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Effect of reinforcing steel bond on the cracking behaviour of lightly reinforced concrete members

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HIGHLIGHTS

- Influence of reinforcement bond strength on lightly reinforced concrete members.
- Pull out and prism tests using reinforcement with different deformation patterns.
- Greater yield penetration when using half rib height reinforcement.
- Greater crack distribution (secondary cracking) when using standard reinforcement.

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ABSTRACT

The ductility of lightly reinforced concrete (RC) members is dependent on the distribution of cracks, as well as the strain penetration of reinforcement at each crack. A series of experimental tests were conducted to investigate how the bond characteristics of reinforcing steel would influence the strain penetration and crack distribution in lightly reinforced concrete members. To vary the bond characteristics, reinforcement with three different deformation patterns were investigated, including a standard deformation pattern and two modified bars with either half the rib height or double the rib spacing of a standard bar. Pull-out tests were conducted to quantify the bond strength of the reinforcement with different deformations patterns, followed by direct tension prism tests that represented the end region of an RC wall with minimum vertical reinforcement. The pull-out tests indicated that the standard deformation pattern achieved the highest initial bond stiffness, whereas the double rib spaced deformation pattern achieved the highest ultimate bond strength. The direct tension prism tests showed similar crack distributions for the two modified bar types, but increased secondary cracking for the standard bar due to higher initial bond strength. However, only the half rib height bar displayed a higher ductility than the standard bar, with significantly greater yield penetration at each crack causing larger ultimate crack widths prior to bar fracture.

1. Introduction

A ductile reinforced concrete (RC) member is typically expected to form distributed cracks within the plastic hinge region when subjected to earthquakes. Distributed cracking encourages the reinforcing steel to yield over a significant length, allowing the RC member to achieve a greater plastic rotation prior to the reinforcement reaching its elongation capacity. During the 2010/2011 Canterbury earthquakes in New Zealand, several lightly reinforced concrete walls did not behave in a ductile manner, and instead formed only a limited number of cracks at the wall base [24]. For example, a single crack was observed at the base of one of the RC walls in the Gallery Apartments building, and the concentrated inelastic demand resulted in premature fracture of the vertical reinforcement [23]. Lightly reinforced concrete members are unlikely to form distributed cracks when the cracking moment exceeds the nominal moment of the cracked section, or when the reinforcement tension force is insufficient to develop secondary cracks [9,14]. In addition, experimental tests of RC frames have also indicated that premature fracture of beam longitudinal reinforcement could limit the formation of catenary action under a central column loss scenario [5,28].

The distribution of cracks and the degree of reinforcement strain penetration at each crack face are two significant factors that influence the rotational capacity of a RC plastic hinge. The objective of this research was to investigate how reducing the bond strength of the reinforcing steel would influence crack formation,

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reinforcement strain penetration, and overall ductility of lightly reinforced concrete members. The effect of deformation (rib) pattern geometry on bond strength of reinforcing steel is well understood and has been studied extensively to develop bond–slip relationships. Therefore, the deformation patterns on the reinforcing steel were altered to investigate the influence of reinforcement bond strength on lightly reinforced concrete members. Trial bars were manufactured with three different deformation patterns and a series of experimental tests were conducted to assess the bond characteristics and potential impact of the deformation patterns on the ductility of RC prisms with low longitudinal reinforcement contents.

2. Background

For a RC member with limited flexural cracking in the plastic hinge region, the ultimate plastic rotation is proportional to the number of cracks and the ultimate crack width that can be sustained [9]. The elongation of the reinforcing steel is governed by the steel strain and the depth that inelastic strains can penetrate into the concrete, referred to as strain penetration [9]. Numerical models developed by Haskett et al. [13] show that bars with lower bond strength will allow inelastic strains to penetrate further into the uncracked concrete section. As a result of observed damage during the 2010/2011 Canterbury earthquakes, the Structural Engineering Society of New Zealand [25] has recommended debonding the vertical reinforcement at joints between precast concrete panels to mitigate strain concentrations causing premature reinforcing bar fracture. This recommendation is supported by Bao et al. [5], who found that that debonding reinforcing steel 203 mm each side of the crack on a beam-column structure enhanced the resistance of RC frames to disproportionate collapse, with the peak displacement that could be sustained increased by about 38% compared with specimen where no debonding was used.

