MODELLING AND ANALYSIS OF INTERACTIONS BETWEEN OCCUPANT, SEATBACK AND HEADREST IN REAR IMPACT

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ABSTRACT

The improvement of neck protection in rear impact requires a better understanding of the interactions between occupant, seatback and headrest. A mathematical approach was developed to analyse the interactions and to quantify the influences of different design parameters on neck responses.

The first phase of this development consisted of neck modelling. To begin with, the RID-neck was compared to the Hybrid-III neck in terms of sensitivity with regards to some design parameter changes. A series of mini-sled tests showed the sensitivity of the RID-neck to be better than that of the Hybrid-III neck. Following this preliminary study, a numerical neck model was developed on the basis of the RID-neck and of two existing sources of biomechanical data on the human neck behaviour in rear impact.

For the second phase of this development, the interactions of the thorax and the pelvis with the seatback were modelized, as was that of the head and the headrest. Component tests were conducted to characterise these interactions. With these data, two types of seatback model were constructed. One is a global seatback modelling and the other a more detailed approach which allows the consideration of more design parameters. To evaluate the models, a series of sled tests was performed and the validation level of the above models was assessed against these tests.

Finally the influences on the neck responses of four design parameters - head to headrest distance, seatback joint stiffness, upper and lower seatback stiffnesses - were analysed with this model. Special attention was paid to the interactions between these parameters. The results indicate that softening of the upper seatback allows reduction of all neck injury risk indicators and enhances the headrest performance. Softening of the lower seatback increases the moment force at the C7/T1 joint and the head extension angle. Stiffening of the seatback joint aggravates, for a classical upper seatback structure, the moment loading of the neck and the head extension angle. Only the moment force at the C7/T1 joint is significantly affected by all parameter changes.

NECK INJURY IS THE MOST FREQUENT IN REAR IMPACT. Numerous accident investigations demonstrated that the majority of these injuries were classified as minor with an AIS 1 level and the injuries, occurring generally at low impact velocity (less than 20 km/h), caused high insurance costs and could lead to human suffering during a relative long period, even permanent disability (Kahane,1982, Romilly,1989, Olsson,1990, Foret-Bruno,1991, Kampen,1993, Ono,1993).

The headrest is the principal protective device for this type of accident. Its effectiveness, evaluated by different accident studies, varies nevertheless considerably, from 10% to 60% (Foret-Bruno,1991). In fact the performance of a headrest is conditioned not only by the quality of its design but also by other car design parameters, such as car stiffness, seatback joint stiffness, seatback frame form and stiffness. The improvement of the headrest performance requires a better understanding of the influences of these design parameters.

The aim of this study was to develop a mathematical approach for rear impact. The absence of dispersion of such an approach makes it an adequate tool for determining the influences of a design parameter, especially for the low velocity tests where result dispersions occur more often. The low cost of a mathematical simulation makes it also possible to follow a test matrix which allows analysis of a design parameter taking into account its interactions with other parameters, such as between head-headrest distance, seatback joint stiffness, seatback stiffness.

The first part of this paper presents the neck model development. The second part deals with two types of seatback/occupant interaction model. The third part presents an analysis of the influences of four major design parameters, i.e., headrest distance, seatback joint stiffness, upper seat frame stiffness and lower seat frame stiffness. The analysis was conducted with special attention being paid to the interactions between these parameters.

NECK MODELLING

HYBRID-III NECK AND RID-NECK - SENSITIVITY COMPARISON

Two mechanical models are available for simulating the human neck behaviour in rear impact. One is the Hybrid-III neck (Faster,1977) which was designed for frontal impact but also for rear impact. Another is the RID-neck (Svensson,1992) which was specially developed for rear impact, and in particular for low impact velocity (inferior to 15 km/h).

The RID-neck, with the same number of cervical vertebrae as the human neck, was demonstrated as having a better biofidelity than the Hybrid-III neck (Svensson,1992). Our laboratory tests demonstrated also a better sensitivity of the RID-neck to headrest design changes. These tests were performed with a mini-sled test set-up (Fig.1). The impact severity was about that of a 15 km/h collision. The responses of the Hybrid-III neck and the RID-neck were tested with respect to three types of headrest : a standard production one, the same

Figure 1 : Mini-sled test set-up

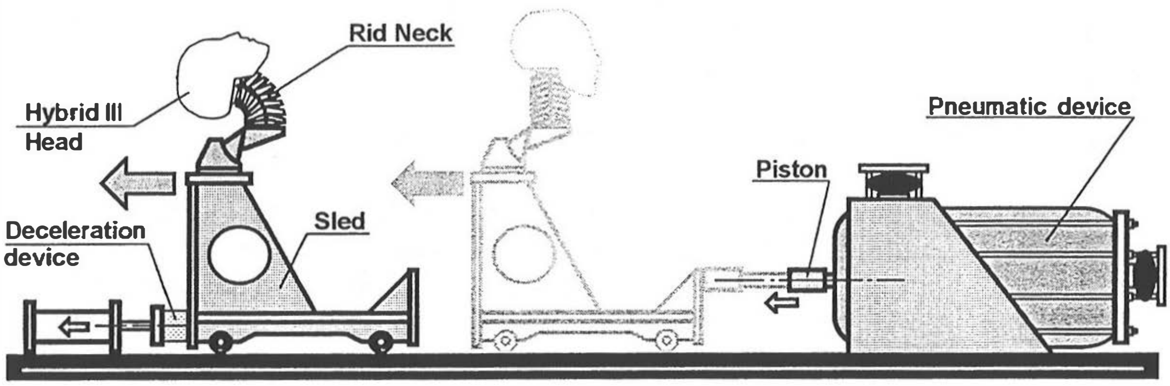
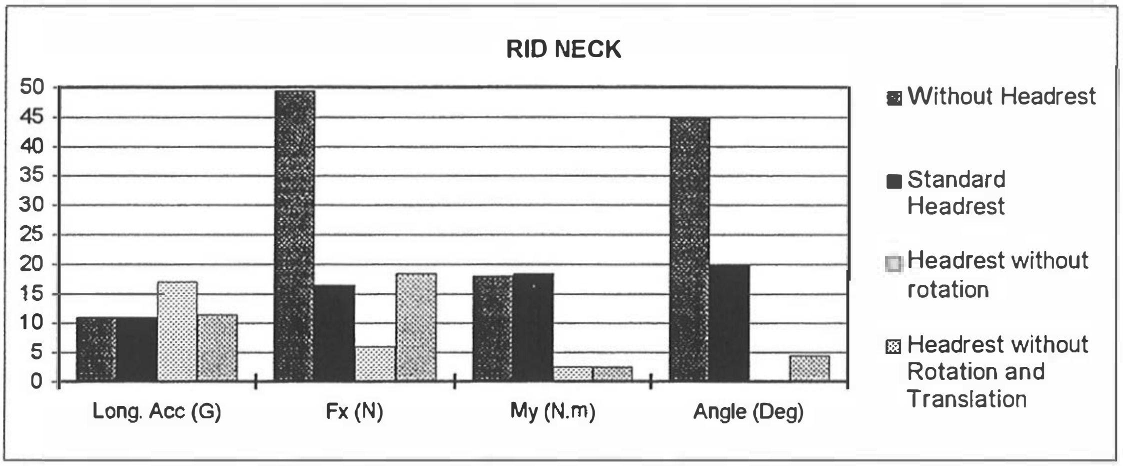
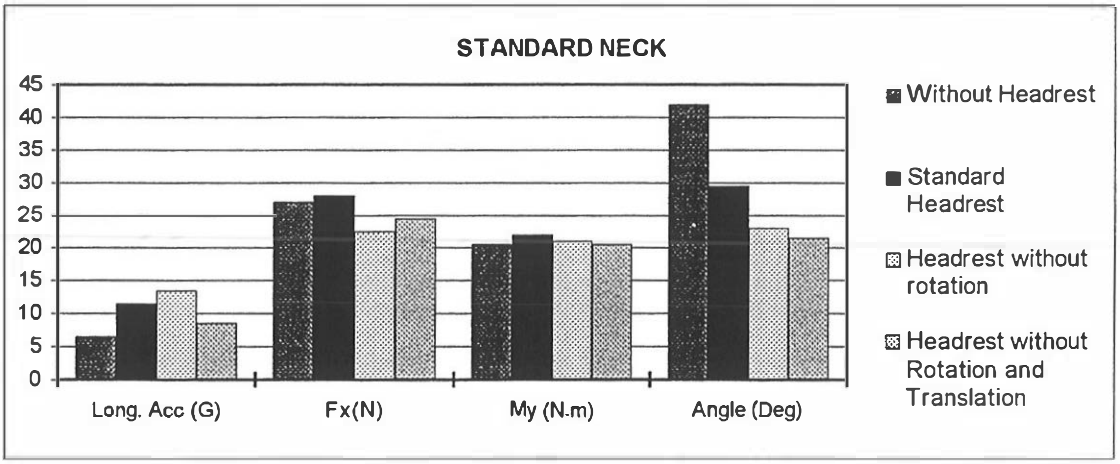


Figure 2 : Sensibility of Hybrid-III neck and Rid-neck responses with respect to headrest design changes





headrest but locked for translational movement and another with no possible relative movement with respect to the mini-sled. Figure 2 shows the results of the tests in terms of occipital shear force and moment (My, Fx), head acceleration and head extension angle. It can be seen that the RID-neck discriminates better the mechanical property changes of a headrest than the Hybrid-III neck. The RID-neck was so chosen in this study as the starting point for the purpose of modelling human neck.

