A COMPARISON STUDY ON CHARACTERISTIC BEHAVIOUR OF HOT-ROLLED BEAMS OF CARBON STEEL AND STAINLESS STEEL UNDER STANDARD FIRE

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ABSTRACT

In the last few decades, there has been a conspicuous phase shift in construction materials from concrete structures toward steel structures all over the world. However, fire resistance characteristics (i.e., fire rating, temperature, displacement) of different types of construction steels are still not culminated at their best. Addressing this research scope, this study has presented a comparison study between the time of failure and the behaviour of different grades of steels under standard fire. The study is conducted based on two factors- change in load capacity and change in the beam section. To augment this study, three hot-rolled beams HEB 200, HEB 300, HEB 400 of carbon steel and stainless steel s (austenitic: grade 1.4301, grade 1.4401, and grade 1.4571; duplex: grade 1.4462 and ferritic: grade 1.4003) were exposed under standard fire for the convenient period were simulated using Abaqus 6.14-1. Each beam was analyzed at 30%, 50% and 70% load of their maximum capacity.

Results show that, except for ferritic steel, in almost all cases, the performance of all the other stainless steel is better than that of carbon steel. At a low loading condition of 30% of beam capacity, the fire ratings of austenitic grade 1.4301 and duplex 1.4462 beams are almost twice that of carbon steels. Furthermore, at the same loading condition, the fire rating of austenitic grade 1.4571 beams is almost four times and grade 1.4401 beams is almost thrice that of carbon steel respectively. The case is also applicable for other loading conditions. In contrast, the fire ratings of ferritic stainless steel beams were lower than that of carbon steel.

Comparing the performance of austenitic steel unveils that the performance of stabilized stainless steel of grade 1.4571 is higher than that of molybdenum-chromium-nickel austenitic steel grade 1.4401 and basic chromium-nickel austenitic steel of grade 1.4301 respectively. On the other hand, analyzing the effect of change of beam section, it can be seen that the change in beam section has almost no effect in time of failure given that the load applied is directly proportional to its capacity. This shows that the effect of fire is more likely to be related to the material behaviour at elevated temperature and loading level of the beam.

Keywords: *Fire resistance; Stainless- steel; Carbon- steel; Standard fire; Euro-code*

1. INTRODUCTION

Fire resistance structure design is a vital aspect of structural engineering (Ng & Gardner, 2007). Metallic constructions can lose strength and stiffness when exposed to fire because of their quick increase in temperature, especially if unprotected (Xing et al., 2021). A number of previous studies have examined the behaviours and characteristics of stainless steel members in fire under compression (Ding et al., 2019; Fan et al., 2016; Lopes et al., 2010; Mohammed & Afshan, 2019; To & Young, 2008; Tondini et al., 2013; Uppfeldt et al., 2008). Studies related to the bending capacity of stainless steel members have also been conducted (Ng & Gardner, 2007; Vila Real et al., 2008). It was found that stainless steel retains a higher Young's Modulus at elevated temperatures than carbon steel and austenitic stainless steel expands some 30% more than carbon steel (Baddoo & Burgan, 1998; Gardner & Baddoo, 2006). Based on strength and stiffness retention ability at elevated temperatures, stainless steel s, in particular the commonly used austenitic grades, are found to be more suitable as construction material for fire-prone constructions than carbon steel (L. Gardner & Baddoo, 2006; L. Gardner & Ng, 2006; Leroy Gardner, 2019). These clearly suggest the importance and availability of wide scopes in analyzing stainless steel behaviour in case of fire.

Considering the difficulties and costing of the mass-scale test under fire, numerical simulations backed by test results has become a popular practice for predicting the behaviours of stainless steel structure at higher temperatures. The test results of the stainless beams were found to be closely predicted by FE analysis (Gardner & Baddoo, 2006; To & Young, 2008; Uppfeldt et al., 2008). Furthermore, numerical modelling has been widely and effectively used in modelling stainless steel in elevated temperatures such as assessing the buckling performance (Kucukler et al., 2020; Mohammed & Afshan, 2019); for analysing the structural response of thin-walled stainless steel structural elements (Lopes et al., 2010); lateral-torsional buckling of stainless steel beams (Vila Real et al., 2008); evaluation of accuracy and safety of design rules at elevated temperature (Kucukler et al., 2020; Lopes et al., 2012), etc.

The aim of this study was to evaluate the performances of different grades of stainless steel beams under standard fire and compare them with carbon steel beams For this, the FE model of the steel beam was developed for different loading conditions and analysed for fire. Three beam sections with five different grades of stainless steel were considered in this study among them three were austenitic grades, one was a duplex grade and one was a ferritic grade. Each beam was analysed for 30%, 50% and 70% loading capacity. Finally, the performance was evaluated based on the fire rating of unprotected beams.

