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Push-out tests and evaluation of FRP perfobond rib shear connectors performance

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Abstract. The behavioural characteristics of FRP (fibre-reinforced polymer) perfobond rib shear connector was examined through push-out tests in order to verify the applicability for pedestrian bridge structure. The aim of this study is to determine interaction between high performance concrete slab and handmade FRP plate which represent web of the composite beam. Combination of these modern materials leads to structural system with both great load bearing capacity and also sufficient flexural stiffness of the composite element. Openings cut into the GFRP plate at a variable spacing allow GFRP reinforcement bars to be inserted to act as shear studs. Hand lay-up process can increase suitable properties of FRP for connection by perfobond rib shear connectors. In this study, three push-out tests on fiber-reinforced polymer were performed to investigate their shear behaviour. The results of the push-out tests on FRP perfobond rib shear connector indicates great promise for application in full scale structures.

1. Introduction

Bridges play a central role as an essential component of the infrastructures network as they do not only cover a large investment volume but also guarantee the smooth transport of goods and passengers. Compared to building, bridges are especially long living structures with scheduled service life of at least 100 years [1]. Most bridges suffer from inadequate maintenance and therefore lot of them must be repaired more times during their life cycle than it is necessary. Some of them end up being unrepairable and must be removed before their planned service life. Clients start to demand sustainable structures which can survive the whole life cycle without any crucial defects and related high maintenance costs.

Although the traditional material for this purpose is steel, the maintenance expenses are forcing the bridge operators to look for more durable and maintenance free solutions. The main goal is to replace steel elements that require service and coating, by more durable FRP systems. The advantages are especially high durability and no additional expenses.

1.1. Performed research on composite connection

One of the first research of composite FRP-concrete beam was carried out by Descovic [2]. Beam specimens composed of a rectangular FRP tube in the tensile region and plain concrete in the compression zone. In their work shear connectors between upper flange and concrete slab was provided by applying epoxy resin before pouring the concrete. This solution was not sufficient, because the beam failed suddenly by debonding of concrete slab. As a conclusion of this experimental study there was a demand for more robust shear connectors.

Next study was focused on feasibility of composite connection by steel bolts [3]. This connection system showed some level of ductility, but the initial stiffness was very low in comparison with the epoxy adhesive joint.

Cho performed tests on pultrude square hollow sections FRP tube connected by concrete wedge and coarse sand coating [4]. Connection by coarse sand coating resisted higher maximum load, but the failure was brittle. The advantage of the connection by concrete wedge was some level of ductility. In the fatigue flexural tests two variants of connections were tested. Tests of connection by coarse sand coating and mixed shear connection system (coarse sand coating together with concrete wedge) were performed. Coarse sand coating can resist fatigue load only at low level loading. The mixed shear system performed the remarkable fatigue resistance for identical fatigue loading.

To obtain the influence of wedge diameter and spacing they performed additional pull-out tests of the FRP pultrude plates embedded in concrete block [5]. Pultrude profiles were lubricated to exclude the bonding effect. From the extensive research the discrete spring model was derived and proposed for the concrete dowel action including post-failure frictional effects, considering the diameter of the hole and spacing between them as parameters. The resistance induced by concrete dowel action increase practically linearly to the area of the rib hole. The number of rib holes did not increase the resistance linearly due to imperfect reallocation of load after occurrence of failure caused by low stiffness of FRP.

Pultrude profiles are reinforced by fibers mostly in the longitudinal direction which leads into very low transverse strength. In FRP made by hand lay-up process the amount of fibers and their direction can be adjusted in order to increase suitable properties. This paper focused on the development of composite FRP-HPC beam, which consists of pultrude lower flange, hand lay-up FRP webs and high performance concrete slab. The modulus of elasticity is low, for common profiles between 17 – 30 GPa which implies that the serviceability limit state is much more important here, than in other usual materials, especially due to deflection requirements and local failures in connections. The disadvantage of low modulus of elasticity is compensated by the use of concrete part in the composite cross-section.

2. Cross-section of proposed beam

For this study we propose following composite cross-section (see Figure 1 below). Composite box girder using trapezoidal FRP box made by hand lay-up process. FRP box consist of glass fibers in the whole section and additional carbon fibers in the bottom flange. Webs are embedded to the HPC slab and form the composite action.