Beeby [6] discusses the development of cracking theory of RC members. Beeby outlines that for axially reinforced tension members, the crack patterns are controlled by the reinforcement cover, bar diameter, reinforcement ratio and bond properties of the reinforcing steel. Forces between concrete and reinforcement are transferred through bond stresses, which are longitudinal shear stresses that act along the interface between the concrete and reinforcing bars [15]. Chemical adhesion, friction and mechanical interlock are the main mechanisms by which these bond forces are transferred [7]. For deformed reinforcing bars, the bond strength is primarily provided by bearing of the deformation patterns, or ribs, against the concrete [7]. There are many variations of deformation patterns available from reinforcing steel suppliers globally. However, a review of previous studies indicated that the main parameter relevant to reinforcement bond strength is the relative rib area (R_r), which is defined as the ratio of the projected rib area perpendicular to the bar axis to the shearing surface area between each rib [8,15,18]. It is therefore expected that the deformation patterns on reinforcing steel bars has a significant influence on the bond strength and thus cracking patterns observed in RC members.

3. Trial bars

To investigate the effect of reinforcement bond strength on the behaviour of lightly reinforced concrete members, trial bars with different bond characteristics were manufactured. As discussed, altering the rib geometry has a direct effect on the reinforcement bond strength and so trial bars with different rib geometry to standard reinforcement were used to achieve the desired reduction in bond strength. Reinforcing steel with three different deformation patterns was investigated using D12 bars, which are 12 mm diameter deformed bars manufactured with grade 300E steel [21]. The deformation patterns considered comprised of the standard rib deformations produced by Pacific Steel Group, and two reduced bond bars. The reduced bond bars included one that had deformations with double the standard rib spacing, and another with half the standard rib height. Details of the rib height and spacing for each of the three deformation patterns used are provided in Table 1. The mechanical interlock provided by deformation patterns can be measured by calculating the relative rib area (R_r), as shown by Eq. (1) [8], where A_r is the projected rib area normal to the bar axis, P_b is the nominal bar perimeter, and S_r is the centre to centre rib spacing. Although the half rib height and double rib spaced bars possessed the same projected rib area, both variations were included to investigate whether the rib geometries also affected bond strength and RC member ductility.

Table 1
Deformation pattern details for the test bars.

Deformation pattern	Rib height (mm)	Rib spacing (mm)
Standard D12 bar	1.2	8.5
Double rib-spaced D12 bar	1.2	17
Half rib-height D12 bar	0.6	8.5

$$R_r = \frac{A_r}{P_b \cdot S_r} \tag{1}$$

4. Experimental setup

To compare the effect of the altered reinforcement deformation patterns on the ductility of lightly reinforced concrete members, pull-out tests and direct tension prism tests were conducted. The pull-out test followed a standard test method that was used to compare the bond characteristics of the three deformation patterns and the direct tension tests were conducted to evaluate the crack development, crack spacing, crack width, and overall ductility of RC prisms.

4.1. Pull-out test

Three pull-out tests were conducted for each deformation pattern and the bond characteristics were evaluated by comparing the pull-out force and resulting bond stress against the free end slip. The pull-out test setup was adopted from that previously used by Kimura and Jirsa [15], and is shown in Fig. 1. The D12 bar was embedded into a 200 mm cube concrete block that was anchored to a strong floor using steel bearing plate and a short steel beam. The reinforcing steel that protruded from the top of the concrete block was secured to an actuator that applied a tension load. An LVDT was attached to the unloaded end of the reinforcing steel to measure the force-slip response. Pseudo-static monotonic loading was applied at a rate of 1 mm/min until the reinforcement yield strength, after which the rate was increased to 2 mm/min.

The pull-out test was designed to achieve bar pull-out, as opposed to bar fracture, as bond degradation was more likely to be observed with a pull-out failure mode. A bonded length of 90 mm was selected for all specimens to achieve a pull-out type failure. The bonded length adopted was derived from the basic development length (L_{db}) given in the New Zealand Concrete Structures Standard, NZS 3101:2006 [19]. The L_{db} for a D12 bar embedded in 40 MPa concrete was 285 mm. However, the relative rib area of a reinforcement with standard deformation patterns was 2.52 times the minimum relative rib area specified in Steel