2. FINITE ELEMENT MODELING

The performance of steel beams under fire was evaluated using the FE model developed by FE Software package Abaqus/CAE (Version 6.14-4; Dassault Systemes Simulia Corp, 2014). The full analysis was conducted in two steps: the loading step and the thermal step. At the first step, structural analysis was performed where a steel beam was modelled using solid 3D element C3D8T at room temperature assigning all support conditions. Two-point loading at desired magnitude was applied and analysed for structural stability under load. After completion of structural analysis, standard fire load was applied on the loaded beam. In thermal analysis, ISO-834 developed by International Organization for Standardization (1975), see Figure 3(c), the fire curve was applied as a firing temperature on the bottom and sides of the beam. The top flange of the beam was considered unexposed to fire due to the presence of a slab. The convective heat transfer coefficients were taken as 25 and 9 W/(m2.K) for fire exposed and unexposed surfaces of RC beam respectively, in accordance with Eurocode 2 (Franssen & Vila Real, 2015). While considering radiative heat transfer, the emissivity constant of 0.8 was considered for fire exposed surface. Due to the fire, the strength and stiffness of the steel beam decreased and the deflection increased with the increase of exposure time. When the deflection of the beam reached a limiting value, it was considered as a failure point and the corresponding fire exposure time required for failure was considered as the time rating of the beam.

2.1 Model validation

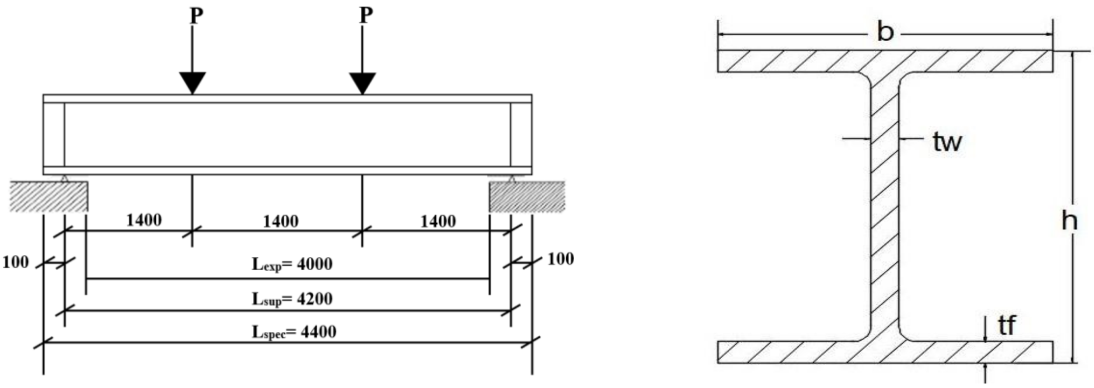
For validation of the FE model, the steel beam testes by M. Łukomski et al. (Łukomski et al., 2017) was simulated following the process discussed above. In their experiment, HEB 300 beam made of CS355 steel was tested under ISO-834 standard fire. Initially, two-point loading of 100 KN was applied on the beam. The beam was 4.4 m long and simply supported with a span length of 4.2 m as shown in Figure-1. At left support, translation about three directions was restrained. At right support, translation about two directions except longitudinal was restrained. All rotational degrees of freedom remained unrestrained for all supports. The material properties at room temperature and a cross-section dimension of the beam are shown in Table-1 and 2 respectively. After that ISO-834 standard fire was applied on the middle 4 m of the beam. The bottom flange and web were exposed to the fire. As the top flange was not exposed in the fire, it was covered with aerated concrete blocks. Here the maximum global mesh size was taken as 20 mm. The temperatures at different locations and deflection at mid-span were recorded with exposure time. For FE modelling, the material properties of CS355 at elevated temperature was incorporated according to Table C.3 and Annex A of Part 1.2 of Eurocode 3 (Franssen & Vila Real, 2015). The FE model of the beam is shown in Figure-2.

