DEVELOPMENT OF A FINITE ELEMENT PAM-CRASH MODEL OF HYBRID III ANTHROPOMORPHIC TEST DEVICE WITH HIGH FIDELITY

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ABSTRACT

Prior studies indicate that a majority of Hybrid III dummy models are validated over a limited range of loading velocities in accordance with the specification of CFR 49 Part 572. The shortcoming is that the dummy model response, based on validation at regulatory velocities, may not correlate well with experiments when loaded at different velocities. The fidelity of models at an extended range of velocities is important, as in car crash tests dummies are frequently exposed to a variety of loading conditions in terms of loading type and loading velocity, which are differing from that of the Hybrid III standard certification tests.

In this study, a finite element model of Hybrid III 50th percentile dummy with high-fidelity response is developed using the non-linear finite element code PAM-CRASH. The methodology implemented for the model development is presented, with particular focus on material calibration and validation of the model against experimental data at different structure levels (component level, sub-system level, and system level), under a wide range of loading velocities. In addition to compliance with the typical certification requirements, the developed model has reasonable correlations with the physical dummy for a series of loading conditions. The model response has proven to be robust and reliable while maintaining computational efficiency, showing good potential to be used for accurate prediction of occupant injury numbers in crash simulation.

INTRODUCTION

Anthropomorphic test devices (ATDs) are designed to approximate human physical characteristics and mechanical response under impact loading[1]. Vehicle safety related regulation requires use of crash test dummies for the evaluation of vehicle crashworthiness and occupant protection within the automotive industry. Among various dummies meeting diverse need, the Hybrid III 50th percentile male dummy is the most commonly used ATD. In 1986, the Hybrid III dummy was specified as the standard front impact test dummy for FMVSS 208 by the National Highway Traffic Safety Administration (NHTSA). Currently, the dummy is extensively used worldwide for front impact tests on evaluation of restraint-system effectiveness to protect occupants and meet regulations[2].

With growing performance of computer hardware and analytical software, finite element (FE) simulations play a significant role in the field of automotive crash safety research and development. Use of finite element modeling approach provides fast insight into the performance of systems in great detail, and thus largely shortens the development period of the vehicle model. At present, diverse computer models of test devices (dummies, barriers, …) are already developed and routinely used for crash simulation[3][4]. The dummy models, as an indispensible part of a car crash model, allow efficient evaluation of restraint-system effectiveness. To date, crash simulation users demand increasingly higher dummy model quality, for accurate prediction of the injury risk to occupants. An essential feature for such dummy models is the fidelity, which means to what extent the model response is correlated to the hardware.

In the practice of dummy model development, the minimum requirement for the Hybrid III model is compliance with the standard certification tests as specified in the CFR 49 Part 572. However, the loading velocities in the regulatory certification tests are within a very limited range. The shortcoming is that the performance of the model, based on validation at limited range of regulatory velocities, may not always give satisfactory results in simulations at different velocities[5]. It was suggested that validation tests should be conducted under wide range of strain rates and in deformation ranges typical of loading conditions for dummies in vehicle crash[6]. Therefore, in addition to compliance with the regulation, the performance of the dummy model could be further improved through a larger scale validation against experiments with the physical dummy tested at different structural levels under wide range of loading velocities. Previous studies indicate that, a majority of dummy models are merely validated in accordance with the dummy regulation[7][8][9]. While there is the practice of validation of the dummy model under multiple loading velocities, the velocity range at the sub-system level is not wide enough[10][11].

In this paper, a finite element model of Hybrid III dummy with high fidelity and robust response is developed using the nonlinear finite element code PAM-CRASH[12][13]. The dummy model is constructed in great detail in terms of physical characteristics to accurately represent the hardware. Material properties of the model are optimized to represent the mechanical behavior of the hardware through validations at different structure levels and loading velocity levels. The dummy model developed in this study has shown reasonable correlations with the hardware for a variety of loading conditions. The model has proven to be of good fidelity to the hardware, robust, reliable, computationally efficient, and is a reasonable basis for further work to reach accurate prediction of occupant injury numbers in automotive crash simulations.

MODEL CONSTRUCTION APPROACH

Prior to the project, an extensive literature survey was conducted to gather the Hybrid III related information. Then, a three dimensional finite element model of the Hybrid III torso is constructed from measurements on a disassembled physical dummy. Limbs and head models from an existing ESI commercial BioRID model are connected to the the torso model with joints leading to generation of a full dummy assembly.

Geometry Acquisition

Rather than relying on nominal geometries from dummy drawings, a realistic geometry is developed from measurements on a physical dummy torso structure, totally disassembled for the purpose of the project. In acquiring the geometry of individual components, the parts with regular shapes are directly measured. The skin parts that feature complex three dimensional surfaces are digitized by CT scan. The CAD models and subsequent assembly are constructed in CATIA. Weight of parts including small accessories is measured, while the exterior dimension and moment of inertia of Hybrid III can be directly referred to the dummy user manual and public literature.

