural components which are essential to protect the occupants are selected [10]. In this HMMVV model, this includes: BIW, seat frames, doors, roof, etc. The rest of the structures that do not have any bearings on occupant injuries are eliminated. Figure 11 shows the selected HMMWV components for interface component analysis. Segments sets are created for the elements of these selected components. LS-DYNA has two options to choose from, INTERFACE COMPONENT NODE or INTERFACE COMPONENT SEGMENT method.

The second option using elements was used in this analysis. Now we need to define the output frequencies for the selected segment sets in the CONTROL OUTPUT card 5th field output interval for interface file (OPIFS) at every 3 ms interval. This will generate a binary output file called ISF1, which contains nodal displacements and velocities. LS-DYNA stores the time history data per node basis in a binary file defined by ISF. In the second step ISF1 file will be used as master segments.

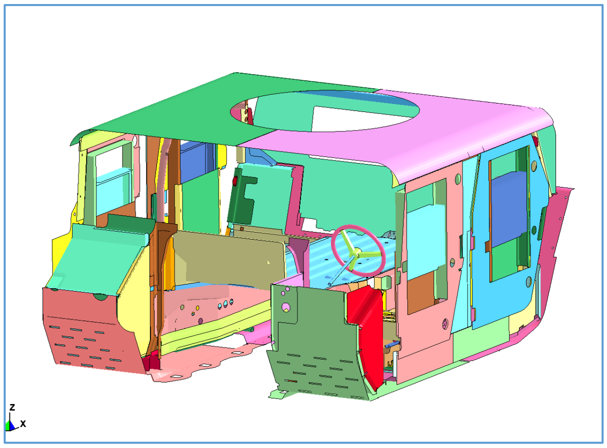

Figure 11: BIW for Interface Component

The second step is carried out by selecting the segmented sets created in step 1 as the main BIW model. To this all the non-structural components such as seats, seatbelt restraints systems and occupants are integrated (Figure 12). A tied contact is created between the BIW components as slave set and the binary ISF1 file from Step 1 as master segment. This ensures that the BIW will move as prescribed by the ISF1 file and all the non-structural components will move as they are coupled to the structure with contacts and seatbelts. All the necessary contacts between the occupants, seats, seatbelts and structure are defined as needed. Table 2 summarizes the ROMM model statistics.

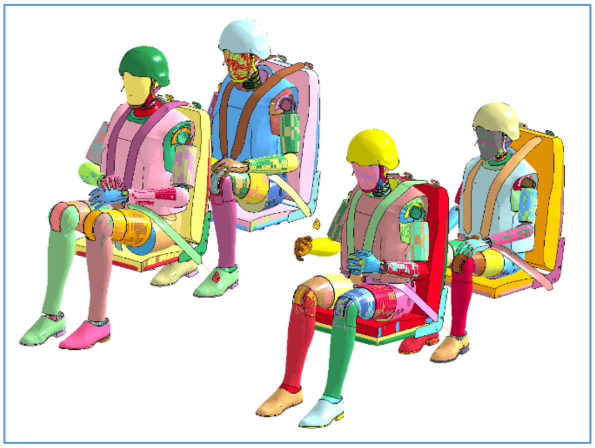

Figure 12: Occupants, Seats and Seat Restraints

Table 2: ROMM Model Statistics

Total no. of parts	1730
Total no. of elements	699,120
No. of CPU's	20
Termination time	2 seconds
Competition time	37 hours

ROMM takes 37 hours with 20 CPU's to complete 2 seconds of rollover event, which is 53% less than that of the FSM run time of 79 hours. This ROMM will help evaluate AOA more quickly and make design changes faster.

3. SIMULATION RESULTS, COMPARISON & DISCUSSION

Results from ROMM and FSM were compared to those of the test in detail. Intent of the correlation is to establish a high degree of confidence in the developed models. This will enable us to carry out AOA phase. A few of the selected channels from the 3-pt belt system with buckle pre-tensioner for driver, passenger, driver-rear and passenger-rear occupants are shown in Figures 13-31 below. The values on Y-axis are normalized to the test peak in this paper.

