

# Experimental Analysis of Composite Beams

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Composite polymer-concrete beams represent new modern structures that can take an advantage of the polymer's practical tensile properties and combine them with the concrete's favourable compressive properties. Drawing on this knowledge, a set of polymer beams acting compositely with a concrete slab was designed and manufactured. The aim of the research was to utilise the low weight and high strength of the polymer I-sections and combine them with the high stiffness of the concrete slab, which forms the upper part of the cross-section. The advantage of fibre-reinforced polymer (FRP) beams is their anisotropy, where the strength of the material is increased by placing the fibres uniformly in one direction, and the composite elements are then stressed in the most reinforced direction. To ensure the interaction between the polymer element and the concrete slab, strip shear connectors of a precisely defined shape were developed and utilised. The designed composite beam simulates a pre-cast component that can be applied in bridge structures for short and medium spans. The pre-cast beams were subjected to four-point bending. Apart from the overall deflections of the structure, the stresses in the cross-section of the composite material and the relative deformations/strains on the surface of the concrete part of the cross-section were monitored during the test. The whole experiment yielded new results in both laboratory and theoretical respects, not only regarding the interaction of materials with distinct characteristics but also the properties of composites per se.

## Introduction

Composite materials are nowadays gradually replacing the previous commonly used mineral raw materials. Due to the rapid development of science, technology, and industry, the technical requirements for commonly used materials have also become more demanding. Recently, a great deal of emphasis has been placed on the amount of energy consumed in the production of building materials. Compared to steel, composite materials meet more stringent energy requirements and save considerable energy in structural production. Thanks to their outstanding properties, composite materials with higher strength characteristics, higher resistance to external influences but lower weight and lower energy consumption in production are coming to the fore. The further development of

progressive composite materials is unavoidable because the gradual increase in structural strength and durability requirements cannot be satisfied by current methods, i.e., adding chemical-based additives, heat treatment, or forming [1]. For this particular reason, various unconventional materials have begun to be combined into a single structural unit, such as brittle or high-strength materials with plastic ones, so that the distinct and desirable characteristics of the individual materials can be fully taken advantage of. Based on their properties, polymer composite materials are becoming very popular as a replacement for the original steel-concrete composite structures [2].

An essential part of composite beams is the elements providing shear transfer at the interface between the materials, thus enabling their composite action and significantly affecting the behaviour of the whole structure. Two directions are defined in the study of shear connectors. One is a detailed analysis of shear studs, for example, the use of studs larger in diameter or a greater number of studs providing composite action; bent, angled or horizontal studs; studs with elliptical or reinforced shanks; doubled studs or studs made of high-strength steel.

Another type of shear connector is strips incorporated into a composite cross-section, the so-called Perfobond Strips, first designed and practically used by Leonhardt in 1938. Standing/vertical perforated connecting strips, developed in Germany in 1985, effectively ensure that the composite components efficiently work together in resisting applied loads [3]. Research on strip shear connectors gradually took off in other countries such as

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Canada in 1988, Australia in 1992, Japan in 1994, and the Czech Republic in 1996. In Slovakia, the investigation of strip connectors began in 1996 at the Faculty of Civil Engineering of the Technical University in Košice. The gradual development of the connecting elements is shown in the following **Table 1**.

**Table 1.**

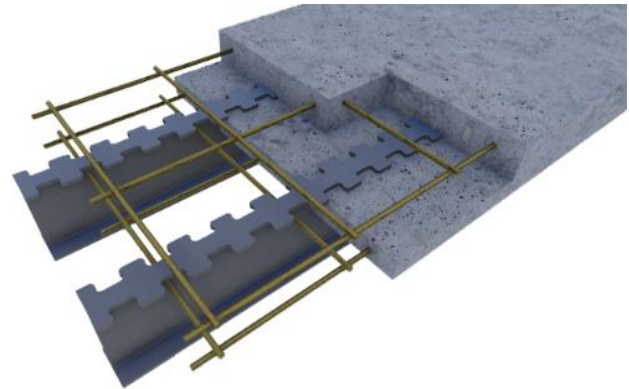
No.	Title	Country
1	1938	Germany, Leonhardt
2	1988	Canada
3	1992	Australia
4	1994	Japan
5	1996	Slovakia
6	1996	Czech Republic

