論文 FRP Panels as Shear Member for a New Generation of PC Composite Bridges

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ABSTRACT: Fibre Reinforced Plastics (FRP) and their structural applications are widely introduced to the construction market. This paper deals with a new field of application of FRP panels, designed to be used for PC bridges with spans of around 100 m. Extensive theoretical research and tests have proven that FRP panels can replace conventional steel panels in box girder concrete composite bridges. Benefits of this new panel are weight reduction in comparison to conventional PC superstructures and reduction of maintenance work and measures for corrosion protection.

KEYWORDS: bridge, composite structure, concrete, concrete dowel, fibre reinforced plastics, FRP, joint-slip, life cycle cost, maintenance cost, prestressed concrete, shear.

1. INTRODUCTION

As result of the manufacturing process of FRP the fibre orientation is mainly unidirectional. FRP is a non-isotropic material. The tensile strength is larger than the compression strength. Recently, there is an increasing demand for fibre reinforced plastics for structural applications. The most common are strengthening of existing structures, FRP reinforcement or stay cables. Beside these applications, first “all composite bridges” were constructed only using FRP materials [1].

FRP panels can be used as a shear member, if the panels consist of several FRP layers with perpendicular fibre orientation. Shear strengths of more than 100 MPa have been achieved. But still compression strength of the FRP dominates the shear failure. The use of FRP in shear walls of box-girder bridges is a step towards new statical systems and erection methods, as new detailing and erection methods have to be considered.

2. MATERIAL PROPERTIES OF FRP

FRP is produced in various cross sections by continuous pultrusion process. Theoretically the length of the pultruded material is unlimited. FRP consists of fibre material embedded in a resin matrix. Various kinds of fibres and matrixes are available. Thus, there is a large spread in material properties. FRP used for the present research project consists of glass fibres and isophthalic acid unsaturated polyester resin matrix only. FRP of this type is recently used in structural and non-structural applications.

FRP is known as an elastic brittle material. The chemical formulation of the matrix material influences its long-term behaviour, such as creep and resistance against environmental conditions. In order to guarantee resistance against ultra-violet radiation (UV), the material can be coated. Also UV-resistant matrix material is available.

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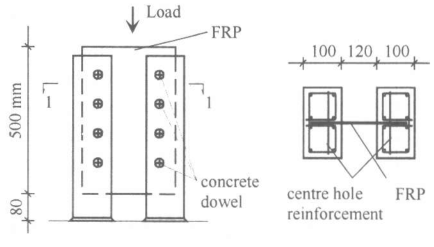
3. COMPOSITE INTERACTION BETWEEN FRP PANELS AND CONCRETE

In the past, research focussed on local bond properties between FRP and concrete. Primarily two concepts of bonding are applied in practice: Direct mechanical load transfer of embedded FRP reinforcing bars and gluing FRP sheets onto existing concrete surfaces. In order to secure a ductile connection between concrete and FRP plates of larger thickness and under higher shear forces, these concepts are believed not to be applicable.

Shear transfer and joint behaviour between FRP and concrete is studied by push-out tests. FRP plates of 18 mm thickness were embedded into the concrete. For shear transfer holes were drilled into the FRP plate and reinforced by crossing steel bars as shown in Fig.1. This system is developed from shear connectors in steel composite structures, known as "concrete dowel" [2],[3].



a) Elevation

b) Plan

Fig. 1: A push-out specimen

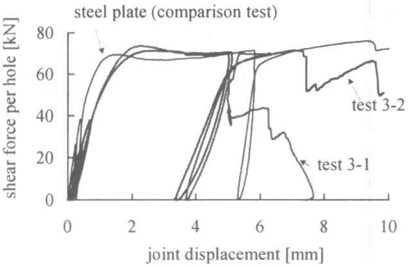


Fig. 2: Results of push-out tests

Four holes were drilled on each side. The diameter was varied between 30 and 45 mm. The concrete dowels were reinforced by crossing steel bars of 10 mm in diameter (grade SD295B). The concrete compressive strength was around 45 MPa. Load was first applied stepwise with intermediate unloading. Finally the displacement was gradually increased. Load displacement curves of two representative tests with FRP panels and one test with a steel panel is shown in Fig. 2. Joint slip and concrete and reinforcement strains were measured continuously. The Joint opening was measured manually.

From the first loading stage joint slip has been observed. This effect can be explained by the smooth surface of the FRP and steel panels, resulting in low friction and adhesion. At early loading stages the final stress transfer mechanism of the concrete dowel is not completely developed and initial cracking due to high local tensile stresses seems to occur. This effect is not particular for FRP. As shown in Fig. 2, steel panels show a two times larger stiffness of the concrete dowel connection compared to FRP. This caused by around 10 times higher Young's modulus of steel compared to FRP.