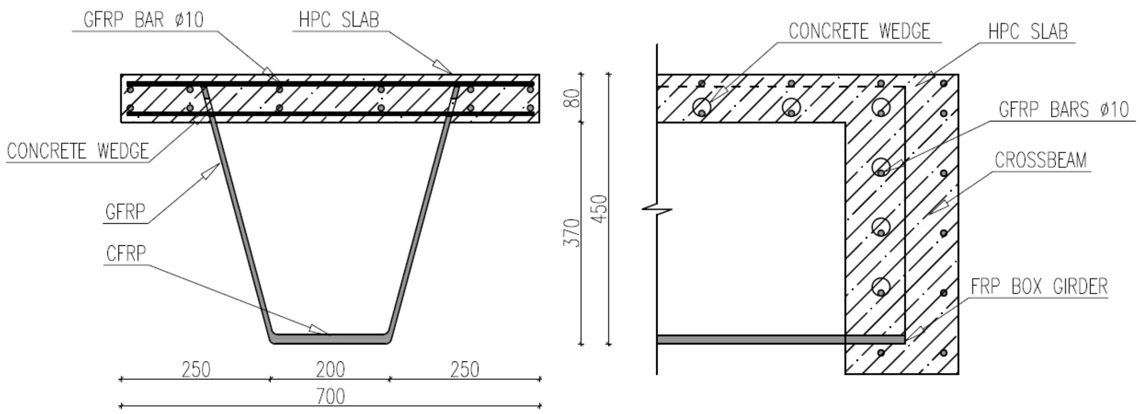

Figure 1. Proposed composite FRP-HPC cross-section.

Concrete is used as the top layer due to its high compressive strength. The use of HPC (high performance concrete) should limit the initiation and development of cracks. HPC has significant role in aggressive environment to ensure high durability. Hand lay-up FRP plates are used as webs due to their good properties in transverse direction. The second reason for this choice is that the high pultrude I profiles are still not available in supply of manufacturers.

3. Setup of the push out tests

Three push-out tests were performed in order to study the behavior of composite system and to compare the influence of diameter of holes and their spacing. The shear performance of rib shear connectors was examined using the 40 a 50 mm diameter with spacing of 250 and 300 mm as it is shown in Table 1. The specimen is illustrated in Figure 2. The load is transmitted by steel fixture to the FRP plates.

FRP plates with dimensions 580 x 540 mm were connected to steel fixture by 16 bolts of diameter 30 mm. In order to minimize the effect of slip between steel fixture and FRP plates the holes were drilled with the same diameters as bolts. Holes with 50 mm or 40 mm diameter were drilled into each side of the plate. After connection of the FRP plate to the fixture, GFRP bars were installed and fixed in the position by steel wire. On the bottom side of the FRP plates foam blocks with thickness of 30 mm were inserted to eliminate the effect of supporting the frontal side of the FRP plate.

Specimen was placed into the formwork and the concrete was poured to the form and vibrated on the shaking table. The concrete was cured indoors for 28 days.