Strips of various shapes such as straight and corrugated strips with holes, strips with holes and cut-outs, strips with cut-outs only, comb-like strips, strips for double-sided composite action, strips with concrete reinforcement, possibly in combination with studs, or perforated strips to form the edge of the straight and corrugated web of the beam to eliminate the top flange, have been designed and experimentally and theoretically verified. In the design of the experimental beams in question, horizontal strips with regular comb-like cut-outs on both sides of the top flange of the polymer section were used. The standard procedure according to STN-EN 1994-1-1 verified this method of composite action by push-out tests [4]. The composite effect proves to be sufficient to transfer the shear force generated in the composite beam. The theoretical and numerical simulations were further verified experimentally. The presented analyses show that the method of composite action using a specifically modified flange can be applied in the design of composite polymer-concrete structures. Using the polymer I-section instead of a steel I-section opens us the new possibilities in ecologically building constructions. Nowadays there is a significant demand for raw materials so the precondition is that once they will be missing. This experiment can show us that the steel can be replaceable and polymers can be useful not only for building construction but also for bridges.

## Experiment

The experiment was carried out on pre-cast composite polymer-concrete beams. The beam dimension was 6000 x 900 mm, and the concrete slab thickness was 150 mm, designed so that the neutral axis under load passes just at the location of the top flange of the polymer section. The concrete slab was placed on two 200/100 polymer I-sections, with a 10-mm thick web plate and the top flange cast in concrete. To further enhance the shear capacity, there were holes in the polymer section's web plate for FRP reinforcement bars to pass through, spaced evenly at 300 mm intervals along the length of the beam. The holes were at a distance of 30 mm from the top edge. Transverse reinforcement was placed at the top and bottom edges of the concrete slab at a distance of 300 mm all along the beam.

In the longitudinal direction, three bars of 12-mm FRP reinforcement were placed at both the bottom and top edges. A schematic representation of the composite beam is shown in **Fig. 1**.



**Fig. 1.** Composite beam.

For this experiment was used FRP samples with particular properties. These properties come from chemical composition, material experiments and the type of manufacturing. The average tensile strength of five FRP samples was 442 MPa and the yield stress was 32,6 GPa in the longitudinal orientation of fibres. This was measured according to the test described in the standard EN ISO 527-1:2012: Plastics — Determination of tensile properties. The average quantity of fibres in three samples is 66,18% and it was determined at the temperature of 625 °C. This experiment is described in the standard for determination of the content of fibres with mark EN ISO 1172:1999. These properties of FRP beams were provided in the protocol together with beams. For the concrete part of the experiment, it was used the concrete with class C30/70 for the environmental condition of XC4 with a count of chlorides CI 0,2. The actual values of material characteristics of concrete and polymer sections were examined by experiment. For each type of test, three standard test specimens were used. Based on the tests, the compressive strength of concrete on cylinders, cubes and bars, flexural tensile strength, transverse tensile strength, and the modulus of elasticity of concrete were determined. Out of several polymer properties, tensile tests in both longitudinal and transverse tension and a shear test of the material with interrupted longitudinal fibres were carried out. The specimens after the shear force test are shown in **Fig. 2(a)**.

This test best describes the mechanical stress behaviour of the flange of the polymer cross-section acting compositely with the concrete. The protruding parts on the polymer beam are subjected to a shear force shown in **Fig. 2(b)**. Using the maximum shear force that the polymer material can withstand, determined in the shear tests, the average values were then determined and taken as nominal for calculating the ultimate theoretical loads and the result evaluation.