Mesh Construction

Most parts are meshed with hexahedral elements in order to reduce the number of elements. For complex surface parts, like pelvis and abdomen, meshes are made of tetrahedral elements. In meshing rigid body of complex structure with hexahedral elements, a slight gap of 1.1 mm is maintained between internal adjacent sub-parts for easier contact interface management. As compared with the more classical method of solid meshing with shared nodes, the total element number for a given part is largely reduced. As a result, the model size is comparable to existing commercial dummy models, meanwhile the mesh quality of flexible parts is rigorously ensured.

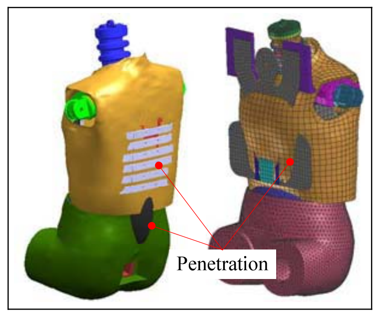

Figure 1. Penetration issues in preliminary model assembly.

Model Assembly

When individual CAD models are assembled together, there are many penetrations in the chest model, as shown in Figure 1. The main reason for these penetrations is that the dummy hardware has pre-deformations that are released when its parts are disassembled. For example, without the assembling constraint, urethane bib is flat and not accommodated in the chest structure. Therefore, enforcing certain pre-deformation to the pre-stressed parts is necessary to make them assume their ultimate shape during the chest assembly process. Simulation runs of six rib components, the bib and jacket are performed to capture the pre-deformed shapes of the assembled dummy hardware. With all the pre-deformation to the parts in place, the torso model is properly assembled, as illustrated in Figure 2. Limbs and head obtained from an existing ESI commercial BioRID model are connected to the torso model using joint definition. Figure 3 shows the assembled full dummy model. It should be noted that pre-stresses from assembly are not included in the model.

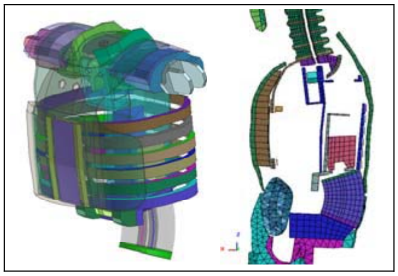

Figure 2. Adapted mesh for model assembly.

Figure 3. Developed Hybrid III 50th percentile PAM-CRASH FE model.

MODEL DESCRIPTION

The full dummy model consists of 160 parts, 42518 nodes and 87764 elements. The entities are regularly numbered for clear organization.

The model geometry complies with the specifications of Hybrid III in terms of external dimension, mass and inertia. Instruments of Hybrid III are properly modeled in accordance with the hardware and SAE J211. Load cells and accelerometers are commonly modeled as joints and nodal local time history, respectively. Chest potentiometer is realistically modeled using a joint at the base of the transducer and a general kinematic joint at the sternum. The rotational angle of the transducer arm about y-axis can be easily converted to chest frontal compression with a simple formula.

Material properties of different parts are defined using different material types in PAM-CRASH. Rigid bodies and null material (types 99, 100), elastic plastic material (types 1, 103) are frequently used to model metal parts that undergo small elastic deformations. Linear visco-elastic material (type 5) and nonlinear strain rate dependent foam (type 45) are used to model typical flexible parts, like vinyl skin and flesh foam, respectively. In addition, types 301 and 221 are used to model tied link and generalized spherical joint.

EXPERIMENTAL DATABASE AND MODEL VALIDATION

A variety of tests are carried out at different levels in terms of structure complexity and loading velocity. Experiments at the component level include single rib drop test and abdomen drop test. Dummy calibration tests at the sub-assembly level include head drop test, neck flexion and extension test as well as chest frontal impact test. In addition to above tests on local response of the dummy, a sled test with a belted full dummy at the system level is conducted, recording dummy kinematics and injury numbers.

Most tests at different structural levels are conducted for a series of loading velocities. To prevent damage of the dummy or segments in high-velocity impacts, tests are in general conducted at progressive loading velocities. During the tests, the sampling rate for data channels and high speed movie is set at 20,000 samples/s and 1,000 frames/s, respectively. Test ambient temperature and relative humidity are recorded.

Besides, above experimental data, publicly available test conditions and results, e.g., lumbar spine bending and the dummy calibration curves from the hardware owner's manual[15], are also referred to expand the experimental database for the model validation purpose. Therefore, the accumulated experimental data for the model validation are derived from three major sources, i.e., tests conducted in this project, the hardware owner's manual and public literature. In this paper, most test curves selected for comparison against the model response are from the tests in this project, unless otherwise noted. It should also be noted that the test data and the model response are both filtered with protocols in accordance with SAE J211.

In the dummy modeling, the most challenging work is material characterization through validation of the model at different levels. In order to enhance the fidelity of the model response, critical material parameters are identified using optimization techniques, as schematically shown in Figure 4.

