STRUCTURE AND PADDING OPTIMISATION FOR SIDE IMPACT PROTECTION

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ABSTRACT

This paper aims to show methods to design and optimise vehicle side structure and padding to improve side impact protection.

To limit injuries at thorax level, intrusion profile during impact must perform a negative vertical tilt: a way to obtain this is to avoid B pillar deforming above R point. A static analysis may be useful to determine a proper distribution along B pillar axis of sections' moments of inertia.

A good structural behaviour is necessary but not sufficient to perform good results in side impact. A proper control of padding stiffness is very important especially for abdomen protection.

A method to evaluate the stiffness of padding at thorax level is proposed. A similar method is used to determine failure load of armrest for abdomen protection.

INTRODUCTION

European side-impact test regulation, which is going to be compulsory from 1st October 1998, has become popular due to EURO-NCAP safety rating. This one asks for heavy requirements especially for thorax and abdomen protection. Is it possible to comply with them in standard cars, for the benefit of all customers, and without adopting a side-bag, which has got very high development costs?

Some production vehicles with bio-mechanical values near to Euro-NCAP requirements already exist, but this happens only under very precise conditions and several parameters must be taken into account.

PARAMETERS AFFECTING PERFORMANCE.

It is well known from literature that an intrusion profile which shows a negative vertical tilt is the best one to comply with regulation requirements ([1], [2], [3], [7],[14]) while padding behaviour must be controlled properly ([4], [5], [6], [8], [9], [10], [11], [12], [13]).

The effect of the first one is to reduce side intrusion speed, relative to the thorax, both by limiting the deformation at thorax level and by favouring the intrusion at pelvis level to push the dummy away from the side.

The effect of the second one is to limit acceleration of the ribs and load on abdomen.

Using MADYMO software and DOE technique it is possible to show what are the most important parameters on the performance.

A MADYMO model was generated and correlated to a crash test. Three factors were considered with a variation range as detailed below:

- upper door velocity: between the baseline intruding velocity profile and a profile which includes a reduction of 5 m/s on the first peak (Figure 1);

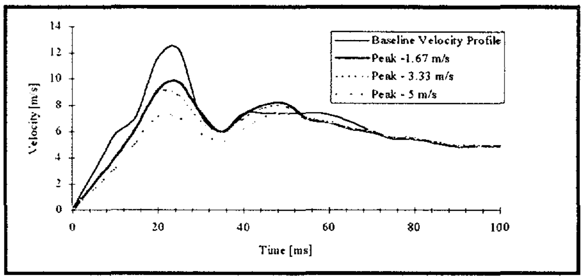

Figure 1. Velocity profiles used in the study.

- upper door stiffness: between 80 kN/m and 40 kN/m (Figure 2);

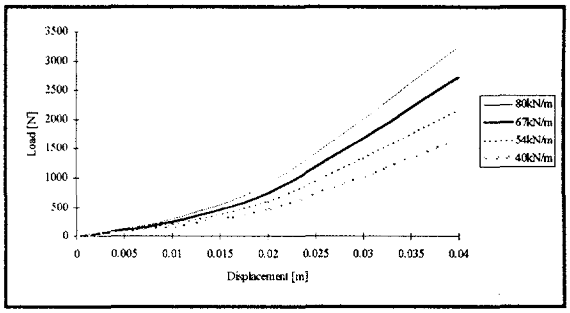

Figure 2. Upper door stiffness characteristics

- Lower distance from the occupant: from the baseline correlated position to 100 mm closer to occupant (Figure 3).

The experimental matrix that was generated is shown in Table 1. Table 1 shows also the results on middle rib (other ribs have similar behaviour). Results on abdomen are meaningless because of correlation problems and a parametric analysis can't be done.

