Mechanical Characterisation of GFRP Frame and Beam-to-Column Joints Including Steel Plate Fastened Connections of the top concrete cover with load automatically decreasing. It is obvious that beams with large concrete cover has higher drop in capacity and the second peak load level was lower. In finale face, spoiling of the web occurred and load drop very fast, while deformations increased, see Fig. 3. Beams with more dense stirrups can sustain more loading after first peak and they showed behaviour that is more ductile. In beam without stirrups in testing area and with low concrete cover second peak load was not registered. The beam failed immediately after first peak load level. Since all the beams were over-reinforced, tensile reinforcement did not yield.

From Fig. 3 it can be concluded that strains recorded by measuring devices LVDTs and DIC was the same. Ultimate compressive strain registered in the beams was in range 3.4-3.8‰. By using DIC, detailed strain fields of the observed compressive zones have been recorded, and DIC was able to measure strain after spoiling of the top concrete cover together with LVDTs. From the detailed strain field it can be seen localisation of the largest strains in areas prior to failure. It is also visible that strains distribution followed reinforcement detailing. In a beam with the largest compressive reinforcement, strains were deeper. The same holds for concrete cover, with larger cover, large strains are deeper and spalling of concrete follows reinforcement layout. In addition, it is visible that reinforcement layout influence the most crack development. Cracks were formed between stirrups. Having in mind that EC2 [6] has special rules for LWAC, which are reduction factors applied to regular design criteria, the results in this study indicate that EC2 underestimates LWAC. Recorded maximum strains in the tested beams were for 30-50 % larger than the standard allowed maximum strain (ε_{lcu2}=2.52‰), for this type of concrete.

In general, observed cracking in all the tested beams were very similar as could be expected in normal weight concrete beams, see Fig. 4.

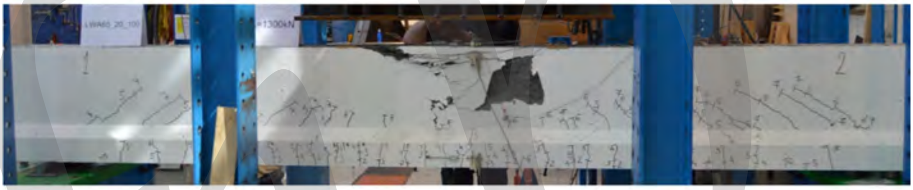

Fig. 4 Figure of the failure for beam 4 (LWAC65_20_100).

5 Conclusions

For all tested beams in this research cracking were similar. All the beams showed ductile behaviour since they were able to increase loading after formation of shear cracks. Cracking of the testing area depend on the test parameters varied in the experiment. Beams with dense stirrup spacing showed small, shallow cracks and spoiling were smallest. In beams where cover was deeper spoiling and cracking were larger. The beam containing the largest compressive reinforcement resisted the largest load. Beam without stirrups in testing area failed at first peak load level. Measuring devices were able to capture the ultimate compressive strain in LWAC beams.

In general, the characteristics of LWAC depend on the type of lightweight aggregate. EC2 does not differentiate between types of aggregate used in LWAC. From the experimental results, it can be seen that EC2 underestimates ultimate strain level with 30-50%. This study with LWAC indicates bending behaviour similar to NDC. From the experimental program, it can be concluded that by proper reinforcement detailing it is possible to achieve ductile response of lightweight concrete structures. The response in the tested beams were only a small reduction in load capacity after reaching a peak load, followed by an increased deformation. By being able to document a larger ultimate compressive strain in LWAC beams, an increased use of LWAC in structural applications are possible. Further investigations of LWAC as a structural material should therefore continued.

