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Proceeding Paper

Flexure Response of Stainless-Steel-Reinforced Concrete (SSRC) Beams Subjected to Fire †

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Abstract: This paper examines the behavior of stainless-steel-reinforced concrete (SSRC) flexural members subjected to fire. Stainless steel (SS) reinforcement has gained popularity due to its corrosion resistance and long maintenance-free life. However, there is an insufficiency of performance data and design guidance in the present literature. This paper presents a numerical assessment of SSRC structural elements using a material model based on experimental tests. A finite element model was utilized to simulate and analyze the response of SSRC beams under fire. This study compared the behavior of SSRC beams with traditional carbon-steel-reinforced concrete (CSRC) beams, demonstrating that SSRC members have a higher load carrying capacity and can sustain fire exposure for longer durations. Additionally, SSRC beams exhibited higher deflections during fire exposure compared to CSRC beams.

Keywords: ABAQUS; finite element modeling; stainless steel; reinforced concrete

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1. Introduction

In past few years, there has been a noticeable surge in the utilization of stainless steel (SS) rebars as an appealing substitute for traditional carbon steel reinforcement in the United Kingdom. This growing trend can be attributed to its advantageous and sustainable characteristics, including exceptional resistance to corrosion, leading to extended periods of maintenance-free durability. However, there remains a significant gap in publicly available data concerning the performance and design aspects, particularly in extreme circumstances like fires. While SS rebars were primarily employed in bridges and structures such as water treatment plants, which were susceptible to corrosion, their application has broadened to encompass various structural uses in recent years, including industrial buildings, car parks, and marine environments.

Despite the extensive research on various aspects of SS rebars, there is a notable scarcity of information regarding its behavior at elevated temperatures. Figure 1a,b depict the retention factors for yield strength and Young's modulus at different elevated temperature levels for bare SS structural sections, comparing the performance to both carbon steel (CS) [1] and grade 1.4301 [2,3] stainless steel. These distinct properties of SS prove highly beneficial during fire incidents. However, it is important to note that stainless steel's higher coefficient of linear thermal expansion (between 14–17 $\times 10^{-6}/°C$) compared to carbon steel ($12 \times 10^{-6}/°C$) presents a challenge in maintaining the bond between SS rebars and the surrounding concrete under elevated temperature scenarios. This can lead to compromised composite action, increased cracking, and heightened levels of concrete spalling.

