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Bond behaviour of substandard splices in RC beams externally confined with CFRP

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HIGHLIGHTS

- Bond splitting is studied by testing RC beams with substandard lap spliced bars.
- Steel stirrups or CFRP confinement, concrete cover and bar size were investigated.
- CFRP confinement enhances the lap bond strength by up to 65% over unconfined laps.
- Equations predicting the additional bond strength due to CFRP show a large scatter.
- A new "strain approach" to compute the latter value is proposed and validated.

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ABSTRACT

Bond splitting failures of substandard lap-spliced columns have led to collapse of many RC buildings during recent earthquakes in developing countries. The strengthening of lap-spliced regions with CFRP confinement can reduce the seismic vulnerability of such buildings. This paper investigates bond splitting using flexural tests on twelve RC beams with substandard lap splices (25 bar diameters) at midspan. Different confinement configurations (no confinement, internal stirrups or CFRP sheets), concrete covers and bar sizes are examined at the splice region. The results show that light CFRP confinement enhances the splice bond strength by up to 65% compared to unconfined specimens. Predictive equations from the literature are shown to yield a large scatter in results and to overestimate the strain developed in the CFRP confinement. An alternative approach to calculate the confinement strain and the additional bond strength provided by CFRP confinement is proposed and validated.

1. Introduction

Disastrous human and economic losses in recent destructive earthquakes (Kashmir, 2005; China, 2008; Sumatra and Italy, 2009; Haiti, 2010; Turkey, 2011) are a consequence of the high seismic vulnerability of existing substandard buildings, a large proportion of which is reinforced concrete (RC) (e.g. [1–3]). Many catastrophic failures in RC structures can be attributed to failure of inadequate spliced reinforcement at locations of large demand, such as column-footing interfaces or in starter bars above beam-column joints. The local strengthening of these deficient members is a feasible option for reducing the seismic vulnerability of such substandard buildings. Over the last two decades, externally bonded Fibre Reinforced Polymers (FRP) have been used widely to strengthen seismically deficient members. Compared to other strengthening materials, FRP possess advantages such as high strength to weight ratio, high resistance to corrosion, excellent durability, ease and speed of in situ application and flexibility to strengthen selectively only those members seismically deficient [4].

Many experimental studies have shown the effectiveness of FRP confinement at improving the behaviour of columns with inadequate short lapped reinforcement (e.g. lap length $l_b = 20–35d_b$, where d_b is the bar size) [5–18]. Despite the extensive research efforts, relatively little research has focused on developing appropriate analytical models for the strengthening of column splices using FRP materials. Seible et al. [7] proposed the first model for FRP strengthening of short lapped bars in columns where failure was governed by splitting. Whilst this model is included in current FRP guidelines [19–20], its use in actual strengthening applications may lead to very conservative amounts of FRP confinement [10,13].

More recently, the strengthening of short laps with FRP materials was investigated by adopting a bond approach similar to that used for internal steel stirrups [16,21,22]. The results of these studies indicate that (a) the maximum bond strength of the lapped bars could be developed using less confinement than that

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recommended by current FRP strengthening guidelines, and (b) in splitting-prone RC members, FRP confinement is effective at enhancing bond strength up to the point where bar pullout dominates failure. Based on limited experimental work, some analytical models were proposed to compute the additional contribution of FRP confinement to the bond strength of splices [e.g. 16,21,22]. These models are mainly based on modifications of existing equations originally developed for steel confinement, and assume the total bond strength of a lap as the sum of the individual contributions of concrete cover and FRP confinement. Therefore, the concrete contribution to bond strength is computed using bond strength equations available in the literature, whereas the contribution of the FRP confinement is computed by adopting either (i) a "strain approach" that considers the effective strain developed in the FRP [e.g. 16,21], or (ii) an equivalent area of FRP confinement accounting for the different stiffness of steel stirrups and FRP [22]. Recent research by the authors on very short splices [23] showed that these models overestimate the strains developed in Carbon FRP (CFRP) confinement and show a large scatter when predicting experimental results. Based on results from twelve CFRP-confined short beams with very short splices (l_b = 10 and 16d_b), a new strain approach was proposed that yields more consistent predictions of bond strength enhancement due to FRP confinement. However, the accuracy of the proposed approach needs to be verified using tests on lap splices as those found in typical substandard RC constructions.

This research is part of a multistage research project focusing on the seismic strengthening of substandard RC buildings [23–28]. This paper investigates the effectiveness of externally bonded carbon FRP (CFRP) confinement at enhancing the bond strength of substandard lapped bars ($l_b = 25d_b$) in RC beams. The test results are used to examine and discuss the accuracy of predictive models available in the literature.

2. Experimental programme

Twelve RC beams were tested in flexure. The beams were designed to fail by bond-splitting at midspan, where the main bottom reinforcement was lapped. Consequently, the use of confinement at this zone is expected to improve considerably the bond behaviour of the bars.