Acknowledgements

The work presented in this paper is part of an ongoing PhD study in the DACS project (Durable Advanced Concrete Solutions). The DACS partners are Kværner AS (project owner), Norwegian Research Council, Axion AS (Stalite), AF Gruppen Norge AS, Concrete Structures AS, Mapei AS, Multiconsult AS, NorBetong AS, Norcem AS, NPRA (Statens vegvesen), Norwegian University of Science and Technology (NTNU), SINTEF Byggforsk, Skanska Norge AS, Unicon AS and Veidekke Entreprenør AS. The first author would like to express her outmost gratitude to the supervisors and all the project partners for contributions and making this PhD study possible. In addition, special gratitude goes to master students Simon André Petersen, Henrik Nesje Johannesen, Jonas Andås Belayachi and Khaled Bastami for help during production and testing in this study.

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Strenghtening and repair

Behaviour of torsionally strengthened reinforced concrete beam-column joints with carbon fibre reinforced polymer sheets

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Abstract

This paper aims to consider a number of FRP strengthening schemes which have previously been utilised in simply supported beam tests and investigate their influence on exterior reinforced concrete beam-column joints. A literature review was performed to identify suitable beam strengthening configurations and to determine the potential effect of torsional moments on beam-column joints. Subsequently, two wrapping ratios and fibre orientation were examined in addition to unstrengthened control specimens. Tests results showed a significant reduction in the load-deformation capacity of unstrengthened members due to the applied torque. However, the joint capacities were improved by the carbon-fibre strengthening methods. The level of enhancements of the member capacities corresponds with wrapping degree, while failure mechanism, plastic hinge, joint cracking, and ductility index are varied with wrapping configurations. Moreover, this paper identified stresses escalation in the steel rebars with relation to the magnitude of beam torque and fibre arrangement.

1 Introduction

Structural members in a reinforced concrete structure are subjected to various types and magnitudes of loads and forces. Accordingly, it is crucial to ensure structural integrity between main members and provide robust load paths. These loads could be flexural, shear, axial and torsional forces. Flexural and shear forces govern the design of the structural members in buildings with symmetric layouts or concentric loadings. In contrast, the effect of spandrel beams, unequal spans or eccentric loadings, asymmetric building layouts and an alternating loading pattern could induce significant torque. As the loading alters in the three-dimensional system, torsional cracking could be promoted in the beam significantly at exterior joints. However, at the design stage, ACI 318-14 code [1] stipulates that compatible torsional forces can be neglected if they do not exceed the threshold value which is defined as 25% of the torsional cracking moment (T_{cr}). Likewise, the CEB-FIP Model Code [2] and Eurocode-2 [3] propose at the ultimate limit state that it is not required to consider torsion induced by compatibility. While to avoid excessive cracking, a minimum reinforcement should be incorporated by way of stirrups and longitudinal bars [2].

Torsional forces can considerably affect RC members by increasing the level of crack formation and altering structural behaviour to the brittle failure mode. Moreover, torsional forces affect the location of plastic hinges, the flexural strength and ductility in which could be substantially reduced [4]. It is, therefore, essential to recognise the mechanism and influences of torsional stresses to identify appropriate intervention strategies that can safely restore the structural integrity and functionality. The efficiency of Fibre Reinforced Polymers (FRP) External Reinforcement Systems (ERS) for shear and flexural strengthening have driven a number of researchers to explore this system for torsion [5] - [17]. However, most of the torsional strengthening schemes were carried out to strengthen beams subjected to either pure torque or under combined forces. Hence, several wrapping and strengthening configurations are presented in the next section of this paper.

2 Literature review and research significance

Very few studies have attempted to address the torsion effects on RC joint; most of the available studies investigated the influence of the eccentricity of the beam axis from the column axis [18]- [21]. Also, torsion in transverse beams and a slab restraining effect have been investigated where severe cracking and anchorage loss have been observed [22]- [23]. Recently, Elshafiey et al. [24] examined the effect of beam torsion on the joint area where the beam sections were detailed to ensure that they could resist the torsional loads. However, joints failures were observed due to the lack of joint stirrups and the high rigidity of the beams.

