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DESIGN OF LONG LIFE CONCRETE STRUCTURES USING HIGH PERFORMANCE REINFORCING STEELS

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ABSTRACT

The need to upgrade the large number of aging reinforced concrete (RC) structures that are exposed to aggressive environments, such as de-icing salts in cold regions and sea water requires the development of innovative solutions that will lead to the construction of long life RC structures with low life cycle costs. In this paper, the impacts of using high performance reinforcing steels (HPS), such as 316 LN, 304 and 2205 duplex stainless steels and ASTM - 1035 (or chromium) steel on the service life and structural behaviour of RC structures are investigated. In terms of resistance to chloride attack, 316 LN stainless steel provided the highest value, followed by 2205 duplex steel, chromium steel and then carbon steel. In terms of yield and ultimate strengths, chromium steel exhibited the highest values followed by 316 LN and 22065 duplex steels then carbon steel. In terms of ductility, the RC beams reinforced with 316 LN steel exhibited the highest capacity to deform before fracture, followed by duplex 2205 steel, carbon steel, and then chromium steel. In terms of flexural design of RC beams reinforced with HPS, the same flexural capacity is achieved by using much lower areas of reinforcement for chromium steel, followed by stainless steel and then carbon steel. This suggests that greater savings in material, labour, and maintenance costs are possible when using chromium steel and stainless steel as a reinforcement for RC structures built in aggressive environments, such as highway bridge decks, parking structures, marine and off-shore structures.

Keywords: chloride threshold, concrete structures, corrosion, ductility, flexural design, high performance reinforcing steel

INTRODUCTION

Chloride-induced corrosion of steel reinforcement has been identified as one of the main causes of deterioration of reinforced concrete (RC) structures, such as highway bridges, parking structures, marine structures, etc. This led to very high costs of highway bridge repair in North America and Europe from the effects of de-icing salts used during winter or from seawater for costal structures. From a durability-design point of view, the development of a performance-based approach is critical to ensure adequate safety and serviceability throughout the design life of concrete structures. Such an approach will also help identify the appropriate maintenance strategies to extend the service life and minimize the risk of failure of RC structures built in chloride-laden environments.

The service life of RC structures built in corrosive environments depends on several parameters, including the rate of ingress of chlorides (and possibly carbon dioxide) into concrete, corrosion resistance of reinforcing steel to chloride attack, rate of corrosion, concrete cover depth, rebar diameter and spacing, and tensile strength of concrete. The corrosion of the reinforcing steel is assumed to start when the concentration of chlorides at the level of the reinforcement reaches the so-called chloride threshold value, which is used as a corrosion resistance indicator for reinforcing steel[1,2,3,4]. The use of high performance reinforcing steels (HPS), such as stainless steel and the newly developed ASTM 1035 steel[5] referred to as chromium steel in this paper, in addition to the use of high performance concrete (HPC) are two approaches that have been used to extend the service life of concrete structures for more than three decades. In addition to the improved corrosion resistance of these reinforcing steels, they also provide much higher tensile strengths than carbon steel, which can be used to reduce the amount of required reinforcement, concrete cover depth, as well as overall size of structural members. However, the lack of well defined yield point for these high performance steels and the reduced ductility of chromium steel compared to carbon steel require further investigation and greater attention in the design and detailing of structures reinforced with these steels. Furthermore, current design codes and standards limit the yield strength of reinforcing steel to 500 MPa, which is well below the yield strengths of chromium and stainless steels.

The current practice of design of concrete structures for durability is mainly based on prescriptive rules, such as specifying minimum concrete cover, maximum water/cement ratio, use of corrosion-resistant reinforcing steels, limitation of crack width, etc. They are deemed to satisfy the design life requirements of safety and serviceability without providing an explicit and quantitative relationship between the demand on the structure, its capacity and service life[2,6]. However, the observed extensive deterioration and failure of a large number of reinforced concrete (RC) structures (e.g. bridge decks, parking structures, etc.) in North America well before the end of their design life have illustrated the serious shortcomings of the current “deem-to-satisfy” prescriptive rules.

The objective of this paper is to investigate the impacts of using high performance reinforcing steel on the time to corrosion initiation of RC structures exposed to chlorides and on the flexural behaviour of RC beams and their implications for design.

