Bond Degradation and Reduced Cover in Concrete with Transverse Reinforcement

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Abstract

Corrosion of the internal steel reinforcement is among the main causes of deterioration in concrete bridges. The expansive nature of corrosion products can lead to cracking, delamination or complete spalling of the concrete cover. The subsequent reduction in reinforcement anchorage is difficult to assess accurately. To study the effects of spalling on the steel-to-concrete bond, pull-out tests were carried out on half-joint cantilever specimens. Spalling was simulated with progressively reduced cover. This led to degradation of bond and anchorage of the longitudinal bars. However, the presence of transverse confining reinforcement had beneficial effects, limiting bond degradation and avoiding brittle failures where splitting occurred.

1 Introduction

Structures are often not as strong as they should be. Due to the effects of repeated loading, exposure to the environment and other sources of deterioration, the strength of reinforced concrete bridges generally decreases over time. Moreover, existing structures were designed and built according to design codes that progressively become obsolete as theories and design criteria evolve. Sometime defects that weaken the structure are due to discrepancies between construction and design provisions. Additionally, the service loads applied on bridges can increase in magnitude, reducing the associated safety margins. As a result of all these factors, structures can become sub-standard according to the latest codes. The concomitance of more than one problem makes certain structures more critical than others [1], [2]. The impact on the infrastructure network is significant, leading to high costs of management, maintenance, repair, strengthening and premature decommissioning. In extreme cases, this leads to structural collapses and tragic consequences for the community [3]–[5]. To avoid failures and manage costs effectively, it is crucial to identify priorities within the infrastructure network.

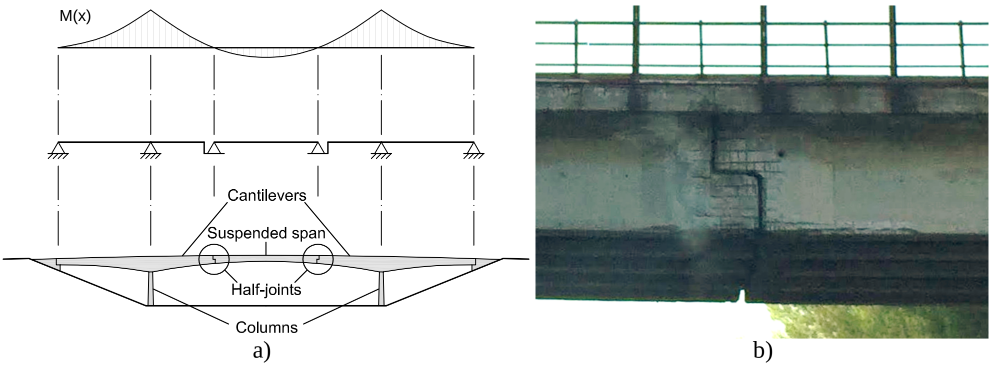

Fig. 1 Reinforced concrete half-joints: a) Typical double cantilever bridge (Gerber system) and associated static scheme; b) Corrosion-induced spalling of a half-joint bridge in Italy.

A critical category of infrastructure is the half-joint bridge [1]–[6]. Half-joints, also called dapped-ends, are a recurring support configuration in concrete bridges. They are characterised by a sudden reduction in depth at the support end of a structural element. A typical static scheme is indicatively shown in Fig.1.a. The advantages for design and construction in Gerber-type (or double cantilever) systems have justified their widespread use in the past. However, there are concerns associated with this joint. Firstly, the complex distribution of internal forces was not well understood in the past. Superseded code provisions led to inadequate reinforcement and detailing. A common problem is leakage of contaminated water from above, which leads to corrosion of the internal steel bars. Reinforcement corrosion has several structural consequences. It causes a reduction in cross section of the bars. The expansive nature of corrosion products induces pressure that can lead to cracking, delamination or complete spalling of the concrete cover, as shown in Fig. 1.b for a deteriorated half-joint. Concrete cracking is particularly detrimental for the anchorage of the reinforcement [7], before the reduction in steel cross section becomes problematic. In half-joints in particular, the anchorage of the bottom bars is vulnerable to deterioration. Since the support is moved from the full-depth to the nib, the anchorage zone of the bottom tension reinforcement does not see the beneficial confining effect of the transverse support reaction [6], which can be seen as external 'active' confinement locally enhancing bond performance. Instead, in the anchorage zone of half-joints only the 'passive' confinement of the transverse reinforcement is present. This is schematically shown in Fig. 2. The combination of all the above mentioned deterioration phenomena leads to a reduction in load-carrying capacity that is difficult to assess in existing half-joints. Experimental evidence is therefore necessary to develop accurate assessment theories and models.