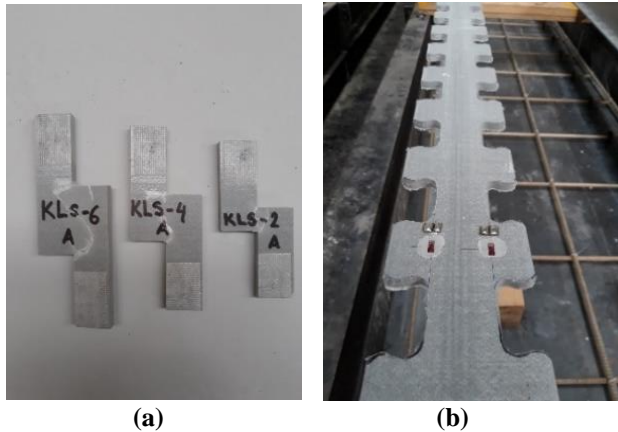


Fig. 2. Shear force test and shear transfer in one of the polymer beams.

Strain gauges were affixed to the beams at the point most stressed by shear so that the relative deformations/ strains of the material could be measured during the load test. The specimens were concreted at the Laboratory Centre for Research and Innovation in Construction. During concrete placement, the polymer beams were placed in a rigid steel formwork at the required height. The concrete slab was concreted in a reverse manner so that the top of the beam was on the underside of the formwork during concreting. After the concrete had hardened, the beams were inverted, and the forms struck. The cut-outs in the polymer beams according to a precisely defined shape were provided by a specialist company. The concrete was supplied from a central concrete plant to ensure the correct formulation and consistency of the material. Three 6-metre-long composite polymer-concrete beams were made, and cylinders, cubes, and bars were used to test the material properties of the concrete. Concrete strength tests were performed 28 days after concreting and subsequently at the time of testing the composite beams so that the actual material properties could be used in the numerical calculations. All tests were based on standards for hardened concrete with the number EN 12390: Testing hardened concrete.

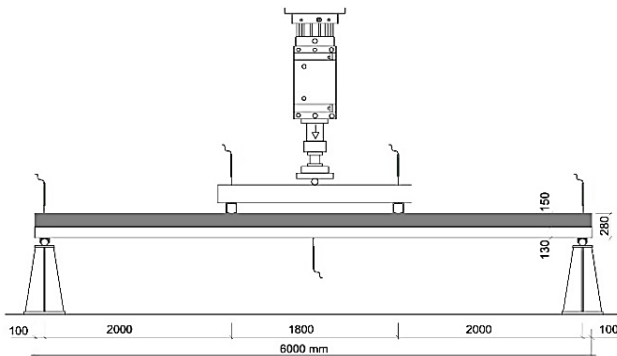


Fig. 3. Loading scheme

The loading scheme in Fig. 3 was designed according to standard EN 1994-1-1 called the Design of composite steel and concrete structures. As the specimens were placed in the rigid formwork during concrete placement, the zero

load states corresponded to the dead load of the beams. The test on the composite beams was carried out by four-point bending. The force from a press attached to a frame above the middle part of the beam was divided into a pair of vertical forces spaced 2000 mm from the edge using a balance, while the axial distance between the forces was 1800 mm and the free end was extended 100 mm beyond the support. The beam was reinforced with a steel prop/bar at the point of the attachment to the support to prevent deformation of the polymer beam's web plate during loading.

All specimens were loaded with symmetrically spaced hydraulic presses so that pure bending occurred in the segment between the presses. After reading the zero-load state, which corresponded to the dead load of the beam, the following loading procedure was carried out successively in steps with a force increment of 10kN. The loading composite beam is shown in Fig. 4.



