OPTIMISATION OF SIDE STRUCTURE AND SIDE PADDING OF A PASSENGER CAR WITH THE AID OF MATHEMATICAL AND EXPERIMENTAL SIMULATION

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ABSTRACT

Side structure stiffness and side padding characteristics are optimised with the aid of a mathematical simulation model for the side-on vehicle-to-vehicle collision. The relation between the optimum side padding characteristics and the side structure stiffness is determined on the basis of a defined combination of test conditions. The results are formulated in terms of a design concept, and the effectiveness of this concept for occupant protection is investigated in crash tests.

INTRODUCTION

Occupant protection in a side-on collision is influenced to a very great extent by two parameters: the stiffness of the side structure relative to the stiffness of the impacting body, and the deformation characteristics of the side padding. Both parameters can be optimised in such a way as to give minimum occupant loading, in which case the optimum padding stiffness is a function of the stiffness of the side structure.

The following contribution describes a theoretical optimisation of both parameters with the aid of a mathematical simulation model. The results are formulated into terms of a design concept. A modified vehicle is constructed with a stiffened side structure and optimised padding in the pelvis impact area, and the vehicle is crash tested. The test results are compared with those for the corresponding crash test for the standard production vehicle. The benefit of these improvements is shown as a reduction in structural deformation and the loadings to which the occupants are subjected.

THEORETICAL INVESTIGATION

The theoretical analysis provides information regarding the optimum degrees of stiffness for the side structure and side padding, and their functional interrelationship. The analysis is conducted using the simulation model shown in Fig.1. Refer to /1/ and /2/ for a more detailed description of the model.

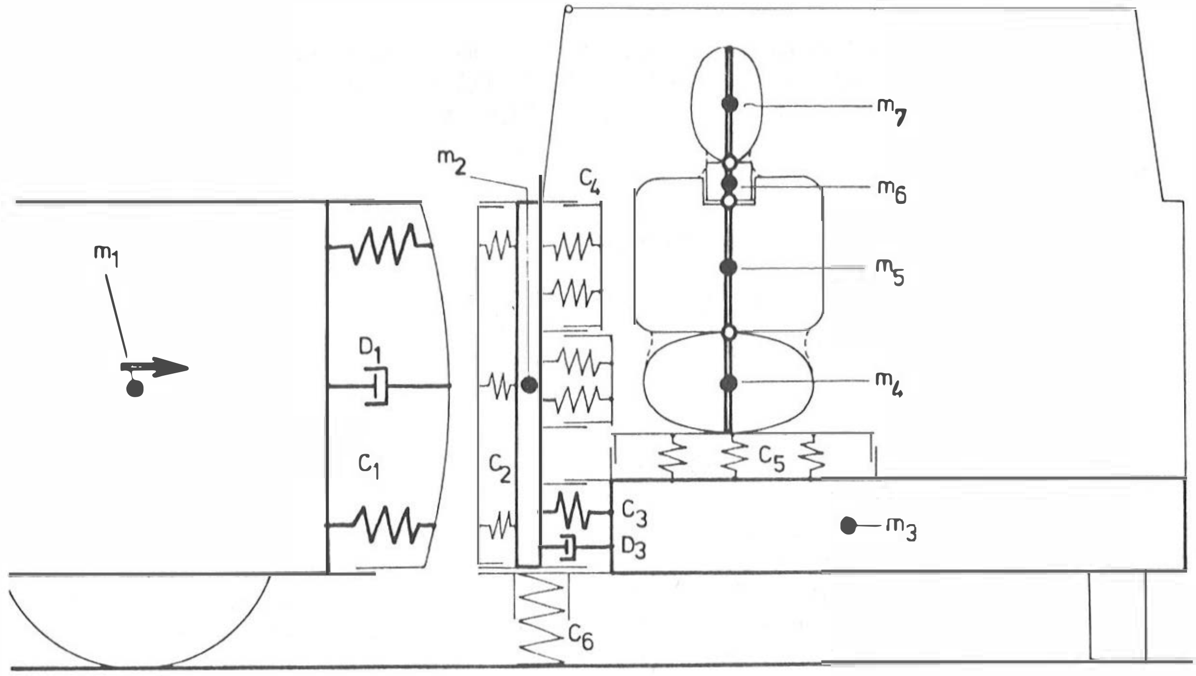

Fig. 1 Mathematical simulation model for the side on vehicle-to-vehicle collision

This model makes it possible to program any desired side structure characteristics and variations in the thickness and energy absorption of the side padding. The input data for the model were derived from a vehicle-to-vehicle side-on collision with standard production vehicles. The procedure of optimisation is based on a 50 kph collision of a 1700 kg vehicle into the side structure of a stationary vehicle at an angle of 90°.

