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Interface-controlled chloride corrosion in grouted sleeve joints of prefabricated RC elements: Performance enhancement using duplex stainless steel (Grade 2205)

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ABSTRACT

Prefabricated reinforced concrete (RC) systems are efficient in terms of construction, but their durability is highly dependent on the behaviour of joint regions with several material interfaces. This research examines the chloride-induced corrosion performance of prefabricated beam–column joints connected by grouted sleeves, as compared with traditional cast-in-situ counterparts. The study employed an experimental–analytical method with wetting-drying cycles in a 3.5% NaCl solution to represent severe environmental exposure. The findings show that prefabricated joints demonstrate faster corrosion, with corrosion initiation 40–60% earlier than in cast-in-situ joints. The rate of corrosion was about 2.8 times faster, and the chloride diffusion coefficient increased by 2.5 times, confirming increased transport via the interfacial regions. Damage was concentrated at the sleeve interfaces, with a Damage Localisation Index (DLI) of about 0.62, and led to wider cracks than observed in traditional structures (more than twice the width). This study shows that the corrosion behaviour of prefabricated joints is largely controlled by the interface rather than the bulk properties. Targeted application of duplex stainless steel (Grade 2205) in key areas was effective in delaying the onset of corrosion and in diminishing its impact, showing the benefit of using this material in critical areas. The research provides evidence of interface-controlled corrosion and highlights the need for interface engineering and material design to enhance the sustainability of prefabricated concrete structures.

1 Introduction

Prefabricated reinforced concrete (RC) systems are gaining momentum in contemporary construction for their benefits in speed, quality and sustainability [1–4]. Such systems are extensively used in infrastructure works and buildings where time is of the essence. But their structural integrity relies on the performance of their joints or connections, which are the main load-bearing zones and often the most vulnerable parts of prefabricated structures.

In contrast to the cast-in-situ approach, prefabricated systems include multiple interfaces between various materials, such as concrete–grout, grout–steel, and sleeve–concrete [5–7]. These boundaries introduce heterogeneity and are often more porous, less bonded and microscopically discontinuous. The higher porosity, poorer bonding and existence of microvoids and discontinuities make the interface more prone to damage under aggressive environmental conditions [8–11]. These characteristics i.e. higher porosity, poorer bonding and existence of microvoids

and discontinuities are usually associated with variations in material characteristics, surface properties and construction processes, such as voids, air pockets, and poor surface preparation. The interfaces are thus more susceptible to damage, especially when subjected to hostile environments.

Chloride-induced reinforcement corrosion is the most significant durability issue that impacts the performance of reinforced concrete. In traditional systems, chloride penetration is usually assumed to be a diffusion process through a dense and homogeneous concrete matrix [12–14]. Yet, in prefabricated joints, this process is quite different. Chloride ions are more likely to travel through the concrete via pathways of lower resistance (such as interfaces), resulting in accelerated accumulation at the reinforcing steel.

This preferential transport is exacerbated by uneven moisture, oxygen and ionic concentrations within the joint. These differences promote the establishment of local anodic and cathodic sites, leading to pitting. These forms of corrosion are especially aggressive at sleeve ends, grout imperfections, and construction joints such as pump and vent

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holes, where corrosion initiation and propagation is more likely. This can result in considerable loss of steel cross-section, bond deterioration and a decrease in strength over time.

Such effects are particularly prevalent in conventional reinforcement (Fe-415 and Fe-500) as it tends to lose its passive layer in high-chloride environments. This issue is more prevalent in precast systems, in which the corrosion performance is highly dependent on the interface. To address this issue, duplex stainless steel (Grade 2205) has gained traction as a viable alternative material, thanks to its high strength and excellent resistance to chloride attack. Its capacity to sustain a stable passive layer and resist pitting corrosion make it an excellent candidate for application in critical zones where corrosion is likely to occur.

Although prefabricated construction is gaining momentum, most of the previous studies on reinforced concrete corrosion have been related to cast-in-situ construction and have assumed uniform material properties. This means that traditional models are primarily based on bulk diffusion and do not sufficiently account for the effect of interfaces, which are predominant in prefabricated joints. The role of interfaces, defects and discontinuities in providing local transport pathways to corrosion initiation and growth is poorly understood.

Furthermore, although corrosion-resistant materials have been investigated for general use in reinforced concrete, they have received little consideration for use in the critical interfacial areas of prefabricated joints. Specifically, the performance of duplex stainless steel in situations where corrosion is controlled by interfacial properties has not been rigorously investigated. This underscores a need to better understand the interplay between material choice and interface characteristics in prefabricated systems.

To overcome these limitations, this research examines the corrosion of reinforcement in prefabricated beam-column joints with grouted sleeve connections exposed to chlorides, with particular emphasis on the effect of interfaces. An experimental-analytical framework was used to investigate corrosion initiation, propagation and damage localisation, and to compare prefabricated and cast-in-situ systems. Moreover, the study examines the suitability of duplex stainless-steel Grade 2205, in accordance with ASTM A240/A240M, as a targeted reinforcement approach in critical regions.

Key findings of this study include:

- Developing an interface-controlled corrosion process, demonstrating that the transport of chlorides and corrosion initiation are largely controlled by the interface rather than the concrete matrix.
- Development of a Damage Localisation Index (DLI) to measure how much and how concentrated the corrosion damage is in prefabricated joints.
- Offering experimental evidence under accelerated chloride attack, showing the difference in time to corrosion initiation, corrosion rate and damage evolution between prefabricated and cast-in-situ systems.
- Showing the potential benefits of using duplex stainless steel (Grade 2205) as a local mitigation measure to limit localised corrosion at critical locations.

1.1 Chloride-induced corrosion in prefabricated joints

Corrosion of RC structures is a well-known degradation process, especially in marine and de-icing salt environments. The conventional cast-in-situ systems generally have a

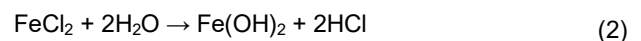
relatively uniform and dense concrete matrix through which the diffusing chloride is usually moving. In the case of prefabricated RC structures, however, the chloride ingress mechanism has a strong dependency on the material interfaces and construction discontinuities, and its corrosion behaviour is highly interface-sensitive.

Prefabricated beam-column connections with grouted sleeve joints are composed of a number of distinct regions, including concrete-grout interfaces, grout-steel interfaces and sleeve-concrete interfaces. These regions are more porous and susceptible to microcracking and a lack of bonding because of incompatibility in material properties, shrinkage, surface preparation, and construction errors such as air voids or poor compaction of grout. As a result, these zones serve as potential channels for the penetration of chloride ions, water and oxygen, giving rise to a highly non-homogeneous and localised diffusion process compared to monolithic concrete.

Once the chloride ions penetrate through these susceptible zones and reach the reinforcing steel, they disrupt the alkaline passive oxide layer normally formed on the steel surface. The reaction between ferrous ions and the chloride ions results in the formation of soluble iron chloride:



One of the distinctive features of chloride-induced corrosion is that it is self-catalysing. The iron chloride formed reacts with water to form ferrous hydroxide and hydrochloric acid:



The hydrochloric acid further lowers the pH, thereby enhancing the depassivation and dissolution of steel. This regeneration process allows the corrosion process to continue and accelerate, even in the absence of further chloride ingress, making it highly corrosive in small and susceptible interfacial areas.

In prefabricated joints, higher chloride concentrations are typically found in the vicinity of interfaces (e.g., sleeve ends, grout-concrete interface), and construction joints (e.g., pump hole and vent hole). Such microclimatic conditions enable the formation of electrochemical gradients caused by differences in moisture, oxygen and ion concentrations. This effectively creates corrosion cells that result in pitting as opposed to uniform corrosion. This type of damage is particularly insidious because of the rapid loss of cross-section of the reinforcement.

The sleeve (steel or polymer)-cementitious material interface is of particular importance. Lack of bonding and thermal or shrinkage compatibility can result in micro-gaps, which can act as both pathways for chlorides and sites for cracking and corrosion to initiate. Likewise, variations in the quality of bonding between grout and steel in sleeves also enhance corrosion.

Previous experimental studies have indicated that localised corrosion is more likely to occur at the vicinity of interfaces between sleeves, grout discontinuities and construction defects than in relatively homogenous concrete areas [3]. Wang et al. [14] found that accelerated corrosion occurred near the interfaces of grouting in the case of chloride exposure, and Li and Luo [4] showed that the existence of defects at the interfaces of prefabricated joints greatly promoted chloride transport and localised corrosion. In summary, corrosion in prefabricated joints is determined not just by the intrinsic properties of materials, but more importantly, by the nature of interfaces. The existence of preferential transport paths, microstructural imperfections

and electrochemical heterogeneities promotes the initiation and development of corrosion. Consequently, upgrading interfacial integrity by better matching material properties, surface treatment, and construction procedures is a key strategy to reduce the durability risks and enable long-term reliable performance of prefabricated reinforced concrete structures.

