STRUCTURAL APPLICATIONS OF STAINLESS STEEL

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ABSTRACT

In the recent years a need has been developed in several countries for a more comprehensive design specification for cold-formed and hot-rolled stainless steel structural members. Because of the limited life of carbon steel in bridges and structures that are exposed to moderately to highly aggressive atmospheres, stainless steels in spite of their higher cost can be an alternative to carbon steels. The excellent performance of the austenitic stainless steels in fire conditions and during seismic events is a good reason to introduce stainless steels as structural elements in construction.
With this increasing attention being paid to crashworthiness, energy absorption is a key property of the material used for structural parts. Stainless steels and among them austenitic stainless steels have the advantage over aluminium alloys and carbon steels of being highly strain rate sensitive. This means that the faster the loading is applied, the more the material resists deformation. This is a particularly good feature for crash worthiness as in all crash events the loadings are applied very rapidly.
Due to the good energy absorption properties of stainless steel a number of alternative ideas are being continuously developed throughout the automotive industry.
Starting from the fifties, a lot of research was done about the beneficial effect of nitrogen on the mechanical and corrosion properties and now the class of low-Ni high Mn-N steels is going to play an important role in materials selection for structural applications.

KEYWORDS

Structural application, Stainless steel, Automotive, Architecture, Fire resistance.

INTRODUCTION

During its nearly one-century story, stainless steel has been used mainly for corrosion resistance, durability and beautiful appearance.
Stainless shows excellent corrosion resistance in many atmospheres, due to a phenomenon known as passivity. The material protects itself from its environment by forming a very thin passive film, or layer, at its surface. Strongly bonded to the substrate, this film prevents further contact between the metal and surroundings. This passive layer is also self-healing. If there is chemical or mechanical damage to the film, repassivation will occur, in oxidising environments.
Stainless steel is a light material, with a specific stiffness equal to that of so-called light alloys. High strength grades provide a unique combination of strength, fatigue resistance, ease of forming and ease of joining (by welding, brazing, adhesive bonding, etc). High strength stainless means reduced thickness and, thus, reduced weight. The absence of surface protection both reduces weight and eliminates chemical emissions from anti-corrosive protection processes.

More recently the need to combine corrosion resistance and good mechanical properties led to the introduction of new classes of materials ferritic structure (3Cr12 and then EN 1.4003) or of austenitic structure with manganese addition (AISI 2xx series). Another interesting chance is due to the high increase of mechanical strength that can be obtained with austenitic stainless steel subject to cold working. Fig. 1 shows the work hardening of some austenitic grades as a function of cold rolling reduction.

Structural grades

The austenitic stainless steels are generally the more useful groups for structural applications. The combination of good mechanical properties, particularly ductility, ease of forming and excellent resistance to corrosion, makes these grades largely used for various components and fasteners in buildings and in the mechanical industry. 1.4301 (AISI 304) and 1.4401 (AISI 316) are the most popular grades, but also low-carbon and stabilised grades are frequently used for welded joints.

1.4003 (chemical composition in Table I) is a chromium containing corrosion resisting steel developed as an alternative material of construction where the mechanical properties, corrosion resistance and fabrication requirements of other materials such as mild steel, galvanised or aluminised steel, aluminium or pre-painted steels are unsuited. It was developed specifically as a utility grade combining low cost with good resistance to wet abrasion and mildly corrosive environments.

Typical applications include:

- Mining and mineral processing and transport equipment
- Rail wagons for coal and iron ore
- Sugar processing equipment
- Furnace and oven parts

This steel was developed to obtain a ferritic grade with a good weldability up to thicknesses of approximately 30 mm. This made available small to large sized sections also in the hot-rolled condition [1]. Further developments were presented on the market by ThyssenKrupp and Sandvik regarding a new titanium stabilised grade with higher mechanical properties and good weldability [2].

Mn-N steels, 1.4372 (AISI 201) and 1.4373 (AISI 202), whose chemical compositions are also reported in Table I, are more sensitive to cold working than chromium-nickel steels and their yield stress is higher both in the annealed and in cold worked condition and regarding specifically toughness, do not show any transition temperature.

Further improvements have been obtained by slight composition modifications with the purpose to reduce to minimum delta-ferrite volume fraction and to increase corrosion resistance and now different alloys are under development for structural applications in particular in the automotive industry with very encouraging performances (see for instance STR18 steel in Fig.1).

