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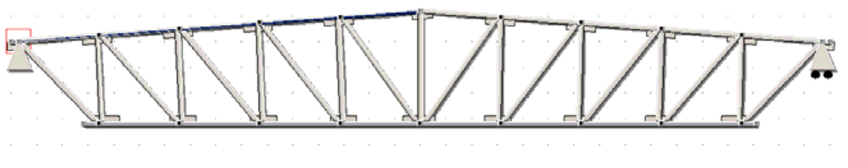

Structural Applications of Ferritic Stainless Steels (SAFSS)
WP2: Structural performance of steel members
Task 2.2 Comparative design of a roof truss at room and fire temperatures

Comparative study of roof truss design

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Report's title

Comparative study of roof truss design

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Structural Applications of Ferritic Stainless Steels	SAFSS

Summary

This study aims to introduce the possibilities of different stainless steel grades in fire-resistant applications. The grades in the comparison are the austenitic grades 1.4301, 1.4571, and 1.4318 and the ferritic grades 1.4003, 1.4509, and 1.4521. In addition, carbon steel grade S355 is compared to a certain extent.

The comparison is performed for a truss which consists of structural hollow section members. The structural design was performed at room temperature and for R15 and R30 fire cases, which correspond to fire resistances of 15 and 30 minutes in an ISO 834 standard fire. The load ratio, which indicates the loads used in a fire situation divided by the room temperature loads, is 0.35 in this case study.

The lightest truss, based on room temperature and the R15 fire design, was obtained by using the ferritic grades 1.4521 and 1.4509 or the austenitic grade 1.4318. In these cases the room temperature design determines the dimensions. In the case of the R30 design the lightest truss was got by using the austenitic grades 1.4571 and 1.4318. The hollow section dimensions of grade 1.4571 were determined by the room temperature design and the hollow section dimensions of grade 1.4318 by the fire design.

The most cost-effective solution, on the basis of the R15 fire design and base material price, is a lattice girder made of ferritic grade 1.4509. In the case of an R30 fire the ferritic grade 1.4509 and the austenitic grade 1.4318 are the best choices in terms of cost-effectiveness.

The ferritic grade 1.4003 and structural carbon grade S355 have the lowest strength at temperatures over 700°C and therefore the fire design already determines the hollow section dimensions in the R15 fire case. Because, unlike stainless steels, the modulus of elasticity of grade S355 drops very fast after 650°C, the use of grade S355 without any fire protection is therefore usually limited to R10 fires.

Helsinki 15.4.2013

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Comparative study of roof truss design

1. Scope

The structural fire design of a ferritic stainless steel plane truss is compared to designs for identical austenitic and carbon steel truss. The aim of the study is to compare the structural differences resulting from different high-temperature properties when the structural design is performed according to EN 1993-1-4 and EN 1993-1-2. The stainless steel grades chosen are the austenitic grades 1.4301, 1.4571, and 1.4318 and the ferritic grades 1.4521, 1.4509, and 1.4003. Some comparisons have also been made with respect to the structural carbon steel S355, which has no fire protection. The truss is composed of welded structural stainless steel hollow (RHS) sections.

The fire cases R15 and R30, which correspond to fire resistances of 15 and 30 minutes according to the ISO 834 fire standard, are studied. The load ratio that indicates the load in a fire situation, compared to the normal load, is 0.35 in this case study. The fire cases R15 and R30 have been chosen on the basis of the assumption that an unprotected stainless steel structure can have enough resistance also to carry the loadings imposed on it at fire temperatures corresponding to R15 and R30. This is due to the fact that the yield strength and modulus of elasticity remain quite high at these temperatures.

The following study is performed to introduce the possibilities of choosing the stainless steel grade for structural application in the design case of normal room temperature (RT) and fire actions. The comparison is targeted at comparing the required material needs for different grades of stainless steels. The comparison makes it possible to cover the cost aspect as well by taking the price of the materials into account (Figure 1).

