NUMERICAL BENCHMARK ON MATERIAL PERFORMANCE

IN ANTI-INTRUSION BEAMS

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Abstract

Passive safety of vehicles is increasing by means of solutions based on new design and new materials for structural components. Stainless steels have a strong potential application in crash resistance devices due to their high strength and energy absorption properties. In this paper the application in side impact protection devices (door beams) is explored. A finite element model of an anti-intrusion beam, inserted into a simplified scheme of the car body, has been set up and used to compare the material response during a lateral impact. Several materials have been selected and applied in the numerical simulations of the impact, ranging from standard and high strength carbon steels to different stainless steels, including austenitic, martensitic and duplex grades, both in the annealed and hardened state. The material response has been studied focusing the attention on the safety criteria ruled by the international standards on car crash testing. The study demonstrated that stainless steels have a wider application range in terms of yield strength selection. Good formability properties and residual plastic deformations are available in the component even for the hardened states. On the contrary, high strength carbon steels may have some formability problems and low energy absorption capacity during crash phenomena. In this case a strong design effort is needed to match the manufacturing and performance criteria.

1. Introduction

Due to the increasing requirements for passive safety of vehicles, car manufacturers are continuously developing improved solutions for crash resistance. At the same time, the safety requirements must also meet other car design criteria, such as the lowering of costs and the body weight reduction. To gain the target, solutions are studied including the proper material selection for each component and the design optimisation. From some point of views, stainless steels (SS) have appropriate structural crash characteristics, due to their good formability and to the strong hardening properties. It is possible in fact to balance at best high strength and residual ductility, as function of the specific application.
Previous works available have been devoted to the study of crash absorption characteristic of SS in axial impact [1]. All these studies have been conducted on experimental basis at laboratory scale. In those cases SS demonstrated great energy absorption properties, due to the hardening properties and ductility. The aim of this work is to find out if the same conclusions can be also applied to the side impact on cars.

2. Standards on side impact testing

The only regulation available for the full scale side impact testing on cars is from USA. Test characteristics, procedures and evaluation criteria are collected in the FMVSS 214 standard. In the European Community, no official standards are available, but studies for regulations are under development. On the other side, all car manufacturers have in house procedures for evaluating the crash resistance, that all converge on the general aspects of the test (mass of the impacting vehicle, impact velocity). The final EC document probably will meet the car manufacturers indication, suggestion and experience.
It must be remarked the main point on side impact testing and on full scale crash testing in general. Not only the structural resistance must be verified, which implies the respect of the surviving space in the cockpit (like

indicated in the US norms), but also the safety criteria must be satisfied. This implies that the performance is measured on the occupant damage, involving limitations on accelerations, velocity and forces acting on the dummies during the test. The safety criteria are evaluated by comparing the values of a collection of indexes built from measurements on dummies (velocities, accelerations and forces are measured in several point, as the head, the chest and the pelvis) with specified values, obtained from experience on wounded people.

3. Review of existing door beam design

The beam inside the door is only one of anti intrusion devices used for safety during the lateral crash. Other reinforcements are located in the floor, under the door, to absorb in a distributed way the energy, and in the upper part of the door itself. These structures are integrated in the door frame or in the car body, consisting of box shaped sections. In particular the under floor structure is devoted to absorb the distributed load due to the impacting car, while the door beam is devoted to avoid the intrusion in the cockpit due to concentrated loads (i.e. corners during not perpendicular impact). In almost all the examined models the anti intrusion beam consists of round or square tubes. In fig. 1 and 2 some examples of car body structure and anti intrusion devices are shown.
To understand the design trends, several car models have been selected for a market search on door beams. The most used structures observed in the analysed car models are single round tube, double tube, rectangular closed section and sandwich closed omega sections.
About the material used, such data are confidential and not available. The few information collected shows that in general the tube types are made by very high strength steels, probably cold worked or heat treated. As an example of sheet formed beam, the rectangular section in SAAB 90 beam is built starting from a high strength carbon steel (CS) sheet. There is one exception, AUDI, which uses in some models an extruded aluminium bar for the beam.
If we evaluate the section performance by means of only simple static analysis it can be demonstrated that the round section is the less fit to the purpose and that boxed sections would be preferable, both for bending performance and mass. It must be noticed that, on the contrary, the past trend seems to be strongly directed to the use of round tubes. This fact could be understood as a choice for simple components, even if not optimised for mass. Another indication from the market is that a more recent trend is appearing to use sheet stamped parts, generally in omega sections, assembled or not in sandwich.

