

Hybrid modelling of crash dummies for numerical simulation

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HYBRID MODELLING OF CRASH DUMMIES FOR NUMERICAL SIMULATION

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ABSTRACT

In crash dummy models two different mathematical formulations can be distinguished: multibody techniques and finite element techniques. Both approaches offer their specific advantages and disadvantages. Multibody techniques are particularly attractive for the simulation of crash dummy segment motions and complex joint behaviour. Finite element techniques allow the calculation of local deformations in dummy segments.

The use of combined multibody and finite element techniques, the so-called hybrid approach, allows the user to benefit from the capabilities of both approaches and offers the flexibility of merging more global models with, whenever needed, detailed representations of certain parts in the model.

In this paper the strategy for hybrid modelling is illustrated. Several examples of recently developed and validated hybrid models will be presented in order to demonstrate the potential of this technique. In the examples flexible bodies and arbitrary shaped contact surfaces are shown to be efficient and accurate alternatives to traditional modelling methods. Criteria which can guide the user in the selection of the optimal setup of a crash dummy model are formulated and future developments are indicated.

THE EFFECTIVE USE OF COMPUTER MODELS in the field of crash safety simulations requires that well validated models of crash dummies are available (Prasad et al. 1989). Such numerical models of crash dummies are generally referred to as "dummy databases". Dummy databases have been implemented using either multibody modelling techniques, or finite element modelling techniques.

Many multibody dummy databases are now established tools for occupant simulations (de Co, et al. 1990; Philippens et al. 1991; Lupker et al. 1991; Happee et al. 1996). Multibody databases are used in combination with multibody or finite element models of the car interior, airbags and belts. Finite element (FE) databases have been stated to be more detailed and more accurate, but actually many FE databases are largely based on existing multibody models combined with a more detailed surface description (Saha et al. 1991; Midoun et al. 1991; Midoun et al. 1993; Song et al. 1993). Such models mostly use rigid finite elements, and therefore behave in a way similar to

the multibody models on which they were based. They have some advantages (eg. detailed surface geometry can be described) but also disadvantages (eg. less efficient than multibody models).

Various dummy databases have also been developed using detailed FE meshes, with many deformable elements in addition to rigid sections (Du Bios and Tilakasiri, 1991; Schlosser et al. 1993). Whilst these models are able to represent the true deformation of the dummy more accurately, they require excessive computing power. The simplified FE models represent the attempts that have been made to make models with the abilities of such "full" finite element models, but with acceptable CPU times. However, both simplified and detailed finite element models have many limitations, and new techniques are clearly required.

In addition to the well known rigid body and FE modelling techniques, the flexible body method has been shown to be an effective tool for dummy modelling (Koppens et al. 1993; Broekmeulen, 1995; Fountain, 1996). Flexible body models combine the ability of FE to describe complex deformations with the efficiency of multibody methods.

These techniques can be combined into one dummy model which yields so called "hybrid databases" (Fountain et al. 1994; Happee et al. 1996). The maximum advantage is obtained from the hybrid method by selecting the most appropriate technique for each model section. This paper deals with the suitability of rigid body, finite element and flexible body techniques for dummy modelling. These methods will be compared with respect to efficiency, accuracy, robustness and user friendliness. First the three modelling methods will be described shortly. Then they will be evaluated based on modelling of the neck of the Hybrid III. A comparison of finite element and multibody techniques for representing contact surfaces will be made using the EEVC (1994) adult pedestrian headform. Finally, hybrid modelling of a complete dummy will be illustrated using the BioSID dummy.

MODELLING METHODS

Three numerical methods will be considered in this paper, namely rigid bodies, flexible bodies, and finite elements. These methods will be described below, mentioning some exclusive MADYMO features because the models presented in this paper were prepared in this code.

The MADYMO multibody module is based on a so-called relative description of the kinematics using a recursive algorithm. It is particularly efficient for tree-structured systems due to the fact that the motion of any body can be written in an explicit form of the joint degrees of freedom. Generally in multibody models the bodies are modelled as being rigid. This leads to "rigid body models". Alternatively flexibility of bodies can be added which yields "flexible body models".

RIGID BODY MODELS - In the rigid body method, a structure is represented by chains of rigid bodies. Flexibility due to surface compliance can be accounted for by prescribing force-penetration characteristics. Physical structures like ball and socket joints

(eg. hip joints) and joints with physical rotation axes (eg. knee joints) can be modelled accurately using kinematic joints. The location of the joints and the degrees of freedom are determined from the known geometry of the physical joints. Kinematic joints can also be used to describe structures undergoing complex deformations such as necks, lumbar spines and ribs. Joints are then defined at well chosen points in the deforming structure. The joint locations and degrees of freedom have to be carefully selected taking into account the application of the model.

In the MADYMO software several standard kinematic joints can be used including revolute, translational, universal, cylindrical, spherical, and planar joints, as well as user-defined kinematic joints. Joints may be locked or unlocked based on specified conditions. To every type of kinematic joint corresponds a dynamic restraint model that defines elastic, damping and friction loads depending on the relative motion in the joint. For revolute, translational and spherical joints a special friction model is available which includes slip-stick which cannot be described by the standard friction model.

Specific geometric surfaces like ellipsoids, cylinders, and planes can be attached to any body. These surfaces allow the modelling of contact interactions between different bodies and with finite element structures. Where required the contact surfaces of multibody models can be described in detail using several ellipsoids, etc. Recently an alternative surface description for multibody models has been developed for MADYMO (TNO, 1996). An arbitrary surface with a user-defined contact stiffness can be made by covering the surface with triangular facets. This is referred to as a "facet surface". An example of a facet model is shown in Figure 1.

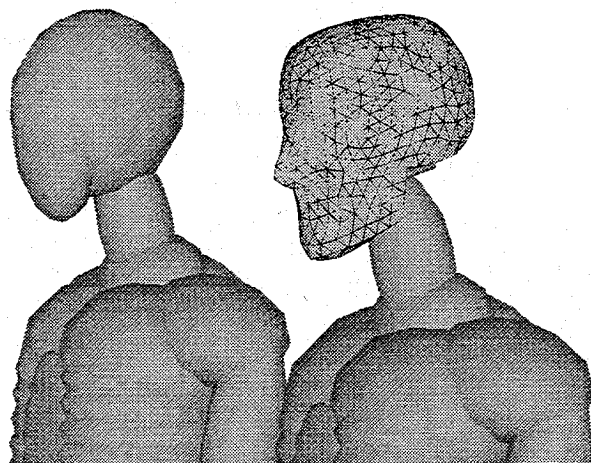


Figure 1. Hybrid-III Databases with Ellipsoid and FACET Heads.