OPTIMISATION OF SIDE STRUCTURE STIFFNESS

The safety principle of the rigid passenger cell cannot be realised in practice for the side-on collision as it can for the frontal collision. The side stiffness values of modern cars are lower in relation to the stiffness of the front structure (by a factor of 1/2 - 1/6), so the occupant sitting on the side of the collision is struck by the side structure penetrating into the cell and accelerated towards the opposite side of the vehicle. The acceleration imparted to the vehicle is therefore less relevant for the occupant, and the decisive factor is the large amount of relative motion between the side structure and the vehicle. By stiffening the side structure this relative movement is reduced, at the same time increasing vehicle acceleration. Theoretically the optimum stiffness is the value at which the internal deformation of the cell just equals the initial distance between the occupant and the side padding. The velocity of impact between the occupant and the side padding is then at a minimum; the occupant is subjected to the lowest acceleration values /1/. Insufficient side stiffness leads to a high internal impact velocity, while excessive side stiffness leads to a high level of vehicle acceleration.

Calculation was based on the Audi 4000. The front and side structure characteristics employed in the computation model are shown in Fig. 2.

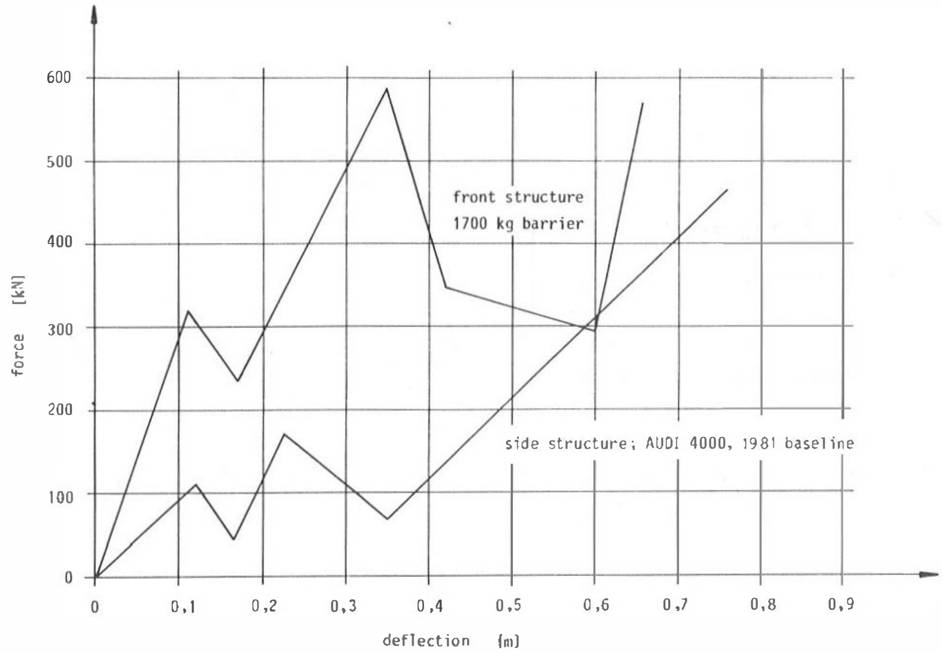

Fig. 2 Deformation characteristics of front and side structures

The front structure characteristics correspond to those of the Audi 4000, extrapolated for a vehicle mass of 1700 kg. The side stiffness was now gradually increased, maintaining the same characteristic configuration, and the effect on the relevant parameters was calculated. The result is shown in Figs. 3 and 4. Side penetration is naturally reduced as side stiffness is increased, whilst at the same time the extent of front deformation of the colliding vehicle increases. The clearance between the side padding and the occupant was 0.115 m in this calculation. In order to limit side intrusion to this amount it is necessary to increase side stiffness by a factor of 5 in relation to the standard vehicle. The calculated acceleration values for the dummy (Fig. 4) do indeed reach minimum levels with stiffness increased by a factor of 5, so this does correspond to the minimum occupant loading.

