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EXPERIMENTAL INVESTIGATIONS ON CONCRETE BEAMS REINFORCED WITH CFRP LAMELLAS

Abstract

Paper presents experimental investigation made on two concrete beams reinforced with internal Carbon Fibre Reinforced Polymer (CFRP) lamellas (i.e. strips, bands). The reinforcement geometrical arrangement was similar as in normal concrete beams reinforced with steel bars and stirrups. The beams were destroyed by the shear forces, as intended. Obtained load-carrying capacities were lower as expected: below 40% of a calculated value. The reason of the untimely fracture was insufficient strength of connections between the vertical and longitudinal lamellas.

1. Description of the tested samples.

Two samples were made for the purpose of the test [1]. They were concrete T-beams reinforced with the CFRP lamellas. The length of the beams was 276 cm, effective span was 240 cm, the depth of the beams was 32 cm. Figure 1 presents the geometry of the beams and their reinforcement.

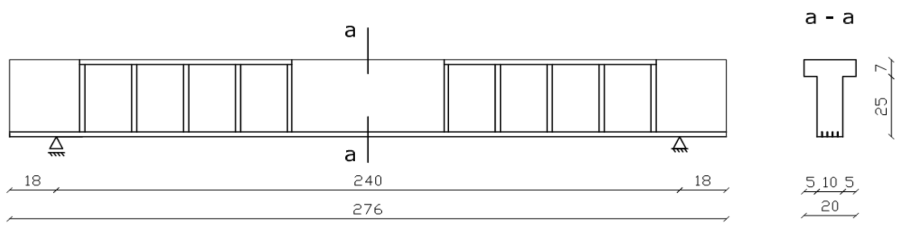

Fig. 1. Geometry of the beams.

Samples were made using concrete grade C30/37. The real mean compressive strength of the concrete, as measured on six 150/300mm cylinder samples after 28 days, was 41,75 MPa.

As the reinforcement CFRP lamellas were used made from carbon fibres infused into an epoxy resin matrix. The lamellas (S&P Lamelle CFK 200/2000) were provided by S&P. Calculations and analysis were based on material parameters as provided by the manufacturer: tensile strength f_t=2500 MPa and elastic modulus E_t=210 GPa.

The reinforcement was prepared as a series of frames which were fixed together with the appropriate segments of the lamellas. The mounting material was a two-ingredient epoxy resin glue, also provided by S&P.

The main flexural reinforcement was taken as eight segments of the lamella which were mounted in pairs. The external segments were made as frames consisting of 10 vertical segments of lamellas (5 for each side of the beam) acting as stirrups connected with the bottom and the top longitudinal reinforcement. The arrangement of the reinforcement is shown in Figure 2. Figure 3 presents one of the reinforcing cages.

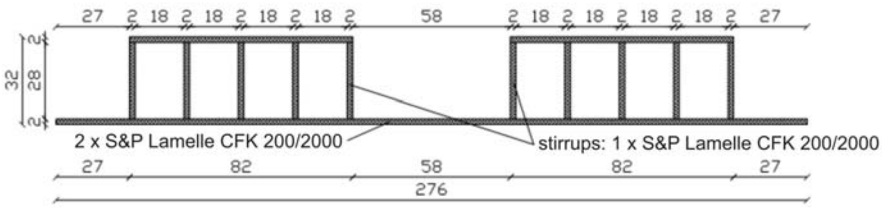

Fig. 2. Scheme of the reinforcement with CFRP lamellas.

Fig. 3. Reinforcing cage before covering with sand

In order to improve the bond between the reinforcement and the concrete, the frames were covered with 1.0-2.0mm grain sand, following the application of the epoxy resin. The same epoxy resin was used for the mounting of he separate reinforcement parts. Gaps were left for strain gauges only.

2. Description of the setup

The force from the piston of the tester (2P) was transferred to the beam by the travers, which was decomposing it into two concentrated forces. (Fig. 4, Fig. 5). With such parameters of the setup, the slenderness of the shear was *a/d* = 70/30 = 2,33.

