

Modelling Carpet for Use in Occupant Crash Simulations

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ABSTRACT

Predictions of occupant injury using explicit finite element crash simulations may be enhanced by including numerical representation of materials that are not normally included within the structural model. Intuitively, it makes sense that the carpet would be useful to predict the tibia index during frontal crash events; however, there appears to be little published on the topic. The tibia index is an injury criteria that needs to be predicted during the Insurance Institute for Highway Safety (IIHS) frontal offset occupant simulations, but may also be looked at during unbelted Federal Motor Vehicle Safety Standard (FMVSS) 208 simulations. Since carpet behaves quite differently during compressive and tensile loading, a numerical representation that can stably capture both regimes during occupant modelling is needed.

This paper outlines a method to model the carpet using a specific meshing method and two material models. Shell elements in combination with a piecewise linear plasticity material model are used to model the tensile load carrying capacity of the carpet, while brick elements and a foam material model are used to represent the compressibility of the carpet. Validation of using this modelling method with test data is presented, as well as the application of the carpet model in larger occupant models.

1. Introduction

Frontal occupant simulations typically require a wide variety of materials to be defined when creating a finite element model of the vehicle interior. The carpet supports the occupant's heels at the beginning of the event and may absorb crash energy if sufficient backing material is present. Since the carpet supports the feet during the beginning of the simulation, its presence in the finite element model can affect the kinematics of the occupant's legs, which ultimately determines the loads they can experience during a crash event.

Previous occupant models did not have a representation of the carpet. In these models the occupant's feet were left to interact directly with the sheet metal of the vehicle floor. Based on previous development experience it was felt that the simulation models could be improved if a representation of the carpet could be included within the occupant simulation models.

This work highlights the steps taken to include a representation of the carpet within a finite element crash model. Samples of carpet were physically tested by cyclically loading both in tension and compression. Shell elements are used in combination with a piecewise

linear plasticity material model to represent the majority of the tensile load carrying capacity of the carpet. Brick elements combined with a foam material model are used to represent the compressibility of the carpet.

2. Material testing

Physical tests were undertaken on the carpet material using a 25 kN Instron 5866 testing machine. For the purposes of this work, the tensile loading direction is defined as being in the plane of the carpet as shown in Fig. 1. The compressive loading direction is defined as being normal to the plane of the carpet, which is also shown in Fig. 1.

To gain an understanding of the tensile loading and unloading characteristics of the carpet, one sample was loaded monotonically in tension to failure, while five samples of the carpet were cyclically loaded and unloaded in tension. Figure 2 shows a sampling of these tensile loading tests. During these cyclic loading tests, each specimen was loaded to 5 percent engineering strain, then unloaded and loaded 5 times to generate the first hysteresis loop shown in Fig. 2. Tensile loading then continued to 10% engineering strain, and 5 loading / unloading cycles were repeated. This sequence was continued at 5%

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increments in strain until the specimen broke.

The compressive tests were performed in a similar manner as shown in Fig. 3. One sample was loaded monotonically in compression until the limit of the machine was reached. Three samples were loaded cyclically in compression to generate both compressive

loading and unloading curves. During these cyclic compression tests, the carpet was compressed to increasing compressive strains of 50%, 66%, 75% and 79%. For each strain level, five load and unload cycles were performed before proceeding to the next strain level.

Figures 2 and 3 highlight the difference in tensile

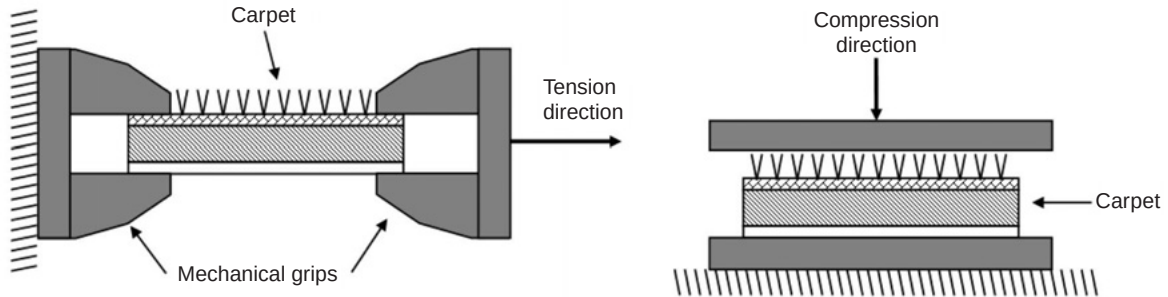


Fig. 1 Tensile and compressive loading directions that were adopted for this work.