IMPACT OF HIGH PERFORMANCE REINFORCING STEEL ON SERVICE LIFE OF RC STRUCTURES

FICKIAN DIFFUSION-BASED SERVICE LIFE MODEL

In porous solids, such as concrete chlorides can penetrate into concrete via different physical mechanisms, such as diffusion, capillary absorption, electrical migration, and permeation due to hydraulic pressure heads[3]. Most models for chloride ingress into concrete however, are based on the assumption of a Fickian process of diffusion as the main transport mechanism. These models represent quantitatively an adequate understanding of the physico-chemical processes that induce deterioration in RC structures, namely: (i) simplified diffusion-based model for chloride ingress into concrete; and (ii) chloride threshold value as a corrosion resistance indicator of the reinforcement. Based on these, a mechanistic model of the corrosion initiation time can be expressed as a function of four key parameters[3,4,6,7], as follows:

$$T_i = f(C_s, C_{th}, D, d_c) = \frac{d_c^2}{4D[erf^{-1}(1-\frac{C_{th}}{C_s})]^2} \qquad (1)$$

where T_i is the time to onset of corrosion, C_s is the surface chloride concentration, C_{th} is the chloride threshold value, D is the chloride diffusion coefficient, d_c is the depth of concrete cover over the reinforcing steel, and *erf* is the error function. The model is a transformation of Crank's solution to Fick's second law of diffusion for one-dimensional flow over a semi-infinite medium[7] with the mathematical interpretation of Tuutti's corrosion initiation model[1], under the assumptions of a constant diffusion coefficient, constant surface chloride content as the boundary condition, and the initial chloride concentration condition specified as zero. This model can be used to study the sensitivity of the time to corrosion initiation to each of the four parameters[6,8,9] and to explore the quantitative relationships between pairs of governing parameters[8]. This paper will present how the other parameters can be selected by using the high performance steel with high chloride threshold values.

In this paper, the emphasis is on the physical performance and no consideration is given to cost implications. It should be pointed out that for a truly effective design of RC structures, the cost implications of changing the different design parameters should be explicitly considered in order to determine the optimal combination of values that satisfy the design life and minimize the life cycle costs of RC structures (including the costs of design, construction, maintenance, rehabilitation)[9,10].

SENSITIVITY ANALYSIS OF SERVICE LIFE MODEL

Differential sensitivity analysis by using a Taylor's series is used to assess the sensitivity of the time to corrosion initiation to its four governing parameters. The diffusion-based corrosion initiation time model of Eq. (1) can be represented as the following function:

$$T_i = f(C_s, C_{th}, D, d_c) = f(X_1, X_2, X_3, X_4) \qquad (2)$$

The first-order sensitivity S_j is defined as a normalized relative change in T_i that results from a relative change in X_j , when the other variables are kept constant[6,8,11]:

$$S_j = \frac{\partial f(X_0)}{\partial X_j}\frac{X_{jo}}{T_{i0}} \qquad j=1,\ldots\ldots,4 \qquad (3)$$

Using Eq.(3), the first-order sensitivity coefficients of T_i to C_s, C_{th}, D, or d_c, can be obtained[6] and are presented in Fig.1, and T_i is more sensitive to the variable X_m rather than X_n if $|S(X_m)| > |S(X_n)|$. For example, the values of $S(d_c)$ and $S(D)$, are constant and equal to 2 and –1, respectively, which indicate that T_i is much more sensitive to d_c than D. The first order sensitivity coefficients of T_i to C_{th} are complex functions of the variables C_s and C_{th}, so are the higher order sensitivity coefficients. A numerical relationship is therefore developed to evaluate $\Delta T_i / T_i$ versus $\Delta C_{th} / C_{th}$ [6]. In addition to the relationships derived from Eq. (1), the sensitivity between parameters can also be explored to take into account the considerable level of uncertainty in chloride threshold value, which depends on the type of reinforcing steel, type of cementing materials, test methods, etc[4,9]. This enables to illustrate how one design parameter needs to be modified to accommodate for the variation in chloride threshold values, especially for the case of detrimental impacts on service life.