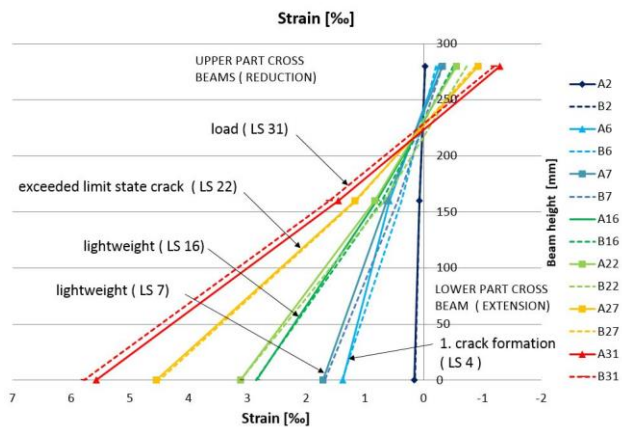
Fig. 4. Composite beam during the loading test.

The specimens were unloaded twice during the loading test. When the tensile strength of the concrete was exceeded during loading, hairline cracks started to form in the tensioned concrete. These cracks continued to open and widen until they reached a length of approximately 85 mm from the bottom edge of the concrete, which was the assumed position of the plastic neutral axis of the entire composite beam. The tests were terminated when it was not possible to increase the load carried by the specimens because of a significant uncontrollable increase in deflection.

## Results and discussion

During the tests, the relative deformations of the polymer section were measured and recorded by strain gauges. Strain gauges were positioned at the locations most stressed by bending and around the holes. Inductive sensors recorded mid-span deflections and subsidence at the supports. During the static load test, the cracking occurring on the composite polymer-concrete beam was monitored, the crack widths were measured, and the crack penetration was observed for each loading stage. The composite beam was divided into an A-side and a B-side. The initial loading

stage was considered with zero loads. The first cracks were observed at a load of 50kN. Increasing crack width and penetration depth were monitored by progressively loading the beam. The beam was unloaded during the test; however, the failed concrete did not allow the beam to return to its initial position. The crack width limit value exceeded at load condition 22 at a force of 110 kN. A total of 46 loading cycles were performed, with a maximum force value of 340kN. At the last of loading, cycles were cracking connection in polymer beam. The loading states for the individual cracks were continuously recorded, and their gradual opening and penetrating towards the neutral axis in the composite beam were monitored.



**Fig. 5.** Graphical representation of the relative deformations/strains along with the beam height.

The experiment shows that the neutral axis is located approximately in the region of the top flange of the polymer beam, which is close to the underlying assumptions. Relative deformations of push and pull part of beams are shown in **Fig. 5**. The cracks in the composite polymer-concrete beam occur relatively early, at lower load levels, but the effect of these microcracks does not essentially impact the durability and service life of the structure since the corrosion is wholly eliminated from the structure.

## Conclusion

The experiment verified the assumptions regarding the behaviour of the composite polymer-concrete beams. Mechanical connection through embedded precisely-shaped, comb-like polymer strips appears sufficient to transfer the shear force. Nevertheless, further attention will have to be paid to the dynamic loading of the composite beams. Moreover, other possibilities of shear connection to enable the combined effect of the two different materials without damaging the longitudinal fibres on the polymer beam need to be explored. This type of composite polymer-concrete beams could be utilised for pedestrian footbridges and short- and medium-span bridges in the future. In the future, we will prepare composite polymer-concrete samples for the dynamic cyclic stress, that arises on the bridge structure from the traffic load.

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## Conflicts of Interest

There are no conflicts to declare.

## Keywords

Composite polymer-concrete materials, composite bridges, composite beams encased in concrete

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## Authors biography



**Prof. Ing. Vincent Kvočák, PhD.**, is a professor at the Civil Engineering Faculty of the Technical University of Košice. He specialises in Civil Engineering Theory and Construction Works, focusing predominately on bridges. His work also involves stability problems and composite steel-concrete structures. He has been the principal investigator of many research projects on steel bridges with concrete beams. He is the author of more than 200 scientific papers published in journals and presented at international conferences. He has received several awards for his scientific and pedagogical work.



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## Graphical abstract