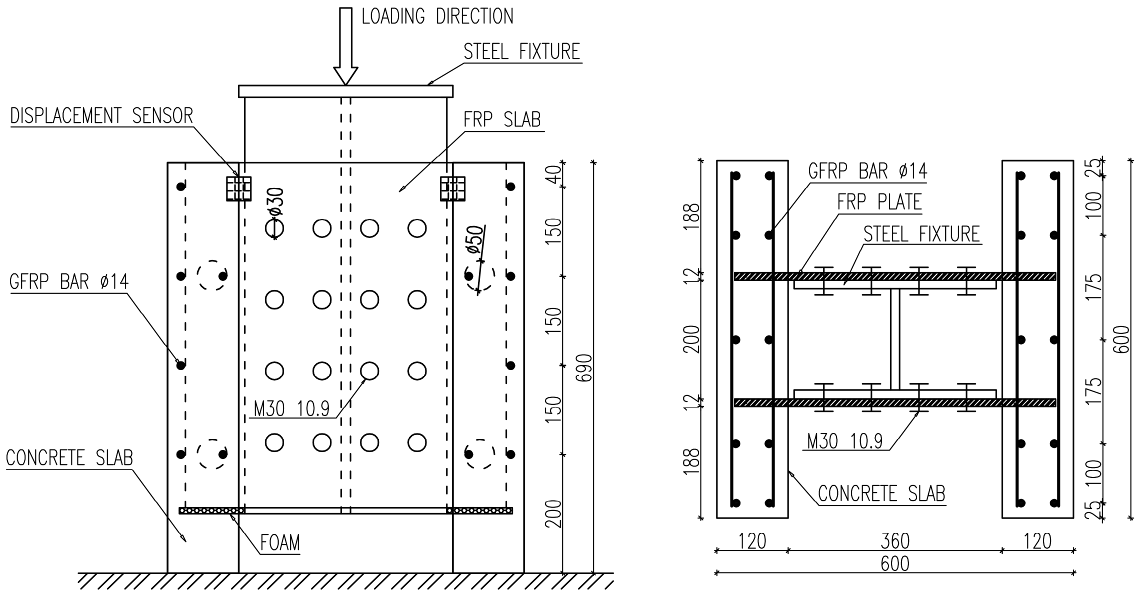

Figure 2. Shape of push out test specimen S1.

Table 1. Parameters of the push out test specimens.

	Diameter of rib hole (*mm*)	Number of rib holes (*mm*)	Spacing of rib holes (*mm*)	Thickness of the slab (*mm*)
S1	50	2	300	120
S2	50	2	250	120
S3	40	2	250	110

4. Material specifications

4.1. Concrete

In order to obtain concrete strength class C70/85 for the test specimen, the concrete was mixed and casted in a laboratory. The properties of concrete were determined by six cube tests and three tensile bending strength tests at the time of push out testing. The average compressive strength and the tensile strength were 91.7 MPa and 6.8 MPa, respectively.

4.2. GFRP plates

The handmade 12 mm thick FRP plates were supplied by Tatragrate, Slovak republic. Tensile characterisation of the material was carried out in accordance with ASTM D 3039. The strip specimens were cut out from the FRP plate used in push-out specimen. From the strip specimens the maximum failure stress and stiffness of the material were determined. The material properties are the same in longitudinal and transverse direction due to used textile reinforcement. An average tensile strength is 120 MPa and tensile modulus 8.5 GPa. To obtain the tensile modulus extensometer Epsilon 3542 was used.

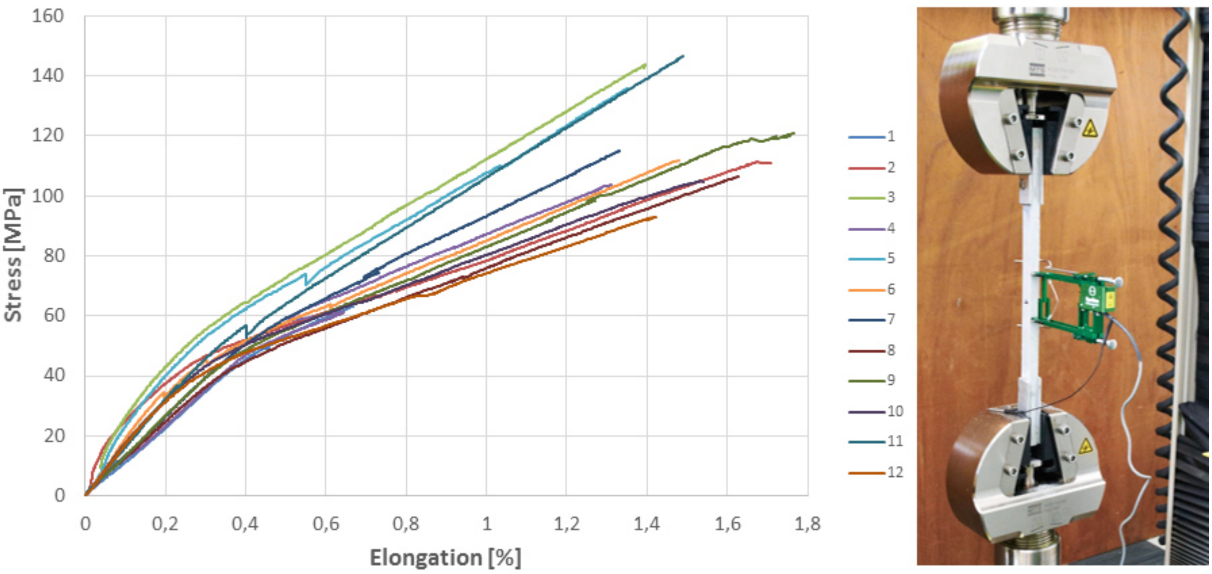

Figure 3. Stress-elongation curve of tensile test specimens and view of the test.

