POTENTIAL APPLICATION OF STAINLESS STEEL FOR VEHICLE CRASHWORTHINESS STRUCTURES

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ABSTRACT

The occupants protection in vehicle crashes is directly related to the “safety capability” of the vehicles themselves: crash avoidance systems, passive safety devices and crashworthiness structures are all important to reduce injury risks for passengers but the vehicle structure’s ability to manage the impact energy represents the main line of defense.

Traditionally the material choice for vehicles body has been carbon steel due to its easy of manufacturing, energy absorption capability and relative low costs. However, in the last years, the exigency to match new targets such as weight reduction (and then fuel economy), durability, crashworthiness and limited NVH levels (Noise, Vibration and Harshness) moved the interest toward other materials.

In this context a more and more significant role is coming by stainless steels; their high mechanical properties, very high energy absorption capabilities, excellent formability/strength rate, high corrosion resistance and many other important characteristics get them potentially very suitable as structural materials.

Scope of this paper is to provide a brief overview on stainless steels potential in crashworthiness applications and to present few structural applications of them in the automotive field.

KEYWORDS

Crashworthiness, safety, stainless steel.

INTRODUCTION

Nowadays, energy saving and safety demands motivate vehicle manufacturers to use materials which make vehicles safer and lighter. In the past, the only alternative to usual materials has been light materials; nevertheless, those materials involve problems regarding cost and weldability. Stainless steel, instead, has outstanding mechanical and work-hardening properties, formability and weldability. Today, in a passenger car, this material is mainly used for its ability in preventing rusting: about 20 kilos of stainless steel are used to build the exhausts system and various small components. But a broader usage of stainless steel, i.e. for structural applications, allows obtaining not only corrosion resistance, but weight savings and better crashworthiness too.

1. BRIEF OVERVIEW ON STAINLESS STEEL

“Stainless Steel” is the name for a family of corrosion resistant steels. Its origins date from over 50 years ago, when it was discovered that a minimum of 12% chromium would impart corrosion and oxidation resistance to steel by means of the formation of a self-healing protective clear oxide layer. Hence the definition “Stainless Steels”, are those ferrous alloys that contain a minimum of 12% chromium.

Main applications of stainless steels are in areas such as domestic appliances, household objectives, chemical and petrochemical plants, construction industry, containers, tanks and food pickling plants.

With respect to carbon mild steels, stainless steels in general have higher corrosion resistance, cryogenic toughness, work hardening rate, hot strength, ductility, a more attractive appearance, lower maintenance and a better formability.

Although corrosion resistance of stainless steels comes from the presence of chromium, other elements are added to improve their properties, by altering the steel microstructures.

On the base of their metallurgical microstructure, stainless steels are grouped into the following families:

- **Austenitic Grades:** are those alloys which are commonly in use for stainless applications. The austenitic grades are no magnetic. The most common austenitic alloys are iron-chromium-nickel steels and are widely known as the 300 series (e.g. 301, 304, 316, etc). Due to their high chromium and nickel content, they are the most corrosion resistant of the stainless group providing unusually fine mechanical properties. They cannot be hardened by heat treatment, but can be hardened significantly by cold working.

- **Martensitic Grades:** were developed in order to provide a group of stainless alloys that would be corrosion resistant and hardenable by heat treating. They are straight chromium steels containing no nickel. The martensitic grades are magnetic and mainly used where hardness, strength and wear resistance are required.

- **Ferritic Grades:** have been developed to provide a group of stainless steels to resist corrosion and oxidation, while being highly resistant to stress corrosion cracking. These steels are magnetic but cannot be hardened or strengthened by heat treatment. They can be cold worked and softened by annealing. As a group, they are more corrosion resistant than the martensitic grades, but generally inferior to the austenitic grades. Like martensitic grades, they are straight chromium with no nickel. These steels are used for decorative trim, sinks and automotive applications, particularly exhaust systems.

- **Duplex Grades:** duplex grades are the newest of the stainless steels. They have high chromium and low nickel contents. This gives duplex stainless steels microstructures that include both austenitic and ferritic phases. Duplex grades are resistant to stress corrosion cracking, are readly welded and also have high tensile strength. Typical application areas are off-shore oil & gas installations, heat exchangers, marine applications, food pickling plants chemical and petrochemical plants.

- **Precipitation Hardening Grades:** they contain both chromium and nickel and develop very high tensile strength with heat treatment. Precipitation hardening grades are usually supplied in a

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"solution treated" condition that allows the steel to be machined. After machining or forming the steel can be aged in a low temperature heat treatment process. As the treatment is performed at low temperature, no distortion is induced in the work piece. These grades are typically used for aerospace applications, turbine blades, mechanical components, pulp and paper industry equipment and nuclear waste casks.

- **Superalloy Grades:** they are used when 316 or 317 are inadequate to withstand attack. Superalloys contain very large amounts of nickel and/or chromium and molybdenum. They are usually much more expensive than the usual 300 series alloys and can be more difficult to find.

2. INOX AS STRUCTURAL MATERIAL

Vehicle mass reduction and high structural crashworthiness are presently two priorities for vehicle manufactures. Lightweight motor vehicles, in fact, mean fuel economy and less exhaust emission, according to the last environmental Regulations. High energy absorption capabilities contribute significantly to improve the vehicle passive safety reducing road injuries and fatalities.