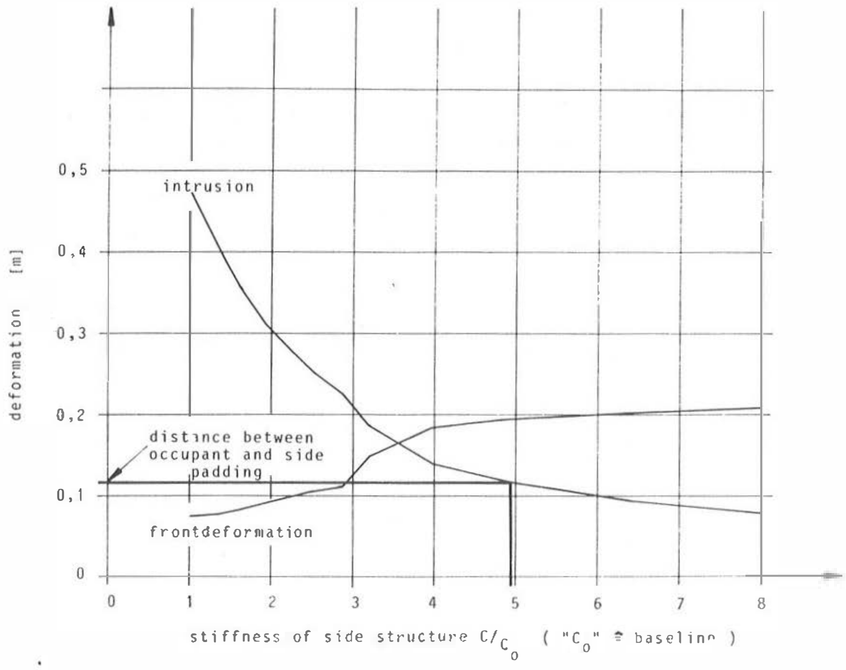

Fig. 3 Deformation of front and side structure versus side stiffness

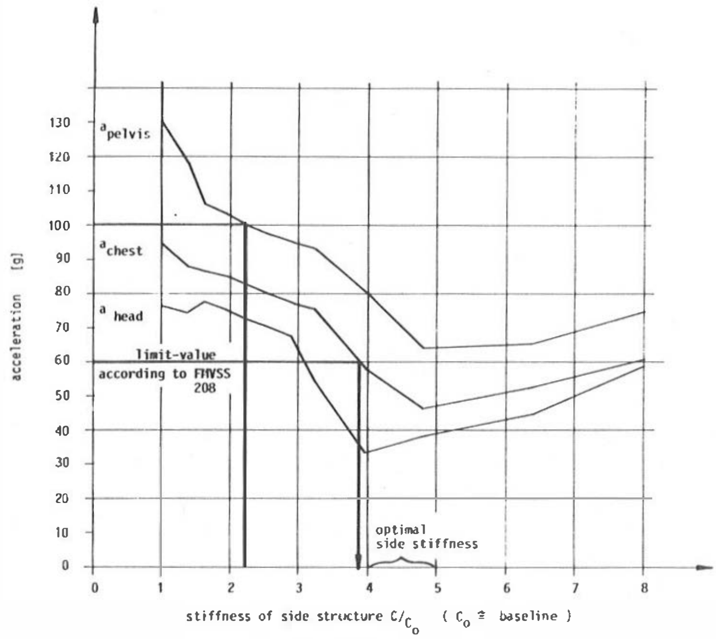

Fig. 4 Dummy acceleration versus side structure stiffness;
mass of the striking vehicle: 1700 kg;
no additional interior padding

It is therefore possible to establish an optimum side structure stiffness for a given set of test conditions, but this stiffness is so extremely high that a practical design is not possible. In order to exceed the FMVSS 208 protection criteria it will also be necessary to improve the side restraint system, i.e. the internal padding, because of the limited design freedom in stiffening the side structure.

OPTIMISING SIDE PADDING STIFFNESS

The side padding is defined by 2 parameters: the padding thickness and the ability to absorb energy. The required padding for maximum occupant protection can thus be defined as follows: the padding should be as thick as possible subject to considerations of vehicle shape, interior width and comfort requirements. In the pelvis area it would be possible to provide padding with a thickness of 0.05 - 0.10 m. additional padding in the shoulder impact area is however problematic because the interior width measured at this point is a comfort requirement. The padding thickness will therefore ultimately be determined by the priority given to occupant protection in side impact.

The energy absorption capability on the other hand can be optimised with the goal of minimum occupant loading. The optimum characteristics are achieved when the whole thickness of the padding is utilized to absorb the movement of the occupant relative to the side structure, with a constant force which is as low as possible. This requirement of maximum energy absorption with a minimum force level results in a rectangular characteristic curve. By using the padding thickness the deformation force can be controlled in such a way that it is maintained below the force threshold applicable for the given occupant protection criteria.

The influence of the padding characteristics shown in Fig. 5 on the occupant loadings was now calculated with the computation model. The maximum deformation capability of the padding and the force limit were varied.