1.2 Aim

This research will explore interface-controlled corrosion in prefabricated RC beam-to-column joints exposed to chlorides and assess targeted strategies using duplex stainless steel.

2 Literature review

Reinforcement deterioration in RC structures is affected significantly by exposure to chloride surroundings. There has been considerable research on chloride ingress and the initiation of corrosion, where concrete is assumed to be a relatively homogeneous material. Traditional approaches based on Fick's Second Law have been commonly applied to model chloride ingress and service life [1], [2]. These methods have been largely successful in modelling cast-in-situ concrete but may miss the complexities associated with interfaces in prefabricated concrete.

Recent research has shown that the durability of prefabricated reinforced concrete structures is different from that of cast-in-situ concrete structures due to the existence of multiple interfaces. Bao et al. [3] and Li and Luo [4] have demonstrated that grouted sleeve connections exhibit higher porosity and reduced interfacial bonding between grout and concrete, which can lead to increased chloride penetration. Similarly, Liao et al. [5] showed through microstructural investigations that the interfacial transition zone (ITZ) of prefabricated connections often has microvoids and defects that provide transport pathways for aggressive ions.

The significance of these interfacial defects in controlling transport has been highlighted by studies of permeability and diffusivity. For example, Li et al. [6] found that chloride ingress in prefabricated elements is highly localised, with much higher concentrations at the interfaces than in the bulk concrete. This observation complicates the notion of uniform diffusion and indicates that chloride transport in these systems is strongly affected by the local transport pathways, rather than the overall material properties.

Besides transport, some researchers have considered the electrochemical aspects of corrosion in non-uniform concrete systems. Potgieter and Marjanovic [7] reported that differences in moisture and oxygen content can result in local anodic and cathodic areas, leading to pitting. This is especially important in prefabricated joints, where there are heterogeneities that promote local electrochemical processes. Li and Luo [4] reported that joint and defect regions of reinforcement are subject to more intense and localised corrosion than the surrounding reinforcement in uniform concrete.

Various methods to protect materials from corrosion have been studied, such as protective coatings, corrosion inhibitors and stainless-steel reinforcement. Of these, Grade 2205 duplex stainless steel has the highest corrosion resistance and mechanical properties. However, due to its relatively high initial cost compared with traditional carbon steel, it is more economical to apply it in specific application areas, especially in critical interfacial regions. Research by Pérez-Quiroz et al. [8] and Duarte et al. [9] showed that

duplex stainless steel retains its passivity at elevated chloride levels, greatly improving its lifespan. But most of these studies were conducted under uniform exposure and do not specifically investigate behaviour in prefabricated joints that are prone to localised corrosion.

However, there remains a significant gap in knowledge about corrosion in prefabricated reinforced concrete. Most of these studies are based on models for uniform materials and overlook the role of interfaces in chloride transport and initiation of corrosion. Additionally, the spatial variability of corrosion damage — especially in vulnerable locations such as sleeve boundaries and grout defects — has yet to be quantified in detail. Although laboratory experiments indicate the importance of interfacial zones, a holistic approach to relate microstructural features, transport processes and corrosion mechanisms remains to be established.

Additionally, the idea of mitigation (using corrosion-resistant materials) in high-risk areas has rarely been considered. Specifically, the role of duplex stainless steel in vulnerable interfaces of prefabricated joints under accelerated chloride attack has yet to be explored [10], [11].

Hence, there is a need for a more realistic and mechanistic perspective on corrosion in prefabricated structures. The current study seeks to overcome these limitations by creating a mechanistic view of interface-controlled corrosion and experimentally testing this view in prefabricated beam-column connections with grouted sleeves. Previous studies do not consider the degree of corrosion localisation and do not explicitly account for interface-controlled transport, both of which are treated in the present study.

2.1 Objective

- Quantify corrosion initiation and propagation in prefabricated vs cast-in-situ systems.
- Characterise chloride transport at interfaces.
- Create a Damage Localisation Index (DLI) for corrosion spread.
- Evaluate the effectiveness of duplex stainless steel in key areas.

2.2 Novelty

- Establishes an interface-controlled mechanism of corrosion, instead of the traditional uniform diffusion.
- Develops a Damage Localisation Index (DLI) to measure non-uniform corrosion.
- Furnishes experimental evidence of enhanced kinetics in prefabricated joints.
- Shows effective localised mitigation by using duplex stainless steel.

3 Methodology

3.1 Overview

Localised corrosion behaviour was evaluated in sleeve-connected joints, with the help of experimental observation and analytical interpretation. For a systematic comparison, three types of specimens were examined: (i) cast-in-situ specimens (C), (ii) prefabricated specimens with grouted sleeve connections (PC), and (iii) modified prefabricated specimens with conventional reinforcement but using duplex stainless steel (Grade 2205) in critical locations (PC-DSS).

Geometric consistency was maintained for all specimens in terms of geometry and reinforcement arrangement, to exclude any effects on the corrosion behaviour. The use of duplex stainless steel was focused on critical areas, specifically the stirrups placed in close proximity to the sleeve–grout–concrete interface, to investigate its role as a localised anti-corrosion measure.

The details of the grouted sleeve connection and critical interfacial regions are shown in Fig. 1.

3.2 Materials

In this study, normal-grade concrete of grade M30 was used for the structural elements and high-performance cementitious grout was used in the sleeve connections. Standard deformed (Fe-500) steel bars were used for the longitudinal reinforcement and stirrups in the C and PC specimens, while in the PC-DSS specimens the longitudinal bars and the stirrups located within the joint zone (one stirrup spacing on either side of the sleeve – the highlighted DSS region in Fig. 2) were replaced with duplex stainless steel (Grade 2205, ASTM A240/A240M) bars as a corrosion-resistant material. Concrete compressive strength, steel yield strength and grout flowability were measured using standard laboratory tests. Special attention was paid to the compatibility between grout, steel, and concrete, as this is crucial for the performance of the interface and the durability of the entire system.

3.3 Exposure conditions and corrosion simulation

To simulate harsh environmental exposure, all specimens were exposed to alternating wet–dry cycles in a 3.5% solution of sodium chloride (NaCl) — a typical representation of marine or chloride-rich environments.

The exposure programme involved repetitive cycles of wetting and drying to hasten chloride ingress and induce corrosion in a laboratory environment over a shorter period. This approach allows the acceleration of field conditions within the timespan of the laboratory work and enables the investigation of the initiation and propagation of corrosion. The geometry, reinforcement details, exposure conditions and corrosion simulation set-up for the three specimen categories (C, PC, PC-DSS) are illustrated in Fig. 2.

3.4 Corrosion assessment techniques

The corrosion performance was assessed through electrochemical tests, visual observations, and post-exposure investigations. Periodic half-cell potential measurements were taken to detect corrosion activity and to determine when active corrosion began.

Visual inspection was also conducted to identify signs of damage such as rust discolouration, cracking and concrete spalling. The width of cracks was measured digitally to assess deterioration.

After exposure, the steel bars were removed from the specimens to measure the steel mass loss, and to evaluate the distribution of corrosion along the bar length. Furthermore, non-destructive imaging techniques such as X-ray computed tomography (CT) were used to assess internal damage, including thickness of the corrosion layer, voids and flaws at the interfaces.

The half-cell potential tests were performed in a manner consistent with ASTM C876, using a Cu/CuSO₄ reference electrode. The measurements were taken at predefined grid points in the beam–column joint area, with particular focus on the sleeve interfaces and the pump/vent hole positions where localised corrosion was predicted. The half-cell potential measurement arrangement and predefined grid locations are illustrated in Fig. 3.