In this context stainless steels can play a primary role. These steels offer a broad range of strength, combining excellent formability and fatigue resistance, a good weldability and remarkable work-hardening properties, not to mention their corrosion and oxidant resistance. In particular austenitic grades such as AISI 301 L, AISI 304 and the new austenitic high strength stainless steels seem to be the most suitable as structural materials due to their excellent mechanical properties and their effective workability by usual automotive technologies:

- **Forming:** stainless steels present very high work hardening capabilities, generally higher than mild carbon steels usually adopted in the automotive field (Fig. 1); that get them particularly suitable for vehicle components manufacturing by forming, allowing more complex shapes manteining a large amount of plastic energy to be absorbed. In particular, austenitic stainless steels have cold working properties so good to be ideal for hydroforming, by both sheet and welded tube. Fig.2 shows two hydroformed vehicle components: an exhaust collector element and an oil sump respectively.

Fig.1 – Stainless and carbon steels mechanical characteristics comparison.

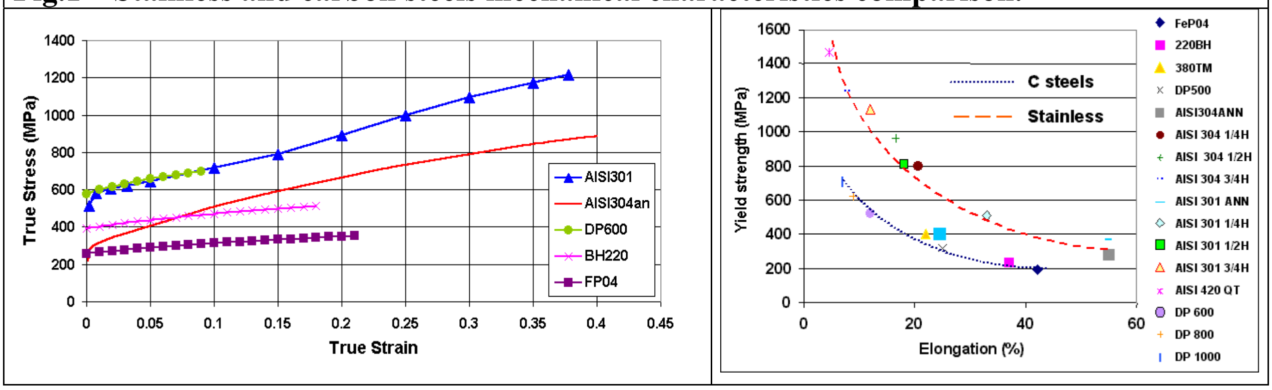

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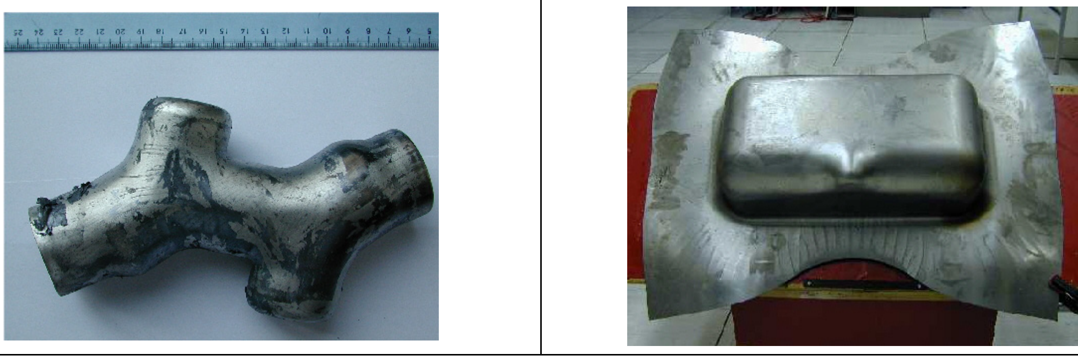
Fig. 2 – Hydroformed parts: an exhaust component and a 304 stainless truck oil sump.



- **Welding:** stainless steels are easy to weld by any traditional technique (laser, MIG, TIG, etc.).
- **Painting:** stainless steels (especially the austenitic ones) do not need painting treatment because of their corrosion resistance; if a painting is required for aesthetic appeal, the steel surfaces must be only de-greased and painted by cataphoresis because stainless steels are neutral to phosphatizing.
- **Adhesive bonding:** any structural adhesive is effective in stainless steel bonding, and is not needed any preventative treatment.
- **Joining problems:** it has to be taken into account the different thermal dilation coefficient and electrochemical potential which stainless steels have with respect to other materials (carbon steel, aluminium, etc).

Other two aspects make stainless steels suitable as structural material:

- **"Geometrical stiffness":** the large plastic strain available with stainless steels allows to increase a component size reducing, at the same time, its thickness (and then its weight), maintaining the component structural performances (rigidity and crash behaviour).
- **Crash behaviour:** under the same geometry, a vehicle component made of stainless steels presents higher energy absorption capabilities than in case of mild carbon steel, just because of the excellent work hardening properties of such materials and their high strain rate sensitivity.

Then stainless steel becomes an effective solution instead of carbon steel as structural material when formability, rigidity and crash behaviour are required.

3. AUTOMOTIVE APPLICATIONS

In many automotive sectors stainless steel already covers a significant role, such as in trims, outer panels, exhaust, wipers, etc. (Fig.3).

Fig.3 – Fields of stainless steel well-established application in automotive.