4. Material data collection on high strength stainless steels and carbon steels

Properties on several SS have been collected to study the material influence on crash behaviour. The selected materials are reported in table 1; the delivery state and some mechanical properties are also shown. Together with the common AISI 304 and 301, a modified 304 with low Nickel[1] content has been evaluated due to its promising characteristics and the lower cost with respect to the standard 304. The AISI 420 has been considered for its great resistance in the quenched and tempered state (QT), which can be achieved on the final component by first shaping the beam and next passing it to the heat treatment stage. Finally a Duplex (22 Cr 5 Ni) and another austenitic low nickel steel (Cromanite™)[2] have been considered.
For the comparison between CS and SS, a series of CS have been selected, starting from the common FeP04 and 260BH, used in the car body, up to the high strength CS grades 600, 800 and 1000. In particular grade 600 and 800 are under evaluation by car manufacturers for the application in specific body components and seem now the most promising choice for increasing the passive safety. The materials selected are reported in table 1.
Data on mechanical behaviour have been collected for the above listed materials in terms of true stress vs true strain curve. In fig. 3, the direct comparison between CS and SS is proposed. It can be noticed that SS are equivalent or better than CS both in strength and energy absorption, measured by the area under the stress vs strain curve. To notice the SS higher hardening properties in the annealed state and the higher elongation to rupture in all conditions.

5. Finite Element modelling of side impact

[1] AISI 304 with low Nickel content is under development by Acerinox (E).
[2] Cromanite™ is a trade mark from Columbus Stainless Steel (SA).

The anti intrusion beam is inserted into a complex structure, which comprises the attachments, the door frame, the internal door padding, the car body and the suspension system. All these parts are loaded during the impact, each one reacting according to its inertia and stiffness. Nevertheless the study is focused on the beam, so is more convenient to consider the *car body/attachment system* as an invariant and insert in this system different solutions for the material. The system can be reduced, as a first schematisation, to a chain of elements, which have an associated mass, stiffness and damping. The elements are the attachments of the beam to the door, the door frame, the door internal padding, the door pillars, the car body, the suspensions and the wheels.

The system can be represented by the simplified dynamic scheme shown in fig. 4. In this scheme, we have the impacting punch (P) which acts directly on the door beam. The impact is transferred to the car body (M) through the door pillars. The car body is fixed to the ground through the suspensions. When deformed, the door beam can also impact the internal door structure and transfer the impact through the padding, in case of severe intrusion, to the passenger. So the occupant is subjected to the car body pulse, expressed in terms of velocity and acceleration and the direct impact from the beam, if case of severe intrusion.

The k_1 and k_2 springs represent the stiffness of the door frame and door pillar, M is the car body mass and the spring k_3 represents the stiffness of the suspension system, reduced to a translational degree of freedom. The k_1 and k_2 spring stiffness can be evaluated on the basis of standard pillars structures. The vehicle behaviour (k_3 spring) can be derived from vehicle dynamic theories, assuming a simplified suspension system. The mass M is of 1000 kg, representative of a mid class car model. The beam is impacted by a mass of 250 kg at an initial speed of 10 m/s. The impacting surface is a rigid punch of 340 mm diameter. Only the beam is modelled, by using 4 nodes shell elements. A simple geometry has been selected for the beam section, consisting in an omega shaped section and a spot welded flat closure (sandwich). The sheet thickness was set to 1.5 mm. The properties collected for the different materials have been inserted into the model in terms of true stress-true strain curves. The PamCrash commercial code from ESI, dedicated to crash analysis, has been used. In fig. 5 an example of finite element result is presented. The deformed mesh of the beam, with the equivalent plastic strain plotted, and the rigid punch are shown.