Duplex stainless steels are a class of steel characterised by a biphasic structure $50\alpha/50\gamma$ with reduced carbon and nickel content thanks to nitrogen addition (from 0.12% up to 0.25%). Their elevated mechanical properties allow lightening the structures and, due to their very good corrosion resistance, they can be used in those applications requiring long duration in service in aggressive environments (e.g. bridges, facing the sea buildings). Despite the strength ($Rp_{0.2}$>400 MPa for 1.4462 steel as a hot rolled plate), duplex stainless steels exhibit good ductility and toughness. Compared with carbon steels and ferritic stainless steels, the ductile-to-brittle transition is more gradual, so they retain good toughness even to ambient temperatures as low as -40°C [3].

Table I – Chemical composition (mass %) of the most commonly used stainless steels for structural application

EN Type	Description	C	Si	Mn	P	S	N	Cr	Ni	Mo	Others
1.4003	Ferritic; the lowest structural grade	0,03	1	1,5	0,040	0,015	0,03	10,5-12,5	0,3-1		
1.4372	Mn-N steel resistant to abrasion	0.15	1	5,5-7,5	0,045	0,015	0,05-0,25	16-18	3,5-5,5		
1.4373	High Mo alloy for severe corrosive environments	0.15	1	7,5-10,5	0,045	0,015	0,05-0,25	17-19	3,5-5,5	4,7-5,7	Cu: 1-2
1.4310	Can be rolled to high tensile strength	0,15	2	2	0,045	0,015	0,11	16-19	6-9,5	-	
1.4301	Most commonly used	0,07	1	2	0,045	0,015	0,11	17-19,5	8-10,5	-	
1.4306	Low carbon grade for welding heavy-gauge sections	0,03	1	2	0,045	0,015	0,11	18-20	10-12	-	
1.4401	Suitable for seaside atmosphere	0,07	1	2	0,045	0,015	0,11	16,5-18,5	10-13	2-2,5	
1.4404	Low carbon grade for welding heavy-gauge sections	0,03	1	2	0,045	0,015	0,11	16,5-18,5	10-13	2-2,5	
1.4571	Stabilised grade for welding heavy-gauge sections	0,08	1	2	0,045	0,015	0,11	16,5-18,5	10,5-13,5	2-2,5	Ti=5C-0,70
1.4462	Duplex grade. High strength and corrosion resistance	0,03	1	2	0,035	0,015	0,1-0,22	21-23	4,5-6,5	2,5-3,5	

2. AUTOMOTIVE APPLICATIONS

These days, automobile constructors have to build lightweight vehicles. In the past, the only alternative to conventional materials has been so-called light metals. These, however, are expensive, and lend themselves ill to welding. Stainless steels have outstanding mechanical properties. Combining exceptional weldability and formability, they enable designers to make stainless steel parts as light as their "light metal" counterparts. The number of parts can often be reduced and assembly complexity optimised. Stainless steel can thus have economic benefits over competing materials. Offering weight savings, enhanced "crashworthiness" and corrosion resistance, it can also be recycled. The material blends tough mechanical and fire-resistant properties with excellent manufacturability.

The applications in the automotive market are based on those properties that are particularly interesting and significant in sheet and plate components and structures such as:

- The opportunity to utilise the large strain hardening of these steels to reach high strengths by cold working (Fig. 1).
- Cold worked austenitic stainless steels exhibit generally a better combination of strength and formability than high strength carbon steels (see also Fig. 1).
- Similarly the fatigue strength of the stainless steels is better.
- The strain hardening and the behaviour at high strain rates of the austenitic and duplex steels make them especially suitable in components for energy absorption in crashes [4].

