A FIRE ENGINEERING APPROACH TO THE DESIGN OF STAINLESS STEEL STRUCTURAL SYSTEMS

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Abstract

The relatively sparse body of existing data on the behaviour of structural stainless steel at high temperatures suggests that stainless steel performs very well in certain circumstances due to its strength and stiffness retention characteristics at elevated temperatures. This paper gives an overview of the findings of a three year European research project which studied the behaviour of a range of structural stainless steel solutions subject to fire loading. The project included tests on materials, members and connections, numerical analysis and development of design guidance aligned to Eurocode 3: *Design of steel structures* and Eurocode 4: *Design of composite steel and concrete structures*. The performance of the stainless steel systems compared favourably with that of similar carbon steel systems at temperatures between 600ºC and 800ºC.

Introduction

All metals lose strength and stiffness when heated, though there is considerable variation in the rate of the degradation of mechanical properties between different metals. Austenitic stainless steels exhibit better strength retention than carbon steels above about 550ºC and better stiffness retention at all temperatures. The main reason for this is the difference in crystal structure of the two metals. The atoms in an austenitic microstructure are more closely packed than in carbon steels, which have a ferritic microstructure. Austenitic stainless steels have a relatively high level of alloying elements compared to carbon steels. Alloying additions tend to lower the diffusion rates of atoms within the crystal lattice at a given temperature which slows down the softening, recrystallisation and creep deformation mechanisms which control strength and plasticity at elevated temperatures. Additionally, carbon steels undergo transformation from ferrite to leanly alloyed austenite on heating. The austenitic steels, in contrast, do not undergo a structure change in the range of temperatures relevant to fire resistant design.

As a result of the superior strength and stiffness retention, stainless steel columns and beams generally retain their load-bearing capacity for a longer time than equivalent carbon steel columns. A conservative approach to fire resistant design of stainless steel structures is covered in an informative annex to EN 1993-1-2[1], despite fire test data on stainless steel structural members being sparse. In an attempt to develop more comprehensive and economic design guidance, the Stainless Steel in Fire project started in 2004, funded by the European Research Fund for Coal and Steel (RFCS) and stainless steel producers. The final report of the project will be presented to the RFCS in 2008[2]. SCI co-ordinated this project and the partners were CTICM, CSM, Outokumpu Stainless, Univeristy of Hannover, VTT, SBI and ArcelorMittal Stainless. Stainless steel in buildings is almost always exposed, so the Stainless Steel in Fire project aimed to identify structural solutions which give a specified period of fire resistance without any fire protection applied to the surface of the steel. Benefits of eliminating fire protection include lower construction costs, shorter construction time, more effective use of the internal floor area and more attractive appearance. The project included tests on materials, members and connections, numerical analysis and development of design guidance aligned to European design standards. The scope of the work was limited to austenitic grades as these exhibit the most promising behaviour at high temperature. The topics studied were:

- Load-bearing and separating elements with 30 and 60 minutes fire resistance
- Concrete filled hollow sections in fire
- Hybrid stainless-carbon steel composite floor beams in fire
- Slender hollow sections in fire
- Strength and stiffness retention of grades not previously studied
- Welded and bolted connections in fire
- Behaviour of external stainless steel columns and stainless steel columns in open car parks subject to realistic fire loads

Mechanical properties of stainless steel at elevated temperatures

Strength and stiffness retention factors have been derived from isothermal and anisothermal test data for a number of grades of stainless steel used in structural applications[3]. It is generally accepted that the results of isothermal tests are only accurate up to temperatures of about 400ºC; above this temperature they give unconservatively high results and data from anisothermal tests should be used which more closely replicate a real fire situation. Figure 1 shows the 0.2% proof strength retention curves for a number of grades, including two grades in the work hardened condition C850.