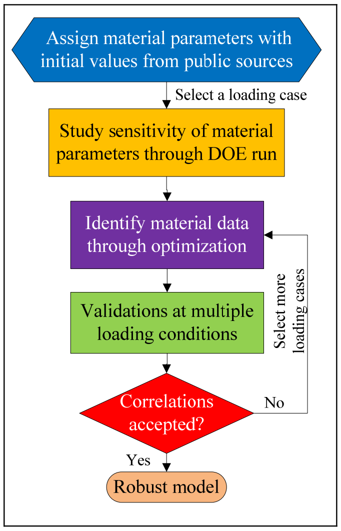

Figure 4. Technical approach used in material parameters identification.

Material data available from public literature[5][7][10], serving as a good starting point for the model validation, are first assigned to various material parameters. Design of experiments (DOE) analysis is then performed to investigate the sensitivity of different material parameters at a selected loading condition, during which critical material parameters are determined. This is followed by launching an optimization run in which values of the afore-identified critical material parameters are iteratively adjusted until convergence is reached. The model with optimized material data is subsequently validated at remaining loading conditions. If correlation of the model with tests is not accepted, the material data will be re-calibrated through optimization by simultaneous simulation at two or more loading conditions. The optimized model is again validated at multiple loading conditions and this process continues until adequate correlations between simulation and tests at a series of loading conditions are achieved. Using the optimization protocol, the material properties of the dummy model are calibrated at component and sub-system levels, then validated at the system level.

Material Calibration and Model Validation at Component Level

The material properties of rib component, abdomen and lumbar spine are calibrated at the component level through optimization using respectively single rib impact, abdomen impact, and lumbar spine bending load cases.

Single rib impact In frontal impact, ribs play a dominant role in chest response. A dummy rib is composed of a spring steel plate bonded with a damping material for providing proper dynamic response. Each rib is supported at the rear by a stiffener.

A series of single rib impact tests is carried out using a drop tower, as shown in Figure 5. The rib is positioned in a configuration that loads the rib in a similar way as in the dummy in a frontal crash situation. Rib ends are rigidly constrained to ensure stability of rib deformation during impact. Impact load and rib compression are calculated by acceleration signal and high speed movie, respectively. Nominal velocity of loading is ranging from 2.0 m/s to 6.7 m/s.

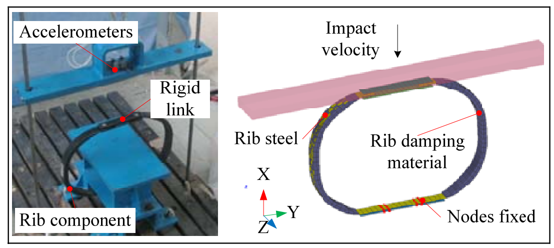

Figure 5. Setup for rib drop test and simulation.

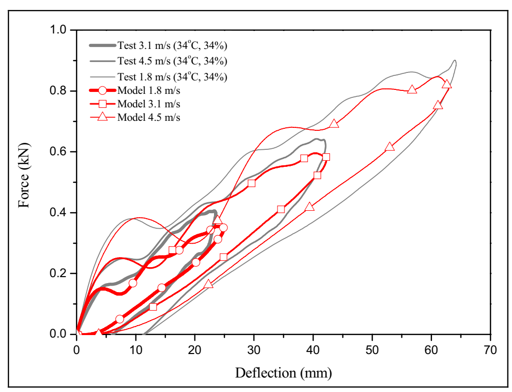

Figure 6. Correlations between rib model response and test data.

In the single rib model, sharing nodes is applied to simulate the bond on the interface between the rib steel and the damping material. The rib steel and the stiffener are modeled as elastic material. The damping material is modeled as linearly visco-elastic. Figure 6 gives the correlations results indicating that the simulated structural response shows good agreement with the tests at different loading velocities. Note that correlation at 6.7 m/s is not shown as the effective test data is rather limited.

Abdomen impact Impact tests with the abdomen, composed of vinyl-encased foam, are also conducted with the drop tower, as shown in Figure 7. The abdomen is properly positioned to best spread the load. Although the loading direction is not identical with that experienced by dummy in a typical car crash, it still can serve the component validation purpose as the abdomen component is quite homogeneous and isotropic. Impact load and abdomen compression are calculated by acceleration signal and double integration of the signal, respectively. Nominal impact velocities are ranging from 2 m/s to 4 m/s, which is sufficient to generate substantial compression of the abdomen.

In the abdomen model, the vinyl skin is meshed with shell elements that share nodes with the solid tetrahedral elements of the interior foam mesh. The vinyl skin and the interior foam are modeled as elastic plastic material and general strain rate dependent foam, respectively. Figure 8 shows the simulation results, indicating that the model correlates reasonably with tests at different loading velocities, except for the hysteresis of the high speed loading. Since good correlations in loading stage are reached under different velocities loading, the model behavior is adequate for injury prediction at this stage.