3.1 ROMM Results

Driver responses:

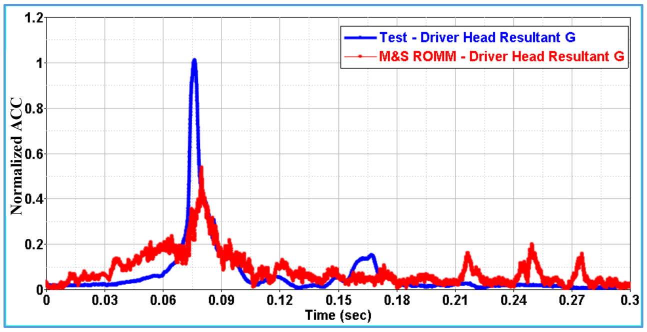

Figure 13: Driver – Head Resultant Acceleration

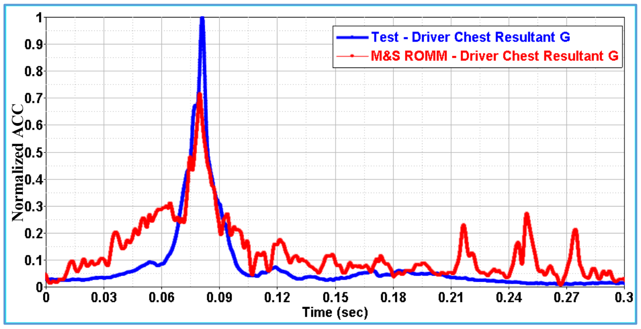

Figure 14: Driver Chest Resultant Acceleration

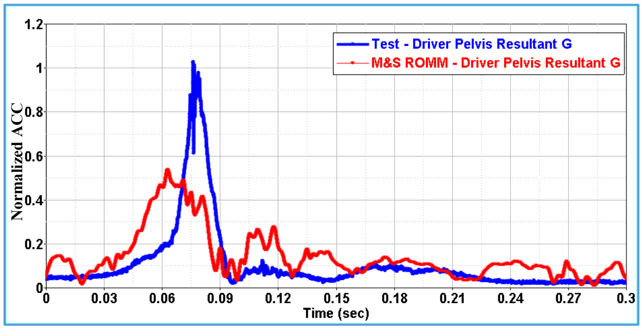

Figure 15: Driver Pelvis Resultant Acceleration

Driver head, chest and pelvis acceleration responses shown in Figures 13, 14 and 15 compare well to the test responses. Neck and Lumbar forces capture nicely for loading and unloading as shown in Figures 16 and 17, but differ in magnitude. ROMM response tends to over predict the lumbar load peak values but loading and unloading phase follows that of the test.

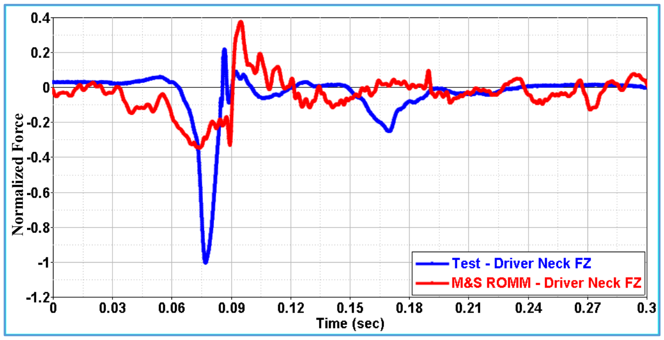

Figure 16: Driver – Neck FZ

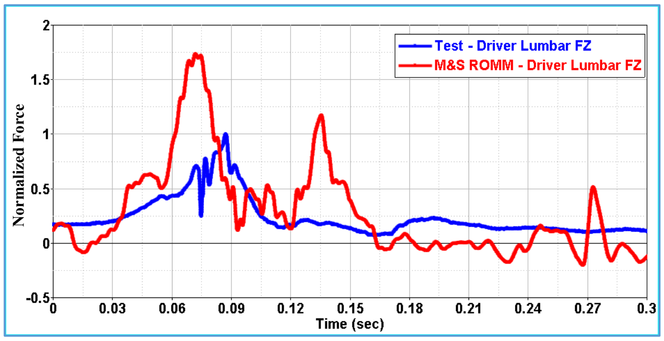

Figure 17: Driver – Lumbar FZ

Passenger responses:

