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Size Effect in Shear-Deficient Reinforced Concrete T-Beams Strengthened with Embedded FRP Bars

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Abstract
Size effect in shear-deficient reinforced concrete (RC) beams instigates a reduction in shear stress at failure with the increase in beam size. However, size effect in RC beams shear-strengthened with deep embedment (DE), also known as embedded through section (ETS), fibre reinforced polymer (FRP) bars is yet to be fully understood. This paper investigates size effect in geometrically similar unstrengthened as well as DE/ETS shear-strengthened RC T-beams. Two T-shaped cross-sections with a scale factor of 2.0 were tested. The T-beams had web width of either 75 or 150 mm, flange width of either 200 or 400 mm, flange depth of either 63 or 125 mm and overall height of either 325 or 650 mm. All beams had a shear span-to-effective depth ratio of 3.0, steel shear reinforcement ratio of 0.11%, FRP shear reinforcement ratio of 0.25%, and concrete cube compressive strength of 50 MPa. For the unstrengthened beams, the shear stress at failure decreased by 50% with the increase in beam size. The corresponding result for the shear-strengthened beams was 18%, demonstrating that DE/ETS FRP bars can significantly mitigate size effect.

Keywords: Beams, Deep embedment, FRP, Reinforced Concrete, Size effect, Shear strengthening

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Introduction

The deep embedment (DE) technique [1], also known as the embedded through section (ETS) technique [2], has been demonstrated to outperform externally bonded and near-surface mounted techniques for concrete shear strengthening [2]. Yet, the majority of tested reinforced concrete (RC) beams shear-strengthened with DE/ETS fibre reinforced polymer (FRP) bars had relatively small cross-section dimensions [1-3]. This is of particular concern as size effect in RC beams instigates a reduction in shear strength and a transition from ductile to brittle behaviour with the increase in beam size [4]. It is therefore important to quantify size effect in RC beams shear-strengthened with DE/ETS FRP bars. This paper critically investigates size effect in geometrically similar shear-deficient RC T-beams as well as RC T-beams shear-strengthened with DE/ETS glass FRP (GFRP) bars.

Experimental Programme

Test specimens

Two series of beams, small-scale (SS) and large-scale (LS), were tested. Figure 1 shows the details of the tested beams. The SS beams were tested in three-point bending. This setup allowed two tests to be conducted on one beam by testing one beam end zone while keeping the other end unstressed and vice versa. The LS beams were tested in four-point bending.