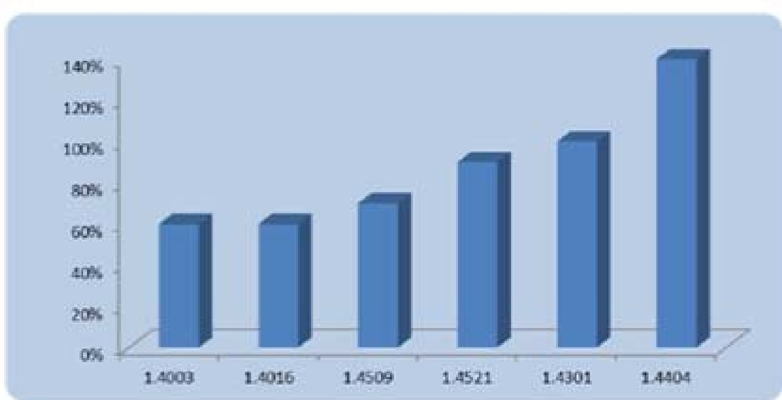

Figure 1. Price of Cold-rolled Stainless Steels (March 2013, published in Annual Report of SAFSS project).

The comparisons are based on the results of the of the other tasks of SAFSS project which were available at the time when this report was written. Therefore some details may differ from the final recommendations which will be given in the final report of the SAFSS project.

2. Material properties

The mechanical properties of the materials as a function of steel temperature are shown in Figures 2 and 3.

The room temperature properties of the materials for structural design are given in Table 2 of EN 1993-1-4. For the ferritic grades 1.4521, 1.4509, and 1.4003 the properties have been determined in the SAFSS project. The austenitic and ferritic grades chosen for this study cover yield strengths from 230 N/mm^2 to 380 N/mm^2 at room temperature.

The mechanical properties at room temperature and at fire temperatures are dependent on the stainless steel grade. In the fire case the important material parameters that affect the structural resistance are the reductions in the yield strength and in the modulus of elasticity as a function of the temperature of the steel. The mechanical properties in a fire situation for the austenitic grades are given in EN 1993-1-2 Annex C and in the Euroinox Design Manual. The mechanical properties at fire temperatures for the ferritic stainless steels are determined in the SAFSS project, WP4: Task 4.1 Structural fire resistance.

Figure 2 shows that on the basis of the type of stainless steel (i.e. ferritic and austenitic) it is difficult to group stainless steels into certain classes at fire temperatures. Only the ferritic grades 1.4509 and 1.4521 are similar. Mechanical properties seem to be related to chemical alloying and are specific to a certain grade.

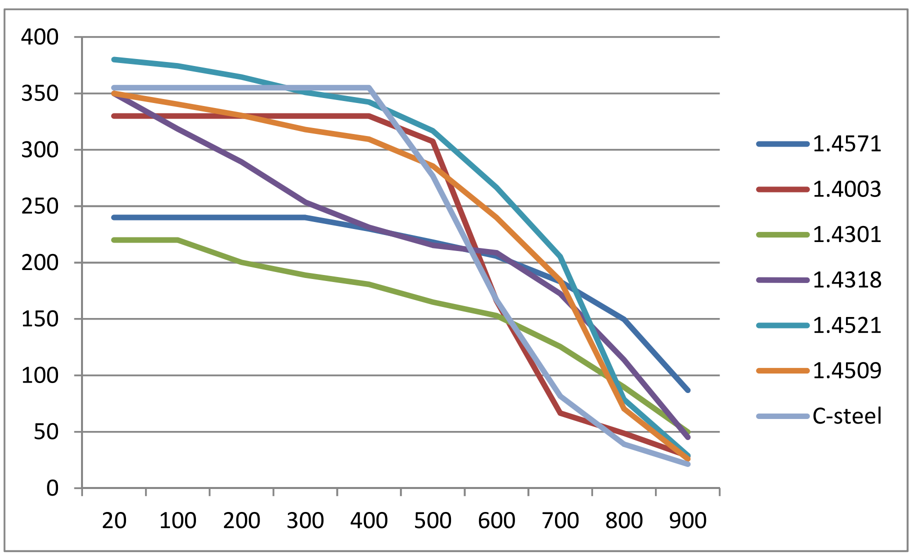

Figure 2. The yield strength (y-axis, MPa) of structural materials as a function of steel temperature (x-axis, °C) during exposure to fire.