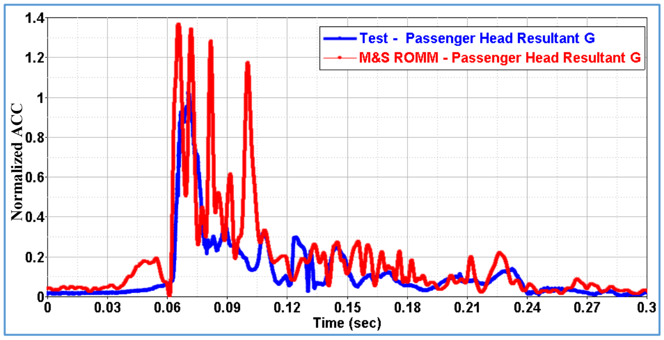

Figure 18: Passenger – Head Resultant Acceleration

Passenger occupant responses are shown in Figures 18-24. Passenger occupant also shows very good correlation responses to the test responses. Most of the loading and unloading are very well captured and a few channels are off either by time or by magnitude.

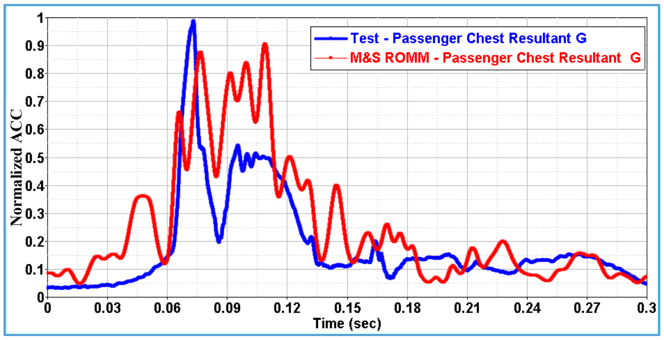

Figure 19: Passenger Chest Resultant Acceleration

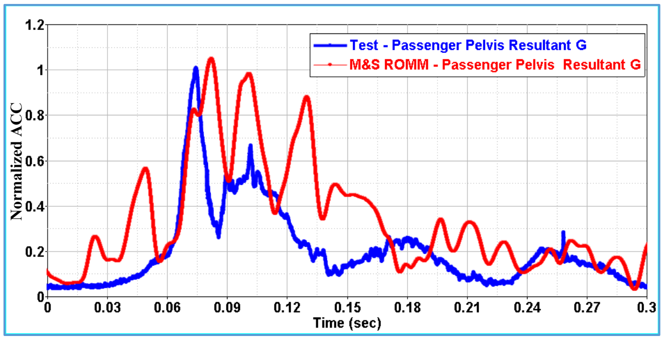

Figure 20: Passenger Pelvis Resultant Acceleration

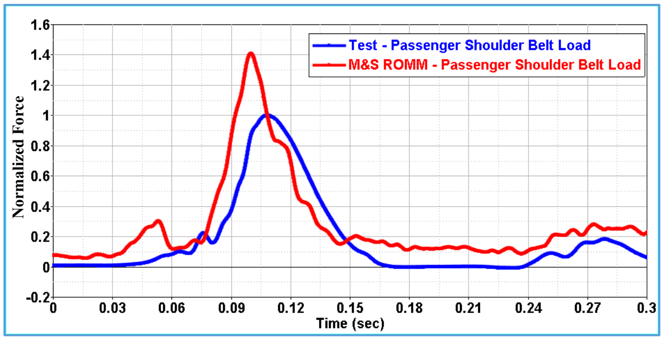

Figure 21: Passenger Shoulder Belt Load

Both shoulder and lap belt loads show higher values in ROMM simulation compared to the test results. This can be attributed to variations in belt properties, as well as retractor and pre-tensioner definition in M&S. As explained earlier most of the occupant positioning and belt routing are via visual by looking the pre-test and post-test pictures.