A value of 50 years is assumed as the specific design life (T_i) throughout the numerical illustrations in this paper. Realistic ranges of values of the four governing parameters, C_s, C_{th}, D, and d_c, are summarized below, with emphasis on highway bridge deck applications[9,12]. Values of C_{th} are taken from the reported values from Trejo and Pillai[13,14], with the mean values of C_{th} of 0.52 kg/m^3, 4.6 kg/m^3, 5.0 kg/m^3, and 10.8 kg/m^{3}for carbon steel, chromium steel, stainless steel SS304 and SS316LN, respectively. A constant value of d_c is chosen to be 50 mm when studying the relationships between other parameters, and the associated variation of d_c is between 20 mm and 80 mm, which is ±60%, representing the range of variation for cast-in-place bridge decks built in the sixties and seventies[8]. The chloride diffusion coefficient D of normal concrete is considered to vary from 10^{-12} m^2/s to 10^{-11} m^2/s[6,15]. Lower values of D from 10^{-13} m^2/s to 10^{-12} m^2/s are referred to as high performance concrete (HPC) only in terms of resistance to chloride penetration in this paper[15]. The exposure condition is considered as a corrosion load for concrete structures and a constant for each of the exposure conditions. The constant values of C_s are 1.8 kg/m^3, 3.5 kg/ m^3, 5.3 kg/ m^3, and 7.4 kg/ m^3, for the four exposure conditions of *Light, Moderate, Heavy, and Severe Exposures,* respectively[12].

RESULTS OF SENSITIVITY ANALYSIS AND DESIGN IMPLICATIONS

Fig. 1 represents plots of the variations of the sensitivity coefficients of T_i to the four governing variables versus the C_s/C_{th} ratio, which is varied from 1 to 10, representing an increasingly corrosive environment for a given steel reinforcement. Fig. 1 shows that both $|S(C_{th})|$ and $|S(C_s)|$ decrease exponentially with increasing C_s/C_{th} ratios from values higher than 4 then decrease asymptotically towards zero.

For conventional carbon steel, C_s/C_{th} ratios for may vary from 3.5 to 14.2 depending on the environmental exposures[6]. In this range, it yields the ranking of sensitivities (Fig.1) shown in

Eq.(4), which means that increasing concrete cover depth for carbon steel reinforcement is the most effective measure to increase the service life, followed by increasing the quality of concrete. For corrosion resistant steels, the C_s/C_{th} ratios could be less than 1.6. In this range, it yields the ranking (Fig.1) shown in Eq.(5), which implies that for RC structures reinforced with high performance steels, it is critical to determine a reliable value of chloride threshold in order to properly predict the service life.

$$|S(dc)| > |S(D)| > |S(Cth)| = |S(Cs)| \quad (4)$$

$$|S(Cth)| = |S(Cs)| > |S(dc)| > |S(D)| \quad (5)$$

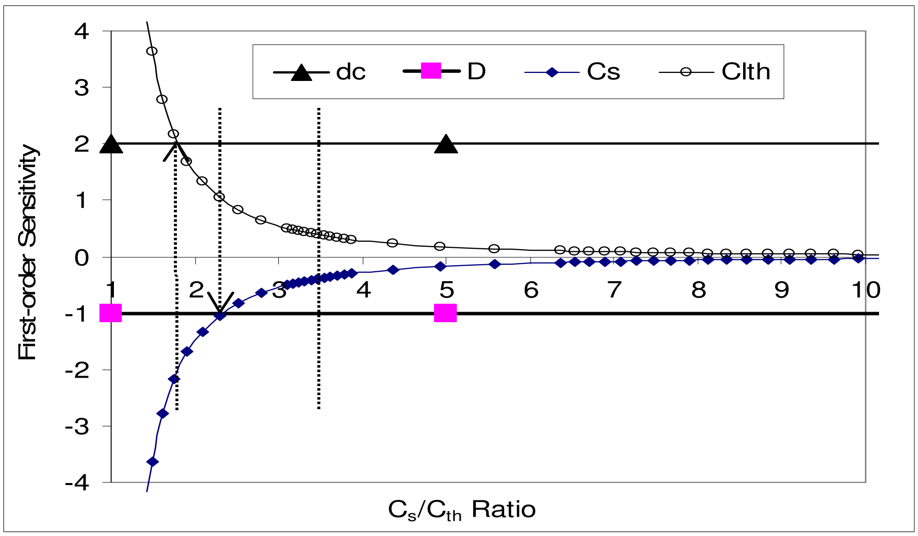

Fig. 1. Sensitivities of T_i to D, d_c, C_s, C_{th} as functions of C_s/C_{th} ratio

