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Flexural behavior of short reinforced concrete hybrid beams – experiment and numerical simulations

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Summary

The paper presents the experimental results on the influence of the longitudinal reinforcement ratio on the flexural behavior of the short reinforced concrete hybrid beams. The beams are made of two materials: high strength concrete (HSC) in the upper part (in order to take over compressive stresses) and polymer concrete at the bottom part (in order to withstand tensile stresses). Different longitudinal reinforcement ratios and reinforcement placing on the cross-section were used in order to study its influence on the overall flexural behavior of the beams.

A finite element nonlinear analysis was performed using the LUSAS program. The high strength concrete and the polymer concrete were modeled using linear plane stress elements. The reinforcement was considered as bar type with embedded functions in the plane stress elements. The complete bonding between the reinforcement and the polymer concrete was considered during the initial stages of the simulation.

The contribution of the longitudinal reinforcement to the peak resisted load is negligible once a certain value of ρ is attained. The midspan deflection corresponding to the peak load decreases with the increase in the longitudinal reinforcement ratio. The arrangement of the reinforcement on the cross-section has an important influence both on the load carrying capacity and on the maximum midspan deflection of the beams.

KEYWORDS: polymer concrete, hybrid beams, flexural behavior, FEM analysis

1. INTRODUCTION

Since the early times, engineers have been looking for ways to combine two or more materials in a structural element in order to take advantage of their strong

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features. This is how the so called hybrid structural elements were born. A very common type of hybrid structural element is the reinforced concrete made from the combination of concrete, which is good in compression, and steel, as reinforcement, which behaves very well in tension. This gave the engineers the possibility to build new structures with larger spans than before. Reinforced concrete is so widely spread and utilized today that it isn't even considered a hybrid material anymore.

The present paper brings its contribution to a better understanding of the flexural behavior of short reinforced concrete hybrid beams. The beams consist of a high strength concrete (HSC) part in the compression zone and a polymer concrete part (PoC) in the tensile zone. As it was first reported by Snell et al. in 1972 [1], polymer concrete is characterized by high tensile strength (2.92 times higher than the normal or high strength concrete), improved freeze-thaw durability and negligible water durability. A few decades later, the ACI Committee 548 in 2003 [2] issued a report in which the same properties were listed for the polymer concrete.

To the normal process of cement hydration, polymer modifications add a process of coalescence. As cement hardens, there form small spaces between the aggregate particles. These spaces are what allow water to penetrate, and do damage in freezing conditions. Polymer particles coalesce to fill these voids. That is why the concrete becomes less permeable and better protected against freezing [3]. Interestingly, polymer concrete does not produce bleed water. It makes an excellent overlay because it needs very little finishing. It is more accurate to say that it dries, than to call it curing. The polymer bonds not only to the concrete and the aggregate in the mix but also in the underlying concrete. It is for that reason that it is used to resurface concrete, Park et al. [4]. The patch method used to repair deteriorated reinforced concrete structures should produce patches that are dimensionally and electrochemically stable, resistant against penetration of deterioration factors, and mechanically strong. Today, the patch repair materials that are widely used contain admixtures, such as silica fume and polymers, to improve the performance of cement mortar [5].

The main objective of this research work is to assess the structural behavior of the polymer concrete. There has been quite extensive research done in the field of using polymers in construction materials [6-7]. However, the experimental research on different types of materials and elements is very seldomly completed by numerical models. The combination of the two materials with different properties such as high strength concrete and polymer concrete was used for obtaining short reinforced hybrid beams. In the present paper both the experimental results and the finite element (FEM) analysis of the behavior of short hybrid beams are presented.

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Table 1. Mix proportion for the high strength concrete

HSC	Cement [kg/m^3]	Aggregates [kg/m^3] 0–4 mm	4–8 mm	8–16 mm	Water [l/m^3]	W/C W/C+SF	Super-plasticizer [l/m^3]	Silica fume [kg/m^3]
	550	457	359	815	159.5	0.295 0.264	6.6	55

Table 2. Mechanical properties of the high strength concrete

HSC	Density [kg/m^3]	Young's modulus [GPa]	f_c' [MPa]	f_{ti} [MPa]	f_{td} [MPa]
	2506	30	90.3	5.53	4.01

Table 3. Mix proportion for the polymer concrete

Polymer Concrete	Epoxy resin [%]	Fly ash [%]	Aggregate [%] 0–4 mm	4–8 mm
	12.4	12.8	37.4	37.4

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1. Concrete

The mix proportion of the high strength concrete used in the compression zone of the beams is presented in Table 1. The mechanical properties of the HSC were determined experimentally and are summarized in Table 2.