RID-NECK MODEL CONSTRUCTION AND VALIDATION

The RID-neck is composed of seven cervical vertebrae (C1 -> C7) and two dorsal vertebrae (T1 ->T2). The vertebrae are made of acetal plastic and are connected together with pin joints. The distances between the joints are the same, 16 mm. All joints have the same angular range of motion, 10° in extension and 5.6° in flexion, apart from the joint T1/T2 whose motion range is 3° for both extension and flexion. The intervertebral spaces are filled with blocks of Neoprene plastic foam which give the angular stiffness of each joint. There are three versions of the RID-neck (RID1, RID2 and RID3) which correspond to three different foam-block dimensions. The RID3 was found to fit closest to the volunteer test results (Svensson, 1992). The RID-neck used in this study is the RID3.

A multi-segment model (Fig.3) was constructed to represent the RID-neck. Each vertebra is considered as a rigid body with a mass of 0.110 kg. Each joint is modelized by a 6-DOF spring for which only the rotation about the pin joint axis is allowed. For defining the mechanical properties of these spring elements, quasi-static tests (Fig.4) were conducted for joints T1/T2, Head/C1 and C6/C7, in extension and in flexion. The characteristics of the other joints are the same as those of the C6/C7 joint. Figure 5 shows an example of the moment-angle relationships obtained.

Figure 3 : RID-neck model

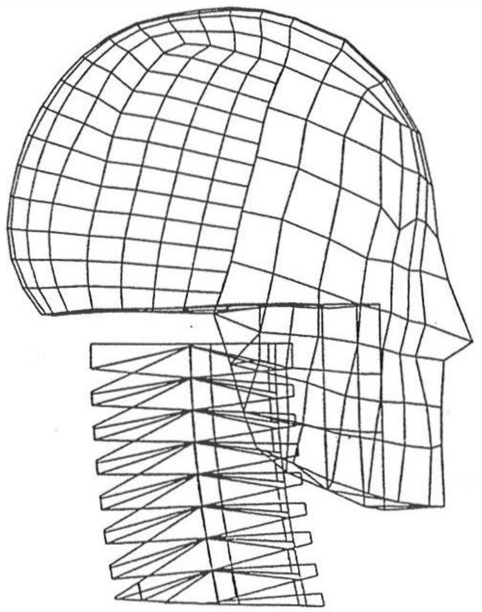


Figure 4 : Static test set-up

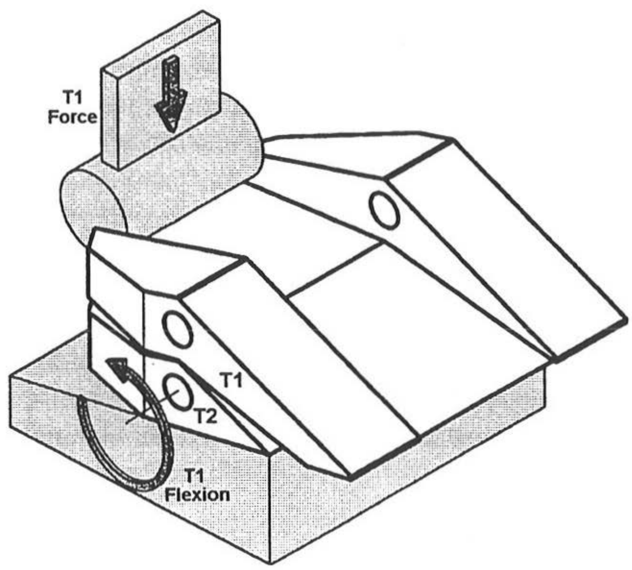
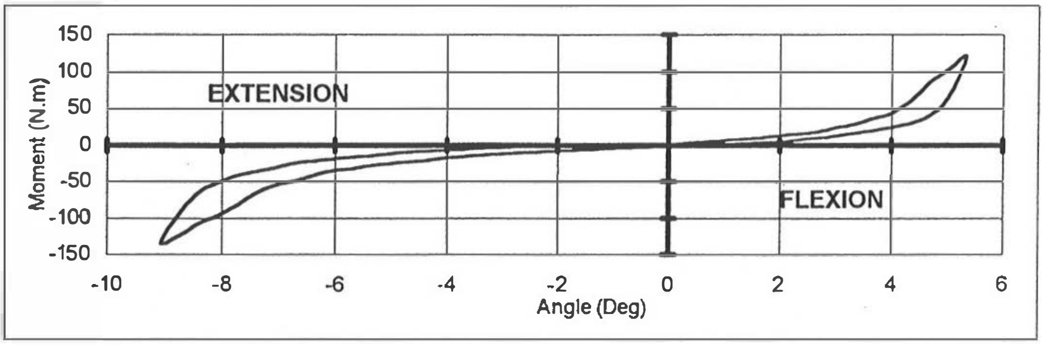


Figure 5 : Measured static head/C1 moment-angle relationship



The dynamic tests were also conducted with the foam blocks but little dynamic effect was detected. Based on experimental data, the moment-rotation relationship of each spring was defined for the pin joint axis. The displacement and rotation about other axes are locked by high stiffness restraints.

In order to evaluate the response of the model, mini-sled tests were performed and simulated with the model. Figure 6 compares the model responses to the measurements of two repetitive tests corresponding to a 15 km/h severity. It can be seen that the model allows a good simulation of the RID-neck behaviour.

BIOFIDELITY CONSIDERATION AND NECK MODEL

The biofedelity of the RID-neck was evaluated by Svensson et al. (1992) with respect to the volunteer experimental test results reported by Tarriere et al. (1969). In these tests, standing volunteers were impacted, at shoulder level, from behind by a heavy pendulum. The mean acceleration at shoulder level was 2-3 g with 120 ms duration (corresponding to a velocity change of about 10 km/h). The absolute head rotation with respect to time was given for each subject. Svensson et al. reported that the RID-neck response fits the Tarriere test results more closely than that of the Hybrid-III neck, and that the RID-neck allows an initial horizontal translational-motion of the head relative to the thorax, considered as a sign of a better biofidelity.

Another available biofidelity requirement for the neck surrogate development in rear impact is the corridor proposed by Mertz et al. (1971). It is interesting to evaluate the biofidelity level of the numerical RID-neck model presented above with respect to the corridor. To do this, the model was subjected to a deceleration similar to that of the tests of Mertz, i.e., an average deceleration of 3.2 g during 130 ms. An average deceleration of 5 g during the same period was also applied to assess the behaviour of the model in a more severe impact.