6. Results and discussion

To evaluate the beam behaviour and the material influence on the system response, it is necessary first to define some evaluation criteria and create a link between the general criteria and the FE model results. The door beam behaviour is related to several crash safety aspects that can be summarised as follows:

1. To avoid the door intrusion and the direct impact to the passenger.
2. To avoid high accelerations on the car body, even without direct contact on the passenger. The acceleration value is related to the displacement that the passenger can have, due to inertia, inside the cockpit, with high risk of impact on parts of the cockpit itself.
3. To reduce the impact velocity between the passenger and the cockpit. For the same reason described at the above point, higher is the maximum relative velocity between the passenger and the cockpit, higher will be the damage due to impact on the cockpit interiors.

To compare the different solutions in terms of material performance it is necessary to translate the safety criteria in measurable quantities calculated by the simplified finite element model. The numerical quantities considered as important to evaluate the beam performance and proposed to measure the above criteria are:

1. The door beam mid-section velocity at the time when the contact with the passenger is detected (velocity at impact). It is necessary to choose an intrusion distance, which was defined as 152.4 mm. This is the value for the maximum deflection derived from the FMVSS 214 standard.
2. The maximum value for the acceleration measured on the point representing the car body mass (cockpit). The higher the acceleration, the higher is the pulse transferred to the passenger.
3. The maximum intrusion into the cockpit. This is a measure of the beam strength.

The above quantities have been calculated for all the material listed in table 1. Data have been elaborated as function of the material yield point, obtaining the graphs in fig. 6, 7 and 8. The points have been divided into two families, to represent the CS (blue) and SS (red) materials. The empty symbols represent a result in which, during the simulation, the starting of material failure occurred. The failure criteria is defined accordingly to the maximum elongation allowable for the material. When the limit value is reached inside an element, this is no

more considered in the calculation. Linear interpolation trends have also been plotted on the graphs, not considering the spurious points representing the material which showed failures.
A strong relationship is visible in the results. The material properties that lower the intrusion and the impact velocity on passenger at the same time rise the acceleration transferred to the vehicle. This general result suggests an important conclusion about the design problem of automotive lateral crash: the problem is not a matter of optimisation. The desired behaviour must be tuned according to safety criteria used and to the importance given to each single safety aspect. In other words the car manufacturers could have different goals when designing the safety devices (i.e.: the intrusion or stiffness could be more important than accelerations).
The main material parameter affecting the performances is the yield point. A division in the two families (CS and SS) could be present, with possibly different trends for CS and SS, showing that the hardening, even if having some influence, is less important. A limit in the application of CS seems to appear, with a maximum yield strength applicable of 500 MPa. It is important to notice that above this strength limit, also formability limitations could arise for the CS due to the poor elongation properties. On the contrary, due to the higher shaping properties, even in the hardened states, SS could be considered for the design of more complex parts, having higher geometrical stiffness respect to sections formed in CS.
The best performances of SS can be also used to reduce the sheet thickness and the weight of the component. Additional simulations were performed comparing DP 600, DP 800 and AISI 304 in the 1.2 mm thickness and AISI 304 3/4 hard in 1.0 mm thickness. Now the graph representing the load on the punch vs beam displacement for the four materials is shown (fig. 9). From the comparison, considering the penetration (surviving space) and the maximum load (component structural resistance) as performance parameters, we can say that AISI 304 annealed can be assumed equivalent to DP 600, but with less performance respect to DP 800. Better performances are obtained by using the ¾ hard state in 1.0 mm thickness, which also allows a 20% saving in weight.

7. Conclusions

In conclusion, the following main points can be highlighted. The high strength SS can be a technically valid choice for crash resistance device applications. In this work the anti-intrusion door beams have been selected, but the conclusions are applicable to all structural components.
The material properties that lower the intrusion and the impact velocity on passenger at the same time rise the acceleration transferred to the vehicle, so the problem of crash resistance devices design is not a matter of optimisation. This means that the final choice on geometry or material depends on the car manufacturer design criteria.
The study demonstrated that SS have a wider application range in terms of yield strength selection. Good formability properties and residual plastic deformations are available in the component even for the hardened states. On the contrary, high strength CS, like DP 800 and DP 1000, may have some formability problems and low energy absorption capacity during crash phenomena. In this case a strong design effort is needed to match the manufacturing and performance criteria.
An open point remains about the cost evaluation in an industrial application, which also depend on car manufacturer evaluations.