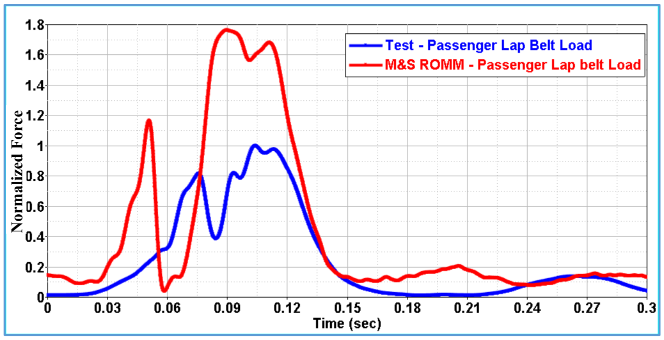

Figure 22: Passenger Lap Belt Load

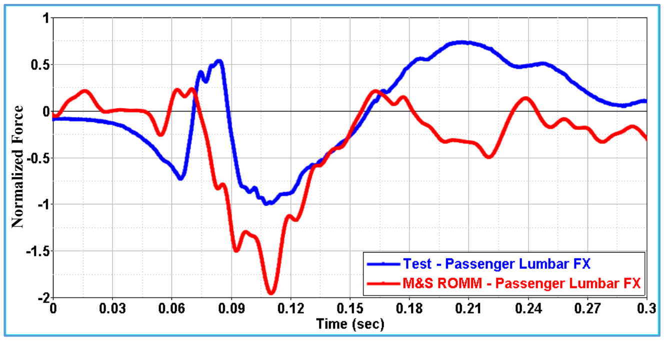

Figure 23: Passenger Lumbar FX

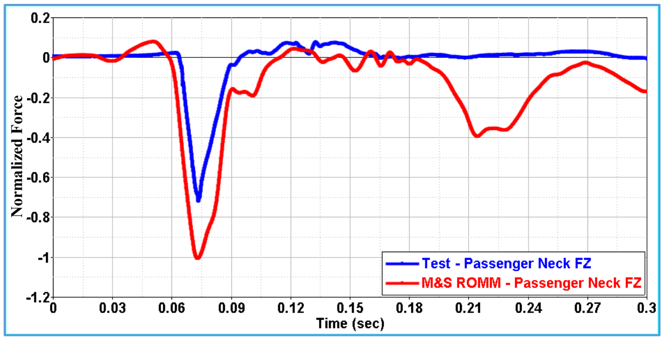

Figure 24: Passenger Neck FZ

Driver-rear responses:

Driver Rear occupants head acceleration, chest acceleration, lumbar FZ and pelvis acceleration are shown in Figures 25-28. Overall M&S ROMM results are in agreement with that of the test results.

