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Published in:
FERRO-11

Publication date:
2015

Citation for published version (APA):
Verbruggen, S., Wastiels, J., Tysmans, T., De Sutter, S., & Wozniak, M. (2015). Evaluation of the FIB bulletin 14 design guideline for external TRC bending reinforcement. In W. Brameshuber (Ed.), *FERRO-11: Proceedings of the 11th international symposium on ferrocement and 3rd ICTRC international conderence on textile reinforced concrete* (pp. 473-481). RILEM.

EVALUATION OF THE FIB BULLETIN 14 DESIGN GUIDELINE FOR EXTERNAL TRC BENDING REINFORCEMENT

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Abstract: Due to their advantages related to fire safety and their relatively low cost, Textile Reinforced Cement (TRC) composites are emerging as external reinforcing materials for concrete structures. The current design guidelines for external reinforcement are mostly elaborated for the Carbon Fibre Reinforced Polymers (CFRP) material solutions. Considering the major differences between both the CFRP and TRC materials, the validity of these CFRP design guidelines for the TRC external reinforcement should be verified and eventually the design rules should be adapted. This paper contributes to the evaluation of the European FIB bulletin 14 design guideline for TRC by comparing 2.3-meter-span externally reinforced concrete beams designed according to the FIB bulletin 14 with experimental results from four point bending tests. The results show that the design guidelines underestimate the ultimate load by almost 20 % due to a difference in occurring failure mode (experimental: failure in composite action; predicted: failure by loss of composite action). These observations indicate that the FIB design guideline cannot be used to accurately predict the bending behaviour of a TRC-reinforced beam and thus that adapted calculation techniques are needed.

INTRODUCTION

Recent developments in Textile Reinforced Cements (TRC) have led to the possibility to use these materials in structural applications such as the external reinforcement of concrete structures. The use of a continuous fibre reinforcement allows a controlled fibre distribution and the possibility to align the fibres along the principal stress directions. All papers studying the use of these TRCs as external shear [1-6] and bending [7-11] reinforcement indicate the feasibility of the concept and the high potential of this technique. In comparison with the existing external reinforcing techniques like Carbon Fibre Reinforced Polymers (CFRP), the use of TRCs can present some advantages like the material fire resistance, and the lower material cost. However, most of the studies on TRCs are not able to reach the same loadbearing performance as the current CFRP solution. This is mostly the consequence of the use of open grid textile structures, resulting in a relatively low fibre volume fraction (typically 5 %). These open grids are used for manufacturing reasons, as the mortar can easily penetrate the fibre structure through the grid openings.

At the Vrije Universiteit Brussel (VUB) Inorganic Phosphate Cement (IPC) [12] (commercially available under the name Vubonite [13]) was developed. This is a cementitious material which is suitable to be used as a matrix material for standard E-glass fibre composites due to its neutral pH after hardening. IPC consists of a powder-liquid combination which hardens at room temperature and becomes a strong, durable, heat resisting and fire safe material. Its relatively small grain size (between 10 and 100 µm) enables the impregnation of dense fibre textiles up to high fibre volume fractions (up to 25 % [14]). As a result, a cementitious composite with high tensile (up to 60 MPa for IPC reinforced with randomly oriented glass fibre textiles) and compressive (80 MPa) capacities and which is heat- and fire resistant (highest European class A1), is created, what makes it appropriate for structural applications and thus also for external reinforcement of concrete structures. In previous studies the authors of this paper already indicated the possibilities of this high fibre volume fraction cementitious composite as an external bending reinforcement for concrete beams [15-17]. However, no appropriate design guidelines exist for external reinforcement made of IPC TRC, or any type of high fibre volume fraction TRC in general. Therefore this paper verifies the validity of the CFRP design guidelines for TRC external reinforcement. The applicability of the European FIB bulletin 14 design guideline [18] will be verified for IPC TRC as an external bending reinforcement for concrete beams.