The user can specify the contact stress as a function of the vertex penetration, or the resultant contact force as a function of the largest vertex penetration, both including hysteresis and friction. The compliance of a flexible layer on a rigid foundation (such as the flesh of dummies, padded surfaces and seat cushions) is best approximated with the first option; the second option is more suitable to model the compliance of a thin plate structure. A facet surface has the abilities of a finite element model to accurately describe the actual geometry and to calculate distributed (rather than point) contact forces. They

require more CPU time than ellipsoids, because more calculations are required to evaluate the contact behaviour, but significantly less time than a finite element model, as no additional degrees of freedom are introduced into the model.

FLEXIBLE BODY MODELS - In the flexible body method, a body may deform elastically. The displacements of flexible bodies are subdivided into displacements due to rigid body motions and displacements due to deformation. The latter define the way in which a body can deform. These displacements are approximated by a linear combination of predefined displacement fields or modes (Koppens et al. 1993). The modes may, in general, describe any shape, but they must be chosen such that the deformation of the body is approximated well. These modes can be obtained experimentally, analytically, or with a finite element model. For bodies with complex geometry or deformation behaviour it is advantageous to use a finite element model to determine the modes. The modes need only to be determined once, prior to performing simulations with the model. This makes flexible bodies particularly useful for models that are set-up once and used numerous times, as is the case for crash dummy databases.

Previous flexible body methods have assumed linear structural behaviour. This has been successfully used to model several dummy parts, including the EuroSID-1 rib (Koppens et al. 1993) and the Hybrid III thorax (Broekmeulen, 1995). Such models are referred to as "linear" flexible body models. In creating a linear flexible body model the modes and modal parameter values are determined in advance. However for some dummy parts material nonlinearities have a significant contribution to the behaviour. The modal stiffness and damping of these parts are not constant, and a method is required that can continuously update the material parameters during the analysis. Previously it has only been possible to model such behaviour using the finite element method.

To avoid the computational expense of FE, a new method has been developed and is introduced in this paper which allows the inclusion of nonlinear material effects into the flexible body description. In the new technique a finite element discretisation of the deforming part is used to calculate the internal loads due to deformation. The nonlinear effects are included using standard finite element techniques, but without solving the equations of motion of the finite element assembly. By doing this, the integration timestep is based on stability of the multibody, rather than the finite element method. This results in significant savings in processing time in comparison with an equivalent finite element model. This method is referred to in this paper as the non-linear flexible multi-body (NLFMB) method.

FINITE ELEMENT MODELS - In the finite element method, a continuum is discretised into a number of small parts (elements) which can deform in a pre-defined manner. The element shape function defines the way in which an element can deform. These are usually linear functions or low-order polynomials. Because of this, they are accurate only over small domains, so many elements are required to accurately capture the deformation patterns of a body. The MADYMO finite element module uses a displacement-based formulation with a Lagrangian material description allowing large translations, rotations and deformations. Several elements can be used including truss, beam, membrane, shell and brick elements. The material library includes elastic, elasto-plastic and visco-elastic models with strain-rate effects and material damage. Specific

material models have been implemented for fabrics, foams, composites and honeycomb. Contact can be defined between nodes and elements, as well as between nodes and ellipsoids, etc. Kinematic constraints between nodal degrees of freedom can be specified, eg. to model spotwelds.

HYBRID MODELS - The hybrid approach combines different modelling techniques in one database. The art in setting up such hybrid databases is to choose the "best" technique for every model section. It is recognised that the "best" choice will depend on the application, and that for any given dummy database, different methods will be preferable in different conditions. In the following sections, models are presented which demonstrate the advantages of hybrid modelling.

HYBRID III NECK MODELLING

In this section, the ability of multibody and finite element methods to represent highly deforming dummy parts is tested, using the neck of the Hybrid III. Rigid body models which use kinematic joints to provide for the flexibility of the neck have been presented by many authors (Seemann et al. 1986; Kaleps et al. 1988; Paver et al. 1990; Fountain, 1994), and several finite element models have also been developed in recent years (Yang et al. 1992; Khalil et al. 1994; Fountain, 1994). In the following sections a multi-segment rigid body model and a finite element model are presented, and compared with flexible body models of the neck.

RIGID BODY MODEL - Figure 2a shows the rigid body neck model. Five rigid bodies are used to represent each of the aluminium disks in the neck. These are connected by spherical joints which are located at the centre of the aluminium disks. Flexion-torsion restraints with nonlinear stiffnesses describe the bending and torsional resistance of the rubber disks. A single rigid body model has also been developed (TNO, 1994), but this 4-segment model allows more direct comparison with the other models in this paper.

FINITE ELEMENT MODEL - This model uses four identical FE sections, which each represent one rubber disk. Rigid bodies are used to model the aluminium disks; this is more efficient than using finite elements. Free joints are defined between these bodies. Massless spring elements are used to model the cable which runs through the centre of the neck. The Mooney-Rivlin material model is used to describe the rubber. This is a nonlinear material model whereby the strain energy density is described by a polynomial function. It is well suited to modelling incompressible or nearly incompressible hyperelastic materials such as rubber. Two versions of the model exist, with and without the slit in the rubber. In both models 544 8-node brick elements are used for each disk. The models with and without the slit contain 827 and 785 nodes, respectively. The model is shown in Figure 2b.

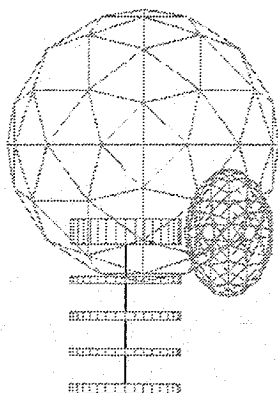
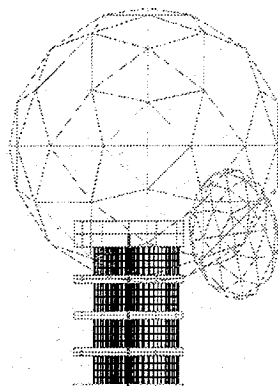
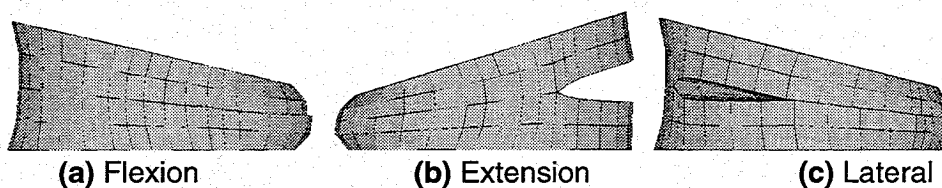


Figure 2(a). Multiple Rigid Body Neck Model.



2(b). Hybrid Rigid Body-FE Model.

