HIGH STRENGTH SHEET AND PLATE STEELS FOR OPTIMUM STRUCTURAL PERFORMANCE

Jan-Olof Sperle
SSAB Tunnplåt AB, Borlänge, Sweden

SUMMARY

Modern quench and tempering as well as continuous annealing make it possible to produce high strength steel with up to 1200 MPa yield strength. This high yield strength gives potential for considerable improvements in performance and reduction in weight, which are of increasing importance in the transport sector and in vehicles used in the construction industry.

This paper describes briefly the static properties, forming, joining and structural strength characteristics as well as crash resistance and energy absorption of high strength steels. Examples of applications are given. Special attention is paid to extra high strength and ultra high strength steels.

Conventional forming and joining methods can be used. By taking into account the qualities and characteristics of high strength steel at the design stage and in production technique the full potential of the material can be utilized.

INTRODUCTION

Industry, particularly in the transport sector, is constantly aiming to reduce weight, increase performance and safety and rationalize production methods. The use of high strength steels with good formability and weldability is increasingly seen as one important way in which these aims can be met.

Quenched and tempered steels with yield strength levels up to 1100 MPa and hot rolled cold forming steels with yield strength levels up to 740 MPa are successfully used in cranes, trucks, dumpers, temporary bridges and similar products. For automotive applications rephosphorized, micro-alloyed and dual-phase cold rolled grades with tensile strengths of up to 1400 MPa and metallized grades with tensile strengths of up to 600 MPa have been introduced.

On the basis of yield strength new types of high strength steels give a great potential for weight reduction and cost effective designs. To exploit the full potential of high strength steels the design philosophy and production techniques must take into accont factors such as formability, weldability, stiffness, buckling, crush resistance and fatigue.

In this paper the high strength steels will be presented with focus on the higher strength levels. The above factors are exemplified and discussed on the basis of optimum structural performance in using high strength steels. Most of the test results presented in this paper refer to cold rolled high strength sheet steel, however, many aspects of the use of these steels are generally applicable. Applications are presented where different high strength steels are successfully used.

THE MOTIVES FOR USING HIGH STRENGTH STEELS

The driving forces behind the increasing use of high strength steels are often connected to the wish to achieve the best structural performance at the lowest possible weight and cost. In general, overall economy of the final product is usually the deciding factor. This is based on material cost, production economy and, increasingly, Life Cycle Costs - an analysis of all the costs and benefits during the entire life of the product.

In such an analysis one should for example consider that by using high strength steel it is possible to reduce material thickness and dead weight of a structure which in turn give higher pay-loads. Lower production weights lead to lower handling costs and less filler material in welding operations. Additionally, modern high strength steels combine several favourable properties such as high strength, weldability, excellent forming and punching characteristics and minor variations in physical properties. All these factors are of primary importance in keeping production costs down.

The environmental advantages of low weight and increased pay-load are also extremely important today when fuel consumption, exhaust emissions and the use of finite global resources must be kept to a minimum.

The use of high strength steel usually leads to lower material costs since the weight reduction more than compensates for the higher price of high strength steel. This means that there is a strong motivation to use high strength steels outside the transport sector and in structures that are regarded as ”simple” such as shelf systems and hinges.

STEEL GRADES

All high strength steel grades produced at SSAB are made by basic oxygen furnace steelmaking followed by continuous casting. Inclusion control is used to increase formability. Steel gradesand mechanical properties are shown in **Table I.** This paper primarily refers to Extra High Strength, EHS ($450 \leq R_e \leq 800$ MPa) and Ultra High Strength, UHS ($R_e > 800$ MPa) steels. When placing steels in these groups the yield strength for DP steels is the one after 2 % work-hardening and bake-hardening.