IMPACT OF CHLORIDE THRESHOLD ON SERVICE LIFE OF RC STRUCTURES

The variations $\Delta C_{th}/C_{th}$ associated with the mean values C_{th} for each of the four types of steel are used to calculate the variations induced in T_i, for each of the four exposure conditions, if applicable (assuming $C_{th} \le C_s$). The variations of $\Delta T_i / T_i$ with $\Delta C_{th} / C_{th}$ are illustrated in Fig. 2 for carbon steel under four exposure conditions. The results can be summarized as follows:

- The closer C_{th} is to C_s, the more T_i is sensible to C_{th}. In other words, the higher the value of C_{th}, the higher its impact on T_i. This is also confirmed by comparing different steels, e.g. for severe exposure: C_s=7.4 kg/m^3, the variations associated with carbon steel, chromium steel, and SS304 steel are –24% to 19%,–40% to 96%,–50% to 400%, respectively.
- Increasing of C_{th} is an effective measure to increase the design life. The rate of increase of T_i is higher for larger increases in C_{th}, e.g., a 100% increase in C_{th} increases T_i by 69%, while a 300% increase in C_{th} increases T_i by as much as 280%. It means that if carbon steel is replaced by an HPS with 3 times higher corrosion resistance, T_i will be increased by 3 times.

IMPACT OF CHLORIDE THRESHOLD ON CONCRETE COVER

Fig. 3 illustrates the relationship between d_c and C_{th} under "*Heavy Exposure*" condition for different D values, which vary from those of normal concrete to HPC for an assumed design life of 50 years. It can be clearly seen that an increase in C_{th} can effectively reduce the requirement on concrete cover depth. For example, for a concrete with $D = 5\times10^{-13}$ m^2/s (HPC), an increase of C_{th} from 0.52 kg/m^3 (that of carbon steel) to about 3.0 kg/m^3 can bring down the required cover (d_c) from 65 mm to about 20 mm.