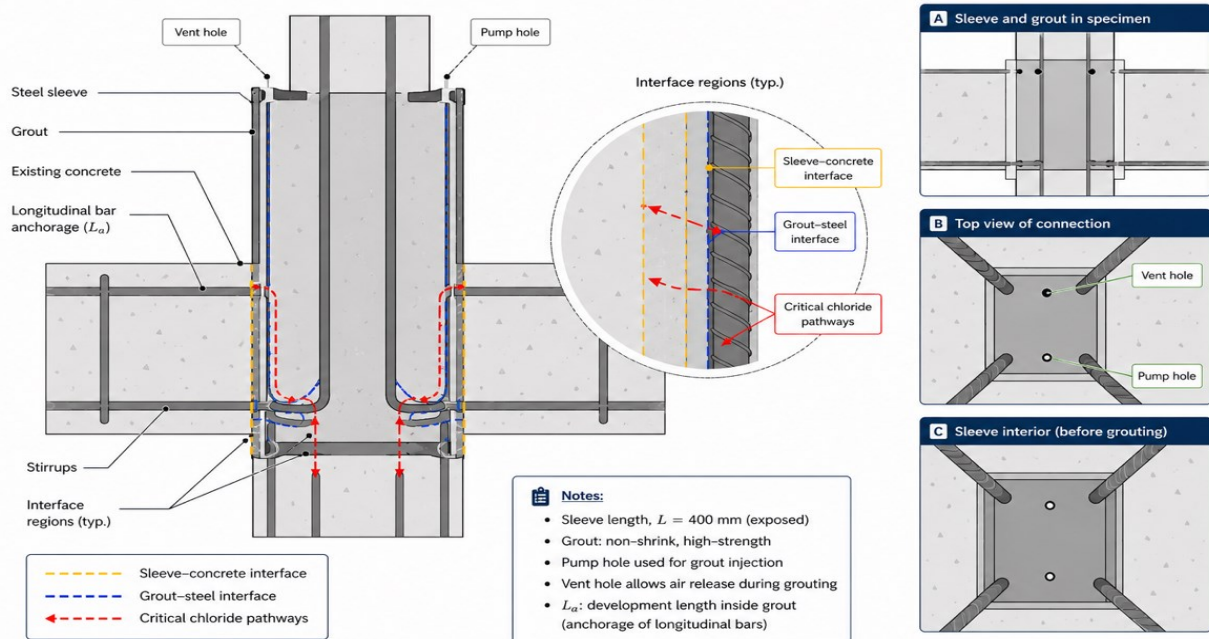


Figure 1. Schematic of the grouted sleeve connection detail used in the prefabricated beam–column joint, showing the steel sleeve, grout, existing concrete, longitudinal bar anchorage (L_d), stirrups, pump hole, vent hole and the critical chloride pathways along the sleeve–concrete and grout–steel interfaces

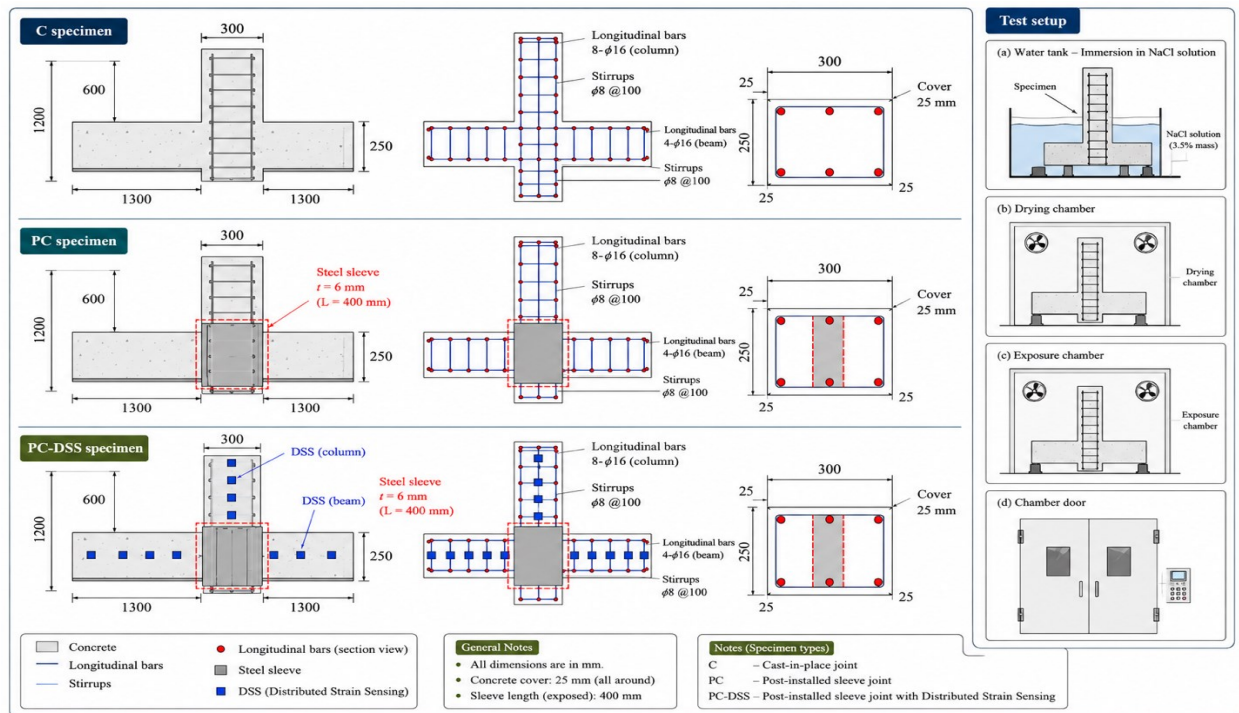


Figure 2. Geometry, reinforcement details and experimental set-up for the three specimen categories: (top) cast-in-situ (C), (middle) prefabricated with grouted sleeve (PC), and (bottom) prefabricated with duplex stainless-steel reinforcement in critical regions (PC-DSS). The right-hand panels show the test set-up: (a) NaCl immersion tank, (b) drying chamber, (c) exposure chamber, and (d) chamber door. All dimensions are in mm. Concrete cover: 25 mm; sleeve length (exposed): 400 mm. Red dashed regions indicate the grouted sleeve and the DSS placement zones

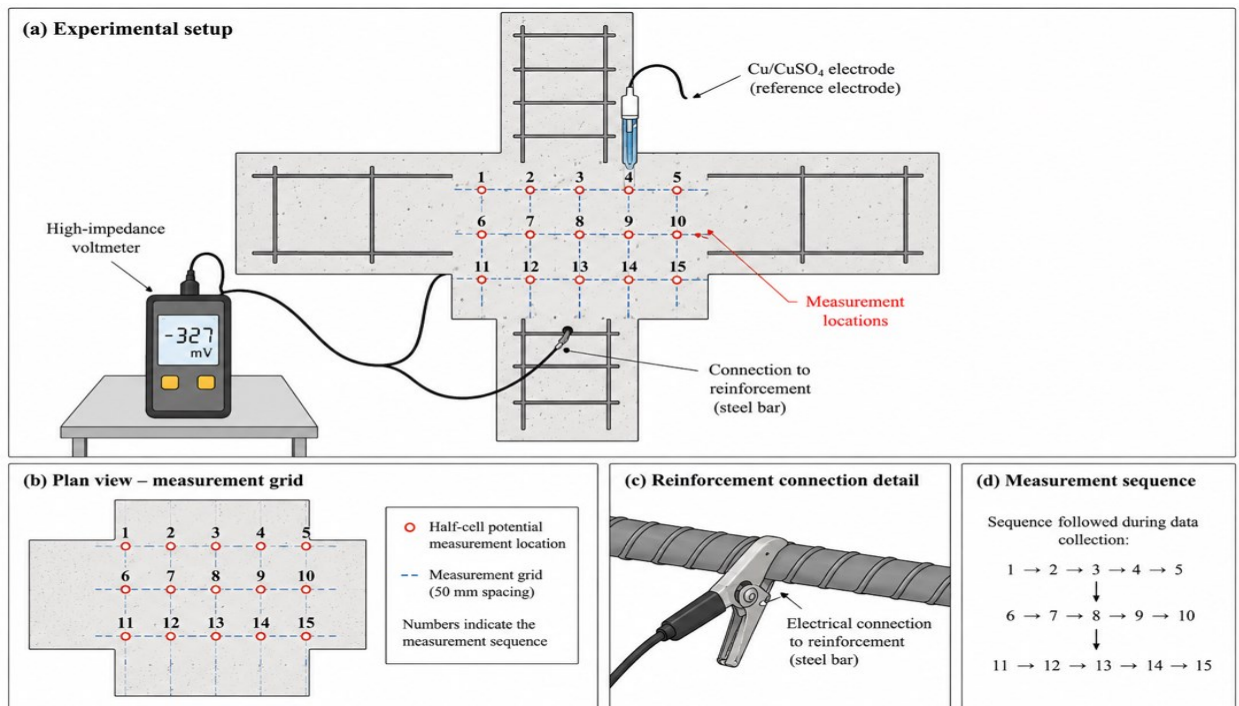


Figure 3. Half-cell potential measurement set-up. (a) Experimental set-up showing the high-impedance voltmeter, the Cu/CuSO₄ reference electrode and the connection to the reinforcement; (b) plan view of the measurement grid with 15 measurement locations spaced at 50 mm; (c) detail of the electrical connection to the steel bar; and (d) sequence followed during data collection (1 → 2 → ... → 15)

The corrosion rates were measured by linear polarisation resistance (LPR) and calculated as the average of three readings per specimen. The widest crack on each specimen was selected, and the crack width was measured using a digital crack microscope with a resolution of 0.01 mm.