Table I: Mechanical properties for high strength steel grades

Grade	Steel[1] type	Yield strength (MPa) min	Tensile strength (MPa) min	Elongation (%) A_5 min	A_{80} min	E_c[2]
Weldox 500	HR-MA	500	570	16	-	.39
Weldox 700	HR-MA	700	780	14	-	.38
Weldox 900	HR-MA	900	940	12	-	.56
Weldox 1100	HR-MA	1100	1200	10	-	.68
Domex 350 YP	HR-MA	350	430	26	-	.17
Domex 490 XP	HR-MA	490	550	18	-	.33
Domex 590 XP	HR-MA	590	650	15	-	.32
Domex 690 XP	HR-MA	690	750	15	-	.32
Domex 740 XP	HR-MA	740	790	13	-	.37
Docol 350 YP	CR-MA	350	410	-	22	
Docol 500 YP	CR-MA	500	570	-	12	
Docol 600 DP	CR-DP	350	600	-	16	
Docol 800 DP	CR-DP	500	800	-	8	
Docol 1000 DP	CR-DP	700	1000	-	5	
Docol 1200 DP	CR-DP	1000	1200		4	
Docol 1400 DP	CR-DP	1200	1400		3	
Dogal 350 YP	HDG-MA	350	420	-	22	
Dogal 500 YP	HDG-MA	500	600	-	10	

1) HR = hot rolled MA = microalloyed
CR = cold rolled DP = dual-phase
HDG = hot-dip galvanized

2) $E_c = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$ (Carbon equivalent, typical values)

The Weldox grades are produced in thicknesses 5 - 80 mm. Domex grades are produced in thicknesses 2 - 10 mm and Docol and Dogal in 0.5 to 2 mm.

The Weldox grades are either thermomecanically processed (Weldox 500) or quenched and tempered (Weldox 700 - 1100) hot rolled microalloyed steel plates.

Domex grades are all hot rolled thermomecanically processed microalloyed strip steels. Docol grades are either cold rolled microalloyed steels (Docol 350 - 500 YP) or cold rolled dual-phase steels (Docol 600 - 1400 DP). Dogal grades, finally, are hot-dip galvanized microalloyed steels.

FORMABILITY

All grades mentioned above are intended for cold forming without any extra heating. A low level of non-metallic inclusions and sulphide-shape control are very important for bend formability and edge ductility in hole expansion.

A Domex 690 XP hot-rolled grade can be bent without cracks to a bending radius of 1.6xt (t = sheet thickness). The corresponding value for Weldox 700 is 2xt.

The dual-phase grades can be work-hardened after forming and bake-hardened after paint baking to increase the yield strength by up to a maximum of 300 MPa. Press-forming can be used even on the tensile strength level 1400 MPa but rollforming is the most suitable method for forming Docol 1200 DP and Docol 1400 DP. The press formability of Docol 600 - 1400 DP in comparison with mild steel is illustrated in **Figure 1 [1].**

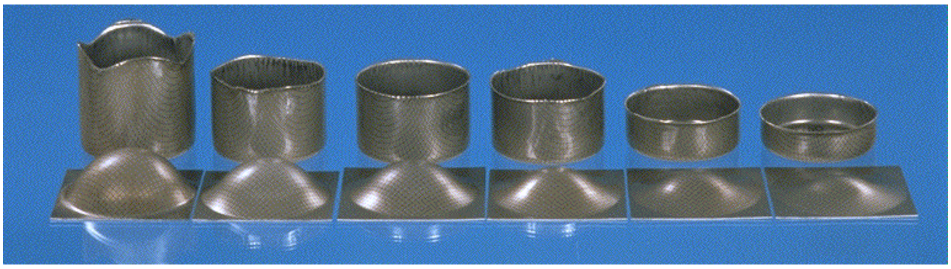


Fig 1 Examples from tests in deep drawing and stretch forming of steels DC O4 (mild steel), Docol 600 DP, Docol 800 DP, Docol 1000 DP, Docol 1200 DP and Docol 1400 DP

Press hardening using the Plannja process, where boron steel sheets are hot formed in cooled tools, is a very interesting alternative to cold forming for complicated parts of very high strength (R_e = 1200 MPa).

WELDABILITY

All grades described in this paper can be welded with conventional welding methods. The reason for the good weldability is the lean chemistry of the steels.