4.3. GFRP bars

GFRP pultruded bars of 14 mm diameter, consist of E-glass fibers with carbon fibers in the middle of the cross section, were supplied by Prefa kompozity, Czech Republic, and were used as shear connectors in this study. These bars with sand coating are commercially available as reinforcement for concrete structures. Tensile tests were provided by the producer according to ACI 440.3R-04. Bars had average tensile strength, modulus and ultimate strain of 1050 MPa, 67 GPa and 2.14 %, respectively.

5. Experimental results

Tests were performed using a hydraulic jack and loading was applied through displacement control at speed of 0.2 mm/min. Four displacement sensors were installed at each composition of FRP plate and concrete slab to measure the relative slip. According to EN 1994-1-1 the specimens were loaded 25x till 40% of the estimated maximum force and then loaded to the failure.

The maximum force 1000 kN of the jack was reached without failure. The curve S1_1 shows that loading. The following specimens were tested on hydraulic jack with maximum loading force of 2000 kN. Figure 4 shows the comparison of load-relative slip curves of three specimens. In the second loading case of first specimen the stiffness was lower due to debonding between FRP plate and concrete slab during the first loading.

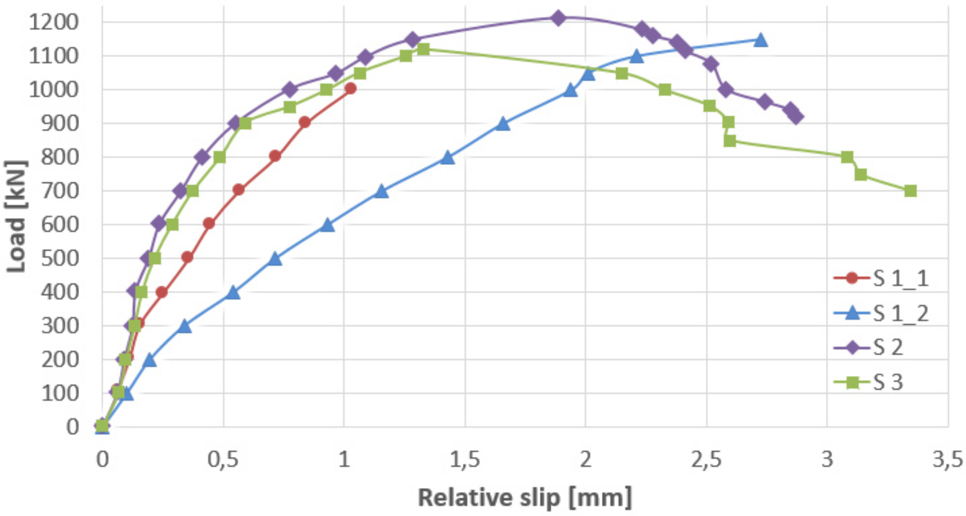

Figure 4. Load-relative slip curve of push out test specimens and view of the test.

Table 2. Summary of load and displacement of push out test.

	Diameter of rib hole (*mm*)	Number of rib holes (*mm*)	Spacing of rib holes (*mm*)	Thickness of the slab (*mm*)	Ultimate load (*kN*)	Displacement at ultimate load (*mm*)
S1	50	2	300	120	1150	2.37
S2	50	2	250	120	1214	2.78
S3	40	2	250	110	1119	3.34

The experiment demonstrated that there were no significant differences between the three specimens. As can be seen in Table 2 the ultimate force was between 1119 – 1214 kN with a maximum difference of a 8.5 %. Figure 4 shows that all three specimens had a high initial stiffness of 2.43 x10^{-6} kN/m. Near the load 1000 kN the loud cracking of glass fibers was heard. When the shear resistance was reached, the shear crack developed from the upper rib hole in slope of 45 degrees. When the load gradually dropped by 20%, next shear crack appeared.