Table 1: Material property of CS355

Steel grades	Density (kg/m^3)	E (Mpa)	f_y (Mpa)
CS355	7850	210000	448

Table 2: Cross-section dimensions of HEB 300 beam

Beam Section	Depth, h (mm)	Width, b (mm)	Web thickness, t_w (mm)	Flange thickness, t_c (mm)
HEB 300	300	300	11	19



(a) (b)

Figure 1: (a) Loading profile of the steel beam (b) Cross sectional of the steel beam

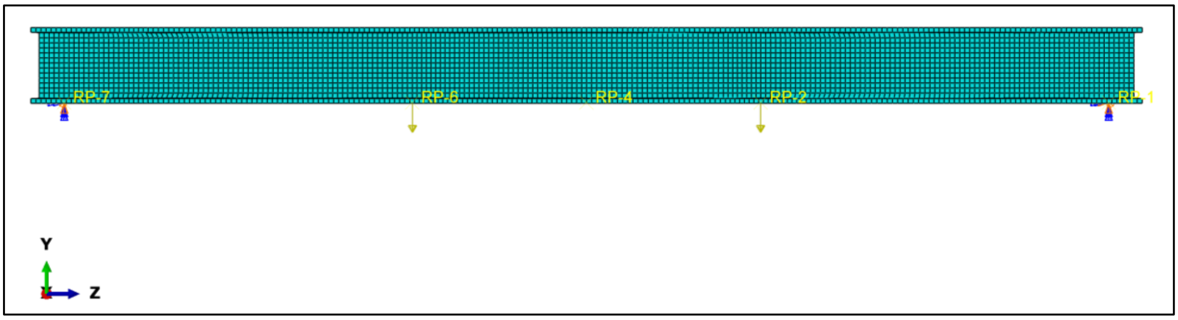
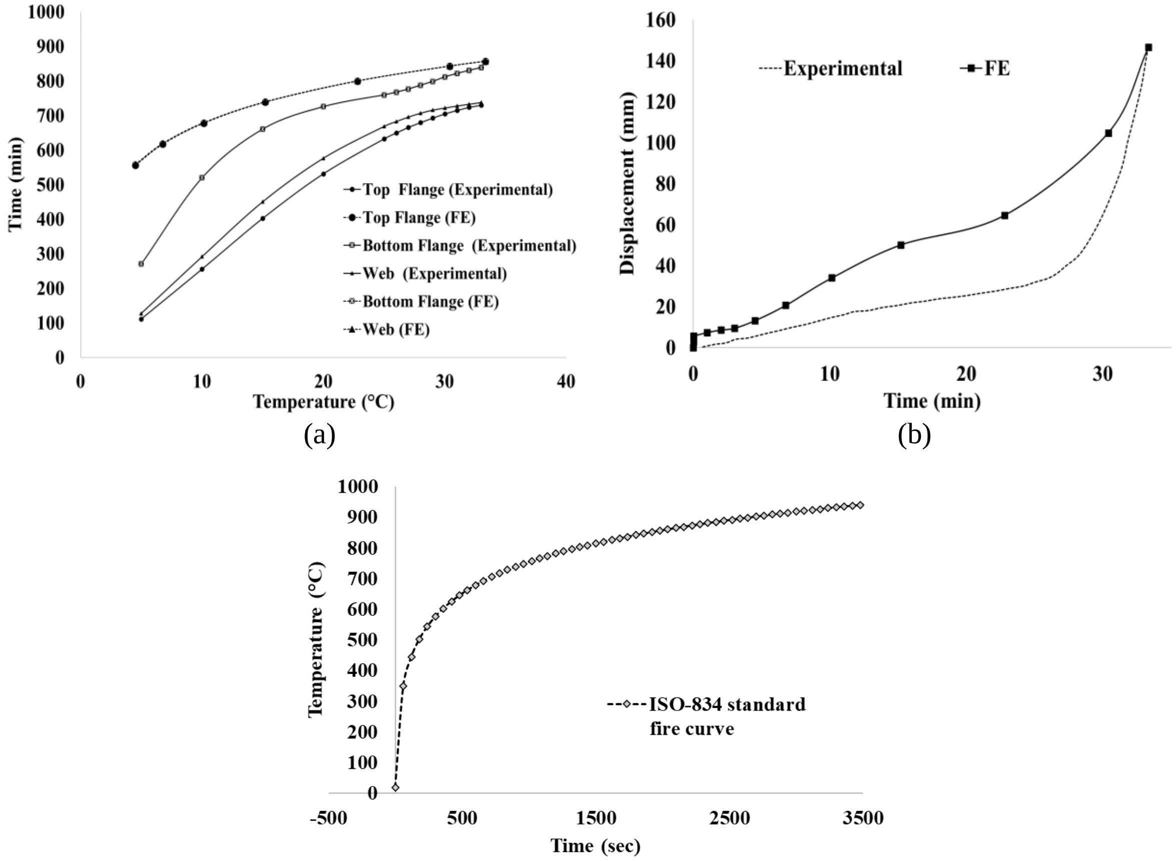


Figure 2: FE Model of the HEB 300 beam

In Figure-3(a) the temperature measured during the experiment was compared with those obtained from FE analysis for top flange, bottom flange and web. It was observed that the final temperature obtained from the FE model and experiment closely matched each other. There is a slight difference between the numerical FE and experimental model. This is thought to be due to not incorporating the shadow effect in the numerical analysis which has been proven to produce reduced temperature values (Virdi & Wickström, 2013).