The most common welding methods for hot rolled steel grades are manual metal arc (MMA) and gas shielded arc welding (MAG). For cold rolled and metallized grades spot welding and MAG-welding are most frequently used.

When discussing weldability of high strength steels the matter of most concern is normally cold cracking in the heat affected zone (HAZ). Brittle microstructures such as martensite of high carbon content and high levels of hydrogen together with high restraint forces increase the risk of cold cracking. The carbon equivalent CE, being a measure of the richness in chemical composition, is often used as a value to estimate the susceptibility to cold cracking. If the CE-values given in table I are compared to the CE-value of 0.4 for an ordinary standard high strength steel St 52-3 (R_e = 350 MPa) it is obvious that Weldox and Domex extra high strength steels normally show little risk of cold cracking. For plate thicknesses greater than 10 mm preheating is recommended when working with Weldox 900 and 1100. The weldability of Weldox and Domex steels is discussed in more detail in [2] and [3].

All Docol cold rolled and Dogal metallized products can be MAG-welded or spot welded, but, it is important to adjust the welding parameters according to the alloy content of each grade. For Docol 1200 DP and 1400 DP only spot welding to mild steel is recommended.

MMA- and MAG-welded EHS and UHS steels often show a narrow soft zone in HAZ. In the case of Weldox QT grades and Docol DP grades this is mainly due to tempering and in Domex, Docol and Dogal microalloyed grades due to loss of precipitation hardening in the microstructure. If the soft zone is small in comparison to the thickness of the plate or sheet the strength of the welded joint is not effected due to the high degree of constraint.

The width of the soft zone depends mainly on heat input and the thickness. Low heat input is therefore recommended when welding EHS and UHS steels which have a structural load perpendicular to the weld. In such cases it is also advisable to choose a welding wire which matches the strength of the material to be welded.

Tensile test results on butt welded joints in Domex cold forming steel and Docol cold rolled steels are shown in **Figure 2**. It can be seen that the tensile strength of the MAG-welds in Docol DP steels is somewhat lower than the base metal strength when the tensile strength exceeds 800 MPa. The lower heat input in laser welding does not result in such a loss of strength.

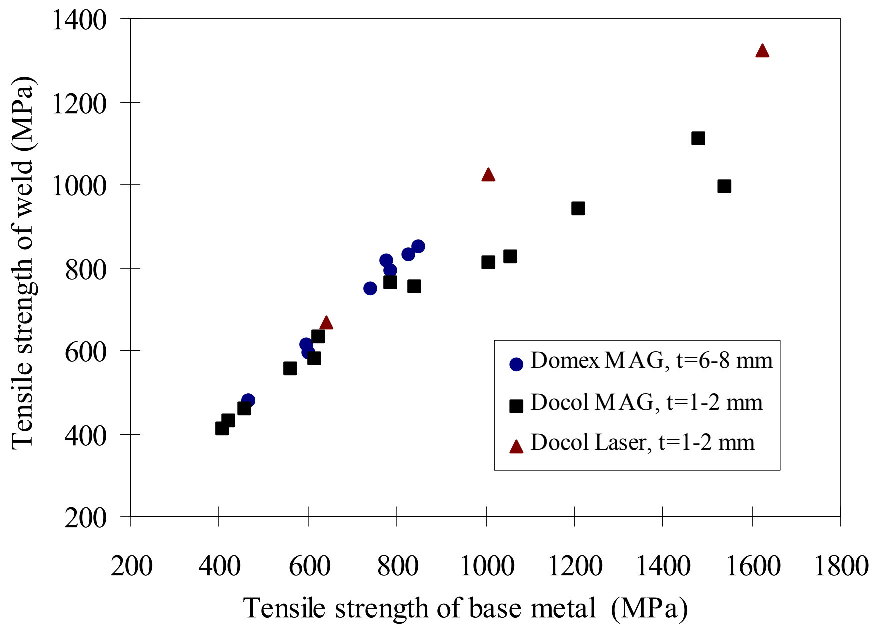
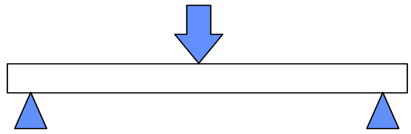


Fig 2 Tensile strength of MAG and Laser welds as a function of base metal tensile strength.