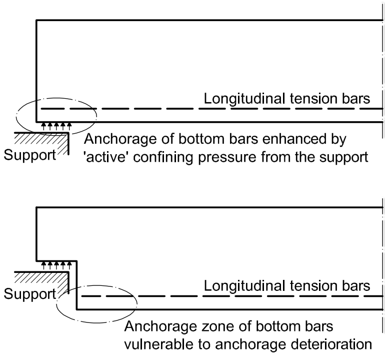

Fig. 2 Confining effect of direct support pressure on the anchorage of bottom longitudinal bars. Difference between conventional support arrangement and half-joint configuration.

Recent studies [7] suggest that for plain concrete, corrosion-induced crack widths could be good indicators of bond degradation, leading to better predictions than those based on degree of corrosion (such as mass loss or attack penetration). This is based on the assumption that cracks mainly develop radially, from the longitudinal bars towards the surface, as shown indicatively in Fig. 3.a. However, when transverse reinforcement is present, both longitudinal and transverse bars are subjected to corrosion. Cracks that are visible on the concrete surface are partially due to corrosion of the stirrups and their influence on the bond of longitudinal bars is more complex (see Fig. 3.b). The approach adopted in this study was therefore to investigate the extreme scenario where severe corrosion has led to complete delamination and spalling of the concrete cover. From an assessment perspective, this would lead to conservative results and estimates close to a lower bound.

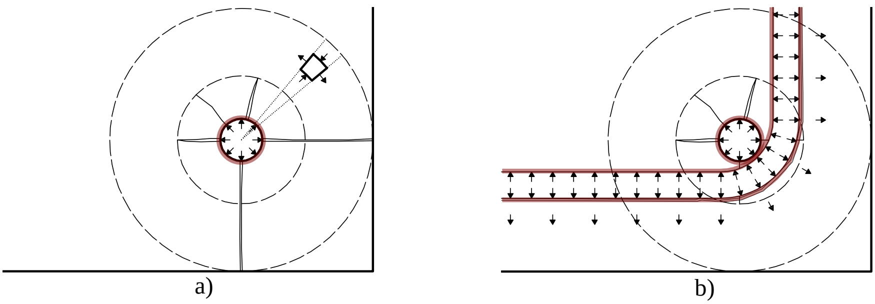

Fig. 3 Corrosion-induced expansions on the underside of a generic reinforced concrete element (images are indicative): a) 2D Thick Walled Cylinder analogy for pressure due to longitudinal bars only, in the absence of transverse reinforcement; b) 3D pressure distribution due to simultaneous corrosion of longitudinal and transverse bars.

