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# Bond and slip of coated reinforcement in concrete

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Concrete beams reinforced with black, epoxy coated or galvanized steel were tested to failure in flexure and the slip of the reinforcement was monitored. While there was clear evidence of the influence of bar deformations on the bond capacity of beams reinforced with smooth compared to ribbed black steel bars, the majority of the work concentrated on comparing the load–slip behaviour of ribbed bars as affected by the presence of surface coatings. The ultimate capacity in flexure of beams reinforced with ribbed galvanized or epoxy coated bars was not statistically different to that of black steel reinforced beams. The results from load–slip measurements were indicative of the variation in bond for the different bar coatings. It was found that loads at a slip of 0.05 mm were generally too close to the ultimate load and accordingly lower slip values in the serviceability range, i.e. 0.01 and 0.02 mm, were adopted for the analysis. From this it was found that the mean critical load at these slip values for the ribbed galvanized bars was not statistically different to the black steel. On the other hand, the load at slip for the epoxy coated ribbed bars was significantly lower, by about 20%, than that for both the black and galvanized steel bars. Overall, the results of this work indicated that there was no significant loss in bond with the use of galvanized bars, though a significant reduction was observed with epoxy coated bars.

**Keywords: bond; slip; coated reinforcement**

Corrosion of steel reinforcement in concrete is a major factor in the deterioration of concrete structures. As the need to design for durability has become a necessary practice, measures to protect steel reinforcement from corrosion are now more common. Coating of the steel bars is one of those measures. Several coating materials and techniques are known and two coating systems in particular have become prominent in structural practice; namely galvanizing and epoxy coating.

Galvanizing produces a metallurgically alloyed coating of zinc and zinc–iron alloys which is tightly adherent to the steel. Protection from corrosion is achieved both by barrier effects due to the coating itself and through the sacrificial anodic function of zinc in respect of adjacent exposed steel. Galvanized reinforcement in concrete can remain passivated when the pH of the surrounding concrete drops to perhaps as low as 9.5 and thus offers protection against carbonation related corrosion. Moreover, galvanized reinforcement can tolerate substantially higher concentrations of chloride ions than black steel reinforcement[1]. Passivation of galvanized steel which occurs when it is embedded in concrete is due to reaction between zinc and the wet cement paste. This reaction produces hydrogen on the surface of the bars which may reduce the bond between the reinforcement and the concrete. Passivation of the zinc can be lost and corrosion of the coating can occur in circumstances outside the scope of this paper. If this were to happen, however, the coating would have acted to delay the onset of corrosion of the steel base.

Epoxy coating produces an essentially inert barrier which provides excellent protection against corrosion by completely isolating the steel base. The coating is highly resistant to both the alkaline environment of concrete and to the penetration of chlorides. The protection afforded by epoxies lasts for as long as the epoxy coating remains adhered to the steel base and is undamaged. Where there are gaps in the coating, local small anodes can form, resulting in severe corrosion[1].

With the introduction of such protection methods to reinforcement it has become necessary to examine the performance of the structural elements in which these methods are employed. The bond between concrete and the reinforcing steel is fundamental to the performance of structural concrete, and this characteristic has become central in research on reinforcement coatings. Hydrogen evolution in the case of galvanized steel has been shown to reduce bond[2]. A solution to this problem is through the use of potassium dichromate either as an additive to the concrete mixing water, or by chromate passivation of bars during galvanizing and prior to their embedment in concrete. These practices, however, are controversial because of recently raised concerns on health hazards which might accompany the use of

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*Correspondence to Dr O.A. Kayyali, Department of Civil Engineering, University College, The University of New South Wales, Australian Defence Force Academy, Canberra, ACT 2600, Australia chromates. Alternatively, since most cements contain small quantities of chromates passivation will result, providing at least 20 ppm of chromates are present in the final concrete mix[3]. It is to be noted that Australian cements usually contain quite low levels of residual chromates (typically 7–10 ppm) and certainly well below the 20 ppm threshold value required for automatic passivation of galvanized reinforcement. Reduction in bond between epoxy coated bars and concrete is also expected due to the smooth nature of the coating.

