SIDE IMPACT INJURY PREDICTION WITH FE SIMULATIONS OF THE NEW ADVANCED WORLD SID FE DUMMY MODELS

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Paper Number 07-0372

ABSTRACT

Two new World SID (50th and 5th) FE models were developed for providing virtual tools of predicting occupant injuries during vehicle side collisions. The virtual dummy models have been verified with their physical counterparts in aspects of lab certification tests, bio-fidelity and sled tests. Many new techniques have been utilized in the model development including advanced testing and material modeling which guaranteed the high fidelity between the virtual models and the physical dummies. The good model-to-test correlations of various loading configurations have shown that the new FE models could be used as new tools in virtual simulations of vehicle side impact crash worthiness studies as options to other side impact dummies to predict better occupant injury due to superior bio-fidelity performances of the World SID dummies. The new dummy models were also tested under vehicle FMVSS214 impact conditions. A comparison of occupant injury parameters extracted from the models between the World SID 5th and SID-IIs dummy were also made using the load case.

INTRODUCTION

In recent years, developments of internationally harmonized Anthropomorphic Test Devices (ATDs) have been initiated by the International Organization for Standardization (ISO). These efforts have lead to the birth of two new side impact dummies, i.e. the World SID 50th and 5th (representing a 50th percentile male and a 5th percentile female), aiming to replace the existing worldwide regulatory and research side impact dummies.

The World SID 50th dummy has been evaluated by organizations around the world such as the US OSRP, NHTSA, APROSYS (the European funded program) and others against the current 50th percentile male side impact dummies such as DOT-SID, EuroSID-1 and EuroSID-2, and BioSID to compare the bio-fidelity ratings. As shown in Table 1, the World SID 50th (revised prototype) achieved the best overall dummy rating and also the best single body region ratings for the head, thorax, abdomen and pelvis. [1] It can be seen that according to Table 1, the World SID 50th new dummy exhibits a more human-like response in the specified crash events and has the highest bio-fidelity rating of any existing side impact crash test dummies in the world.

Table 1. Bio-fidelity comparison of side impact dummies

	World SID 50th	**BioSID**	**EuroSID-2**	**EuroSID-1**	**DOT SID**
Head	**10.0**	**6.7**	**5.0**	**5.0**	**0.0**
Neck	**5.2**	**6.7**	**4.4**	**7.8**	**2.5**
Shoulder	**7.0**	**7.3**	**5.3**	**7.3**	**0.0**
Thorax	**7.9**	**6.3**	**5.2**	**5.4**	**3.1**
Abdomen	**6.4**	**3.8**	**2.6**	**0.9**	**4.4**
Pelvis	**7.8**	**4.0**	**5.3**	**1.5**	**2.5**
Overall	**7.3**	**5.7**	**4.6**	**4.4**	**2.3**

The World SID 5th dummy was created by FTSS after the successful launch of the World SID 50th production dummy. This is a scaled down version of the World SID 50th dummy. Like the World SID 50th dummy, the World SID 5th dummy (representing a woman of small stature and a young adolescent) was also developed under the direction of the ISO through the APROSYS in consultation with the World SID Task Group (ISO). Under current efforts, both versions of the World SID dummies will endeavor to provide the foundation for future common and internationally accepted regulatory test procedures. This will also enable automakers and researchers worldwide to improve passenger safety by facilitating the comparison of crash test results.

The demand for virtual simulations of vehicle crash by CAE has seen rapid increases in recent years thanks to the large increase in computing power and decrease in cost. The usage of Finite Element (FE) dummy models has been increasing over the years in CAE simulations of crashworthiness analysis and occupant protection. FTSS has been making great efforts on the successful development of virtual (FE) dummies since 1995. The World SID 50th and 5th FE dummy models have been developed recently to add to the ever expanding FE dummy database.

NEW DEVELOPMENT IN FE DUMMY MODELS

The development of new dummy models have been keeping the pace with advancing of new technologies available both in computing technique and in engineering software such as Ls-dyna3d and Pamcrash. Many new FE modeling technologies have been adopted in the new virtual dummy model development such as laser scanning for accurate dummy geometry, finer mesh and increasing use of solid (Hexa) elements, more component level model-to-test validations and better material models.