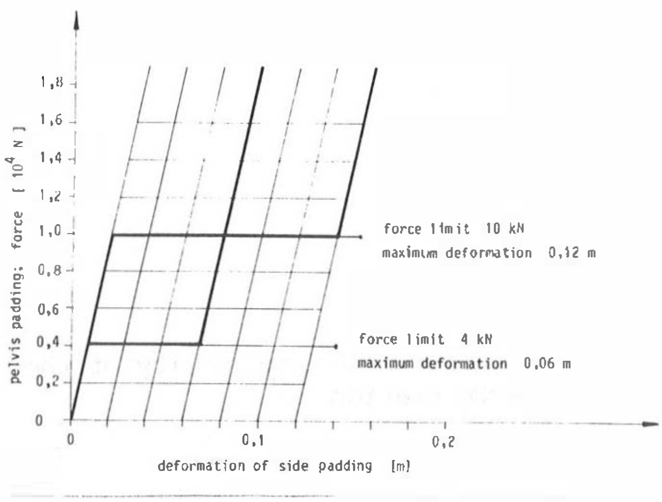

Fig. 5 Padding characteristics with different force limitations and deformation lengths

The result of the calculation is shown in Fig. 6 with the example of the chest acceleration. With increasing padding stiffness and deformation capability the loading on the dummy decreases towards a minimum. At the minimum level the total deformation capability of the padding is just utilized to absorb the motion of the occupant relative to the side structure. If the padding is too soft the rigidity of the compressed padding after complete deformation has a negative effect; if the padding is too hard the available energy absorption capability is not utilized fully. Fig. 6 shows that chest acceleration remains below the critical value by using ideal padding characteristics and a deformation distance of 0.06 m.

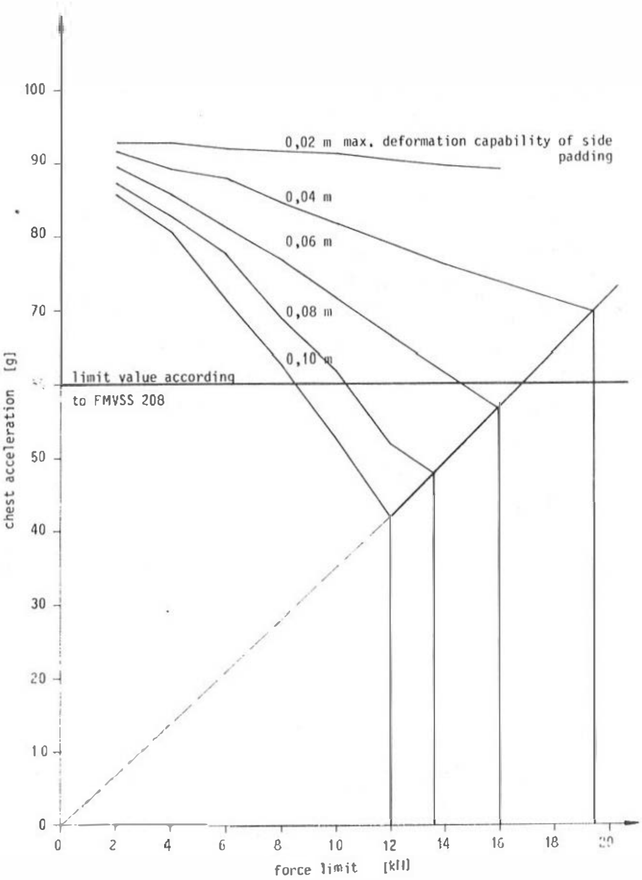

Fig. 6 Influence of force limitation and deformation capability of the side padding on the dummy chest acceleration

The optimum limit of the padding force is of course a funktion of the side structure stiffness (Fig. 7).