Nevertheless, bond of the reinforcement to concrete is due to three main factors: chemical adhesion; friction along the bar surface; and bearing of concrete against irregularities or deformations on the surface of the bar[4]. It is believed that chemical adhesion and frictional resistance would play dominant roles in the development of bond strength if the bars were plain, i.e. undeformed. The bars used in concrete reinforcement are in the vast majority of cases deformed (i.e. ribbed). Any research in this area, therefore, must take into account the possibility that the bearing action in the case of ribbed reinforcement may be the dominant factor contributing to bond strength. This action can to an extent obscure the effect of smoothness in the case of epoxy coating. It may also obscure the loss of bond caused by hydrogen generation in the case of galvanized bars.

A large amount of research in this regard has used the pullout test as both an indicator and means of comparison between various methods and coating materials. Particular conditions and localized compression which accompany the pullout test make the test valuable mainly for comparative purposes only and conclusions of limited generality may be drawn. Two modes of failure occur in pullout testing: splitting and pullout. The pullout mode happens with plain bars while the splitting mode happens more commonly in tests where deformed bars are used and the maximum load attained may be dictated by the low tensile strength of the concrete which leads to premature cracking. Moreover, it would be hard to compare results from specimens if different modes of failure took place. This may explain the often conflicting results obtained by different researchers. For example, Al-Sulaimani *et al.*[5] and Cairns and Abdullah[6] concluded that epoxy coating reduces bond strength of ribbed reinforcement, while Yeomans and Ellis[7] found that for ribbed bars in pullout tests there was no significant difference in the bond strength of black steel, galvanized steel, and epoxy coated steel in concrete. Yeomans and Ellis also reported that for ribbed galvanized bars there does not appear to be any significant difference in the bond, from pullout tests, of weathered galvanized bars, cleaned galvanized bars, and chromate treated galvanized bars in concrete. This finding brings into question the relevance of requirements for chromate treatment as far as bond of galvanized ribbed bars is concerned.

The performance of coating systems in the development of bond strength in more realistic situations as with beams in structures is of paramount importance, especially since the vast majority of reinforced concrete is made with ribbed bars. This paper reports the results of a preliminary investigation into the bond of galvanized, and epoxy coated reinforcement in reinforced concrete beams acting in flexure, compared to equivalent black steel reinforcement. It takes into account previous work done using pullout testing and compares it with the results obtained from flexural testing.

## Experimental

Twelve reinforced concrete beams were cast for the testing programme. The beams were divided into four sets. One consisted of three beams which were reinforced with smooth black steel bars. The second set consisted of three beams reinforced with ribbed black steel bars. The beams of the third set were reinforced with fusion bonded epoxy coated ribbed bars, while the fourth set were reinforced with ribbed hot dip galvanized steel bars. In all the beams, the cover to the main reinforcement was 32 mm from the bottom and 72 mm from the side face. Superplasticized ready mix concrete was used with a characteristic 28 day strength of 30 MPa and slump of 75 mm. Compressive strength testing at 35 days gave a mean strength of 33 MPa.

The beams were cast at the same time from a single batch of concrete. Concrete was poured in the beam moulds which were placed on the laboratory floor in the same orientation as the test position. The concrete was poured in three layers and vibrated using an internal 'pencil' vibrator. They were covered with saturated hessian for five days. The 12 beams were left in their moulds at room temperature for a further 30 days. They were then demoulded and tested on four consecutive days. Details of the mix, concrete materials and specimen designations are given in *Table 1*. All the beams had similar design details as shown in *Figure 1*. The beams were designed such that they would not fail in shear prior to a predicted failure load in flexure being reached. Provisions of the Australian Standard AS 3600[8] were adhered to in this regard. No stirrups were provided within the middle third of the beams where constant moment was expected.