Figure 6 : Comparison of RID-neck model responses
with two repetitive mini-sled tests for a 15 km/h severity

A : model ; B and C : tests

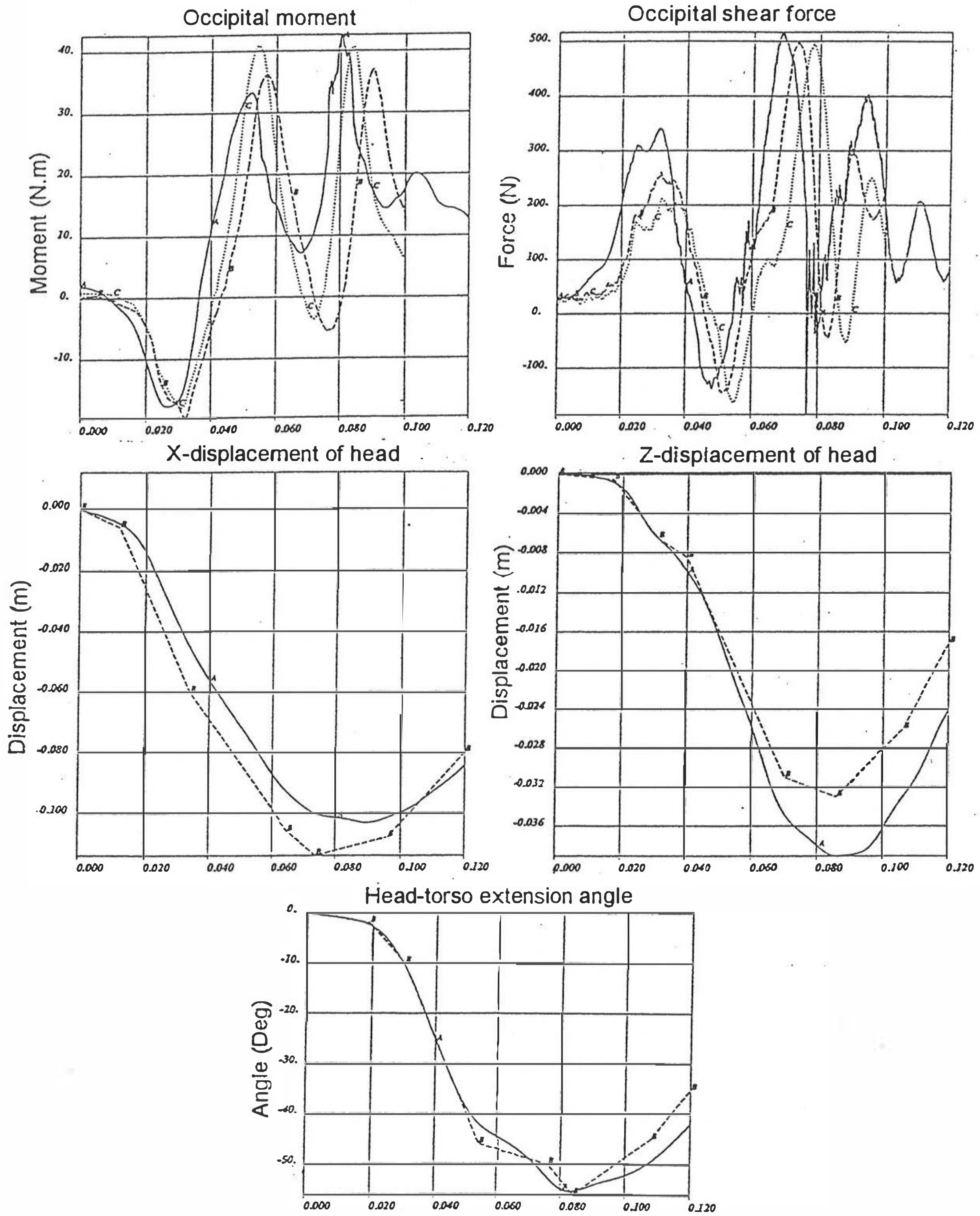


Figure 7 shows the relationship between the occipital joint moment and the head -thorax extension angle. It can be seen that the RID-neck model is still stiff compared to the Mertz corridor requirement when the impact severity increases.

Our objective was to develop a neck model on the basis of the RID-neck model, which should be consistent with not only the volunteer test results of Tarriere but also with the Mertz corridor requirement for both lower and higher impact severity. Such a model was obtained by modifying the joint characteristics of the RID-neck model. Figure 9 gives the moment-angle relationships used for the different joints of this model.

The test configuration of Mertz and that of Tarriere were simulated with the neck model. Figure 8 compares the model responses with respect to the Mertz corridor. For the volunteer tests of Tarriere, the maximum head-torso extension angle given by the model was 43°, reached at 130 ms. That given by the experiments was respectively 26°, 49°, 49° et 35°, reached at between 100-130 ms, for the four volunteer tests.

This neck model constitutes a first approach to the simulation of the human neck behaviour in rear impact. Developed on the basis of the RID-neck and of the two available biomechanical data sources presented above, the neck model should be more biofidelic than a Hybrid-III-based model.

Figure 7 : Occipital moment/head-thorax extension angle of the RID-neck model compared to the Mertz corridor

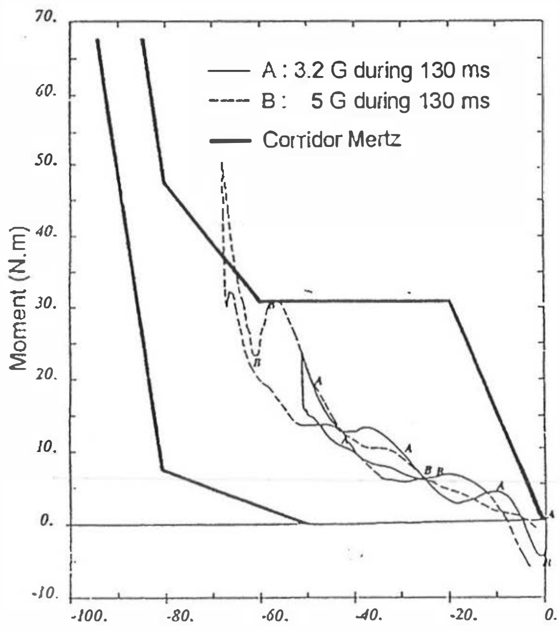


Figure 8 : Occipital moment/head-thorax extension angle of the neck model compared to the Mertz corridor