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The main application is in exhaust systems manufacturing: for these components, high temperatures and corrosive gases imply the use of tough and corrosion resistant materials to prevent rust and creep phenomena. Stainless steel represents an excellent solution.
In detail, an exhaust system requires several types of stainless steel: for the hot end of the system (i.e. for exhaust manifold, down pipe and catalytic converter) a material able to withstand both oxidation and creep is required. Instead, the cold end (i.e. the resonator, intermediate pipe, silencer and tail pipe) has to tolerate more onerous oxidation conditions, due to the agents used to eliminate snow and ice on the roads. Typical choices for the hot end are more highly alloyed grades, such as the 309 or 310 (25% chromium, 20% nickel) austenitic grades. The cold end, instead, requires materials such as the austenitic 304 (18% chromium, 9% nickel) or the ferritic 409 (12% chromium).

Another relevant application area for stainless steel is in fuel tanks manufacturing industry: incoming and more and more severe environmental Regulations are making current tank materials out of standard due to emission limits. Stainless steels can be a solution also taking into account their high formability that get possible complex tank shapes, in particular by hydroforming, for tight chassis spaces. The Fig.4 shows a real application: the Fiat Barchetta 304 stainless fuel tank (thickness = 0.6 mm) realised by welding two semi-shells.

Fig.4 – Fiat Barchetta stainless steel fuel tank, 14301, 0.6 mm thick.

Stainless steel is also more and more used in parts such as hose clamps, head gaskets, pump bodies, heat shields, windscreen wipers, containers for airbag inflation and seatbelt springs. Among these applications, the cylinder head gaskets manufacturing is maybe the most interesting one. Traditionally such gaskets are made of superimposed layers of asbestos and steel sheets. The recent ban on using asbestos and the onerous working conditions of last engine generation require to use materials characterised by excellent heat and corrosion resistance. New head gaskets have been developed: they consists in 3-5 layers of 0.25 mm thick hardened stainless steel sheet.

Suspension systems and rims represent other interesting fields for stainless steel. The Fig.5 displays a knuckle suspension arm made of AISI304: it make possible to save up to 25% in weight with respect to the original solution made of carbon steel.

The Fig.6 shows a rim made of AISI 301L cold worked: with respect to the Fe 355 standard solution, it allows to save up to 15% in weight, besides increasing the component fatigue resistance

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Fig.5 – Knuckle suspension arm made of AISI304.

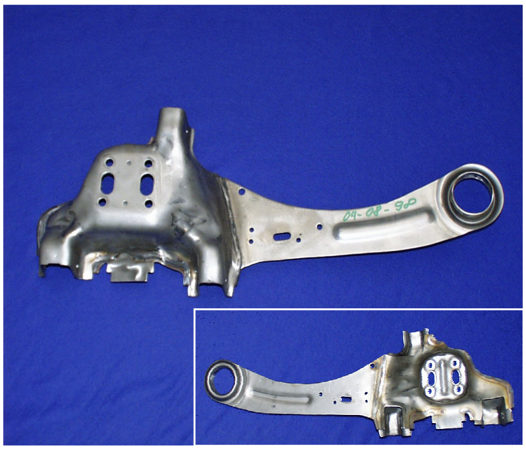
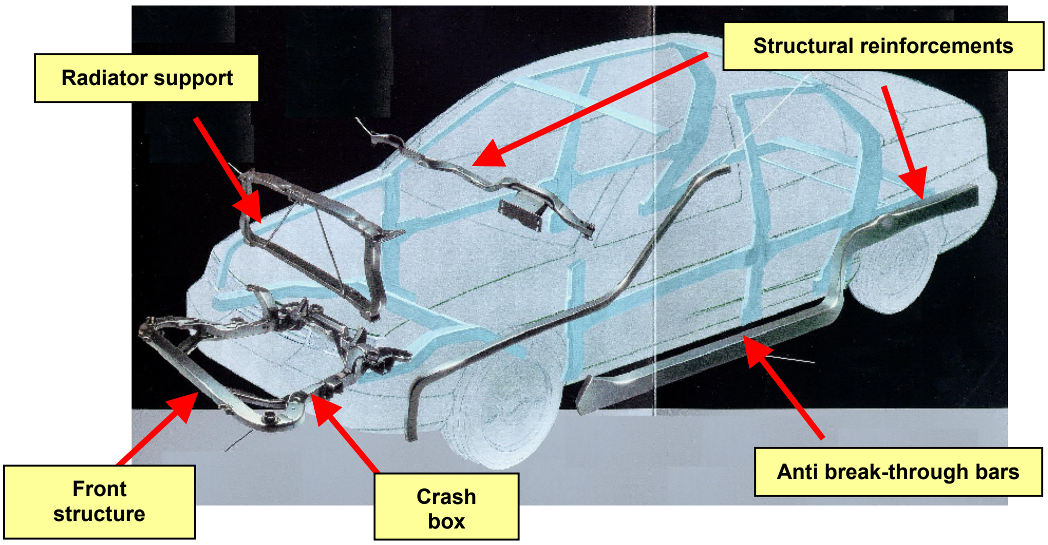


Fig.6 – Cold worked Inox 301 L wheel.

But the most recent studies for stainless steels are relevant to the vehicle structures. Today's vehicle-bodies are spot-welded assemblies of stamped-sheet steel panels and folded channel beams. These stiff-shell structures, named body in white (BIW), typically account for one-third of a vehicle's total weight. One of the target of the present automotive industry is to lightweight the BIWs improving, at the same time, both their stiffness and crashworthiness. In this context stainless steel are getting more and more important role due to its excellent mechanical properties (formability, weldability, work hardening capability, strain rate sensitivity, ...), also taking into account the current trend toward making efficient structural parts by using tube-hydroforming processing.
The figure below (Fig.7) shows a few potential applications of stainless steel in structural automotive field.