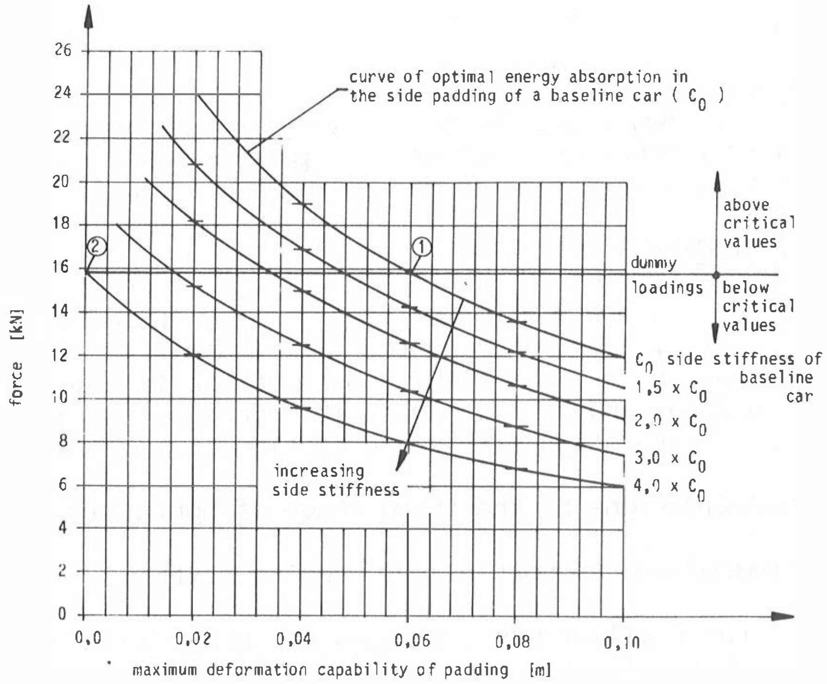

Fig. 7 Optimum padding deformation force as a funktion of padding deformation capability and side structure stiffness

The figure shows the optimum padding deformation force as a function of the padding deformation capability and the side structure stiffness. This diagram provides the first basis for devising and developing a new side padding. When the stiffness of the side structure is known, the required minimum deformation length and the energy absorption of the padding necessary to remain under the protection criteria can be determined. The diagram illustrates two significant points:

1. With the stiffness of the standard side structure the ideal padding requires a deformation length of 0.06 m in order to ensure occupant protection

2. If side stiffness is increased by a factor of 4, the required protection is possible without additional side padding

Since a padding deformation length of 0.06 m with a rectangular characteristic curve, using a realistic padding design taking into account the length when fully compressed and non-ideal characteristics, would require an unacceptable padding thickness of > 0.12 m, and since a four-fold increase in the stiffness of the side structure is not practicable, it is therefore necessary to employ a combination of side structure stiffening and interior padding in order to comply with the occupant protection and comfort requirements.

EXPERIMENTAL INVESTIGATION

An experimental study was carried out to put these theoretically derived results into actual structures. Modifications to stiffen the side structure were applied to a standard Audi 4000, and special side padding with optimised energy absorption capability was installed in the pelvis impact area.

STRUCTURAL MODIFICATIONS TO INCREASE STIFFNESS

The basic approach is to create a kind of safety frame by increasing the bending stiffness of the B pillar, strengthening the roof frame with a cross member and adding a floor cross member; the resulting structure is able to withstand high transverse loadings and is also a feasible design. The concept was optimised in three steps of iteration with crash testing in each case.

The main structural modifications at the third stage of optimisation were:

- Metal gauge was increased and support plates used to stiffen the sill

- Bending stiffness of the B pillar was increased by using thicker gauge metal and an additional reinforcement plate

- A floor cross member between the B pillar and tunnel was employed as a new part. The keying of the B pillar into the sill was improved to enable large forces to be transmitted into the floor cross member

- A strong roof cross member with an improved joint at the B pillar was installed in the roof area

- The door beam was repositioned downwards and outwards at impact height

- The front seats were strengthened in the transverse direction by design modifications

The weight increase associated with these combined modifications is about 12 kg per vehicle.

DEVELOPMENT OF PADDING IN THE PELVIS IMPACT AREA

It is only feasible to add affective side padding ($\geq$ 0.06 m) in the pelvis impact area. At shoulder impact height additional padding causes problems since it restricts interior width, an essential comfort requirement.

One possibility is to design the door sheet itself to be deformable in the shoulder contact area so it absorbs energy on impact with the shoulder. But this is also subject to limitations because it would reduce side stiffness and the bracing effect of the door in a frontal collision.

But with the HSRI side impact dummy used for this study, which is very soft in the chest and shoulder area, the chest acceleration is in any case less critical than the pelvis acceleration. The deformability of the HSRI dummy has the same positive effect as special padding in the shoulder impact area for a front impact dummy.

Padding was now developed for the pelvis impact area in conjunction with this study. The padding consists of a 0.6 mm thick aluminium sheet outer skin with a plastic coating, filled with an energy-absorbing polyurethane hard foam. The metal gauge and the density of the foam filler were optimised so that the resulting deformation characteristics were as close as possible to the theoretically derived ideal characteristic curve (Fig. 8).