The tension zone of the beams was cast out of polymer concrete. The mix proportion of the polymer concrete is given in Table 3. Fly ash was used as filler instead of Portland cement. Even though the mechanical properties of concrete using fly ash are tremendously improved [8], there are still concerns about the radioactivity levels of fly ashes [9].

2.2. Reinforcement

The reinforcement used in the experimental procedure was with smooth surface, made of mild steel, OB37 type. The mechanical properties of the longitudinal reinforcement were determined experimentally by means of the uniaxial tensile test on 10 mm diameter steel bars. The obtained yield strength was f_y = 318 MPa and the ultimate tensile strength was f_u = 484 MPa.

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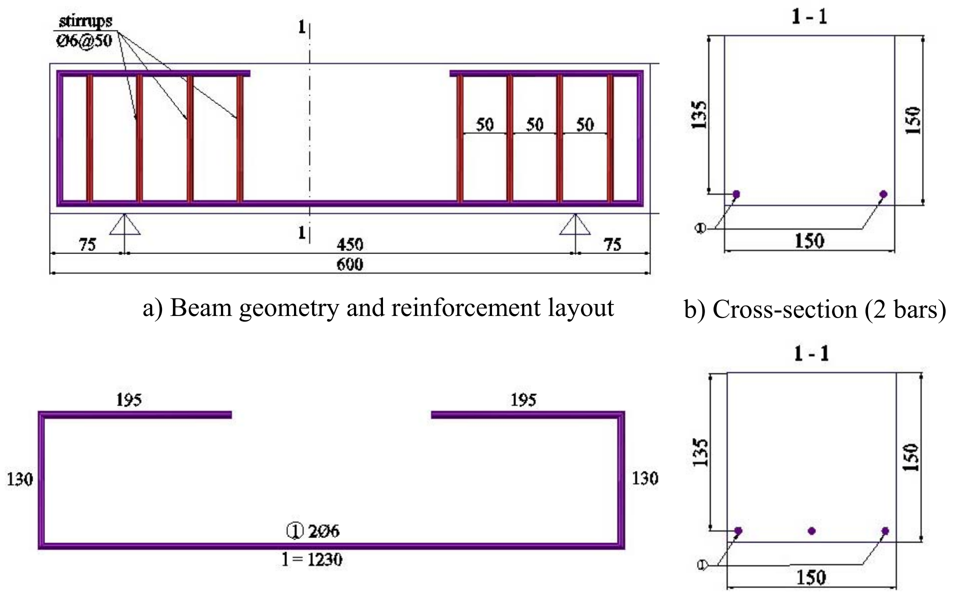
Figure 1a shows the reinforcement layout of the hybrid concrete beams. The shear reinforcement consisted of Φ6 smooth stirrups made out of OB37 steel. The stirrups are located in both shear spans so that to prevent the occurrence of the shear failure. Depending on the specimen, the longitudinal reinforcement consisted of 2 or 3 bars of different diameters. Their distribution is shown in Figure 1b for HBS029, HBS049 and HBS077 and in Figure 1c for HBS041 and HBS074. Figure 1d presents the geometry of a Φ6 longitudinal reinforcing bar. Its characteristics were the same for all other longitudinal reinforcing bars.

Each specimen was denoted in the form HBS029 where HB stands for hybrid beam, S stands for smooth (smooth longitudinal reinforcement) and 029 stands for the longitudinal reinforcement ration (which in this case is 0.29%).

2.3. Hybrid beams

Five hybrid beams with the dimensions of 600 × 150 × 150 mm (L × b × h) were cast in two stages. First, the high strength concrete part was cast and, after its hardening, the polymer concrete was cast. This procedure was chosen due the high bonding capacity of the polymer concrete [4].



a) Beam geometry and reinforcement layout

b) Cross-section (2 bars)

d) Geometry of the longitudinal reinforcement

c) Cross-section (3 bars)

Figure 1. Beam geometry and reinforcement layout

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Table 4. Longitudinal reinforcement ratio ρ

Specimen	No. of bars	Diameter [mm]	Area of the reinforcement [mm^2]	Longitudinal reinforcement ratio [%]
HSB029	2	6	56.55	0.29
HSB049	2	8	100.53	0.49
HSB077	2	10	157.08	0.77
HSB041	3	6	84.82	0.41
HSB074	3	8	150.79	0.74

Figure 2. Three point loading test of the hybrid beams

The main parameter was the longitudinal reinforcement ratio ρ. Its values varied from 0.29% to 0.77%. In order to reach the above mentioned values of the longitudinal reinforcement ratio, the flexural reinforcement was distributed as shown in Figure 1b and 1c. The specimens together with their longitudinal reinforcement ratio ρ as well as the number to bars forming the tensile reinforcement are presented in Table 4. After 28 days, the beams were subjected to a three point loading test, Figure 2, in order to determine their flexural strength.