Fig.7 – Potential application of stainless steel in structural automotive field.



In the last years several concep cars and vehicle structures using stainless steel have been developed to investigate their real feasibility. In Fig. 8 the ARMCO-Autokinetics space frame is reported. This body structure is made of Nitronic (low Cr and Ni stainless), while structural junctions are made by Duplex casting. This solution allows to obtain higher stiffness and lower vehicle’s total weight, as shown in Fig.9. In Tab.1 the ARMCO solution is compared with another one presented by ULSAB (Ultra Light Steel Auto Body) and a traditional unibody chassy. The table reports also the PNGV

(Partnership for a New Generation of Vehicles) target requirements. It can be noticedt as the ARMCO-Autokinetics space frame meets such limits.

Fig.8 – ARMCO-Autokinetics concept space frame.

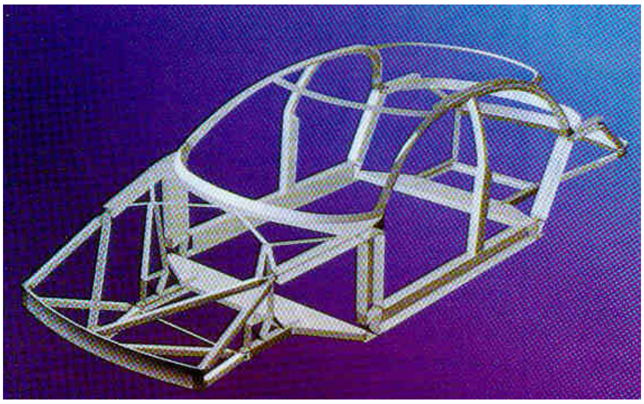
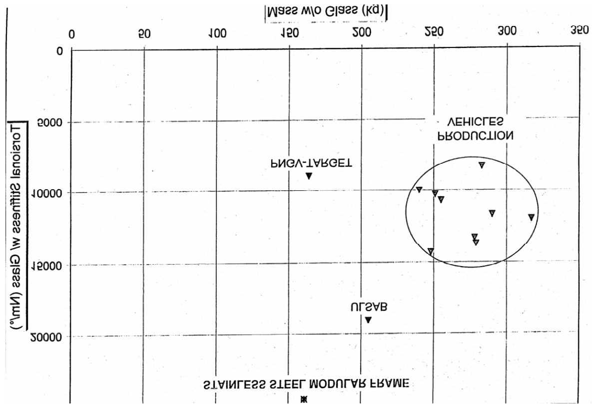


Fig.9 - comparison between ARMCO-Autokinetics space frame and other solutions.



Tab.1 – Weight and stiffness comparison between stainless steel modular frame and other state-of-the-art solutions		
Solution	**Weight (kg)**	**Torsional stiffness (°/Nm)**
Customary unibody structure	300	>15000
ULSAB	210	>19000
Stainless Steel Modular Frame	160	>25000
PNGV target	160	>9000

4. MECHANICAL COMPUTATIONS

Following three different feasibility studies regarding the stainless steel use as structural material in the automotive field are breafly presented. Moreover a preliminary investigation relevant to the possible use of stainless steel in road safety barriers manufacturing is reported. All these investigations have been carried out by using the mechanical computation tools.

The three feasibility studies' objectives have been a crash box, an anti-intrusion beam for automotive side doors and a truck cabin.

Crash boxes have to exhibit high specific strength and large scale deformation energy absorption. Its scope is to absorb part of the impact energy preserving the car body integrity and reducing the accelerations transmitted to passengers.
The study has been conducted comparing the crash box behaviour during the impact phenomenon for different steel grades (carbon steels and stainless steel) and thickness. In particular the following simulations have been carried out:

- Test: impact against a fixed rigid wall
- Impact velocity: 8 km/h
- Vehicle mass: 1200 kg
- Steel grades: FeP04, DP500, AISI304
- Crash box thickness: 0.8, 1.6 (FeP04), 1.2 (DP500), 0.6 (AISI304)

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The Fig.10 and Fig.11 show the CAD model and the FEM model respectively.

Fig.10 – Crash box CAD model.