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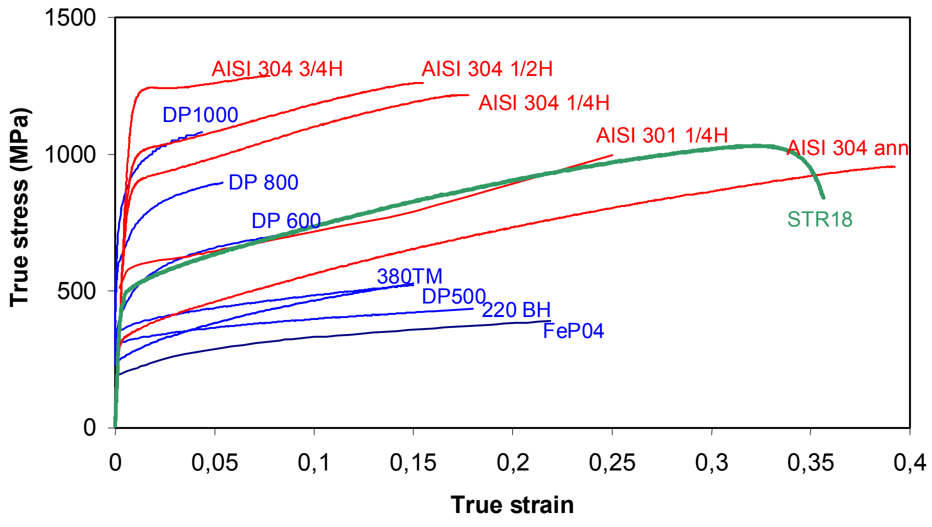

Fig. 1 – True stress-true strain curves of carbon steels (in blue) and austenitic stainless steels (in red). New structural high Mn-N-low Ni steel STR18 is also shown in green.

Stainless steel is an excellent candidate for structural applications in cars. The competition between different materials in this area is intense. Choice centres on mass saving, formability, weldability, corrosion resistance, fatigue resistance, cost and environmental factors. Safety and crashworthiness, especially, should take priority. Crashworthiness refers to the ability of a vehicle's structure to protect the passengers. It now also means the ability to withstand minor accidents with little damage. Car designers today seek the very best stiffness, mass-reduction and safety performance

The average passenger car uses about 15 to 22 kilos of stainless steel. Mainly found in the exhaust system, stainless also occurs in sundry small parts.

Exhaust systems

Most cars have stainless in the exhaust, around the catalytic converter area. This is the main, well-established automotive growth market for stainless steels. Exhausts release polluting hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx) into the atmosphere. The catalytic converter became a must in densely populated urban regions of the U.S. and Japan in the 1970s and has since become obligatory in many parts of the world. It changes HC, CO, and nitrogen oxides into harmless water, carbon dioxide, and nitrogen. However, its action changes the temperature and the corrosive conditions in the system. Non-corrosive materials are thus needed to prevent rusting. An exhaust system has a hot end (the exhaust manifold, down pipe and catalytic converter) and a cold end (the resonator, intermediate pipe, silencer and tail pipe).

At the hot end, the material must resist creep (due to high temperatures) and oxidation. Special "refractory" stainless grades have been developed for this area. The cold end has to deal with agents, such as salt, used on the roads to combat snow and ice. Both inside and outside corrosive factors are thus at work. The hot end really requires high-temperature austenitic stainless - the more highly alloyed grades such as 1.4828 or 1.4845(AISI 310) (25% chromium, 20% nickel) but ferritic grades are finding larger and larger application as 1.4509 (AISI 441) and research activities are in progress to adequate hot temperature performance to the even more stringent requirements of the national standard on exhaust gas emissions.

Towards the cold end ferritic type 1.4512 (AISI 409) or 1.4510 (AISI 439) will do. Austenitic grades, type 1.4301 (AISI 304), is used for tail pipe due to its good resistance to heat tinting. They are also more resistant to corrosion, the presence of which could be cosmetically undesirable. Many manufacturers use ferritic for the entire system avoiding compensation joints for the thermal expansion different between austenitics and ferritics [5, 6].

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Fig. 2 summarises the selection criteria for the use of the most suitable grade in the different parts of a car exhaust system.