The structural effects of concrete delamination and spalling have not been studied extensively. Their consequences on the steel-to-concrete bond and anchorage are not well understood. Higgins and Farrow III [8] investigated the effects of stirrup corrosion on reinforced concrete beams. Sodium chloride was added to the mix, and accelerated corrosion using an impressed current was induced on the stirrups, not on the longitudinal flexural reinforcement. In zones where stirrups were closely spaced, the authors observed extensive cover cracking, delamination and spalling. Where stirrups were widely spaced, the concrete cover damage was more localised and spalling did not always occur. The authors concluded that the level of visual damage may not be correlated with structural performance. This would result in significant challenges when using visual indicators of deterioration to assess the residual load-carrying capacity of structures. Regan and Kennedy Reid [9] replicated the effects of delamination and loss of cover by casting specimens where the longitudinal reinforcement bars were partially exposed. In the most extreme case the bars were exposed for half of their surface area and the level of the concrete cover corresponded to the mid-height of the bars (defined as exposure to ‘mid-barrel’). Confining transverse stirrups were present. Rectangular bond specimens and beams were tested. The results showed a trend of progressive bond reduction as the cover dimension decreased. Bending tests indicated that a beam can develop resisting arch mechanisms if the bond reduction occurs within the central span and does not affect the anchorage of longitudinal bars at their ends. Their conclusions are in line with the findings of earlier work by Kani [10]. This highlights the importance of the anchorage zone of longitudinal bars, especially in the presence of bond deterioration. In the context of prestressed concrete, the problem of delamination and spalling was studied by Orr et al. [11]. They performed eccentric bond tests on prestressing tendons using prismatic specimens, investigating the effects of progressively reducing the concrete cover. A similar approach to replicate corrosion-induced spalling by casting specimens with progressively reduced cover was adopted in the current work. The objective of the project was to investigate the subsequent bond reduction of ribbed steel bars, and the implications on half-joints as structural components. To gain a fundamental understanding of the effects of spalling in isolation, the phenomenon was investigated independently from other consequences of reinforcement corrosion, such as the presence of corrosion products at the steel-to-concrete interface, the reduction in rib height or localised pitting corrosion along the bars.

2 Experimental programme

The experimental programme focused on the bond behaviour of individual bars with short embedment lengths. The objective was to investigate the effects of spalling on the bond stress-slip curves of steel reinforcement in pull-out, isolating the behaviour of single deformed bars. Spalling was simulated on the bottom zone of the full-depth section of the joint to induce anchorage failure of the longitudinal tension reinforcement.

Several bond test set-ups have been adopted in the literature. One of the crucial aspects that influence the test results is the confinement conditions of the concrete surrounding the pull-out bars. In particular, attempts have been made to remove the direct support pressure from the bonded region in different ways, by developing new specimen geometries or adopting debonding sleeves over the supports. However, authors reported that the effects of support pressure were not completely removed. To overcome this drawback with existing test set-ups, a novel specimen geometry was developed and validated in a previous study [12] to remove the parasitic effects of the support pressure and avoid additional confinement from the reaction forces. By adopting a nib and a similar geometry to that of half-joints, the support reaction was moved away from the bonded region of the pull-out bars. The surrounding concrete that affects the anchorage performance is therefore not subjected to the effect of ‘active’ confinement of external reaction forces, but only the ‘passive’ confinement of the transverse reinforcement within that zone. The experimental programme is hereby described in more detail.

2.1 Specimens

Bond pull-out tests were performed on eccentric half-joint cantilever specimens with progressively reduced cover. The geometry of the specimens and reinforcement layout are shown in Fig. 4.

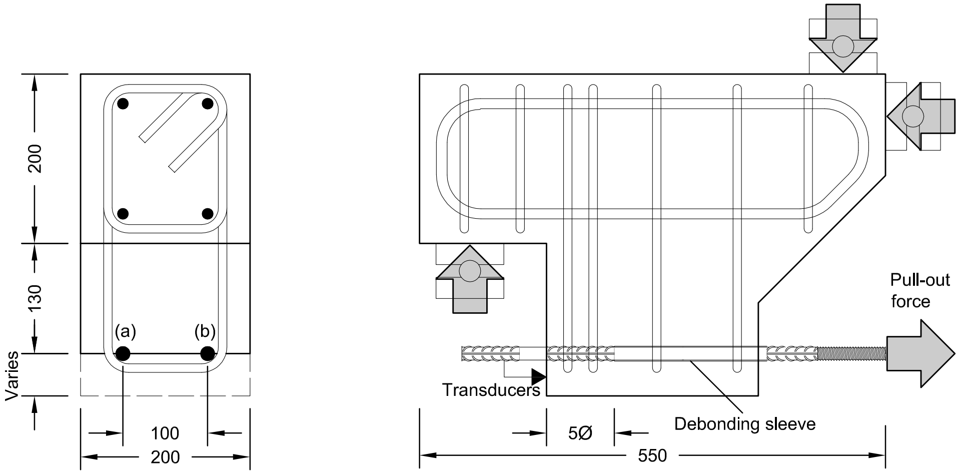

Fig. 4 Geometry of eccentric bond test specimens with reduced bottom cover (dimension varies) to simulate corrosion-induced spalling.