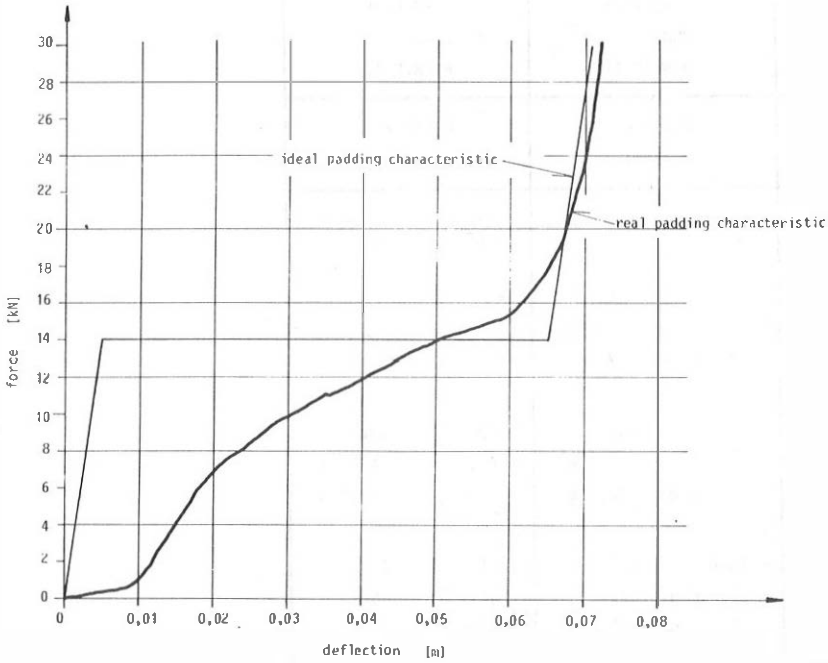

Fig. 8 Real padding characteristic in comparison with the calculated ideal padding characteristic

The stiffening effect of the modifications to the side structure was estimated at a factor of 1.5 in relation to the standard version. The data for the ideal padding characteristics were then taken from the diagram shown in Fig. 7. Results closey approximated the ideal rectangular characteristic curve. The weight of the padding for the pelvis area is 0.45 kg.

Alternative solutions were also examined, for example energy-absorbing designs using sheet metal with a honeycomb construction. However, the resulting characteristics were inferior and the structure was heavier than the version with the foam filler, although the sheet metal version has the advantage of a shorter fully compressed length than with foam padding.

TEST RESULTS

An Audi 4000 with the combined modifications as described was crash tested with a representative USA saloon (Chevrolet IMPALA) with a mass of 1700 kg. The test results are summarized in Table 1 and compared against the corresponding results from the standard car crash test.

		baseline vehicle		modified vehicle	
struck vehicle		AUDI 4000 baseline		AUDI 4000 modified	
striking vehicle		Chevrolet IMPALA		Chevrolet IMPALA	
mass of striking vehicle		1700 kg		1700 kg	
mass of struck vehicle		1270 kg		1283 kg	
impact speed		50 km/h		50 km/h	
dummy struck side		HSRI		HSRI	
dummy opposite side		HYBRID II		HYBRID II	
max. outside deformation		0,461 m		0,345 m	
max. intrusion		0,382 m		0,258 m	
		struck side	opposite side	struck side	opposite side
dummy loadings: head	HIC	811	68	857	110
	a_{max}	220,0 g	22,0 g	170,0 g	32,0 g
	a_{3ms}	100,0 g	22,0 g	103,0 g	31,5 g
dummy loadings: chest	SI	422	143	370	174
	a_{max}	64,5 g	58,7 g	64,7 g	60,5 g
	a_{3ms}	61,5 g	42,2 g	54,6 g	49,1 g
dummy loadings: pelvis	SI	1364	317	601	233
	a_{max}	130,8 g	76,6 g	81,5 g	53,3 g
	a_{3ms}	118,5 g	64,7 g	79,0 g	48,3 g

Table 1 Summary of test results

The stiffening modifications to the structure led to a reduction in the maximum amount of intrusion from 0.382 to 0.258 m. The structural deformation is illustrated in Fig. 9. It can be seen that there is an even reduction in deformation between the A and C pillars. Maximum deformation still occurs in the area around the B pillar. The reduction is greater at the sill/lower door level than in the centre of the door because the most effective stiffening measures were applied to the floor area.

As Table 1 shows, the loading values on the dummy in the pelvic area were considerably reduced, and are below the critical range. In terms of chest loading the overall benefit of the concept is smaller because no additional padding was employed in the impact area and the acceleration level is in any case lower than in the pelvic area. The acceleration-time curves are shown in Fig. 10.