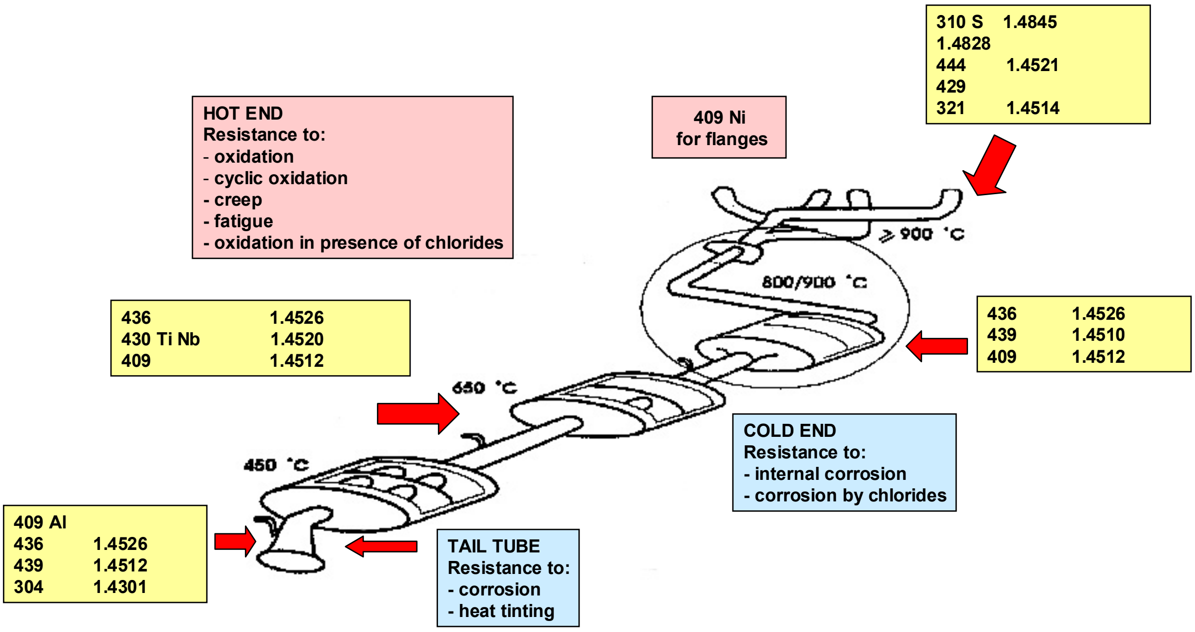

Fig. 2 – Selection guide to the most suitable grades for car exhaust system components

All-stainless catalytic converters

Exhaust systems are an example of stainless winning market share from other materials. Next the all-stainless catalytic converter will come. Currently, the catalytic surface is ceramic material, which makes it large and heavy. Now, size and weight can be reduced by replacing the ceramic substrate with specially designed high-Al stainless steel foil, of 40 microns or less, which form a thin compact layer of alpha-alumina on the surface that is essential for good performance of the catalyst [7]. Stainless also has the advantage of conductivity, so the catalytic converter can be preheated electrically. The catalytic effect is thus there from the moment the engine is started. At present, driving down to the local store might generate no catalytic effect. With stainless steel, the 'cat' reaches working temperature in seconds.

Trim, gaskets and suspension systems

Ferritic for interior and exterior decorative trim is a well-established growth area. It is easy to work, and specific grades containing molybdenum and niobium have high corrosion resistance and excellent appearance when formed. Stainless is increasingly used in parts such as hose clamps, head gaskets, pump bodies, heat shields, windscreen wipers, airbag inflation-gas containers and seatbelt springs. This is due to its corrosion resistance, manufacturability (fabrication-friendliness) and tough mechanical properties. In the past, cylinder head gaskets were made of a "sandwich" of asbestos and steel sheets. Today, with the total ban on asbestos and the higher pressures and temperatures of modern engines, a new design is needed. One of these gives excellent resistance to heat and corrosion. It uses 3-5 layers of thin rubber coated, hardened stainless steel sheets, each 0.25mm thick or less [8]. Using various demonstration models, it has been shown that stainless can be used to give advantage to suspension systems with interesting weight reduction.

Fig.3 illustrates an example [9]: The carbon steel reference part weight is 2.730 kg. Two stainless steel suspension arms were studied in 1.4318 (301L) grade with the same performance as the reference part:

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1. Two plain stamped parts, MIG welding assembled: weight =2.180 kg
   Weight reduction of 20% (550g)
2. Single part: special design with windows: weight =1.740 kg
   Weight reduction of 36% (990g)

Fig. 3 – Suspension arm in 1.4318 stainless steel

Fuel tanks
Producers also have high hopes for fuel tanks as a major new market. With tighter environmental legislation, becoming effective in California in 2004, current tank materials will have difficulty meeting emission laws. Some automotive manufacturers are considering stainless tanks for their entire U.S. vehicle range. A stainless steel tank neither leaks nor absorbs vapour. It does not require a protective coating and it can be fully recycled. New hydro-forming techniques make it easy to form it into complex shapes for tight chassis spaces [10]. As the cost reduction is a chief factor for inducing tanks producers to move from plastics to stainless steel, interesting perspectives are open by the use of low-Ni austenitic stainless steels that combine excellent formability and lower cost.