On each specimen, 2 bars were tested sequentially in pull-out, for a total of 36 experiments. Three nominal sizes were used for the pull-out bars (10, 12 and 16 mm). Five progressively reducing values were adopted for the axis distance (a = 50, 35, 25, 20 and 0 mm), defined as the dimension between the external concrete surface and the centroidal axis of the longitudinal bars. This dimension is effectively equal to sum of the concrete cover and half the bar diameter ($a = c + \varnothing/2$). In the specimens where the longitudinal steel bars were exposed, the cover therefore had a negative value. Different combinations of bar diameter and axis distance allowed for the cover-to-diameter ratio $c/\varnothing$ to be adopted as a key parameter in the study. The bonded length was equal to 5 times the bar diameter in all specimens. The short embedment length was chosen to avoid premature failure of the steel in tension. This also justified the assumption of constant bond stresses along the bars in the analysis of the results. The same transverse confining reinforcement was adopted in all tests, consisting of two 8 mm diameter stirrups within the embedment length. The specimen naming convention consists of three numbers e.g.:

$$\varnothing 16-50-35-\mathrm{a}$$

where the first number after the diameter symbol indicates the size of the longitudinal bar tested, the second number indicates the horizontal axis distance to the bar centreline measured from the concrete side face (fixed at either 25 or 50 mm) and the third number indicates the vertical axis distance measured from the bottom concrete face. The last lowercase letter indicates the first bar (a) or second bar (b) tested on a given specimen. All the reinforcement consisted of deformed high-strength steel bars with a nominal yield strength of 500 MPa. An Ordinary Portland Cement (OPC) mix was used in all the bond specimens. The average material properties obtained with standard characterisation tests at 28 days were f_c= 24.2 MPa (SD= 1.4 MPa) for 100 mm cubes and $f_{c,cub}$= 26.5 MPa (SD= 1.8 MPa) for 100 mm diameter and 200 mm long cylinders in compression. The average split tensile strength was $f_{ct,sp}$= 2.17 MPa (SD= 0.25 MPa) measured on cylinders of the same dimensions. Bond tests were also carried out 28 days after casting. The force was applied with a hydraulic jack and measured with a tension load cell. The slip of the bars relative to the face of the concrete was measured with two Linear Potentiometric Displacement Transducers (LPDTs) clamped on the passive (unloaded) side of the bars. The average of the two readings was typically used in the analysis of the results.

2.2 Results

The results are hereby presented in terms of equivalent nominal bond stresses and slip. In the calculation of the equivalent bond stresses, the pull-out force was assumed to be distributed uniformly over the nominal surface area of the bar and the surface area was adjusted to take into account the progressive reduction in contact between the two materials as the slip increased:

$$\tau = \frac{F}{\pi \cdot \varnothing \cdot (l_{b,0} - s)}$$

where F is the pull-out force, $\varnothing$ is the nominal diameter of the bar, $l_{b,0}$ is the initial bonded length and s is the slip measured during the test. Fig. 5 shows the results of the pull-out tests. All the bond stress-slip curves are shown, grouped by bar size (respectively = 10, 12 and 16 mm bars).