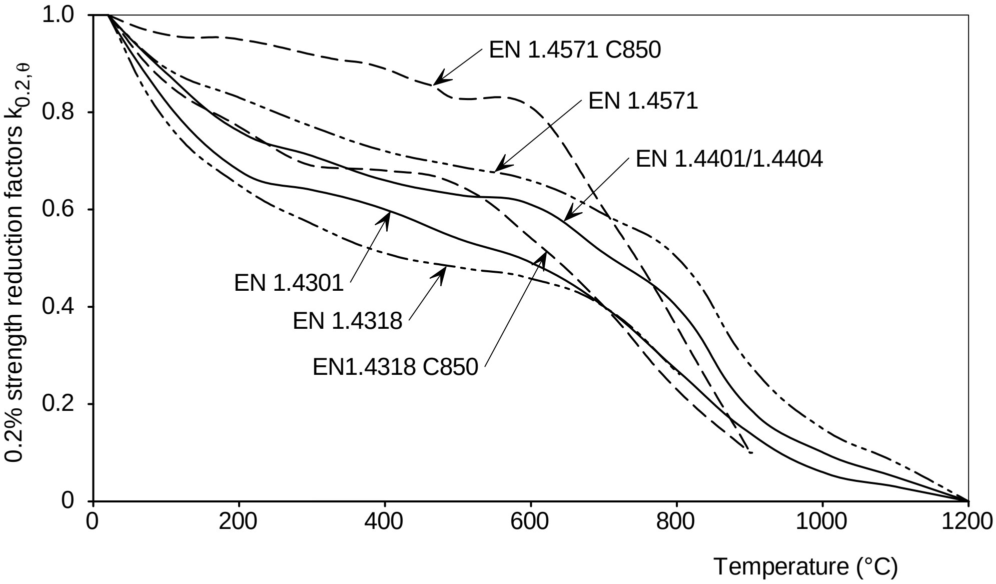


Figure 1. 0.2% proof strength retention curves for austenitic structural stainless steels

Having a unique set of reduction factors for each different grade is awkward for designers and unjustified due to the high scatter in the test data. Bearing in mind that carbon steels are currently described in EN 1993-1-2 by one set of strength retention curves, work is underway rationalising the stainless steel curves into a smaller number of generic curves. It is proposed that the following five generic curves are developed:

- Chromium-nickel austenitic grades (e.g. 1.4301)
- Chromium-nickel-molybdenum austenitic grades (e.g. 1.4401)
- Stabilised austenitic grades (e.g. 1.4571)

- Ferritic grades (e.g. 1.4003)
- Duplex grades (e.g. 1.4462)

Stainless steel columns in fire

The structural performance of a stainless steel rectangular hollow section (RHS) column (200x200x8) from grade 1.4301 was compared to the performance of an identical carbon steel column from grade S235 at different temperatures using finite element analysis (Figure 2). For a cross-sectional temperature of 400°C, the stainless and carbon steel columns showed similar load-bearing capacity. At 600°C, the stainless steel columns exhibited much higher load-bearing capacity than the carbon steel columns; the ratio of ultimate loads of the stainless to the carbon steel column is about 2.0. The explanation for this is that the good stiffness retention results in the non-dimensional slenderness of the column tending to reduce as the temperature increases. This improves the flexural buckling behaviour of the column leading to smaller lateral deflections and reducing second order effects. For temperatures between 600°C and 800°C, the ratio of stainless to carbon steel ultimate load rises significantly, clearly demonstrating that stainless steel columns show superior load-bearing behaviour to carbon steel columns in this temperature range.

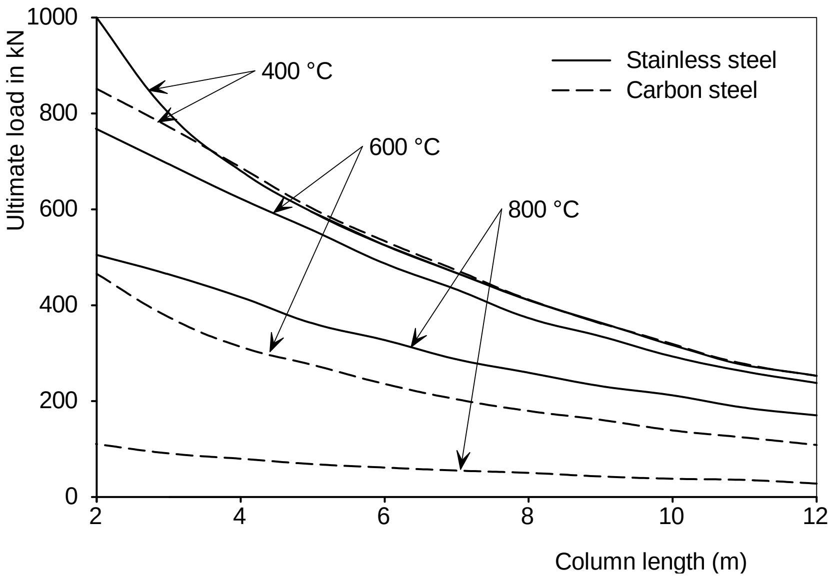


Figure 2. Ultimate loads for varying column length and cross-sectional temperatures

Limiting the temperature rise will enable the load-bearing capacity of a member to be retained for a longer period. In the Stainless Steel in Fire project, the temperature development in a range of concepts designed to suppress temperature rise was studied. Using finite element analysis, the EN 1363-1[4] standard fire curve was applied for 60 minutes to a range of systems including:

- concentric tubes (with the annulus between the sections either empty, filled with mineral wool or filled with concrete),
- a corner column section partially protected by concrete walls,
- a column exposed to fire from one side,
- two profiles side by side filled with mineral wool.