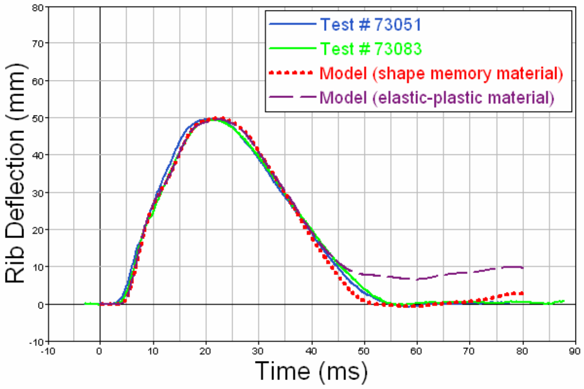


Figure 1. Rib deflection in dummy certification test – material model using latest technology

In the World SID dummy hardware development, many new advanced materials were used. For example, Nitinol shape memory alloy was used for the rib to replace the high strength steel. The virtual dummy development also needs to match the new advances in hardware. Since no numerical material models for shape memory alloy (in solid elements) were available at the beginning of the virtual dummy model development, great effort has been made to work with the software developer and test the new material model to meet the challenge. The outcome is shown in Figure 1, the rib deflection in the virtual dummy model performed better and closer to test results when the new material model (for shape memory material) was used. Another example showing here is how to use of a numerical material model to describe the hyperlast material that was used for pelvis flesh. To decide what material model to use, firstly the material was tested at quasi-static and dynamic loading as well as stress relaxation. Then the material behavior was analyzed and identified as non-linear elastic with viscous (highly strain rate dependent with fast stress relaxation behavior). As a result, Ogden material model [2] was chosen to model the Hyperlast material in the virtual dummy models:

$$W = \sum_{i=1}^{3}\sum_{j=1}^{n}\frac{\mu_j}{\alpha_j}(\lambda_i^{*\alpha_j}-1)+K(J-1-\ln J) \qquad (1).$$

Here, λ is stretch, K is the bulk modulus, $J = \lambda_1\lambda_2\lambda_3$ and $\lambda_i^* = \lambda_i J^{-1/3}$, μ_i and α_I terms are non-integer values. The stress expression is

$$\sigma_i = \frac{1}{\lambda_j\lambda_k}\frac{\partial W}{\partial \lambda_i} = \frac{\lambda_i}{J}\frac{\partial W}{\partial \lambda_i}$$
$$= \sum_{j=1}^{n}\frac{\mu_j}{J}\left(\lambda_i^{*\alpha_j} - \sum_{k=1}^{3}\frac{\lambda_k^{*\alpha_j}}{3}\right) + K\frac{(J-1)}{J} \qquad (2).$$

This can be simplified further for the hyperlast material (ν ~ 0.5):

$$\sigma_i = \sum_{j=1}^{n}\mu_j\left(\lambda_i^{\alpha_j} - \sum_{k=1}^{3}\frac{\lambda_k^{\alpha_j}}{3}\right) - p \qquad (3).$$

Here $\boldsymbol{p}$ is pressure. In uni-axial case, $\lambda_2 = \lambda_3 = \lambda_1^{-1/2}$,

and $p = -\frac{\sigma_1}{3}$, therefore

$$\sigma_1 = \sum_{j=1}^{n} \mu_j \left(\lambda_1^{\alpha_j} - \lambda_1^{-\alpha_j/2} \right) \qquad (4).$$

A numerical procedure has been developed at FTSS to extract the Ogden parameters (up to 8 pairs of μ_i and α_i) for rubber and hyperlast materials by curve-fitting eq.(4) to the stress-stretch data obtained from uni-axial material tests.

MODEL VALIDATIONS

Before an FE model was released, it had to pass various certification tests. Typical certification tests for the World SID dummies include head drop, neck pendulum impact, and full dummy pendulum impact at different locations on the dummy. Besides the certification tests, more model-to-test validations were carried out such as sled impact tests, arm and rib cage drop tests.

The FE models were validated at three levels: material, component and whole dummy assembly. Table 2 and 3 list the material/component, dummy certification and bio-fidelity tests for World SID 50th and 5th dummies that have been used for the virtual dummy model development.