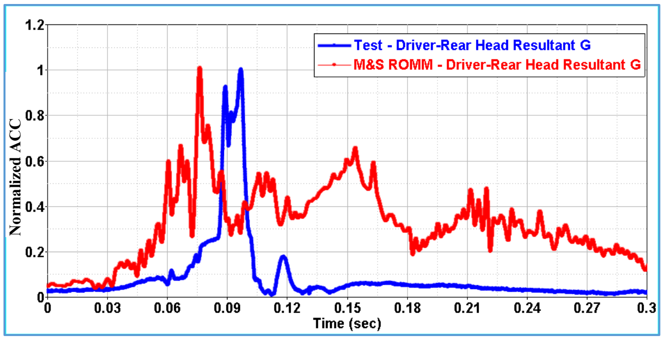

Figure 25: Driver Rear Head Resultant

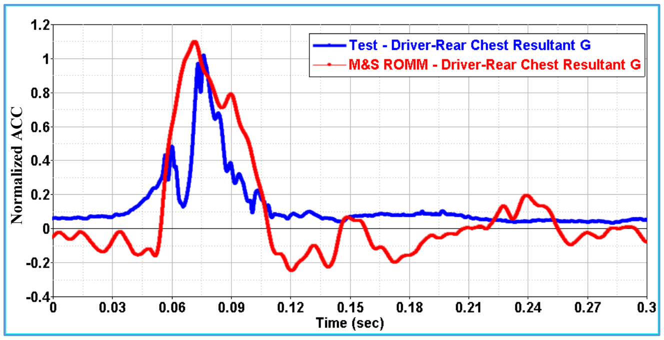

Figure 26: Driver Rear Chest Resultant Acceleration

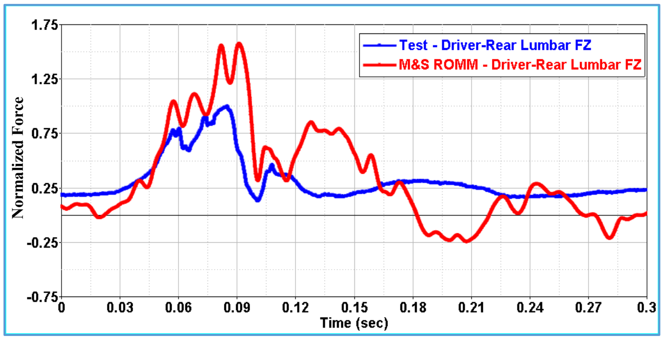

Figure 27: Driver Rear Lumbar FZ

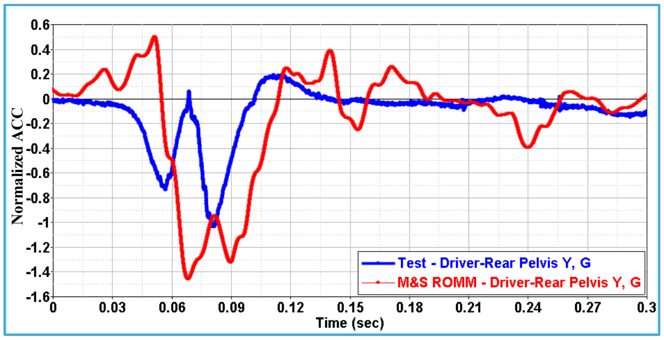

Figure 28: Driver Rear Pelvis Acceleration

Passenger-rear responses

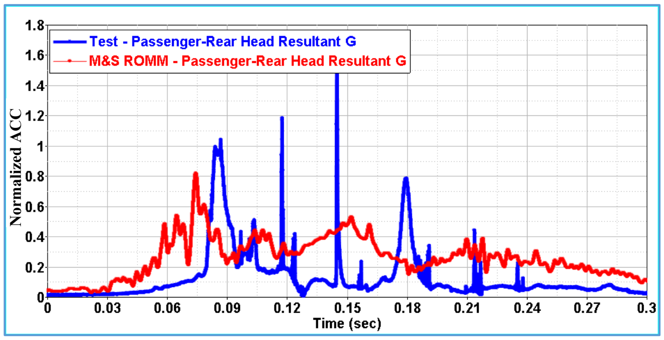

Figure 29: Passenger-Rear Head Resultant Acceleration

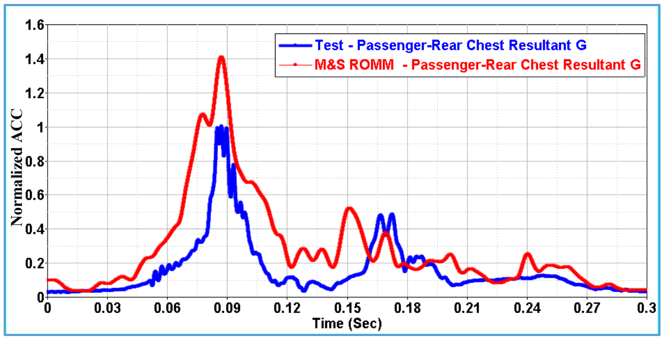

Figure 30: Passenger-Rear Chest Resultant Acceleration

Passenger Rear occupant responses are plotted in Figures 29-31. Shoulder belt loads shown in Figure 21 shows higher forces in ROMM model compared to the test

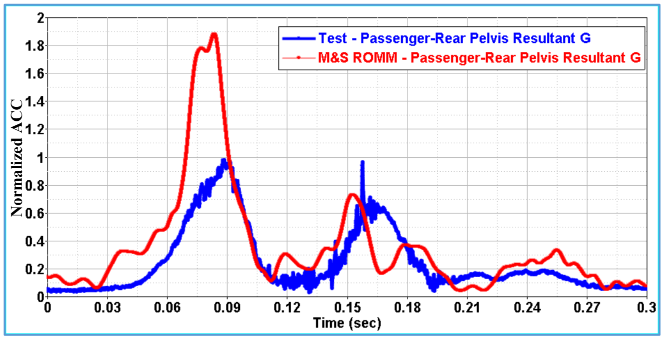

Figure 31: Passenger Rear Pelvis Resultant Acceleration

Both the passenger and passenger rear occupants experience higher vertical jump compared to the driver and driver rear occupants. This results in higher belt loads for passenger and passenger rear occupants.