Distinctive torsional strengthening schemes have been experimentally and analytically explored and verified for RC beams [5] - [17]. These showed that a different levels of torsional capacity could be obtained with different fibre arrangements. Continuouss full-wrapping along the beam member is the most effective scheme ; the highest increment in ultimate strength is reported to be between 70% to 149% [6] - [7], [13]. A three sided U-wrap is the more practical configuration for strengthening a beam that is monolithically cast with a slab or a flanged beam. However, an 'unanchored' U-wrap was less effective than full-wrapping and the partial wrapping (FRP hoops) due to premature debonding [15]. The influence of horizontally oriented wrapping on the beam torsional strength is insignificant [5], [17]. The effectiveness of vertically oriented fibres has been widely confirmed in the literature [5], [7], [11], [12], [13], [25], [16]. Unidirectional Carbon fibres (CFRP) were the dominant fibre type that were employed for torsional strengthening as their efficiencies have been verified, while Ameli et al. [12] and Ghobarah et al. [5] have reported that Glass Fibre Reinforced Polymer (GFRP) wraps were less effective than CFRP. These strengthening configurations have enhanced the torsional capacity and cracking torsional moments in beams. However, the influence of torsional strengthening on the stress escalation in a joint area and the location of the plastic hinge have not been investigated yet. This is crucial, as strong beam-column joints are the key component to safely transfer forces from slabs and beams to columns as well as maintaining the preferable strong column – weak beam behaviour in dynamic design. Also, to date, there has been no study which has explored the effectiveness of FRP torsional strengthening schemes on the exterior beam-column joint subjected to a beam torsional moment. Therefore, this study aims to assess, experimentally the use of previously established CFRP torsional wrapping schemes for strengthening exterior beam-column joints.

3 Experimental programme

Fig. 1, left and right, shows a schematic test diagram and the test rig photo with R.C. exterior beam-column specimen, respectively. The beam-column joint consists of a beam (300 x 210 mm) and column (285 x 280 mm) which is hypothetically located at the 4th floor of a six storeys ordinary moment resisting frame. The joint aspect ratio is 1.05; a number of studies noted a decrease in the joint shear capacity with aspect ratio larger than 1.4 [26]- [27].

The members have been designed according to ACI 318-14 code [1]. The joint details correspond to ACI-ASCE 352 Committee (Type-1) [29]. Adequate anchorage (90° hooked) for beam rebars were provided to prevent anchorage failure at the joint; also no splices were used. The beam and column lengths of the exterior joint have been extended to beyond the contra-flexure points. Furthermore, alterations in live load have been considered between floors and spans such that the maximum induced beam torque is 2.24 kN.m which is close to the calculated threshold value (2.53 kN.m). Hence, no additional torsional reinforcement was needed in accordance with ACI 318-14 recommendations. A typical section detail and the layout of the exterior beam-column joint specimens are shown in Fig.2 (left).

3.1 Materials

The required compressive strength for concrete is 36 MPa which has been based according to ACI committee 214R [30]. A high strength Portland cement (C 52.5) with 5 mm maximum fine aggregate size and 10 mm maximum coarse aggregate size were used in the mix. High strength steel bars with nominal yielding strength of 510 MPa were used for reinforcing the specimens. Unidirectional carbon fibre reinforced fabrics (CFRP) were employed to strengthen the beam areas. The specifications of the un-impregnated CFRP fabric (coupon details) are as follows: thickness of 0.22 mm, fibre tensile strength of 3530 MPa, the tensile modulus of 230 GPa and 1.5% of ultimate strain.

3.2 Strengthening schemes with CFRP

This study considered full and partial strengthening systems to explore the influence of two different levels of strength and confinement of the beam area on the joint behaviour. Hence, two different externally bonded CFRP schemes were employed to strengthen the beam regions as shown in Fig.2

(right). These schemes consisted of either continuous full-wrapping or partial warping, with vertically oriented CFRP hoops.