The FE and experimental deflection at the mid-section of the beam with exposure time were compared in Figure-3(b). FE model shows a displacement of 146.6 mm at 33.3 minutes of exposure time and from the experiment (Łukomski et al. 2017) 147 mm displacement was found after 33.25 minutes. 147 mm is the limiting deflection value for failure criteria. So, the fire rating of the beam obtained from FE analysis and experiment were almost the same. From the comparison, it was observed that the FE model can predict the temperature and fire rating of a steel beam with great accuracy.



(c)

Figure 3: (a) Comparison of Temperature Vs Time cures of FE model and experiment ((Łukomski et al., 2017) (b) Comparison of deflection Vs Time curves of FE model and experiment ((Łukomski et al., 2017) (c) ISO-834 standard fire curve

2.2 Parametric Study

The FE model developed in Section 2 was used to evaluate the performance of stainless steel beams under fire. Three different beam sections were analysed for five different grades of stainless steel s and CS355 carbon steel. In this study austenitic grade 1.4301, 1.4401 and 1.4571; duplex grade 1.4462 and ferritic grade 1.4003 were used. Along with HEB 300, beam sections of HEB 200 and HEB 400 were modelled. The cross-sectional dimension of HEB and HEB 400 is given in Table-3. According to Eurocode 3, all three beams were classified as class 1 section. The material properties of stainless steel grades at room temperature is shown in Table 4. The properties of CS355 were taken according to Łukomski et al. (2017). For material modelling at elevated temperatures and thermal properties of stainless steel , the revised equations as suggested in the design manual of Badoo N. (2017) was applied accordingly. Stress-strain behaviour of Austenitic grade 1.4301 at different temperatures was shown in Figure-4. Each beam was analysed applying 30%, 50% and 70% load of their flexural capacity. The flexural capacity of each beam for different materials was calculated according to Eurocode 3. The corresponding two-point loads were determined according to Figure 1 and shown in Table-5. A total 54 models were analysed for this study.

Table 3: Beam profile dimensions

Beam Profile	**Depth, h (mm)**	**Width, b (mm)**	**Web thickness, t_w (mm)**	**Flange thickness, t_f (mm)**
HEB 200	200	200	9	15
HEB 400	400	300	13.5	24

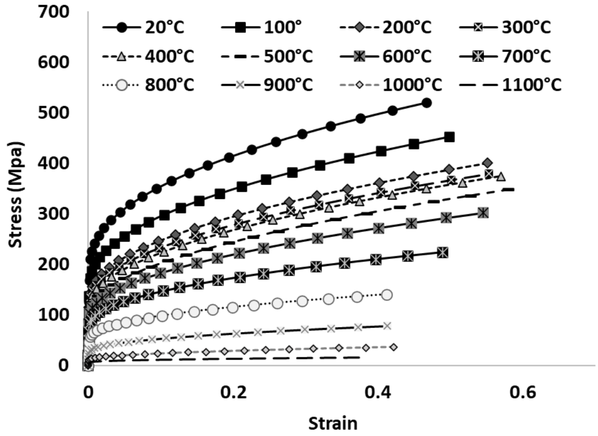


Figure 4: Stress-Strain curve of Austenitic 1.4301 (Baddoo N., 2017)

Table 4: Material properties of steel grades (Baddoo N., 2017)

Steel grades	Density (kg/m^3)	E (Mpa)	f_y (Mpa)	f_u (Mpa)	Coefficient n
1.4301	7900	200000	210	520	7
1.4401	8000	200000	220	530	7
1.4571	7900	200000	220	540	7
1.4462	7800	200000	460	700	8
1.4003	7700	200000	280	450	14

Table 5: load capacity determination of beam

Steel grade	HEB200		HEB300		HEB400	
	$M_{pL,Rd}$ (kNm)	Load Capacity, P (kN)	$M_{pL,Rd}$ (kNm)	Load Capacity, P (kN)	$M_{pL,Rd}$ (kNm)	Load Capacity, P (kN)
CS355	278	198	802	573	1400	1000
1.4301	130	93	376	269	656	469
1.4401	136	97	394	281	688	491
1.4571	136	97	394	281	688	491
1.4462	285	204	824	588	1438	1027
1.4003	174	124	501	358	875	625

3. RESULTS AND DISCUSSION

The performance of the steel beams was compared based on the fire rating i.e., the time a beam can sustain the applied load during exposure of fire. According to European standard, EN 1363-1, a beam is considered to fail when its deflection crosses a limited value D_{lim} (Łukomski et al. 2017). The limiting value of deflection, D_{lim} can be calculated using Equation (1). D_{lim} values for all the considered beams are shown in Table 6.

$$D_{lim} = \frac{L^2}{400d}\ mm \quad (1)$$

In the above equation, L and d are the clear span length between the support in mm and the distance from the extreme fibre of the cold design compression zone to the extreme fibre of the cold design tension zone of the structural section respectively.