The main reinforcement was 16 mm diameter bar to the requirements of AS 1302[9]. The plain bar (designated 250R) was hot rolled low carbon steel with a minimum yield stress of 250 MPa, 22% minimum elongation and a minimum ultimate stress of 1.1 × yield stress. The deformed bar (designated 400Y) was a micro-alloyed steel, quenched and auto-tempered to give a minimum yield stress of 400 MPa, 16% minimum elongation and a minimum ultimate stress also of 1.1 × yield stress. The deformation pattern of the ribbed bars consisted of two longitudinal chords (on opposite sides of the bar) with ribs inclined at approximately 70° to the horizontal between the chords. For 16 mm diameter bar, the maximum average deformation spacing was 11.2 mm and the minimum average rib height was 0.7 mm. The maximum deformation gap across the chord was 6.3

**Table 1** Details of concrete mix parameters and materials, and beam designations

| Materials/specimen | Quantity/m$^3$ | Designation |
|---|---|---|
| Crushed 20 mm aggregates | 950 kg | |
| Washed sand | 900 kg | |
| Cement | 290 kg | |
| Water | 80 kg | |
| Air entraining and water reducing agent | 340 ml | |
| Beams with ribbed black steel bars | | B1,B2,B3 |
| Beams with smooth black steel bars | | P1,P2,P3 |
| Beams with ribbed epoxy coated bars | | E1,E2,E3 |
| Beams with ribbed galvanized bars | | G1,G2,G3 |

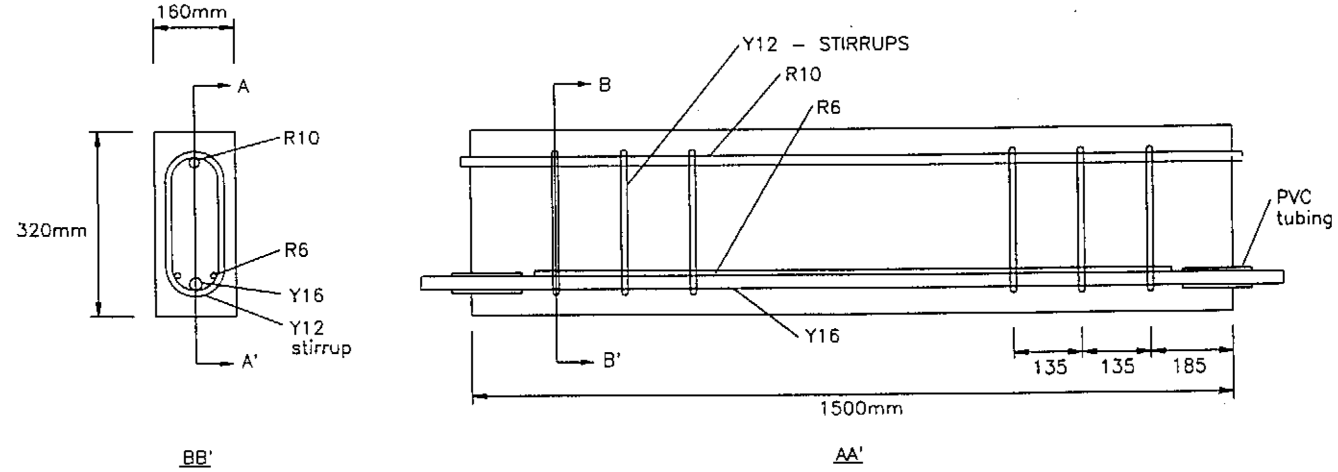

**Figure 1** Details of beam and reinforcement

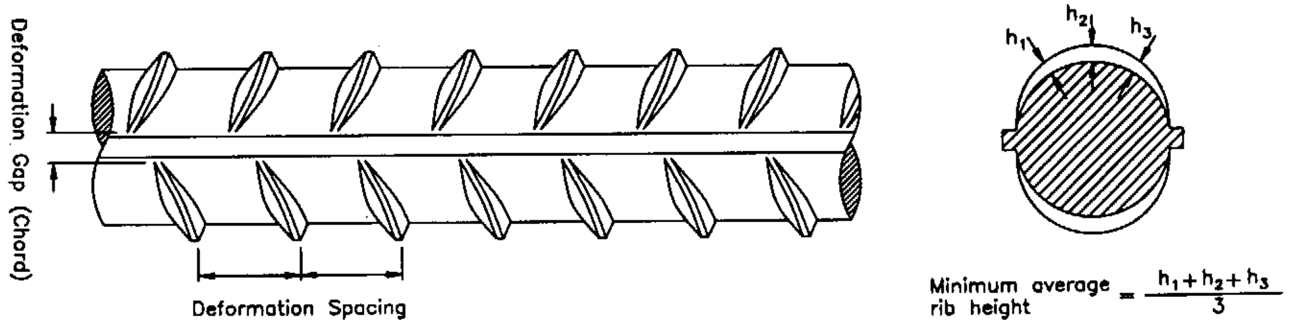

**Figure 2** Deformation pattern of Grade 400Y reinforcing bars to AS 1302

mm. A schematic of the deformation pattern of the 400Y bars is shown in *Figure 2*.