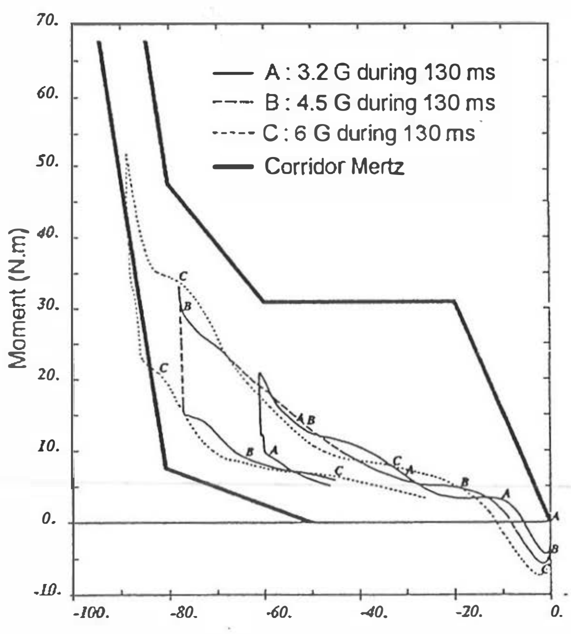
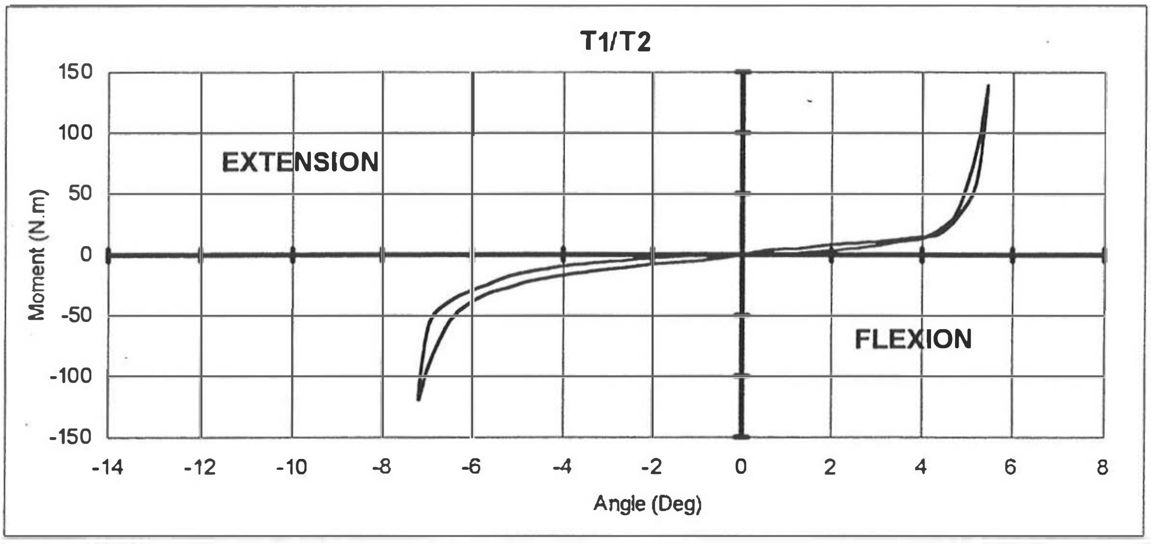
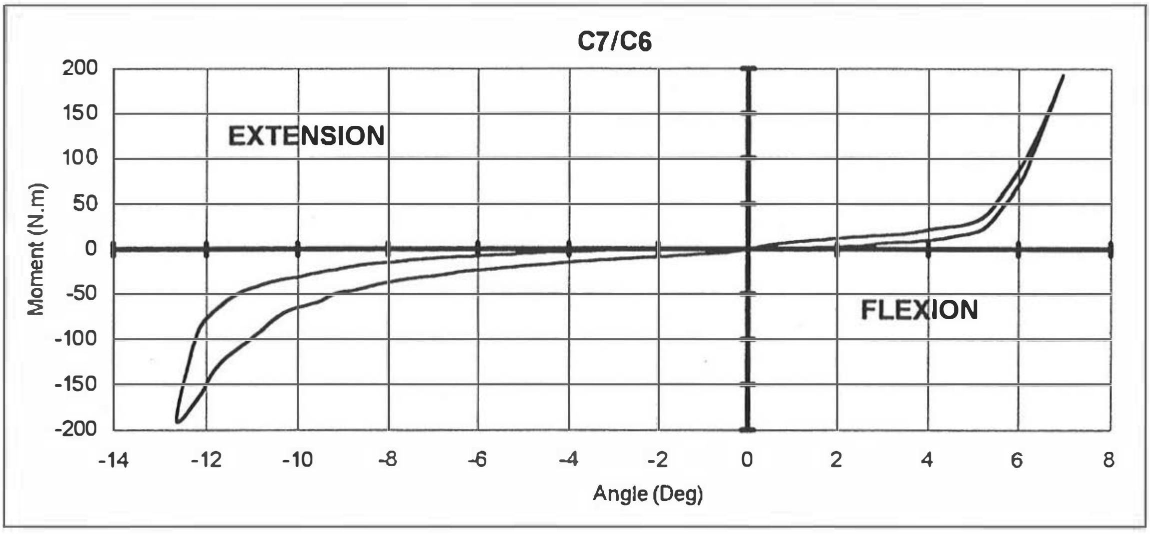
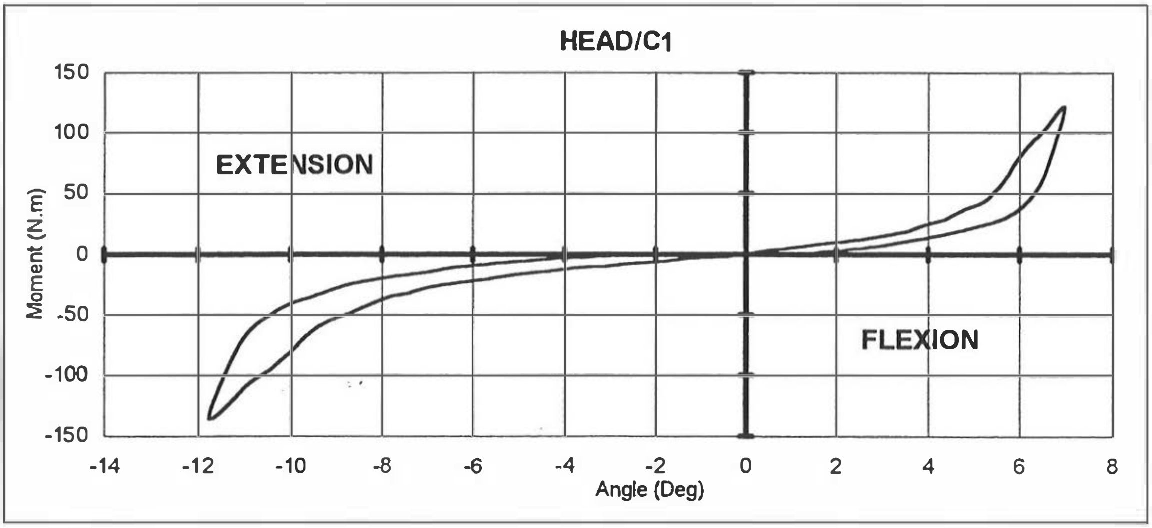


Figure 9 : Moment-angle relationships used for diferent joints of the neck model







OCCUPANT/SEATBACK INTERACTION MODELLING

SEATBACK STRUCTURE

A seatback can be decomposed into three parts relating to its interactions with the occupant :

*Seatback foam : In direct contact with occupant, it is in general against a steel thread net.
*Seatback frame : In the most case, it consists of an upper cross member and a beam structure at the pelvis level.
*Seatback joint : It connects the seatback to the seat structure.

In a rear impact, the torso penetration into the seatback is firstly resisted by the seatback foam part and then stopped essentially by the seatback fame.

SEATBACK MODELLING

Two types of model were constructed : one is a global representation of a seatback and another a more detailed approach.

Global seatback model (Fig.10) : the seatback is represented by a rigid body, connected to the seat structure by a pin joint derived from a 6-DOF spring. Two planes are attached to the seatback : one simulating the upper part of the seatback and another the lower part. The attachment of each plane is realised by four general springs which allow only the perpendicular relative motion of the plane to the seatback. The stiffness of the seatback is described by that of the springs which defines the load-penetration relationship for the upper and lower parts of the seatback. The contact between occupant and seatback is simulated by two interfaces : one between thorax and upper seatback, another between pelvis and lower seatback.

Figure 10: Global seatback model

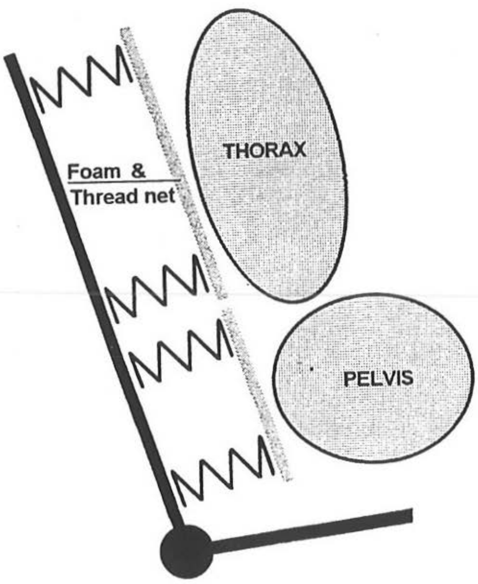
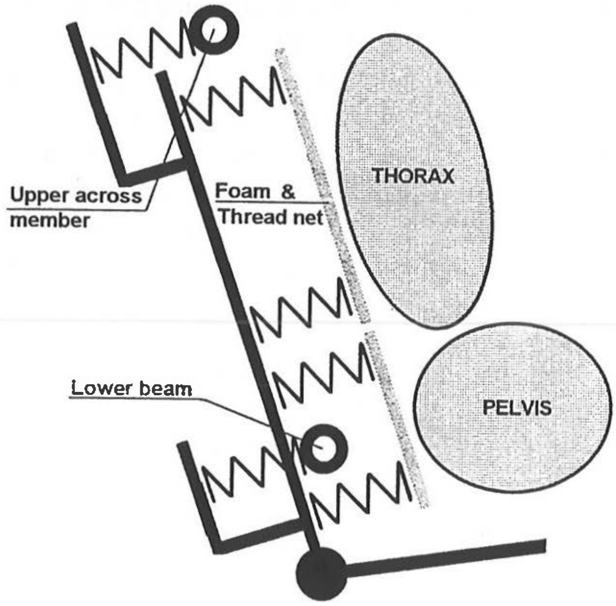


Figure 11: Advanced global seatback model



Advanced global seatback model (Fig.11) : A more detailed representation of a seatback can be made by separating the seatback foam stiffness from that of the seatback frame. The stiffness of the springs connecting planes and seatback simulates in this case only the seat foam part stiffness contribution. The role of the seat frame is taken into account by two rigid beams - one representing the upper across member and another the lower transversal beam. The stiffness of the springs connecting these two beams to the seatback body represent the seat frame stiffness contributions. Two additional interfaces, compared to the global seatback model, are defined : one between thorax and upper cross member, the other between pelvis and lower beam structure. This approach allows a more precise contact force distribution between occupant and seatback.