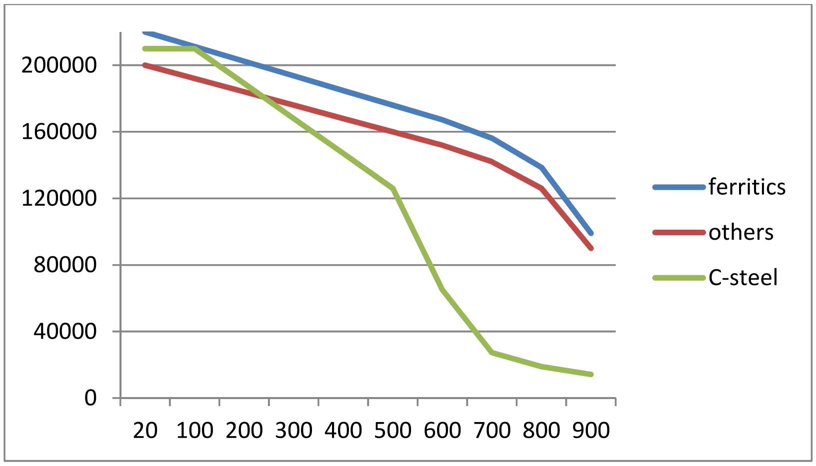

Figure 3. The modulus of elasticity (y-axis, GPa) as a function of steel temperature (x-axis, °C) during exposure to fire.

Around temperatures of 700°C and 800°C the yield strength values vary greatly, depending on the grade of the stainless steel. There is a distinct difference in the reduction of the yield strength between the ferritic and austenitic grades; the slope of reduction in the ferritic grades is steeper at temperatures of 700°C and 800°C, which correspond to the temperatures of 15 minutes and 30 minutes in a standard fire. Relatively the most stable reduction in yield strength occurs with grade 1.4571. The following conclusions can be drawn on the basis of Figure 2:

- at a temperature corresponding to a 15-minute fire (about 700°C) the ferritic grade 1.4521 has the highest yield strength. The strengths of the ferritic grade 1.4509 and the austenitic grades 1.4571 and 1.4318 are only slightly lower;
- at a temperature conforming to a 30-minute fire (about 800°C) the yield strength of the austenitic grade 1.4571 has a superior yield strength;
- the austenitic grade 1.4318 has a high yield strength at room temperature, but has a value between 1.4301 and 1.4571 at temperatures corresponding to a 30-minute fire;
- the ferritic grade 1.4003 loses its yield quite rapidly at temperatures higher than 600°C;
- carbon steel (C-steel in Figure 2) has roughly the same curve shape as the ferritic grade 1.4003.

The reduction factor values for the modulus of elasticity are the same for all the stainless steel grades. The ferritic grades have a slightly higher modulus of elasticity at room temperature (220 000 N/mm^2) compared to austenitics (200 000 N/mm^2), thus causing greater values at fire temperatures too. All the stainless steel grades have a much higher modulus of elasticity than the carbon steels at fire temperatures.

The density of the steels is 7.7 kg/dm^3 for 1.4521, 1.4509, and 1.4003, 7.9 kg/dm^3 for 1.4301 and 1.4318, and 8.0 kg/dm^3 for 1.4571.

3. The lattice girder geometry and loading

The SAFFS project has mainly studied material thicknesses up to 3 mm but for the material 1.4003 the value was limited to 6 mm. Therefore, in the case of ferritic hollow sections, except 1.4003, the lattice girder design was targeted to satisfy the load-bearing capacity with a wall thickness not thicker than 3 mm. In the case of the austenitic grades thicker members were allowed. The lattice girder used in the calculations is shown in Figure 4.