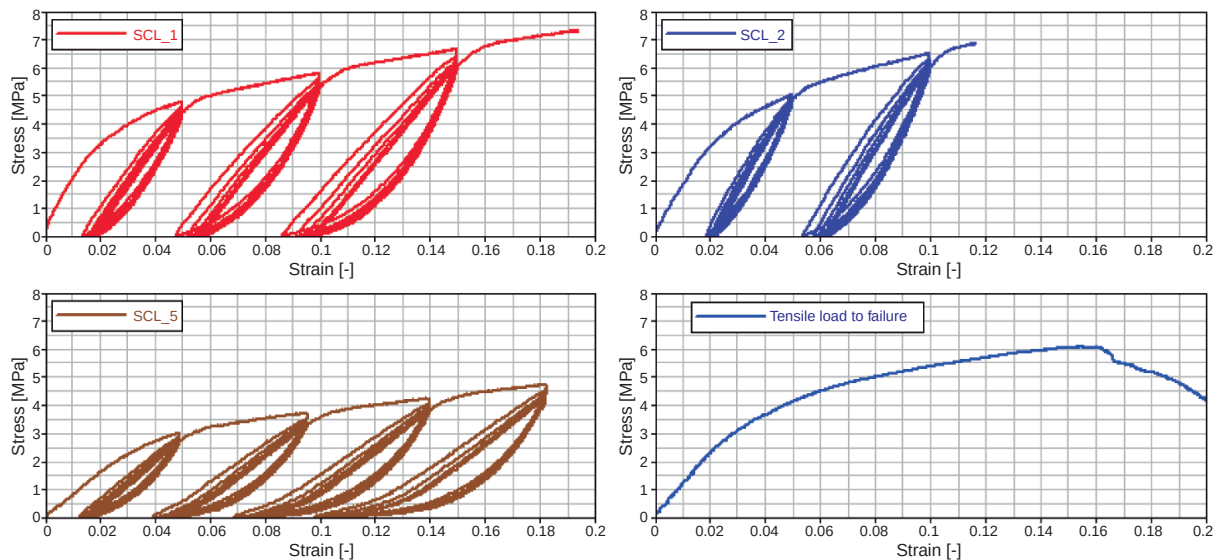


Fig. 2 Tensile loading and unloading test data

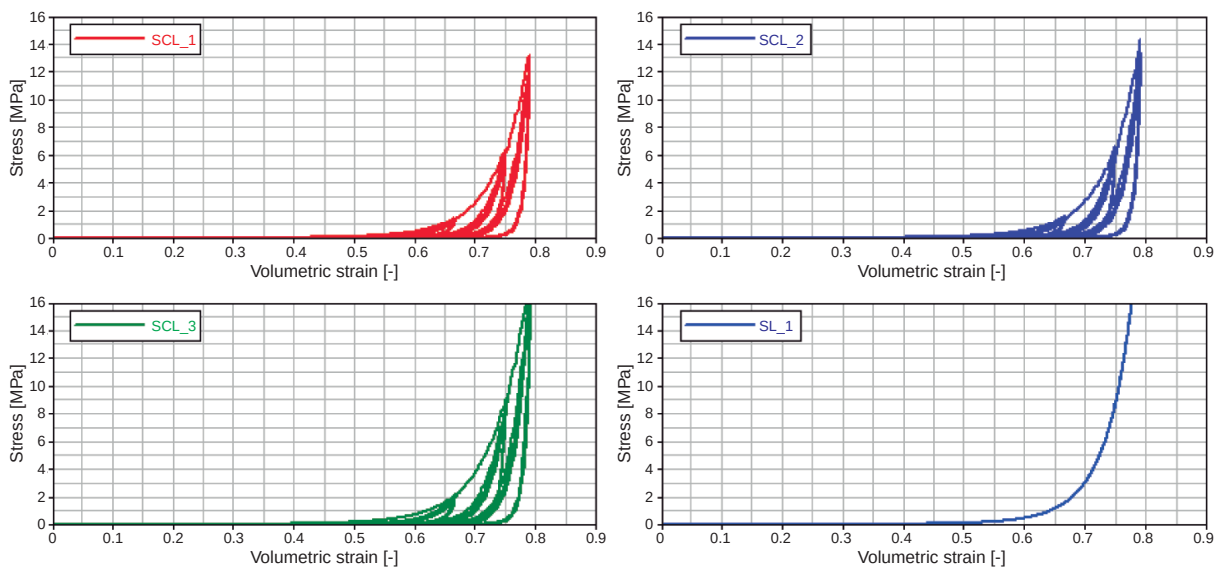


Fig. 3 Compressive loading and unloading test data

and compressive loading behaviour of the carpet. Figure 2 shows that there are fairly large variations in the carpet tensile strength and failure strain as each of the four samples were cut from the same piece of carpet. The variability of compressive strength is less noticeable, but still present, as shown in Fig. 3.