References

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Acknowledgements

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Table 1. Materials selected for the benchmark

Material	State	Yield strength MPa	UTS MPa	Elongation %
AISI 304	Annealed	298	654	55
AISI 304	1/4 hard	795	1021	21
AISI 304	1/2 hard	964	1075	17
AISI 304	3/4 hard	1154	1208	8
AISI 304 LNi	Annealed	367	683	48
AISI 304 LNi	1/4 hard	928	997	17
AISI 304 LNi	1/2 hard	971	1062	12
AISI 304 LNi	3/4 hard	1116	1191	8
AISI 420	Annealed	331	597	27
AISI 420	Quenched+Tempered	1497	1805	7
AISI 301 LN	1/4 hard	510	830	45
Cromanite^{TM}	Annealed	529	838	42
Duplex 22Cr5Ni	Annealed	672	825	32
FeP04	-	160	190	42
220 BH	-	198	230	37
380 TM	-	350	400	22
DP 500	-	243	500	25
DP 600	-	389	600	12
DP 800	-	609	800	9
DP 1000	-	750	1000	7

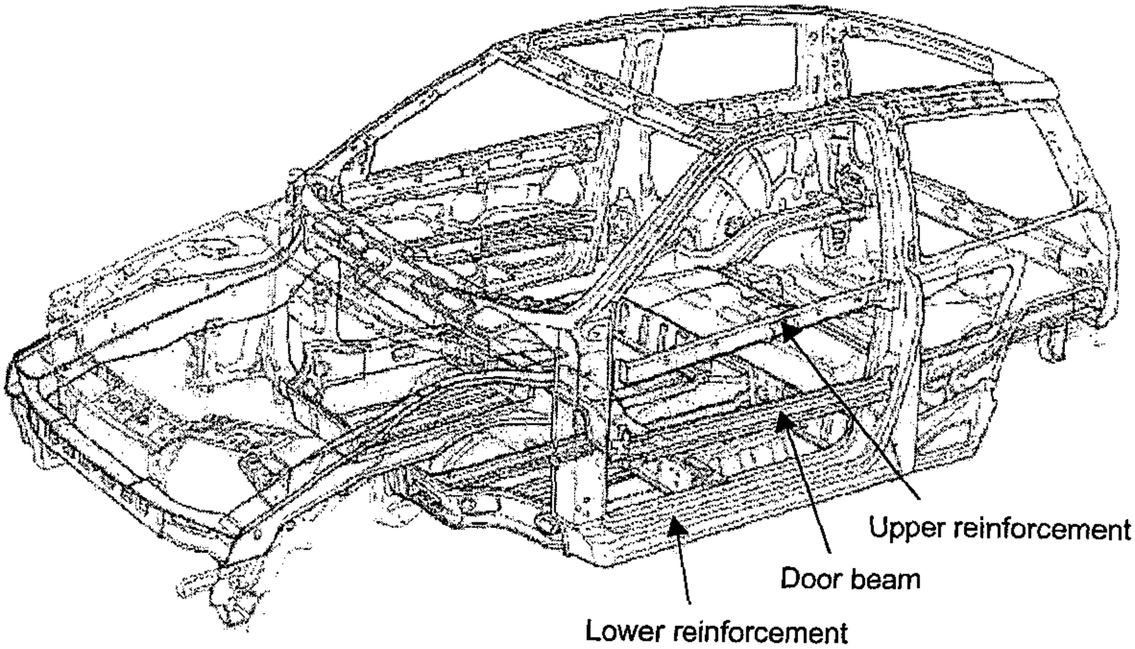

Fig. 1. Example of car structure with passive safety devices for side impact resistance.