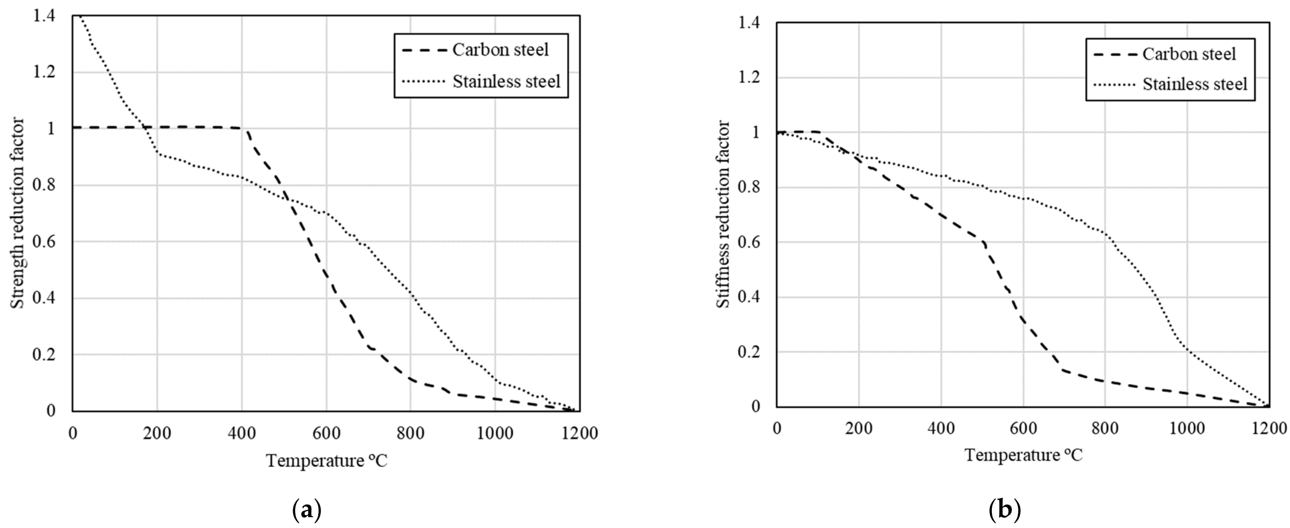

Figure 1. Retention of mechanical properties for stainless steel (SS) and carbon steel (CS) including (**a**) strength; (**b**) stiffness (adapted from Ref. [3]).

In light of this dearth of data, the current study aimed to address the elevated temperature behavior of SSRC in fire. The approach involves the development and validation of a finite element model, incorporating experimental data [4], to accurately represent the material properties of SS rebars at elevated temperatures.

2. Finite Element Analysis

2.1. General

A numerical model was developed to simulate and study the behavior of SSRC structural members at elevated temperatures. To date, there is no physical test data for this type of structural behavior. In terms of the ambient temperature behavior, a number of researchers have conducted a numerical analysis of SSRC beams (e.g., [5–7]). Therefore, the numerical model developed in this paper was validated using CSRC beams tested by Dwaikat and Kodur [8].

2.2. Structural Arrangement

The numerical model was developed based on a sample beam with the details of Beam B-1, which was examined by Dwaikat and Kodur [8] under standard fire curve ASTM E119 [9], and was made of normal strength concrete with a 58 MPa compressive strength. As shown in Figure 2, the simply supported beam was 3960 mm in length, 254 mm in width, and had a total depth of 406 mm. The beam had tensile reinforcement from three 19 mm bars and compression reinforcement from two 13 mm bars. Shear reinforcement was also included in the cross-section and this was 6 mm bars at a constant spacing of 150 mm. The nominal yield strength of the longitudinal rebar was 420 N/mm^2 and 280 N/mm^2 for the stirrups. The beam was loaded in 4-point loading conditions; the two loading points were 1200 mm apart from each other.

2.3. Material Modeling

The concrete material behavior is defined through the damage plasticity material model (CDP), available in the ABAQUS [10] library. The CDP model includes the effect of elevated temperature and can model the inelastic response of concrete in both tension and compression. The concrete material model was developed using Eurocode 2 [2].

An isotropic yielding of steel reinforcement with temperature dependence can be defined in ABAQUS [10] by a uniaxial yield surface against uniaxial plastic strain. A constitutive material model of the carbon steel reinforcement was also taken from Eurocode 2 [2]. In the current study, actual stress–strain curves for both austenitic and duplex steel, determined through practical tests [4] and shown in Figures 2 and 3, were implemented in the ABAQUS model for validation at elevated temperatures.