Table 2. Lab certification and bio-fidelity tests for the World SID 50th dummy

	Certification tests	**Material/Component tests**	**Sled tests**
Head	**200mm later drop (L+R)** **376mm frontal drop**	**Head skin vinyl**	
Neck	**Lateral impact at 3.4m/s**	**Neck rubber**	
Shoulder	**Pendulum impact at 4.3m/s**	**Arm foam, Arm drop** **Rib drop at 3 velocities**	**WSU – 6.8m/s** **Heidelberg – 6.8m/s**
Thorax w/o arm	**Pendulum impact at 4.3m/s**	**Rib drop at 3 velocities**	
Thorax with half arm	**Pendulum impact at 6.7m/s**	**Rib drop at 3 velocities**	**WSU – 6.8m/s** **Heidelberg – 6.8m/s**
Abdomen	**Pendulum impact at 4.3m/s**	**Rib drop at 3 velocities**	**WSU – 6.8m/s** **Heidelberg – 6.8m/s**
Pelvis	**Pendulum impact at 6.7m/s**	**Pelvis hyperlast foam**	**WSU – 6.8m/s** **Heidelberg – 6.8m/s**

Table 3. Lab certification and bio-fidelity tests for the World SID 5th dummy

	Certification tests	**Material/Component tests**	**Drop tests**	**Sled tests**
Head	**200mm later drop (L+R)** **376mm frontal drop**	**Head skin vinyl**		
Neck	**Lateral impact at 3.4m/s**	**Neck rubber**		
Shoulder	**Pendulum impact at 4.3m/s**	**Arm foam, Arm drop** **Rib drop at 3 velocities**		**WSU – 6.8m/s** **Heidelberg – 6.8m/s**
Thorax w/o arm	**Pendulum impact at 4.3m/s**	**Rib drop at 3 velocities**		
Thorax with half arm	**Pendulum impact at 6.7m/s**	**Rib drop at 3 velocities**	**1.0m** **0.5m**	**WSU – 6.8m/s** **Heidelberg – 6.8m/s**
Abdomen	**Pendulum impact at 4.3m/s**	**Rib drop at 3 velocities**	**1.0m** **0.5m**	**WSU – 6.8m/s** **Heidelberg – 6.8m/s**
Pelvis	**Pendulum impact at 6.7m/s**	**Pelvis hyperlast foam**	**1.0m** **0.5m**	**WSU – 6.8m/s** **Heidelberg – 6.8m/s**

COMPONENT LEVEL VALIDATIONS

As a typical example, Figure 2 and 3 shows the model-to-test validation of the World SID 5th FE rib model. Three impact velocities were used in the validations that resulted the rib deflections in the range of 20 ~ 40 mm. Both the rib deflections and pendulum impact accelerations (forces) from the FE model are correlated very well with the tests. The 'shape memory' material model worked well in this case to represent the Nitinol shape memory material in the physical dummy as shown in the rib deflection plots. Other component level validations including head drop, neck pendulum and arm drop are detailed in the FTSS technical publications. [3]