Headrest/head contact modelling : The headrest and the head were meshed exactly following their forms. A global contact was defined between two surfaces by specifying a load-penetration relationship which combines the foam stiffness and that of the steel support of the headrest.

MODEL VALIDATION ASSESSMENT

To asses the validation of these two types of model, static and dynamic tests were conducted.

Static tests : The stiffness of the seatback joint and those of the seatback and the headrest were evaluated by quasi-static tests. Figure 12 shows the test set-ups used.

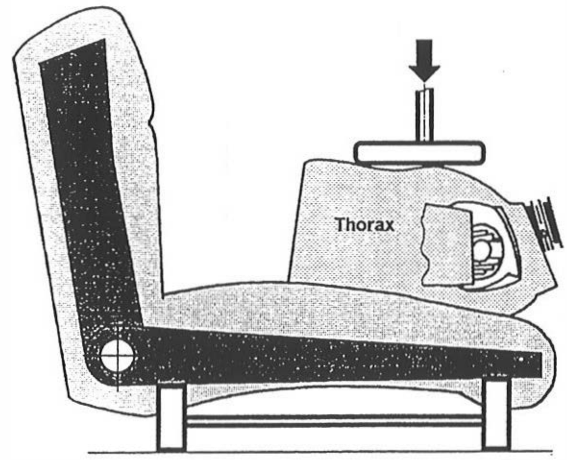
Dynamic tests : A series of sled tests was performed with a 50th Hybrid-III dummy equipped with a RID-neck. It is to be noted that in the tests the seat structure was fixed rigidly to the sled in order to eliminate the influence of its deformation on the seatback /occupant interaction.

Two models, one with the global seatback approach and another the advanced global seatback approach, were constructed for each test configuration. The stiffness of the seatback joint and those of the upper and lower seatback parts were directly introduced into these two models. Friction coefficients for occupant and seatback interfaces were estimated. The standard PAM-SAFE Hybrid-III dummy model (ESI,1995) was used for the occupant simulation. The Hybrid-III neck model was replaced by that of the RID-neck presented above. The car deceleration pulse (Fig.12-a) was applied to the occupant and the seatback. Figure 12-b shows the initial configuration of the model.

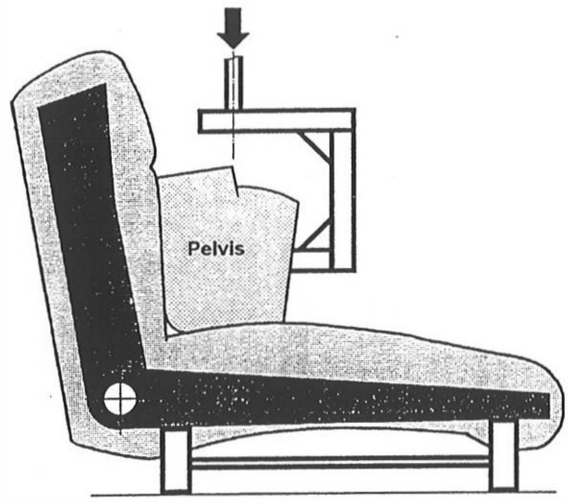
Figures 13 (a-b) show examples of the comparisons between calculated results and test measurements for two impact severity levels. It can be seen that the model gave the results similar to those of the tests. It is noted that this correlation level was obtained with a model whose mechanical properties were directly defined from the quasi-static test data. No parametric tuning was taken to reduce the existing divergence between simulation and test results since the

Figure 12 : Quasi-static test set-up used
for seat back and head rest stiffness measurement