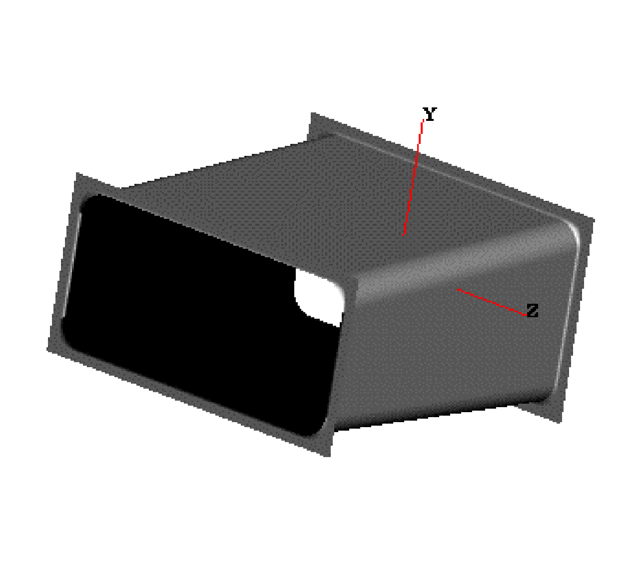
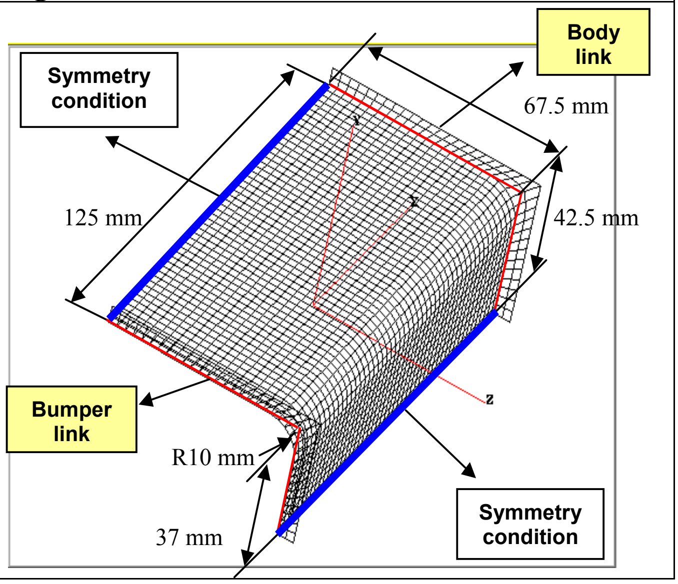


Fig.11 – Crash box FEM model.



The numerical results are reported below. Figures 12, 13, 14 and 15 show distances of each element in the model from the FLD curve (Forming Limit Diagram) for the different material solutions analysed: values greater than zero represent failure zones. As it can be noticed the crash boxes made of AISI 304 and FeP04, 1.6 mm thick, keep their integrity, whilst those ones in DP500 and FeP04, 0.8 mm thick, fail.

For what concern the forces transferred to the body structure the crash box in AISI304 allows to reduce them almost of 50% with respect to the FeP04, 1.6 mm thick solution, with a comparable absorbed energy (Fig.16). Taking into account the different thickness between the solution in AISI304 (0.6 mm) and that one not failured in FeP04 (1.6 mm) it is clear as stainless steel can represent an suitable solution to obtain more performing absorbers in terms of both crashworthiness and weight saving.

Fig.12 - FeP04 0.8 mm behaviour during numerical simulation.

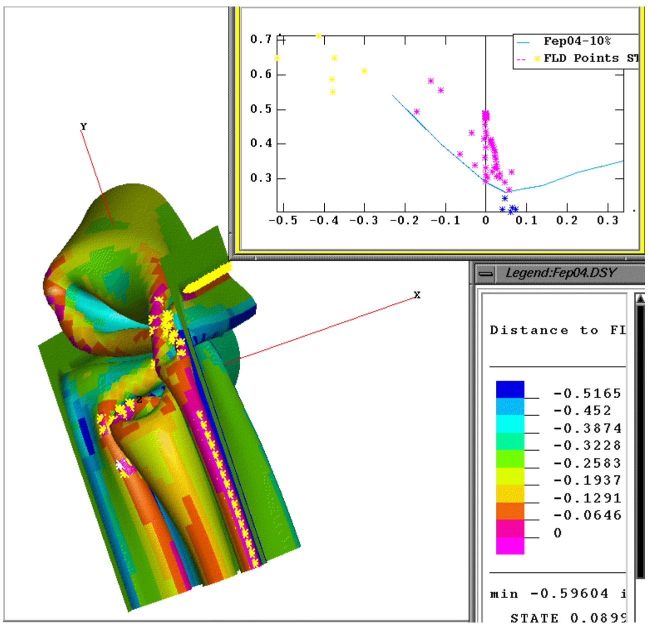


Fig.13 - FeP04 1.6 mm behaviour during numerical simulation.

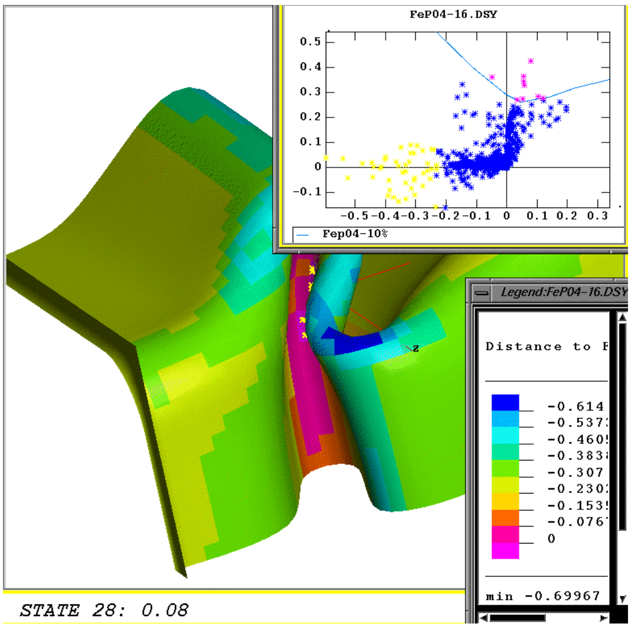


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Fig.14 - DP500 1.2 mm behaviour during numerical simulation.