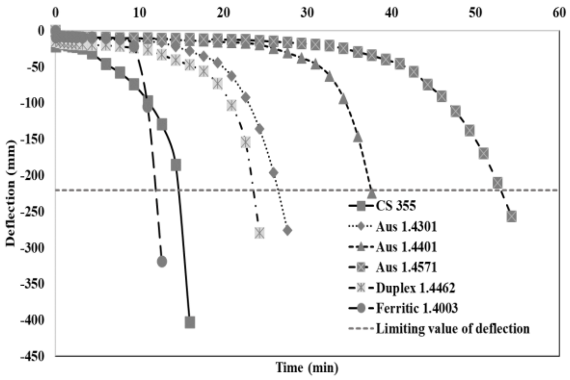
Table 6: Limiting value of deflection of each beam section

Beam profile	Limiting value of deflection, D_{lim} (mm)
HEB 200	220.5
HEB 300	147
HEB 400	110.25

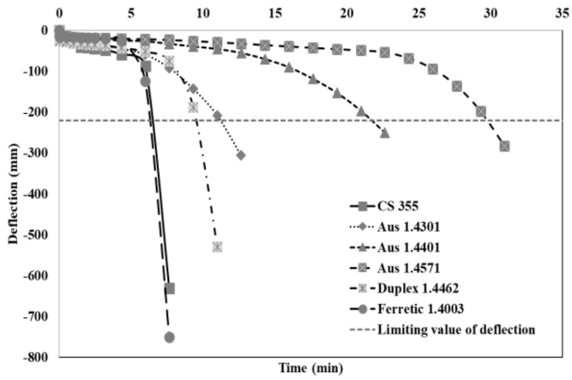
In Figure-5, the deflection of the different beams with respect to fire exposure time at different loading levels are illustrated. From these figures, it is clear that the fire resistance of considered austenitic and duplex grades of stainless steel is better than that of carbon steel. However, ferritic grade steel beams sustain lesser time than carbon steel beams under fire. This can be explained by analysing the chemical composition provided in EN 10088. The carbon content in stainless steel is less than that of stainless steel. Furthermore, the family of these heat resistant stainless steels contain a minimum of 10.5% chromium (EN 10088) which is completely absent in carbon steel. Again, the mentioned grades of austenitic are found to contain a considerable amount of nickel (maximum permitted weight range is 8-13.5%) which is more than that of duplex grade 1.4662 (maximum permitted weight range is 3-4.5%) (EN 10088). Except for austenitic grade 1.4301, all of the mentioned grades of austenitic and duplex contain a small amount of molybdenum (EN 10088). In ferritic grade 1.4003 there is almost no Nickel (maximum permitted weight range is 0.3-1%) and molybdenum is fully absent (EN 10088).

The limiting deflection values are also shown in Figure-5. The fire rating of the beams at different loading conditions is also determined and presented in Table-7. From the table, it was also observed that except for ferritic grade, the time of failure for stainless steel grades in almost all cases is greater than that of carbon steel. At a low loading condition of 30% of beam capacity, the performance of austenitic steel grades 1.4301 (26.5 min) and duplex 1.4462 (23.7 min) is almost twice that of carbon steels (14.7 min). Furthermore, at the same loading condition, the performance of austenitic grade 1.4571 (53.1 min) is almost four times and grade 1.4401 (37.6 min) is almost thrice that of carbon steel respectively.

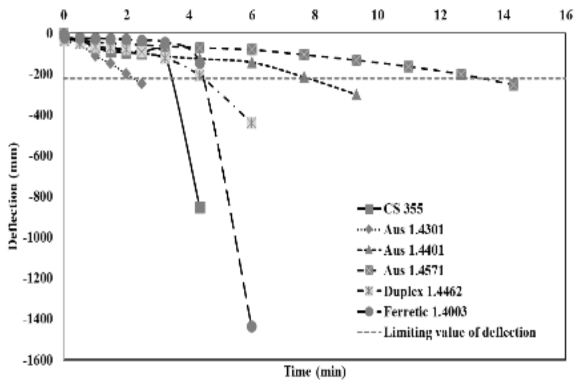
Comparing different grades of austenitic grades of stainless steel at the same loading condition shows that stabilized stainless steel of grade 1.4571 is the best performing steel under fire, followed by molybdenum-chromium-nickel austenitic steel grade 1.4401. The performance of basic chromium-nickel austenitic steel of grade 1.4301 is the lowest. In HEB 300 at 50% load capacity the time of failure of austenitic: grade 1.4571 is 29.8 min, of grade 1.4401 is 21.8 min and that of grade 1.4301 is 11.2 min respectively. It is to be noted that though the chromium and carbon content in all the three austenitic grades are the same but the content of nickel is higher in grade 1.4571 (EN 10088). Again, the thermal properties, such as thermal conductivity and specific heat are the same for all austenitic. The performance of duplex grade was in between austenitic grades and carbon steel.