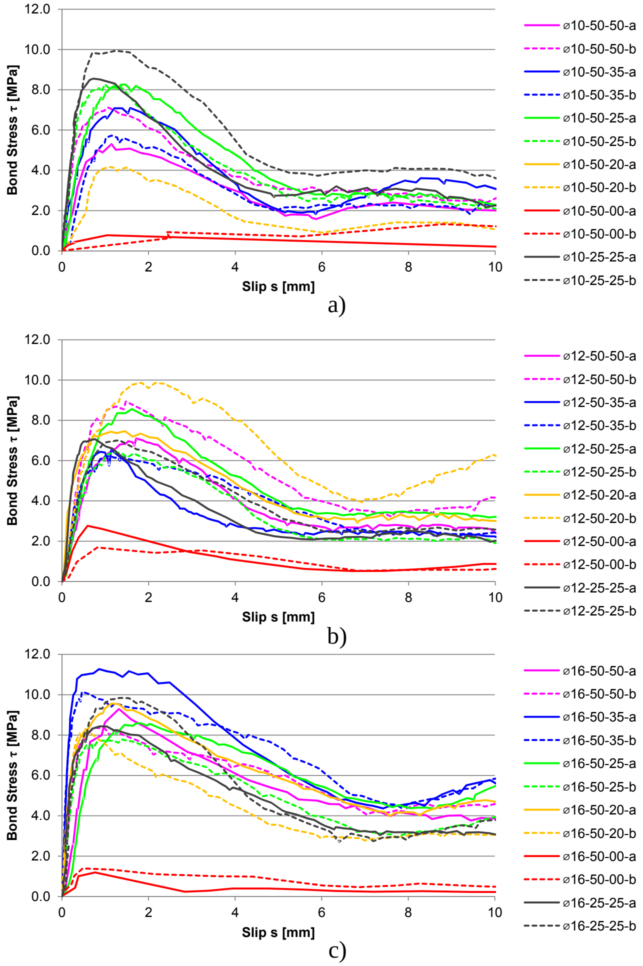

Fig. 5 Eccentric bond test results on half-joint cantilever specimens. Bond stress-slip pull-out curves for: a) $\varnothing$= 10 mm; b) $\varnothing$= 12 mm; c) $\varnothing$= 16 mm bars. Solid lines indicate test on the first bar *(a)* and dashed lines indicates test on the second bar *(b)* for a given specimen.

To compare the results for different dimensions and highlight the dependence on $c/\varnothing$, the nominal peak bond stresses for all bar diameters are plotted as a function of $c/\varnothing$ in Fig. 6. The bond strength is also normalised with respect to the concrete splitting tensile strength to reduce the scatter in the results due to variations in concrete quality between specimens. The two curves in the plot indicate two analytical solutions based on a Thick Walled Cylinder formulation by Tepfers [13], where two concrete models in tension were used to obtain a lower and upper bound: brittle partially cracked (dashed line) and perfectly plastic (continuous line) respectively. The contribution of transverse reinforcement is neglected in the analytical formulation. The space between the two analytical solutions can be interpreted as a domain of possible intermediate results for unconfined concrete.

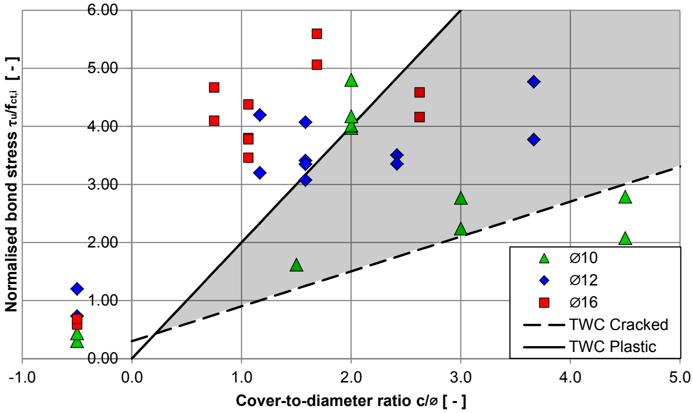

Fig. 6 Bond strength (peak stress) results from all tests, normalised by concrete splitting tensile strength. Dependence on *c/⌀* and comparison with Thick Walled Cylinder analysis [13].

Specimens with high *c/⌀* values failed by pull-out, whereas those with smaller *c/⌀* failed mainly by splitting. However, the bond stress-slip curves showed that all tests exhibited a gradual post-peak decrease in resistance, even in the case of splitting failure. Sudden drops typically associated with brittle splitting failure in unconfined specimens were not recorded. With respect to the peak bond resistance, the results do not show a marked trend of reducing strength as the *c/⌀* decreases from 4.5 to 0.75. However, a significant drop in resistance can be observed when the longitudinal bars are exposed to mid-barrel, corresponding to a negative *c/⌀* = -0.5. The cracking pattern of six significant specimens is shown in Fig. 7.