Unloaded fire tests on the most promising concepts were then carried out. The temperature development measured in the tests agreed reasonably well with the temperatures predicted by numerical analysis. After 60 minutes, the temperature of the outer RHS in the concentric tube concept had reached 925°C whereas the temperature of the inner section was only 414°C, which meant that the inner tube retained about 60% of its load-bearing capacity according to EN 1993-1-2. For the corner column concept, the maximum temperature in the exposed corner was 806°C whereas the unexposed corner only reached 299°C. Design guidance which takes into account non-uniform temperature distribution of a member subject to flexural buckling needs to be developed to take advantage of the protection offered by concrete walls to corner columns.

A programme of tests on RHS with slender (Class 4) cross-sections was also performed in the project (Figure 3). Numerical models were calibrated against test results and then parametric studies carried out to develop more economic design guidance for Class 4 RHS than is currently in existing guidance[1,3].

Figure 3. Tests on RHS with slender cross-sections
Left: Test specimen in furnace, *Right*: Test specimens after fire tests (RHS 150x150x3)

Composite stainless steel-concrete columns in fire

Fire tests were carried out on seven RHS columns filled with concrete (reinforced and unreinforced). The specimens were designed to achieve a fire rating of 30 and 60 minutes and were made from grade 1.4404 stainless steel. The columns were subjected to an eccentrically applied compressive load and exposed to controlled heating following the EN 1363-1 standard fire curve. The specimens were pinned at both ends, which were free to rotate about one direction but were restrained to rotate about the perpendicular direction. The measured failure times exceeded the expected fire ratings in all cases.

The tests were modelled numerically using the advanced finite element model SISMEF to simulate the mechanical behaviour and resistance of composite members exposed to fire. Subsequently, parametric studies were carried out in order to develop design rules for composite columns. The proposed design methods are consistent with the general flow charts in EN 1994-1-2[5] used to check the fire resistance of composite members but include some specific characteristics to account for the distinctive behaviour of stainless steel.

To compare the performance of stainless and carbon steel composite columns, a numerical study was carried out on three different RHS column cross-sections filled with unreinforced concrete; the results are given in Table 1. It is clear that carbon steel columns buckle at a lower load than stainless steel columns of identical size and length. For a given fire rating, maximum load level of stainless steel columns increases with increasing cross-section size. This is mainly due to the lower temperature rise of the large cross-section in comparison to the smaller cross-section.

Table 1. Comparison of maximum load level for concrete filled RHS columns (length = 3 m)

Column	Fire rating (minutes)	Maximum load level[1)]	
		Stainless steel column (grade 1.4401)	Carbon steel column (grade S235)
150x150x8	30	0.36	0.15
	60	0.16	0.04
200x200x8	30	0.36	0.15
	60	0.16	0.06
300x300x8	30	0.65	0.47
	60	0.29	0.15

[1)] The load level is the ratio of the buckling resistance at the fire ultimate state to the buckling resistance at room temperature

Composite carbon steel-stainless steel-concrete beams in fire

Under the Stainless Steel in Fire project, two fire tests were carried out on 'Slimflor' composite beams from grade 1.4404 with the stainless steel lower flange exposed and the carbon steel section unexposed (Figure 4). The specimens were 5 m in length and designed to achieve a fire rating of 30 and 60 minutes. As with the composite columns, the measured failure times exceeded the expected fire ratings in all cases. The tests were modelled numerically using the advanced finite element model SISMEF. Subsequently, parametric studies were carried out in order to develop design rules for composite beams. The proposed design method is based on simple plastic moment theory, requiring the calculation of the neutral axis and corresponding moment resistance by taking into account the temperature distribution through the cross-section and the corresponding reduction in material strength.