Overall all the signature of the occupant load channels from simulation compares reasonably well with that in test, and some of the channel responses such as head acceleration, chest acceleration, and pelvic accelerations correlate both in signature and in magnitude.

3.2 FSM results

ROMM provided good correlation responses to that of the test results. Having established good confidence in ROMM models, full system models were evaluated to confirm the responses. Since ROMM mass (1,745 kg) is significantly less compared to the full system (41,680 kg), occupant responses will differ slightly due to mass and momentum, and will be closer to the test responses. A few selected occupant channels displayed in the next few figures shows the improvement in occupant responses.

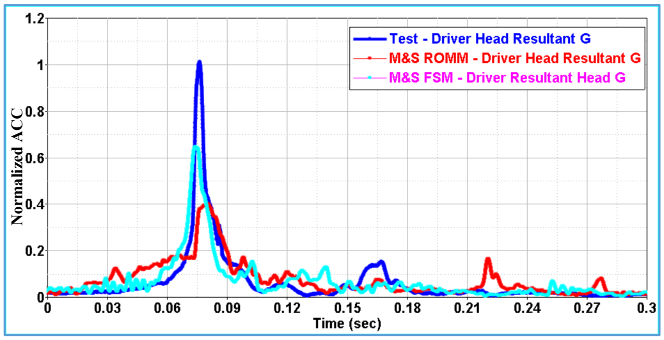

Figure 32: Driver head acceleration

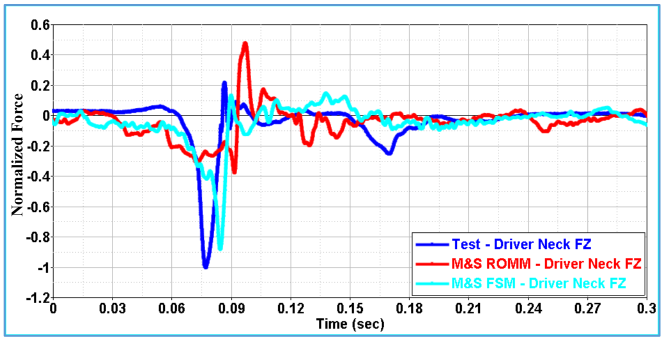

Figure 33: Driver neck FZ

Driver neck FZ forces (Figure 33) are more aligned to the test results in FSM compared to ROMM. This can be attributed to the higher mass and momentum, but over shoots while ROMM result under shoots the test result. Both are not too far off from the test responses which is important.