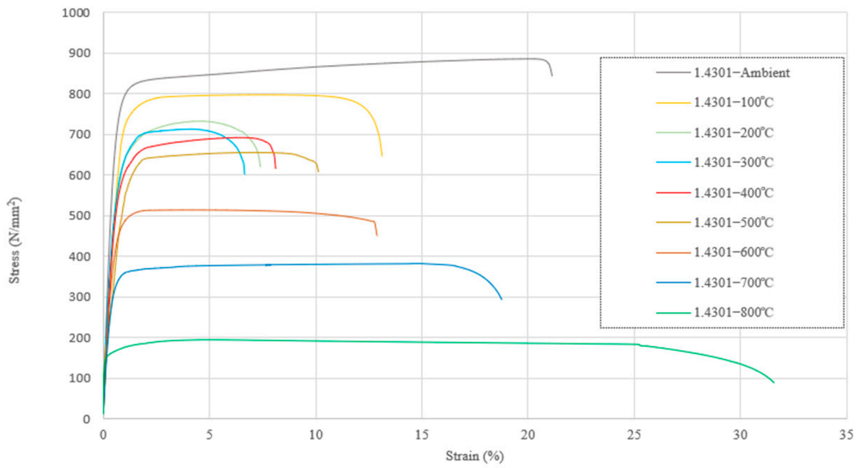

Figure 2. Stress-strain responses for grade 1.4301 at elevated temperatures adapted from Ref. [4].

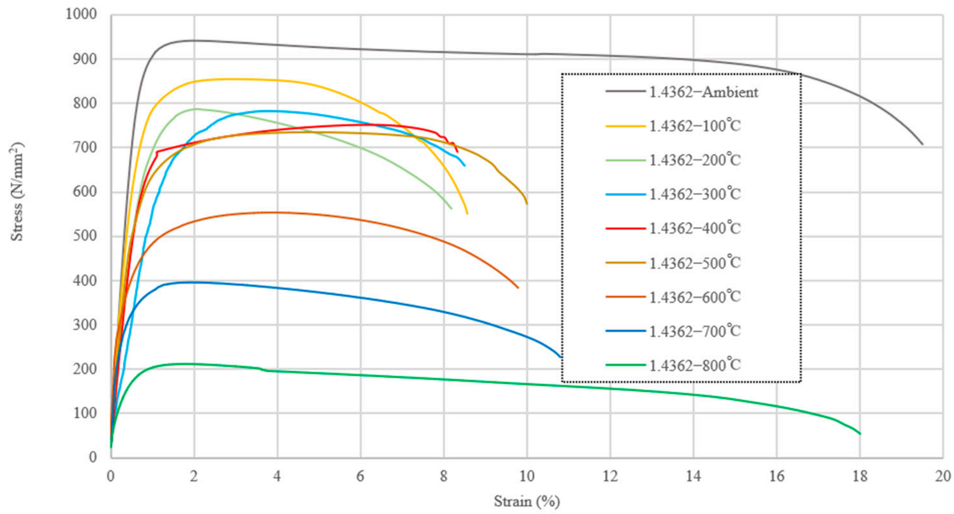

Figure 3. Stress–strain responses for grade 1.4362 at elevated temperature adapted from Ref. [4].

2.4. Sequentially Coupled Thermal Stress Analysis

There are generally two different approaches in finite element analysis for the solution of structural fire analyses. There are fully coupled and sequentially coupled thermal-stress analyses. The former of these is hugely computationally demanding and therefore, for RC structures, a sequentially coupled stress analysis is typically employed as it is more computationally efficient; this was employed in the current work. A sequentially coupled thermal-stress analysis is performed in two steps: (i) a heat transfer analysis is first conducted to simulate the spread of an elevated temperature through the sections and (ii) a thermal-stress analysis is then performed to apply the thermal loads and compute displacements. The temperature at each node of the element is calculated in the first step and these are then applied as a predefined field in the second step. Details of these steps are given in another paper by the author that was published earlier [11].

2.5. Validation of the Numerical Model

The validated numerical model was employed for the simulation of SSRC beams under fire. The only difference in the model is the material model for the reinforcement. The interaction between the rebar and the concrete is modeled as a perfect bond in both cases; however, the tensile stiffening modeled for concrete allows for modeling the effect of interaction in a simple manner [10]. In the current study, stress–strain curves measured in practical tests for both austenitic (1.4301) steel and duplex (1.4362) steel at elevated temperatures were used in the numerical model to determine the fire resistance of SSRC beams under fire. There was a wide difference in the thermal expansion of CS and SS rebars, but it did not result in any changes in the heat distribution between the concrete and rebars (Figure 4).