The mass loss of the steel was measured after exposure by removing the reinforcement, cleaning the corrosion products following ASTM G1, and calculating the percentage of mass loss relative to the original bar mass.

The chloride diffusion coefficients were determined by inverse fitting of experimental chloride concentration profiles using the solution of Fick's second law. After 90 wetting–drying cycles (equivalent to 120 days), the chloride concentration was measured in powder samples at various depths from the exposed surface using titration analysis.

3.5 Interfacial characterisation

Since interfaces play a vital role in prefabricated structures, the interfacial zones — the sleeve–concrete interface and the grout–steel interface — were thoroughly investigated.

Microstructural examination was conducted to detect the presence of voids, micro-gaps and differences in bonding. These interfacial features were then linked with the level of corrosion to examine the correlation between interfacial properties and corrosion behaviour.

3.6 Analytical modelling of corrosion behaviour

A diffusion-based analytical model based on Fick's second law was developed to estimate chloride penetration and corrosion initiation at critical interface regions. The effective diffusion coefficient (D) for prefabricated specimens was approximately 2.5× higher than in cast-in-situ specimens, indicating a higher rate of chloride ingress at the

interface zones. The diffusion of chloride ions in the concrete matrix and regions was described by Fick's second law:

$$C(x, t) = C_s \cdot \left[1 - \operatorname{erf} \left(\frac{x}{(2\sqrt{D \cdot t})} \right) \right] \quad (3)$$

where $C(x, t)$ is the chloride concentration at depth x and time t , C_s is the surface chloride concentration, D is the apparent diffusion coefficient, and erf is the error function. The diffusion coefficient was determined by inverse analysis of the experimental data. An alternative formulation accounting for interfacial effects was also considered to capture the higher permeability in prefabricated joints.

3.7 Comparative Evaluation

A comparative study was undertaken to assess the corrosion behaviour of the three specimen categories. The parameters compared include time to corrosion initiation, corrosion rate, steel mass loss, crack-width evolution and Damage Localisation Index (DLI). This comparative approach enables the identification of key differences between cast-in-place and prefabricated construction systems and the role of duplex stainless steel in mitigating corrosion in joint zones.

3.8 Experimental design and statistical analysis

Five independent specimens ($N = 5$) were used for each category, with three replicate measurements per specimen. The corrosion-related parameters (corrosion rate, mass loss, crack width, and diffusion coefficient) are presented as mean $\pm$ standard deviation (SD), where SD is the variability among independent specimens. Triplicate measurements were used to reduce measurement uncertainty. The statistical significance of the results was determined by a two-tailed t -test, with $\alpha = 0.05$.

The experimental design is summarised in Table 1.

Table 1. Experimental design summary

Parameter	Description
Specimen Categories	C (Cast-in-situ), PC (Prefabricated), PC-DSS (Prefabricated with Duplex Stainless Steel)
Number of Specimens per Category (N)	5
Replicates per Specimen	3
Total Measurements per Category	15
Exposure Condition	Cyclic wetting–drying in 3.5% NaCl solution
Measured Parameters	Half-cell potential, corrosion rate, steel mass loss, crack width, diffusion coefficient
Data Reporting	Mean $\pm$ Standard Deviation (SD)
Error Bars	Represent SD across specimens
Statistical Test	Two-tailed t -test
Significance Level	$\alpha = 0.05$

Before the start of cyclic exposure, all specimens were visually documented to record their pristine surface condition (uniform light-grey concrete, no surface staining, no visible cracks, exposed sleeve free of corrosion). The corresponding post-exposure photographs of the extracted reinforcement are presented in Fig. 5 and provide the before/after comparison.

4 Results and discussion

This chapter discusses the results of the experimental and analytical work conducted and their interpretation. The section provides insights into the corrosion processes in prefabricated joints against cast-in-situ systems, and the role of the interface and the materials used on the durability of the system.

4.1 Corrosion initiation and half-cell potential

The variation of half-cell potential (E_{corr}) with exposure cycles is shown in Fig. 4. A steady decline in potential is observed in all samples, reflecting the progression of corrosion.

The PC specimens showed a much more rapid decrease in potential towards negative values than the C specimens.

The potential value of -350 mV (corresponding to a high risk of active corrosion) was reached at around 35 cycles for the PC specimens, while the C specimens reached this threshold at around 62 cycles. The PC-DSS specimens did not reach the -350 mV threshold within the test duration (>70 cycles).

The corresponding numerical results are summarised in Table 2.

As shown in Table 2, prefabricated specimens reached the critical corrosion threshold significantly earlier than cast-in-situ specimens. This premature corrosion in prefabricated joints is due to the presence of defects and increased permeability, which allow for quicker chloride ingress. On the other hand, the PC-DSS specimens exhibited a delayed potential shift, suggesting better resistance to the initiation of corrosion, which can be attributed to the higher passivity of duplex stainless steel.

4.2 Steel mass loss and corrosion distribution

Photographs of the reinforcement bars extracted after exposure testing are presented in Fig. 5. The pristine DSS bars shown in the right-hand column also serve as the before-testing reference for the corroded carbon-steel stirrups and longitudinal bars on the left and centre columns.

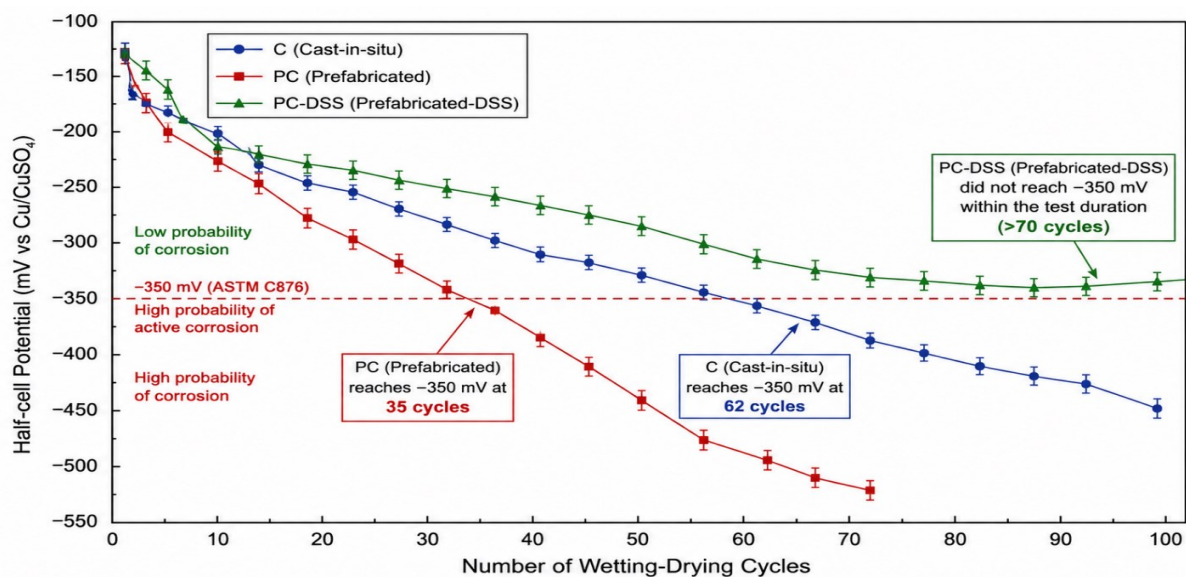


Figure 4. Variation of half-cell potential (E_{corr}) with wetting–drying exposure cycles for cast-in-situ (C), prefabricated (PC), and prefabricated with duplex stainless steel (PC-DSS) specimens under 3.5% NaCl exposure. The dashed line at -350 mV (vs. Cu/CuSO_4) represents the threshold for high probability of active corrosion according to ASTM C876. Corrosion initiation occurred after approximately 35 cycles for PC specimens and 62 cycles for C specimens, whereas PC-DSS specimens did not reach the corrosion threshold within the experimental duration (>70 cycles). Error bars represent standard deviation ($N=5$)