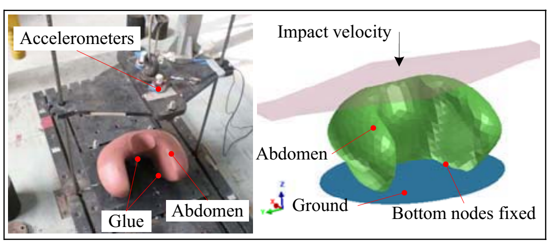

Figure 7. Setup for abdomen drop test and simulation.

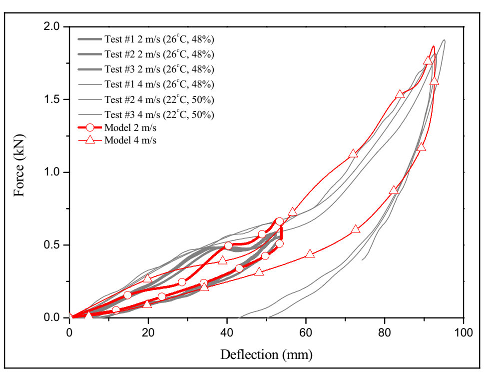

Figure 8. Correlations between abdomen model response and test data.

Lumbar bending Material characterization of the lumbar spine is performed with reference to the lumbar bending test in the literature[2]. The lumbar spine is modeled as linear visco-elastic solid rubber clamped by two rigid-body steel plates on each end. The two cables are modeled as a number of bar elements going through the lumbar spine. A rotational angle-time function with a constant loading velocity of 0.13 s^{-1} is applied at the upper end of the loading beam while keeping the lower end of the lumbar spine constrained. The moment-rotation history of the lumbar spine is calculated. Simulation result shows an approximate linear representation of the experimental data, considered accurate enough at this stage in the absence of measurements on the available hardware. The lumbar spine can be further improved by validation against the test under dynamic loading.

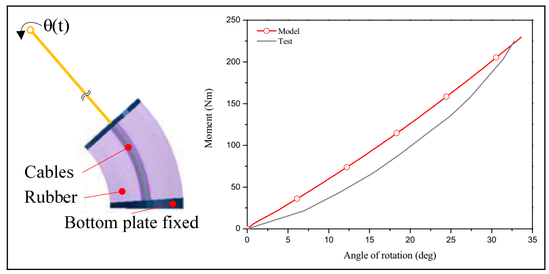

Figure 9. Setup for lumbar bending simulation and correlation of the model with test.

Material Calibration and Model Validation at Sub-System Level

Typical certification tests of Hybrid III at the sub-system level are carried out, including head drop test, neck flexion and extension test and chest pendulum test, as shown in Figure 10. Configuration for the tests and the performance target is briefly presented below. Readers are referred to CFR 49 Part 572 subpart E for more detailed information[16].

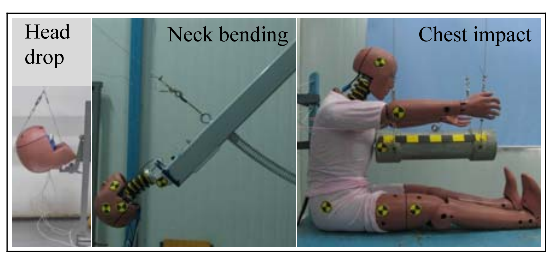

Figure 10. Setup for Hybrid III calibration tests.

Head drop test The test measures Hybrid III forehead response to frontal impact with a hard surface. The head assembly is suspended at a height of 376 mm and dropped freely on a smooth and hard steel plate, according to the regulation. The peak resultant acceleration of the head center of gravity should lie between 225 g and 275 g. In the project phase 1, we carry out head certification test at the regulatory drop height of 376mm, corresponding to the impact velocity of approximately 2.7 m/s. Mechanical response of the hardware segment at other impact velocities can be found in the literature[10][11]. With the Hybrid III head model, the material properties of head skin that is modeled as linearly visco-elastic are calibrated. Figure 11 shows the correlations between simulation and tests. It is clearly observed that the head model response is in conformity with the regulatory performance requirement at 2.7 m/s. In addition, the model also correlates properly with the test data at velocities ranging from 2.2 m/s to 3.1 m/s. As for the high velocity of 4.2 m/s, however, the head model shows 10% lower peak value than test data.

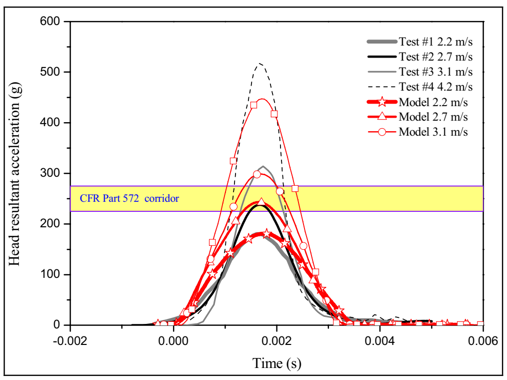

Figure 11. Correlations between head model response and test data; Test 2.2 m/s and 3.1 m/s from reference[11]; Test 4.2 m/s from reference[10].