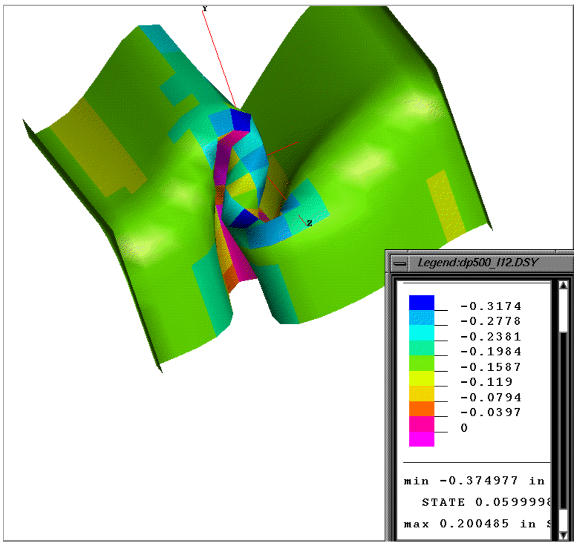


Fig.15 - AISI 304 0.6 mm behaviour during numerical simulation.

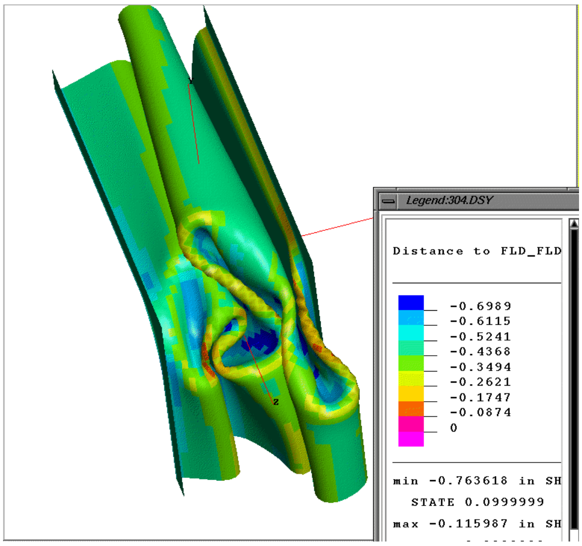
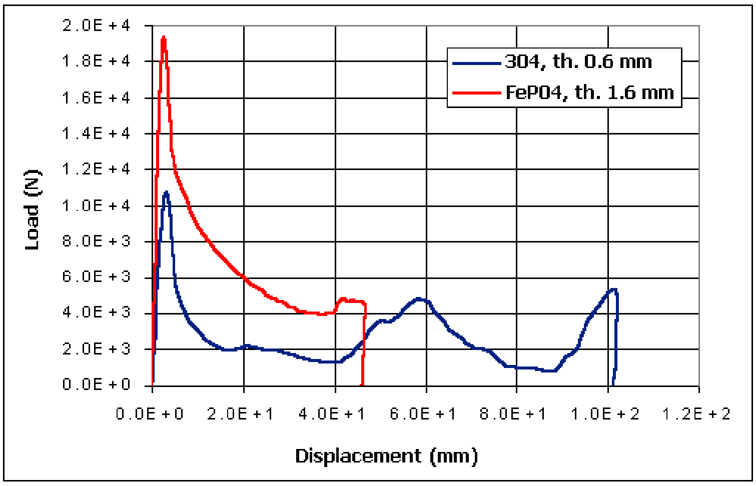


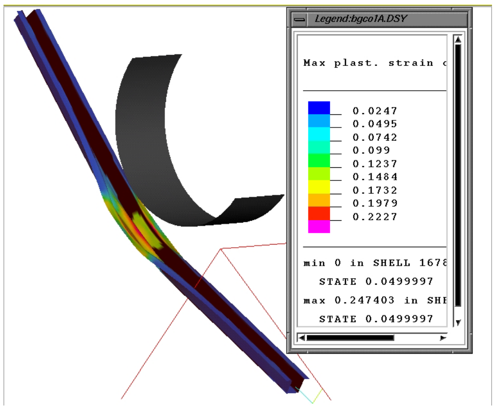
Fig.16 – Crash box analysis - Force vs. Dispalcement



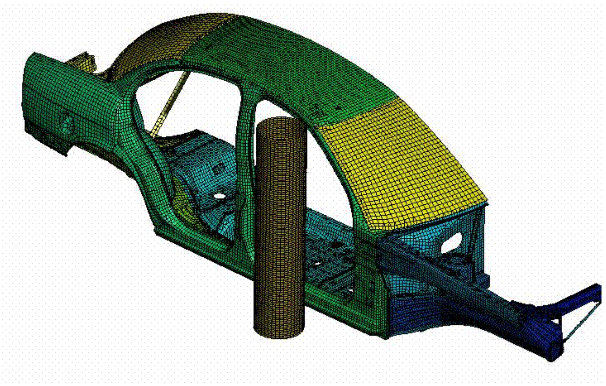
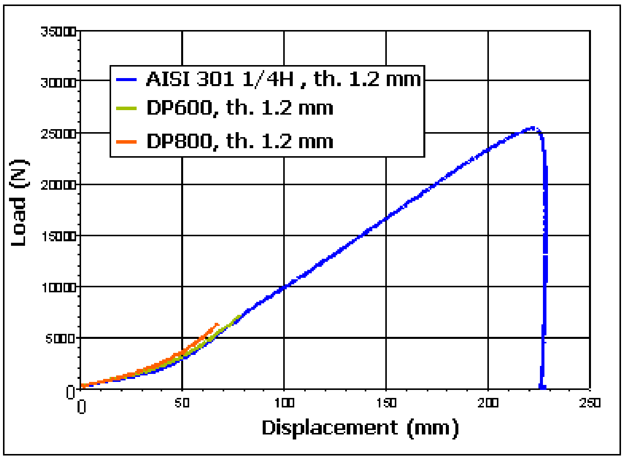
The second feasibility study regarded an anti-intrusion side door beam. This component is designed to protect the passengers inside a vehicle during a lateral impact against fixed objects or other circulating vehicles. The investigation has been carried out comparing the crash behaviour of the anti-intrusion beam for different steel grades after a preliminary geometry optimisation carried out by means of experimental tests on prototipies (Fig.17) and similar mechanical computations (Fig.18).