Table 2. Corrosion initiation and half-cell potential results

Specimen Type	Cycles to reach -350 mV	Corrosion Initiation (years, equivalent)	Observation
C	62	4.6	Delayed corrosion initiation
PC	35	1.8	Early corrosion initiation
PC-DSS	>70 (approx.)	Significantly delayed	Improved corrosion resistance

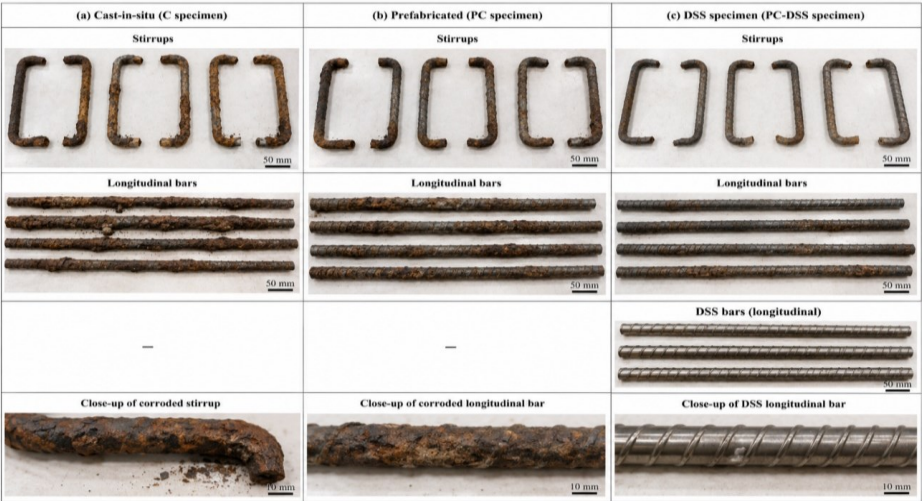


Figure 5. Extracted reinforcement after testing. (a) Cast-in-situ (C) specimen — stirrups, longitudinal bars and close-up of corroded stirrup. (b) Prefabricated (PC) specimen — stirrups, longitudinal bars and close-up of corroded longitudinal bar near the sleeve. (c) DSS specimen (PC-DSS) — stirrups, longitudinal carbon-steel bars (outside the joint zone) and pristine duplex stainless-steel (Grade 2205) longitudinal bars used inside the joint zone. The pristine appearance of the DSS bars after the same exposure programme contrasts with the heavy localised pitting observed on the carbon-steel stirrups and bars

Table 3. Steel mass loss and corrosion distribution

Specimen Type	Stirrups Mass Loss (%)	Longitudinal Bars (%)	Key Observation
C	2.8	2.1	Uniform corrosion
PC	7.6	2.5	Localised corrosion ($\approx 2.7\times$ higher in stirrups)
PC-DSS	Negligible (<0.5)	Negligible (<0.5)	Corrosion effectively mitigated

The steel mass loss and corrosion-distribution results for the different specimen categories are summarised in Table 3 and the time-dependent cumulative mass loss is illustrated in Fig. 6. As shown in Table 3, stirrups in prefabricated joints suffered approximately 2.7 times more mass loss than those in cast-in-situ specimens, while the difference for longitudinal bars was comparatively small.

This indicates that the corrosion in the prefabricated joints is highly concentrated. The localised damage in the vicinity of the sleeve junction and pump/vent holes shows the influence of discontinuities in controlling corrosion. For PC-DSS specimens, mass loss was minimal, demonstrating the excellent corrosion resistance of DSS in a chloride environment.

4.3 Corrosion rate analysis

The corrosion rates extracted by linear polarisation resistance confirm the trends discussed above. The corrosion rate of the prefabricated specimens was approximately 0.145 mm/year, almost 2.8 times that of the cast-in-situ specimens (0.052 mm/year). The numerical values are reported in Table 4 along with the chloride diffusion coefficients.

This shows that the interface permeability controls chloride ingress in prefabricated specimens. The PC-DSS specimens exhibited a much lower corrosion rate, suggesting that the localised application of corrosion-resistant reinforcement was effective in reducing deterioration in the system. This indicates that prefabricated joints are likely to have a significantly shorter service life unless properly mitigated.

Table 4. Corrosion rate and chloride diffusion characteristics.

Specimen Type	Corrosion Rate (mm/year)	Diffusion Coefficient (m^2/s)	Relative Increase
C	0.052	0.9×10^{-12}	Baseline
PC	0.145	2.3×10^{-12}	$\sim 2.8\times$ (rate), $\sim 2.5\times$ (diffusion)
PC-DSS	Very low (<0.01)	Similar to PC	Delayed corrosion response

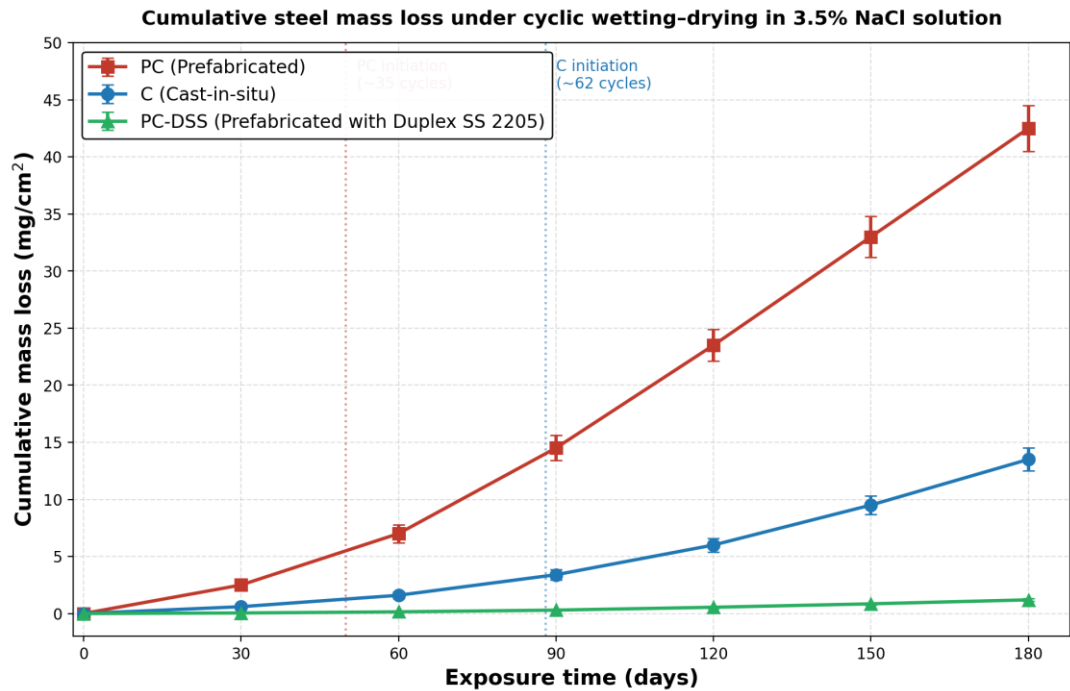


Figure 6. Cumulative steel mass loss (mg/cm^2) as a function of exposure time (days) for C, PC and PC-DSS specimens under cyclic wetting–drying in a 3.5% NaCl solution. The PC specimens display a sharp acceleration after the corrosion-initiation threshold (~ 35 cycles ≈ 50 days). C specimens accumulate damage more gradually after their later initiation (~ 62 cycles ≈ 88 days), and PC-DSS specimens remain almost unaffected over the entire 180-day programme. Error bars: $\pm \text{SD}$, $N = 5$

Note: Fig. 6 presents the cumulative mass loss in mg/cm^2 of exposed steel surface as a function of exposure time, while Table 3 reports the percentage mass loss at the end of the exposure programme (after specimen extraction and ASTM G1 cleaning). The two are complementary expressions of the corrosion damage and use different units; they should therefore not be compared numerically.

