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Elevated temperature material properties of stainless steel reinforcing bar

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HIGHLIGHTS

- Review of use of stainless steel reinforcing bars.
- Isothermal and anisothermal testing of stainless steel reinforcing bars.
- Reduction factors proposed for key elevated temperature properties of stainless steel rebar.
- Room and elevated temperature stress-strain curves proposed for stainless steel rebar.

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ABSTRACT

Corrosion of carbon steel reinforcing bar can lead to deterioration of concrete structures, especially in regions where road salt is heavily used or in areas close to sea water. Although stainless steel reinforcing bar costs more than carbon steel, its selective use for high risk elements is cost-effective when the whole life costs of the structure are taken into account. Considerations for specifying stainless steel reinforcing bars and a review of applications are presented herein. Attention is then given to the elevated temperature properties of stainless steel reinforcing bars, which are needed for structural fire design, but have been unexplored to date. A programme of isothermal and anisothermal tensile tests on four types of stainless steel reinforcing bar is described: 1.4307 (304L), 1.4311 (304LN), 1.4162 (LDX 2101®) and 1.4362 (2304). Bars of diameter 12 mm and 16 mm were studied, plain round and ribbed. Reduction factors were calculated for the key strength, stiffness and ductility properties and compared to equivalent factors for stainless steel plate and strip, as well as those for carbon steel reinforcement. The test results demonstrate that the reduction factors for 0.2% proof strength, strength at 2% strain and ultimate strength derived for stainless steel plate and strip can also be applied to stainless steel reinforcing bar. Revised reduction factors for ultimate strain and fracture strain at elevated temperatures have been proposed. The ability of two-stage Ramberg-Osgood expressions to capture accurately the stress-strain response of stainless steel reinforcement at both room temperature and elevated temperatures is also demonstrated.

1. Introduction

The traditional approach to improving the durability of reinforced concrete structures is to modify the concrete specification, in terms of composition and/or cover requirements. Whilst this approach can improve the performance, it is not an inherently durable solution to the problem of chloride-induced corrosion and there is a risk that significant maintenance may be required within the design life of the structure. Maintenance is disruptive and costly, especially when it results in transportation disruptions and/or the loss of production due to facility shut-down. The use of stainless steel reinforcing bar can be a cost-effective option for structures in potentially corrosive environments which are expensive to maintain and repair because stainless steel is highly resistant to corrosion from chloride ions and does not rely on the high alkalinity of concrete for protection. As well as reduced maintenance costs, the use of stainless steel reinforcement will give the

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structure a longer design life (>100 years) compared with carbon steel and enable a reduction in concrete cover and weight of deck and substructure.

Stainless steels derive their inherent corrosion resistance from the presence of certain alloying elements, primarily chromium and nickel, which result in differences in microstructure compared to carbon steel. The physical and mechanical properties of stainless steels at room temperature, and at elevated temperatures, also differ from carbon steel. Stainless steels generally retain more of their room temperature strength than carbon steel above temperatures of about 550 °C, and more of their stiffness than carbon steel across the whole temperature range [1,2]. Although there have been a number of investigations into the performance of stainless steel flat material at elevated temperatures, data on the performance of stainless steel reinforcing bar at elevated temperatures are scarce and no information is given in EN 1992-1-2, the Eurocode dealing with the performance of concrete structures at elevated temperatures [3]. This is an important gap in technical knowledge, especially since the protection of key infrastructure elements is becoming increasingly important. As described by Garlock et al. [4], the majority of fires that occur on bridges are hydrocarbon fires, often as a result of spillage from crashed oil tankers. These hydrocarbon fires are characterised by high heating rates, which means failure can occur only a short time after ignition. A notable bridge fire occurred in Birmingham, Alabama in 2002 when a petroleum truck collided with a bridge support at the junction of Interstates 65, 20, and 59. The tanker's cargo ignited, causing a severe fire which damaged the bridge to such an extent that it had to be completely replaced; the consequent traffic disruption was enormously costly [5]. Giuliani et al. [6] studied the vulnerability of bridges to fire and concluded that in the majority of bridge fires, the bridge structure was significantly damaged and high repair costs were sustained. Even where limited structural damage had occurred, high costs due to the temporary closure of the bridge and traffic disruption had to be sustained.