3. Finite Element Material Model Creation

From analysis of Figs. 2 and 3, one can see that the carpet behaves quite differently during tensile and compressive loading. During a frontal crash event, the carpet can be both in tension, and compression. For example, inertial loads placed on the carpet creates tension that must be reacted internally (by the carpet), towards the attachment points of the carpet to the vehicle. In other regions, such as underneath the feet of the occupants, the carpet can be compressed during the crash event.

In order to match this behaviour a unique approach was created that allows both the tensile and compressive behaviour of the carpet to be modelled. Figure 4 shows a cross section of a typical carpet construction used in vehicles. From inspection of the carpet samples it was felt that the majority of tensile strength came from the outer layers, while the majority of compressive compliance came from the pile and middle layer. The pile layer is comprised of upstanding yarn fibres and a woven backing. The woven backing is strong in tension, while the upstanding yarn fibres are weak both in the compression and tension directions. The height of these fibres do, however contribute to the overall thickness dimension of the carpet.

For the current work, it was assumed that the contribution of the upstanding yarn portion of the pile layer was negligible. This necessitated that the thickness of the carpet used in the models to be adjusted to not include the upstanding yarn portion, but allows the carpet to be modelled using a simple, three ply construction. When constructed this way, the outer layers provide the majority of the tensile stiffness and the middle layer provides the compressive compliance.

In this manner, the behaviour of the carpet could be matched during different loading regimes. The tensile behaviour of the carpet shown in Fig. 2 appears to yield, but carries an increasing amount of load prior to failure. This material flow behaviour is similar to metals, which are represented in many of the commercially available finite element solvers using linear plasticity material models. For the current work, LS-DYNA⁽¹⁾ was used as the general finite element solver, so the *MAT_PIECEWISE_LINEAR_PLASTICITY⁽²⁾ material model was chosen to represent the outer layers. The compressive loading behaviour of the carpet looked similar to that of typical foams, so the LS-DYNA *MAT_FU_CHANG_FOAM⁽³⁾ material model was chosen to represent the middle layer. Similar material models are available for use in the other commercially available finite element solvers.

Figure 5 shows the manner in which the carpet should be meshed for this method to work. For the carpet that was tested, 2 mm thick shell elements were used for the top and bottom layers, while a 10 mm thick layer of brick elements are used for the middle. For clarity, in Fig. 5 the shells are shown with the LS-PRE/POST⁽⁴⁾ thickness option, so they appear as brick elements.

The data from each cyclic tensile test was post processed using linear regression to find average Young's modulus values for the initial loading and each hysteresis loop portion of the test. An average Tangent modulus was also calculated from the appropriate post-yield portion of the data. Figure 6 shows these moduli for the first cyclic tensile test. In Fig. 6, E0 represents Young's modulus, E1, E2 and E3 represent the average loading and unloading modulus for the first, second and third hysteresis loops, and ETan represents the tangent modulus.

The averaged Young's and Tangent modulus values were used to create a simple *MAT_PIECEWISE_LINEAR_PLASTICITY LS-DYNA material model which matched the average tensile strength of the carpet. This material model is prescribed to the two outer shell layers of the

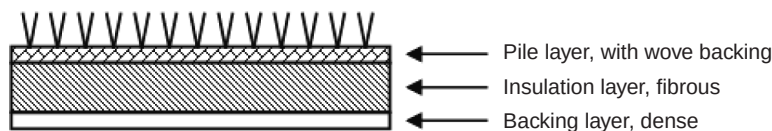


Fig. 4 Construction of typical automotive carpet

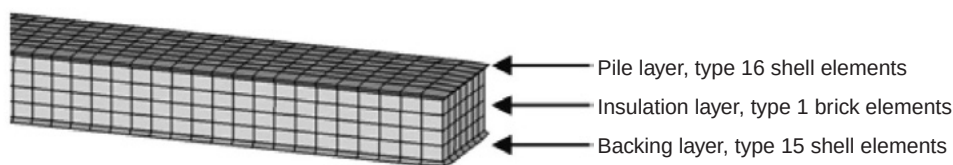


Fig. 5 Finite element meshing method chosen for the Carpet

carpet shown in Fig. 5.