Figure 5. Shear cracks of the push out test specimen.

To explore the failure of the composition, specimens were cut in longitudinal direction of the web. Figure 6 shows the failure modes of the specimen S3. The upper rib hole failed by shear crack combined with tensile crack. The bottom rib hole failed by crushed concrete wedge and delamination of the FRP web.

Figure 6. View of the failure of the composite connectors.

Before the composite concrete slab was casted, on the FRP webs were installed strain gauges, 12 pieces on each web. The distribution of strain gauges on the web is apparent on the Fig. 7.In the vicinity of each corner wedge were used 3 strain gauges: 1 in horizontal direction, one in vertical direction and 1 in 45 degrees inclination along expected shear crack. Strain gauges HBM 1-LD20-6/120 with high strain were used on the specimens.

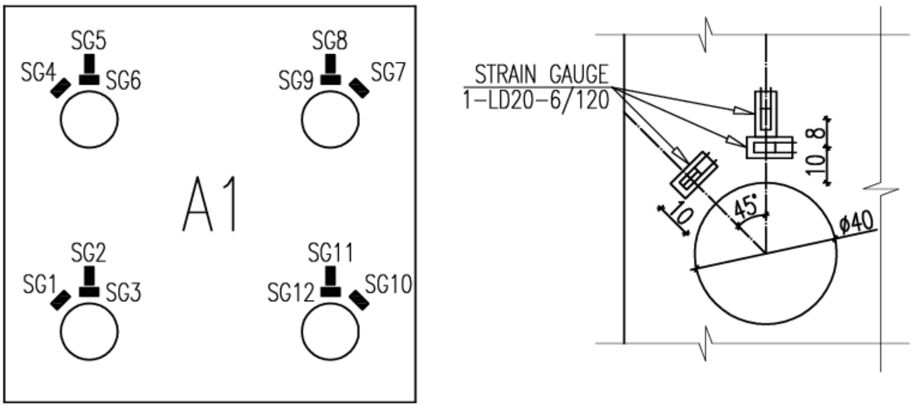

Figure 7. Location of the strain gauges on the FRP plate A1.

The strain-stress diagrams for all gauges of the specimen 1, FRP plate 1A are displayed on Figure 8.