<u>**Neck flexion and extension test**</u> This test measures structural response of the head-neck assembly subjected to forward bending and rear bending, respectively. The head-neck sub-assembly is mounted at the bottom of a pendulum, as shown in Figure 12, which is released from a given height to achieve the impact velocity of about 7 m/s for flexion and approximate 6 m/s for extension, as specified in the certification test specification. A block of honeycomb material is used to stop the pendulum at the lowest point. Rotation angle of the D-plane is recorded by the combined use of head potentiometer and neck potentiometer. In the project phase 1, neck tests are carried out with a drop velocity range of 3 m/s to 6 m/s for both flexion and extension.

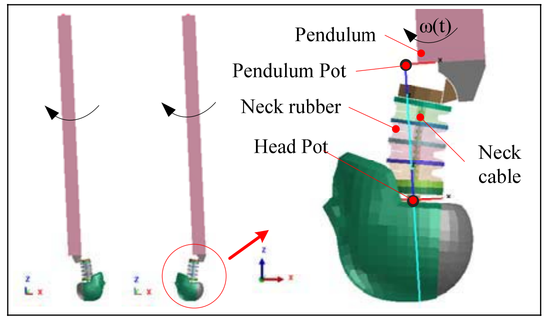

Figure 12. Setup for neck extension and flexion simulation.

The head-neck bending tests are realistically simulated through construction of the neck model in detail and true loading condition applied to the model, as illustrated in Figure 12. The simulation starts at the time of contact between the pendulum and the honeycomb. An angular velocity time history, converted from the crash pulse, is applied to the pendulum to avoid the difficulty in modeling the honeycomb material. Motion of the head-neck sub-assembly during impact is schematically shown in Figure 13. Material properties of the neck are optimized for the flexion at 7 m/s and validated at other loading conditions, including extension at 6m/s and 3m/s, and flexion at 3m/s. Results indicate that the optimized neck model has responses of high fidelity at high velocities (Figure 14, 15) and shows reasonable correlation with tests at low velocities (Figure 16).

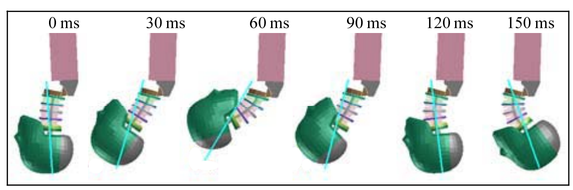

Figure 13. Head-neck sub-assembly kinematics, flexion at 7 m/s.

<u>**Thorax impact test**</u> In this test, chest response at the system level under frontal impact loading is measured. The dummy regulation specifies that a rigid pendulum with a mass of 23.4 kg is released from a given height to achieve the chest impact velocity of approximately 6.7 m/s. In the project phase 1, the impact speeds are ranging from 3.0 m/s to 5 m/s. Experimental data at 6.7 m/s is referred to public literature and the dummy owner's manual.

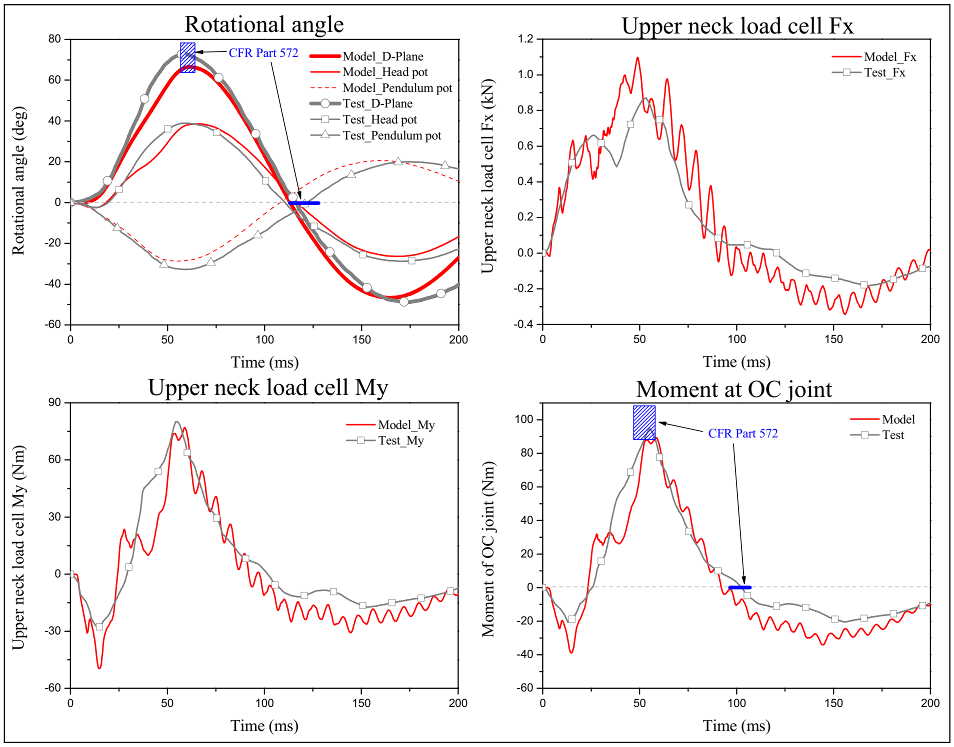

Figure 14. Optimization for flexion at 7 m/s, test data from the dummy owner's manual[15].