The compressive test data shown in Fig. 3 looked similar to foam materials, consequently the test data was post-processed to create a *MAT_FU_CHANG_FOAM material model. In LS-DYNA, this material model has the capability to model rate - sensitive loading and unloading, but since rate sensitivity was not tested, just one loading and one unloading curve was used. The monotonic loading curve was calculated for each compression test by taking the cyclic compressive test data and removing the unloading and intermediate reloading portions. These resulting monotonic loading

curves were then averaged and smoothed to create a single monotonically increasing loading curve that represented the compression characteristics of the carpet. The same procedure was used to create an averaged unloading curve, but the loading portions, and intermediate unloading portions were removed. The resulting averaged test loading and unloading curves are shown in Fig. 7 with a very small stress scale on the ordinate axis.

During testing, a 25 kN load cell was used to obtain accurate load measurements during the initial compression of the carpet, which limits the amount of

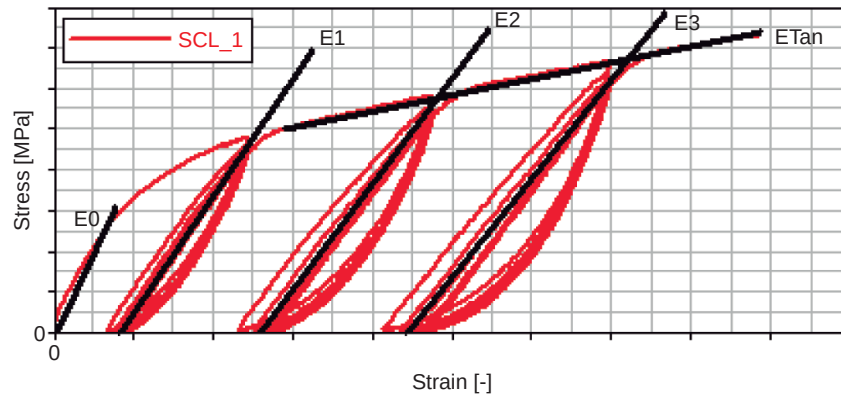


Fig. 6 Average elastic moduli that were calculated for each portion of the cyclic tensile test data

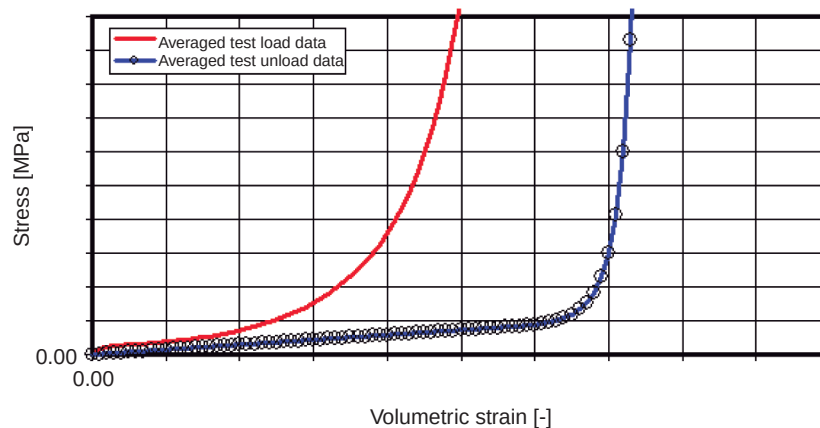


Fig. 7 Averaged and smoothed loading and unloading curves from compression test data primarily representing deformation of upstanding yarn position

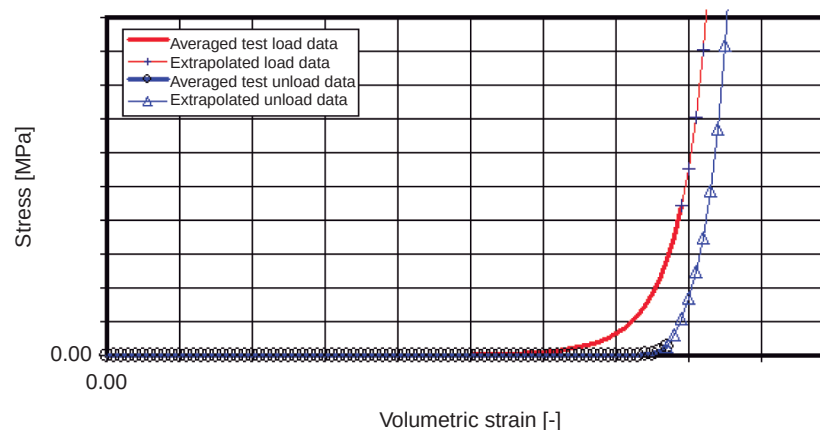


Fig. 8 Averaged, smoothed and extrapolated compression test data showing loading and unloading curves at intermediate stress levels