4.4 Chloride diffusion behaviour

Fig. 7 shows the chloride concentration profiles with depth after 90 wetting–drying cycles (equivalent to 120 days) and the apparent chloride diffusion coefficients obtained by inverse Fick's law analysis. The prefabricated specimens exhibit a diffusion coefficient of $2.3 \times 10^{-12} \text{ m}^2/\text{s}$, which is

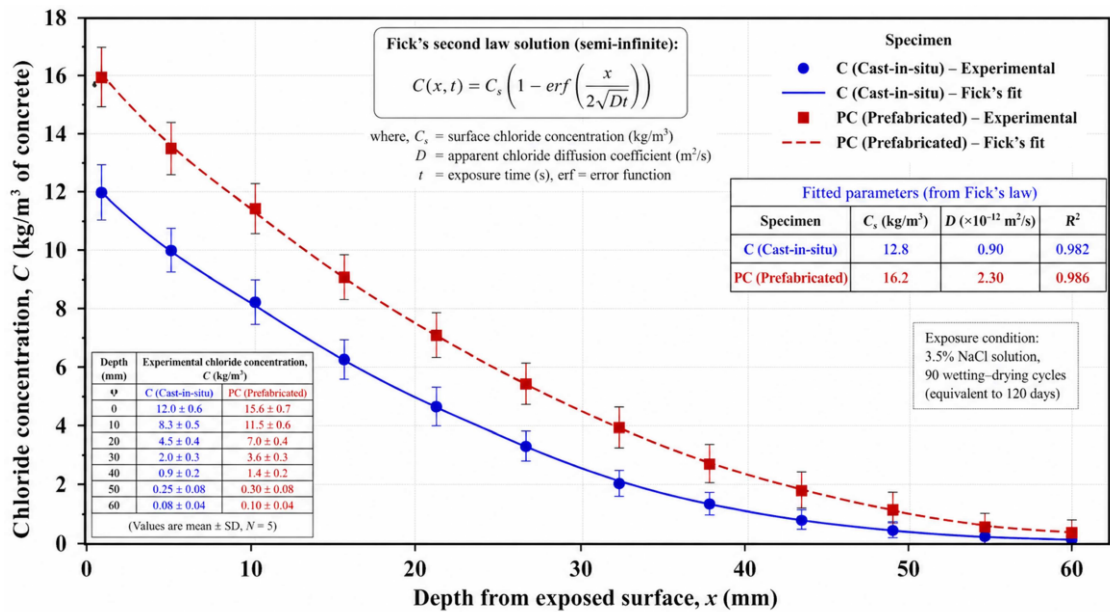


Figure 7. Chloride concentration profiles with depth after 90 wetting–drying cycles (120 days). Symbols: experimental results (mean $\pm \text{SD}$, $N = 5$); lines: fitted curves using Fick's second law solution. The prefabricated specimens exhibit a higher diffusion coefficient ($2.30 \times 10^{-12} \text{ m}^2/\text{s}$) than cast-in-situ specimens ($0.90 \times 10^{-12} \text{ m}^2/\text{s}$), indicating accelerated chloride ingress along interfacial regions

about 2.5 times the value for cast-in-situ specimens ($0.9 \times 10^{-12} \text{ m}^2/\text{s}$). This confirms the presence of preferential chloride pathways in prefabricated joints, especially at the interfaces.

An increase in diffusion coefficient leads to rapid chloride accumulation at the level of the reinforcement, which results in earlier initiation of corrosion. This suggests that the diffusion process obeys Fick's law, and that permeability plays a crucial role in the rate of chloride ingress. In PC-DSS specimens, despite the chloride ingress being similar, the time to corrosion initiation was delayed because of the enhanced durability of DSS.

4.5 Time to corrosion initiation

The time to corrosion initiation differs significantly between specimen categories. Corrosion initiation in prefabricated specimens occurred at about 1.8 years (accelerated equivalent), while it occurred at 4.6 years for cast-in-situ specimens. This corresponds to almost a 60% reduction in time to initiation for prefabricated joints. The observed delay in PC-DSS specimens demonstrates the effectiveness of corrosion-resistant reinforcement in delaying initiation, even under high levels of chloride exposure.

4.6 Crack width development

The cracking behaviour is shown in Fig. 8. The crack widths of prefabricated joints were more than double those found in cast-in-situ joints.

An interesting feature is that cracking in prefabricated joints seemed to be delayed initially, but once initiated, the deterioration accelerated. This is indicative of an internal corrosion-product build-up before surface damage becomes visible. When the internal pressure reached the tensile strength of concrete, rapid cracking took place, resulting in rapid decay. This suggests a delayed onset of surface damage caused by internal corrosion products, typical of localised corrosion at interfaces. PC-DSS specimens exhibited fewer cracks, suggesting higher resistance to expansion due to corrosion.

The maximum crack width and Damage Localisation Index (DLI) for each specimen category are summarised in **Table 5**. Specimens with prefabricated joints show a much larger crack width and DLI than cast-in-situ specimens, suggesting a very concentrated damage pattern in the vicinity of the joints. The increased standard deviation in prefabricated specimens reflects the variability of interfacial defects and transport paths in the specimens, reinforcing the interface-controlled corrosion mechanism.

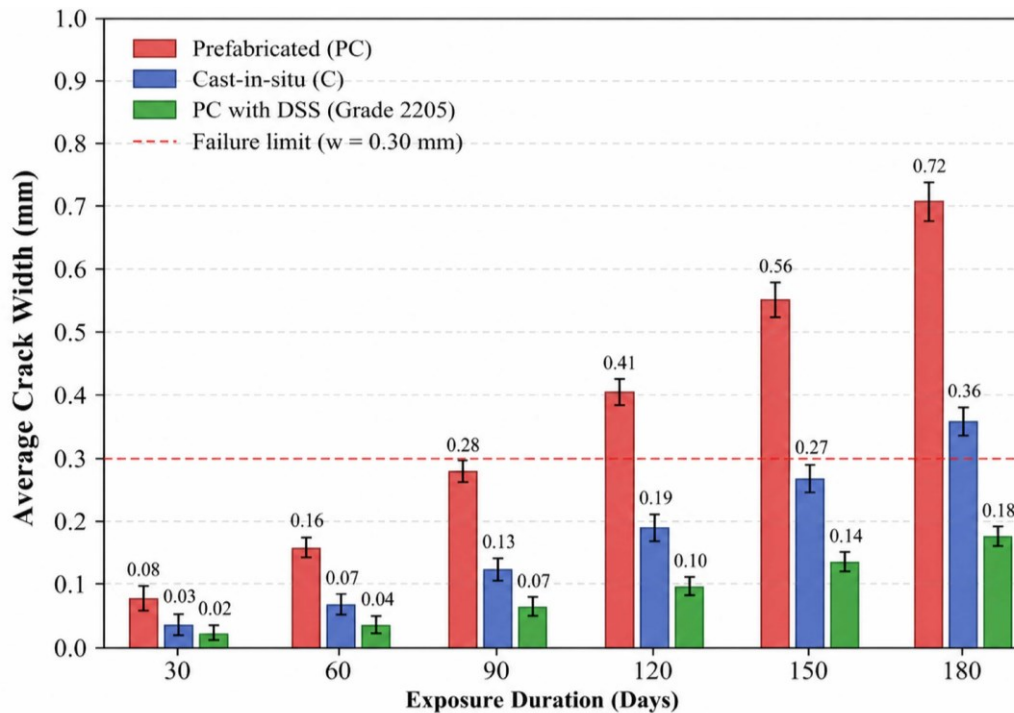


Figure 8. Average crack width versus exposure duration under cyclic wetting–drying in 3.5% NaCl solution for the three specimen categories. The red dashed line indicates the typical serviceability failure limit ($w = 0.30 \text{ mm}$). The PC specimens cross the failure limit between 60 and 90 days, while the C specimens cross it only after about 150 days. The PC-DSS specimens remain well below the limit throughout. Error bars: $\pm \text{SD}$, $N = 5$

Table 5. Crack width and damage localisation.

Specimen Type	Max Crack Width (mm)	SD (mm)	DLI = $M_{\text{interface}} / M_{\text{total}}$	Observation
C	0.18	0.003	0.28	Distributed damage
PC	0.42	0.006	0.62	Highly localised damage
PC-DSS	0.09	0.002	0.13	Minimal damage

4.7 Microstructural quantification

Microstructural analysis by CT scanning (Fig. 9) confirms that prefabricated joints have about 2–3 times more porosity than cast-in-situ joints. These discontinuities are predominantly located at the interface and confirm these defects as the pathway for chloride penetration. Such microstructural imperfections are responsible for the increased corrosion of prefabricated joints. The PC-DSS specimens had a comparable pore microstructure; however, the level of corrosion was minimal, suggesting that the choice of reinforcement plays a key role in the resulting deterioration.