DESIGN PRINCIPALS

In the recent decades several regional design codes and guidelines, such as the FIB bulletin 14 (Europe), ACI-guide (USA), JSCE-recommendation (Japan) and CSA-code (Canada) are published concerning the calculation of externally reinforced concrete structures. These design guidelines are mostly elaborated for the CFRP strengthening and repair technique. Generally the design of externally reinforced concrete structures is similar to the design of internally steel reinforced alternatives (Eurocode 2 [19]). However, special attention needs to be paid to the loss of composite action (and thus loss of connexion) between the external reinforcement and the concrete substrate, mainly due to the low tensile strength of the concrete material. Depending on different phenomena causing shear en tensile forces in the bond zone, the debonding can initiate at different places along the beam's length: the end anchorage, flexural or shear cracks or by end shear failure (Figure 1). The FIB bulletin 14 presents different design guidelines depending on the debonding location. Considering the complexity of these debonding phenomena and the wide variety of available calculation methods, the FIB bulletin 14 offers the user the choice between three significantly different calculation approaches for the debonding at the end anchorage and at flexural cracks.

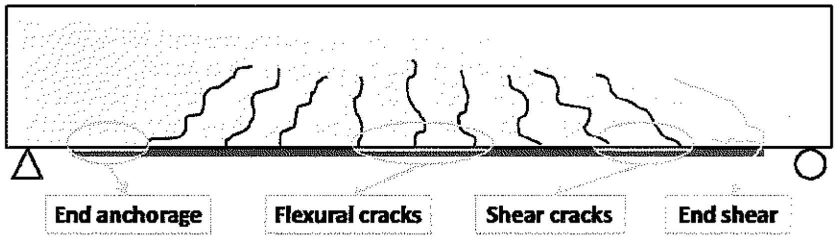

Figure 1: Depending on different phenomena causing shear en tensile forces in the bond zone, the debonding can initiate at different places along the beam's length.

The fact that the current design for debonding is based on experiments performed on the CFRP material and that there exist severe variances in the constituents of IPC TRC and CFRP composite materials, could lead to new failure types and mechanisms for the IPC TRC external reinforcement. Additionally, mayor differences exist in the materials tensile stress-strain behaviour as illustrated in Figure 2. Apart from a considerable difference in achievable tensile strength, a deviating overall evolution is obtained: the CFRP composite shows a linear stress-strain behaviour, while the IPC TRC exhibits three different stages, as illustrated in the upper left corner of Figure 2.

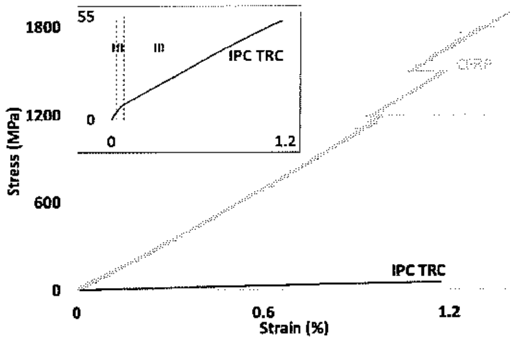

Figure 2: Considerable differences exist in the tensile stress-strain behaviour of CFRP and IPC TRC.

EXPERIMENTAL PROGRAM

Test set-up

Four point bending tests with third point load are performed on reinforced concrete beams with a span of 2.3 m (total length of 2.5 m), a height of 0.3 m and a width of 0.2 m. The loading is displacement controlled using a servo-hydraulic actuator with an initial displacement rate of 0.2 mm/min. After the cracking moment is clearly surpassed (load of 60 kN), the displacement rate is increased to 2 mm/min. Figure 3 illustrates the test set-up.

Three different beam types are tested. The first beam type is a reference reinforced concrete beam without any external reinforcement. The second type is a steel-reinforced concrete beam that is externally strengthened by gluing a strip made of IPC reinforced with 16 glass fibre mat layers (resulting in a nominal thickness of 8 mm). To simulate actual loading conditions a third beam type is tested where a steel-reinforced concrete is precracked before it is repaired with the same amount of externally bonded IPC TRC as for the second beam type. In both cases the external reinforcement is applied over the entire tensioned lower surface of the beam and thus continues over the supports. The IPC TRC is glued onto the concrete using a two-component epoxy glue (PC 5800/BL [23]). Before attaching the reinforcement to the beams, the concrete surface is pretreated to remove the laitance layer. All beams have an internal steel reinforcement that consists of two longitudinal bars with a diameter of 16 mm and stirrups with a diameter of 6 mm placed every 100 mm in the shear zones of the beams. This shear reinforcement is overdimensioned in order to cause a bending failure in the zone of constant moment. The reinforcement bars are welded to steel plates at the end of the beams; this eases the positioning and placing of the rebars and eliminates potential problems with the anchoring length of the reinforcement bars. The stirrups are welded to the longitudinal bars as well. Apart from Linear Variable Differential Transformers (LVDT), monitoring the vertical displacement of the beams, the Digital Image Correlation (DIC) measuring technique is applied. Two cameras follow the side edge of the beam and are able to measure a 0.4 m wide zone within the constant moment area at the centre of the beam. The analysis is done using the VIC3D-2009 software package from Correlated Solutions where a subset size of 21 pixels, a step size of 5 pixels and a strain window size of 11 are used.