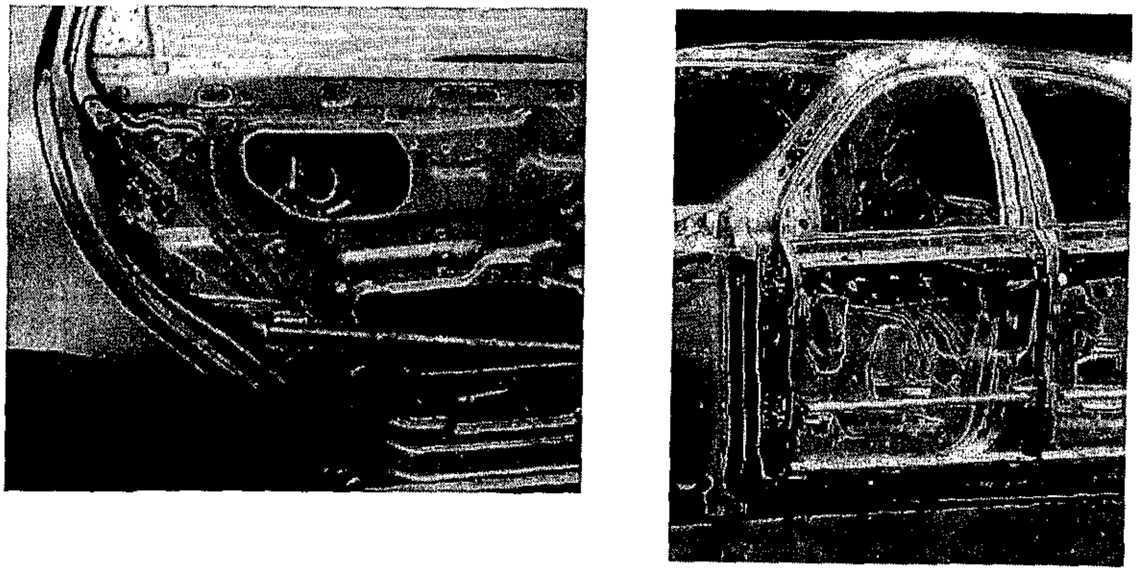

Fig. 2. Examples of anti intrusion beam insertion in the door frame.