force that can be applied. For our compression test specimen size, the corresponding stress levels were less than 20 MPa. During occupant simulations, the carpet can be in contact with other materials that have much higher yield strengths, and localized compressive stresses may become quite large. Thus, for numerical stability the curves should be extrapolated to create a more robust material model. Both the loading and unloading curves were extrapolated to 99% volumetric strain using a Hyperbolic function to smoothly extend the data. This technique, suggested by Du Bois⁽⁵⁾ relates the rate of change of yield strength with respect to strain:

$$\left. \frac{\partial \sigma}{\partial \varepsilon} \right|_i = \left(\left. \frac{\partial \sigma}{\partial \varepsilon} \right|_{\varepsilon_0} \right) \left(\frac{1.0 - \varepsilon_0}{1.0 - \varepsilon_i} \right)^n \quad (1)$$

where ε_0 is the strain value from which the extrapolation starts. The exponent n should be calculated from the test data for strain points just below ε_0 to get an idea of what the value should be. The extrapolated yield strength values are given by:

$$\sigma_{i+1} = \sigma_i + \left. \frac{\partial \sigma}{\partial \varepsilon} \right|_i \Delta \varepsilon \quad (2)$$

Using this method, extrapolated compressive load and unload curves for the material model were calculated, as shown in Fig. 8, along with the original test data shown in Fig. 7. Note that averaged test load and unload curves in Fig. 8 are the same as in Fig. 7, however the scale on the ordinate axis in Fig. 8 is 500 times larger, which allows us to present both the measured and extrapolated data. This material model is prescribed for the inner brick layer of the carpet shown in Fig. 5. It should be mentioned that the *MAT_FU_CHANG_FOAM material model also requires an Elastic modulus to be prescribed in the case of tensile loading. For the current study, a value of 5.0 MPa was used. This value was chosen by running several of the simulation models described in the next section to determine the minimum value that was numerically stable. Unfortunately, this value also introduces error when the carpet is pulled in the tensile direction, however since the carpet does not yield during

occupant simulations, the level of error was deemed acceptable. Nonetheless, it was decided to apply a correction factor to the tangent modulus that was calculated in the previous section for the tensile direction, which mitigated the error.

4. Finite Element Material Model Validation

A simple LS-DYNA simulation model was created that tested the resulting material models in both tension and compression. Figure 9 shows the simulation model. As described earlier, the meshes of both the tensile and compressive sample are created by extruding brick elements between two shell meshes. The shell meshes have a thickness of 2 mm and the thickness of the bricks is 10 mm. Prescribed motion is used to pull the tensile sample in the same manner as the cyclic tensile tests, although only one unload and re-load cycle was performed at 5%, 10%, 15% and 20% engineering strain. The compression sample is also simulated in the same manner as the compression tests, with prescribed motion compressing and then unloading the sample to the increasing compressive strain levels of 50%, 66%, 75% and 79%. As with the tensile simulations, only one load and unload cycle was performed at each compressive strain level.

Figure 10 shows the behaviour of the combined carpet model for the tensile sample. The simulation