STIFFNESS

The use of high strength steel often leads to weight and thickness reductions. Since the Young’s modulus is the same for high strength steel and mild steel the stiffness decreases when the material thickness is reduced. If this reduction is not acceptable the stiffness loss can be compensated by changing the shape of the section.



Section	t=1.5 25	t=1.0 31	
Grade	Fe P01	Docol 350 YP	Change
Yield strength	220 MPa	350 MPa	MS to HS
Stiffness	**1**	**1**	
Weight	1	0.73	-27%
Load carrying capacity	1	1.14	+14%
Material cost	1	0.80	-20%

Fig 3 Reduced weight and cost with unchanged stiffness

Figure 3 illustrates that a small increase in section height of a beam can compensate for the stiffness loss associated with a thickness reduction, the stiffness being proportional to the square of the section height. This is a very clear example of the advantage of thinking in terms of the properties of high strength steel at the design stage.

BUCKLING

Decreased thickness can result in buckling. The governing parameter for buckling is the width to thickness ratio (w/t) rather than the absolute thickness. This means that the risk of buckling is the same for a 1 mm thick sheet in an automotive structure as in a 20 mm thick bridge structure if the value of w/t is the same. The critical value of the width to thickness ratio, over which buckling will take place before the yield load is reached, is related to the yield strength by

$$(w/t)_{cr} = C \sqrt{\frac{1}{R_e}}$$

where $(w/t)_{cr}$ = critical width to thickness ratio
C = constant depending on overall geometry
R_e = yield strength (MPa)

Cross sections which buckle before the nominal stress in the flanges reaches the yield strength are categorised in cross section class 3 [4]. Cross sections that can be bent plastically without buckling are categorised in section class 1 and cross sections in between those limits in section class 2. The value of C for the limit between section class 2 and 3 is C = 200 for flanges in I, T, C and U sections and C = 520 for flanges in box sections, **Figure 4.**

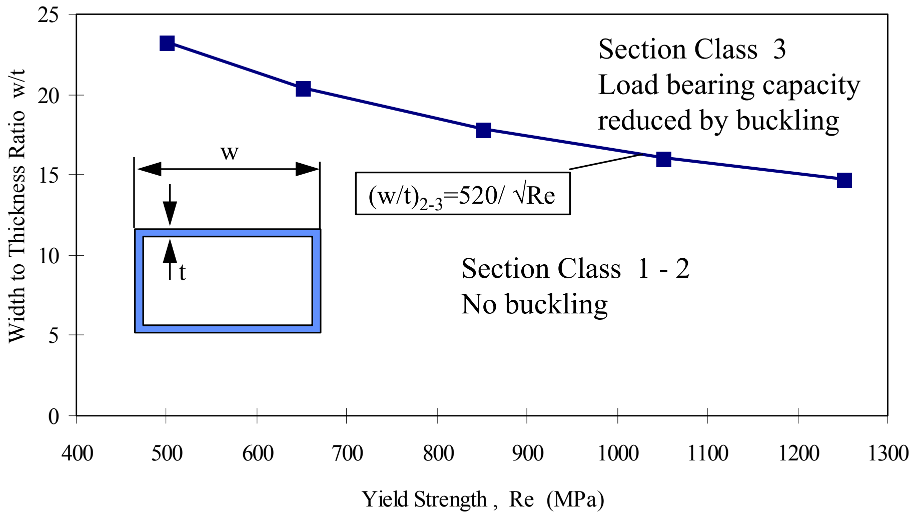


Fig 4 Limiting width to thickness ratio (w/t) for buckling

In order to take full advantage of the properties of high strength steel, cross sections should be in section class 1 or 2. For sections in section class 3 there is, however, still the positive effect of increased yield strength on the load-bearing capacity although it will be somewhat reduced by buckling.