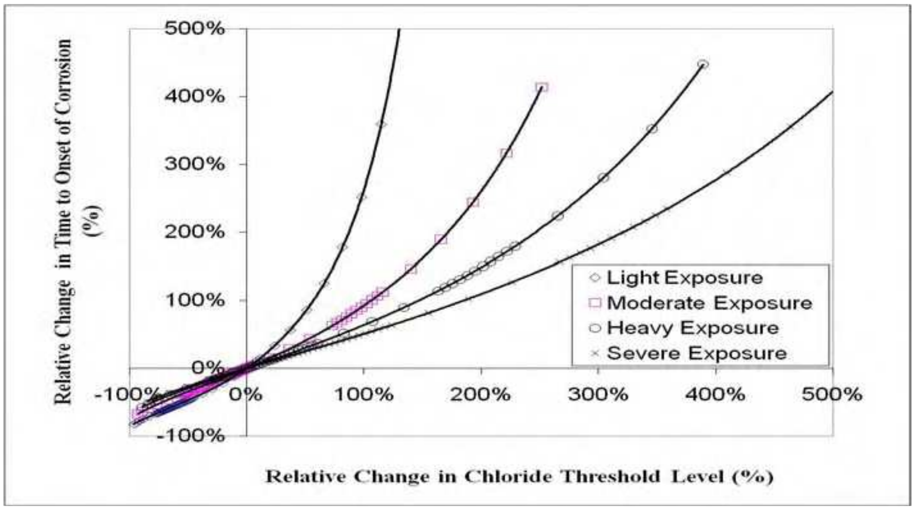

Fig. 2. Impact of Chloride Threshold Level on Corrosion Initiation Time

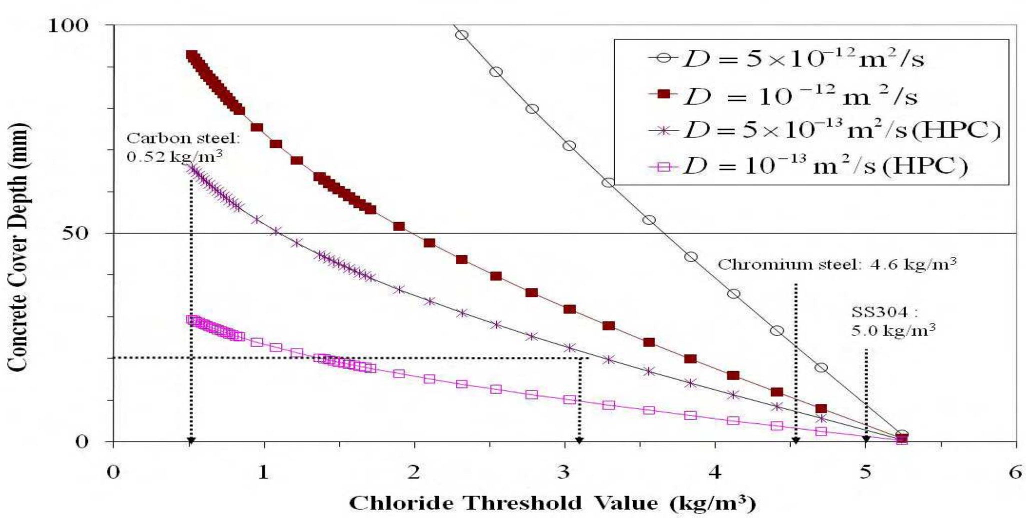

Fig.3. Sensitivity of Cover Depth to Chloride Threshold for Heavy Exposure

IMPACT OF CHLORIDE THRESHOLD ON DIFFUSION COEFFICIENT

The relationship between the concrete diffusion coefficient and corrosion resistance of steel (in terms of C_{th}) is affected by the concrete cover depth and exposure condition. Fig. 4

illustrates the relationship under "*Heavy Exposure*" for different d_c values and for an assumed design life of 50 years. An increase of d_c from 20 mm to 80 mm can lead to a reduction of C_{th} from about 3.6 kg/m^3 to 0.52 kg/m^3 (that of carbon steel) in HPC, for a value of D slightly lower than 10^{-12} m^2/s; however, it reduces C_{th} from about 4.8 kg/m^3 (e.g. chromium or SS 304 steel) only to 3.3 kg/m^3 in normal concrete, for a value of D slightly lower than 10^{-11} m^2/s. This means that the selection of an adequate concrete cover is more critical for normal concrete, because the larger D values of normal concrete result in a limited choice of steel types that can be used to achieve the specified design life. Their relationship also suggests that the use of a steel with C_{th} around 5.0 kg/m^3 (e.g. stainless steel SS 304) under "*Heavy Exposure*" will help achieve a design life T_i of 50 years, even for a low cover (d_c = 20 mm) and normal concrete (D = 10^{-11}m^2/s).