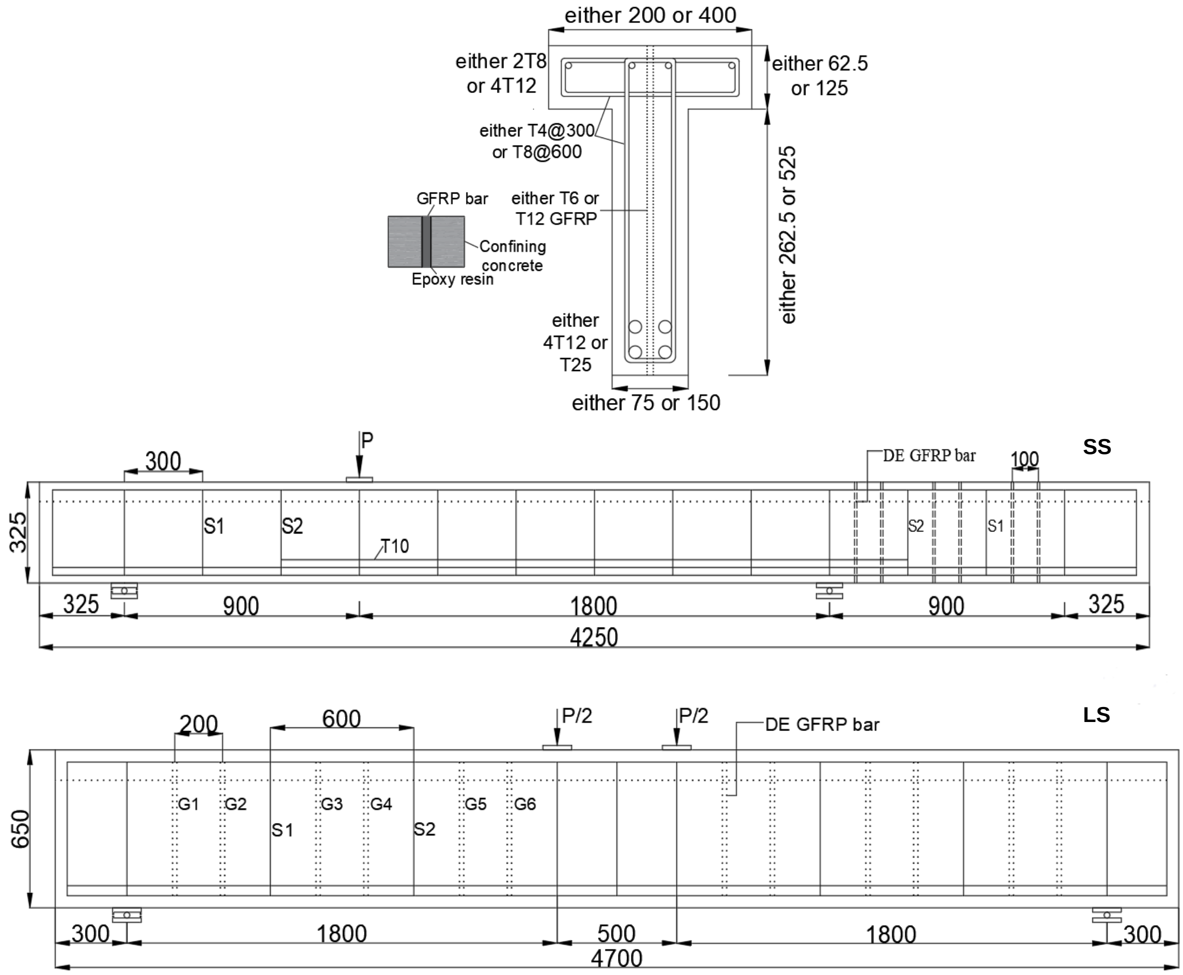

Figure 1: Details of the tested beams – all dimensions in mm

Each series consisted of an unstrengthened control beam and a DE/ETS shear strengthened beam. All beams had a shear span-to-effective depth ratio of 3.0. The beams were designed to fail in shear and had a significant difference between their unstrengthened shear force capacity and their flexural capacity so as to provide a sufficient range over which the level of shear strength enhancement could be measured. The spacing of the steel shear links was equal to the effective depth of the beam (either 300 mm or 600 mm), resulting in a steel shear reinforcement ratio of 0.11% in each beam. This is representative of earlier design practice in the UK [3]. The DE/ETS shear strengthening system consisted of either six 6 mm or six 12 mm sand-coated GFRP bars, resulting in a FRP shear reinforcement ratio of 0.25%.

Material properties

The concrete used to cast the beams had a maximum aggregate size of 10 mm. Standard tests conducted on the day of beam testing showed that the average concrete cube compressive strength was 50.5 MPa. The longitudinal reinforcement had yield and ultimate strengths of 580 and 680 MPa, respectively. The yield and ultimate strengths of the transverse reinforcement were 540 and 680 MPa, respectively. The tensile strength, elastic modulus, and ultimate strain of the sand-coated GFRP bars (supplied by SIREG) were 973 MPa, 40 GPa, and 2.43%, respectively. The bond strength, compressive strength, compressive modulus, tensile strength, and elongation at failure of the epoxy resin (supplied by HILTI) used to bond the GFRP bars to the concrete was 12.4 MPa, 82.7 MPa, 1493 MPa, 43.5 MPa, and 2%, respectively.

Embedding the GFRP bars

In order to install the GFRP bars, vertical holes were created in the shear spans, through the centreline of the cross-section, at the GFRP bar locations shown in Figure 1. The vertical holes were created by installing PVC rods at the required positions within the steel reinforcement cage before casting the concrete. The PVC rods were removed from the concrete 24 hours after casting. A drill bit was then used to enlarge the cast-in-place holes in the SS and LS beams to 10 mm and 18 mm, respectively. Prior to installing the GFRP bars, the drilled holes were roughened by a wire brush and cleaned with compressed air. The lower ends of the holes were sealed and the epoxy resin was used to fill two-thirds of the holes. The GFRP bars were covered with a thin layer of the adhesive and inserted into the holes. Any excess epoxy was removed. It has been already demonstrated that it is possible to install FRP bars without using cast-in-place holes [1-2]. The procedure explained above for installing the GFRP bars was used for simplicity.

Instrumentation

The load was applied using a 1000 kN hydraulic cylinder and measured by a 1000 kN load cell. The maximum vertical deflection was measured using displacement transducers. The readings of the load cell and displacement transducers were recorded using a data logger.

