QUEEN'S UNIVERSITY BELFAST

International Institute for FRP in Construction

FRPRCS-14, Belfast - June 2019

Shear Capacity of Carbon Fibre Textile Reinforced Concrete Slabs with Planar and C-Shaped Shear Reinforcement

Bielak, J.[1], Hegger, J.[1], Schmidt, M.[1]

[1] *Institute of Structural Concrete, RWTH Aachen University, 52074 Aachen, Germany*

Abstract

In contrast to design for bending, both engineers and researchers are still confronted with fundamental questions regarding shear design of carbon fibre reinforced concrete. While numerous applications already exist for slabs without shear reinforcement, there is still a need for research into the technical and economic application of components with shear reinforcement made of non-metallic textiles. The right shape of shear reinforcement is one important subject of discussion. On the one hand, the anchorage in the tension and compression zone must be effective. On the other hand, the manufacturability, e.g. regarding conflict points with the longitudinal reinforcement, must be ensured. At the Institute of Structural Concrete, RWTH Aachen University, an extensive test programme on slab segments with planar and c-shaped shear reinforcement was conducted. The results presented in this paper give insight into the effectivity of both types of shear reinforcement. Overall, there are clear parallels to the shear failure of concrete reinforced with steel or FRP-rebar.

Keywords: carbon reinforced concrete, textile reinforcement, TRC, shear, slabs, experiments

Corresponding author's email: jbielak@imb.rwth-aachen.de

1. Introduction

In recent years, the application of textile reinforced concrete (TRC) in new constructions gained momentum [1]. While reliable design models are available for bending, research on shear design of TRC is ongoing. One promising application of the non-corrosive material TRC is for thin slabs, e.g. as structural elements in bridges [2] or park decks [3], where a high chloride exposition occurs. There, conventional steel-reinforced slabs require additional protective coatings, whereas TRC can be driven or walked on directly without external polymeric coating. This may lead to cost-reduction in the construction and maintenance throughout the life cycle. For those applications, design models for shear with and without shear reinforcement are required. Especially in regions of concentrated loads, for example due to traffic or near supports, the use of distributed textile shear reinforcement may be necessary. In this paper, an experimental campaign on slab segments made of TRC is presented, which is a first step towards a better understanding of the load transfer and failure mechanisms for different TRC shear reinforcement types.

2. Materials and Methods

2.1 Concrete

A self-compacting concrete (d_{max} = 4 mm) specifically designed for the requirements of TRC was employed. The high compressive and tensile stress of the concrete allows to fully utilize the reinforcement's tensile and bond strength. The bending tensile strength was determined on prisms (40/40/160 mm) at the day of testing (age 13 to 30 days) with a mean value of 11.1 MPa and a coefficient of variation (COV) of 23.6%. The mean modulus of elasticity (of cylinders, d/h = 150/300 mm) was 42402 MPa (COV 4.7%). The mean compressive strength reached 122.5 MPa (COV 4.9%) for 150 mm cubes, 109.3 MPa (COV 5.1%) for cylinders, and 115.6 MPa (COV 5.2%) for the prism halves.

2.2 Reinforcement

The longitudinal reinforcement for the slab segments is made of epoxy-impregnated biaxial carbon fibre grids with a cross-sectional filament area of 95 mm²/m for each layer and a centre-to-centre spacing of 38 mm of the individual yarns. The modulus of elasticity and ultimate strength in longitudinal direction (0°, warp direction) are 244,835 MPa and 3221 MPa, respectively. Further details of the reinforcement characteristics are given in [4]. Two types of shear reinforcement were chosen for the experimental program. The first is planar (I-shaped), taken from the same grids as the longitudinal reinforcement. The second is a c-shaped pre-formed element with the same geometric properties as the longitudinal reinforcement and made from the same fibre and impregnation material. The warp yarns (0°) are aligned in longitudinal direction of the specimens, the weft yarn (90°) in vertical direction. For these c-elements, a different production technique is utilized by the manufacturer where the individual yarns – especially those in transversal direction - are not subjected to prestressing during hardening of the impregnation material. This leads to ~20-40 % reduced ultimate tensile stress and reduced modulus of elasticity, because the fibres are not aligned as parallel as in the planar grids.