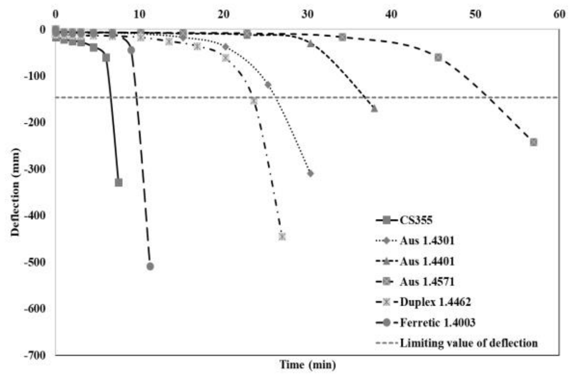
(a) HEB 200 at 30% of load capacity



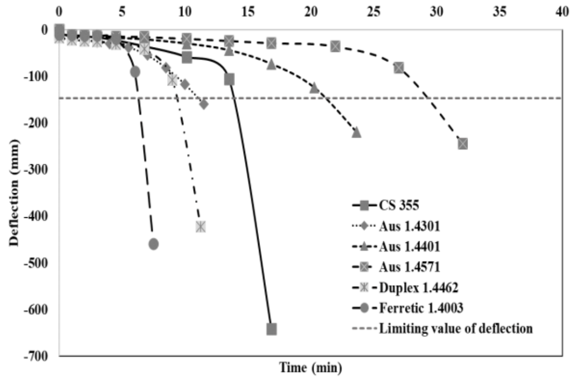
(b) HEB 200 at 50% of load capacity



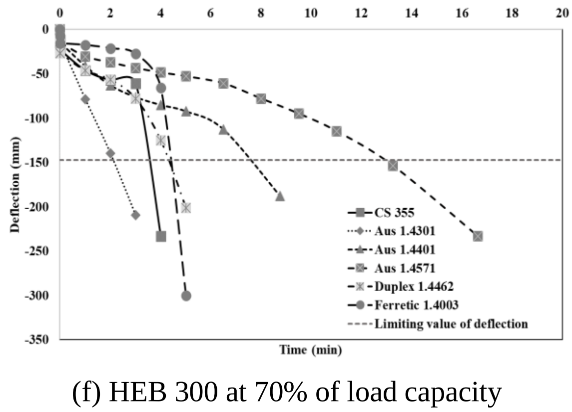
(c) HEB 200 at 70% of load capacity



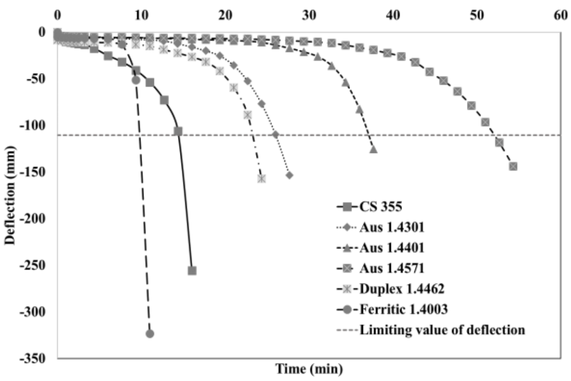
(d) HEB 300 at 30% of load capacity



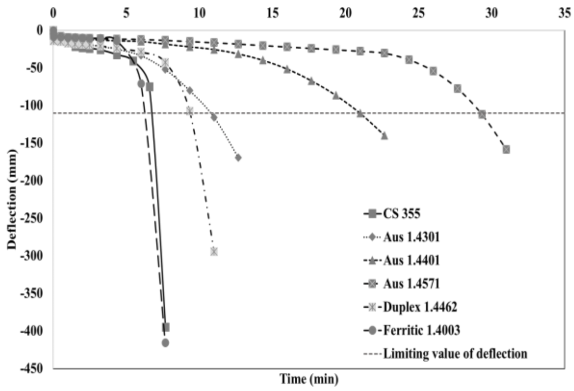
(e) HEB 300 at 50% of load capacity



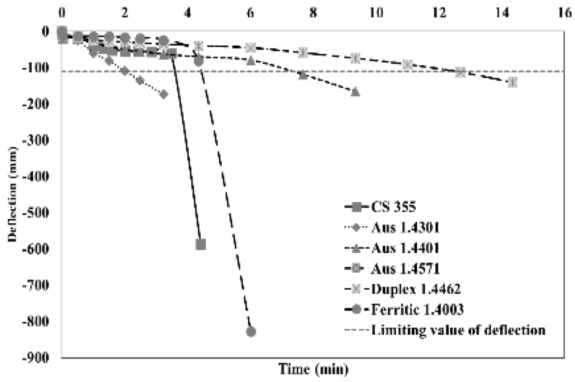
(f) HEB 300 at 70% of load capacity



(g) HEB 400 at 30% of load capacity



(h) HEB 400 at 50% of load capacity



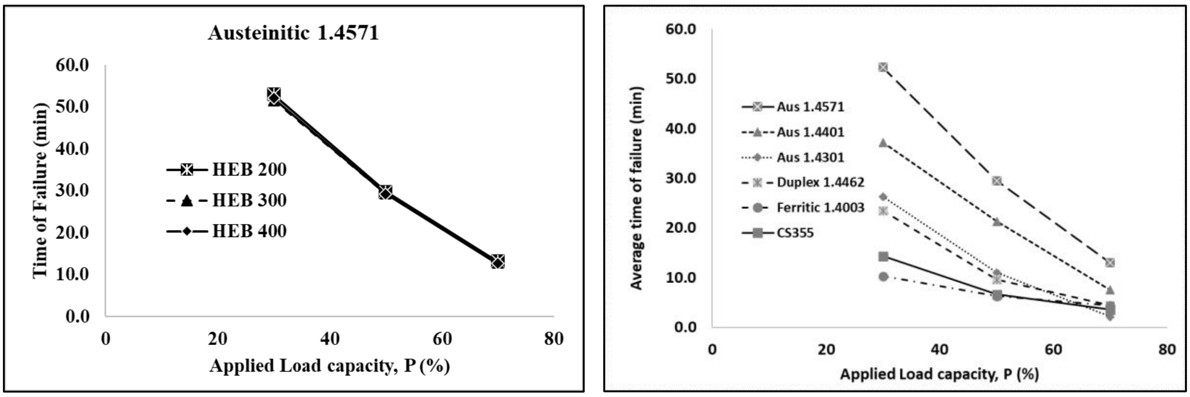
(i) HEB 400 at 70% of load capacity

Figure 5: Deflection Vs. Time graph for HEB 200, HEB 300, and HEB 400 beams for different grades of steel at different loading conditions

Table 7: Fire rating of different steel beams at different load levels

Steel grade	30% of load capacity (min)			50% of load capacity (min)			70% load capacity (min)		
	HEB 200	HEB 300	HEB 400	HEB 200	HEB 300	HEB 400	HEB 200	HEB 300	HEB 400
Aus. 1.4571	53.1	51.7	52.2	29.8	29.3	29.3	13.2	13.0	12.6
Aus. 1.4401	37.6	36.9	37.1	21.8	21.1	21.0	7.8	7.5	7.3
Aus. 1.4301	26.5	26.2	26.1	11.2	11.0	10.8	2.2	2.1	2.0
Dup. 1.4462	23.7	23.5	23.2	9.6	9.3	9.8	4.4	4.3	4.4
Fer. 1.4003	10.7	10.1	10.0	6.3	6.3	6.2	4.3	4.3	4.4
CS355	14.7	13.9	14.5	6.5	6.5	6.7	3.4	3.5	3.6