FATIGUE

When introducing high strength steels into fatigue loaded structures it is important to note that the fatigue strength of welded joints does not normally increase with the increasing base metal strength. The reason for this is that the crack-like defects that are present at the weld toes mean that crack propagation will feature in the major part of the fatigue life. Since the crack growth resistance does not differ between mild steel and high strength steel, neither does the fatigue strength of the welded joints. This is illustrated in **Figure 5** where we also see that if the stress concentration is low or moderate as in holes, radii and recesses, a decreased thickness and a higher working stress can be balanced by the higher fatigue strength of the high strength steel.

The fatigue strength for unnotched base metal is strongly related to the surface roughness. Domex grades normally have a surface roughness $R_a \approx 2$ and Weldox grades $R_a = 4 - 8$ [5].

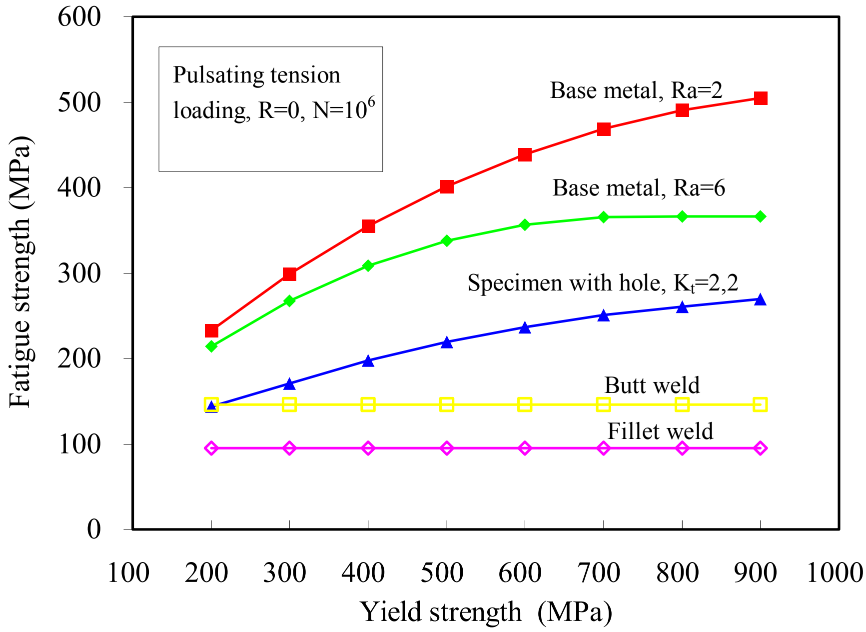


Fig 5 Fatigue strength as a function of yield strength

In order to achieve optimum performance of high strength steels in fatigue loaded welded structures, welds should be sited in areas of low stress. For spot welds the electrode diameter can be increased and the spot pitch reduced. For butt and fillet welds the toe of the weld can be ground or TIG-dressed in order that the fatigue strength of the weld may be adapted to the high strength steel. [4, 6].

CRASH RESISTANCE - ENERGY ABSORPTION

Tougher safety standards, for example regarding crash resistance of cars, have highlighted the interest in extra high strength and ultra high strength cold rolled, metallized and thinner hot rolled sheet steels. These steels are effective both for absorbing large amounts of energy, as in the front and rear of a car, and for withstanding high peak loads, as in the structure constituting the passenger compartment.

In order to increase knowledge of how yield strength, thickness and overall geometry influence the energy absorption, static and dynamic tests in axial compression and bending have been performed on different sections.

These tests, summarized below, are described in more detail in [7, 8, 9].

Axial crush tests

Static and dynamic axial tests have been performed on DP steels. The test specimens were 300 mm long rectangular hollow sections, 60x60x1.2 mm, developing an accordion-like deformation pattern when loaded in axial compression. The specimens were manufactured by joining two formed U-sections together by gas metal arc welding. Impact loads were achieved by accelerating steel pistons in a horizontal tube to the predetermined speed, 50 km/h.