The galvanized steel was hot-dip galvanized to AS 1650[10] with a specified minimum zinc alloy coating thickness of 85 $\mu$m (610 g m$^{-2}$). Typical coating thickness was measured in the range 120–150 $\mu$m. The epoxy coating was electrostatically applied by the fusion bond process resulting in film thickness after curing in the range 175–195 $\mu$m. This value was at the lower end of the film thickness range specified in ASTM A 775 M (i.e. 180–300 $\mu$m), but individual measurements were generally above the 180 $\mu$m lower limit[11].

The reinforcement was cut to size in order to allow for approximately 100 mm excess at either end of the beam. This provided for sufficient room for LVDT (linear variable displacement transducer) clamps to be attached. The reinforcement was inserted in the mould through 20 mm holes drilled in the end pieces of the formwork. A 100 mm length of polyvinyl chloride (PVC) tube was placed over the bar and pushed up flush to the formwork. The PVC tubing prevented the formation of bond up to the centre line of the supports, as recommended by ACI[12].

Shortly before the concrete was poured, the reinforcement was wiped clean in order to remove dust or oil that might have come in contact with the bars. Testing was conducted such that pure flexure occurred within the middle third of the beam, as shown in *Figure 3*. The slip was measured using two LVDTs arranged as shown. The data from the LVDTs were converted into digital signals and read into a personal computer. The data were then saved as an ASCII file with the use of