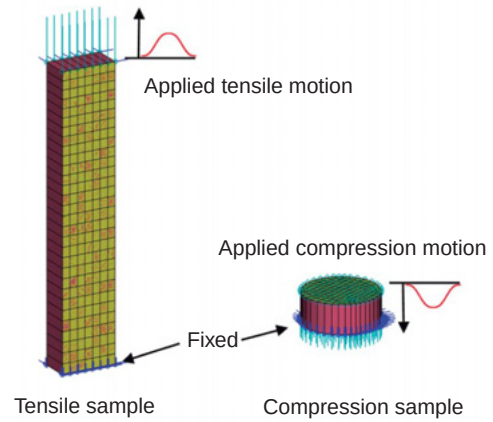


Fig. 9 Finite element simulation validation models

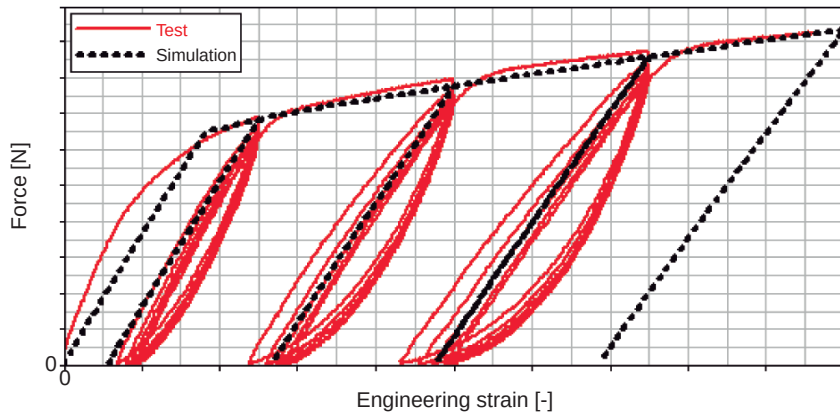


Fig. 10 Comparison of finite element simulation to one of the tests during tensile loading and unloading

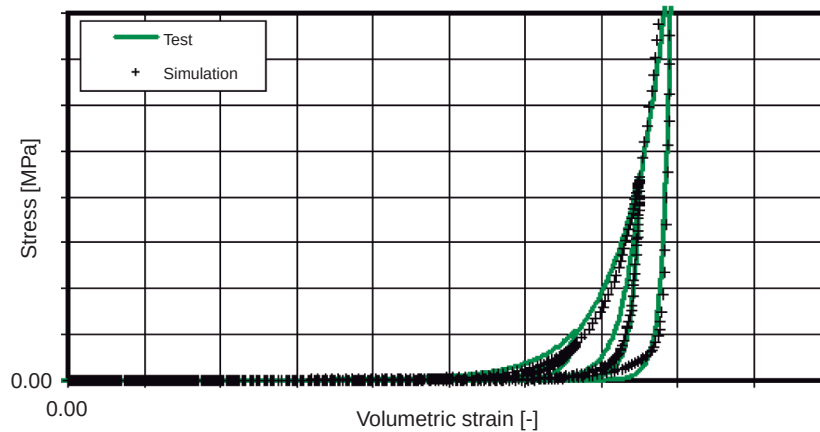


Fig. 11 Comparison of finite element simulation to test data during compressive loading

results are shown as a dotted line, while the test results are shown as a solid red line. From Fig. 10, it can be said that the simulation model is capturing the loading and unloading characteristics of the carpet when pulled in tension.

Figure 11 shows the behaviour of the carpet model for the compressive loading and unloading cycles, along with one of the cyclic compressive tests previously shown in Fig. 2. The test curve is shown in green and while the simulation is shown as black points. From Fig. 11, it can be said that the general loading and unloading characteristics of the carpet has been matched in compression.

5. Application in Occupant Crash Models

For a model of the carpet to be included within the occupant crash models, several steps should be taken. The carpet should be meshed as described previously, with a layer of shell elements sandwiching one or more

layers of brick elements. Contact of the occupant with the carpet should be allowed to initialize prior to the crash event. This can be performed by allowing the dummy to settle under gravity, or by prescribed motion of the occupant to its equilibrium or initial position. Figure 12 shows an example of the carpet in an unbelted occupant simulation model. This simulation model represents the unbelted 40 km/hour United States Government crash test specified in the Code of Federal Regulations⁽⁶⁾. Also shown in this model is the floor mat which lies on top of the carpet. In these models, the floor mat was modelled in the exact same manner, using the same properties as the carpet. This simulation model was run twice, once with the carpet and floor mat and once without to show the importance of simulating the carpet when predicting lower leg injury. This study focused on improving the lower left Tibia Index predictions within the finite element models. A future study will focus on improving the lower right Tibia Index, which has additional influences such as the