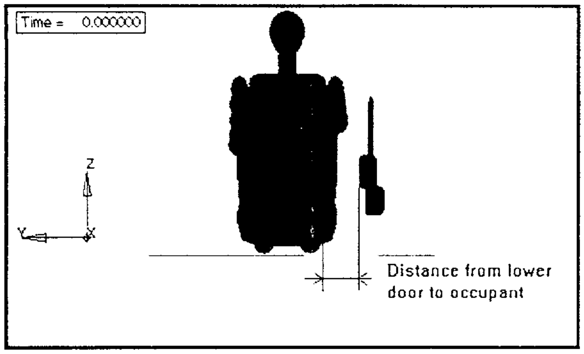

Figure3. Lower door position geometry

Table 1.
Simulation Matrix and results
Note[1] : Value is reduction in the first peak (m/s)
Note[2] : Value is movement closer to the occupant (mm)

Simu-lation	Upper Door Stiff. (kN/m)	Upper Door Velo-city Profile [1]	Dist. lower Door to Occu-pant [2]	Mid Rib Def. [mm]	Mid Rib VC [m/s]
Base-line	80	0	0	36	0.47
C1	80	-5	66	5	0.01
C2	54	-5	0	4	0.02
C3	54	0	100	29	0.25
C4	67	-5	100	4	0.01
C5	80	-3.3	100	16	0.17
C6	54	-3.3	66	10	0.06
C7	40	-5	100	5	0.02
C8	67	-3.3	33	14	0.1
C9	80	-1.67	0	26	0.3
C10	80	0	0	36	0.47
C11	40	-3.3	0	20	0.2
C12	40	0	66	14	0.09
C13	80	-5	100	3	0.01
C14	67	0	0	36	0.42
C15	80	0	100	26	0.23
C16	40	0	0	28	0.35
C17	67	-1.67	66	9	0.05
C18	80	0	33	20	0.23
C19	54	-1.67	33	15	0.12
C20	80	-5	0	4	0.01
C21	40	-5	33	5	0.02
C22	40	-5	0	7	0.04
C23	40	-1.67	100	22	0.22
C24	40	0	100	30	0.23
C25	67	0	66	14	0.11

The results show that varying upper door trim stiffness from 80 kN/m to 40 kN/m. VC and rib deflection don't vary so much while upper door velocity profile (i.e. impact speed against thorax) and lower door position level have got main effects. This can be seen in Figures 4 and 5 for middle rib deflection and VC. The lower door position has a non-linear effect on the lower rib deflection, with the minimum injury criteria reached when the position in about 50 mm closer to the occupant.

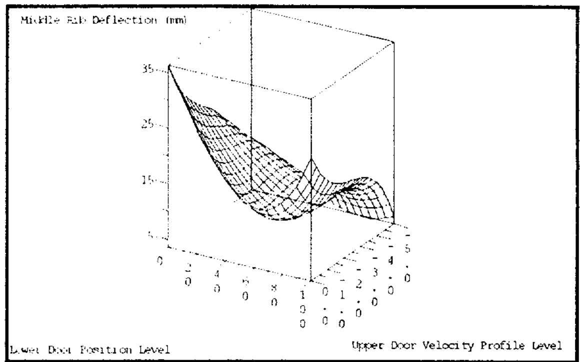

Figure 4. Middle rib deflection: upper door velocity profile level versus lower door position level for middle rib.

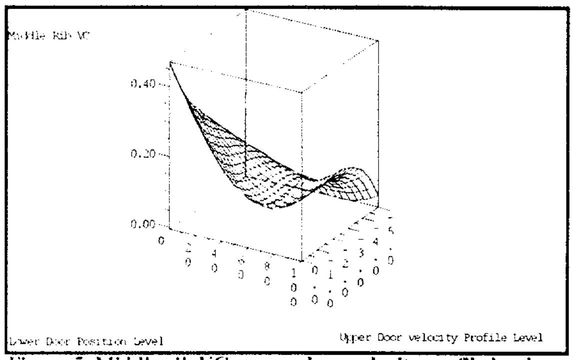

Figure 5. Middle rib VC: upper door velocity profile level versus lower door position level for middle rib.

The upper door velocity profiles should be minimised to further reduce the response results.

Other ribs has got similar behaviour even if the described effect are not the same for all of them because of kinematics effects (for example for a trim with higher stiffness the kinematics show more rotation of the dummies arm across the body and away from the door than a lower stiffness trim).

Let's analyse deeper the effect of lower door distance to occupant. If we consider speed of door relative to ribs' one at the impact time and the difference between contact times against pelvis and thorax it is possible to fill Table 2. It can be seen that the minimum values of rib deflection and VC correspond to a Δv of about 6 m/s and to a Δt of about 10 ms.