FLEXIBLE BODY MODELS - A linear flexible body model and a nonlinear flexible body model were developed. The deformation modes for the models were obtained using a finite element model of an individual rubber disk, which was identical to those used in the FE neck model. In the models presented in this paper, bending and compression modes were used. The primary bending modes, as generated from the finite element model, are shown in Figure 3. The modal stiffnesses for the linear model were approximated from the quasi-static moment-rotation characteristics obtained from finite element component models. These responses are nonlinear, but were approximated with constant stiffness values in the linear flexible body model.



(a) Flexion (b) Extension (c) Lateral
Figure 3. Neck Bending Deformation Modes

In the NLFMB method it is possible to include *any* material description into the model. In these models the Mooney-Rivlin material was used, consistent with the finite element models. The nonlinear flexible body model of the neck is shown in Figure 4. Each rubber disk is represented by one flexible body with several deformation modes. These are identical to the linear flexible body model. The only difference between the models is that constant stiffness and damping matrices are specified in the linear model, and finite element meshes of the rubber disks are used in the nonlinear model. The head is represented by one rigid body (not shown), connected to the neck by a revolute joint. Five rigid bodies are used to represent each of the aluminium disks.

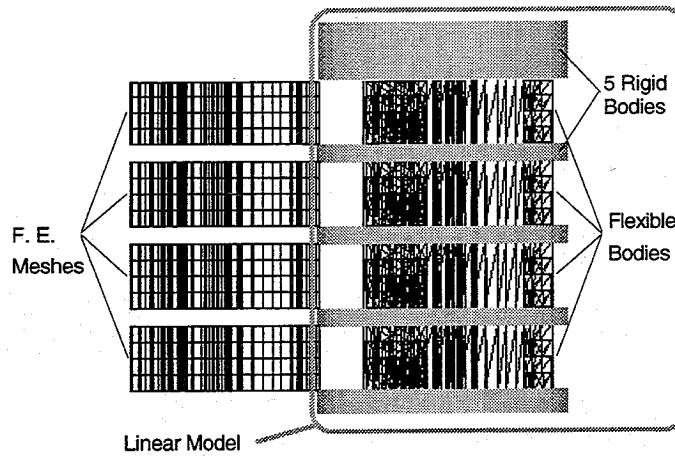


Figure 4. Non Linear Flexible Body Model

RESULTS - The models were validated for loading in flexion, extension, and lateral bending. Figure 5 shows results from the flexion calibration test. These are typical for the results in other loading conditions, and they give a good indication of the level of accuracy that can be expected from the different approaches. Figure 6 shows the deformed shapes of the models at various times during the flexion calibration test.