4. BEAM TESTS-PILOT TESTS

Tests on two types of composite beams were conducted in order to investigate the influence of the non-rigid joint to the performance under bending and shear loads. In Series 1, two 'H'-shaped beams with concrete flanges and FRP webs tested. The concrete flanges were highly reinforced. The lower flanges were additional prestressed by the use of hollow prestressing bars. The total prestressing force was 500 kN. Dimensions and loading conditions are shown in Fig 3. Dimensions of both beams are almost equal. Differences of the second beam loaded in shear are given in brackets.

The web plate consisted of single glass fibre reinforced plastic panels that were glued together to form total thickness of 18 mm. The fibre orientation of each single panel was almost uni-axial. By the use of five perpendicular orientated layers, a more homogeneous behaviour could be achieved and shear capacity would be increased compared to only single orientated fibre layers.

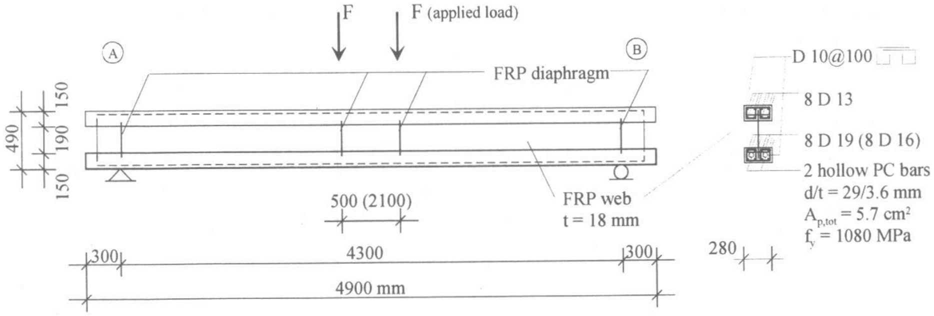


Fig 3: Beam test – pilot tests

The beams were loaded symmetrically by two loads as shown in Fig. 3. The relative distance from loading points to the abutments (x/d) was approximately 4.2 for the bending test and 2.4 for the shear beam, respectively.

The beams were equipped with strain gauges and displacement transducers. Main points of interest were the influence of joint slip between FRP web and concrete flanges to load carrying capacity and stiffness of the structure.

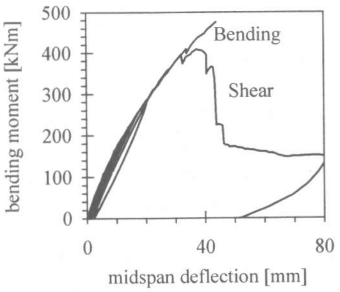


Fig 4: Load deflection curves

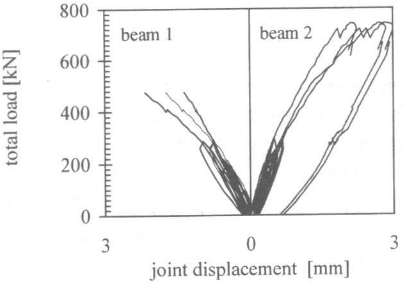


Fig 5: Shear – Joint slip

As shown in Fig 4, the load displacement curves of both specimens were similar. Horizontal joint slips between 2 and 3 mm were observed as shown in Fig. 5. The flexibility of the composite joints decreases the stiffness of the beam under service loading conditions. As stiffness reduction due to joint slip is dependent on the effective depth, in real structures joint slip is less dominant than in small beams. The concrete dowel reinforcement crossing the holes of the FPR panel was equipped with strain gauges. Stresses in the dowel reinforcement first developed at loads around 300 kN. This showed that the concrete dowel remained uncracked under service loading.

The bending beam failed due to crushing of concrete in the upper slab. At ultimate loads, the lower reinforcement and the prestressing bars were yielding. The deflection of the beam at failure was 4.5 cm. The non-ductile failure of the upper concrete slab was coursed by the high reinforcement ratio of 4.6%, which has been chosen to prove sufficient shear transfer across the composite joint even at higher loads and larger slips in the composite joint.