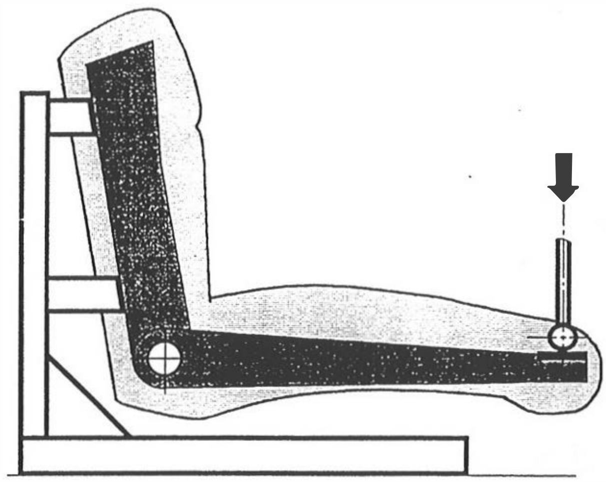
(a) upper seat back part



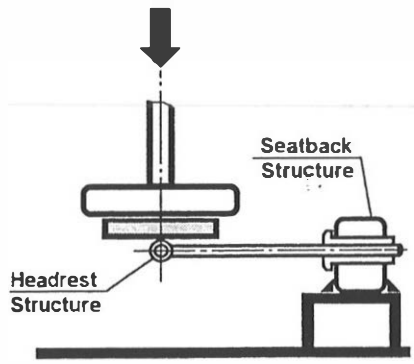
(b) lower seat back part



(c) seat back joint



(d) headrest support



(e) headrest foam

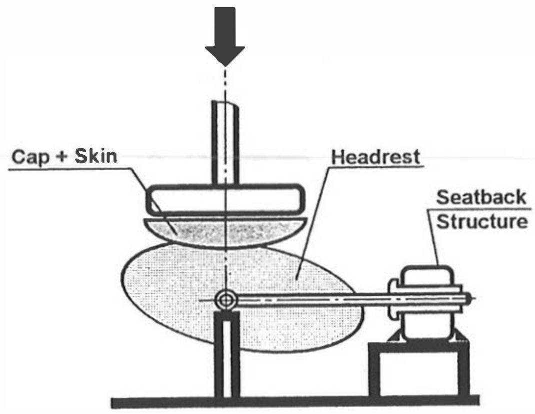


Figure 12-a : Car test acceleration pulse for 15 km/h

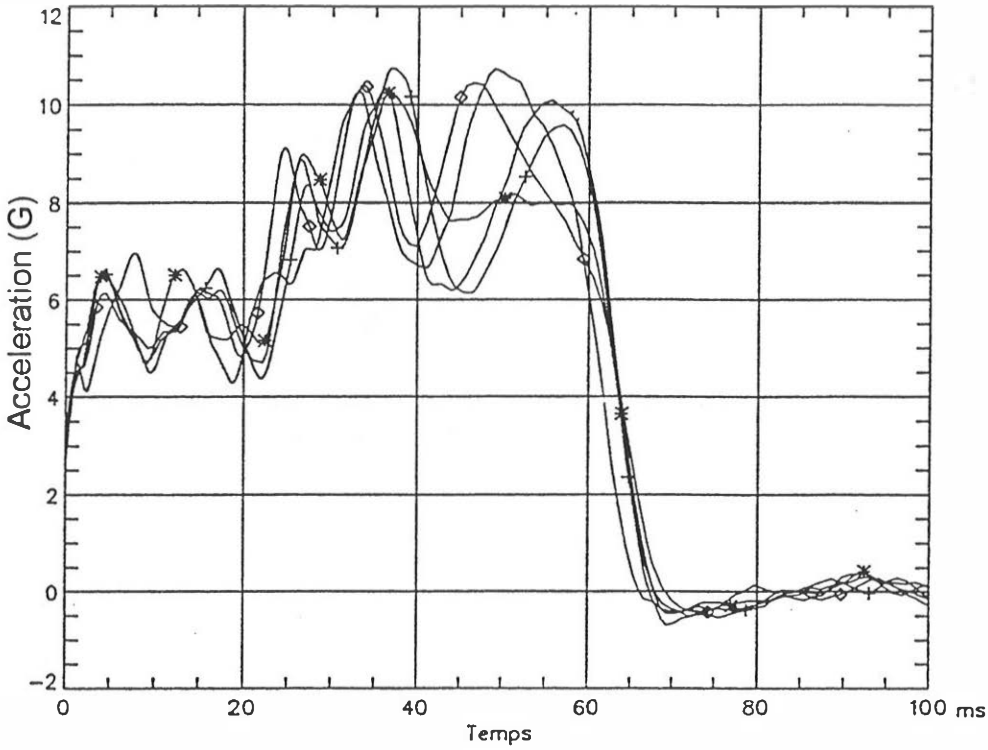


Figure 12-b : Initial configuration of sled model

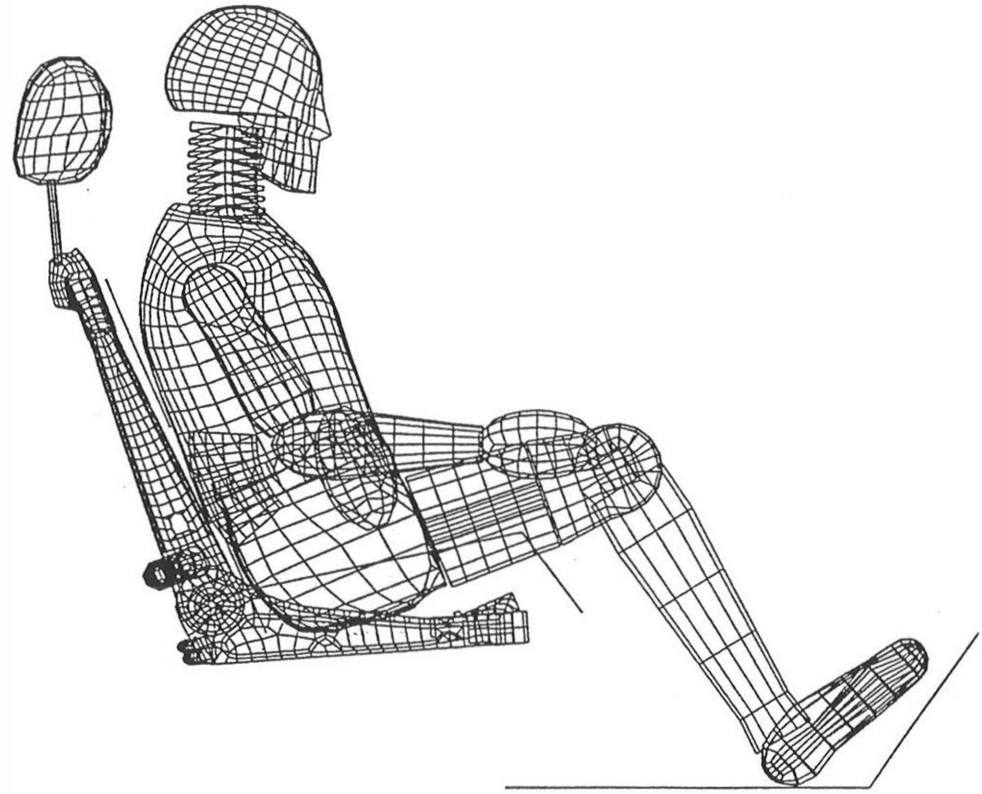


Figure 13 (a) : Comparison of calculated results with measurements for a 15 km/h sled test without headrest
A : with global seat back model
B : with advanced global seat back model
C : test measurement

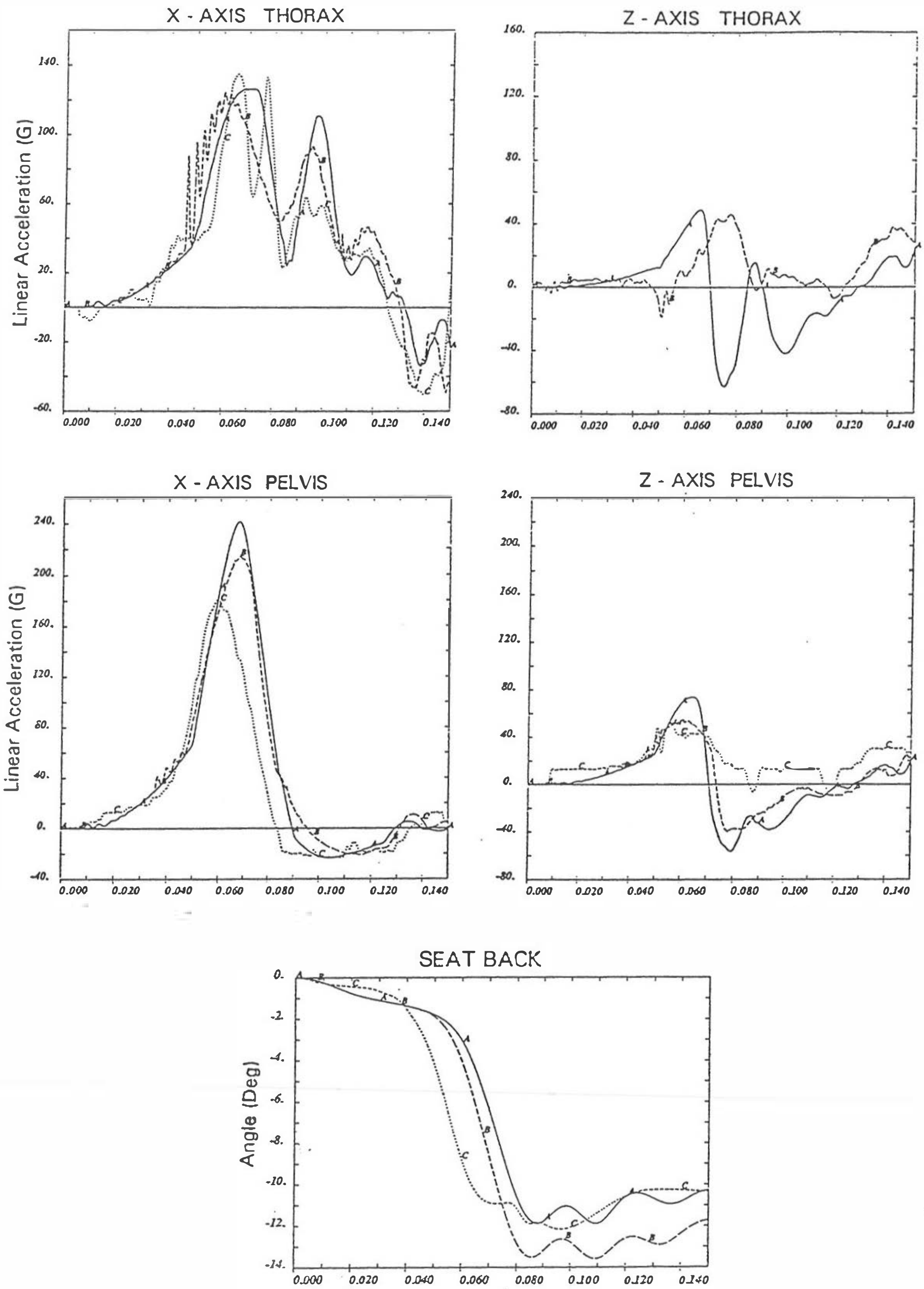
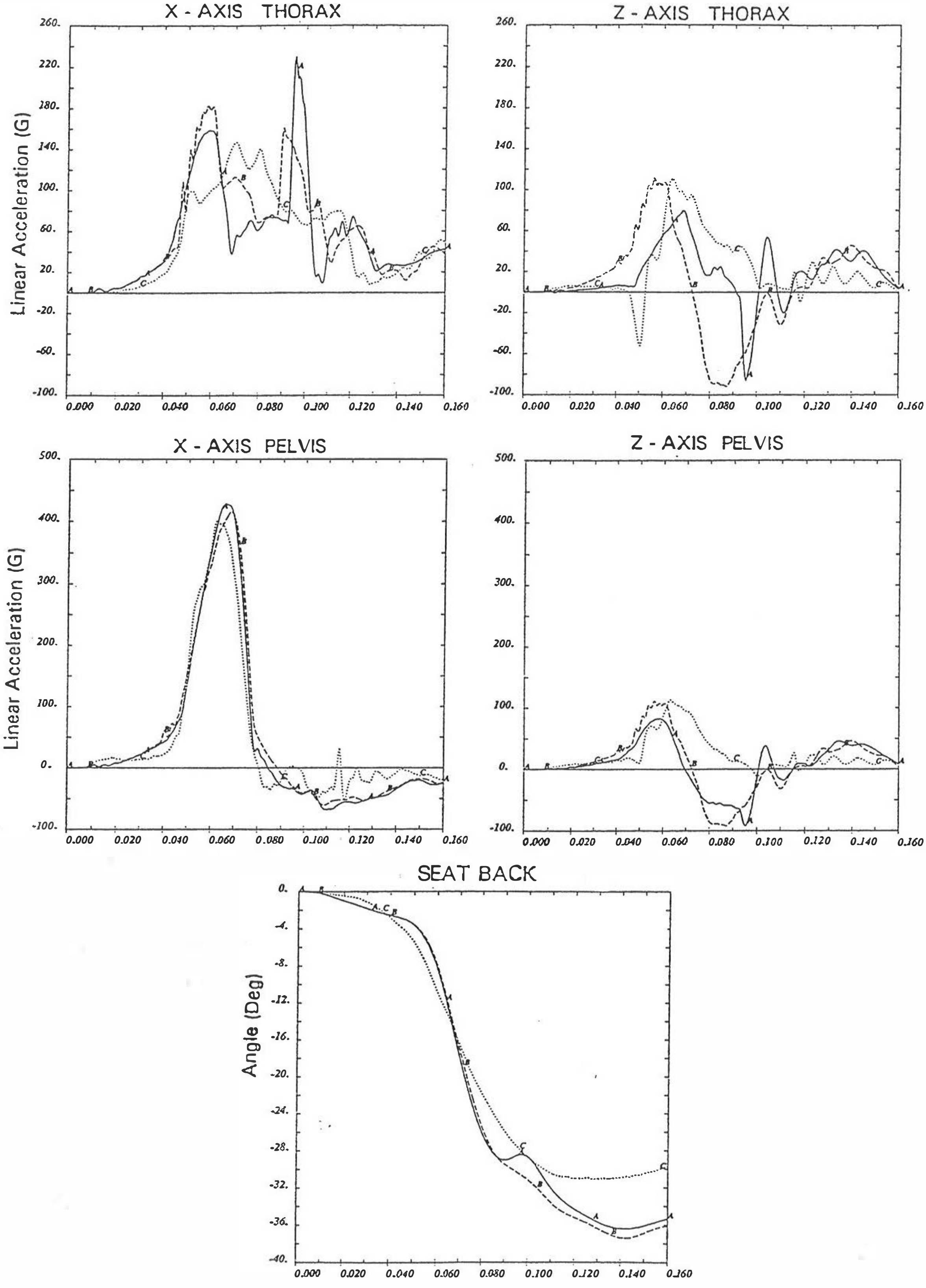