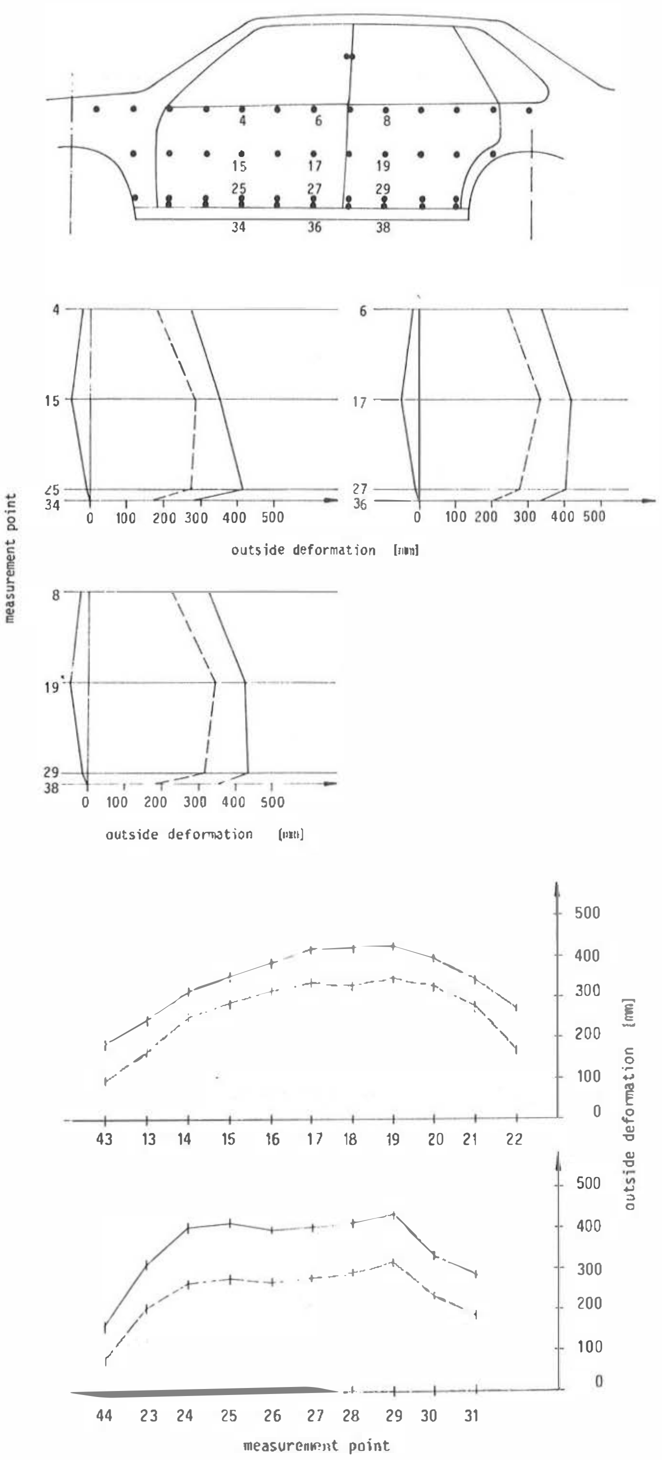

Fig. 9 Structural deformations of the crashed vehicles
—— baseline vehicle
--- modified vehicle