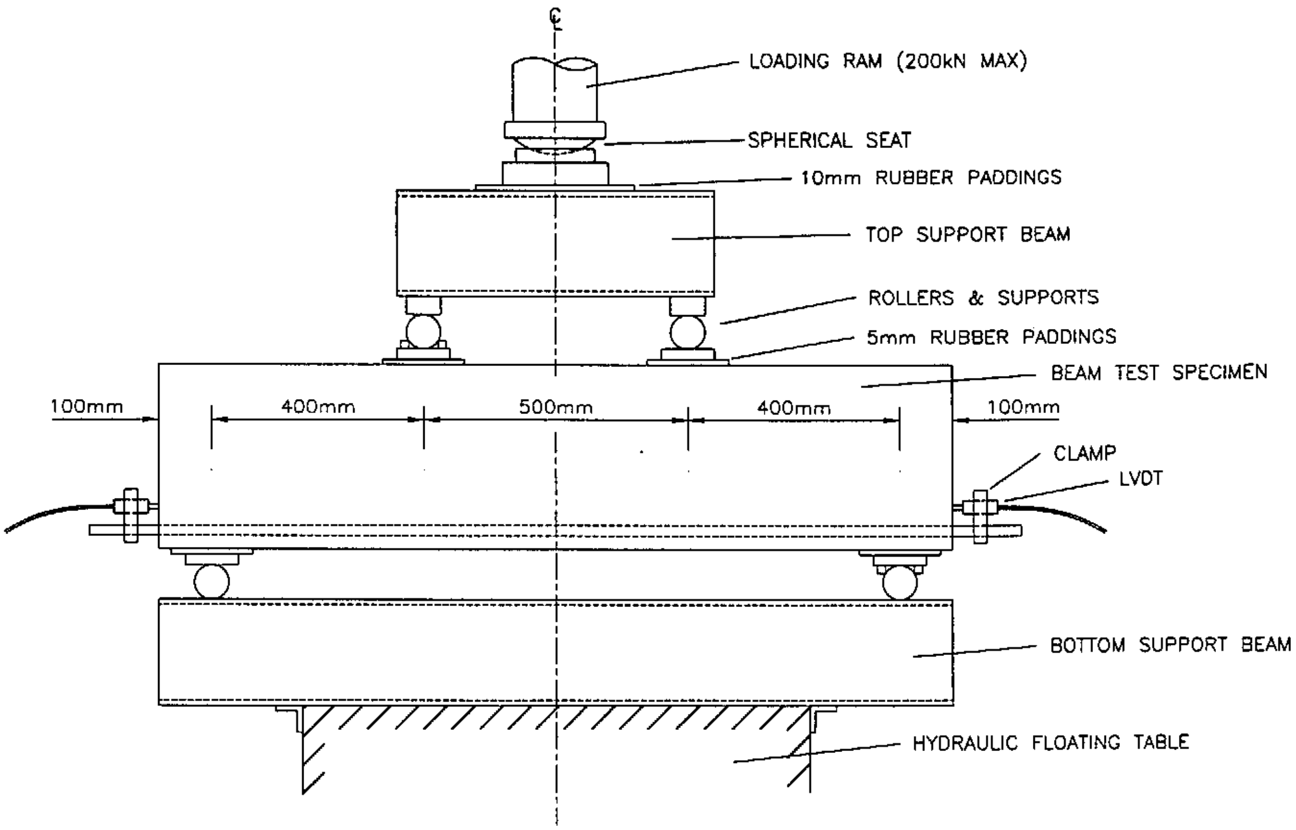

**Figure 3** Test arrangement

Lab Tech Notebook software. The average of the two end slip readings was taken to represent the slip value at that load.

## Results and discussion

### *Flexural capacity*

The performance of the reinforcement in the beams was gauged against the expected ultimate load capacity in flexure. The beams as designed were expected to withstand an ultimate load of at least 163 kN. The performance of the beams reinforced with deformed (ribbed) black steel bars was taken as reference. The results are recorded in *Table 2*. The beams reinforced with smooth black steel (P) failed at an average load of 110 kN, some 40% less than that sustained by the beams reinforced with ribbed black steel (B), i.e. 186 kN. This result is in general agreement with previous findings that the use of deformed bars in concrete reinforcement would nearly double the ultimate capacity in flexure[13]. The beams in the smooth black steel group exhibited a pullout failure mode and very large slip values as can be seen in *Figure 4*.

The group of beams reinforced with ribbed epoxy coated bars (E) failed in flexure at an average load of 182.5 kN which is about 2% lower than the value for the black steel group. In contrast, the beams reinforced with ribbed galvanized bars (G) failed in flexure at an average load of 191 kN which is about 3% above the value for the black steel reinforced beams. Nevertheless statistical analysis of these results at the 95% confidence level confirmed that there was no significant difference in the flexural capacity of beams reinforced with ribbed

**Table 2** Ultimate load capacity (kN) of reinforced beams in flexure

| Beam number | Black steel reinforcement | | | |
|---|---|---|---|---|
| | Smooth bars (P) | Ribbed bars (B) | Epoxy coated ribbed bars (E) | Galvanized ribbed bars (G) |
| 1 | 143.6 | 183.9 | 166.2 | 190.1 |
| 2 | 88.4 | 179.9 | 184 | 192.7 |
| 3 | 99 | 194.2 | 197.2 | 190 |
| Mean load (kN) | 110 | 186 | 182.5 | 191 |
| Standard deviation (kN) | 29.3 | 7.4 | 15.6 | 1.5 |
| Difference from reference (%) | –40% | Reference | –1.9% | +2.7% |
| 95% confidence limits | 77–143 | 177–194 | 165–200 | 189–193 |
| Is the mean significantly different from that of ribbed black steel? | Yes | Reference | No | No |

