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Redistribution of Bending Moment in Continuous Concrete Beams Reinforced with Glass Fibre Reinforced Polymer

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Abstract: The aim of this paper is to investigate the behaviour of concrete continuous beams with domestic GFRP reinforcement. In addition authors focused on the moment redistribution effect in GFRP-reinforced concrete continuous beams. Three beams with different GFRP reinforcement configuration were examined in this paper and compared to the steel-reinforced concrete continuous beam. Concrete continuous beams were 3800 mm long with two uneven spans. One span was 2300 mm long; the other span was 1500 mm long. The cross section of the beams was 130 mm wide and 180 mm high. Point load, deflection and all support reactions were monitored during the experimental program. Load-deflection diagrams of the GFRP-reinforced concrete continuous beams were bi-linear as GFRP rebars had no yield point and no plastic plateau. It was verified experimentally that GFRP-reinforced concrete continuous beam with reinforcement ratio 0.24, 0.43 and 0.67 is able to redistribute 32 %, 28 % and 33 % of moments, respectively. Steel-reinforced concrete beam with reinforcement ratio 0.43 was able to redistribute 52 % of moments.

Keywords: Concrete; Continuous beam; Flexural capacity; GFRP reinforcement; Moment redistribution

1. Introduction

Concrete is by nature a continuous material and its combination with ductile steel is well known for decades. This combination, among other functions, ensures that enormous deflections and wide cracks form prior to the collapse of the structure. It also ensures that internal forces will be at least partially redistributed. Internal force redistribution effect is questionable when brittle FRP reinforcement is used in structural concrete. For this reason a wider experimental database is necessary to better understand the behaviour of GFRP-reinforced concrete continuous beams.

Strengths and weaknesses of FRP reinforcement are well pronounced. Strengths can be found mainly in durability, strength-to-weight ratio and non-magnetism. The other side of the coin refers mainly to initial costs, brittleness and lack of bendability [3]. Experimental work on GFRP-reinforced continuous two span girder was conducted by El-Mogy et al. [5]. It was verified experimentally that GFRP continuous beam with compression failure is able to redistribute 23% of moments.

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Later on, El-Mogy et al. [4] presented experimental results of continuous beams reinforced with GFRP and CFRP bars. The authors reported that both FRP-reinforced concrete beams were able to redistribute the connecting moment over the intermediate support. Theoretical study was carried out by Gravina and Smith [6] concluding significant influence of bond-slip law of FRP and surrounding concrete on moment distribution effect in beams. The authors developed deformation model to predict moment distribution, crack width and crack spacing.

2. Experimental program

Three GFRP-reinforced continuous beams were studied in this paper. Each beam had a different reinforcement configuration. Reinforcement configuration for the each beam can be seen in Table 1. Beams are further marked as GFRP6, GFRP8 and GFRP10. GFRP reinforcement was provided by the local manufacturer. Rebars were wrapped and sand coated. Stress strain diagram of the domestic GFRP reinforcing bars was linear elastic up to the brittle rupture of the rebar.

Table 1. Reinforcement configurations of the tested beams

Beam	Top / Bottom	reinforcement	Bal.rft. ratio [%]
	Bars [mm]	Rft. ratio [%]	
GFRP6	2 No. 6	0.24	
GFRP8	2 No. 8	0.43	0.40 [1] 0.52 [7]
GFRP10	2 No. 10	0.67	
Steel8	2 No. 8 B500A	0.43	2.6 [2]

One beam was reinforced with four steel rebars with diameter 8 mm. Beam is further marked as Steel8. Steel with low ductility B500A ($\varepsilon_u \geq 2.5$ %) was used for steel reinforced beam. Concrete C30/37, which is frequently used as a structural concrete in the Czech Republic, was used to construct all beams. Mechanical properties of concrete and GFRP rebars used during the research were determined before the loading tests were performed (Table 2, Table 3).