Strain rate sensitivity
The dynamic energy involved in a crash is first absorbed through the plastic strain of the material. The higher the material’s mechanical properties, the more energy it can absorb. The mechanical properties of stainless grow with an increase in the dynamic strain rate. The faster the loading is applied, the more stainless resists deformation. This makes for good crashworthiness since, in a crash, loading is applied very rapidly. A well-designed stainless structural part will also collapse progressively, in a controlled and predetermined way. This has obvious passenger-safety advantages. Of all steels, high strength stainless offers the highest energy absorption capability in relation to strain rate.

The space frame
The exciting, new “space frame” concept, still experimental, may revolutionise vehicle structure. It involves bonding non-structural bodywork, like a skin, to a tubular framework of thin-wall tube (Fig. 4). The framework is the structure. This concept would enable very rapid design of a new car. Space frames, currently used in some niche vehicles, could have great potential for stainless steel.

In the passenger car field, Autokinetics Inc. of Rochester Hills, Michigan had developed structural and manufacturing techniques for the cost-effective use of stainless steel in spaceframes and suspensions. A study was conducted with funding from the U.S. Department of Energy to determine whether this approach could be applied to transit buses as well [11] and the conclusion was that high-strength stainless steel has the potential to achieve mass reductions of bus structures on the order of 60%. It also appeared that this can be achieved in a practical and cost-effective manufacturing

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system, using existing processing technology, due to the well demonstrated ability to form, cut, weld, and cast stainless steel into strong, lightweight structures. Based on this experience, an ultralight stainless steel 40-ft hybrid-electric urban bus was developed, featuring a low floor monocoque-type structure, as well as four wheel independent suspension that operates with no interior intrusion for axle clearance, and a front frame crush zone to improve occupant safety in the event of a collision. The bus has an estimated curb weight of only 9,600 pounds, which represents a mass reduction of 64 percent compared to conventional buses, thereby improving passenger carrying payload and fuel economy.

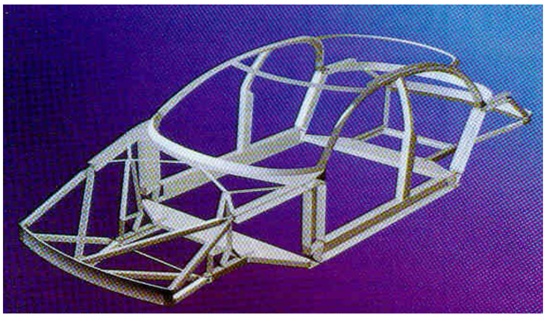


Fig. 4 – ARMCO-Autokinetics spaceframe in Nitronic stainless steel (austenitic with Mn-N alloying): cast sections and nodes.

3. STAINLESS STEEL IN CONSTRUCTION

The use of stainless steel for construction has grown rapidly in recent years, due to a combination of several factors, namely their: structural efficiency, corrosion resistance and ease of maintenance, improved fire resistance, pleasing appearance and, last but not least, increasingly competitive prices [12].

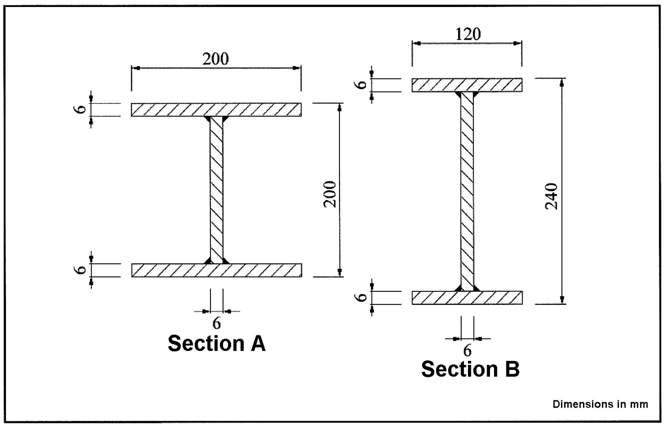
The most promising use of stainless steel in ordinary building is obviously in the form of light-weight members relying on corrosion resistance and good performance in case of fire and seismic events, which may compensate for the high cost of fabrication.

It is clear that for a material with high initial cost, efficient design is paramount, and a more rigorous and complex design approach is justified. Structural design standards for carbon steel should not be applied to stainless steel because stainless steel has different strength and stiffness properties. The major difference between the mechanical properties of carbon and austenitic stainless steel is the stress-strain relationship: stainless steel has a continuous, but non-linear, relationship between stress and strain, whereas carbon steel has a clearly defined yield point.