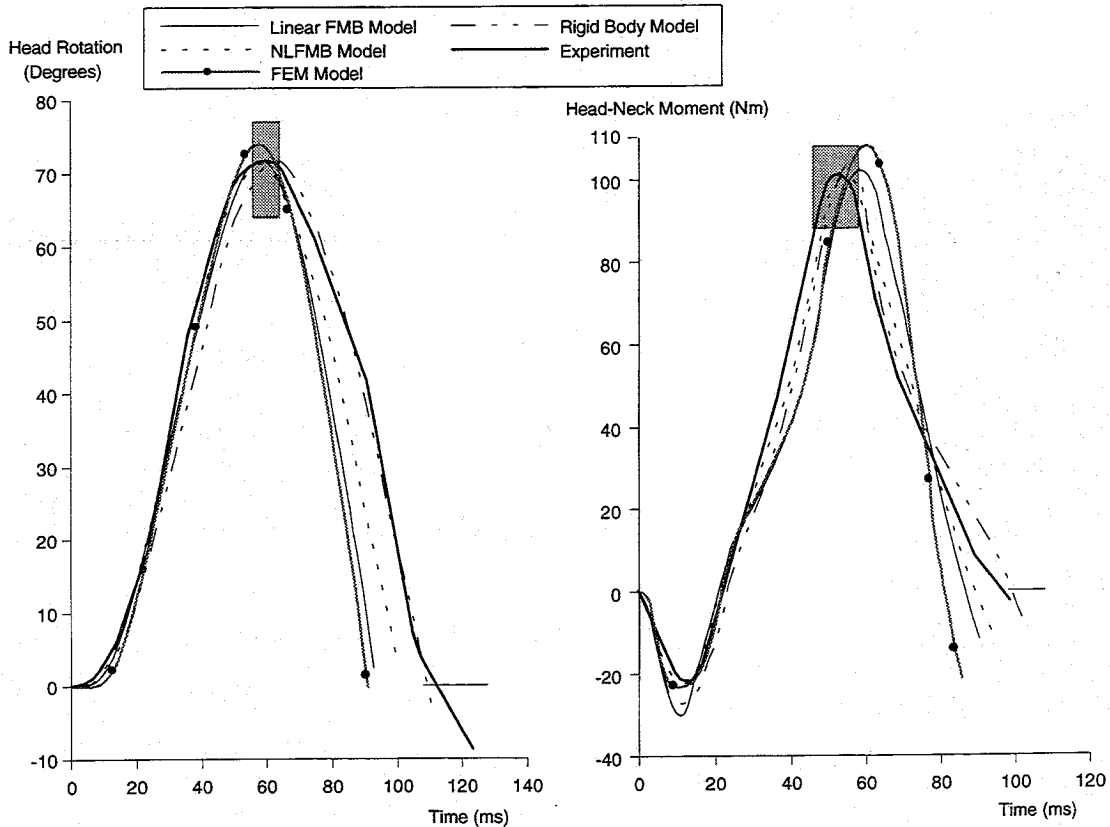


Figure 5. Neck Flexion Calibration Test Results

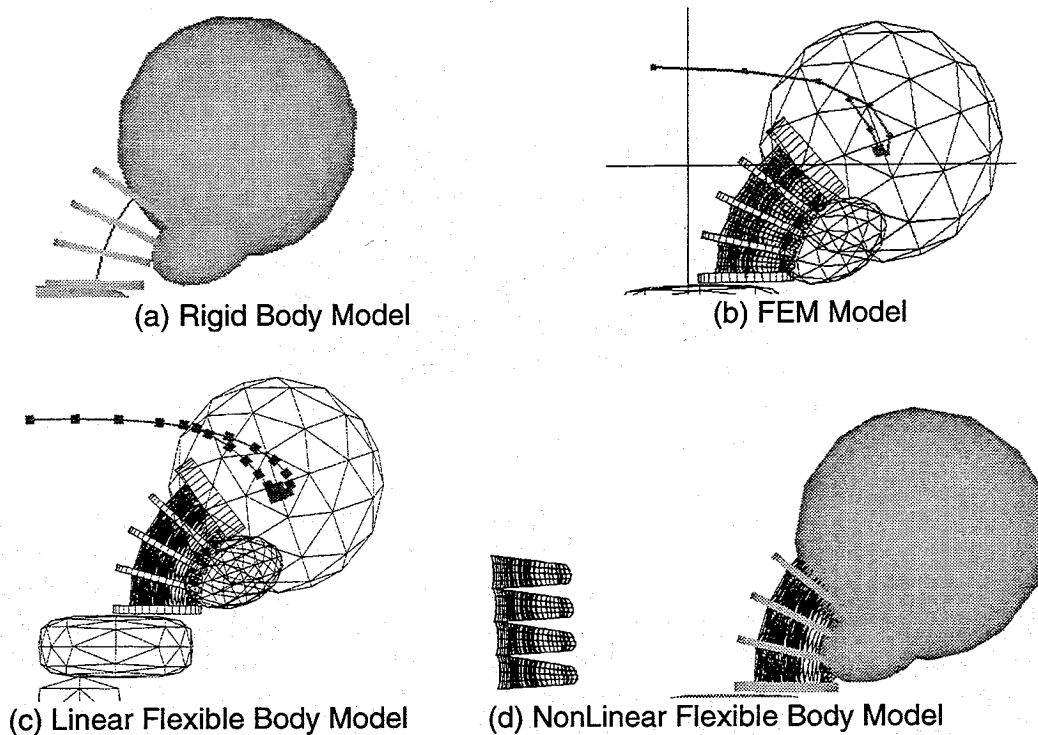


Figure 6. Deformed Shapes of Neck Models in Flexion.

The rigid body model could reproduce the head rotation almost exactly, during both the loading and unloading phases. The hysteresis algorithm in the joint force model allowed a high degree of control over the amount of energy dissipation, and this allows the unloading behaviour to be accurately predicted. The head-neck moment was not predicted with such high accuracy. The initial negative peak was over-predicted, and there was a noticeable timing difference during the loading phase.

The finite element model gave a detailed prediction of the deformation behaviour of the flexible parts, but the global responses were not predicted as accurately as they were by the rigid body model. This is mainly the result of difficulties in including the effects of strain rate sensitivity in the rubber. In the latest release of MADYMO (TNO, 1996) material damping is available for the Mooney-Rivlin model, but this has not yet been applied in these models. It is expected that including damping effects will result in significant improvements.

The flexible body models predict the global behaviour of the head and neck and the local deformations of the rubber disks very well. For both methods, the head rotation responses in all directions during loading are close to the experimental test results. The general responses for the head-neck moment are predicted well, but there are some small discrepancies during the initial part of the moment history for the linear model. These discrepancies are caused by making linear approximations to the nonlinear stiffnesses. The head-neck moment of the nonlinear model agrees almost exactly with the experimental test results.

The linear model does not predict the unloading behaviour very accurately, because it is not possible to define different behaviour in loading and unloading. This is a restriction caused by the use of constant stiffness and damping parameters, which is necessary for the linear flexible body formulation. The unloading behaviour of the nonlinear flexible body model was more accurate, but it also stored excessive energy. This can be improved by including energy dissipation effects in the material description.

The processing times required by the four models to perform a 100ms simulation of the flexion calibration test were recorded, and are compared in Figure 7. The normalised processing times are shown on a logarithmic scale on the vertical axis.

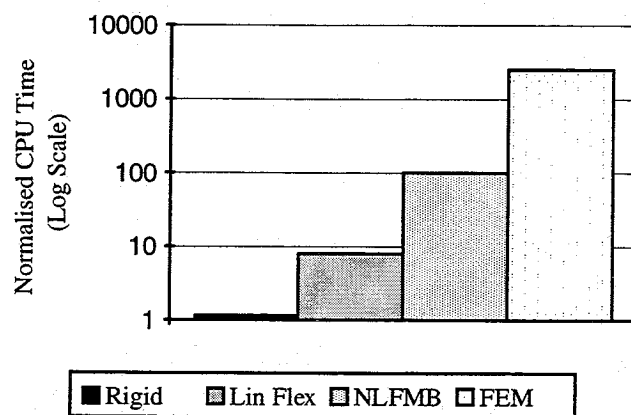


Figure 7. Normalised Processing Times for Neck Models.

The ratio of CPU times for the rigid body model, the flexible body model, the nonlinear flexible body model, and the finite element model was approximately 1:8:100:2500. These values vary depending on the configurations of the models, but there was approximately one order of magnitude difference between the rigid body and linear flexible body models, and another order of magnitude difference between the linear and nonlinear flexible body models. The nonlinear flexible body model was between one- and two-orders of magnitude faster than the finite element model. In situations where one flexible body can be used in place of multiple rigid bodies, flexible body models can even be considerably faster than rigid body models. For example it was found that modelling the EuroSID-1 rib with one flexible body in place of nine rigid bodies reduced the required processing time by a factor of 20 (Koppens et al. 1993).

These results demonstrate the advantages of flexible body methods for modelling deformable dummy parts in which the primary loading mechanism is not through contact forces. In the following section, the possibilities of the hybrid approach for modelling deformable contact surfaces is demonstrated.

EUROPEAN PEDESTRIAN HEADFORM SUBSYSTEM MODELS

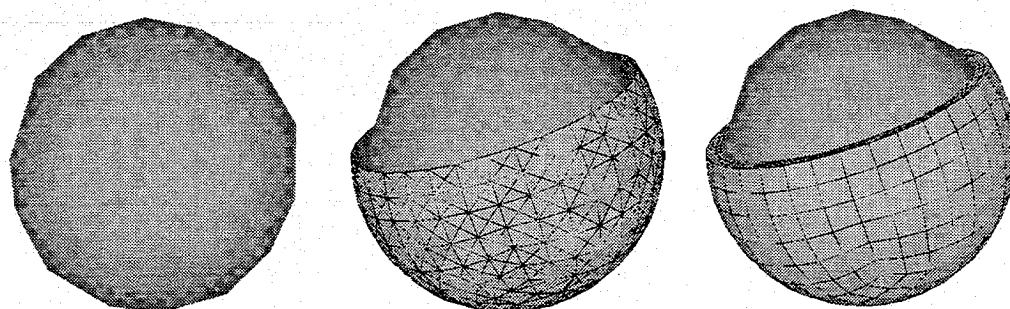
The European Experimental Vehicles Committee working group 10 has developed subsystem tests for assessing the protection afforded to pedestrians by the fronts of cars during an accident (EEVC WG 10, 1994). This led to the development of four EEVC

pedestrian subsystems: the adult headform impactor, the child headform impactor, the upper legform impactor and the complete legform impactor. Databases of the adult and child headform impactors have been developed and validated. The adult headform models are described below. Databases of the legforms are still under development.