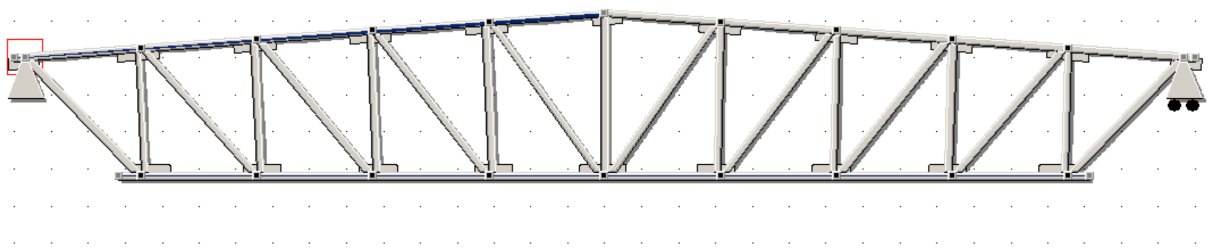

Figure 4. Lattice girder layout.

The dimensions of the lattice girder are:

- girder span 16 m
- frame spacing 5 m
- nodal distance at upper chord 1.6 m
- length of lower chord 13.1 m
- height at the support 1.6 m
- height at the top 2.2 m.

4. Load cases

The girder carries an equally distributed snow load, roofing, and the lattice girder's own weight. The permanent and variable loads for design are:

Permanent actions (G):	Load of roofing and dead load of girder	0.5 kN/m^2
Variable actions (Q):	Snow load	2 kN/m^2

The load cases for room temperature and fire design are:

Load case 1 for room temperature design : $\sum_j \gamma_{G,j} G_{k,j} + \gamma_{Q,1} Q_{k,1}$

Load case 2 for fire design : $\sum_j G_{k,j} + \psi_{1,1} Q_{k,1}$

The load factors for room temperature and fire design are:

For room temperature design	For fire design
$\gamma_{G,j}$=1.35	$\psi_{1,1}$ = 0.4
$\gamma_{Q,1}$=1.5	

On the basis of the above equations the fire case ratio loading to room temperature loading is 0.35.

The equally distributed load is transferred through the nodal points into the lattice girder.

5. Calculation of critical member forces

The critical members are calculated using the Winrami stainless software.

The upper chord consists of two continuous members and the lower chord of one continuous member. The joints of the vertical and diagonal members to the chord members are taken as being hinged connections. The buckling length of the upper chord is expected to be 0.9 times the nodal distance. The bending moment resulting from the eccentricity of the joints is taken into account in determining the resistance of the upper chord.

Maximum member load of upper chord (second bar from the top)

$N_{c,Ed}$ = -262 kN, $N_{c,fire,Ed}$ = -92 kN
$M_{max,Ed}$ = 1.9 kNm, $M_{max,fire,Ed}$ =0.85 kNm

Maximum member load of lower chord

$N_{t,Ed}$ =260 kN, $N_{t,fi,Ed}$ = 92 kN

Maximum member load of diagonals (first diagonal from the support)

$N_{c,Ed}$ = 170 kN, $N_{c,fire,Ed}$ = 60 kN

Maximum member load of verticals (first vertical from the support)

$N_{c,Ed}$ = -129 kN, $N_{c,fire,Ed}$ = -46 kN

6. Resistance of critical members

The resistance calculation of the members is performed according to EN 1993-1-4 and EN 1993-1-2. The resistance calculation is performed for the in-plane behaviour of the girder.