Fig.17 – Anti-intrusion bar - prototype

Fig.18 – Anti-intrusion bar - Simulation



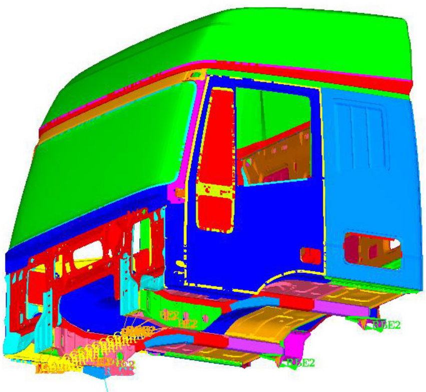
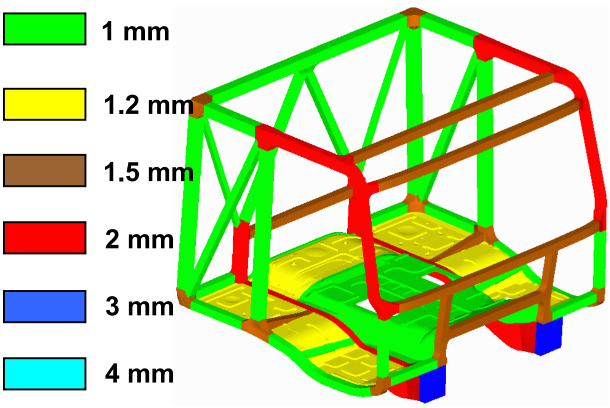
The steel grades considered have been two carbon steels (DP600, DP800) and a stainless steel (AISI 301 1/4 H). The crash behaviour has been analysed according to the pole test defined within EuroNCAP assessment protocols: lateral impact against a 254 mm in diameter rigid pole at a velocity of 29 km/h. In Fig.19 the FEM model used in the pole test numerical simulation is reported whilst the Fig.20 display the load vs. displacement curves obtained with the three investigated solutions. The energy absorbed has been 2700J for the stainless steel, 200J for the DP600 and DP800 with subsequent failure.

Fig.19 – Pole test EuroNCAP.	**Fig.20 – Different solutions - Forces absorbed.**
	

Last feasibilty study regarded a truck cabin, in particular the possibilities to substitute the traditional unibody C steel solution with a stainless steel space frame one. Therefore the feasibility study of stainless steel grades has been associated with a modification of the cabin architecture, substituting the traditional C Steel unibody solution with advanced space frame solution, being the latter one potentially more promising when high strength steel grades are used. Targets of the study were a weight reduction, to enhance the modularity (costs decrease) and improve the cabin structural performances.

First of all, the unibody structure performances have been analysed in terms of both torsional stiffness and crashworthiness by using structural (NASTRAN) and advanced non linear explicit (PAM-CRASH) FEM codes respectively.

Then a first space frame solution, made of AISI 301 stainless steel, has been developed in order to obtain similar mass weight and structural performances with respect to the unibody solution.
Finally a space frame optimisation has been carried out working on both the whole frame configuration and the geometry/thickness of the singular beam. The Figs 21 and 22 show the initial unibody solution and the optimised space frame one. The work has been conducted under the agreement of IVECO.

Fig.21 – Initial truck cabin configuration.	**Fig.22 – Final optimised solution in AISI 301 SS.**
	