The headforms have a spherical shape and are made of a semi-rigid material, which is covered by a rubber skin. They are used to test the top surface of a car bonnet. Databases of the impactors have been developed in order to simulate the contact interactions between the impactor and bonnet. A bonnet will generally be modelled using finite elements, and this requires special attention to the modelling technique applied for the surface of the headform. Three models of the headform have been developed using different techniques:

- Rigid multibody with ellipsoid; one rigid body describes the inertia and an ellipsoid describes the outer surface. Contact is described with force-deflection and damping curves.
- Rigid multibody with facet surface; instead of the ellipsoid a facet surface is defined. Contact is defined by a stress-deflection curve which includes hysteresis.
- Hybrid; the semi-rigid inner skull is modelled as a rigid body while the rubber skin is modelled by (solid) finite elements.

These models are shown in Figure 8. The models were validated by certification (drop) tests on a rigid surface and by guided impact tests on a plastically deforming steel plate. The deforming steel plate was modelled using shell elements, with an elastic-plastic material model. The simulation of the impactor on the deforming plate is shown in Figure 9. Validation results for the deforming plate are shown in Figure 10. Figure 11 compares the processing times of these simulations.



(a) Rigid Body and Ellipsoid (b) Rigid Body and Facets (c) Hybrid Rigid Body-FE
Figure 8. EEVC Adult Pedestrian Headform Models.

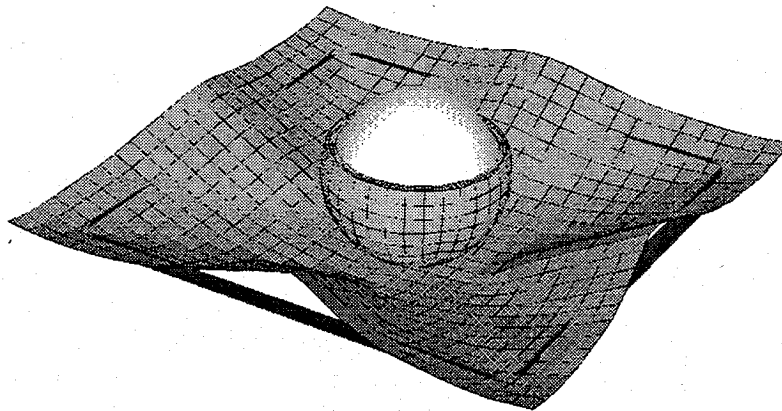


Figure 9. Hybrid Model of the EEVC Adult Pedestrian Subsystem on a Plastically Deforming Steel Plate.

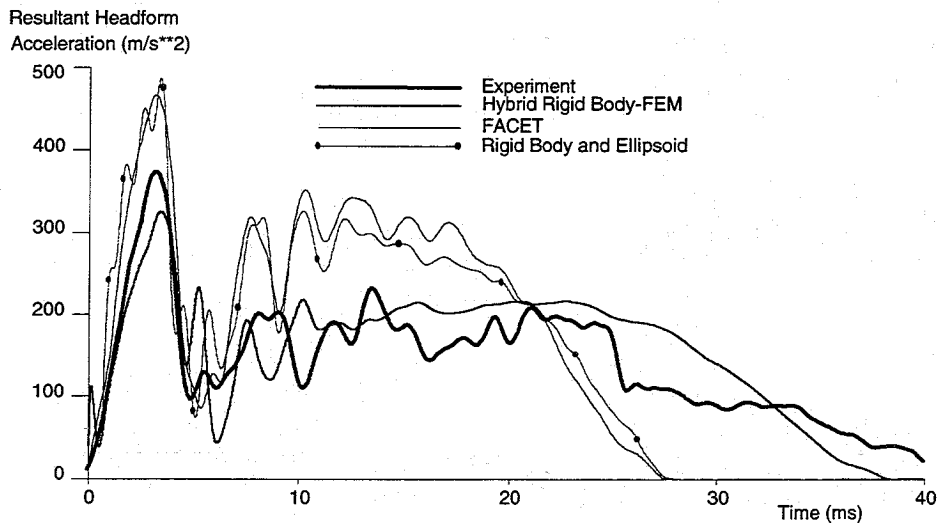


Figure 10. Validation Results of the EEVC Adult Pedestrian Subsystem on a Plastically Deforming Steel Plate.

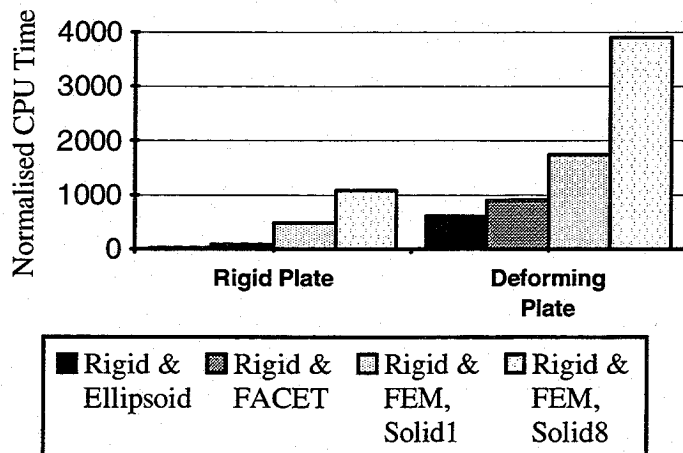


Figure 11. Normalised Processing Times for Headform Models.

The results on the rigid plate most clearly demonstrate the large difference in CPU for the different headform models. The results on the deforming plate are more relevant for the expected application of the database. Here, the timestep was determined by the courant criterion for the deforming plate. Still a large difference in CPU is found for the different headform models. The high CPU for the hybrid headform models shows that the complexity of these headform models dominates the CPU. For this reason single point integration ("Solid1") elements will be preferred to fully integrated ("Solid8") elements for most applications. However, it should be considered that fully integrated elements are more robust. The facet model is much more efficient and is also very robust. However in its current version, rate dependency is not implemented and therefore the results are considerably less accurate compared to the hybrid model. The ellipsoid model is even faster and is also very robust, but as expected, results on a deforming plate are not very accurate. This is because ellipsoids are treated as rigid in contact with FE models.

Summarising, the most accurate results were obtained with hybrid models with a high CPU. The more efficient rigid body models with ellipsoid and facet surface are much more efficient and robust but are less accurate. However, it is expected that the facet model will become much more accurate when rate-dependency is implemented.

These results demonstrate the possibilities for modelling parts in which the primary loading occurs through contact. In the following section, the hybrid modelling approach is illustrated on a complete dummy model, which is subject to a range of inertial and contact forces.

A HYBRID MODEL OF THE BIOSID

The BioSID (**B**iofidelic **S**ide Impact Dummy) represents a fiftieth-percentile adult male during lateral impact conditions (Beebe, 1990). The BioSID shares many common parts with the Hybrid III frontal crash dummy. The head, neck, lower legs and feet are all identical between the two dummies. The upper torso is the most unique part of the BioSID. It has five individual ribs which are designed to represent the human abdomen and thorax. These are mounted on the non-impacted side of the spine box. A large rib at the top of the spine box represents the shoulder, and allows for attachment of the arm. Ensolite™ foam is attached to the struck side of the ribs. This is meant to represent the human flesh, and it also serves to distribute the impact load.