The mechanical properties for the austenitic grades 1.4301 and 1.4571 are according to EN 1993-1-4 and EN 1993-1-2 Annex C. For the ferritic grades the mechanical properties and parameters for calculating the effective 2% yield strength in the fire case were determined by the SAFSS project. The mechanical properties for the austenitic grade 1.4318 are according to the EuroInox Design Manual. In the fire case the mechanical properties for the austenitic grade 1.4318 are only given up to a temperature of 800˚C in the EuroInox Design Manual. In this study Table 7.1 of the EuroInox Design Manual is complemented by the temperature of 900 ˚C for grade 1.4318. The reduction factors at a temperature of 900˚C are equal to the values shown for the material 1.4318 C850 in Table 7.1 of the Euroinox Design Manual. This supplement is expected to be a conservative approach.

Table 1 below shows the difference in effective yield strengths for a material thickness of 3 mm when the steel temperature is 840°C and 710°C. The temperature of 710˚C is the calculated steel temperature after 15 minutes of fire for material with a thickness of 3 mm. After 30 minutes of fire the steel temperature is 840°C for material with a thickness of 3 mm.

Table 1. The mechanical properties of the materials at temperatures of 840°C and 710°C.

Material	RT f_y [N/mm^2]	RT f_u [N/mm^2]	Fire situation design parameters according to	$f_{y,\Theta}$ t=3mm T= 840°C	E [N/mm^2]	$f_{y,\Theta}$ t=3mm T= 710°C	E [N/mm^2]
1.4301	230	540	EN 1993-1-2	74	111600	120	140400
1.4571	240	540	EN 1993-1-2	125	111600	179	140400
1.4521	380	540	SAFFS	59	122760	183	154440
1.4509	350	480	SAFFS	53	122760	169	154440
1.4318	350	650	Euroinox manual	86 [1)]	111600	164	140400
1.4003	330	490	SAFFS	41	122760	64	154440
S355	355	510	EN 1993-1-2	32	23900	77	27300

1) Mechanical properties are complemented by adding information related to a temperature of 900°C.

7. Results:

The results given in Table 2 show the required section sizes based on room temperature design (RT) and on fire design. R15 and R30 correspond to the standard fire temperatures at times of 15 and 30 minutes. Table 3 shows the normalised weights of the critical members and the normalised total weight of the lattice girder corresponding to the optimal grade for the design case.

In the case of room temperature design (RT in the tables) the required section sizes are based on the material yield strength. Then the ferritic grade 1.4521 results in the smallest cross-section dimensions. The carbon grade S355 gives equal dimensions to the ferritic grade 1.4521. The austenitic grades 1.4301 and 1.4571 require larger dimensions because of their lower yield strength at RT.

In the case of an R15 fire (R15 in the tables), the ferritic grades 1.4521 and 1.4509 and also the austenitic grades 1.4571 and 1.4318 result in smaller dimensions than the other grades. The effective yield strengths of these grades, corresponding to the temperature of an R15 fire, are almost equal, even though at room temperature the grades 1.4521 and 1.4318 have 1.5 times the yield strength of grade 1.4571. The ferritic grade 1.4003 loses its effective yield strength dramatically in an R15 fire, which results in the heaviest cross-section dimensions.

In the case of an R30 fire (R30 in the tables), grade 1.4571 results in smaller cross-section sizes and lighter weight compared to the other grades. This result is as expected on the basis of the material properties shown in Figures 2 and 3. Grade 1.4318 gives the second lightest weight. The ferritic grades 1.4521 and 1.4509 have significant loss of strength in this temperature range and therefore larger cross-section dimensions are required.

Table 2. Required cross-section sizes at room temperature (RT) and in fire design (cases R15 and R30).