Table 2. Mechanical properties of the concrete

Mechanical property	Specimen	Average value
Compressive strength	Cube 150 mm	42.8 MPa
Elastic modulus	Cylinder Ø=150 mm, h=300 mm	35.7 GPa
Modulus of rupture	Prism 100x100x400 mm	4.7 MPa

Table 3. Mechanical properties of the GFRP rebar

Mechanical property	Average value
Tensile strength	750 MPa
Elastic modulus	42.1 GPa

Mid-support reaction was located non-symmetrically with respect to the beam centre in order to eliminate shear forces and to approach highest possible ratio between sagging moment at the cross section *x* and hogging moment at the cross section *B*. Moreover steel stirrups were used to avoid shear failure. Figure 1 shows proposed solution with reinforcement layout. Reinforcement ratio along the lower and upper side of the cross section remained unchanged within each type of beam. Clear cover of longitudinal rebars was 20 mm in all beams.

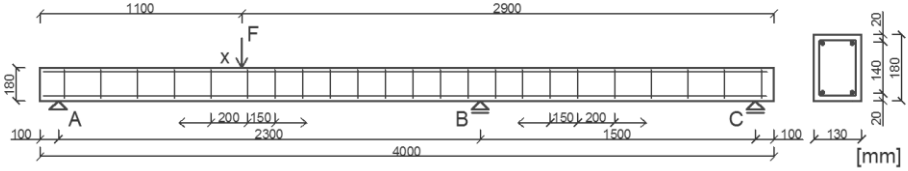

Fig. 1. Continuous beam reinforcement layout

3. Test results and discussion

Quasi-static loading was controlled by monotonic deflection increments up to the failure of the beam. Support reactions, applied point load and deflection under the applied point load were measured continuously with 5 Hz frequency (Figure 2). Load-deflection diagrams of GFRP-reinforced concrete beams were bilinear. First part so called un-cracked elastic was typical for small increments of deflection within rising load. The second linear part is called cracked-elastic and it was expected that the tensile stress was carried solely by the reinforcement (Figure 3). Because the GFRP stress-strain characteristics were entirely linear-elastic the second part of the load-deflection diagram was also liner-elastic.

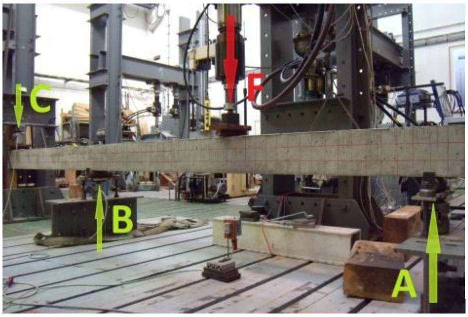

Fig. 2. Experimental program

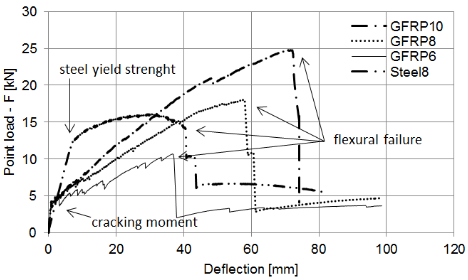

Fig. 3. Load-deflection diagram

Experimentally recorded outcomes from the support reactions can be seen in Figures 4, 5, 6 and 7. Each experimental outcome was compared with its own theoretical (elastic) development. Moment redistribution in GFRP-reinforced beams was formed only by the elastic redistribution as GFRP had no yield point. Elastic redistribution was influenced by cracking of the concrete as tension stiffening caused the flexural stiffness to vary with the applied load [8]. Plastic redistribution occurred when steel yield strength was reached, which is shown in the Figure 7.

Theoretical (elastic) percentage of the support reactions A, B and C was determined to be 46 %, 70.3 % and -16.3 %, respectively. Experimentally measured percentage of the support reactions at the level of the ultimate flexural capacity is tabulated in Table 4.