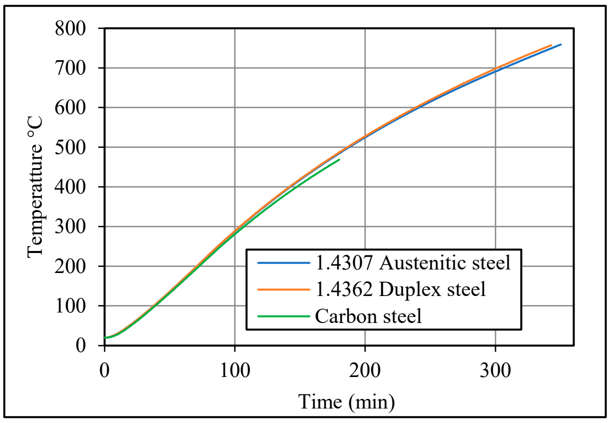

Figure 4. Comparison of temperature in reinforcement of similar RC beams reinforced with SS and CS.

2.6. Results

The comparison of two RC beams reinforced with CS and austenitic steel with a similar cross-sectional geometry, concrete strength, and reinforcement ratio was performed for sample beam validation, is shown in Figure 5. The SSRC beam showed no failure under the ASTM E119 [9] fire curve, allowing for a reduced reinforcement ratio to analyze its behavior under the full-time–temperature curve. A further comparison showed that SSRC sustains loads under fire much longer than CS, even with a reduced reinforcement ratio. The CSRC beam failed at around 175 min, while the austenitic and duplex SSRC beams failed at 237 and 243 min, respectively, with different failure modes: concrete crushing for SSRC beams and a combination of concrete crushing and steel rupture for CSRC beams.

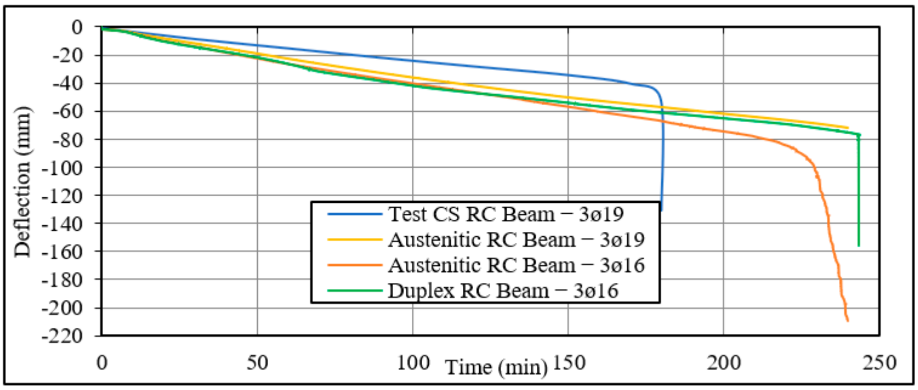

Figure 5. Fire resistance of RC beams reinforced with different steel ratios of CS, austenitic, and duplex steel.

3. Conclusions

This study aimed to examine the mechanical behavior of austenitic and duplex steel rebars when exposed to elevated temperatures. To achieve this, actual material models, developed through a testing program, were incorporated into a validated finite element model of an SSRC beam that was subjected to a fire scenario.

The numerical results obtained from the analysis indicated that the SSRC beams were able to withstand fire for a much longer duration compared to CSRC beams. This suggests that stainless steel exhibits superior fire resistance properties. Furthermore, the SSRC beams experienced higher deflections during the fire exposure when compared to CSRC beams.

Based on these findings, it is recommended that further research studies could be conducted to investigate the behavior of SSRC beams at elevated temperatures with different material strength and load ratios. This would provide a more comprehensive understanding of the performance of SSRC structures in fire scenarios, allowing for the development of more accurate design guidelines and safety standards.

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Conflicts of Interest: The authors declare no conflict of interest.

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