Table 2. Relation between contact times, impact speed and bio-mechanical results (MADYMO analysis)

Simu-lation	Contact times [ms]		Speed at t_2 [ms] ([1] average)		Δt (t_2-t_1)	Δv (v_2-v_1)	Results on ribs (average)	
	Pelv (t_1)	Thor (t_2)	Rib[1] (v_1)	Door (v_2)			Defl [mm]	VC [m/s]
Baseline	24	28	0.1	8.26	4	8.16	38	0.6
33 mm closer	22	28	0.1	8.26	6	8.16	22	0.32
66 mm closer	20	30	1.25	7.5	10	6.25	16	0.16
100 mm closer	14	30	0.98	7.5	16	6.52	28	0.3

This confirms that to obtain good results on thorax pelvis must be hit before than the thorax in order to push away dummy from the intruding side. But if this Δt is higher than 10 ms, kinematics of dummy may worsen results: this will be confirmed on experimental basis and related to the intrusion profile.

As final comment although results on abdomen were meaningless, nevertheless it is evident that armrest must have an influence on abdomen performance: this will be seen on experimental basis.

INTRUSION PROFILE

Several papers deal with the deformation of side structure ([1], [2], [3], [7], [14]) and do confirm the short study described before: it comes out that the most appropriate intrusion profile has a low intrusion at thorax level and a higher intrusion at pelvis level. The relation between biomechanical performance and intrusion profile can be seen comparing two production vehicles in their two doors and four doors versions.

To make such a comparison an *INTRUSION PROFILE INDEX (I.P.I.)* has been defined (see Appendix 1): it says how near real profile is to the theoretical one: theoretical profile is defined as the profile coming from the rigid rotation of side structure around an axis along superior sill for a given intrusion at pelvis level. IPI can be dynamic (measured through accelerometers on the struck side as described in [3]) or static (measured at the end of test). In the following it will be referred to dynamic IPI evaluated ad the time of the first impact, generally against pelvis.

Table 3 shows the relation between IPI and bio-mechanical performance in the said cars.

It is clear that a dynamic IPI of at least 60% on the door must be reached in order to obtain a Δv lower then 10 m/s. With such values good bio-mechanical results look like to be easily achieved. In four doors cars, where B pillar can interfere with dummy, also a dynamic IPI of at least 60% to 80% must be guaranteed and maintained during the whole impact.

Table 3. Relation between contact times, impact speed, intrusion profile and bio-mechanical results (experimental analysis)
Note[1]: differences in time and in speed as defined before for table 2.

Vehicle	Rib values (average)		Forces [kN]		Dynamic IPI		Δt^1 [ms]	Δv^1 [m/s]
	Defl. [mm]	VC [mm]	Abd.	PSF	Door	B pillar		
A 4 doors	31	0.8	1.7	3	50%	80%	3	12
A 2 doors	26	0.4	2.1	4	95%	-	10	7.4
B 4 doors	35	0.5	2.2	3	60%	60%	6	10
B 2 doors	19	0.2	1.5	4.3	60%	-	10	5.8

In a two doors car dynamic IPI is mainly related to inertial effects of the door ([1]), while in a four doors car general intrusion profile is related to structural stability of B pillar.

Through FEM analysis ([7]) it can be seen that during crash MDB transfers momentum through the doors to B pillar. In particular rearward door charges it through its hinges: if load through lower hinge favours appropriate intrusion profile, load through upper hinge can make B pillar unstable. These two loads can be considered concentrated in two points (the hinges), and the load through the upper hinge is the worst one.

Loading quasi-statically at upper hinge level B pillars of several production vehicles It could be stated that this very simple loading condition is able to put in evidence structural instabilities that can occur during dynamic impact.

This is a very helpful and easy way of designing B pillar correctly from the very early stages of project, much before FEM analysis of side impact can be performed, as many details of the structure don't need to be known.

In the followings the develeped method to characterise B pillar will be described. Both experimental and mathematical analysis can be performed.

- B pillar can be isolated and constrained and loaded as shown in Figure 7;
- measurements of intrusions at roof level, R point level and 390 mm higher, are taken through potentiometers (Figure 7);
- *I.P.I.* in respect of R point intrusion can be evaluated: just the first 50 mm of intrusion are enough to establish local plastic hinges (Figure 8).