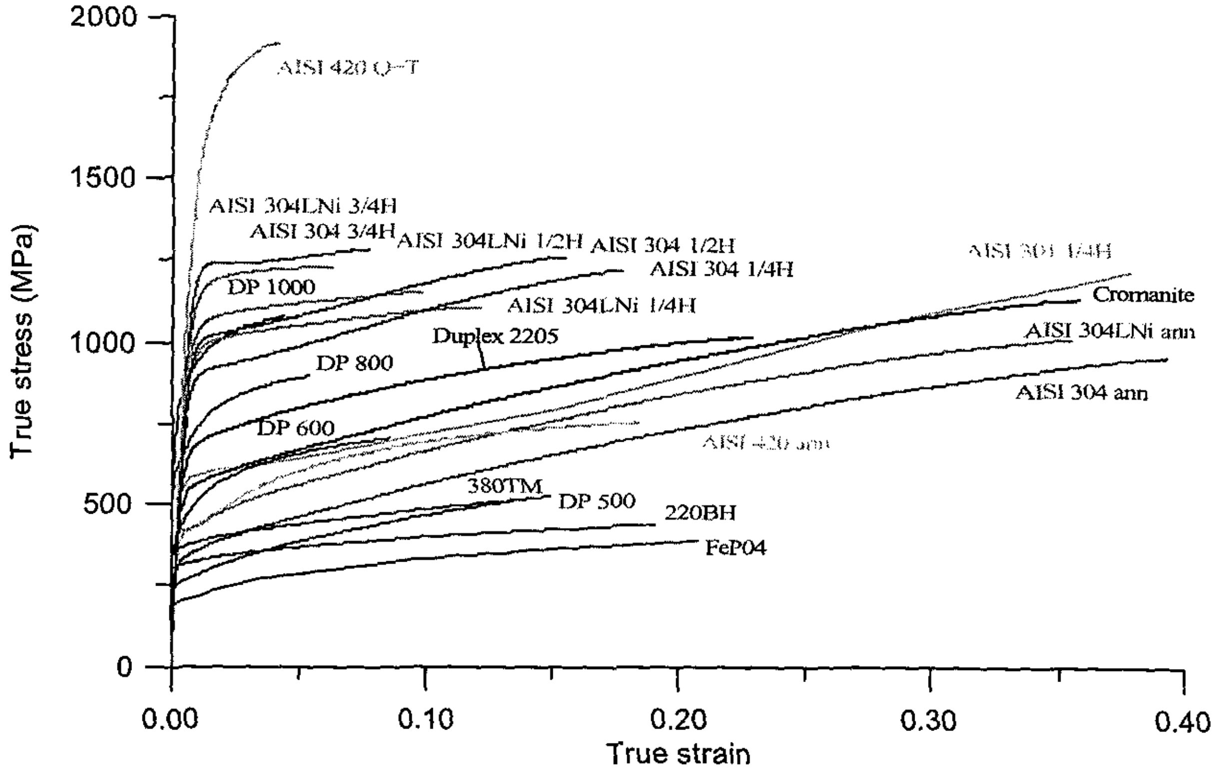

Fig. 3. True stress vs true strain curves for the selected materials.

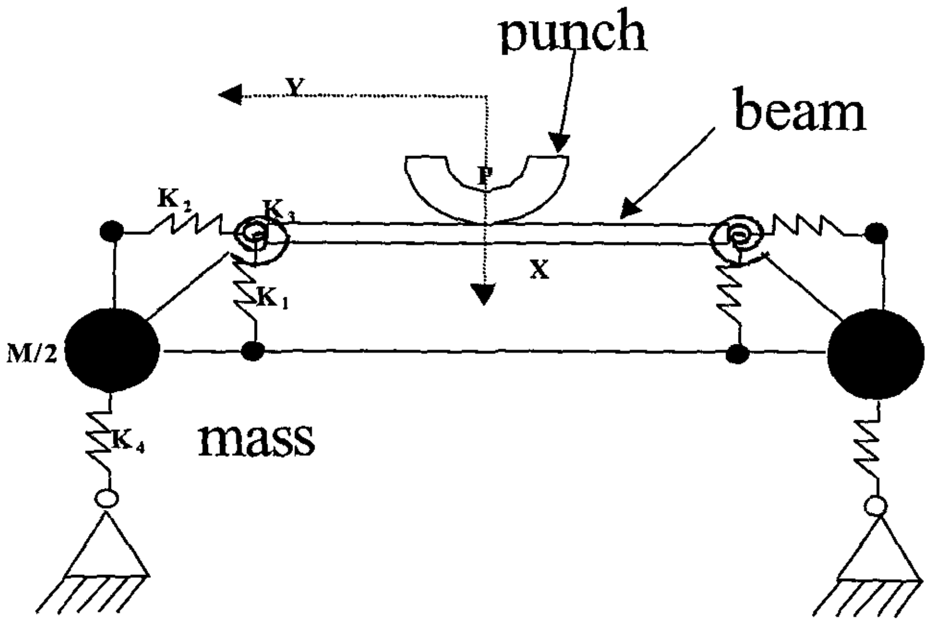

Fig. 4. Simplified model of beam and car body system for side impact simulation.