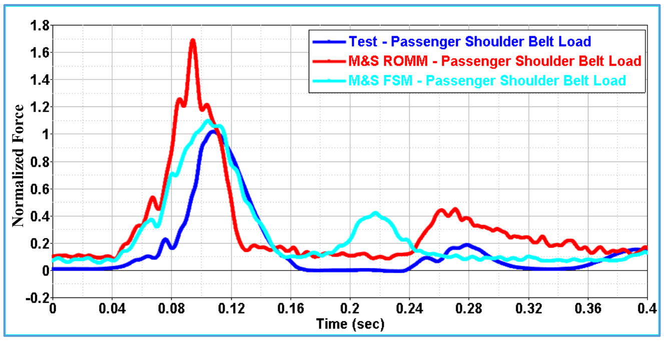

Figure 34: Passenger Shoulder Belt Load

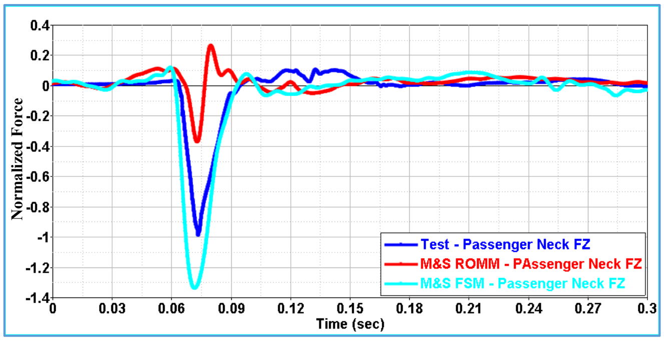

Figure 35: Passenger Neck FZ

Passenger shoulder belt loads (Figure 34) are higher in M&S for both ROMM and FSM methods, but FSM peak value is closer to the test result. Neck FZ loads are in very good agreement with the test responses. Since this is a rollover event, neck forces, moments and head responses are very critical for evaluation as they are near the high end of the threshold injury levels and also contacts the hard roof and other parts.

Figures 36 & 37 show the neck FZ responses for driver-rear occupant and passenger-rear occupant respectively. Both follow similar responses like the driver and responses. Almost all the responses follows similar trend.

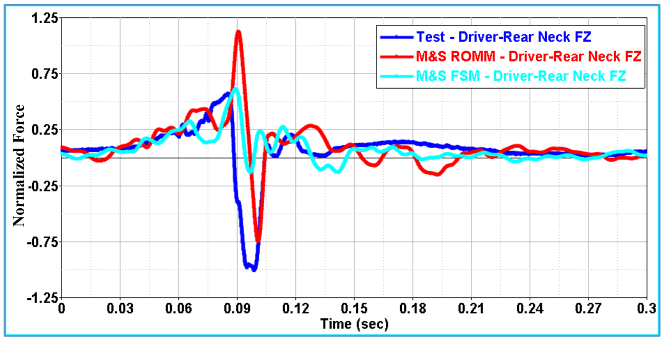

Figure 36: Driver-Rear NECK FZ

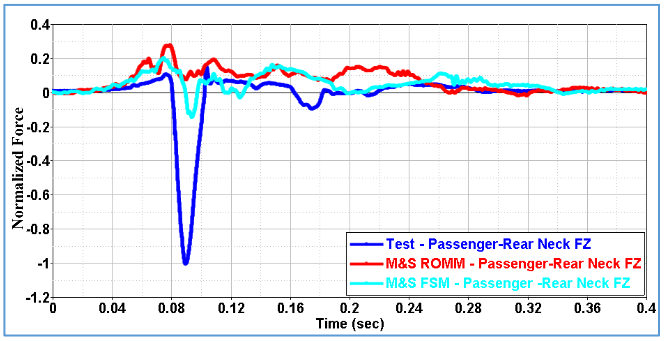

Figure 37: Passenger-Rear NECK FZ

Variations and uncertainties in dummy positioning, belt routing, seat positioning, and material properties such as seat foam, seatbelt fabric and dummy vest between the tested asset and the M&S models have contributed to the difference between M&S responses and test results. Eliminating these variations and material property uncertainties will show significantly improved responses and accuracy from simulation.

In addition to the time-history curves, occupant kinematics also compares very close to the post test positions. Figures 38 to 42 show the occupant postures at the end of rollover event. Both the time-history data of the occupant injury responses and the post-test pictures provide good confidence in the developed M&S models which can be used to analyze different seat and seatbelt restraints systems. This will help the program managers and IMMI to select the right system to test out further instead of testing all the alternatives, which will be expensive and time consuming.