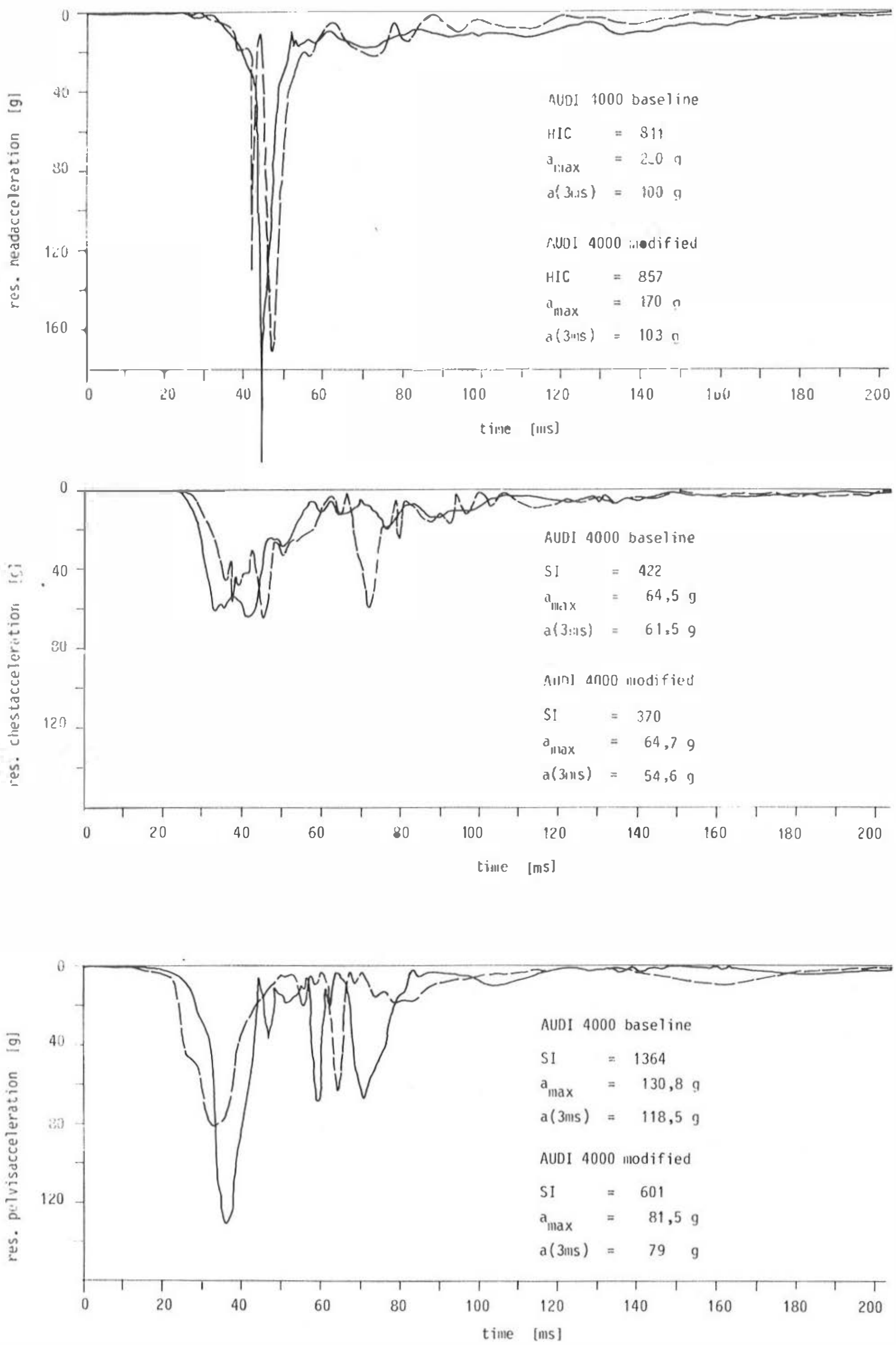

Fig. 10 Dummy accelerations versus time
—— baseline vehicle
--- modified vehicle

Because of its soft shoulder characteristics the HSRI dummy used here gives rise to a new problem, namely the hard impact of the head against the B pillar. In all earlier side-on tests with the HYBRID II dummy the head loading did not prove critical. But with the HSRI dummy the resulting head acceleration is a long way above the critical level, although the HIC value is admittedly still acceptable.

The head impact on the B pillar at a high impact velocity generates an extreme acceleration peak. However, the 3 ms value defined as the criterion for occupant protection is considerably lower because of the low energy value of the peak, and could possibly be easily reduced to a point below the critical range with a small amount of padding on the B pillar (o.5 - 1.0 cm).

SUMMARY

The paper describes a theoretical procedure for optimising the side structure stiffness and the side padding of a vehicle. Both parameters were optimised for a given set of test conditions and the functional relationship between the stiffness of the side structure and ideal padding characteristics was determined. The theoretical findings were put into practice by modifying a standard Audi 4000 for crash testing. The modifications incurred a weight penalty of about 13 kg per vehicle, and were very beneficial in the pelvis impact area, gave a slight benefit in the chest impact area, and no benefit in the head impact area. The head loading can only be significantly reduced by direct padding applied in the head impact area. The study has shown that occupant protection in a side-on collision can only be guaranteed by applying very extensive modifications to the vehicle structure and interior. A realistic concept is only possible by combining modifications to the side structure and the side padding.

References

/1/ Hofmann, J.
Rechnerische Untersuchung zur optimalen Seitenstruktur von Personenkraftwagen
Dissertation, Technische Universität Berlin, 1980

/2/ Hofmann, J.; Appel, H.
Mathematical Simulation of Side Impact -
- A Contribution to the Problem of Rigid/Deformable Barriers
VIII. ESV-Conference, Wolfsburg, October 1980

Illustrations