4.8 Damage localisation index

To assess the corrosion-damage distribution pattern, the Damage Localisation Index (DLI) was calculated as the ratio of the steel mass loss occurring in the interfacial zone to the total steel mass loss. The DLI values for all categories are

summarised in Table 5. The prefabricated specimens had a DLI of 0.62, meaning that damage was very localised and concentrated around critical joint areas. The cast-in-situ specimens had a lower DLI of 0.28, indicating more even corrosion distribution. The use of corrosion-resistant reinforcement was seen to be beneficial in reducing localised deterioration, as the PC-DSS specimens had the lowest DLI (0.13).

4.9 Statistical validation

The experimental results were statistically validated. The mean steel mass loss for prefabricated specimens is 7.6%, with a standard deviation of 0.8% and a coefficient of variation of about 10.5%. The t-test between specimen types yielded a p-value of less than 0.01, which indicates that the observed differences between the specimens are statistically significant and not due to random scatter. The full statistical summary is reported in Table 6.

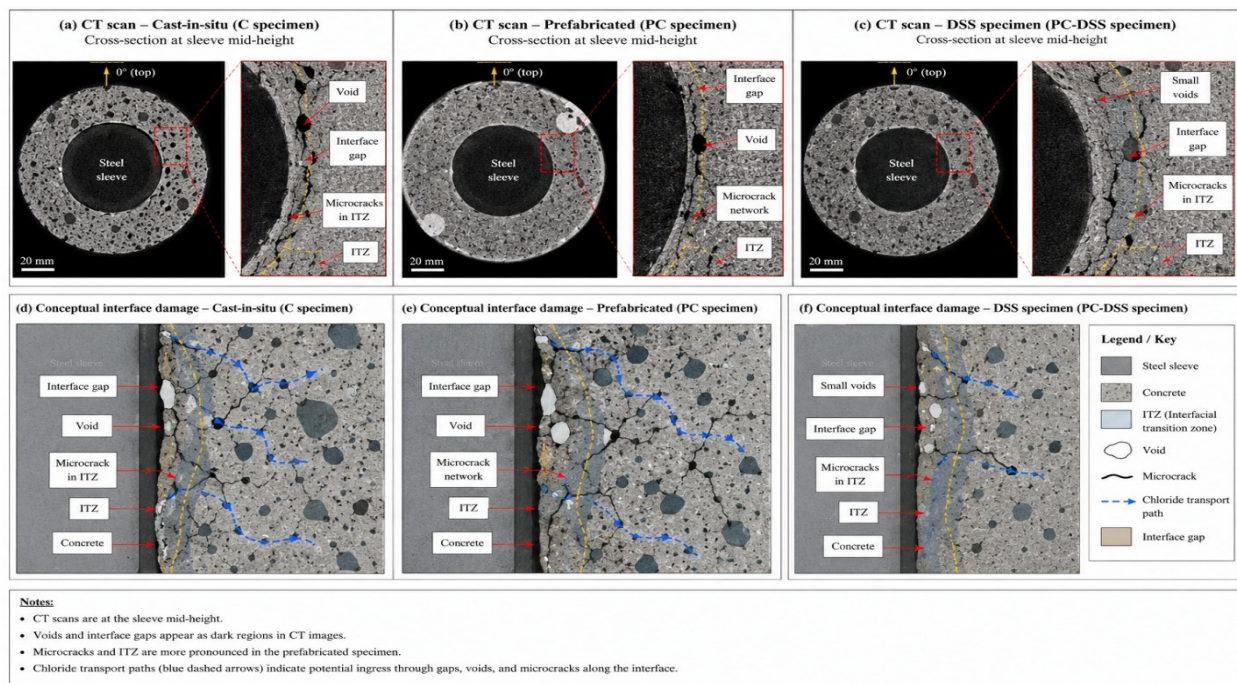


Figure 9. CT scan and conceptual interface damage diagrams of the three specimen categories. (a)–(c): CT scans of cast-in-situ (C), prefabricated (PC) and PC-DSS specimens at the sleeve mid-height cross-section. (d)–(f): conceptual interface damage diagrams highlighting voids, interface gaps, microcracks in the interfacial transition zone (ITZ), and chloride transport paths (blue dashed arrows). The PC specimen shows the densest microcrack network and the widest interface gaps, while the C specimen exhibits localised but discrete defects

Table 6. Statistical summary of corrosion results (PC specimens).

Parameter	Value
Mean Mass Loss (%)	7.6
Standard Deviation	0.8
Coefficient of Variation (%)	10.5
p-value (t-test)	< 0.01
Interpretation	Statistically significant difference

4.10 Interface-controlled corrosion mechanism

The findings suggest that the corrosion process in prefabricated joints cannot be explained by homogeneous diffusion models. Rather, interfaces serve as fast diffusion pathways, resulting in chloride build-up and heterogeneities that lead to pit formation at the interfaces. The elevated DLI values and their variability also support the view that corrosion is driven by the interfacial regions. The multiple interfaces create distinct transport routes that affect chloride penetration and subsequent corrosion [2], [6]. The increased diffusion coefficients in prefabricated specimens verify that interfaces provide fast pathways for chloride ingress due to their lower resistance. This validates the notion of interface-controlled corrosion, where the interfacial discontinuities control the transport and electrochemical reaction [4]. Consequently, corrosion starts earlier and develops more rapidly in prefabricated concrete than in cast-in-situ concrete.

4.11 Localisation of corrosion and damage evolution

The most noteworthy finding of this study is the highly localised corrosion in prefabricated joints. The higher DLI (≈ 0.62) suggests that damage is preferential around critical locations including sleeves and construction imperfections. This behaviour is explained by the spatial distribution of chlorides, moisture and oxygen, which results in an electrochemical gradient and pitting. This is in contrast to the relatively uniform corrosion front observed in cast-in-situ specimens, where loss of reinforcement cross-section is more uniform. This is also reflected in the observed cracking behaviour, where damage is internally confined initially and then suddenly appears as surface cracking when the internal stresses exceed the tensile strength of concrete [12].

4.12 Influence of interfacial characteristics on transport behaviour

Interfacial characteristics play a key role in controlling chloride transport and corrosion. Microstructural studies showed greater porosity, microvoids and poor bonding at the concrete–grout and grout–steel interfaces [13]. Such characteristics result in increased permeability and promote uneven chloride transport. The findings suggest that minor defects in interfacial bonding can lead to high transport rates and increased corrosion rates. This underlines the importance of considering non-uniform material properties when modelling durability and of incorporating interfacial effects when predicting the performance of prefabricated structures [6].

4.13 Effectiveness of duplex stainless steel as a targeted mitigation strategy

The use of duplex stainless steel (Grade 2205) in key areas was very effective in reducing corrosion [8]. Although the PC-DSS specimens were exposed to the same environment and experienced a similar degree of chloride penetration, they showed delayed corrosion onset and much less damage. This can be explained by the protective passive film and excellent pitting resistance of duplex stainless steel in chloride-rich environments [11]. Crucially, the results show that strategic incorporation of corrosion-resistant materials in critical interfacial areas is more effective than complete replacement, providing a cost-effective approach to improve durability.

4.14 Implications for design and durability of prefabricated systems

Our study has significant implications for the design and durability of prefabricated concrete systems. Current design considerations based on bulk properties could overlook durability risks because they fail to consider the impact of interfaces. The accelerated corrosion initiation and higher corrosion rates shown here indicate that prefabricated systems may have a reduced service life if interfaces are not properly managed [1]. Therefore, durability design should focus on interfaces, using better material compatibility, improved construction processes and targeted reinforcement strategies. Furthermore, performance-based durability models incorporating interfacial transport processes are required to improve service-life predictions [14].

4.15 Mitigation Strategies

The high DLI values (≈ 0.62) and localised corrosion near the sleeve interfaces suggest that mitigation strategies should be focused on the interface. The experimental results indicate that the corrosion of prefabricated joints is controlled by interface defects, pathways for the ingress of chlorides, and local exposure of the reinforcement, especially in areas such as the sleeve interface and pump/vent holes [4], [10]. A multi-level and integrated approach should therefore be adopted, including material properties, interface engineering, design considerations, quality control, and long-term monitoring.

One of the core approaches is to employ dense and high-performance materials in the joint region. The use of high-performance concrete (HPC) and dense, non-shrinkable grouting materials helps to minimise chloride diffusion through pore refinement [1]. The incorporation of supplementary cementitious materials such as fly ash, silica fume and ground granulated blast furnace slag is effective in improving durability by reducing permeability and the time to reach a critical chloride concentration at the reinforcement. Another critical factor is interface engineering, since corrosion in prefabricated structures is interface-dominated [4]. Improving the interface between concrete, grout and reinforcement is crucial to prevent the formation of micro-gaps and weak interfaces. This involves roughening the surface of the precast components, cleaning before grouting, and using appropriate bonding agents. Material compatibility also minimises shrinkage and thermal incompatibilities, which are two major causes of joint cracking.