As expected, the absorbed energy increases with the increasing tensile strength of the steel grade, **Figure 6.**

A comparison of results for static and dynamic tests confirm that there is a positive effect of crush speed for all steels including UHS-steels. This means that all these steels have a positive strain rate sensitivity.

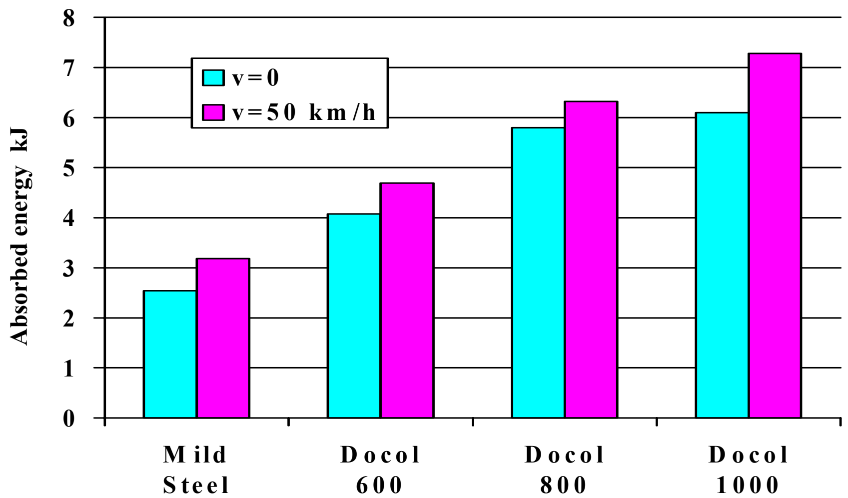


Fig 6 in Absorbed energy in axial crush tests on rectangular hollow sections DP steels

Bending tests

Bending tests related to the application of high strength steels, for example in door intrusion beams, have been performed on rectangular sections 50x30xt mm. The thickness t varied from 1 to 2 mm. Cold rolled dual-phase and microalloyed steels as well as hot rolled microalloyed steels have been tested. The bending tests were carried out using three-point bending. The distance between the supports was 800 mm. During the test the load displacement plot was recorded. The maximum deformation was 150 mm. The maximum ultimate load, P_{max}, as well as the absorbed energy were evaluated.

Results expressed as ultimate load P_{max} are plotted against yield strength in **Figure 7**. As expected the load-bearing capacity increases with increasing yield strength.

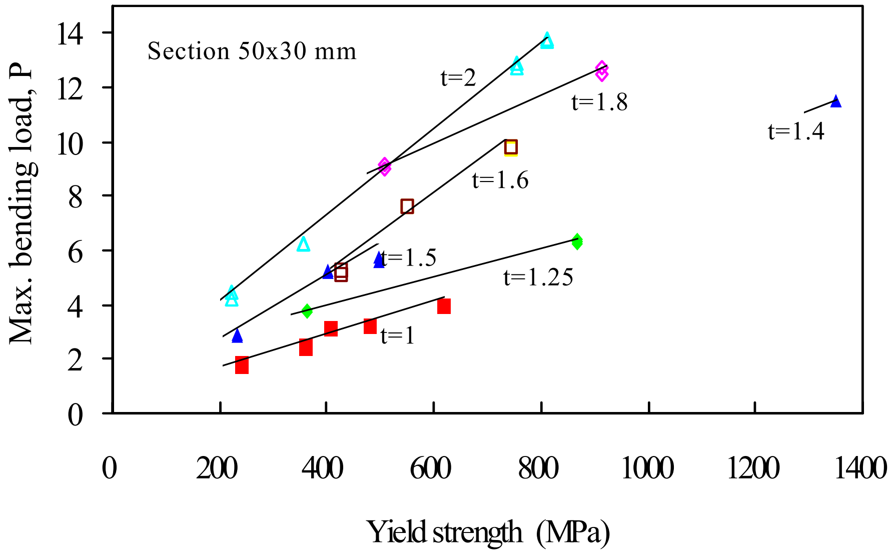


Fig 7 Maximum load P_{max} vs. yield strength for bending tests

Based on results from the axial crash tests and the bending tests we can draw some conclusions as to the gain in energy absorption at unchanged thickness and reduced weight when using high strength steels instead of mild steels, **table II** [9].