Analysing the effect of change of beam section in Figure 6 (a), it can be seen that in austenitic grade 1.4571, the change in beam section has almost no effect in time of failure. A similar trend was also found for other grades of steel.   This shows that in presence of fire, the failure of the beam does not depend on the cross-section. It depends on the characteristic material properties and loading level of the beam. In Figure-6 (b), the average time of failure for different loading levels for all the considered grades of steel is presented.



(a) (b)

Figure 6: (a) Time of failure of 1.4571 grade of stainless steel beams at different loading levels (b) Average time of failure for different grades of steel at different loading levels

4. CONCLUSIONS

In this study, the fire resistance of five different grades of stainless steel beams of three different beam profiles was evaluated and compared with carbon steel under three different loading conditions. Initially, a FE model was developed and validated with experimental results. Using the validated FE model, the fire rating of the stainless steel grades and carbon steel were determined. Analysis showed at all three loading conditions, the fire rating of austenitic grades of stainless steel beams is higher than carbon steel beams. The performance of duplex grade was also higher than carbon steel but lower than austenitic grades. On the other hand, the fire rating of the ferritic grade of stainless steel was lower than carbon steel. Furthermore, analysing the performance of the beams for any particular grade with change in beam profiles showed no notable difference when the loading conditions were changed proportionately with that of the beam section capacity.