A total number of five hybrid beams were cast and tested in order to assess the flexural behavior of such types of elements. Concrete surface strains were measured both at the top fiber and at the bottom fiber of the specimens. The beams were also instrumented with LVDT's located at the midspan in order to record the deflection during the loading (Figure 2).

The experimental results were accompanied by numerical simulations using the FEA program Lusas.

3. RESULTS AND DISCUSSIONS

3.1. Modes of failure

All beams failed in flexure tension mode of failure by yielding of the longitudinal reinforcement. The post-peak behavior of the specimens was characterized by a brittle formation of a single major crack at the midspan.

It should be pointed out that for all specimens, with the exception of HSB041, the bond between the high strength concrete part and the polymer concrete was not destroyed. For the HSB041 beam, a parallel crack with the longitudinal axis of the specimen was formed at the interface between the two materials. This crack, however, was observed only on one side of the beam.

Specimen HSB077 exhibited three flexural cracks. The major crack propagated to the compression zone. The other two cracks developed only within the polymer concrete part, one of them reaching the interface zone between the two materials. Once the interface zone was reached, the crack propagated longitudinally.

The width of the critical flexural crack was measured for all beams and its opening was 1 mm. It can be concluded, based on the recorded data, that the variation of the longitudinal reinforcement ratio does not influence the width of the critical crack in hybrid beams. This is somehow in contradiction with the general practice in reinforced concrete design where the reinforcement is used both for taking over the tensile stresses and to limit the width of the opening cracks. Further research is deemed necessary by the authors with respect to this particular behavior of the polymer hybrid beams.

3.2. Load – deflection curves

Figure 3 shows the load – deflection curves for all the specimens. It can be seen that the higher the longitudinal reinforcement ratio was, the higher the initial stiffness of the beams. However, the peak resisted load did not follow the same trend. The HSB049 (2 bars of Φ8 diameter) resisted a slightly larger load than the HSB077 (2 bars of Φ10 diameter). It can, therefore, be concluded that the contribution of the longitudinal reinforcement to the peak resisted load is negligible once a certain value of ρ is attained. However, it can be observed that the midspan

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deflection corresponding to the peak load decreases with the increase in the longitudinal reinforcement ratio. This observation is strongly related to the initial stiffness of the specimens with the same arrangement of the reinforcing bars on the cross-section (Figure 1b, specimen HSB029, HSB049, HSB077).

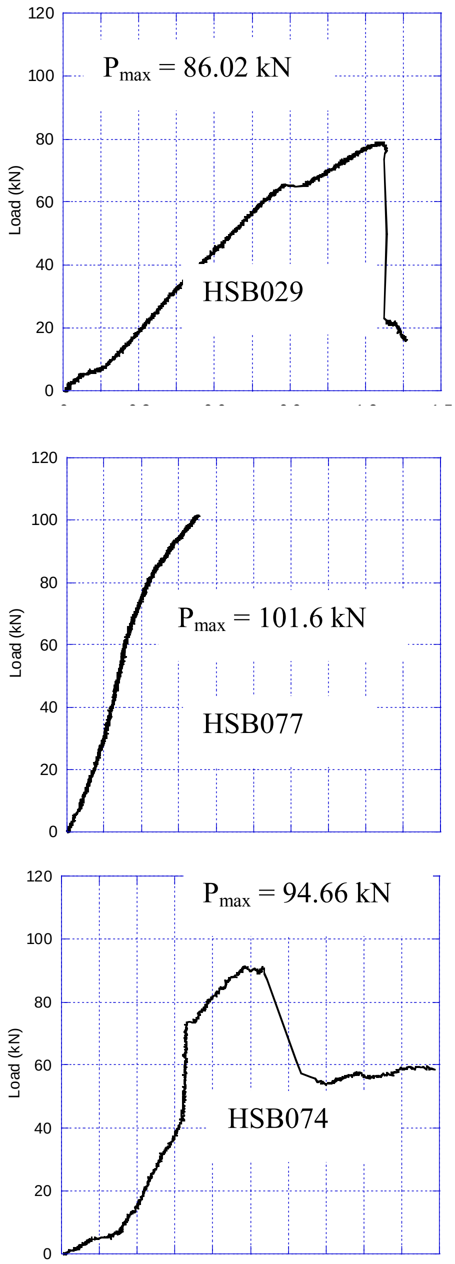

Figure 3. Load – deflection curves of all hybrid beams

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When the reinforcement was placed differently (Table 4 and Figure 1c) in the cross-section, even though the value of the longitudinal reinforcement ratio changed from 0.29% to 0.41%, the ultimate load did not change significantly, 86.02 kN to 89.54 kN, respectively. Even for the slightly similar value of ρ, a different load carrying capacity was obtained, as it can be seen from Figure 3 for the following two pairs of specimens: HSB049 (2 bars, Φ8 diameter) versus HSB041 (3 bars, Φ6 diameter) and HSB077 (2 bars, Φ10 diameter) versus HSB071 (3 bars, Φ8 diameter). The main conclusion that can be drawn from these observations is that the arrangement of the longitudinal reinforcement on the cross-section of the composite hybrid beams plays an important role on the carrying capacity of the specimens.