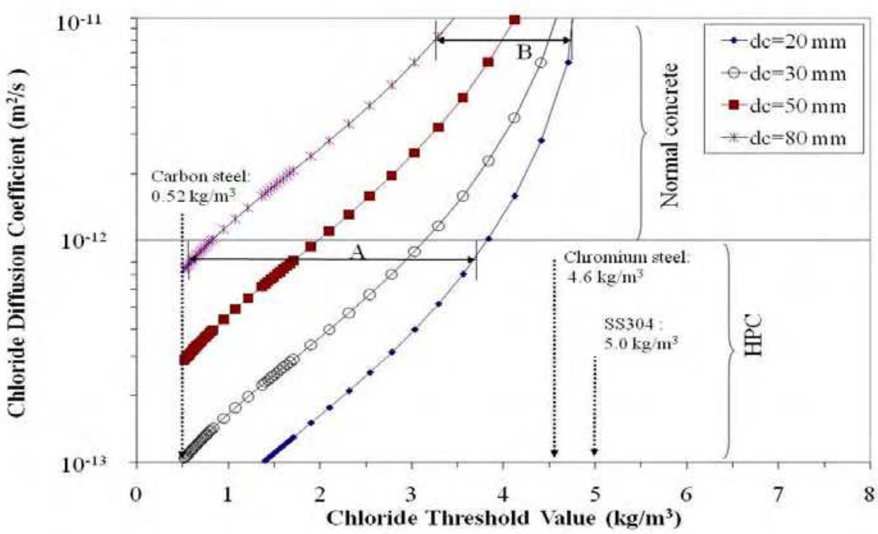

Fig.4. Sensitivity of Chloride Diffusion Coefficient to Chloride Threshold

BEHAVIOR OF RC BEAMS WITH HIGH PERFORMANCE STEEL

CONSTITUTIVE LAWS OF CARBON, CHROMIUM AND STAINLESS STEELS

The stress strain relationships of 400R carbon steel, chromium, 316 LN (SS) and 2205 Duplex Stainless steels S are shown in Fig. 5. Chromium steel exhibits an ultimate strength twice as high than that of carbon steel. The yield points of chromium and stainless steels are not well defined, and their strain hardening behaviours are not well separated from their yielding zones. The yield is traditionally defined by the 0.2% offset method of ASTM (ASTM A370). On the other hand, chromium steel exhibits an ultimate strain of less than half of the ultimate strain of carbon steel. Stainless steels 316 LN and 2205 Duplex have ultimate strains that are 70% and 150% higher than that of carbon steel (CS), respectively. The ultimate strength of 316 LN SS is 25% higher than that of carbon steel, while that of 2205 Duplex SS is almost equal to that of the carbon steel. All steel types have almost the same modulus of elasticity but stainless steels have relatively lower proportional limits.

DESIGN OF RC BEAMS USING HIGH PERFORMANCE REINFORCING STEELS

In order to study the mechanical behaviour of RC flexural elements reinforced with high performance steel, twelve (12) beams, three for each of the four types of steel, have been tested to failure under four points loading. The c/c span between the supports of the beams is 2.7 m, the dimensions of the cross section are 200 mm X 300 mm, and the average 28-day compressive strength of concrete is 50 MPa. The beams are designed to be under-reinforced, having similar flexural strengths and comparable ductility and over-designed for shear. The required area of each steel type is relative to its yield strength and the available bar diameters. The test results show a variation in ultimate strength of up to 10% and a variation of less than 5% in the maximum deflection between the different beam groups, as shown in Fig.6.

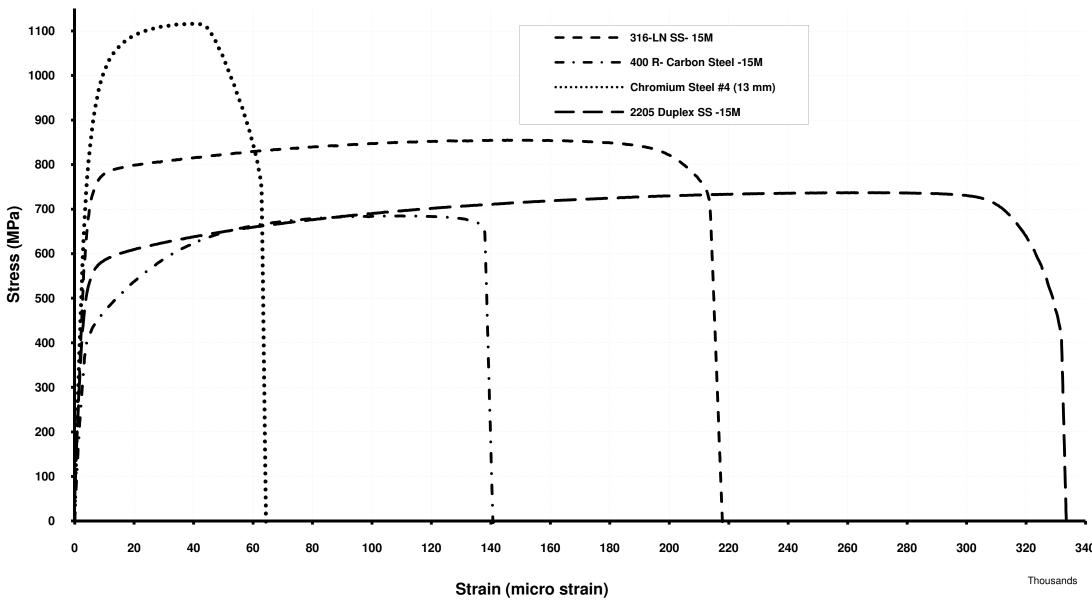

Fig. 5. Stress-Strain Relationships for Carbon Steel and High Performance Steels

Table 1 illustrates that the amount of chromium steel used is only one third of that of carbon steel and the amount of the stainless steel is two third of that of carbon steel. The yield strengths of the beams with HPS are lower than that of the carbon steel by up to 10%. The ductility index $\left(DI = \frac{\Delta_{\text{ult}}}{\Delta_{\text{yield}}}\right)$, is defined as the ratio between the ultimate deflection and the yield deflection, has acceptable values for all the beams, however, the DI values of HPS are 20-25% lower than that of carbon steel due to their higher deflections at "yield". The yielding zones of beams with HPS are not easily distinguished as for carbon steel and the slopes of their load-displacement curves are apparently lower.