2.3 Shear test setup and test program

The setup in this study was chosen in accordance with previous reference tests [4], but the longitudinal reinforcement ratio was increased to prevent bending failure due to the higher test loads. In total 48 slab segments with and 12 reference tests without shear reinforcement were tested in single-span three-point bending (Figure 1, left). The deflection at mid-span was measured with two linear-variable displacement transducers (LVDT). After failure, the crack pattern of each specimen was documented and the actual effective depth of each layer of reinforcement was measured for each specimen in a saw cut in or near the critical shear crack.

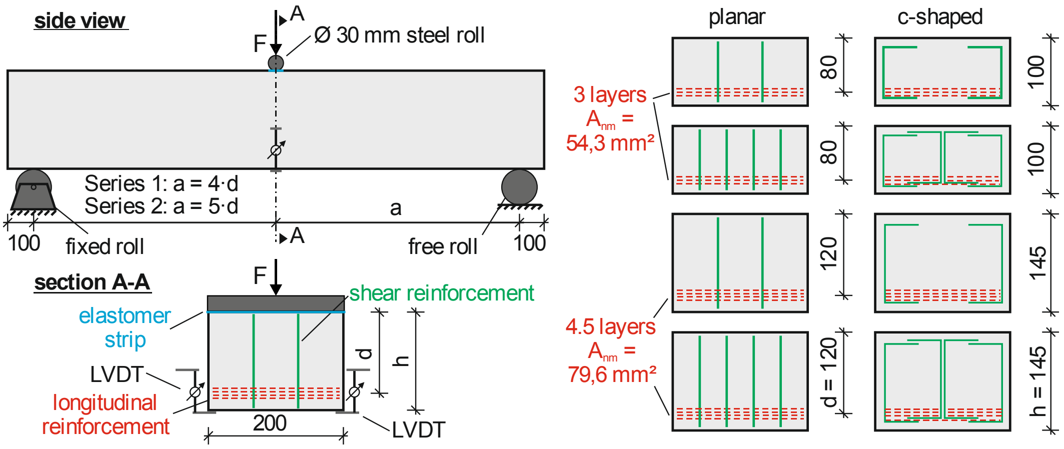

Figure 1: Test setup and specimen configuration of shear test campaign

The main variation parameters of the campaign were member height, shear slenderness *a*/*d* (ratio of load-to-support distance *a* and effective depth *d*), shear reinforcement ratio ρ and shear reinforcement type (planar or c-shaped). The shear slenderness was chosen to 4 and 5 to minimize the influence of direct strutting. The longitudinal reinforcement ratio is nearly the same for both member heights (≈0.34%). For each reinforcement configuration, member height and shear slenderness, three identical repetitions allowed for investigation of the range of scatter.

The proper anchorage is key to an effective utilization of the different shear reinforcement types. Here, the planar shear reinforcement projects in vertical direction through the longitudinal reinforcement almost to the lower concrete surface. This straight and simple anchorage in both the compression and tension chord is possible because of the same spacing of the grids in vertical and horizontal direction. In contrast, the more complex c-shaped elements are anchored with 90°-legs with a length of 50 mm. These elements embrace the longitudinal reinforcement layers in the lower reinforced specimens with 2 c's, much like stirrups in conventional steel reinforced members. However, for the higher reinforced slab segments with 4 c's, a mutual penetration of all longitudinal layers and shear reinforcement proved to be impossible due to production imperfections and the longitudinal yarns attached to the legs of the c-elements. Thus, the upper longitudinal reinforcement's weft yarns were cut at the intersection while the lowest was continuous (Figure 1, right). One alternative would be to systematically omit the longitudinal yarns in the legs of the c in the production process (prior to hardening). This method was utilized for production of the reinforcement cages of the bridges described in [5].