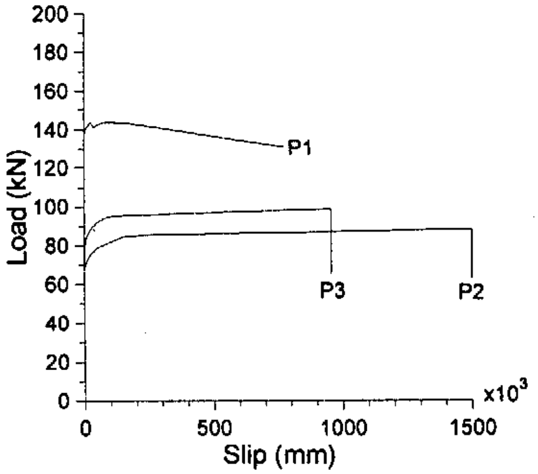

**Figure 4** Load–slip behaviour for smooth black steel (P)

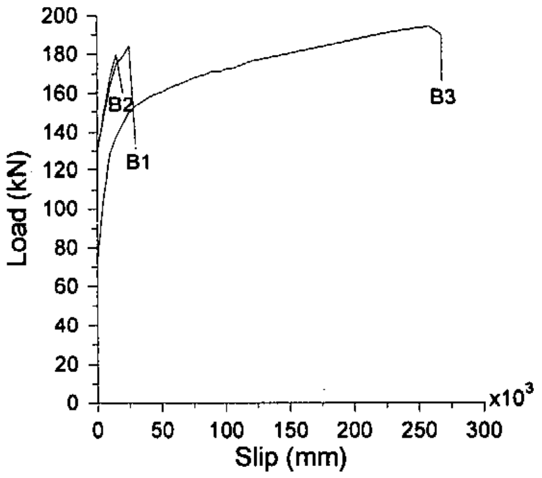

**Figure 5** Load–slip behaviour for ribbed black steel (B)

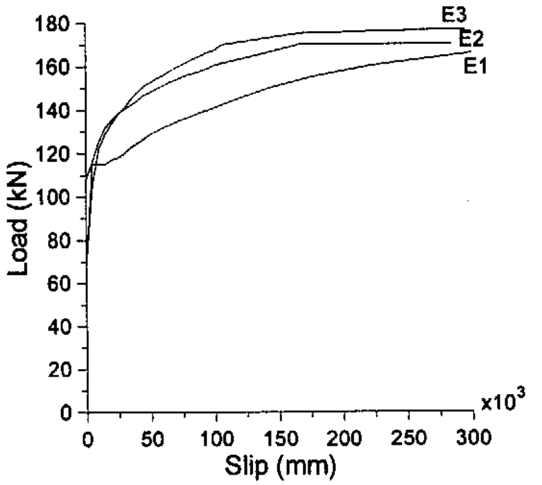

**Figure 6** Load–slip behaviour for ribbed epoxy coated bars (E)

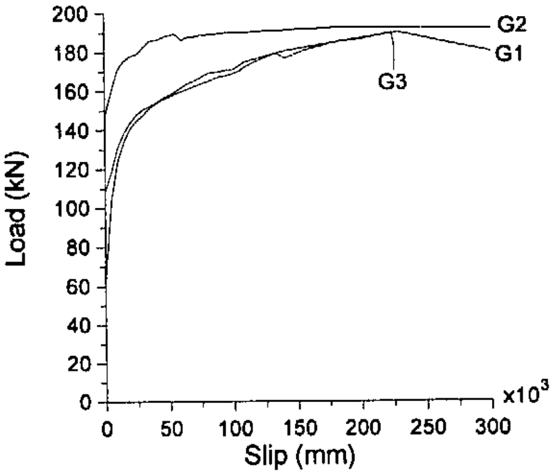

**Figure 7** Load–slip behaviour for ribbed galvanized bars (G)

black, epoxy coated or galvanized bars. This finding supports the conclusion obtained from earlier pullout tests, namely that there is no significant difference in bond strength between ribbed bars whether they were black, epoxy coated or galvanized.

*Load–slip behaviour*

While no significant differences were apparent between the flexural capacities of beams reinforced with ribbed bars whether black, epoxy coated or galvanized, examination of their load–slip behaviour gave a rather different conclusion. In early work on load–slip behaviour in beam pullout testing, Mathey and Watstein[14] defined the criterion of bond failure as the load at which a critical slip value of 0.05 mm occurred. This concept was employed again by Mathey and Clifton[15] in investigations of the bond of coated reinforcing bars in concrete in the mid-1970s. More recently, Hughes and Videla[16] found quite a significant difference between the bond strength of bars at 0.1 mm and 0.2 mm slip values, and pointed out that for anchorage lengths shorter than the development length the bond strength is essentially independent of anchorage length, there being a linear relationship between failure load and anchorage length. However, when the anchorage length exceeds the development length the calculated value for the bond strength becomes smaller the longer the anchorage length due to the tensile failure of the steel or the concrete in such situations.