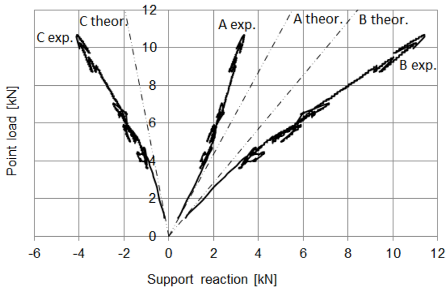

Fig. 4. Load-reaction diagram
GFRP rft ratio 0.24%

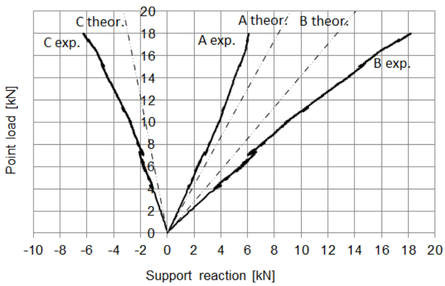

Fig. 5. Load-reaction diagram
GFRP rft ratio 0.43%

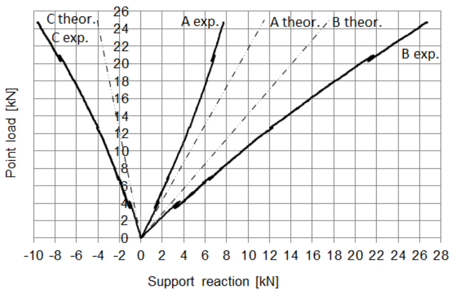

Fig. 6. Load-reaction diagram
GFRP rft ratio 0.67%

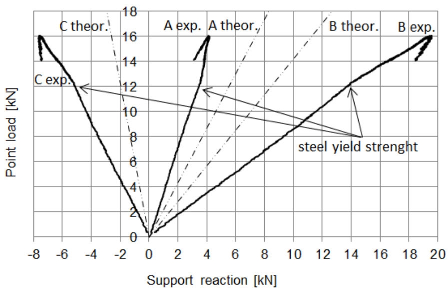

Fig. 7. Load-reaction diagram
Steel B500A rft ratio 0.43%

Table 4. Percentage of the support reactions at the level of the ultimate flexural capacity

	F [%]	A/F [%]	B/F [%]	C/F [%]
Elastic theory		46.0	70.3	-16.3
GFRP6		31.0	108.0	-39.0
GFRP8	100	33.3	102.3	-35.6
GFRP10		31.1	107.5	-38.6
Steel8		21.9	131.2	-53.1

Ratio of the redistributed to theoretical (elastic) moment at the level of the ultimate flexural capacity was determined to be 0.32, 0.28 and 0.33 for beam GFRP6, GFRP8 and GFRP10 where reinforcement ratio was 0.24, 0.43 and 0.67, respectively. Along with this outcome is evident that reinforcement ratio doesn´t play any significant role in moment redistribution effect.

4. Conclusions

Based on the executed experimental work and its outcomes in this particular study one may conclude the following:

- GFRP-reinforced concrete continuous beams behaved bi-linearly as GFRP rebars had no yield point and no plastic plateau.
- Only elastic redistribution of moments was observed in the GFRP-reinforced concrete continuous beams as the behaviour of the GFRP rebars was entirely linear elastic.
- GFRP-reinforced concrete continuous beams with reinforcement ratio 0.24, 0.43 and 0.67 were able to redistribute 32%, 28% and 33% of moments, respectively.
- Differences in reinforcement ratios of GFRP-reinforced concrete continuous beams did not prove any significant influence on total redistribution of moments.
- Both elastic and plastic redistribution of moments was observed at the steel-reinforced concrete continuous beam.
- Steel-reinforced concrete continuous beam was able to redistribute 52 % of moments, although steel with low ductility was used. This is 21% more than all GFRP reinforced concrete continuous beams in average.

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