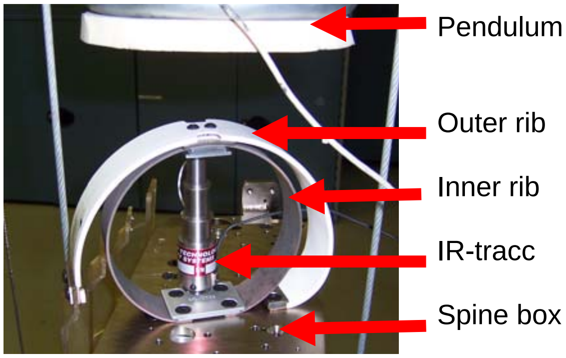


Figure 2. World SID 5th rib drop test set-up

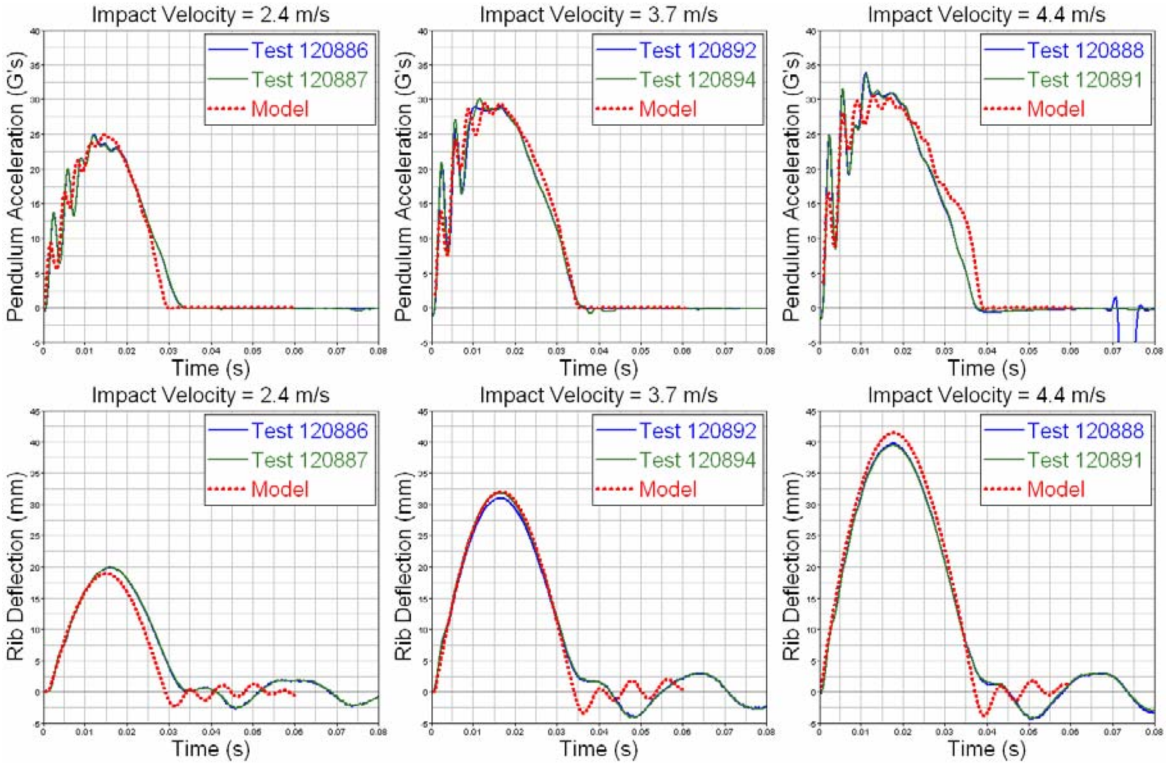
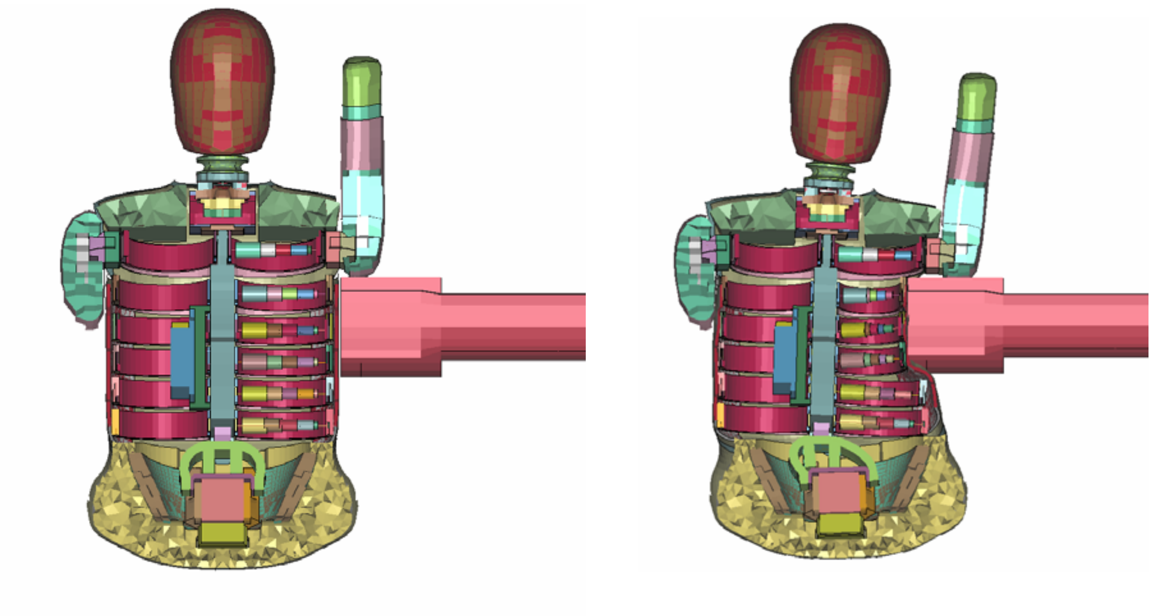


Figure 3. World SID 5th rib drop component level model-to-test validation

WHOLE DUMMY LEVEL VALIDATIONS

Whole dummy level validations including pendulum impact certification tests, sled tests and drop tests designed for biomechanics verification purposes.