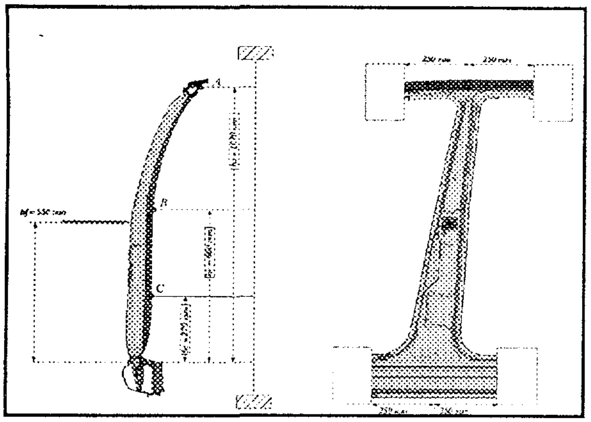

Figure 7. Example of constraining and loading of a B pillar.

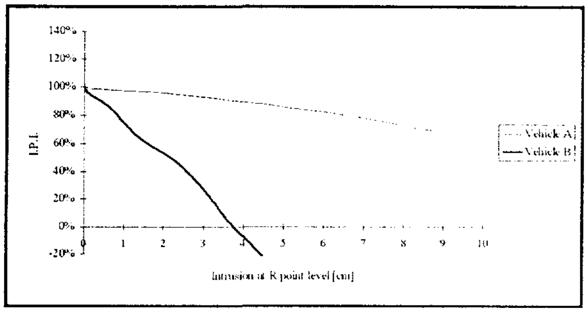

Figure 8. Example of IPI calculated on the basis of a quasi-static loading (FEM analysis).

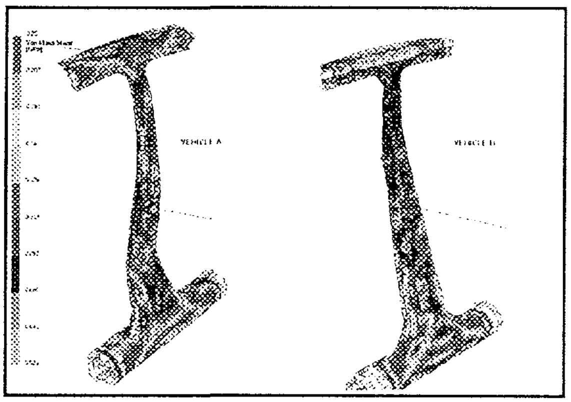

Figure 9. Comparison between the deformations of the B pillars of two vehicle after a quasi-static loading.

Figure 9 shows the comparison of deformations of B pillars of two production vehicles when loaded quasi-statically (FEM analysis). When the deformation is good for side impact protection then the main plastic hinge occurs below R point level (vehicle A). Possible problems may occur when there is a plastic hinge at higher level (vehicle B). IPI detects very well the two situations (Figure 8): in fact IPI for vehicle B decrease quickly, while for vehicle A it is much more stable.

Figure 10 shows the real deformation after a crash test for the vehicle B: plastic hinge is in the place where the quasi-static analysis found it.

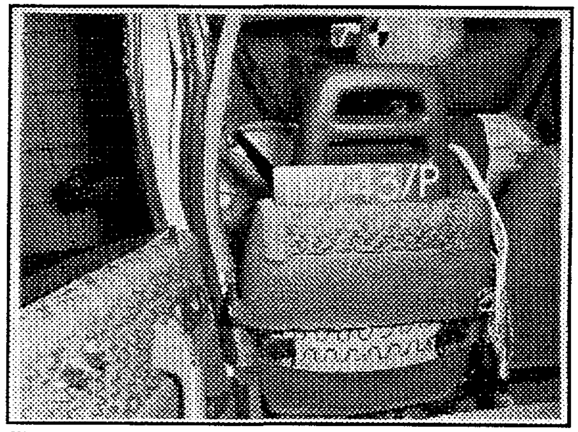

Figure 10. B pillar deformation after a crash test: the upper plastic hinge has been correctly detected through quasi-static analysis

As we are looking for possible instabilities of B pillar when loaded in the described way, a linear analysis can be performed: a simplified method using arch beams theory and few geometrical information has been developed in order to find the most critical sections.