Joint design also helps reduce corrosion. Greater cover thickness in key areas, such as around transverse bars, helps protect against aggressive exposure. Preventing contact of the reinforcement with weak zones, like sleeve ends, can help avoid localised corrosion. Finally, redesigning or sealing pump and vent holes after grouting can restrict direct ingress of chlorides.

Proper construction of prefabricated joints is also critical. Poor grouting, residual voids, and air pockets are typical causes of premature failure. Quality control must therefore be maintained during construction through correct grout injection and compaction, and by checking for full filling of sleeves. Controlling the grouting process and monitoring joint installation also help to ensure a better joint [5].

Corrosion-resistant reinforcement materials offer an effective and cost-conscious solution. Specifically, duplex stainless steel (Grade 2205) has excellent resistance to chloride attack owing to its stable passive film and pitting

resistance [8], [11]. Its localised application in areas prone to damage, such as stirrups at the sleeve junction, can delay the onset of corrosion and minimise localised damage, thus extending the lifetime of prefabricated structures.

Long-term monitoring and maintenance are key to maintaining structural integrity. The use of embedded sensors to monitor moisture, chloride and corrosion potential allows real-time assessment of structural integrity. Together with predictive algorithms, these monitoring systems can enable early detection and mitigation of corrosion, leading to longer service life. Overall, control of corrosion in prefabricated joints requires an integrated strategy that includes material development, better interface conditions, proper design, sound construction practice and new monitoring methods [8].

4.16 Limitations and future research

Although the research offers insights into the corrosion of prefabricated joints, some limitations must be considered. The laboratory-based experimental programme involved an accelerated exposure, which may not fully replicate long-term field conditions. Moreover, the model adopted to describe chloride transport is based on simplifications and does not explicitly quantify interfacial parameters. The next steps for research include the creation of refined multi-scale models considering interfacial features, verification of the results under field conditions, and the development of other mitigation measures, such as coatings and smart sensor technologies [12].

5 Conclusions

This research confirms that the corrosion performance of prefabricated RC beam–column joints with grouted sleeve connections is primarily influenced by interfacial properties. This conclusion was confirmed through half-cell potential, visual damage, loss of mass in the steel and observations of interface deterioration after cyclic chloride exposure. The experimental findings demonstrate that prefabricated specimens have a much earlier onset of corrosion (reduced by 40–60% relative to cast-in-situ joints) because of rapid chloride penetration through the interfaces. Prefabricated joints exhibited a corrosion rate almost 2.8 times higher, with a chloride diffusion coefficient 2.5 times larger, confirming preferential pathways for chloride ingress. Additionally, corrosion damage was highly concentrated, as shown by a Damage Localisation Index (DLI) of approximately 0.62, with damage concentrated around sleeve connections and construction-related discontinuities. This led to more severe cracking, with crack widths over twice those in conventional specimens. By contrast, the use of duplex stainless steel (Grade 2205) in key areas led to a substantial delay in corrosion initiation and less severe damage, confirming the potential of selective reinforcement to mitigate corrosion. In summary, the results confirm the interface-controlled nature of corrosion and highlight the need for interface-oriented design, enhanced construction practices, and localised application of corrosion-resistant materials to improve the sustainability and lifespan of prefabricated concrete structures.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

References

- [1] L. Bertolini, B. Elsener, P. Pedferri, E. Redaelli, and R. B. Polder, *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair*, 2nd ed. Weinheim, Germany: Wiley-VCH, 2013. DOI: [10.1002/9783527651696](https://doi.org/10.1002/9783527651696)
- [2] K. Tuutti, "Corrosion of Steel in Concrete," Doctoral thesis, Swedish Cement and Concrete Research Institute (CBI), CBI Research Report no. 4.82, Stockholm, Sweden, 1982.
- [3] Y. Bao, J. Zhao, G. Xue, L. Bao, L. Yu, H. Yan, X. Han, S. Chen, and B. Li, "Mechanical properties of grouted splice sleeve connectors inside prefabricated concrete structures in cold regions," *Structures*, vol. 80, p. 109737, 2025. DOI: [10.1016/j.istruc.2025.109737](https://doi.org/10.1016/j.istruc.2025.109737)
- [4] F. Li and X. Luo, "Interfacial zone effects of chloride penetration in precast concrete member joints," *Advances in Cement Research*, vol. 31, no. 6, pp. 279–289, 2019. DOI: [10.1680/jadcr.18.00117](https://doi.org/10.1680/jadcr.18.00117)
- [5] K.-Y. Liao, P.-K. Chang, Y.-N. Peng, and C.-C. Yang, "A study on characteristics of interfacial transition zone in concrete," *Cement and Concrete Research*, vol. 34, no. 6, pp. 977–989, 2004. DOI: [10.1016/j.cemconres.2003.11.013](https://doi.org/10.1016/j.cemconres.2003.11.013)
- [6] Q. Li, W. Zhang, W. Shao, and D. Shi, "Numerical modelling of non-uniform corrosion of concrete reinforcement considering calcium leaching and chloride diffusion coupling effect," *Corrosion Science*, vol. 237, p. 112343, 2024. DOI: [10.1016/j.corsci.2024.112343](https://doi.org/10.1016/j.corsci.2024.112343)
- [7] S. S. Potgieter and L. Marjanovic, "A further method for chloride analysis of cement and cementitious materials — ICP-OES," *Cement and Concrete Research*, vol. 37, no. 8, pp. 1172–1175, 2007. DOI: [10.1016/j.cemconres.2007.05.006](https://doi.org/10.1016/j.cemconres.2007.05.006)
- [8] J. T. Pérez-Quiroz, J. Terán, M. J. Herrera, M. Martínez, and J. Genescá, "Assessment of stainless steel reinforcement for concrete structures rehabilitation," *Journal of Constructional Steel Research*, vol. 64, no. 11, pp. 1317–1324, 2008. DOI: [10.1016/j.jcsr.2008.07.002](https://doi.org/10.1016/j.jcsr.2008.07.002)
- [9] R. G. Duarte, A. S. Castela, R. Neves, L. Freire, and M. F. Montemor, "Corrosion behaviour of stainless steel rebars embedded in concrete: an electrochemical impedance spectroscopy study," *Electrochimica Acta*, vol. 124, pp. 218–224, 2014. DOI: [10.1016/j.electacta.2014.01.080](https://doi.org/10.1016/j.electacta.2014.01.080)

- [10] F. Zhang, J. Pan, and C. Lin, "Localised corrosion behaviour of reinforcement steel in simulated concrete pore solution," *Corrosion Science*, vol. 51, no. 9, pp. 2130–2138, 2009. DOI: [10.1016/j.corsci.2009.05.044](https://doi.org/10.1016/j.corsci.2009.05.044)
- [11] M. C. García-Alonso et al., "Corrosion behaviour of new stainless steels reinforcing bars embedded in concrete," *Cement and Concrete Research*, vol. 37, no. 10, pp. 1463–1471, 2007. DOI: [10.1016/j.cemconres.2007.05.007](https://doi.org/10.1016/j.cemconres.2007.05.007)
- [12] U. Angst, B. Elsener, C. K. Larsen, and Ø. Vennesland, "Critical chloride content in reinforced concrete — A review," *Cement and Concrete Research*, vol. 39, no. 12, pp. 1122–1138, 2009. DOI: [10.1016/j.cemconres.2009.08.006](https://doi.org/10.1016/j.cemconres.2009.08.006)
- [13] W. Li, Y. Xie, K. Ma, G. Long, N. Li, and H. Zhao, "The properties and meso/microstructure characteristics of the interfacial zone between precast concrete and self-compacting concrete," *Construction and Building Materials*, vol. 297, p. 123753, 2021. DOI: [10.1016/j.conbuildmat.2021.123753](https://doi.org/10.1016/j.conbuildmat.2021.123753)
- [14] Y. Wang, Y. Zhao, L. Peng, and D. Xu, "Steel corrosion in precast reinforced concrete column–beam joints with grouted sleeve connections under chloride-rich environment," *Journal of Building Engineering*, vol. 77, p. 107533, 2023. DOI: [10.1016/j.jobbe.2023.107533](https://doi.org/10.1016/j.jobbe.2023.107533)