Figure 4 and 5 show the model-to-test set-up and results of the World SID 50th thorax without arm impact. The certification corridors shown in the Figure 5 for such test have been specified by ISO based on biomechanics study on cadavers. [1]. It can be seen the current FE model (World SID 50th) correlates very well with the test results.

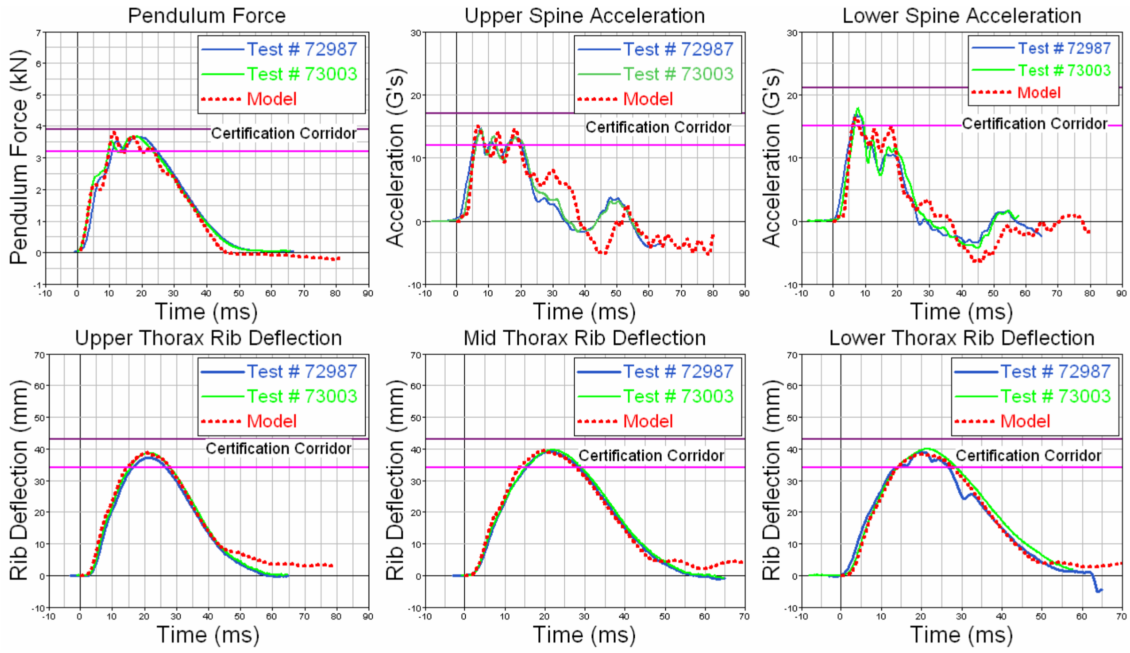


Pendulum mass: 23.4kg
Impact speed: 4.3 m/s

Initial position

Maximum rib deflection at 20ms

Figure 4. World SID 50th pendulum impact FE model set-up



Pendulum Force

Upper Spine Acceleration

Lower Spine Acceleration

Upper Thorax Rib Deflection

Mid Thorax Rib Deflection

Lower Thorax Rib Deflection

Figure 5. World SID 50th thorax without arm pendulum impact certification model-to-test validation

SLED TEST LEVEL VALIDATIONS

The World SID FE dummy models have been validated at sled level tests. These tests include Wayne State University (WSU) type sled test [4] and Heidelberg type sled test [5]. The World SID 50th Heidelberg sled test (6.7m/s impact) configuration and model-to-test validation results are shown in Figure 6 and 7. The FE model correlates with tests very well; as an example, the rib deflections correlations are shown in Figure 7. Other details of validations can be found in FTSS's technical publications [3].