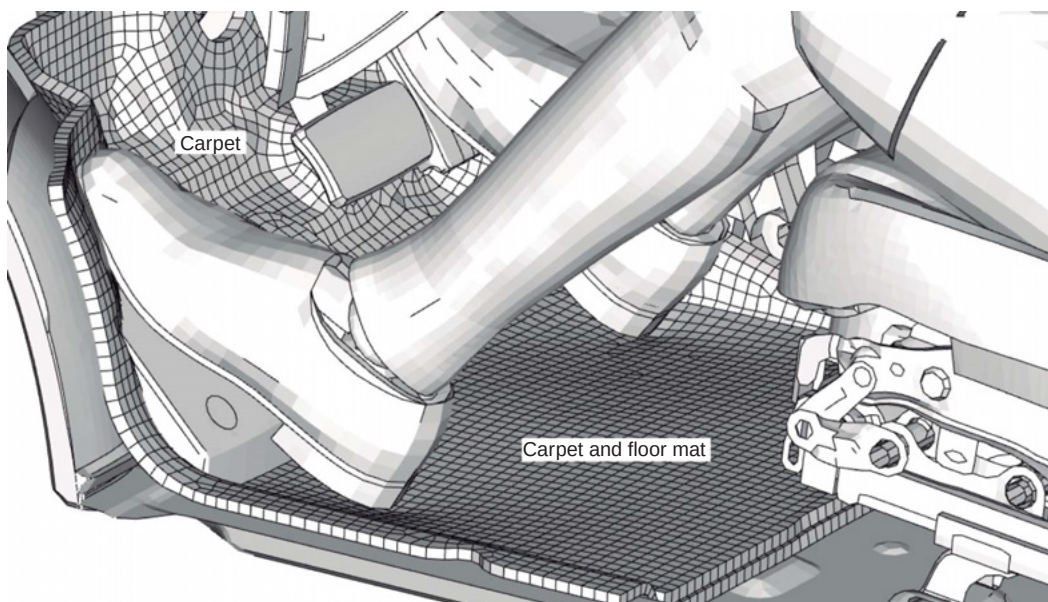


Fig. 12 Carpet and floor mat being modelled within an unbelted occupant sled model

accelerator pedal.

Figure 13 shows the lower left Tibia Index of the occupant for these two simulations compared to test data. The Tibia Index is a function of the axial load and resultant bending moments that the lower leg experiences during a crash test. From Fig. 13, one can see that the Tibia Index prediction from the simulation model with the carpet and floor mat was considerably closer to the actual test than the simulation model without the carpet. Figure 14 shows the left foot and tibia of dummy at key points during the simulations, both with and without the carpet. The key points labelled in Fig. 13 correspond to the pictures in Fig. 14.

Analysis of the occupant models showed that the simulation model without the carpet predicted two additional peaks in the Tibia Index at the points 1A and 3A labelled in Fig. 13. These peaks occurred when the left heel first came to a stop against the foot rest (Fig. 14-1A), and also when the heel contacted the floor (Fig. 14-3A). In the simulation model without the carpet,

higher tibia axial loads were predicted at these times, which caused the peaks to occur. In the simulation model with the carpet, the heel did not contact the foot rest as sharply (Fig. 14-1B) nor did it bottom out against the floor (Fig. 14-3B).

It is felt that the main reason for the improvement in Tibia Index prediction was because the carpet is in contact with the heels of the occupant from the beginning of the simulation, which prevents high impulsive loads in the tibia when the foot rest and the floor are contacted.

6. Conclusions

A method of modelling the carpet during a frontal crash simulation has been developed. This method presents the development of two material models, one for the outer surfaces of the carpet, and one for the compressible portion. The outer surfaces are to be meshed as 2 mm thick shell elements and modelled with