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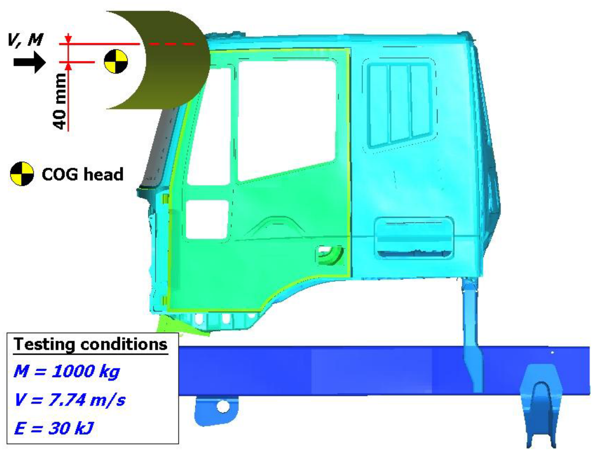
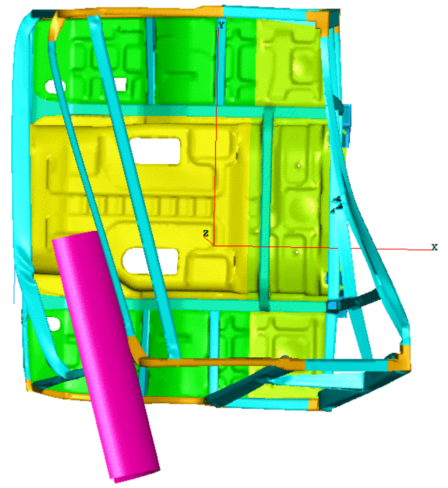
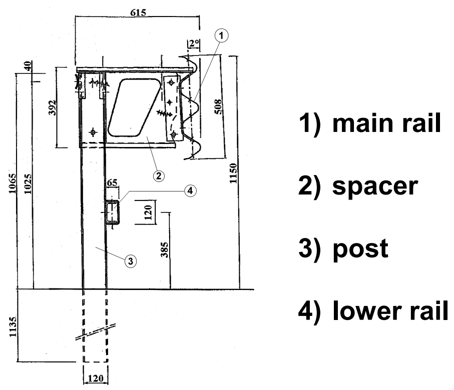
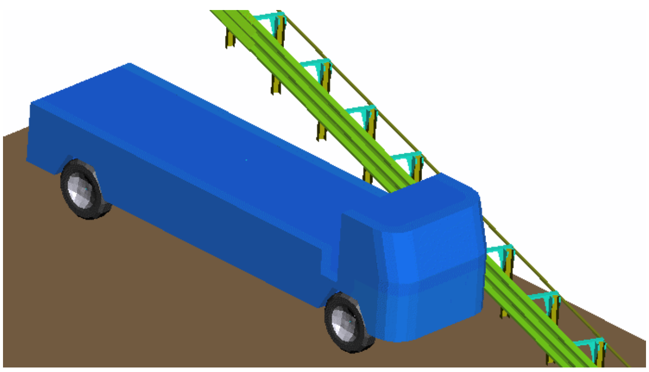
The crash behaviour has been analysed according to the severe Sweden test: it consists in three subsequent impacts on the roof (A), A-pillar (B) and back panel (C) of the cabin.

The Fig.23 reports the Sweden B test configuration: a cilinder of 1000 kg in weight impacts the cabin's A-pillar at a velocity of 7.74 m/s along the truck longitudinal axle, with an inclination of 75 deg with respect to the same direction. In Fig.24 the deformation of the optimised space frame solution after the test is reported.

Fig.23 – Sweden B crash test.	Fig.24 – Space frame - Warped truck cabin.
	

The optimised stainless steel structure allows a total lightening of 64 kg (-27.2%, considering the same final truck cabin configuration) and a stiffness enhancement of over 9800 dNm/rad (+11.5%). In addition, the space frame solution allows a lower loaded point displacement (from 4070 mm to 3650 mm) for the same impacting energy and, subsequently, a better crashworthiness.

As last example of stainless steel structural application a preliminary investigation relevant to the possible use of such steel grades in road safety barriers manufacturing is reported. The study aimed to re-design an existing restraint system by using an AISI304 stainless steel instead of the traditional S235JR carbon steel, maintaining the crash barrier performances and reducing its weight. The Fig.25 shows the barrier cross section whilst the Fig.26 reports the initial state frame of a truck-to-barrier impact simulation.

Fig.25 – High containment road barrier.	Fig.26 – Road barrier and truck FE models.
	

Taking advantage of the higher AISI304 mechanical properties several geometrical parameters of the investigated barrier have been modified:

- Post interdistance: from 1500 mm to 2000 mm (+33%);
- Main rail thickness: from 3.0 mm to 2.8 mm (-7%);

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- Post theickness: from 6.0 mm to 5.0 mm (-15%);
- Lower rail thickness: form 4.0 mm to 3.5 mm (-12.5%).

These modifications allowed a weight reduction of 22 %: 42 kg/m (weight per linear meter) for the stainless steel solution, 55 kg/m for the original barrier. The crash behaviour of both the initial barrier solution (S235JR) and the modified one (AISI304) have been analysed by means of mechanical computations, according to the EN1317 Standard which are relevant to the road barriers homologation. A 900 kg car and a 16 ton truck have been launched against the restraint systems under study at 100 km/h and 80 km/h respectively with an inpact angle of 20 deg with respect to the longitudinal barrier axle.
The two solutions showed similar crash performances in terms of both lateral deformations and accelerations on the impacting vehicles as shown in Tab.2.

Tab.2 – S235 and AISI304 barrier solutions - Numerical results (PAM-CRASH code)

PARAMETERS	Test TB11 – 900 kg car @ 100km/h		Test TB61 – 16 ton truck @ 80km/h	
	S235JR	AISI304	S235JR	AISI304
Permanent lateral deflection [cm]	37	30		
Working Width [m]	1.0	1.0	2.7	2.8
ASI (Acceleration Severity Index)	0.9	0.9	-	-
Exit angle [°]	16	15	-	2
Specific Weight [kg/m]	55	42	55	42

5. CONCLUSION

Material choice is primary to lead automotive industry toward lower weights and higher structural crashworthiness, in order to get fuel economy and less exhaust emission and to improve the vehicle passive safety reducing the road injuries and fatalities.

Stainless steel, thanks to its outstanding cold-workability, fatigue resistance, weldability, corrosion resistance, toughness and ductility characteristics, is a valid choice compared with C steels, HSS and aluminium alloys: it allows to make more performing components and to heavily use new effective technologies such as hydroforming.

Feasibility studies presented show that stainless steel is a very promising material for structural application in the automotive field, allowing the combination of very important features: high formability, corrosion resistance, energy absorption capability.

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