It can also be observed that the midspan deflections corresponding to the peak loads for the specimens with similar longitudinal reinforcement ratios but different arrangements of the bars in the cross-section (HSB049 vs. HSB041 and HSB077 vs. HSB071) are almost the same. Based on the previous observations it can be said that the arrangement of the reinforcement on the cross-section has an important influence both on the load carrying capacity and on the maximum midspan deflection of the beams.

3.3. Finite element analysis

A finite element nonlinear analysis was performed using the LUSAS program. The high strength concrete and the polymer concrete were modeled using linear plane stress elements. The reinforcement was considered as bar type with embedded functions in the plane stress elements. The complete bonding between the reinforcement and the polymer concrete was considered during the initial stages of the simulation.

The material properties and characteristics were determined experimentally and considered in the numerical analysis.

Figure 4 presents the distribution of the tensile strains of the HSB077 beam. The red area in Figure 4 signifies the location of the maximum tensile stresses that lead to the formation of the flexural crack. This is in accordance to the observed behavior of the beam during the experimental stage.

Figure 5 shows the comparison between the load-deflection curve obtained from the experiment and given by the FEM analysis using LUSAS software for the HSB077 beam. It can be observed that there is quite a good agreement between the experiment and the analysis, even though the numerical model showed a slightly larger initial flexural stiffness and peak midspan deflection.

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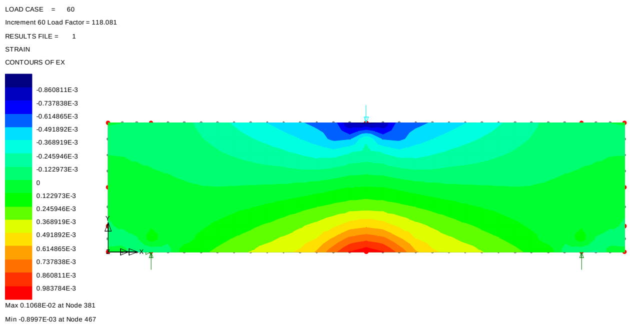

Figure 4. Tensile strains distribution for HSB077 (FEM analysis)

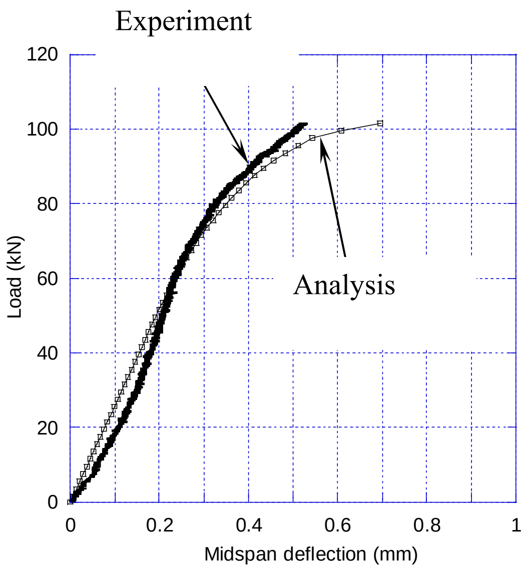

Figure 5. Load-deflection curves for HSB077 (experiment and analysis)

The ultimate load of the HSB077 recorded during the experiment was 101.6 kN. The value for the same load obtained from the analysis was P_{max}^{FEM} = 101.58 kN. There is a very good estimation of the beam carrying capacity by using the FEM analysis. However, further study should be conducted in order to improve the numerical model, especially in terms of the initial stiffness.

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4. CONCLUSIONS

Both experimental tests and numerical simulations were used to investigate the flexural behavior of hybrid reinforced concrete beam. Based on the analysis of the obtained results the following conclusions can be drawn.

The contribution of the longitudinal reinforcement to the peak resisted load is negligible once a certain value of ρ is attained. The midspan deflection corresponding to the peak load decreases with the increase in the longitudinal reinforcement ratio. This observation is strongly related to the initial stiffness of the specimens with the same arrangement of the reinforcing bars on the cross-section.

The arrangement of the reinforcement on the cross-section has an important influence both on the load carrying capacity and on the maximum midspan deflection of the beams.

The FEM analysis results are in good agreement with the experimental results. However, further study is necessary to improve the numerical model mainly in considering all the factors that influence the initial stiffness of the hybrid beams.

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