FIB Bulletin 14 [31] recommendations were adopted to predict the enhancement level in the torsional capacity for each specimen at ULS (ultimate limit state). These recommendations are based on the space truss mechanism to evaluate FRP capacity; while the effective FRP strain (Eq.1) was modified according to the effective fibre ratio (Eq.2) and the thin-walled analogy [11]. The overall member's torsional capacities were determined by the superposition of both rebars and CFRP contributions, as given in Eq.3; a simple thin walled space truss analogy assuming 45° diagonal concrete struts was used to determine the torsional capacity of steel rebars [1].

$$\varepsilon_{ef} = 0.17 \left(\frac{Fc^{\frac{2}{3}}}{Ef\ \rho f}\right)^{0.3} \varepsilon_{fu} \quad (1)$$

$$\rho_f = \frac{4t_f\ b_f\ U_c}{3A_c\ S_f} \quad (2)$$

$$T_u = T_{u\ Steel} + T_{uFRP} \quad (3)$$

where ε_{ef}= effective FRP strain; Fc = concrete compressive strength in Mpa; Ef = FRP Young's modulus in GPa; ρ_f = effective FRP ratio; ε_{fu}= FRP ultimate strain; t_f = FRP thickness in mm; b_f = FRP strips width in mm; U_c = outer perimeter of the sections in mm; Ac = Sections' gross area mm2; Sf= spacing between FRP strips c/c in mm.

In addition to the specimens with CFRP reinforcement, two un-strengthened control specimens were tested in order to investigate and compare the influence of beam torque and the beam torsional configurations on the specimen's behaviour. All specimens were categorised into two groups; the control (group-i) and the strengthened specimens (group-ii), as given in Table 1. The first un-strengthened specimen (CS-F) was tested under flexural and shear load only, while the CS-FT specimen was subjected to torsion, flexural and shear loads. The outcomes of these tests were used as a baseline to address the effects of beam torque on the joints.

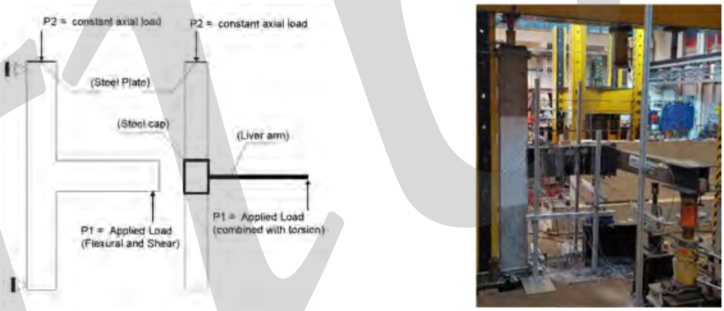

Fig. 1 A test schematic diagram (left), testing rig (right).

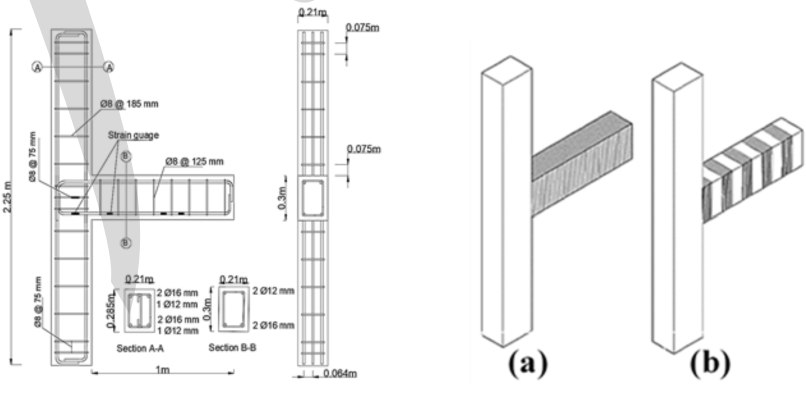

Fig. 2 Members layout and sections (left), strengthening schemes (right): full wrapping (a), strips wrapping- hoops (b).