B pillar is considered as a two hinges arch and the problem is considered plane: because of this it is possible to use equations coming from static; even if these are hard hypotheses, if the pillar is designed for this case it will deform in the desired way in the static test. Nevertheless some corrective factors must be introduced to take into account that constraints aren't perfect hinges.

Then bending moments (M) distribution along the pillar can be found and, dividing it by the inertia module (W), the tension distribution can be calculated.

Comparison between tension distribution calculated in such a way and the same calculated via FE models show good agreement (Figures 11 and 12).

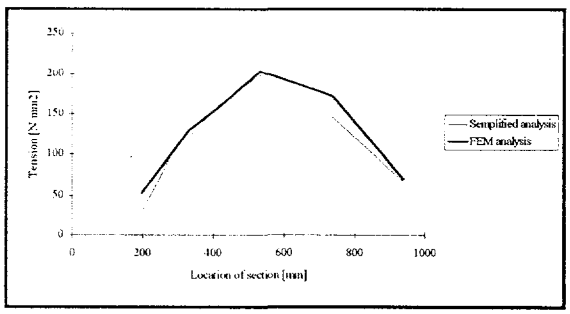

Figure 11. Tension distribution along the beam calculated via simplified analysis and via FEM analysis for B pillar of vehicle A.

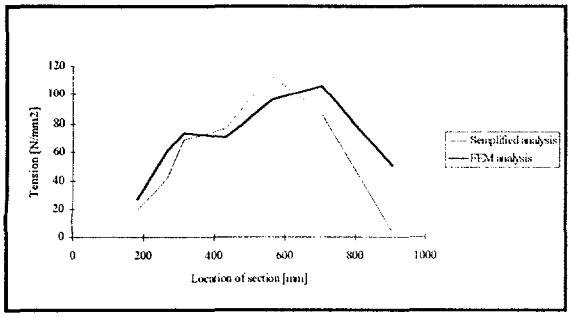

Figure 11. Tension distribution along the beam calculated via simplified analysis and via FEM analysis for B pillar of vehicle B.

Instabilities of B pillar pointed out by simplified analysis are in the sections where M/W is maximum. Then the following design criteria can be expressed:

- critical section where instability occurs must be located under R point level;
- alternatively, stress (M/W) in critical section must be higher then yield stress, while in other sections (i.e. upper then R point level) it must be lower.

This method is useful in the very early stages of design when only the style concept of a new project is available and main dimensions have to be determined.

The same can be applied to a two doors vehicle in order to have a good intrusion profile of bc pillar, being this important mainly for protection of backward occupants: the loading point, anyway, must be considered at 200 mm higher then R point level.

PADDING CHARACTERISTICS

Several papers deal with padding stiffness ([4], [5], [6], [8], [9], [10], [11], [12], [13]) and with methods to evaluate it, but they generally refer it to FMVSS214.

DOE study demonstrated that bio-mechanical parameters at thorax level aren't very much affected by padding stiffness. In [12] and [13] indications of padding stiffness for thorax protection are present and were used to define a specification for side trim panels.

For abdomen protection a correlation between collapse force of armrest and force values measured in side impact tests was found (see table 3).

Table 4. Comparison between failure load of armrest and abdomen force in side impact test.

Vehicle	Failure load at armrest [kN]	Abdomen force in side-impact test [kN]
A	2.5	1.7
B	2.8	2.1
C	3.3	2.3

In this paragraph an experimental method to characterise side trim panels will be described. It will be shown also how a side panel designed to comply with certain specifications will affect bio-mechanical performance.

Let's define *thorax area* the very area hit by the ribs of an Euro-SID, when it is installed in car as defined by regulation and the seat is moved through all its possible positions. In [12] and [13] for a range of 60 to 100 kN/m stiffness was investigated in such an area. To evaluate stiffness of a real panel the following method was developed in FIAT.

A rib-form with the shape of an Euro-SID (i.e. 120 mm × 40 mm) was built and mounted on a trolley suitable to the MTS machine for Body Block test. The mass of the whole trolley and rib-form was 4.3 kg (see Figure 12 and 13).