Databases of the BioSID were required that could cater for all levels of side impact modelling - from simple lumped mass or multibody models, to detailed multibody models, to finite element models. A relatively simple multibody database was developed which can be used for parametric studies in the first two types of vehicle model. Such a database cannot reproduce the localised deformations of the dummy, and it is not able to interact in a realistic way with a highly deforming impacting surface. To cater for more sophisticated types of vehicle model, a hybrid multibody-finite element database was developed. The hybrid modelling approach allows refinement in critical areas of the model. This feature was used to create a more detailed representation of the highly deformable parts of the dummy, namely the thorax and arm, but still uses the very efficient rigid bodies for the less critical areas.

The models are shown in Figure 12. In both models, identical rigid bodies are used for the legs, pelvis, spine, neck and head. A two-pivot model is used for the neck, because this results in substantial savings in processing times. It is possible to use flexible body or finite element neck models in the BioSID database, but detailed neck models are more relevant for frontal crash dummies, so the simplest and most efficient neck model is used in this database. Generally in side impact the response of the thorax is of primary importance, and accordingly most attention is directed to this area of the models.

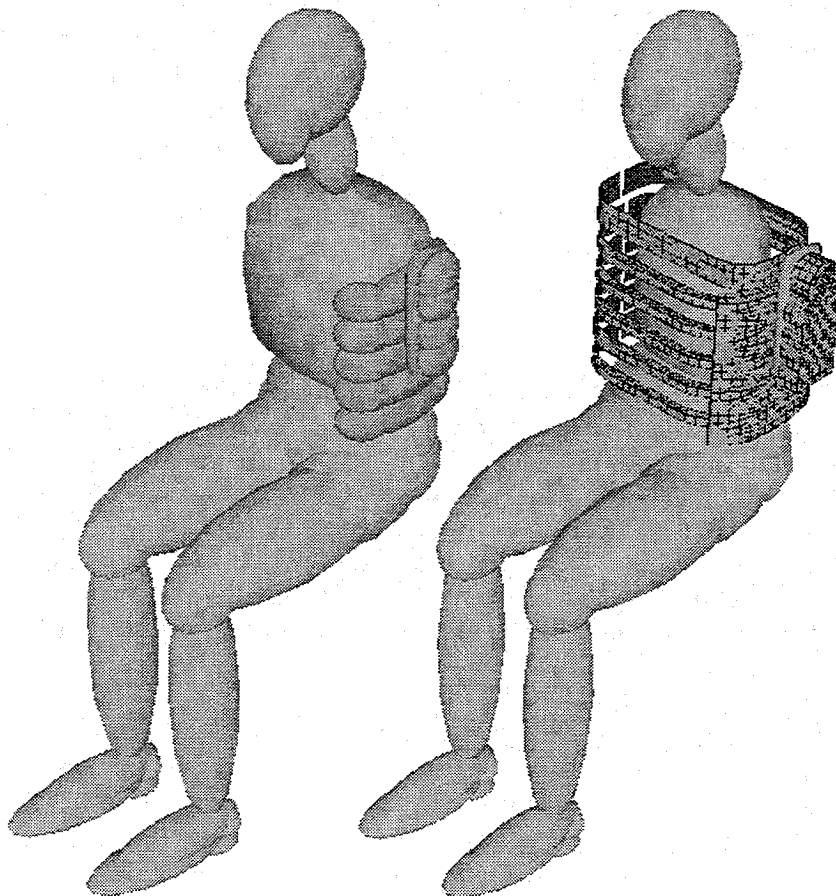


Figure 12. Multibody and Hybrid BioSID Models

In the rigid body model, one body is used to represent each of the five thoracic ribs, the shoulder rib, and the arm. Each body is connected to the spine box using translational joints. Nonlinear springs and dampers are used to represent the stiffness and damping of the ribs. Several ellipsoids are defined on the arm, and on each rib, to allow for contacts with the environment. In the hybrid model, the ribs, rib foam, arm foam and shoulder plug are modelled with finite elements.

The modelling technique used for the ribs needs to be considered separately from the foam on the ribs and arm, because these parts respond to applied loads in very

different ways. Any of the three methods discussed in this paper could have been used for the refinements to the rib (without foam) model. It is possible to use multiple rigid bodies connected with joints, as has been done for example in the EuroSID-1 dummy database (TNO, 1994). This is however a less general solution than flexible bodies, and as previously mentioned it is less efficient than using flexible bodies to represent the ribs.

Koppens et al. (1993) showed that the deformation shape of the EuroSID-1 rib did not change drastically when the impact location was changed, and that a single mode adequately described the deformation behaviour of the rib. The BioSID ribs are less highly constrained than the EuroSID-1 ribs, and therefore it is likely that more than one mode will be required to define the rib behaviour. The deformation response of the BioSID ribs is not well understood, so the finite element model will be used to gain more understanding of this behaviour. If it is found that the deformation can be approximated well by a few modes (as is expected), flexible bodies may be used to model the BioSID ribs in future versions of the database. The finite element model will then be used to generate the mode shapes and modal stiffness data required for the flexible bodies. However, until the deformation behaviour is better understood, finite elements are the most appropriate method for modelling the ribs.

The primary loading mechanism of the foam on the ribs and arm is through contact, and these parts therefore undergo large localised deformations (geometric nonlinearities). In contrast to the ribs, small changes to the impact conditions produce large changes to the deformation behaviour of the foam. An impractically large number of modes would be required in a flexible body model to cater for all possible contact situations. For these reasons the finite element method is preferable to flexible body methods for modelling highly deformable exterior dummy parts. It also allows for greater generality of the model. Therefore, finite elements were used to model the rib foam, shoulder plug and arm foam in the database.

The databases were validated in sled tests with rigid impact surfaces, and according to the requirements described in the BioSID User's Manual (SAE, 1990). This prescribes impacts to the shoulder, arm, thorax, abdomen and pelvis of the complete dummy, a drop test of the head, and a neck pendulum test. A selection of the results from the thorax calibration test are presented in Figures 13 to 16 which shows the typical accuracy of the models. The responses of the models are compared to corridors specified by the ISO (1988), and to physical test results.