The cracking patterns shown in Fig 6 are one of the most significant indicators that composite joint interaction affects the performance of the structure. In beam No. 1 initial cracking of the upper flange occurred even though upper fibres of the lower flange remained in compression. Cracks in upper flange above supporting points also indicated non-rigid composite interaction. However, the tests have proven that the joint behaviour does not affect load-bearing capacity in bending. As predicted, the second beam tests failed in shear. At maximum stresses in the FPR web of around

100 MPa delamination of the outer shell started at the same time when typical shear cracks in the upper flange developed.

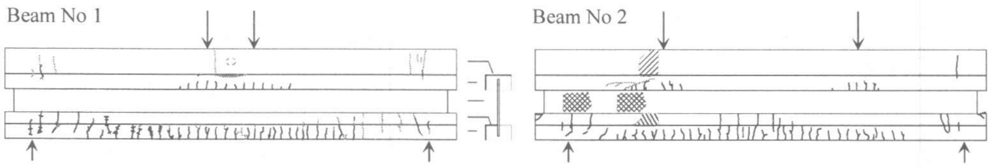


Fig 6: Cracking pattern

At first, the observed failure mode of FRP panel indicates plate buckling, although a further simplified buckling analysis based on the Eurocode 2 [5] for steel structures does not confirm this due to low slenderness. Thus, in contrary to recent design recommendations [6], stability against buckling of FRP can not be simply verified under consideration of isotropic material properties in the same way as for steel structures. The tests have proven the necessity for taking into account lower strengths perpendicular to the main fibre orientation and delamination effects.

5. ANALYSIS

For numerical analysis of the tested FRP concrete composite structures a two-dimensional finite element model is created. It consists of reinforced concrete elements, linear elastic elements for FRP and spring elements to represent the concrete dowel action. The effect of initial prestressing was modeled by the use of external forces. Fig 7 shows the outlines of the computational model and the material properties embedded into the finite elements.

Besides the stress transfer through concrete dowels that mainly influence composite interaction, frictional effects between concrete and FRP exist. The influence of friction on the joint stiffness and stress transfer can be estimated by the simple assumption that the concrete dowels neither transfer vertical forces nor cause bracing effects. Thus, the maximum shear force resulting from frictional effects can not exceed the frictional coefficient multiplied by the total vertical load transferred through the joint interface. Taking a realistic friction coefficient ($\mu = 0.3$) into account, the resulting total horizontal shear resistance by friction at ultimate loading on each side of the beam does not exceed the shear strength of a single concrete dowel. Therefore, at least for structures of similar geometry as investigated, a calculation taking only dowel action into account seems to be appropriate.

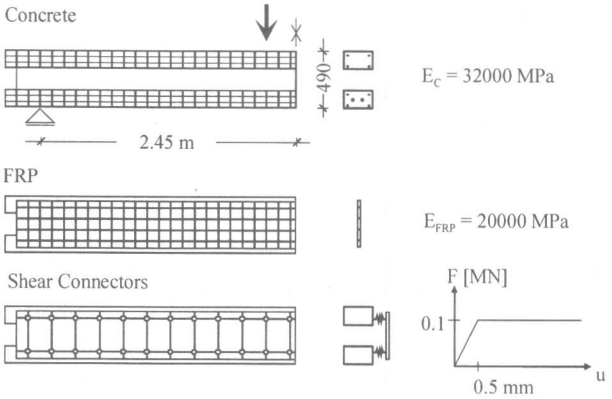


Fig 7: Computational model and material properties

Finite element analysis was conducted. For the finite element analysis the non-linear springs were modelled as equivalent plane elements. Whereas in reality the specimen was loaded stepwise with intermediate unloading, for analysis gradual loading was assumed. Numerical results coincide well with the test data in both shear and bending tests.

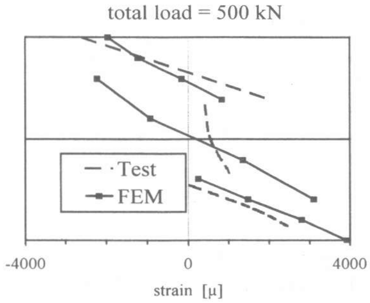


Fig 8: Strain distribution (beam 1)

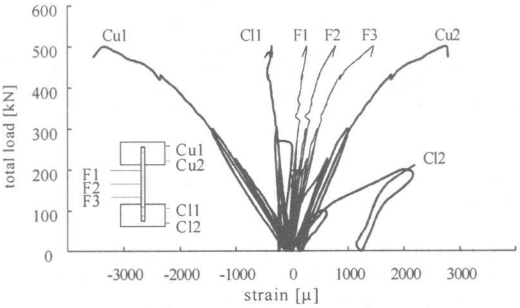


Fig 9: measured strains (beam 1)

Strains were measured on concrete surface, reinforcement, prestressing bars and FRP surface. Fig 8 shows the strain distribution over the cross section at midspan of beam 1. The strain development as function of the external load is drawn in Fig 9. The measured strain gradients of the FRP web differ from that of the concrete flanges. As for the finite element analysis vertical joint displacements were suppressed, the curvature and strain gradients in the flanges and the web are equal. Beside horizontal joint slip, also vertical joint slip occurred. This caused different curvature in flanges and webs as well as cracking of the upper slab near the abutments. In order to simulate this effect, the composite joint has to be modelled using both vertical and horizontal spring elements.