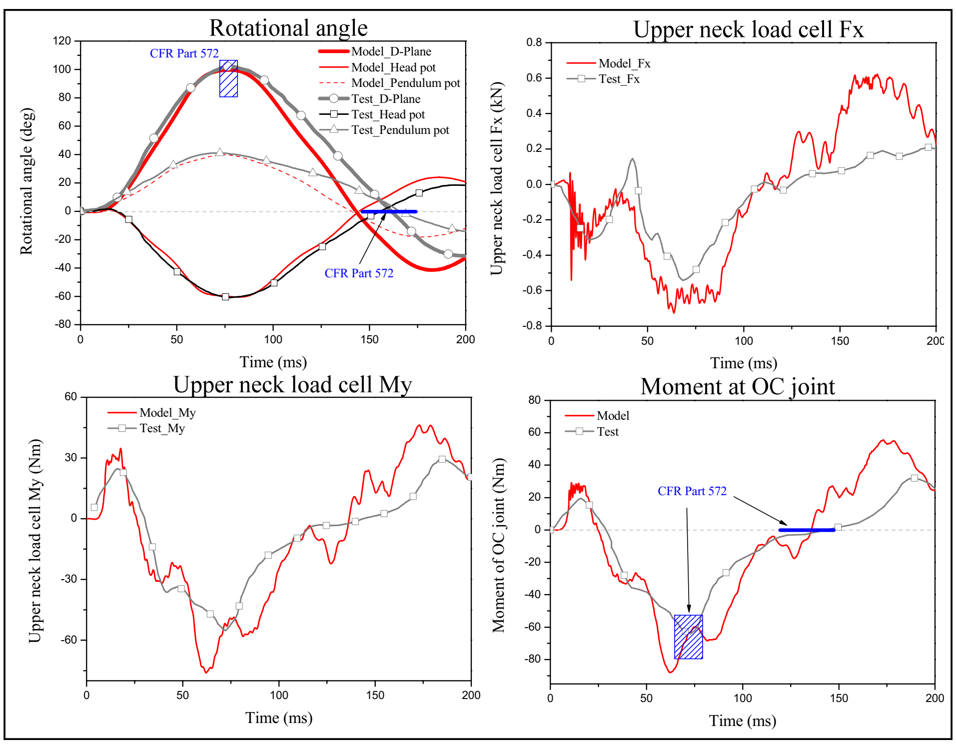

Figure 15. Validation for extension at 6 m/s, test data from the dummy owner's manual[15].

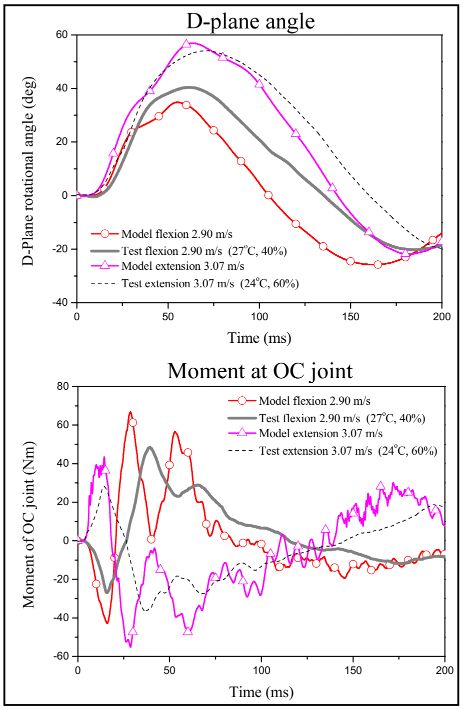

Figure 16. Validation for neck flexion and extension at low velocities.

Figure 17 shows the initial positioning of the chest impact model, in which impact force and chest deflection are recorded from the impactor contact, and the simulated internal chest potentiometer. Note that rib material properties optimized at single rib level are further adapted at the chest assembly level. Figure 18-21, show correlations between the model and test data at a series of loading velocities.

It is observed that the mechanical behavior of the chest model is in conformity with SAE standard performance target at 3 m/s (Figure 18) and the regulatory requirements at 6.7 m/s (Figure 21). The model response agrees well with that of Hybrid III dummy and cadaver corridors both at velocities of 4.3 m/s and 6.7 m/s, as observed in Figure 19 and Figure 21. Additionally, the model shows reasonable correlation with test data at 3 m/s and 5.1 m/s, as respectively shown in Figure 18 and 20, in which relatively larger chest deflection and lower peak force in conducted tests in the project is observed. This is likely to be caused by the non compliance of test ambient temperatures.

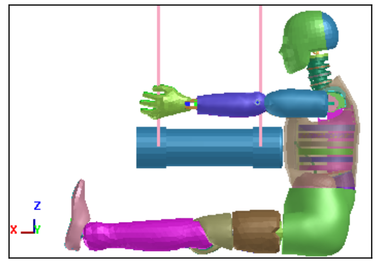

Figure 17. Setup for chest impact simulation.