Table II: Gain in energy absorption and weight reduction when using high strength Docol DP steels instead of mild steels

Docol DP grade	600	800	1000	1200	1400
Gain in energy absorption %	35	55	75	90	105
Weight reduction %	25	30	35	40	45

APPLICATIONS

Based on the knowledge of how yield strength, plate thickness and overall geometry influence the structural properties and manufacturing properties of different constructions, high strength steels have already been successfully used in many applications.

Hot rolled extra high strength steels are used for example in cranes, trucks and earth moving equipment. **Figure 8** shows an application where Weldox 700 and Weldox 900 have been used for a mobile crane boom. Note that there are no welds on the flanges. The longitudinal weld situated in the neutral layer gives optimum structural performance in terms of fatigue.

The use of Domex 690 XP grade is exemplified with a truck frame, **figure 9**. Note that rivets are used instead of welds in order to achieve the best fatigue performance.

Another application for Domex 690 XP is a side reinforcing bar, which is a part of the Volvo side impact protection system, **figure 10**.

Fig 8 Crane boom in Weldox 700 and Weldox 900

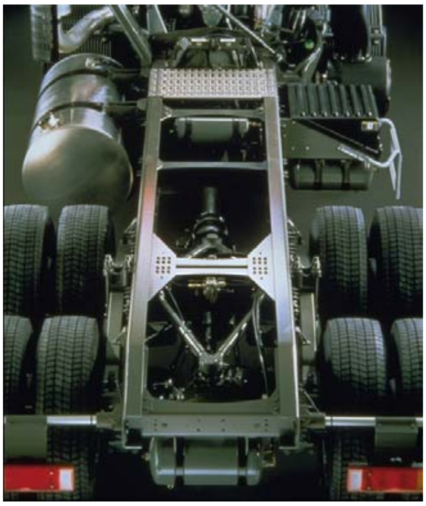


Fig 9 Truck frame in Domex 690 XP

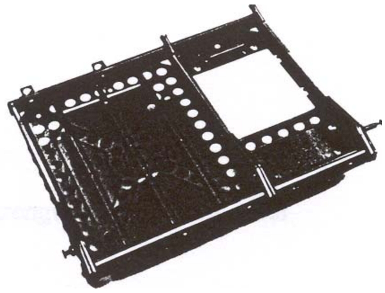


Fig 10 Door intrusion beam in Domex 690 XP

Fig 11 Back seat of the Volvo 850 Docol 600 DP

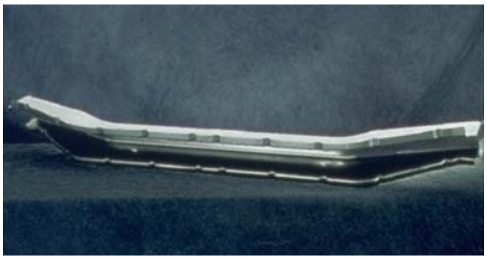


Fig 12 Bumper reinforcement in Docol 600 DL

Fig 13 Back seat top beam in Dogal 500 YP

Figure 10 shows a door beam where the use of Domex 690 XP combines high energy absorption with good cold formability and low weight.

Figure 11 shows the back seat of the Volvo 850, where press-formed parts and tubes produced from Docol 600 DP are included to save weight.

Figure 12 shows a bumper reinforcement made of dual-phase grade Docol 600 DL where the low yield ratio gives the good formability to make the part.

When corrosion protection is of great importance hot-dip galvanized microalloyed steel grades can be used. **Figure 13** shows a transversal safety beam made of Dogal 500 YP which is used in the top of the back seat construction by the SAAB.

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