This paper describes the outcomes of a test programme aimed at investigating the elevated temperature material characteristics for stainless steel reinforcement. Two test methods (anisothermal and isothermal) were used to assess the mechanical behaviour at elevated temperatures of plain and ribbed bars of diameter 12 mm and 16 mm in four grades of stainless steel.

2. Applications of stainless steel reinforcing bar

Stainless reinforcing bar was first developed in the 1930's [7] and the earliest known structure with stainless steel reinforcement was the 2100 m long Progreso Pier in the Gulf of Mexico, which was built in 1940 and is still fit-for-purpose (background, Fig. 1). Stainless steel was selected due to the warm and humid marine environment and the use of local limestone aggregate in the concrete with a relatively high porosity. In 1969, a neighbouring pier was built with carbon steel reinforcement which has now suffered very severe corrosion (foreground, Fig. 1).

No further applications were found until 1970, when the issue of chloride ingress began to be recognised as a significant problem for reinforced concrete structures in corrosive environments. Since then, stainless steel reinforcing bar has been used around the world in a range of large and small structures including bridges, tunnels, buildings, harbour installations, temples and monuments, both for new structures as well as for repairing corrosion-damaged structures [8]. The non-magnetic property of austenitic stainless steel has also led to the use of stainless steel reinforcing bar in buildings such as hospitals, banks, airports and meteorological stations which house equipment sensitive to magnetic fields.

Fig. 1. Progreso Pier, Mexico – the pier in the background was constructed in 1940 and used stainless steel reinforcing bar whereas the pier in the foreground was constructed in 1969 and used carbon steel reinforcing bar (Courtesy of the Nickel Institute).

A more recent example of stainless steel reinforcement being used in a large infrastructure project is in Edmonton, Canada. The very low winter temperatures and high annual snowfall in this area leads to the application of large amounts of salt, both sodium and the more corrosive calcium chloride, to keep the roads as free from ice as possible. Following a successful trial in 2011, around 6000 tonnes of grade 1.4362 duplex stainless steel reinforcing bar were specified for the construction of a new interchange (bridge substructure, retaining walls, overpass, etc) on the ring road around the city [8].

Stainless steels are inevitably more expensive than carbon steel due to the alloying elements they contain. In order to realise a whole life cost benefit, it is generally necessary to concentrate stainless steel reinforcing bar in areas of the structure most at risk. Gedge [9] presents a classification system for structural elements that are likely to benefit from specification of stainless reinforcing bar. For the majority of highway bridges, use of stainless steel reinforcing bar for parapet edge beams, bearing shelves on jointed bridges, abutments and intermediate supports adjacent to the carriageway is considered the most cost-effective solution. The United Kingdom's Highway Agency has specifically recognised selective use of stainless steel as a viable option for reduced whole cost of a structure in its *Design Manual for Roads and Bridges* [10]. Predictive models for specifying the level of corrosion resistance required for reinforcing bar in a range of service environments have also been developed [11].

Research by the Virginia Transportation Research Council found that the whole life cost of a bridge that utilises corrosion resistant metallic reinforcing bars (CRR) is substantially less than standard designs with either conventional or epoxy-coated reinforcing bar. As a result, all projects in the State of Virginia with a design life of 75 years or longer are required to use CRR steels and not epoxy coated or galvanised bars [12].

Reinforcing bar is also available in high strength, high chromium microcomposite steels with improved resistance to corrosion, known as MMFX steels [13]. They contain about 9% chromium, so cannot be classified as stainless steel and do not demonstrate the level of corrosion resistance of the standard stainless steels used in the reinforcing bar which are studied in this paper. Another solution for extending the life of reinforced concrete structures exposed to corrosive environments are glass fibre reinforced polymers reinforcing bar. However glass fibre performs poorly at elevated temperatures, and melts at around 800 °C. Numerical modelling has shown that the fire resistance of a beam with carbon steel reinforcing bar is at least double that of an equivalent beam with glass fibre reinforcement [14].