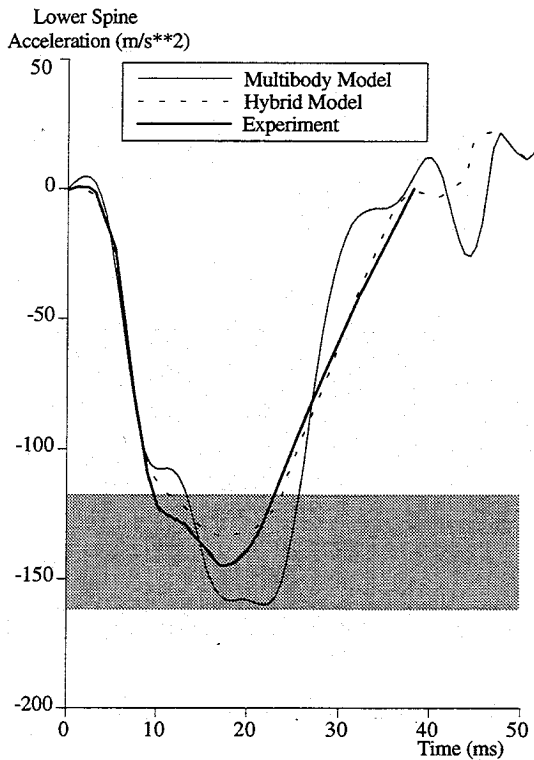


Figure 13. Lower Spine Accels.

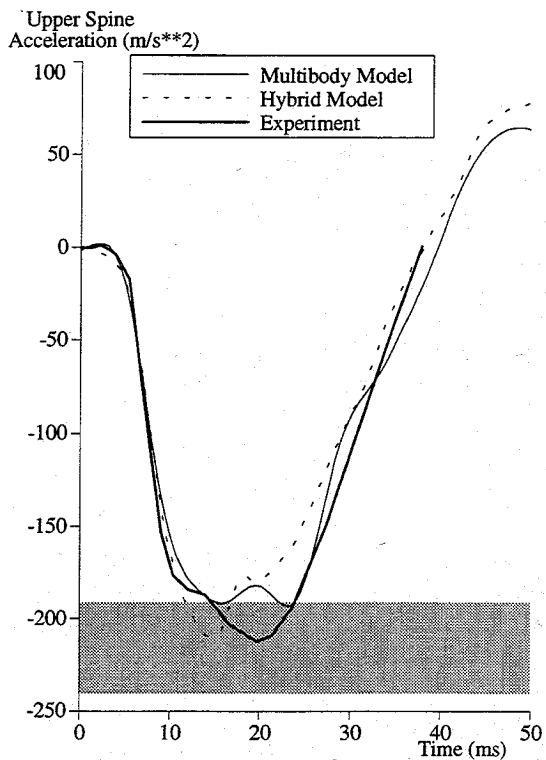


Figure 14. Upper Spine Accel., Thorax Test.

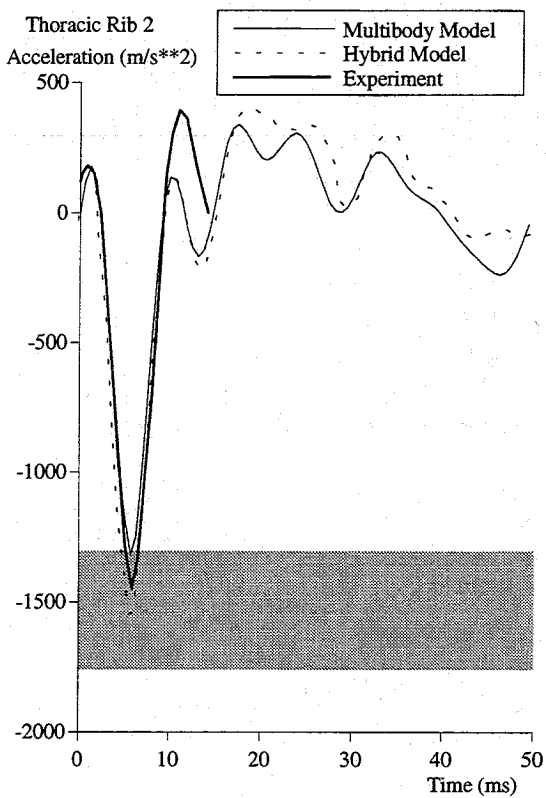


Figure 15. 2nd Thoracic Rib Accel.

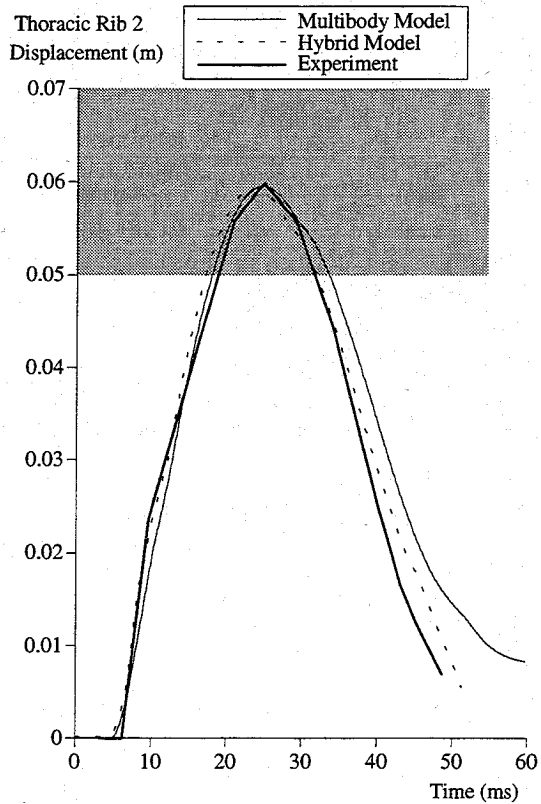


Figure 16. 2nd Rib Deflection, Thorax Test

Although only a few results are shown here, both models perform very well in all of the dummy calibration tests. In these tests, the peak responses are within the ISO biomechanical response corridors, and most responses agree closely with physical tests on dummies. The responses of the hybrid model are generally more accurate than the multibody model, although there are not large differences in the results.

The ratio of processing times required by the multibody and the hybrid model was approximately 1:1100. This cost is compensated for by the improved abilities of the model. These include greater predictive power, more accurate responses in a wider range of impact conditions, and more detailed information about the interaction with the impacting structures. In the test conditions presented in this paper, the impacting surfaces have been rigid. The full potential of the model will be realised when it is used in contacts with deformable finite element surfaces, such as airbags and vehicle side structures. However, the increase in CPU time is still large. Future developments may incorporate flexible bodies for the rib steel, and finite elements or facet surfaces for the rib and arm foam. As has been demonstrated with the flexible body neck models and the facet headform model, this will allow all of the important deformation behaviours to be predicted, but with even greater reductions in processing times.