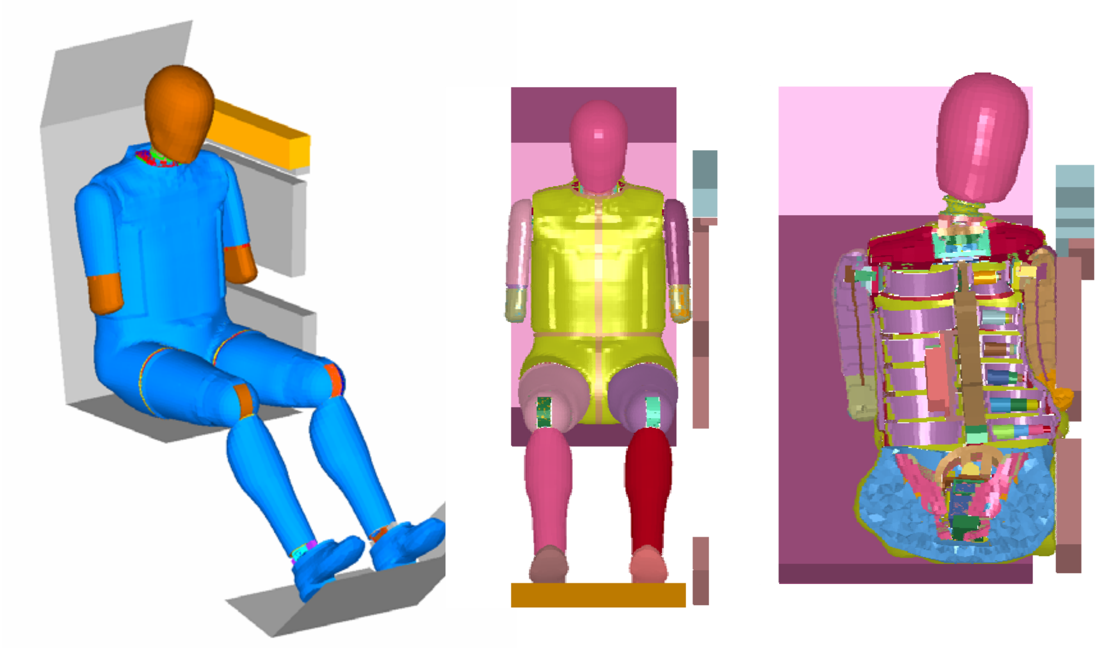

Heidelberg sled impact set-up **Time=0** **Time=25 ms**

Figure 6. World SID 50th FE dummy model Heidelberg sled test set-up

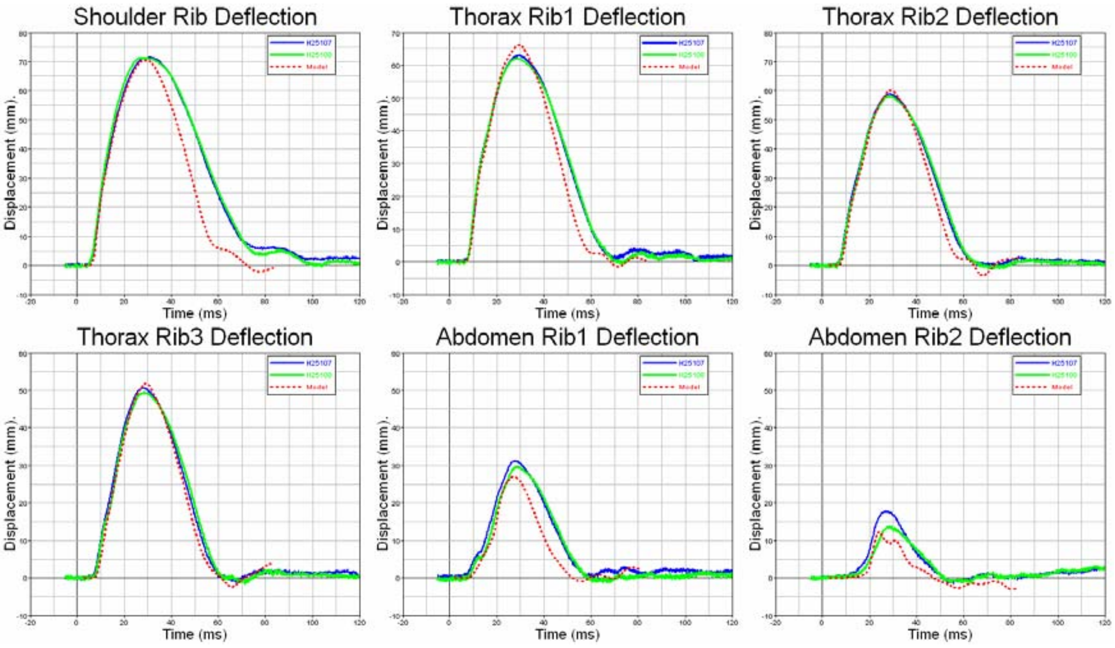


Figure 7. World SID 50th Heidelberg sled test model-to-test validation

DUMMY INJURY PREDICTION WITH VIRTUAL DUMMY MODELS

The occupant injury parameters can be extracted from the virtual dummy models after the simulation. Table 4 summaries the occupant injury parameters from the World SID and other side impact dummies such as SID-IIs and ES2 (ES2-re) that can be used to derive the occupant injury criteria as required by regulations, auto insurers and consumer oriented requirements.

Table 4. Dummy injury parameters extraction (√= available in current dummy)

Occupant injury parameters	**World SID 5th and 50th**	**SID-IIs**	**ES2 (ES2-re)**
HIC36/HIC15	√	√	√
Upper neck force&moment	√	√	√
Lower neck force&moment	√	√	√
Shoulder rib disp. and acc.	√	√	
Thorax rib 1 disp. and acc.	√	√	√
Thorax rib 2 disp. and acc.	√	√	√
Thorax rib 3 disp. and acc.	√	√	√