Fig. 7 Cracking pattern around the bars on the passive side of the specimens, after testing. Cracks are highlighted in red where present.

It can be observed that specimens with high values of *c/⌀* did not exhibit surface cracking (such as ⌀10-50-50). For lower *c/⌀* instead, the extent of cracks developed during the first and second pull-out tests overlap (⌀16-50-50, ⌀12-25-25). In other specimens, the extent of cracked concrete around one bar and the other did not intersect (⌀16-50-35, ⌀16-50-20).

2.3 Discussion

Closely spaced vertical reinforcement (such as hanger bars) is typically present in half-joints at the end of the full depth section. This is necessary to ensure an internal loadpath and the transfer of vertical forces from the nib to the full-depth section. In the presence of corrosion, due the reduced distance between vertical reinforcement, the zones of concrete cover affected by expansive pressure from each stirrup are closely spaced and may overlap. This has detrimental effects as it facilitates delamination and spalling. Nevertheless, the high steel density in the joint has a positive effect on the residual anchorage of longitudinal tension bars, as shown by the experiments. Although the bond test results indicate that reduced cover leads to degradation of bond strength, the beneficial presence of transverse confining reinforcement enables the bars to develop a degree of anchorage resistance, even where the concrete cover is much smaller than typical design provisions. Only where the bars were exposed to mid-barrel, very little resistance to pull-out was provided by the stirrups. This can also be attributed to the complete absence of concrete in the volume between longitudinal and transverse bars, due to the casting procedure.

2.3.1 Limitations

The bond specimens were cast upside-down, with the longitudinal pull-out bars on the top side. The pour was stopped when the concrete reached the required level. The side with reduced cover was therefore a horizontal surface across the reinforcement cage. Corrosion-induced spalling in real structures affects the volume of concrete outside the reinforcement cage only. The concrete between longitudinal and transverse reinforcement remains in place, locally increasing the contact area between the two materials. Therefore, it is reasonable to believe that stirrups are able to provide a distributed and more effective confinement if the concrete within the reinforcement cage is present. In future tests that replicate corrosion-induced spalling, specimens should be fabricated to replicate this configuration to better predict the behaviour of real structures that are operational.

Corrosion of the steel bars has several implications. The presence of corrosion products at the interface between the steel reinforcement and the bars would weaken the bond resistance. Moreover, the rib height is reduced, consequently reducing the interlock between bars and concrete. Localised pitting corrosion also has an influence on the bond behaviour of the bars, as it affects the distribution of bond stresses along the bars. These effects were not replicated in the tests and should be the subject of further studies. More research is necessary to understand the combined effects of spalling and interface deterioration.

3 Conclusions

A total of 36 pull-out bond tests were performed on eccentric half-joint cantilever specimens. Spalling and delamination were simulated by casting the specimens with progressively reduced cover. The effects of reduced cover on the bond behaviour of deformed steel bars with transverse confining reinforcement were investigated. The following conclusions are drawn:

- In half-joints, the underside of the full-depth section does not benefit from the external confinement of direct support pressure. Longitudinal tension bars are therefore vulnerable to anchorage deterioration;
- In some of the bond tests on eccentric half-joint cantilever specimens, the progressive reduction in concrete cover led to a reduction in anchorage capacity of deformed steel bars;
- The presence of transverse confining reinforcement (hanger bars or stirrups) limited the anchorage strength reduction. However, this beneficial effect was not sufficient to anchor the bars when the cover was completely lost and the longitudinal bars exposed to mid-barrel;
- Specimens that artificially replicate corrosion-induced spalling should reproduce the loss of concrete volume outside the reinforcement cage, without affecting the concrete between longitudinal and transverse reinforcement bars;
- More research is necessary to investigate the effects of delamination and spalling together with other corrosion-induced phenomena, such as the presence of corrosion products, reduction in rib height and possible localised pitting corrosion.

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