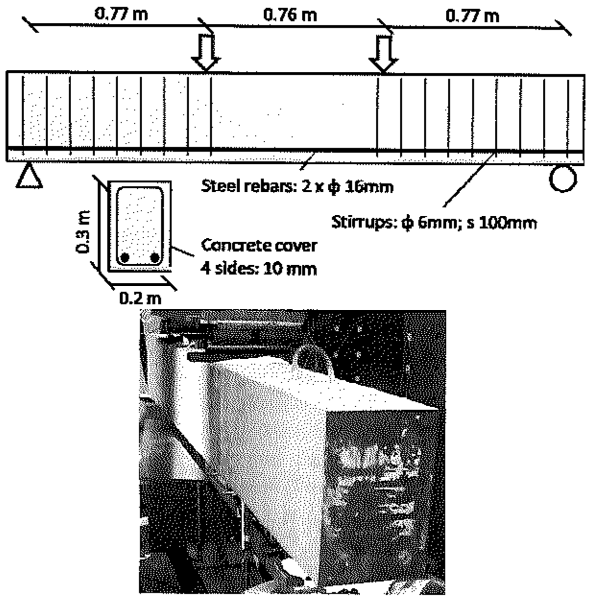

Figure 3: Three beam types are tested in a four point bending test with third point loading.

Materials

Concrete

The concrete has been mixed with the following mass proportions: 375 kg Portland cement CEM I, 32.5R, 210 kg water, 690 kg sand (0/2), 1125 kg gravel (6/14). This results in a compressive strength of 35.0 MPa, a Young modulus of 34.0 GPa and a modulus of rupture of 5.3 MPa. The values are the mean values of 8 specimens for the compressive strength and 3 for the modulus of rupture. These material characteristics are experimentally determined after 48 days. The compressive strength is the cylindrical strength calculated from tests performed on cubic shaped specimens, with sides of 150 mm. The young modulus can be calculated from the compressive strength. All calculations are based on [19, 24].

IPC TRC

The matrix material IPC is obtained by mixing Vubonite liquid component and high performance Vubonite powder in the mass proportion of 1/0.82. The IPC matrix is reinforced with 16 randomly in-plane oriented fibre textiles, being chopped strand mats Vetrotex M5, with a surface density of 300 g/m², resulting in a fibre volume fraction of 21 %. As such a tensile strength of 58.4 MPa, an ultimate strain of 1.2%, a Young modulus for the stage I of 12.5 GPa and a Young modulus for the stage III of 4.8 GPa are obtained. These characteristics are the mean values of 10 specimens.

Steel reinforcement

The traditional steel reinforcement consists of ribbed bars made of S500 steel, of which the material characteristics are not experimentally derived, so the standard values of 500 MPa for the yield stress and 200 GPa for the young modulus are assumed.

RESULTS AND DISCUSSION

Comparison analytical and experimental load-deflection behaviour

The load-deflection curves (Figure 4) show that both externally reinforced beams reach a 37.6 % higher ultimate load compared to the reference beam (209 kN versus 152 kN), indicating the additional capacity and thus the potential of the IPC TRC external bending reinforcement. The effectiveness of an IPC TRC patch as a repair reinforcement method is proven by the equal loadbearing capacity of the pre-cracked and non-pre-cracked beam.