Results and Discussion

Cracking and failure mode

All beams failed in shear as shown in Figure 2. The formation of flexural cracks in the maximum moment zones of the SS and LS beams started at a shear force of 10 and 28 kN, respectively. Upon further loading, the flexural cracks extended into the shear spans. The outermost flexural cracks in the shear spans of the SS and LS beams turned into inclined cracks at a shear force of about 25 and 70 kN, respectively. With increased loading, more inclined cracks appeared in the shear spans and, eventually, an inclined crack caused a diagonal tension failure. Of note is that the inclined cracks that caused failure of the SS beams were steeper than those that caused failure of the LS beams.

Figure 2: Crack patterns at failure: (a) SS control beam, (b) SS strengthened beam, (c) LS control beam and (d) LS strengthened beam

Strength and deflection

Figure 3 presents the shear force-deflection curves for the tested beams. All beams featured a quasi-linear shear force-deflection response up to peak shear force. The sudden drop in load at peak shear force is characteristic of brittle (shear) failure. The unstrengthened and strengthened beams in each series had a comparable stiffness up to about 50% of the unstrengthened shear force capacity. Upon further loading, the strengthened beams had a slightly stiffer response due to the presence of the DE/ETS GFRP bars, which resisted inclined crack opening and consequently controlled deflection. The maximum deflection at failure of the SS and LS strengthened beams increased by 39.8% (from 10.3 to 14.4 mm) and 121% (from 18.8 to 41.5 mm), respectively, compared with those of the unstrengthened beams.

The shear force capacity of the unstrengthened SS and LS beams was 75.5 and 149.5 kN, respectively. The corresponding shear stress at failure, calculated as the shear force at failure divided by the resultant of web width times effective depth, was 3.4 and 1.7 MPa, respectively. The shear force capacity of the strengthened SS and LS beams was 90.5 and 293.0 kN, respectively. The corresponding shear stress at failure was 4.0 and 3.3 MPa, respectively.

The SS and LS strengthened beams had shear strength enhancements of 15 kN (20%) and 143.5 kN (96%), respectively. The higher percentage enhancement in the shear strength of the LS strengthened beam is attributable to the higher effective depth of the LS beam, which provides better bond performance between the DE/ETS GFRP bars and the concrete.

Figure 4 shows the effect of beam size on shear strength. With the increase in effective depth from 300 to 600 mm, the unstrengthened beams had 50% reduction in shear stress at failure. The corresponding reduction for the strengthened beams was 18%. This result demonstrates that DE/ETS GFRP bars can significantly mitigate size effect.

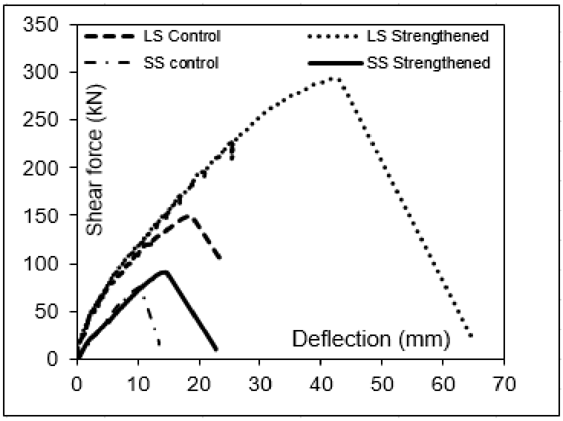

Figure 3: Shear force-deflection curves

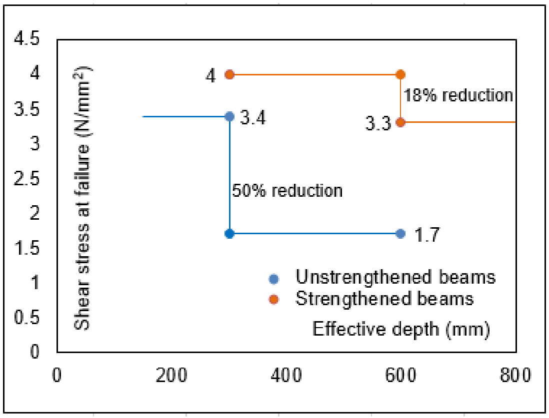

Figure 4: Effect of size on shear strength

Conclusions

This paper investigated size effect in geometrically similar unstrengthened as well as DE/ETS GFRP shear strengthened RC T-beams. The following conclusions are drawn:

- The DE/ETS GFRP bars enhanced the shear strength of small-scale and large-scale RC T-beams by 20% and 96%, respectively.
- The strengthened beams had slightly higher post-cracking stiffness than the unstrengthened beams.
- The reduction in shear stress at failure of the unstrengthened and strengthened beams was 50% and 18%, respectively, suggesting that DE/ETS bars significantly mitigated size effect in RC T-beams.

Acknowledgements

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