*Figures 5–7* show the load–slip behaviour for the three groups of ribbed bar reinforced beams tested in this programme. It may generally be observed that the ribbed epoxy coated steel bars (*Figure 6*) exhibited greater slip near failure than their counterparts of either ribbed black (*Figure 5*) or ribbed galvanized bars (*Figure 7*). In these tests, the embedded length of all bars was 400 mm from the position of zero moment at the end of the beam to the position of maximum moment within the beam. This value satisfies the minimum requirement for development length of ribbed bars as stipulated in AS 3600[8]. It was therefore expected that the ribbed bars would ultimately fail in tension while the smooth bars would not be able to develop their ultimate tensile capacity because of premature slip. The criterion of a critical slip of 0.05 mm when applied to the results of this work is seen to correspond to loads

**Table 3** Load at slip of 0.01 mm (kN)

| Beam number | Black steel reinforcement | | Epoxy coated ribbed bars (E) | Galvanized ribbed bars (G) |
|---|---|---|---|---|
| | Smooth bars (P) | Ribbed bars (B) | | |
| 1 | 141 | 163.5 | 115 | 124 |
| 2 | 71.8 | 167.8 | 125.4 | 170.8 |
| 3 | 84.5 | 128.5 | 122 | 130.8 |
| Mean load (kN) | 99.1 | 153.3 | 120.8 | 141.9 |
| Standard deviation (kN) | 36.8 | 21.6 | 5.3 | 25.3 |
| Difference from reference (%) | –35% | Reference | –21% | –7% |
| 95% confidence limits | 57–141 | Reference<br>129–178 | 115–127 | 113–171 |
| Is the mean significantly different from that of ribbed black steel? | Yes | Reference | Yes | No |

**Table 4** Load at slip of 0.02 mm (kN)

| Beam number | Black steel reinforcement | | Epoxy coated ribbed bars (E) | Galvanized ribbed bars (G) |
|---|---|---|---|---|
| | Smooth bars (P) | Ribbed bars (B) | | |
| 1 | 142.7 | 178.6 | 117 | 141 |
| 2 | 74.3 | 179.9 | 135.6 | 177.9 |
| 3 | 87 | 144.3 | 133.8 | 144 |
| Mean load (kN) | 101.3 | 167.6 | 128.8 | 154.3 |
| Standard deviation (kN) | 36.4 | 20.2 | 10.3 | 20.5 |
| Difference from reference (%) | –39.5% | Reference | –23% | –8% |
| 95% confidence limits | 60–142 | Reference<br>145–191 | 117–140 | 131–177 |
| Is the mean significantly different from that of ribbed black steel? | Yes | Reference | Yes | No |

which are on the plateau approaching the failure loads. In the case of the ribbed black steel it was observed that the slip value of 0.05 mm was not achieved because the embedment length was greater than the development length for deformed bars. It was therefore more appropriate if the load at a lower slip value was reported for this comparison. With this in mind, two values of slip, namely 0.01 and 0.02 mm, have been assessed and the corresponding load results are given in *Tables 3* and *4*.

The load values at a slip of 0.01 mm are shown in *Table 3*. It can be seen from *Table 3* that the load value for 0.01 mm slip of the smooth black steel group (P) is 35% lower than that for the ribbed black steel group (B) which was taken as a reference. In comparison, the mean value for the ribbed epoxy coated group (E) is 21% lower than that for the ribbed black steel group while the mean load value for the ribbed galvanized group (G) is 7% lower than that the reference group of ribbed black steel bars. Statistical analysis of these results indicates that (at a 95% confidence level) the 21% load reduction for epoxy coated bars is statistically significant compared to the reference group, while the 7% reduction in the case of the galvanized bars is probably not significant. It thus appears that, for the sample population and distribution of data in this work, epoxy coating has significantly reduced the bond of ribbed reinforcement compared to black steel while galvanizing has not resulted in a significant reduction in bond.