3. Results

All specimen failed in shear through constriction of the compression zone by the critical shear crack (shear compression failure). At failure, vertical cracks along the planar reinforcement occurred along the shear crack. As subsequent failure, for some specimen the c-shaped shear reinforcement failed in or near the bend while the concrete cover spalled. Generally, both reinforcement types lead to a similar load-deflection behaviour, as shown exemplarily in Figure 2 for a member height of 100 mm with a shear slenderness of a/d ≈ 5.

The slightly stiffer behaviour of the members with c-shaped reinforcement in saturated cracked stage IIb can be attributed to the additional longitudinal yarns attached to the 90°-legs of the shear reinforcement. The ultimate shear capacities are nearly the same, while the scatter for the identical repetitions is surprisingly low.

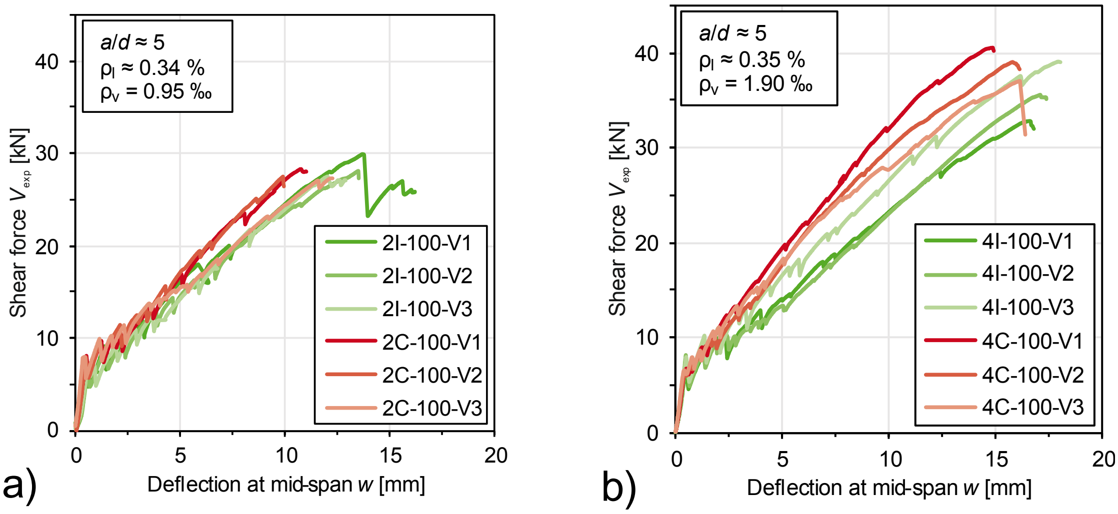

Figure 2: Comparison of load-deflection curves for I- and c-shaped shear reinforcement (a): two shear elements (ρ_v = 0.95 ‰), (b): four shear elements (ρ_v = 1.90 ‰)

Figure 3 a) shows exemplarily for the planar shear reinforcement that no difference in direct load transfer (influence of shear slenderness) between *a*/*d* = 4 to 5 can be identified. Note that for slab segments without shear reinforcement, this influence could be observed [4]. An increase of shear reinforcement leads to higher shear resistance (Figure 3 b)). The higher relative increase for the effective depth of 120 mm might be attributed to better anchorage of straight vertical yarns in the larger compression and tension chord.