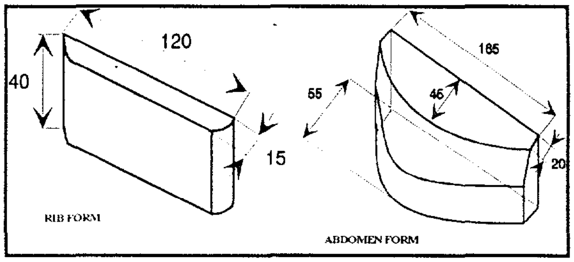

Figure 12. Dimensions of used forms.

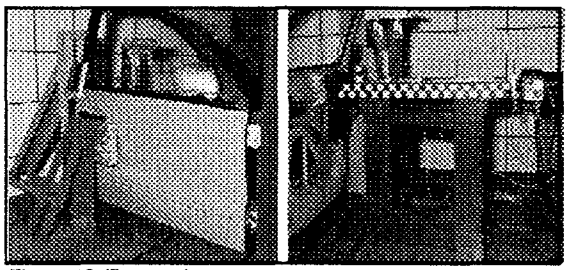

Figure 13. Test equipment.

The form was thrown against the door rigidly mounted through its hinges and latch. Some other constraints are put in order to limit deflection of the door itself. The speed was specified at 24.1 km/h like in the partial test of Regulation, but a range between 20 and 24 km/h was accepted for practical reasons.

The deceleration of the form was measured and used to determine an average stiffness which is related both to door and padding; this was done transforming deceleration results in global parameters like force and energy. By these two quantities it is possible to calculate an average stiffness, sample by sample, using the simple relations of a linear spring, i.e.

$$F = k \times X \quad \text{and} \quad E = \tfrac{1}{2}\, k \times X^2$$

then

$$k = \tfrac{1}{2}\, F^2 / E.$$

The maximum value obtained can be considered as the searched value.

Several tests on production panels were performed and values from 60 kN/m to 290 kN/m were found. The highest values were generally found at the fixation points of the panel to the door structure, while the lowest values correspond to the most flexible panels.

Drawing a graph Force vs. Energy, several typical results can be compared (see Figure 14).

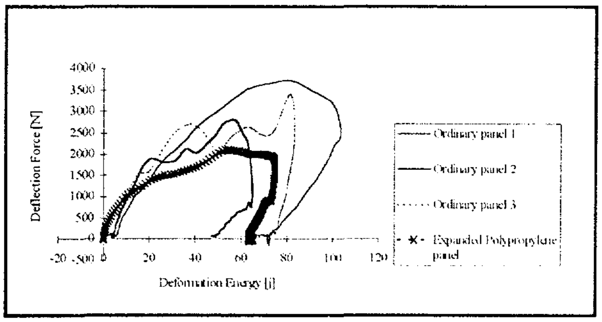

Figure 14. Panel characteristic at thorax level: comparison between current production side panels and Expanded Polypropylene panel.

A similar method was used to determine collapse force of armrest. For this a different form was used, to reproduce abdomen shape (see Figure 12). Measured deceleration is used to calculate a force vs. form's displacement. Several panels were tested and a range from 1.8 kN to 3.7 kN was found (see Table 4 and Figure 15).

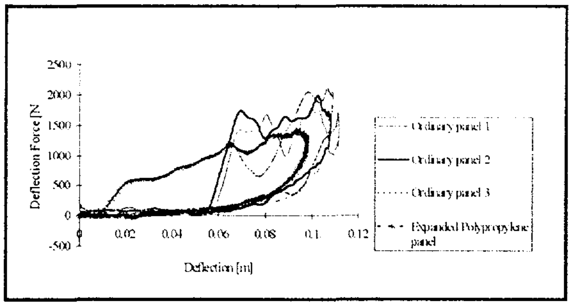

Figure 14. Panel characteristic at abdomen level (armrest): comparison between current production side panels and Expanded Polypropylene panel.

Using the said methods several absorbing materials were tested too. After a proposal from ADLER-PLASTICS® a prototype panel, entirely made with expanded polypropylene, was built. The chosen density was 20 g/l and the thickness at thorax level was 50 mm with internal gaps to reach a global stiffness of 40 kN/m, which is about 25% of the average measured stiffness (see Figure 14).

Finally a maximum force of 1.4 kN was measured at the armrest (see Figure 15).

The same kind of panel was used to perform a full scale side impact test using a production car. The results are summarised in table 5 against standard car.