Abdomen rib 1 disp. and acc.	√	√	
Abdomen rib 2 disp. and acc.	√	√	
T1 acc.	√	√	√
T4 acc.	√		
T12 acc.	√		√
Arm upper&lower acc.		√	
Lumbar force&moment	√	√	
Pubic force	√	√	√
Illiac force	√	√	
Acetabulum force	√	√	
Shoulder force&moment	√		√
Pelvis acc.	√		√
Abdomen force			√
Back plate force&moment			√
T12 force&moment			√
Knee force	√	√	
Upper&lower femur force	√	√	
Upper&lower tibia force	√	√	

The World SID 50th and 5th dummy models have been tested in FMVSS214 oblique pole and moving deformable barrier (MDB) impact environments. Figure 8 shows the World SID 5th FE model simulated in a FMVSS214 MDB load case. The test configuration is that the occupant is seated in driver's seat in standard driving position as specified in FMVSS214. The MDB load case is applied to a mid-size car that equipped with a thorax airbag. The dummy and internal deformation at the peak of impact is depicted in Figure 8.

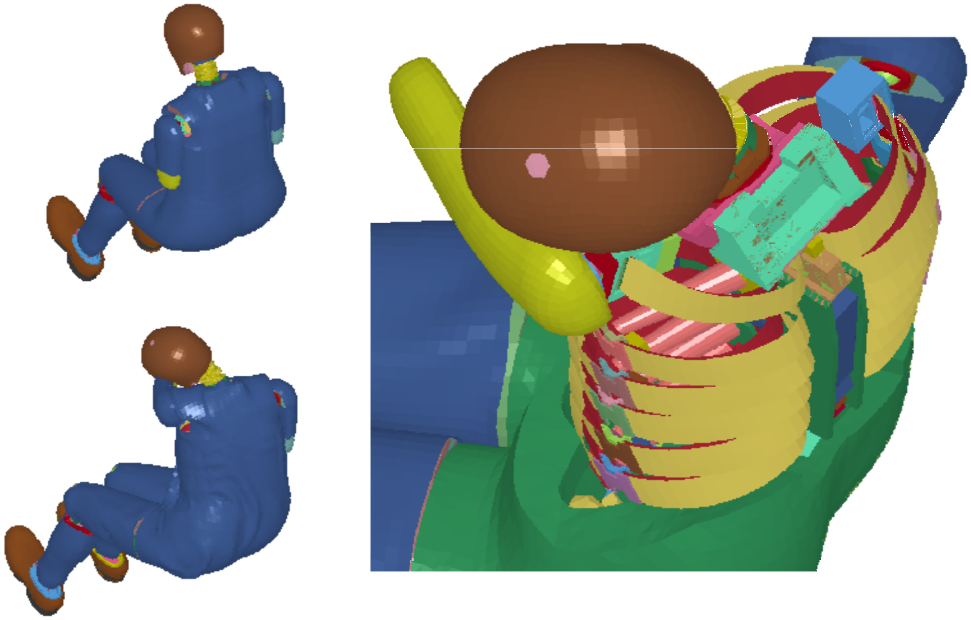


Figure 8. World SID 5th dummy model at peak impact under a FMVSS214 oblique pole impact simulation