	RT					
material / member	1.4301	1.4571	1.4521	1.4509	1.4318	1.4003
upper chord	120x80x4	120x80x4	100x80x3	100x80x3	100x80x3	100x80x4
lower chord	120x80x4	120x80x4	70x70x3	80x80x3	80x80x3	80x80x3
1st diagonal	80x80x3	80x80x3	50x50x3	50x50x3	50x50x3	60x60x3
1st vertical	76x76x3	76x76x3	60x60x3	60x60x3	60x60x3	60x60x3
other diagonals and verticals	76x76x3	76x76x3	60x60x3	60x60x3	60x60x3	60x60x3
	R15					
material / member	1.4301	1.4571	1.4521	1.4509	1.4318	1.4003
upper chord	120x80x3	100x50x3	100x50x3	100x50x3	100x60x3	120x80x4
lower chord	70x70x3	50x50x3	50x50x3	50x50x3	60x60x3	100x80x4
1st diagonal	50x50x3	35x35x3	35x35x3	35x35x3	40x40x3	60x60x4
1st vertical	60x60x3	50x50x3	50x50x3	50x50x3	50x50x3	60x60x4
other diagonals and verticals	60x60x3	50x50x3	50x50x3	50x50x3	50x50x3	60x60x4
	R30					
material / member	1.4301	1.4571	1.4521	1.4509	1.4318	1.4003
upper chord	120x80x5	120x80x3	120x80x6	120x80x6	120x80x4	120x120x6
lower chord	120x80x4	70x70x3	120x80x4	100x80x5	120x80x3	120x120x5
1st diagonal	80x80x3	50x50x3	76x76x4	76x76x4	70x70x3	80x80x5
1st vertical	76x76x3	60x60x3	76x76x4	76x76x4	70x70x3	90x90x4
other diagonals and verticals	76x76x3	60x60x3	76x76x4	76x76x4	70x70x3	90x90x4

Table 3. Normalised weight of lattice girder (normalised to minimum weight of the design case).

	RT					
material / member	1.4301	1.4571	**1.4521**	1.4509	1.4318	1.4003
upper chord	1.50	1.52	**1.00**	1.00	1.03	1.36
lower chord	1.96	1.99	**1.00**	1.15	1.18	1.20
1st diagonal	1.71	1.73	**1.00**	1.00	1.03	1.27
1st vertical	1.32	1.34	**1.00**	1.00	1.03	1.04
other diagonals and verticals	1.32	1.34	**1.00**	1.00	1.03	1.04
total weight	1.52	1.54	**1.00**	1.03	1.06	1.18
	R15					
material / member	1.4301	1.4571	**1.4521**	1.4509	1.4318	1.4003
upper chord	1.39	1.04	**1.00**	1.00	1.10	1.85
lower chord	1.48	1.04	**1.00**	1.00	1.25	1.50
1st diagonal	1.54	1.04	**1.00**	1.00	1.20	2.46
1st vertical	1.25	1.04	**1.00**	1.00	1.03	1.64
other diagonals and verticals	1.25	1.04	**1.00**	1.00	1.03	1.64
total weight	1.35	1.04	**1.00**	1.00	1.09	1.72
	R30					
material / member	1.4301	**1.4571**	1.4521	1.4509	1.4318	1.4003
upper chord	1.59	**1.00**	1.82	1.82	1.29	2.32
lower chord	1.89	**1.00**	1.84	2.02	1.44	2.86
1st diagonal	1.64	**1.00**	1.98	1.98	1.43	2.65
1st vertical	1.27	**1.00**	1.62	1.62	1.17	2.02
other diagonals and verticals	1.27	**1.00**	1.62	1.62	1.17	2.02
total weight	1.51	**1.00**	1.74	1.77	1.27	2.30

Table 4 shows the normalised weight of lattice girders covering all the design cases. The truss weights are normalised to the lightest possible truss, which in this case is made of grade 1.4521. The structural design covers two cases, one for room temperature design and the other for design at fire temperatures (R15 and R30). In the case of an R15 fire, the fire design determines the member sizes only in the case of grade 1.4003, while for the other grades the design at room temperature is the determining factor. In the case of an R30 fire, the fire design always determines the member sizes, except in the case of grade 1.4571.

Table 4. Weight of lattice girders normalised to room temperature case of grade 1.4521.