In 2002, Euro Inox published the Second Edition of the Design Manual for Structural Stainless Steel [13], design recommendations arising out of an international collaboration and aimed at contributing to the Eurocode EN 1993-1-4 "Design of steel structures, Supplementary rules for stainless steels".

FIRE RESISTANCE OF AUSTENITIC STAINLESS STEELS

Studies on fire resistance of stainless steels have been carried out by different European laboratories [14-16] and highlighted the excellent performance of austenitic steels.
CSM research programme was based on 1.4301 welded beams; it was divided into two main activities: the former consisting in a finite-element modelling, the latter based on full scale testing on stainless steel welded beams, with the same nominal dimensions as those utilised for the finite element modelling, at the Fire-Fighting Research Centre of the Fire Department in Rome.



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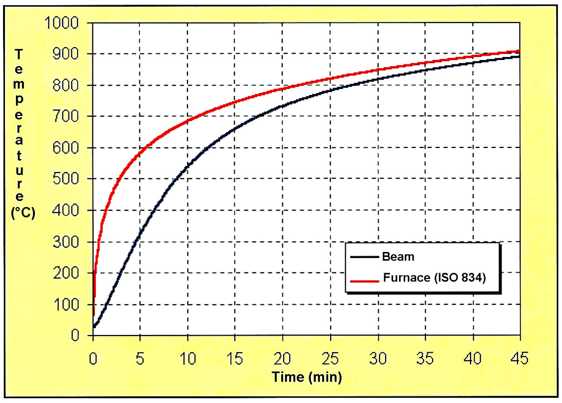
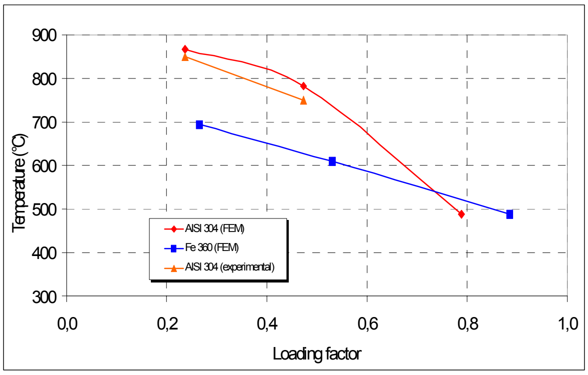


b)

Fig. 5 – Fire resistance testing a) schematic drawing of sections; b) temperature increase curve

Two different sections, marked by A and B (Fig.5a) were considered. Beams were schematised with shell type elements with four nodes and stressed according to the 4-points bent beam configuration A progressive increase in temperature was applied to the section, starting from room temperature, with the particular slope given by ISO CD 834 Standard, establishing the incremental variation of the section temperature as a function of instantaneous furnace temperature and section geometry. The temperature increase with time imposed to the model was as shown in Fig. 5b. Further details on the experimental conditions can be found in [17].



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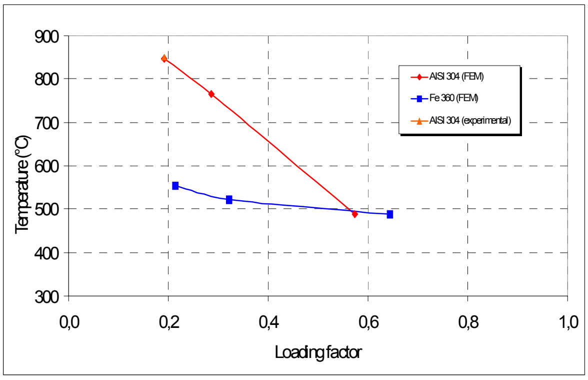

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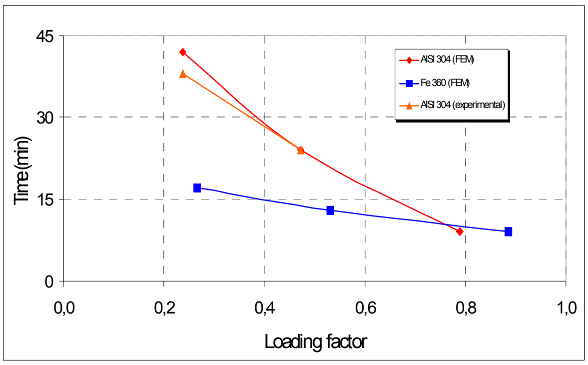