As a comparison of performance a SID-IIs dummy model was also tested in exactly the same FMVSS214 MDB side impact environment as the World SID 5th dummy model. The occupant parameter outputs from the simulations are listed in Table 5 and the rib deflections from both models are shown in Figure 9. As shown in Figure 9, the maximum rib deflections for shoulder and top/middle thorax ribs from the 2 dummies are quite close**.** However the bottom thorax and abdomen rib deflections from the World SID 5th are generally lower. Other injury parameter comparisons between the 2 dummies can be found in Table 5.

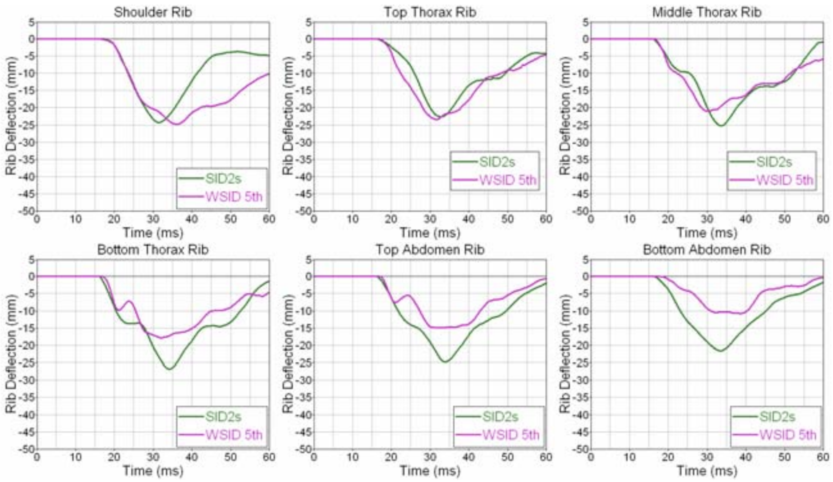


Figure 9. Rib deflections from World SID 5th and SID-IIs in FMVSS214 oblique pole impact

Table 5. Occupant injury parameters comparison: World SID 5th vs. SID-IIs in FMVSS214 MDB impact

Occupant Injury Parameters	World SID 5th	SID-IIs
HIC36	48.46	27.91
Upper Neck Fz+ (kN)	0.911	0.871
Upper Neck Fz - (kN)	-0.070	-0.222
Shoulder Rib Deflection (mm)	24.77	24.26
Top Thorax Rib Deflection (mm)	23.35	22.60
Middle Thorax Rib Deflection (mm)	20.99	25.18
Lower Thorax Rib Deflection (mm)	17.84	26.75
Upper Abdomen Rib Deflection (mm)	14.92	24.80
Lower Abdomen Rib Deflection (mm)	10.76	21.62
Upper Thorax Rib VC (max)	0.294	0.309
Middle Thorax Rib VC (max)	0.263	0.348
Lower Thorax Rib VC (max)	0.271	0.339
Upper Abdomen Rib VC (max)	0.174	0.309
Lower Abdomen Rib VC (max)	0.076	0.155
T12 Lower Spine Accel Resultant (G)	37.96	44.58
Pubic Load (kN)	0.688	0.172
Combined Illiac & Acetabulum Load (kN)	0.451	2.466
Shoulder Compression Force (kN)	0.784	1.223
Pelvis Acceleration (G)	48.81	32.69

CONCLUSIONS

- World SID 5th and 50th virtual dummy models have been developed that incorporated with latest advances in FE technology. The new models correlated very well at components, sub-assembly and full dummy level certification and sled tests.
- The models have been tested in FMVSS214 side collision environments. The injury parameters can be extracted from the dummy models to calculate occupant injury criteria as required by regulatory, insurers and consumer assessment programs.
- It has shown that the current virtual dummy models have performed and validated well against tests and the authors believe that these models are able to predict reasonable and reliable occupant injury in crashworthiness and safety analysis.

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