Figure 13 (b) : Comparison of calculated results with measurements for a 28 km/h sled test with headrest

A : with global seat back model

B : with advanced global seat back model

C : test measurement



objective was to access the reliability of the two types of model for representing the behaviour of occupant/seatback interactions and not for seeking an exact mathematical representation of the physical seatback used. The model can be used for a qualitative evaluation of different design parameter influences.

DESIGN PARAMETER INFLUENCES

The absence of dispersion of results given by a mathematical model makes it a good tool for evaluating design parameter influences, especially for low velocity impact where measurement dispersions appear more often in experimental tests. Otherwise the low cost of a numerical test also allows the examination of a design parameter taking into account its interactions with other parameters, whereas the same approach would be expensive using experimental tests and difficult to be analysed because of result dispersions.

TEST MATRIX

The following parameters, which represent the major orientations for the improvement of seatback design, were chosen in this study and for each parameter two modes were applied :

Seatback joint stiffness (K-joint) : Figure 14 shows the two stiffness curves used. The constant yielding form was chosen which is a simplified but representative description of the seatback joint stiffness for most of production cars. The yielding level is respectively 700 N.m and 1700 N.m.

Upper seatback stiffness (K-upper) : Two seatback frame stiffnesses were used, 350 N/cm for "stiff" one and 87.5 N/cm for "soft" one.

Lower seatback stiffness (K-lower) : Figure 15 shows the two seatback frame stiffness curves applied.

Horizontal distance between headrest and head (D-x) : The headrest was placed 5 cm and 10 cm from the head.

Figure 14 : K-joint modes

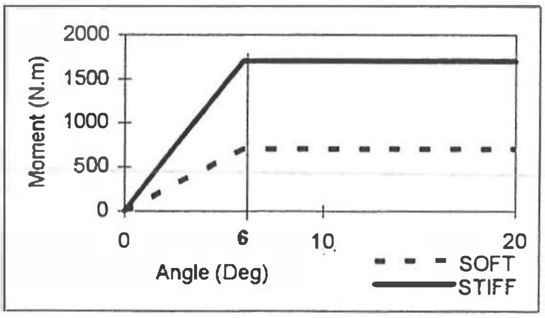
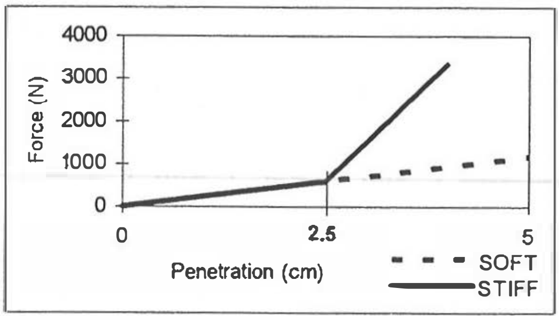


Figure 15 : K-lower modes



A simulation matrix (table 1) was constructed by using the experiment design method, which allows analysis not only of the influence of a single design parameter change for a particular configuration, but also of its interactions with other parameters.

RESULTS AND ANALYSIS

The car acceleration pulse used for this study is the same as that of the validation tests with a 15 km/h velocity change (Fig.12-a). Five output variables were chosen as neck injury risk indicator :

1) the moment force at the occipital condyle joint (My-sup).
2) the shear force at the occipital condyle joint (Fx-sup).
3) the moment force at the C7/T1 joint (My-inf).
4) the shear force at the C7/T1 joint (Fx-inf).
5) the head-torso extension angle (Head Angle).

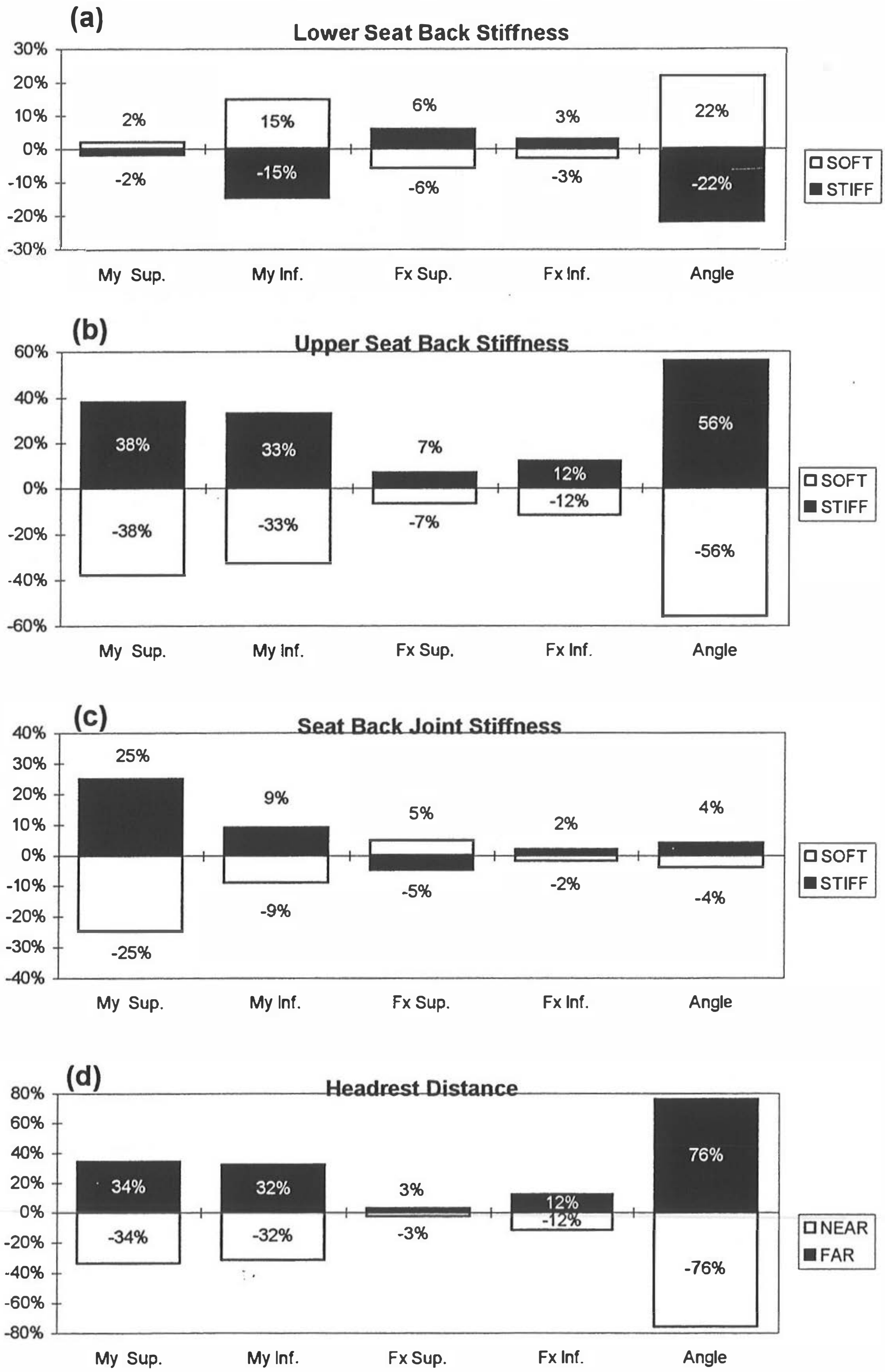
The results of the simulation tests are given in table 1. The influences of these four parameters were analysed by using the experiment design method.