The presence of pre-cracks only influences the stiffness of the initial linear uncracked zone of the curve and thus shows the independency of the history of the concrete structure. The pre-cracked beam exhibits a lower stiffness in this initial stage due to the cracks which are already present. The influence of pre-cracking a concrete beam prior to the application of IPC TRC external reinforcement is already discussed in detail in [15]. Just as in the previous studies using IPC TRC as an external reinforcement on small scale beams [15-17], the load at which the externally reinforced beams lose their high initial stiffness (50 kN) is 43 % higher than for the reference beam (35 kN). This stiffness retention results in an upwards shift of the second part of the curve, causing a lower deflection for the same applied load.

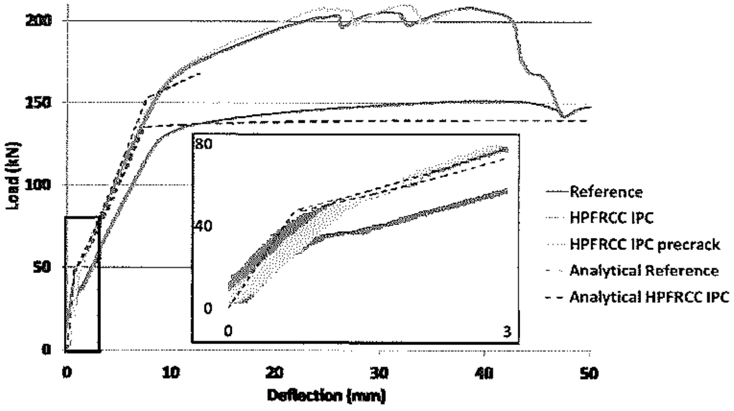

Figure 4: Comparison of the experimental load-deflection behaviour indicates the effectiveness of a TRC repair patch and confirms the retention of initial high stiffness.

The dotted lines in Figure 4 represent the analytical predictions of the load-deflection behaviour, based on the integration of the curvature [18, 25]. Contrarily to the previous observations [15-17], the load at which the high initial stiffness is lost for the externally reinforced beams is quite close to the calculated value of 47.7 kN. Considering the fact that the reference beam is not capable of reaching its predicted cracking load of 46.7 kN, this deviating observation is rather attributed to an overestimation of the tensile strength of the concrete. Besides the experimental cracking moment, also the post-cracking stiffness of the externally reinforced beams is higher than the one of the non-externally-reinforced reference beam, which is caused by the presence of a greater total amount of reinforcement and thus stiffness hereof. The stiffnesses and their respective increase are well predicted by the analytical calculations.

Comparison analytical and experimental failure behaviour

As predicted by the analytical model, the reference beam fails by steel yielding and concrete crushing at a load of 152 kN (analytical: 140 kN). The application of IPC TRC reinforcement over the entire bottom surface results in a failure load of 209 kN. At this ultimate load the externally reinforced beams exhibit several failure modes: steel yielding and concrete crushing, debonding at flexural cracks and debonding at the end anchorage. All these failure modes are indicated in Figure 5.

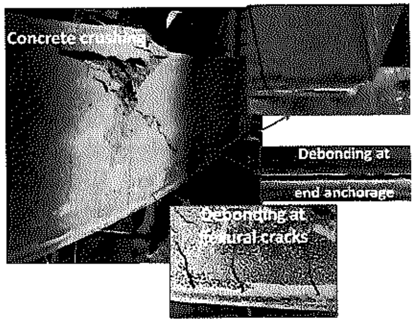

Figure 5: At the ultimate load several failure modes are present for the IPC TRC-reinforced RC beams.

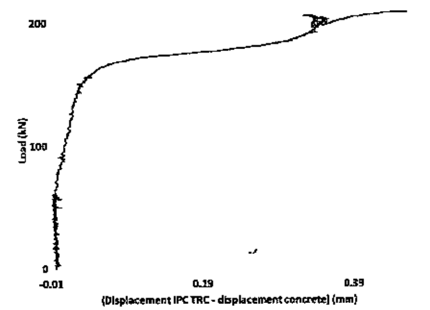

Figure 6: The difference in vertical displacement suddenly increases at 165 kN, but debonding already starts at 80 kN.

As long as the IPC TRC is bonded to the concrete, the vertical displacement of the concrete substrate and the external reinforcement are identical, so the difference between both is close to zero. From the moment debonding starts the IPC TRC will have a larger downward displacement and thus the mutual difference will increase. DIC measurements on these beams (Figure 6) indicate that the first difference in vertical displacement between the concrete and the IPC TRC is noticed at a load of about 80 kN, and thus that debonding already starts at this load. However this difference remains limited up to a load of 165 kN, introducing the final failure.