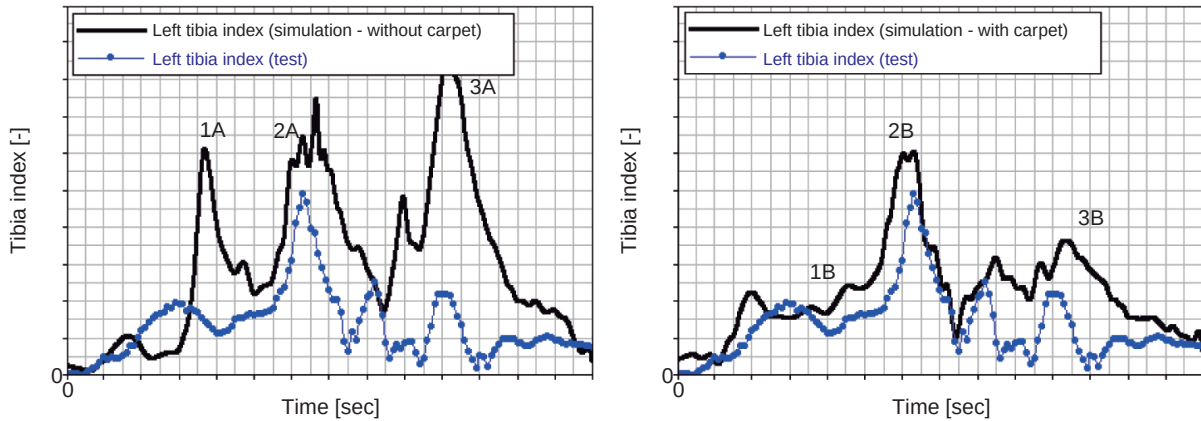


Fig. 13 Left tibia index predictions without carpet model and with carpet model

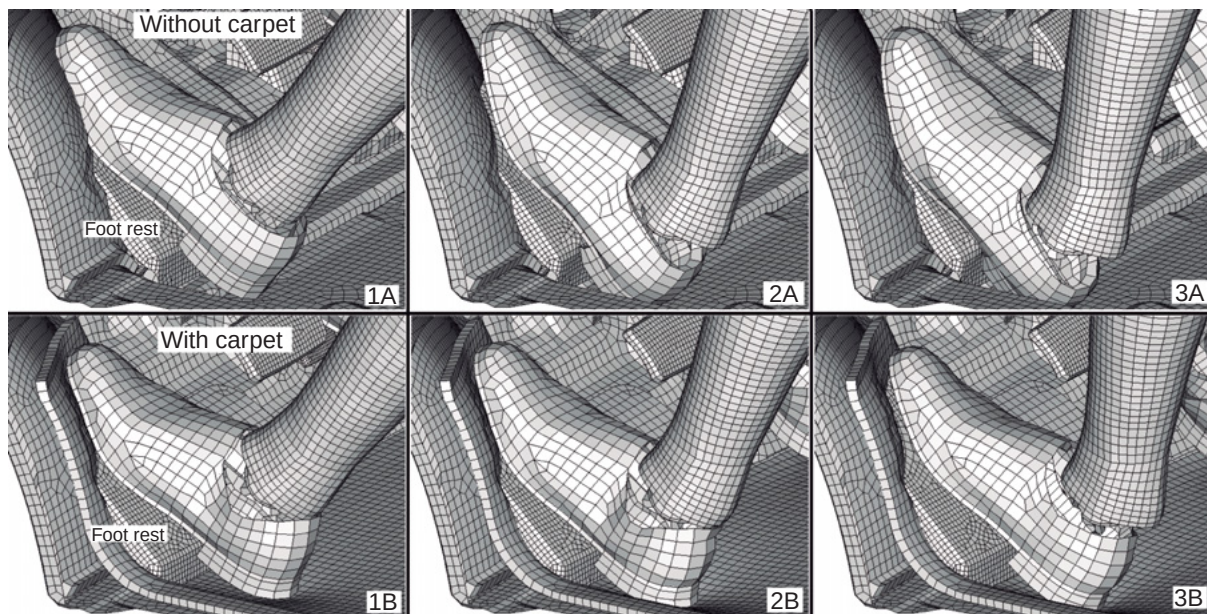


Fig. 14 Comparison of the left foot and tibia kinematics during the occupant simulation with carpet (1A, 2A, 3A) and without the carpet model (1B, 2B, 3B)

a piecewise linear plasticity material model. The inner portion is to be meshed as brick elements and modelled with a compressible foam model. When this new method is followed, the simulation is able to reproduce the behaviour of the carpet during tension and compression, both loading and unloading. Furthermore, enhanced predictions of lower leg injury have been obtained as a result of the improved lower leg kinematics when this carpet model has been used within occupant injury models.

References

- (1) Hallquist, J. O.: LS-DYNA Theoretical Manual, Livermore Software Technology Corporation (1998).
- (2) Hallquist, J. O.: LS-DYNA. Keyword User's Manual, Vol. 2, pp. 110-114. Livermore Software Technology Corporation (2007)
- (3) Chang, F.S.: Constitutive Equation Development of Foam Materials, Wayne State University (1995).
- (4) Hallquist, J. O.: LS-PRE/Post v1.0 Manual, Livermore Software Technology Corporation (2002).
- (5) Du Bois, P.A.: Crashworthiness Engineering Course Notes, Livermore Software Technology Corporation (2004).
- (6) United States Code of Federal Regulations, Title 49 - Transportation, Chapter V - National Highway Traffic Safety Administration, Department of Transportation, Subpart B - Federal Motor Vehicle Safety Standards, Section 571.208 - Standard Number 208; Occupant Crash Protection. [49CFR571.208]

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