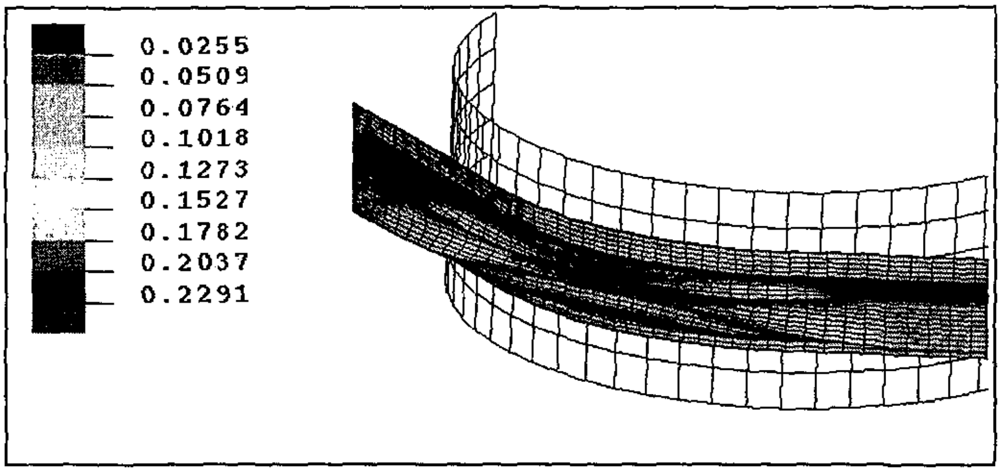

Fig. 5. Example of finite element result. Deformed mesh and plastic strain distribution.

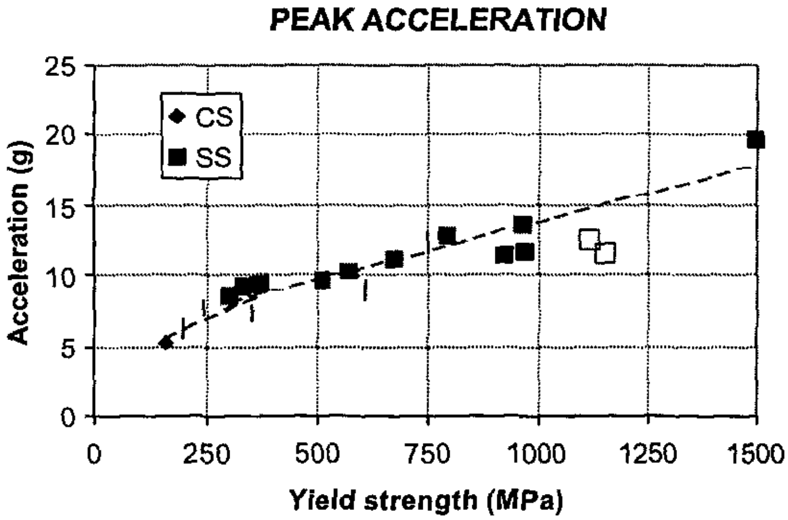

Fig. 6. Maximum cockpit acceleration during impact

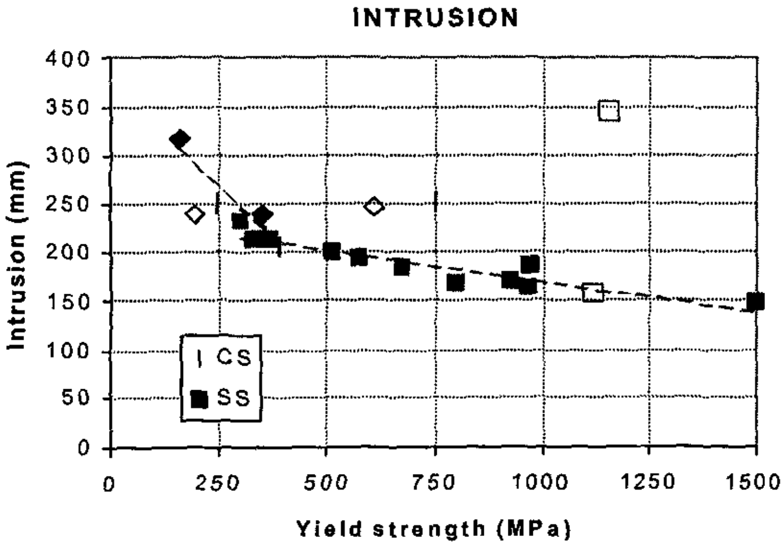

Fig. 7. Beam intrusion into the cockpit (reduction of surviving space)