6. APPROPRIATE DETAILING WITH FRP

From mechanical point of view, tests and analysis have proven that FRP concrete composite structures can replace traditional composite girders. Regarding the execution of such a composite beam, special attention has to be paid on structural detailing. As there are limits in size of FRP panels due to material production, transport and erection on site, several web panels have to be combined on site. Whereas steel can be welded on site easily, on-site gluing of FRP should be avoided, unless an appropriate inspection system is available. As alternatives for direct connections like welding or gluing, bolts and batten platen connections could be used. But this method shall not be worth to be investigated, as it is inconsistent to the philosophy of minimum maintenance constructions.

As the Young's Modulus of FRP is ten times lower than that of steel, lower bending stresses occur in the FRP webs. Rigid connections between single web plates seem less necessary. A non-rigid connection of the same kind as used to combine web and flange shall be tested next. Thus, a special designed concrete diaphragm could be an alternative to rigid connections (gluing / bolts).

7. MAIN TESTS

The pilot tests were designed as a basic study for prestressed FRP-concrete composite beams. With the following main tests on two composite beams shown in Fig. 10 to be carried out in early 2000, practical application for composite bridge girders shall be proven. Furthermore these tests are expected to result in new findings for detailing of FRP and the connection between FRP web panels and concrete slabs, which is needed for applications in practice. Main interests of this experimental research are. (1) Effect of external prestressing on composite behaviour under service and ultimate

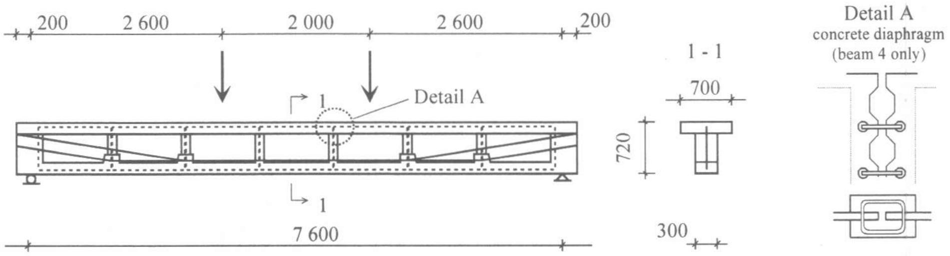


Fig 10: Main beam tests – beam No. 3 and No.4

loading conditions. (2) Influence of vertically jointed FRP panels on shear transfer and crack opening. (3) Performance of new developed multipurpose concrete diaphragms that are used for FRP connection across vertical joints, stiffener and deviation saddle.

8. CONCLUSIONS AND OUTLOOK

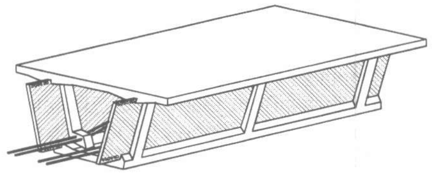


Fig 10: Study of new bridge girder type with FRP webs

Research was conducted on FRP concrete composite structures, in which FRP shear panels act as web in bridge girders, replacing steel panels of the traditional composite superstructure. As this is a new type of application for FRP in structural engineering, the research focussed on composite interaction and performance of FRP in combination with prestressed concrete. Push-out tests were carried out to investigate the behaviour of the composite joint and to define material characteristics. Analysis as well as shear and bending tests on beams have proven the use FRP panels as webs in bridges. Fig.10 shows a study of such a structure with external prestressing cables, FRP web panels and concrete diaphragms that are connecting adjacent FRP panels. Moreover the diaphragms carry deviation saddles and act as stiffener. The weight of FRP composite bridge girders is lower compared to PC-structures, and maintenance costs compared to steel or composite structures are much lower du to the non-corrosive material. As FRP is a brittle material, more attention has to be paid on structural detailing to avoid local stress concentrations. Long term behaviour of FRP subjected to shear and compression should be further investigated in order for the optimisation of resin and fibre type and content of the FRP material.

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