Figure 38: Driver posture at the end of event

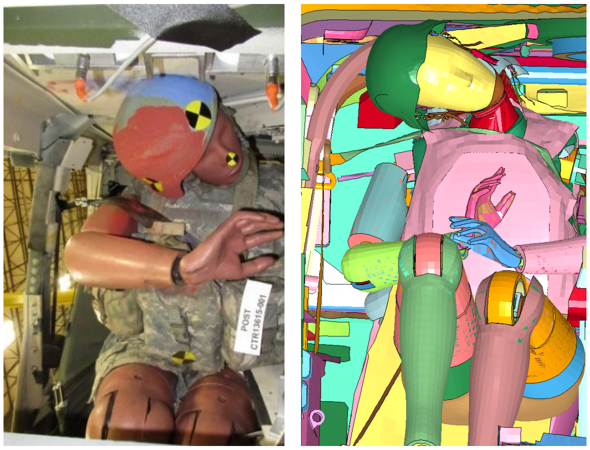

Figure 39: Passenger posture - front view

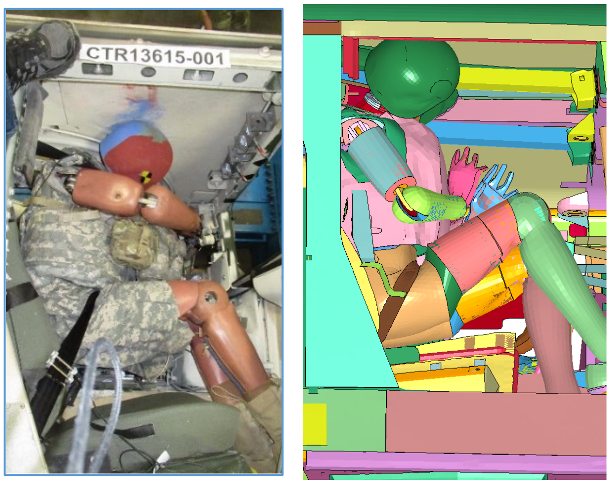

Figure 40: Passenger posture - side view

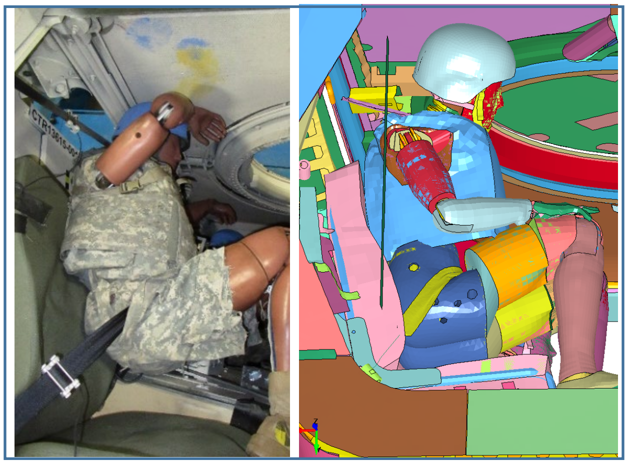

Figure 41: Passenger rear posture - side view

Figure 42: Passenger side posture - side view

4. SUMMARY AND CONCLUSIONS

IMMI has conducted two rollover tests for HMMWV with four occupants, one test with lap belt and shoulder belt restraints system only and another with a 3-pt belts and buckle pre-tensioner. A numerical simulation was performed using LS-

DYNA non-linear software successfully. The two simulation methods used here are called the reduced order modelling method and the full system method.

ROMM, using the LS-DYNA interface component analysis method, is a fast running approach helping to run the model quicker with individually selected structural components and integrated with all non-structural components such as occupants and seatbelt restraint systems. ROMM enabled to root cause the numerical instabilities and develop a robust simulation models. ROMM responses correlated to the IMMI tests. Overall signature of head, chest and pelvic responses compared fairly well fairly well, but responses of lumbar, neck and seatbelt loads lags the test. Developed seat belt restraints models were evaluated in FSM to confirm the trends. Most of the responses from FSM shows improved and much closer correlation to the test responses.

The robust numerical implementation of seatbelt restraints was evaluated in the ROMM and FSM. Both ROMM and FSM results show good comparisons to the test responses, as shown in the Section 3. All the rollover simulations were performed using U.S Army's DSRC High Performing Computing resources with 20 cpus. Computation time to run the HMMWV rollover simulation using ROMM was 37 hours compared to 79 hours with FSM. This is a 53% reduction in computation time. ROMM is a very useful method to evaluate analysis of alternatives such as dual pre-tensioner seat belt system, 5-pt seatbelt system and a stroking seat system, and identify the best seatbelt restraint system to mitigate occupant injuries.

The developed ROMM and FSM simulation approaches are significant value added for product managers in identifying the design weakness and find a suitable cost effective solution.

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