Table 5. Results of side impact crashes with standard and prototype door panels.

Panel	HPC	Rib deflection [mm]		Rib VC [m/s]		Force [kN]	
		Min.	Max.	Min.	Max.	Abd.	Pelv.
Stand.	300	29	33	0.7	0.9	1.7	3.1
Proto.	340	38	43	1.04	1.16	0.98	3.8

It can be seen a general worsening of thorax performance. This is coherent with the parametric analysis: in fact panel stiffness didn't improve the performance and a slight difference in impact speed worsened it.

Abdomen force was very much reduced by the use of a very soft armrest: a maximum failure load of 1.4 kN must be guaranteed in order to have abdominal force lower than 1 kN in the crash test.

Pelvis and head performance changed within experimental variability.

CONCLUSIONS

An analytical study supported by experimental evidence and by laboratory tests demonstrated that the main parameters which influence bio-mechanical performance in side-impacts are upper door velocity against thorax, lower distance from occupant (pelvis level) and failure load of armrest. Upper door stiffness doesn't appear as an important parameter.

Upper door velocity is influenced by structural behaviour of B pillar (in four door cars): a design specification for B pillar has been developed applying simple static analysis in order to guarantee stability of B pillar during impact.

Lower distance to occupant at pelvis level must be reduced by at least 50 mm, in respect to standard geometry, to achieve good performance at thorax level: this is an important item for design preliminary work. Use of foams and other absorbing materials should be validated.

An experimental methodology for characterisation of trim stiffness has been proposed. At abdomen level failure load of armrest can be measured: it comes out that door armrest must be designed to guarantee a maximum failure load of 1.4 kN to obtain a maximum abdomen load of less than 1 kN in side-impact crash.

At thorax level proposed test is very sensitive to change in stiffness of the panel but it shows poor correlation with side impact test results. This could means that methodology must be improved.

AKNOWLEDGMENTS

Author would like to thank ADLER-PLASTICS® for the help for the support given in defining the proper characteristics of the tested panels.

APPENDIX: INTRUSION PROFILE INDEX

To measure intrusion profile an *INTRUSION PROFILE INDEX (I.P.I.)* has been defined: it says how near is real profile to the theoretical one; theoretical profile is defined as the profile coming from the rigid rotation of B pillar around superior sill for a given intrusion at pelvis level.

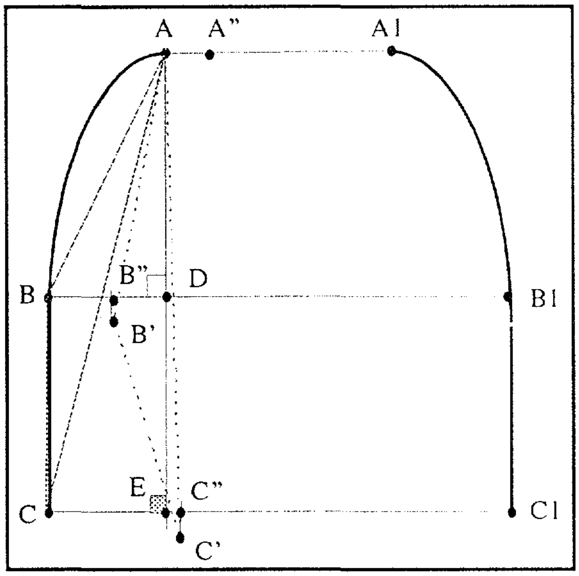

Figure A1. Sketch for definition of IPI.

Refer to Figure A1 where:

AA_1 = roof width before crash;
BB_1 = internal width at thorax level before crash;
CC_1 = internal width at R point level before crash;
$A"A_1$ = roof width after crash;
$B"B_1$ = internal width at thorax level after crash;
$C"C_1$ = internal width at R point level after crash.

Theoretical intrusion profile is obtained through rigid rotation of triangle ABC around A when C moves inward as much as in the crash test. With trigonometry it is possible to calculate how B moves inward in a theoretical profile. Then real B" position relative to B_1 and the theoretical one $B"_t$ can be compared. For mathematical reasons it is better to refer to the areas of polygons $AB"_tC"C_1B_1A_1$ and $A"B"_tC"C_1B_1A_1$. The ratio of these two areas is the desired IPI.

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