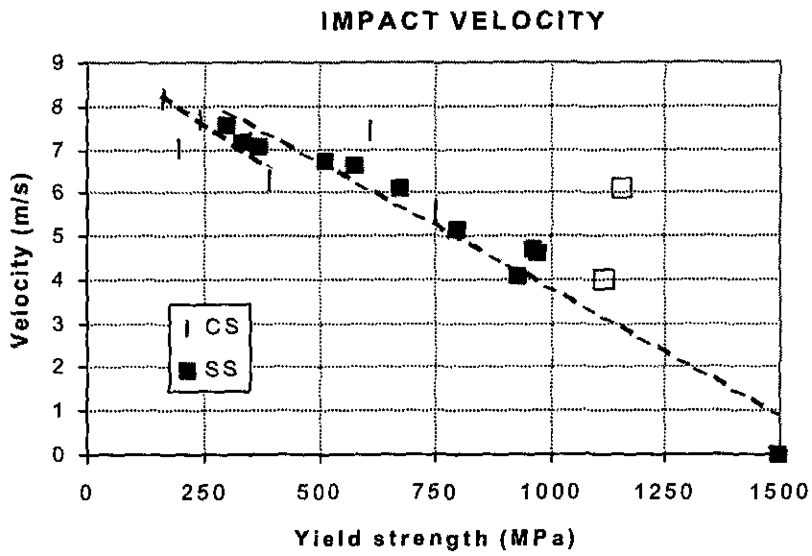

Fig. 8. Beam velocity at impact against the passenger (intrusion 152.4 mm)

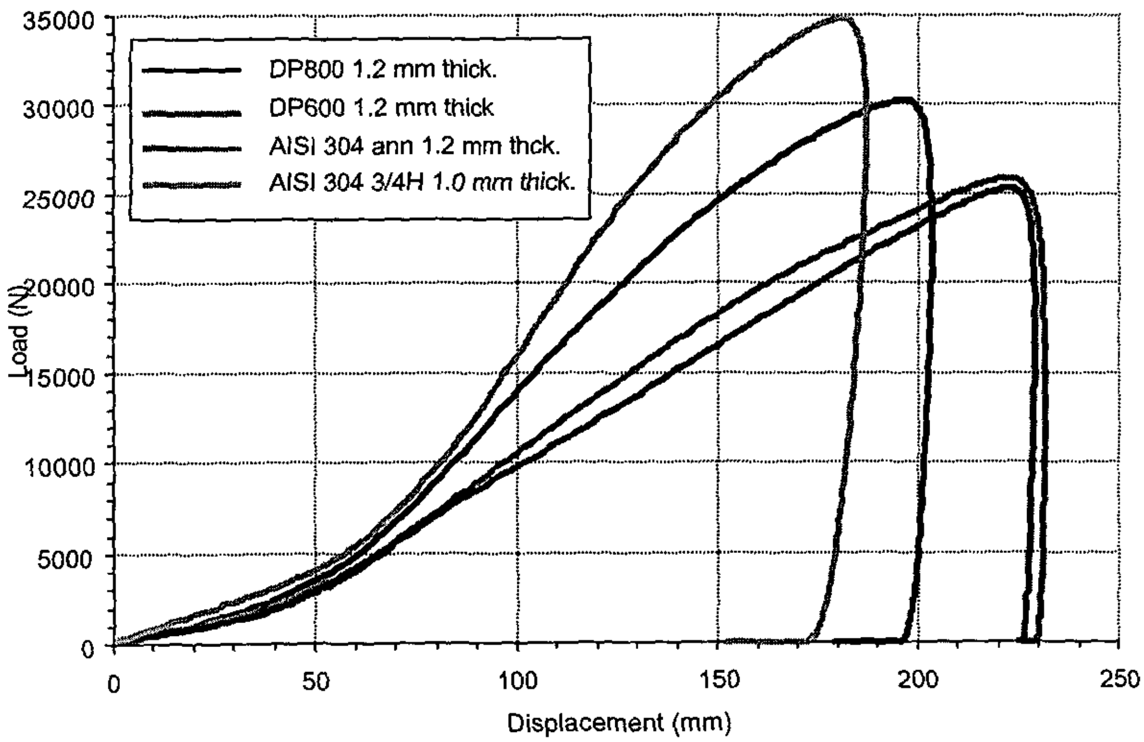

Fig. 9. Comparison between CS and SS. Simplified model. Load vs displacement graph.