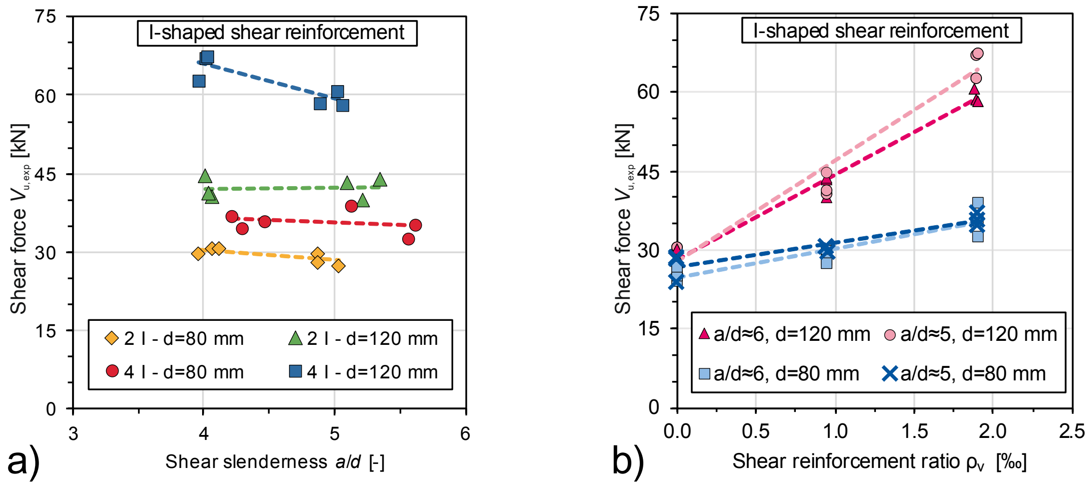

Figure 3: Influence of (a) shear slenderness and (b) reinforcement ratio on shear capacity

4. Discussion and Conclusions

The experimental results of this campaign indicate that planar and c-shaped elements are suitable as shear reinforcement for thin TRC slabs. A low scatter within each series of three identical specimens could be observed. The ultimate shear capacities for the same reinforcement ratios are equal and the load-deflection behaviour of the slab segments is similar, despite different anchorage and tensile properties for both types. One possible explanation for this observation is a compensation of the lower modulus of elasticity of c-shaped reinforcement by better anchorage. The lower ultimate stress of the c-elements was not decisive since shear compression failure occurred. For future evaluation with shear models, the influence of additional longitudinal reinforcement provided by the grid-structure of the I-elements and the legs of the c-elements needs to be considered.

5. References

[1] Hegger, J., Curbach, M., Stark, A. et al., 2018, "Innovative design concepts – Application of textile reinforced concrete to shell structures,". Structural Concrete, Vol. 19, 2018, Iss. 3, pp. 637-646.

[2] Rempel, S., Kulas, C., Will, N. et al., 2017, "Extremely Light and Slender Precast Pedestrian-Bridge Made Out of Textile-Reinforced Concrete (TRC)," In: Hordijk, D.A.; Luković, M. (eds.): "High Tech Concrete: Where Technology and Engineering Meet – Proceedings of the 2017 fib Symposium, held in Maastricht," The Netherlands, June 12-14, 2017. Springer International Publishing, Maastricht, 2017, pp. 2530-2537.

[3] Schumann, A., Michler, H., Schladitz, F. et al., 2018, "Parking slabs made of carbon reinforced concrete," Structural Concrete, Vol. 19 (2018), Iss. 3, pp. 647-655.

[4] Bielak, J., Adam, V., Hegger, J. et al., 2019, "Shear Capacity of Textile-Reinforced Concrete Slabs without Shear Reinforcement," Applied Sciences, Vol. 9, 2019, p. 1382.

[5] Bielak, J., Bergmann, S., Hegger, J., 2019, "Querkrafttragfähigkeit von Carbonbeton-Plattenbrücken mit C-förmiger Querkraftbewehrung," Beton- und Stahlbetonbau 90, 2019, Iss. 7, first published online, DOI: 10.1002/best.201900001

Acknowledgement

This work was supported by the German Federal Ministry of Education and Research (BMBF), project C³-V-I.14 (grant no. 03ZZ0380). This support is gratefully acknowledged.