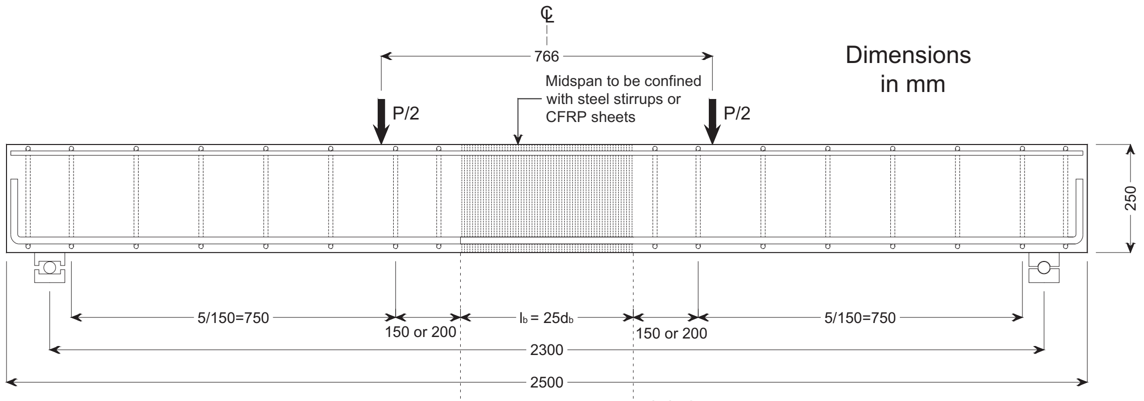
2.1. Characteristics of beam specimens

The twelve tested beams are "splice specimens" as defined by ACI 408R-03 [29]. The beams had a rectangular cross section of 150 × 250 mm, a total length of 2500 mm and a clear span of 2300 mm (see Figs. 1a and b). The main flexural reinforcement was lapped at midspan and consisted of two steel bars of diameter d_b = 12 or 16 mm. The top beam reinforcement consisted of two continuous 10 mm bars. To prevent shear failure, 8 mm deformed stirrups were placed at 150 mm centres outside the lap splice zone. The lap length selected for the beams ($l_b = 25d_b$) is representative of typical deficient laps of substandard (pre-seismic) RC structures in developing countries. To investigate different concrete cover to diameter ratios (c/d_b), side and bottom covers of 10 and 20 mm were selected for the beams reinforced with 12 mm bars, whereas 27 mm covers were used for the beams reinforced with 16 mm bars. Different levels of confinement were investigated. Internal steel stirrups were used to confine the splice region of three of the tested beams. To replicate substandard construction detailing, the stirrups were closed with 90° hooks instead of 135° hooks typically required by current seismic codes (e.g. [20]). CFRP sheets were used for six beams: the midspan of three beams was confined with 1 layer of CFRP confinement and another three with 2 layers. The number of layers was selected to provide minimum confinement to the beams, and is convenient for strengthening substandard structures of developing countries where economic strengthening solutions are sought. For comparison, three unconfined control beams with lapped bars were also cast.

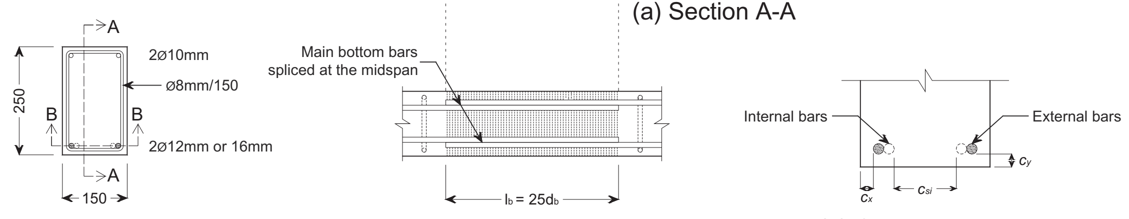
The main characteristics of the tested beams are shown in Table 1. Beams are identified according to the intended concrete cover c (LC10, LC20 and LC27 for c = 10, 20 and 27 mm, respectively) and type of confinement (Ctrl = unconfined control, S = steel-confined, and F = CFRP-confined beams). The last digit of the CFRP-confined beams indicates the number of layers utilised at midspan (1 or 2). Table 1 also reports the measured side (c_x), bottom (c_y) and internal (c_{si}) concrete covers (see definitions in Fig. 1d). These produced c_{min}/d_b ratios ranging from 0.83 to 1.67, where $c_{min} = \min(c_x, c_y, c_{si}/2)$.

2.2. Material properties

Three batches of ready mixed normal-strength concrete were used to cast the beams. The following mix proportions were reported by the supplier: Portland cement CIIIA = 125 kg/m^3, GGBS = 125 kg/m^3, coarse aggregate 4–10 mm = 1002 kg/m^3, sand 0–4 mm = 884 kg/m^3, and water/cement ratio = 0.8. Casting was performed from the top of the beams so that bars are classified as "bottom cast bars" [29]. After casting, the beams were covered with polythene sheets and wet hessian, cured for seven days in the moulds and subsequently stored under standard laboratory conditions. For each batch, the mean concrete compressive strength (f_{cm}) was obtained from tests on at least three 150 × 300 mm concrete cylinders according to BS EN 12390-3 [30]. The indirect tensile splitting strength (f_{ctm}) was determined from tests on six 100 × 200 mm cylinders according to BS EN 12390-6 [31]. The flexural strength (f_{cfm}) was obtained from four-point bending tests on three prisms of 100 × 100 × 500 mm according to BS EN 12390-5 [32]. All cylinders and prisms were cast at the same time and cured together with the beams. Table 2



(a) Section A-A



(b) Cross section (c) Section B-B (lap only) (d) Concrete covers

Fig. 1. General geometry and reinforcement details of tested beams.