REFERENCES

Baddoo, N. R., & Burgan, B. A. (1998). Fire Resistant Design of Austenitic Structural Stainless steel . In *J. Construct. Steel Res* (Vol. 46).

Baddoo Nancy. (2017). *Design manual for structural stainless steel 4th edition*.

Ding, R., Fan, S., Chen, G., Li, C., Du, E., & Liu, C. (2019). Fire resistance design method for restrained stainless steel H-section columns under axial compression. *Fire Safety Journal*, *108*(January), 102837.

Dassault Systmes Simulia Corp (2014). ABAQUS/Standard User's Manual, Version 6.14-4 [Computer software]

Fan, S., Ding, X., Sun, W., Zhang, L., & Liu, M. (2016). Experimental investigation on fire resistance of stainless steel columns with square hollow section. *Thin-Walled Structures*, *98*, 196–211.

Fan, S., Liu, M., Sun, W., Guo, Y., & Han, Y. L. (2018). Experimental investigation of eccentrically compressed stainless steel columns with constraints in fire. *Fire Safety Journal*, *99*(June), 49–62.

Franssen, Jean-Marc & Vila Real, Paulo. (2015). Fire Design of Steel Structures, 2nd edition.

Gardner, L., & Baddoo, N. R. (2006). Fire testing and design of stainless steel structures. *Journal of Constructional Steel Research*, *62*(6), 532–543.

Gardner, L., & Ng, K. T. (2006). Temperature development in structural stainless steel sections exposed to fire. *Fire Safety Journal*, *41*(3), 185–203.

Gardner, Leroy. (2019). Stability and design of stainless steel structures – Review and outlook. *Thin-Walled Structures*, *141*(December 2018), 208–216. https://doi.org/10.1016/j.tws.2019.04.019

Kucukler, M., Xing, Z., & Gardner, L. (2020). Behaviour and design of stainless steel I-section columns in fire. *Journal of Constructional Steel Research*, *165*

Lopes, N., Manuel, M., Sousa, A. R., & Vila Real, P. (2019). Parametric study on austenitic stainless steel beam-columns with hollow sections under fire. *Journal of Constructional Steel Research*, *152*(2017), 274–283.

Lopes, N., Real, P. V., da Silva, L. S., & Franssen, J. M. (2010). Numerical modelling of thin-walled stainless steel structural elements in case of fire. *Fire Technology*, *46*(1), 91–108.

Lopes, N., Vila Real, P., Simões Da Silva, L., & Franssen, J. M. (2012). Numerical analysis of stainless steel beam-columns in case of fire. *Fire Safety Journal*, *50*, 35–50.

Łukomski, M., Turkowski, P., Roszkowski, P., & Papis, B. (2017). Fire Resistance of Unprotected Steel Beams-Comparison between Fire Tests and Calculation Models. *Procedia Engineering*, *172*, 665–672.

Mohammed, A., & Afshan, S. (2019). Numerical modelling and fire design of stainless steel hollow section columns. *Thin-Walled Structures*, *144*

Ng, K. T., & Gardner, L. (2007). Buckling of stainless steel columns and beams in fire. *Engineering Structures*, *29*(5), 717–730.

To, E. C. Y., & Young, B. (2008). Performance of cold-formed stainless steel tubular columns at elevated temperatures. *Engineering Structures*, *30*(7), 2012–2021. https://doi.org/10.1016/j.engstruct.2007.12.015

Tondini, N., Rossi, B., & Franssen, J. M. (2013). Experimental investigation on ferritic stainless steel columns in fire. *Fire Safety Journal*, *62*(PART C), 238–248.

Uppfeldt, B., Ala Outinen, T., & Veljkovic, M. (2008). A design model for stainless steel box columns in fire. *Journal of Constructional Steel Research*, *64*(11), 1294–1301. https://doi.org/10.1016/j.jcsr.2008.05.003

Vila Real, P. M. M., Lopes, N., Simões da Silva, L., & Franssen, J. M. (2008). Lateral-torsional buckling of stainless steel I-beams in case of fire. *Journal of Constructional Steel Research*, *64*(11), 1302–1309.

Virdi, K.S., & Wickström, U. (2013). Influence of shadow effect on the strength of steel beams exposed to fire.

Xing, Z., Zhao, O., Kucukler, M., & Gardner, L. (2021). Fire testing of austenitic stainless steel I-section beam-columns. *Thin-Walled Structures*, *164*(May), 107916.