Table 1: Simulation matrix and results (SI unit)

	K-joint	D-x	K-lower	K-upper	Head Angle	My-inf	Fx-inf	My-sup	Fx-sup
Test 1	Soft	Near	Soft	Soft	0	9	222	9	177
Test 2	Soft	Near	Soft	Stiff	8	18	337	12	289
Test 3	Soft	Near	Stiff	Soft	0	5	294	3	300
Test 4	Soft	Near	Stiff	Stiff	0	11	335	5	320
Test 5	Soft	Far	Soft	Soft	20	18	289	7	235
Test 6	Soft	Far	Soft	Stiff	29	24	403	15	324
Test 7	Soft	Far	Stiff	Soft	16	12	283	6	258
Test 8	Soft	Far	Stiff	Stiff	22	16	357	13	262
Test 9	Stiff	Near	Soft	Soft	0	5	209	0	202
Test 10	Stiff	Near	Soft	Stiff	12	18	293	14	232
Test 11	Stiff	Near	Stiff	Soft	0	4	209	0	235
Test 12	Stiff	Near	Stiff	Stiff	5	15	347	19	256
Test 13	Stiff	Far	Soft	Soft	6	16	327	13	209
Test 14	Stiff	Far	Soft	Stiff	45	35	402	26	263
Test 15	Stiff	Far	Stiff	Soft	3	14	418	20	294
Test 16	Stiff	Far	Stiff	Stiff	31	28	389	25	272

Figure 16 shows average influences of the four design parameters on the neck response. The influences are quantified by measuring the variation of the average response between a mode of the examined parameter and the general average of all tests.

Figure 16 : Average influences of different design parameters on the neck responses taking into account their interactions



Upper seatback stiffness (K-upper) influences : Figure 16-b shows its average influences. We can see that softening of the upper seatback allows reduction of all injury risk indicators. This tendency is present in all test configurations. The only exception is about the shear forces of the neck when the lower seatback and the seatback joint are stiff, and the headrest is far from the head (test 15/test 16). Benefits of such a softening on the neck protection are comparable to those of the headrest-head distance reduction.

Lower seatback stiffness (K-lower) influences : Figure 16-a shows its average influences. It can be seen that softening of the lower seatback increases the head-torso extension angle and the moment force at the C7/T1 joint. This tendency can be verified for all test configurations. Nevertheless the influences on My sup, Fx sup and Fx inf depend on the other three design parameter configurations.

Seatback joint stiffness (K-joint) influences : Figure 16-c shows its average influences. It is to be noted that the influences of the parameter depend closely on the seatback stiffness and the head-headrest distance used. It is impossible to draw general conclusions for this parameter. Nevertheless for the test configuration where the high upper seatback stiffness (corresponding to the classical upper seatback structure) is used, we can observe that stiffening the joint increases the head-thorax extension angle and the moment loading of the neck.

Head-headrest Distance (D-x) influences : Figure 16-d shows its average influences. It confirms the well known benefits of reducing the distance.

By means of variance analysis, the significant parameter changes, for a given criterion, were determined. Table 2 summarises these parameter changes. It can be observed that only My inf is significantly affected by all parameters.

Table 2 : Significant parameter changes

Criterion	Very Significant	Significant
My Sup.	K-upper D-x	K-joint interaction K-joint/D-x
My Inf.	K-upper D-x K-lower interaction K-joint/K-upper	interaction K-joint/D-x K-joint
Fx Sup.		K-upper
Fx Inf.		D-x K-upper
Head Angle	D-x K-upper	interaction K-joint/K-upper interaction D-x/K-upper

DISCUSSION

The above conclusions are drawn for a 15 km/h impact velocity change and for the undertaken parameter variations. The high headrest used in these simulations didn't take into account the rolling of the head over a headrest, which may result from occupant ramping up the seatback when the headrest is low.

The occupant model used in this study is that of the Hybrid-III dummy. Compared to the human thoracic and lumbar spine, that of the dummy is too stiff and in consequence it's interaction with the seatback is probably different to that of the human torso. This can limit the validity of the results obtained with this dummy. Nevertheless it is not unreasonable to assume that this biofidelity limit does not modify the general tendencies of the occupant response obtained with the dummy.

The experiment design method was used in this study in order that the influences of a parameter might be analysed taking into account it's interactions with others parameters. The simulation results demonstrate well the importance of such an analysis. Influences of the seatback joints stiffness, for example, depend closely on the upper and lower seatback stiffnesses and the head-headrest distance used. Conclusion drawn from a test configuration could be false for another.

The simulation results demonstrate that softening of the upper seatback allows reduction of all injury risk indicators. Obviously, for obtaining the benefits, the change of the upper seatback stiffness should not result in the increase of the distance between the head and the headrest during impact.

The significant influences of the head-headrest distance on the neck response, already well demonstrated by experimental tests (e.g. Foret-Bruno et al.,1991, Svensson, 1993), can be observed with the simulation results. Softening the upper seatback enhances considerably the headrest protection performance.

Svensson (1993) reported that increased stiffness of the seatback joint results in slightly increased maximum head-torso extension. This tendency can be seen in most of interaction cases with the simulation results. Nevertheless the inverse tendency can be observed when the upper seatback is soft and the headrest is far from the head (test 5/test 13 and test 7/test 15).

The simulation results demonstrate that in all test configurations stiffening of the lower seatback leads to the reduction of the head-torso extension angle. This conclusion is consistent with the results of two comparative experimental tests conducted by Svensson (1993).

CONCLUSIONS

A mathematical approach of rear impact was developed and then used to analyse some important seatback design parameters.

In this approach, the human neck behaviour was simulated by a muti-segment model, constructed on the basis of the RID-neck and of two existing biomechanical data sources - the neck corridor of Mertz and the volunteer test results of Tarriere.

Two types of seatback model were constructed for modelling the interactions between occupant and seatback. Static and dynamic tests were conducted for their validation. Both models, defined on the basis of quasi-static test data and without recall to parameter tuning, give results similar to those of the corresponding tests. The advanced model gives better results and allows a more precise representation of the seatback.

Four important design parameters - head to headrest distance, seatback joint stiffness, upper and lower seatback stiffnesses - were analysed by means of the model developed. The experiment design method was applied in this analysis in order to study the influences of these parameters taking into account their interactions. For a 15 km/h impact velocity change and in the range of the undertaken parameter variations, the following conclusions can be drawn :

-Softening of the upper seatback allows reduction of all neck injury risk indicators and enhances the headrest performance.

-Softening of the lower seatback increases the head-torso extension angle and the moment force at the C7/T1 joint.

-For a classical upper seatback structure, stiffening of the seatback joint aggravates the moment loading of the neck and the head-torso extension angle.

-Only the moment force at the C7/T1 joint is significantly affected by all parameter changes.

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