DISCUSSION

In general, use of sufficiently detailed finite element models to model a structure such as the Hybrid III neck cannot be justified within the context of optimisation and sensitivity studies. The primary loading mechanism is through inertial forces, not contacts, and there are only limited geometric nonlinearities. For such a problem, the finite element method is too computationally expensive. Conversely, rigid multibody models are very efficient and can predict the global behaviour of the neck and head, but can give no information about the deformation behaviour of the flexible parts.

The flexible body neck models combine the best features of the rigid body method and the finite element method; the important responses of the physical structure can be captured in an efficient way. The global motions, the local deformations, and material nonlinearities are predicted accurately, and significantly less processing time is required than with a finite element model. The NLFMB method is also more robust than the finite element method, in several ways. All explicit finite element crash simulation software uses single-point integration elements to reduce the processing time, which introduces spurious "hourglass" modes into the solution. These are zero energy modes which can grow until they totally dominate the response. This is referred to as "hourglassing". The way in which a flexible body can deform is restricted to agreement with the pre-defined mode shapes (and combinations of those modes). These modes will generally be different to the hourglass modes, which provides an inherent resistance to hourglassing.

The penalty method is used in all FE crash simulation software to define contacts between different parts of the models. When a node penetrates an element face, a force is applied to the node which resists the penetration. The magnitude of this force depends on the material and element properties, and is also scaled by an artificial parameter. If a

suitable value for this parameter is not used, or if large penetrations occur unexpectedly, the resistive forces can jump suddenly, creating instabilities in the model. This scaling parameter must be determined by trial and error, and different values can be required for different impact conditions, which can lead to inaccuracies when the conditions in the simulation are altered. These facts cause the loss of both engineering and calculation time. This was experienced with the FE neck models: different versions of the model were required for flexion and extension because the contact definition was not reliable. Lateral bending simulations could not be reliably performed using the model with the slit.

In the flexible body neck models, it was necessary to use contacts *only* when calculating the mode shapes. In these simulations the conditions are well defined and controlled, and it is simple to ensure that the penalty factor is appropriate. No contact definitions are required in the actual simulations with the flexible body models. Thus, the flexible body models were much more robust, and required much less processing time than finite element models.

Inspection of Figure 4 shows that the linear and nonlinear flexible body models differ only by inclusion of the finite element meshes. The similarities with rigid body models and finite element models is also apparent; by using the finite element meshes in place of the flexible bodies, a standard FE model is obtained. By replacing the flexible bodies by kinematic joints a typical rigid body model is obtained. Thus, a hybrid model in MADYMO may use any of four different modelling methods, and all of these are easily interchangeable. This allows the configuration of the model to be easily modified for use in different circumstances. For example, there will be occasions when nonlinear flexible body method is too expensive, or when the accuracy is not so important, or simply when only the gross motions are of interest. In these cases, the model can simply be converted to a linear flexible body model or a rigid body model. Conversely, when detailed knowledge of the localised deformations are critical, or when the model is used in very unusual conditions, the model can be converted to a standard finite element model.

The performance of the rigid body BioSID model confirms that it is acceptable to use a small number of rigid multibodies and kinematic joints to represent deformable dummy parts. This approach is simple and efficient, but is sophisticated enough to capture the important responses of the dummy during blunt lateral impacts. It is a good example of using kinematic joints to represent a deformable structure. The range of impact conditions in which the database is accurate depends on the level of detail of the model, the modelling features available, and the quality of the data used to create the model. The multibody BioSID model is capable of approximating limited localised effects. For example, the impactor in the abdominal test has a 75mm diameter face, compared to a 150mm diameter face in the other tests. During the arm test only the arm backing plate contacts the thoracic ribs, and this has a much smaller area than the impactor for the thoracic test. During the shoulder test the impactor covers only a small region on the arm. The response of the multibody model is very good during all of these test conditions, which indicates that this simple approach still allows a reasonable range of impact conditions to be simulated.

Rigid body models are capable of accurately predicting the behaviour of almost-rigid dummy parts, such as the extremities. The method can give no information about the true deformation of flexible parts. All flexibility is lumped into discrete joints, which are very simple equivalent systems for representing a deforming structure. In contrast, finite element models can give a detailed prediction of the deformation behaviour of the flexible parts. For some parts (such as the neck), this is not so important, but for other parts (such as the BioSID rib foam) this can be essential. The finite element method has the *potential* to accurately predict a wider range of responses than the rigid body method especially. However this will be at the expense of great cost, in terms of both computation time and modelling effort.

The flexible body approach lies in between these two ends of the spectrum, in both the philosophy of the approach, and in many practical ways: the required processing times, the ability to predict the deformations, etc. The new nonlinear flexible body method is an extension of this method, which allows multibody models to be applied for tasks which were previously only possible using finite element models. There is a direct link between the multibody model and the material properties which allows, for example, parametric studies of the material properties to be performed in much less time than is possible with a finite element model. The NLFMB method represents a step towards the finite element method in terms of abilities, accuracy, predictive power, and computational cost, but not in terms of the philosophy of the approach. It has unique advantages over other techniques in that it can realistically describe the deformations and nonlinear material behaviour of flexible parts with the efficiency and robustness of multibody methods.

Unfortunately, there is no "best" modelling method. The best method for any given problem will be a balance between many considerations: cost, the amount of information required, the abilities of the method, and the test conditions. However, some methods are clearly better suited to certain tasks. Generally, when bodies collide it creates significant localised deformations, and currently the finite element method is preferable. For modelling deformable dummy parts which are subject to well defined impacts (such as the slits in the Hybrid III neck) or no impacts, the flexible body methods are particularly attractive. Most "interior" dummy parts such as ribs, lumbar spines, and necks fit into this category. The cost of generating the modes becomes negligible, and the deformation behaviour is usually quite limited, which means that the motion can be described well by a small number of predefined modes. Many dummy parts, such as arms, legs, feet, spine, and head, undergo negligible deformations. In some cases the localised deformations of flexible parts are of little or no interest, and only the global behaviour needs to be predicted well. In both cases, the rigid body method is the superior method because of its efficiency.

As mentioned in the introduction facet surfaces that can be attached to rigid bodies have been implemented in MADYMO. These surfaces allow a realistic description of the contact phenomena occurring for example in the dummy-structure interaction. The combination of flexible bodies and facet surfaces could prove superior to FE in most occupant safety applications.

CONCLUSIONS

The hybrid modelling approach is superior to using an exclusively multibody approach or an exclusively finite element approach. The advantages of the hybrid approach are even greater when flexible bodies are included in the multibody description. By using the hybrid approach, not only can the best method be selected for each part of a model, but the model can be easily changed to suit different applications. More simple models can be developed in the early stages of the design cycle, and these can become more complex during the later stages, when more detailed information is needed. It allows the most appropriate modelling techniques to be applied in a simple and versatile way, thereby making the best use of computer simulations in the development of improved vehicle safety systems.

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