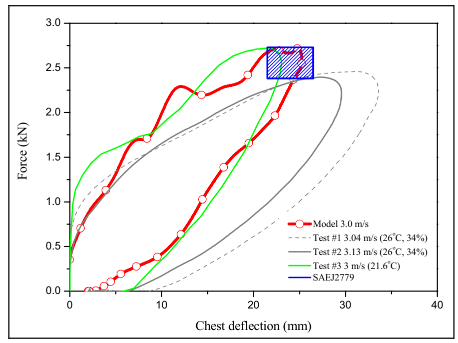

Figure 18. Correlation between chest model and tests at 3 m/s, test #3 from reference[17].

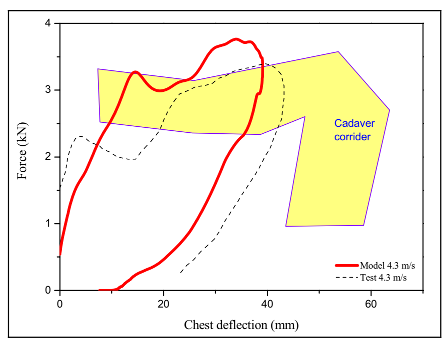

Figure 19. Correlation between chest model and tests at 4.3 m/s, test data from references[1][17].

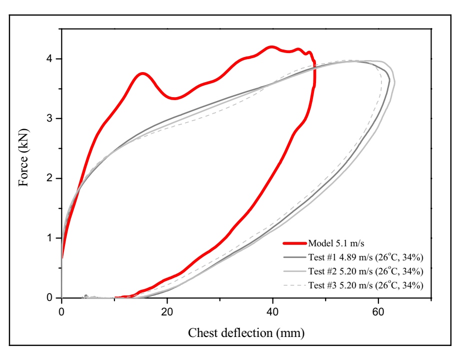

Figure 20. Correlation between chest model and tests at 5.1 m/s.

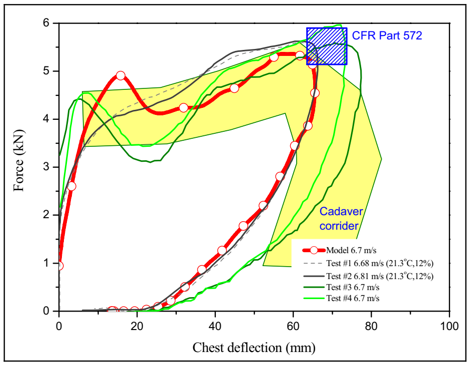

Figure 21. Correlation between chest model and tests at 6.7 m/s, test #1 & #2 from reference[15], test #3 & #4 from references[1][17].

Full Dummy Validation at System Level

<u>**Model validation against a sled test**</u> A sled test is conducted to evaluate the belted dummy response in an environment close to a 50 km/h real car crash situation. A hard seat associated with a piece of TNO child seat testing foam is used to approximate a typical car seat. The knee bolster is removed to avoid any possible complex interaction during the impact. Feet are properly rested on the inclined toe panel. Figure 22 shows the sled test setup and the model configuration.

Simulation is performed by inversely applying a velocity-time history, integral of the crash pulse, to the sled. Validation results of the dummy model against typical test data is given in Figure 23, as well as comparison of their kinematic motion as illustrated in Figure 24. It is clearly examined that good correlation between simulation and experiment is achieved in terms of dummy kinematics and t... Further improvements ...tion of chest deflection.

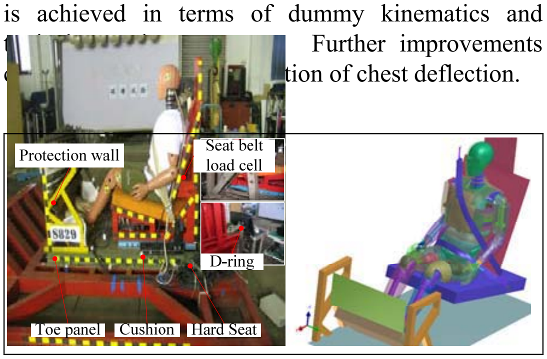

Figure 22. Setup for sled test with a belted full dummy and simulation.