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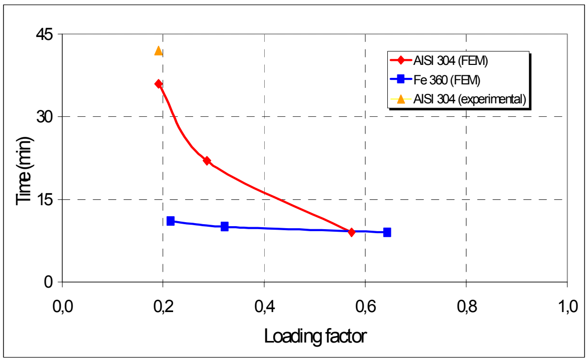

d)

Fig. 6 – Fire resistance test results as a function of loading factor a) Beam A critical temperature; b) Beam B critical temperature; c) Beam A critical time; d) Beam B critical time

The results of the full scale testing are reported in Figs. 6a-d, together with the results of the finite elements calculations. In the figures, critical temperature and critical time to collapse for both the

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beam types examined are shown. Loading factor is the ratio between the applied load and the load that in a full-scale testing induces yield on the beam at ambient temperature

The comparison with the traditional carbon steel Fe 360 performance has been done only for the calculated values, as no experimental data were available on this latter steel.
The excellent agreement between numerical prediction and experimental values on 1.4301 steel is worth to note. This justifies the comparison between stainless steel and carbon steel, for which, as already mentioned, only calculated values are available.

Diagrams show that with loading factors below 0.5, it is possible to attain high temperature without collapse and in this case the use of EN 1.4301 is appreciably more convenient. In fact, the time of resistance to fire of 10 – 15 minutes, typical of Fe 360 increases up to 20 – 30 minutes for EN 1.4301, in a temperature range up to 650 – 800°C that is considered as the most critical for metallic structures during a fire accident. In this way, the time at disposal for the firemen intervention is in theory almost doubled and it is possible to operate on the structure in safe conditions.

4. SEISMIC BEHAVIOUR OF AUSTENITIC STAINLESS STEELS

The steel is also required to have so good toughness that no brittle fracture or important ductility loss occurred when subject to high deformation rates.
As a confirm, mention is to be made of some results, Barba & Forin [18] obtained on austenitic stainless steel for improved-bond reinforcing bars in comparison with the conventional carbon steel Fe B44K. Tests were performed at alternate stresses, reproducing those generated by seismic events (Figs. 7a-c).

Diagrams clearly illustrate that austenitic stainless steel has better performance in all the mechanical properties taken into account: higher yield and ultimate tensile strength, higher deformation energy absorption, higher uniform elongation. In addition, the improved performance of stainless steel are maintained or even increased with increasing stressing rate. In fact, figures show an influence of the stressing rate at low rates, but this markedly decreases at the higher rates that are typical of seismic events.

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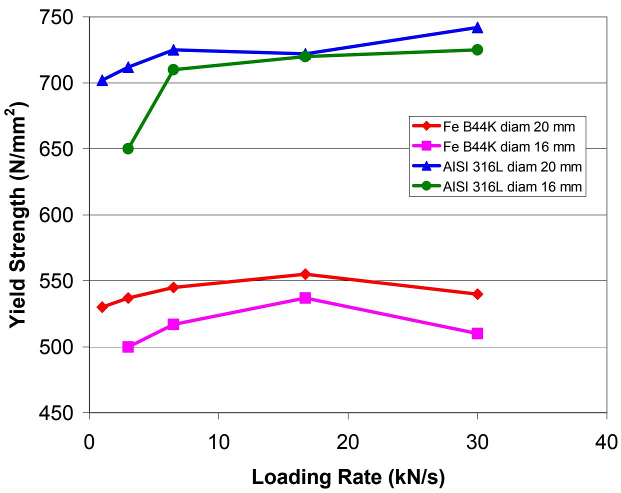