The analytical calculations following the FIB bulletin 14 predict a composite failure at the load of 208.9 kN determined by tensile failure of the IPC TRC. Approaches 1 and 2 of the FIB bulletin 14 predict debonding at flexural cracks at a load of 179.3 kN and 167.9 kN respectively. No debonding at the end anchorage is predicted. The debonding at shear cracks, predicted at a load of 197.6 kN, is not taken into account, considering the overdimensioned shear reinforcement. The observed failure load of 208.6 kN corresponds really close to the predicted composite failure load (208.9 kN), but exceeds the analytical predicted debonding load by 20 %. The predicted debonding value corresponds rather to the sudden differential increase in vertical displacement between the concrete and the IPC TRC, although it does not lead to beam failure.

One of the causes of this underestimation of the analytical force might be the continuation of the external reinforcement over the supports in the experiment, whereas the FIB bulletin 14 is rather intended for the strengthening and repair scenario, where the external reinforcement stops at a certain distance from the supports. Additionally, the FIB bulletin 14 corresponds to a safe and conservative design, where an underestimation is strongly preferred over an overestimation. However, these results indicate the significant difference between the design for CFRP strengthening and external bending reinforcement made of IPC TRC, or any other high fibre volume fraction TRC in general. This demonstrates the need for adapted design guidelines for external TRC reinforcement.

CONCLUSIONS

Four point bending tests on 2.3-meter-span externally TRC reinforced concrete beams indicate an increase in ultimate load and in load at which the initial high stiffness is lost compared to the reference non-externally reinforced concrete beam. Additionally, the independency of this external reinforcing technique on the beam history is shown, as the pre-cracked and non-pre-cracked alternatives exhibit a similar load-deflection behaviour. Comparison of the experimental results with their analytical predictions according to the European FIB bulletin 14 design guideline, yields a correct prediction of the beam stiffness and the stiffness increase with respect to the reference beam. Nevertheless, the FIB bulletin 14 underestimates of the ultimate load by almost 20 %, partially due to a continuation of the reinforcement over the supports and a conservative design philosophy. Still, this underestimation indicates the need for adapted calculation techniques.

ACKNOWLEDGMENTS

Research partially funded by a scholarship of the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen) (first author), by the Brussels Capital Region through the Innoviris Strategic Platform Brussels Retrofit XL (first and fourth author) and by Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO) (fifth author). The authors gratefully acknowledge the cooperation with the company TRADECC, trough the delivery of the epoxy glue.

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FERRO-11 – 11th International Symposium on Ferrocement and 3rd ICTRC - International Conference on Textile Reinforced Concrete, 07 – 10 June 2015, Aachen, Germany

Edited by Wolfgang Brameshuber

RILEM Proceedings PRO 98
ISBN: 978-2-35158-152-0
e-ISBN: 978-2-35158-153-7
2015 Edition

Ferrocement and textile reinforced concrete deal with similar items. Therefore the conference combines FERRO-11 and 3rd ICTRC in 2015. FERRO11 is part of a continuing series of symposia started in 1979 with a special focus on the research, development and applications of ferrocement and thin reinforced cementitious composites. In 2006, the First International Conference on Textile Reinforced Concrete was held in Aachen. In the past both conferences combined presentations on thin fiber or steel mesh reinforced concrete members with items dealing with textile reinforced concrete. The Institute of Building Materials Research of RWTH Aachen University (ibac) is one of the most important research institutes in Germany. Young as well as experienced scientists and industry investigators came together and discuss new developments during the Ferrocement Symposium and the 3rd ICTRC. Specialists in the two fields will share their knowledge and experience offering avenues for unified treatment. All aspects of ferrocement and textile reinforced concrete, including the reinforcement properties (metallic or non-metallic), filament properties, its bond to the matrix, new developments concerning the yarns, innovative textiles, further developments of the matrices including short fibre concretes, mechanical properties of the composite material, the load bearing behaviour of the elements and the applications up to the micro-/macro-mechanical modelling are presented and discussed in this proceedings of the conference in 2015.

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