This result is consistent, as far as epoxy coated bars are concerned, with the trend found by Treece and Jirsa[17] and also by Cleary and Ramirez[18]. On the other hand, while information regarding the bond strength of galvanized bars is very scarce, previous results from pullout tests indicated no significant difference between galvanized and black steel ribbed bars[7]. Moreover, as shown in *Table 4*, when a larger slip value of 0.02 mm is adopted the results led to similar conclusions. In this case, epoxy coating resulted in a reduction of 23% in the load compared to ribbed black steel. Galvanized reinforcement on the other hand resulted in a reduction of 8% which, when tested at the 95% confidence level, was found to be not significant. From this it is apparent that the difference in bond strength of the various ribbed bar types is more evident at slip values which correspond to loads much less than the failure loads. This may further imply that in the range of loading usually encountered in service conditions, the bond strength of ribbed black bars is significantly superior to that of epoxy coated bars but not to galvanized bars.

It was also observed in this work that the contact surface between the epoxy coated bars and the surrounding concrete was smooth and glossy. This observation is similar to that by Treece and Jirsa[17] who cited it as evidence of the absence of adhesion between the epoxy coating and the concrete. On the other hand, Koch and Stuttgart[19] have demonstrated the presence of significant adhesion between galvanized bars and the surrounding concrete. In pullout tests using smooth bars, they found a clear superiority of galvanized over black steel bars in what they termed adhesion bond. This behaviour is believed to be closely related to the chemical reactions between zinc and cement paste resulting in the formation of tightly adhered layer of calcium hydroxyzincate at the interface.

In support of this it is generally observed that it is far more difficult to remove galvanized bars from concrete compared to either black or epoxy coated bars because of tight adhesion of the matrix to the zinc alloy surface of the bar. The chemical reactions between zinc and wet cement release hydrogen which may loosen the surrounding structure of the hydration products resulting in a decrease in bond strength. However, calcium hydroxyzincate is a fibrous hydration product and its presence immediately adjacent to the bars is believed to increase the adhesion between the concrete and the reinforcing bars[19]. Overall, this accounts for the comparatively small and certainly insignificant differences observed in the bond of galvanized and black bars. Indeed, it is often reported that galvanized bars have a bond strength which is at least as good as that of equivalent black steel bars in concrete[7,20].

The results obtained in this study confirm this conclusion. Nevertheless, the release of hydrogen which accompanies the reactions between the zinc coating and the cement, and the different reactivity of the zinc coating with different cements, may contribute to explain the contradictory results reported in the literature[2]. This, of course, emphasizes the importance of bond strength research when chromate addition is envisaged in conjunction with the use of galvanized reinforcement. It also points to the possibility that the form in which the chromate is added, i.e. as mix water additions to the concrete or as a passivating film on the galvanized bar surface, may significantly affect the nature of the adhesion achieved and hence the resultant bond strength.

## Conclusions

The ultimate capacity in flexure of beams reinforced with smooth black steel bars was about half that of beams reinforced with ribbed black steel bars. This is clear evidence of the contribution of the bar deformations to the bond of reinforcement with concrete as has been previously verified.

For beams reinforced with ribbed bars, the ultimate capacity in flexure with galvanized or epoxy coated steel was not significantly different to that of beams reinforced with black steel bars.

While a slip value of 0.05 mm could be successfully utilized as a critical value to define bond failure in beam pullout testing, there were difficulties in applying this criterion to beam flexural tests. Lower slip values, i.e. 0.01 or 0.02 mm, were found to give clearer indications of the differences in bond strength as a result of the presence of surface coatings.

The load at a slip of both 0.01 and 0.02 mm for smooth black steel bars was some 35–40% lower than that for ribbed black steel bars.

For beams reinforced with ribbed bars, there was no significant difference in the value of the load at both 0.01 and 0.02 mm slip for black steel and galvanized steel. In contrast, for epoxy coated steel the value of load at these slip increments was significantly lower, of the order of 15–20%, than that for both the black steel and the galvanized steel.

Although there is ample research on the bond of epoxy coated bars, this is somewhat lacking in the area of galvanized bars. The results of this work indicate that there is probably no significant loss in bond with the use of galvanized bars. It is thus highly likely that the use of chromates to improve the bond of ribbed galvanized bars in concrete is unnecessary. In this context, further research is still needed to establish deflection and cracking behaviour of beams in flexure within the serviceability load range when using galvanized bars, whether chromate treated or not.

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