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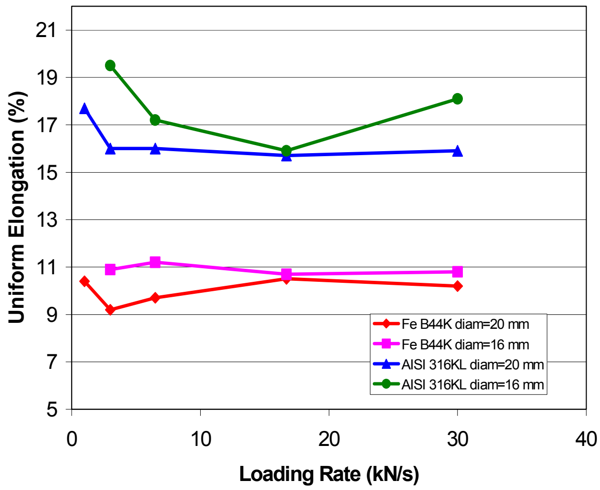

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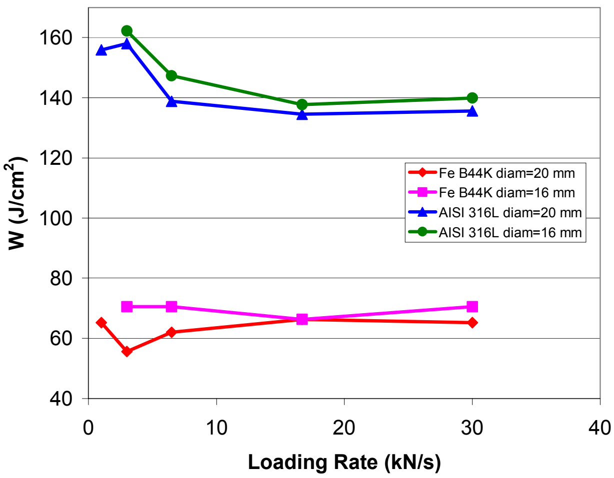

c)

Fig. 7 – a) Yield strength, b) Uniform elongation and c) Deformation energy before necking as a function of loading rate.

5. ARCHITECTURAL APPLICATIONS

In architecture, as in any other industry, stainless steels are used in applications where functions and economics combine to make them a logical choice. In most architectural applications appearance, prestige, and quality image combine with functional considerations such as resistance to impact, abrasion and corrosion, high strength and durability. The durability and diversity of surface finishes on stainless steel are essential attributes for building materials in modern architecture.

Because of the quality image and aesthetic importance of the building components made with stainless steels, proper care in steel mill production, component fabrication and erection and, on the part of the designer, good detail design are of great importance. Minor faults in appearance or function that an architect might accept when other materials or metals are used are considered unacceptable when stainless steel is used.

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The principal areas where stainless steel is often used in architectural metal work are:

- Miscellaneous ornamental metal.
- Building entrances and storefronts.
- Roofing, siding and ductwork.
- Building façades.
- Bridges

Some interesting applications relevant to the last point mentioned are here below briefly reviewed.
A new foot and cycle bridge was built in the town of Terni, Italy on River Nera (Fig. 8). The project was based on an "arch shaped" static scheme with a suspended deck. Stainless steel was chosen to withstand the aggressive environment. The arch has a span of 32 metres and is 7 metres high. The deck is 5,25 metres large [17]. All building elements, included bolts and ties, are made with EN 1.4401 (AISI 316) except for arch shaped tubes and supporting tubes under the deck that are in carbon steel

Figure 8 – Footbridge in Terni (courtesy of Centro Inox).

The shiny new stainless steel bridge for pedestrians and cyclists that spans the Sickla Canal in the Hammarby Sjöstad area of Stockholm (Fig. 9), has received the prestigious European Steel Design Award [19]. The bridge's load-bearing sections have been manufactured using 8 to 25 mm gauge high-strength duplex stainless steel hot rolled plates.

Figure 9 – Duplex stainless steel bridge on Sickla Canal in the Hammarby Sjöstad area of Stockholm.

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6. CONCLUSIONS

The peculiarities making stainless steel a powerful alternative for structural applications have been shortly illustrated:

- Good formability
- High mechanical strength;
- High deformation ability until fracture;
- Ability to absorb high amount of energy;
- Good toughness also at low temperatures.

Stainless steel is a light material, with a specific stiffness equal to that of so-called light alloys.

An important point to be considered is also its intrinsic durability and resistance to corrosion: stainless steel guarantees that these properties stay unaltered during the entire life cycle of the component, without any maintenance.

Some selected applications in the automotive and construction industry have been highlighted. Stainless steel showed a very good resistance to fire in the full scale testing. This material in some structural applications can be therefore a valid alternative to traditional carbon steel coated with insulating anti-fire painting.

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