Normalized weight of lattice (to 1.4521 at RT)	1.4301	1.4571	1.4521	1.4509	1.4318	1.4003
RT	1.52	1.54	1.00	1.03	1.06	1.18
R15	1.06	0.82	0.79	0.79	0.86	1.35
R30	1.62	1.08	1.88	1.91	1.37	2.47

Table 4 shows that in the case of RT and an R15 fire the ferritic grades 1.4521 and 1.4509 and austenitic grade 1.4318 give the lowest truss weight. In the case of RT and the R30 fire case the truss made of grade 1.4318 is the lightest one. The truss made of grade 1.4571 is slightly heavier in weight, because the room temperature design determines the member sizes.

Although the comparison with the carbon steel grade is not shown in detail, it can be concluded that in the R15 fire case the carbon steel grade S355 has lower resistance and higher weight of the members than the ferritic grade 1.4003. This is due to the fact that the modulus of elasticity and effective yield strength at fire temperatures are lower than the values for grade 1.4003.

In Table 5 the cost aspect is included to compare the competitiveness of different grades in an economic sense. Table 5 shows that the lattice girder made of the ferritic grade 1.4509 is the most cost-effective solution at RT and in the R15 fire case. In the R30 fire case the ferritic grade 1.4509 and austenitic grade 1.4318 are quite similar in terms of costs. The cost of lattice girders consists only of the price of the material, which is calculated on the basis of the relative prices shown in Figure 1. The prices for the austenitic grades 1.4318 and 1.4571 are not given in Table 1. The price of the austenitic grade 1.4301 is used for the austenitic grade 1.4318 and that of the austenitic grade 1.4404 is used for the austenitic grade 1.4571 in this study.

Table 5. Cost of lattice girders normalised to room temperature case of grade 1.4521.

Normalised cost of lattice (to 1.4521 at RT)	1.4301	1.4571	1.4521	1.4509	1.4318	1.4003
RT	1.67	2.30	1.00	0.82	1.16	0.82
R15	1.17	1.23	0.79	0.63	0.95	0.95
R30	1.79	1.62	1.88	1.53	1.50	1.73

Conclusions

This study aims to introduce the possibilities of different stainless steel grades in fire-resistant applications. The resistance of a structure mainly depends on the reduction of yield strength as a function of steel temperature. The strength reduction depends on the stainless steel grade. The grades selected for detailed calculation were the austenitic grades 1.4301, 1.4571, and 1.4318 and the ferritic grades 1.4003, 1.4509, and 1.4521.

The comparison was made for a truss which consists of RHS members. The structural design was performed for room temperature and for the fire temperatures. The fire cases R15 and R30, corresponding to fire resistances of 15 and 30 minutes in an ISO 834 standard fire, were studied. The load ratio, which indicates the load in a fire situation compared to the room temperature load, was 0.35 in this case study.

The lightest truss on the basis of room temperature and R15 fire design was achieved by using the ferritic grades 1.4521 and 1.4509 and the austenitic grade 1.4318. In these cases the room temperature design determined the cross-sectional dimensions. In the case of the R30 design the lightest truss was achieved by using the austenitic grades 1.4571 and 1.4318. Then the dimensions of the grade 1.4571 hollow sections were determined by the room temperature design and the dimensions of the grade 1.4318 hollow sections were determined by the fire design.

The most cost effective-solution, on the basis of the base material price (in March 2013) is a lattice girder made of the ferritic grade 1.4509. In the R15 fire case the other ferritic grades, 1.4003 and 1.4521, are competitive as well. In the R30 fire case the optimal grades are ferritic 1.4509 and austenitic 1.4318 and they are quite similar in terms of cost-effectiveness.

The ferritic grade 1.4003 and structural carbon grade S355 have the lowest strength at temperatures over 700°C and therefore the fire design determines the hollow section dimensions, even in the R15 fire case. The use of grade S355 without any fire protection is usually limited to R10 fires, because unlike stainless steels, the modulus of elasticity of S355 drops very fast after 650°C.