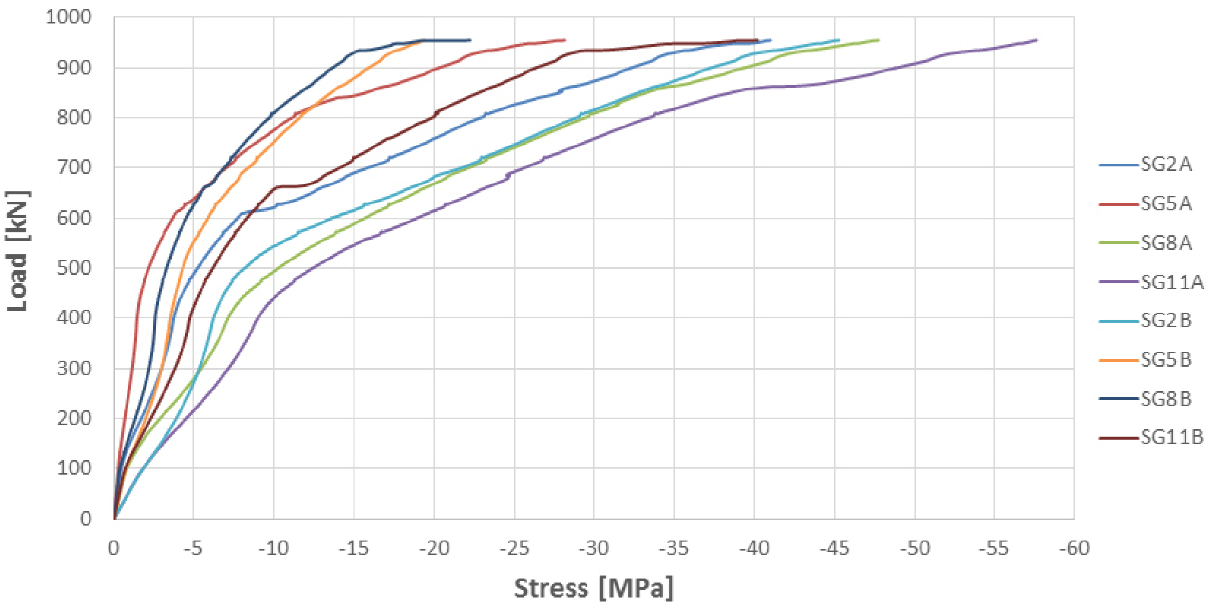

Figure 8. The strain-stress diagrams for vertical gauges of the specimen 3.

From the stress distribution in all wedges it is apparent, that the specimens were not loaded symmetrically as one slab is loaded more than the other one. Figure 8 shows the stresses from the strain gauge positioned vertically above the opening for concrete dowel. The graph shows the uneven distribution of load force for each concrete dowel. From the linear part of the working diagram was calculated load distribution between the individual dowels. To determine the elastic resistance of one dowel, the magnitude of stress was determined when nonlinear behaviour first appeared. From this value was calculated the magnitude of effective acting force on each dowel. Values are shown in Table 3.

Table 3. Summary of distribution, stress and effective acting force.

	Specimen 1			Specimen 2			Specimen 3		
	Distribution (%)	Stress (MPa)	Force (kN)	Distribution (%)	Stress (MPa)	Force (kN)	Distribution (%)	Stress (MPa)	Force (kN)
SG2A	16.3	-12.23	116.4	13.4	-7.87	75.6	9.7	-10.46	82.1
SG5A	7.33	- 8.26	78.6	11.1	-8.34	80.0	4.3	- 4.96	38.7
SG8A	4.0	-6.03	57.4	8.9	-7.76	74.5	15.4	-8.49	66.6
SG11A	7.2	-7.71	73.4	9.0	-5.54	53.2	20.1	-11.54	90.5
SG2B	24.4	-11.38	108,3	11.7	-7.88	75.6	18.6	-10.9	85.5
SG5B	18.0	-6.94	66.0	9.9	-8.62	82.7	10.8	-8.27	64.9
SG8B	13.0	-6.99	66.5	15.5	-10.38	99.6	6.4	-6.31	49.5
SG11B	9.7	-10.29	98.0	20.5	-9.27	88.9	12.2	-6.31	49.5

For the first specimen is the mean value of the elastic performance 83.1 kN, standard deviation 21.75 and 5% quantile 45.1 kN. For the second specimen is the mean value of the performance 78.8 kN, standard deviation 13.35 and 5% quantile 55.5 kN. For the third specimen is the mean value of the performance 69.3 kN, standard deviation 15.31 and 5% quantile 42.5 kN.

6. Conclusions

A reliable connection between FRP and concrete slab is important to prevent sudden and brittle failure. The use of perfobond rib shear connectors can reach this robustness. This study demonstrated the feasibility of composite connection by perfobond rib shear connectors between concrete slab and hand lay-up FRP plates. Concrete wedge together with GFRP bar achieved great properties in performed push out tests.

The effect of diameter of the holes was not observed throughout the tests as all specimens failed by shear crack or debonding. The hand lay-up FRP plates may be further enhanced by adding suitable reinforcement. Additionally, a design with more holes with smaller spacing should lead to more even stress distribution and increase the overall performance of the tested specimens.

Due to small modulus of FRP, composite beam may have problems with serviceability limit states and especially in deflection. Therefore the behavior of the connection should be rigid. Solution of connection with rib shear connectors reached ductile behavior but the debonding between surface of FRP and concrete slab occurred before the maximum load was reached. In order to increase the initial stiffness of the connection, coarse sand coating of the FRP surface can be applied.

Due to uneven distribution of acting force it is apparent that the strength of composite connection between FRP and concrete has even greater load bearing capacity than was determined by performed test with 2 FRP web specimens. The composite connection is therefore evaluated as strong link in the structure and therefore future research will focus on flexural strength of the composite girder.

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