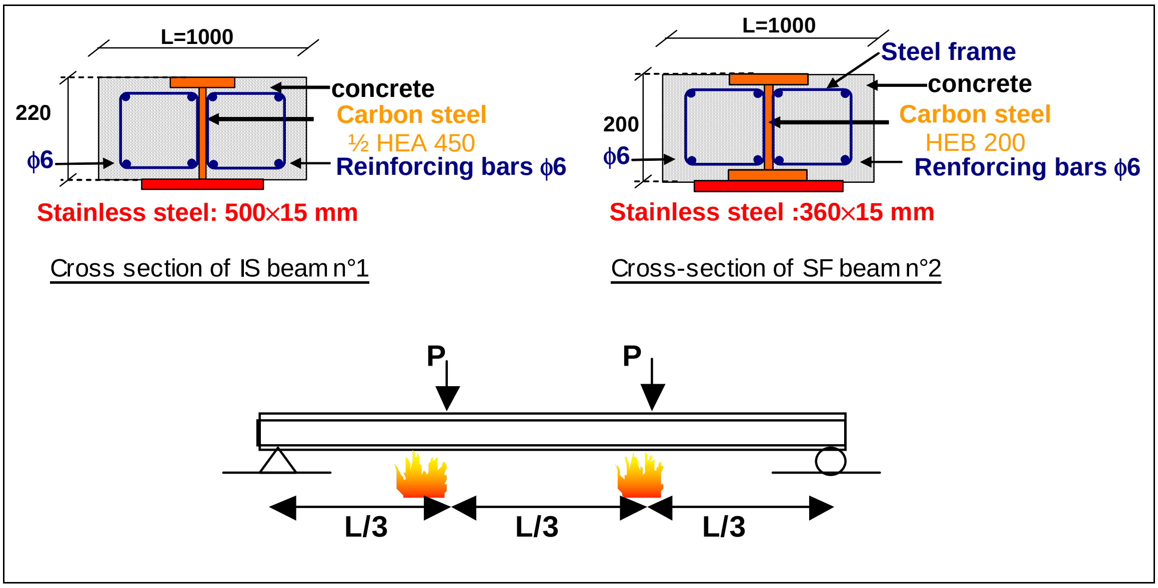
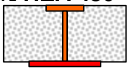
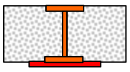


Figure 4. Structural details of the composite beam test specimens

To compare the performance of stainless and carbon steel composite beams, a numerical study was carried out on different beam cross-sections; some results are given in Table 2. For the same fire rating, the bending moment resistance of carbon steel beams is always lower than the beam with the exposed lower flange from stainless steel. 120 minutes fire resistance can easily be achieved by the ½ HEA 450 beam with exposed stainless steel plate providing the load level is lower than 0.33. In contrast to this, the carbon steel beam only achieved a fire resistance of 60 minutes with a load level of 0.27.

Table 1. Comparison of maximum load level for beams with exposed carbon steel and stainless steel plates

Beam	Fire rating	Maximum load level[1]	
		Stainless steel lower plate (grade 1.4401)	Carbon steel lower plate (grade S235)
½ HEA 450  Steel plate: 500×15 mm	R60	0.72	0.27
	R90	0.46	0.17
	R120	0.33	0.15
HEB 280  Steel plate: 480×20 mm	R60	0.92	0.55
	R90	0.77	0.28
	R120	0.58	0.22

[1] The load level is the ratio of the moment resistance at the fire ultimate state to the moment resistance at room temperature

Conclusions

The European Stainless Steel in Fire project has enabled a better understanding of the heating up characteristics and degradation of resistance of stainless steel members in a fire to be studied both through fire tests and numerical modelling. The work has shown that stainless steel structural members exhibit better fire resistance than carbon steel structural members in the temperature range 600ºC to 800ºC. Design guidance aligned to EN 1993-1-2 and EN 1994-1-2 was developed for the structural members studied.

Acknowledgement

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References

[1] EN 1993-1-2. Eurocode 3: Design of steel structures – Part 1.2: General rules. Structural fire design, 2005

[2] "Final Report: Stainless Steel in Fire", RFCS Project RFS-CR-04048, The Steel Construction Institute, March 2008

[3] "Design manual for structural stainless steel", Third Edition, Euro Inox and The Steel Construction Institute, 2006

[4] EN 1363-1:1. Fire resistance tests – Part 1: General requirements, 1999

[5] EN 1994-1-2. Eurocode 3: Design of composite steel and concrete structures – Part 1.2: General rules. Structural fire design, 2005.