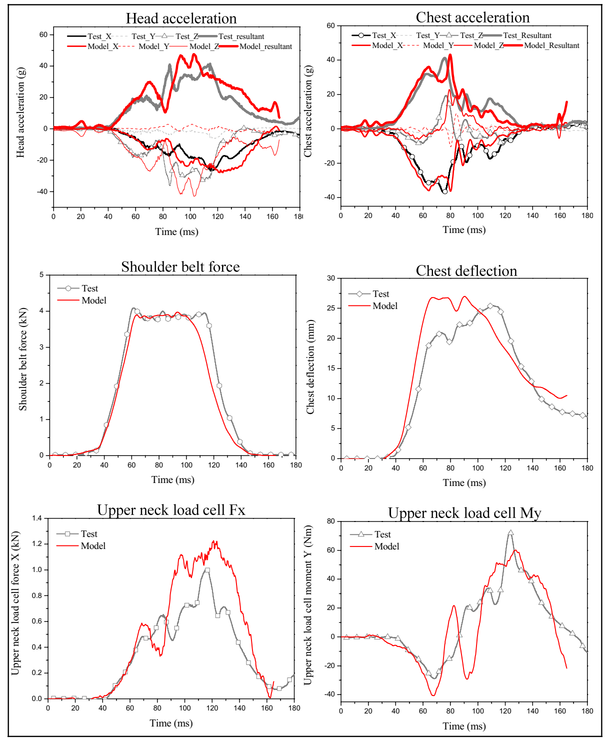

Figure 23. Correlations between model response and test data at system level.

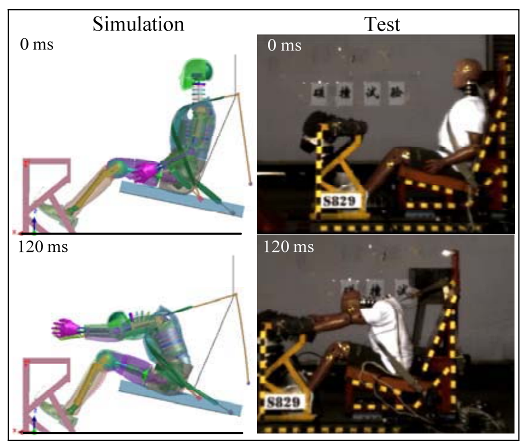

Figure 24. Comparison of dummy kinematics.

CONCLUSIONS

The automotive industry requires high quality dummy models for crash safety simulation in the design of new vehicle models. This paper has introduced a new platform for research and development on the Hybrid III dummy model with PAM-CRASH. It attempts to represent with a reasonable accuracy of the mechanical response of the hardware under loading conditions at various velocities, in addition to compliance with the regulatory requirements. It also uses a new method to approach the real geometry of the assembled dummy, consisting in simulating the assembly of the thorax. In this paper, the current status of the Hybrid III FE model shows reasonable correlation between simulation and experiments. Further developments are still needed to reach a highly realistic model, in particular correlations against a wider range of experiments, statistics on actual dummy properties, further material modeling, and finer account of manufacturing details.

REFERENCES

[1] Foster J, Kortge J, Wolanin M. Hybrid III-A biomechanically-based crash test dummy. SAE Technical Paper No. 770938, 1977

[2] Deng Y C. Analytical study of interaction between belt and HIII dummy in sled tests. SAE Technical Paper No. 880648, 1988

[3] Franz U, Stahlschmidt S, Schelkle E, et al. 15 years of finite element dummy model development within FAT, 2009

[4] Rieser A, Nußbaumer C, et al. A development process for creating finite-element models of crash test dummies based on investigations of the hardware. The 21st International Technical Conference on the Enhanced Safety of Vehicles Conference, ESV 09-0368, 2009

[5] Yu H, Zhou Q, Neat G W. Three-dimensional finite element modelling of the torso of the anthropomorphic test device THOR. International Journal of Vehicle Safety 2(1-2): 116-140, 2007

[6] Arnoux P J and Joonekindt S, et al. RADIOSS finite element model of the Thor dummy. International Journal of Crashworthiness 8(6): 529-541, 2003

[7] Noureddine A, Eskandarian A, Digges K. Computer modeling and validation of a Hybrid III dummy for crashworthiness simulation. Mathematical and Computer Modelling (35): 885-893, 2002

[8] Naravane A, Deb A.Validation of a Hybrid III dummy model and its application in simulation of vehicle frontal NCAP tests. Altair CAE Users Conference, 2005

[9] Mohan P and Marzougui D, et al. Development and Validation of Hybrid III Crash Test Dummy. SAE Technical Paper No. 2009-01-0473, 2009

[10] Khalil T B, Lin T C. Simulation of the Hybrid III dummy response to impact by nonlinear finite element analysis. SAE Technical Paper No. 942227, 1994

[11] Moss S and Huang Y, et al. Development of an advanced finite element model database of the Hybrid III crash test dummy family. SAE Technical Paper No. 971042, 1997

[12] ESI Group. Virtual Performance Solutions-Explicit Solver Notes Manual, 2008

[13] ESI Group. Virtual Performance Solutions-Explicit Solver Reference Manual, 2008

[14] FTSS Inc. User’s manual for the 50th percentile male Hybrid III test dummy, April 2005

[15] FTSS Inc. Owner’s manual for the 50th percentile male Hybrid III test dummy, SN. 1113

[16] NHTSA 49 CFR 49 572.31 Subpart E-Hybrid III Test Dummy

[17] Kai W, Xiangrong L, Haitao Z, Xianglei Z. Research on the low speed thorax calibration test for Hybrid III 50th Male Dummy. The Twelfth Conference of Automotive Safety Technology, 2010