DESIGN IMPLICATIONS

High performance steel (HPS) is intended to be used in bridge elements exposed to corrosive agents. Given their high strengths, the use of HPS could result in significant reduction in the amount of flexural reinforcement needed for RC structures. Similarly, the use of HPS enables concrete covers that are lower than those required with carbon steel for the same design life. However, further testing is required to assess their ductility, bond and serviceability conditions, such as maximum crack width and deflection under service loads to ensure that they comply with all code requirements for safety and serviceability.

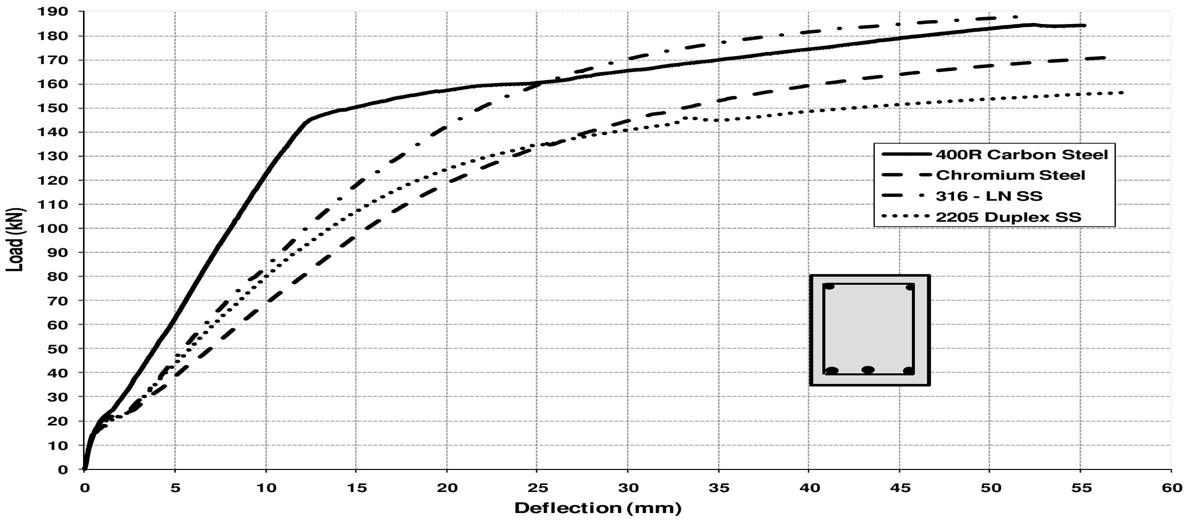

Fig. 6. Load-Deflection Relationships for RC Beams Reinforced with Different Steels

Table 1. Flexural Reinforcement and Mechanical Properties of RC Beams

Steel Type	Flexural steel ratio ρ_s(%)	Yield Load (kN)	Ultimate load (kN)	Deflection at Yield (mm)	Ultimate Deflection (mm)	Ductility Index (DI)
Carbon Steel	1.200	148	185.4	13.2	57.4	4.4
Chromium Steel	0.418	128*	171.3	23.2	57.3	2.5
SS 316 LN Steel	0.798	155*	180.5	23.4	50.7	2.2
SS 2205 Steel	0.788	132*	156.6	22.8	57.8	2.54

*0.2% offset

SUMMARY AND CONCLUSIONS

This paper presented an investigation study of the impact of high performance reinforcing steels on the corrosion performance and mechanical behaviour of RC structures and implications for durability design as well as flexural design. The proposed approaches can be used as guidelines towards performance-based durability design of concrete structures based on the simplified diffusion-based model, which overcomes some of the limitations of the current prescriptive rules of existing design standards.

The sensitivity of the time to corrosion to the type of reinforcing steel used as measured by its chloride threshold level is a function of the ratio of surface chloride content and chloride threshold of the steel. It is found that increasing chloride threshold is an effective measure to increase the time to onset of corrosion. It is also an effective way to reduce the requirement for deep concrete covers, which also implies to reduce the negative impact of variation in concrete cover depth in reality.

The experimental study of the behaviour to failure of beams reinforced with different types of reinforcing steels showed that considerable reductions in the amount of reinforcement can be achieved by using high performance steels. However, further studies are needed regarding the ductility and bond behaviour as well as impacts on serviceability conditions of maximum crack width and deflection under service loads.

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