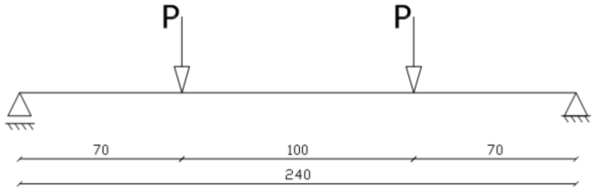

Fig. 4. Scheme of the beam load

Fig. 5. The beam at the setup

3. Implementation of the experimental tests.

Each of the beams was loaded statically, with the load being gradually increased. Readings were taken at each stage of the test. They were taken following a few minute stoppage to stabilize the load. Beams were also inspected for cracks. Following the readings were taken during the test.

- Beam deflection in the middle of the span
- Strain of the concrete – using an extensometer with a 100mm base, with bases mounted vertically in the stirrup lines in the middle of the beam depth.
- Strain in the longitudinal and lateral reinforcement – with electro-resistant strain gauges.

The arrangement and the symbols of the extensometer bases, the strain gauges and the reading positions as described above are shown in Figure 6.

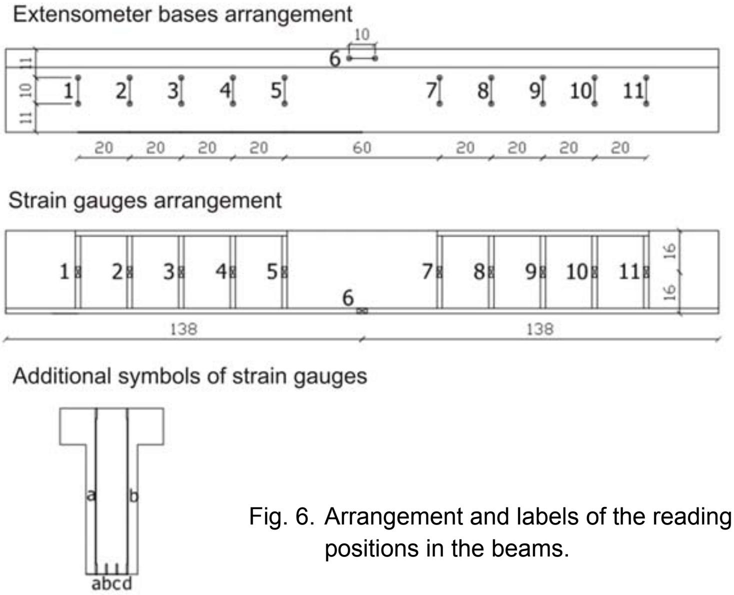

Fig. 6. Arrangement and labels of the reading positions in the beams.

Cracking from bending was noted in both tested beams at the load of 2P = 30 kN. At the force of 2P = 60 kN the first diagonal cracks from shear were noted.

Distinct diagonal crack in beam 1 occurred on the right hand side support. The crack has cut through the base of the extensometer (No 9) The strain of base No 9 was approx. 6‰, with the load of 2P = 100 kN and it grew to 10,6‰ with the further increase of the load. This suggests a 1 mm width of the crack. Further increase of the load resulted in the loss of the load-bearing capacity at the force of 2P = 135 kN. This was accompanied by a distinct sound of a short, single crack. The load was re-applied to the beam. This resulted in the complete damage of the beam with the crushing of the T- flange concrete. (Fig. 7)

Fig. 7. Cracks in beam 1 on right hand side support

Cracking in beam 2 was more even. Distinct diagonal cracks were noted at both supports at the load of 2P = 60 kN. The cracks were increasing with the increase of the load, with a rapid loss of load-bearing capacity at the force of 2P = 151 kN. Similarly to beam 1 it was accompanied by a distinct sound of a short, single crack. Following that the force of 2P = 155 kN was applied to the beam. This resulted in the complete loss of the load bearing ability of the beam.

4. Analysis of the test results

Observation of the beams during the test as well as the results confirm that the beams were destroyed by the shear forces, as intended. Beam 1 lost its bearing capacity under the load of P=67,5 kN, beam 2 under the load of P=77,5 kN. Real load bearing capacities for both beams were much smaller then assumed for such parameters of the lateral reinforcement. Based on the manufacturer's data the load bearing capacity for shear, assuming failure of the stirrup, is P = 197,28 kN. Design code [2] was used to calculate that capacity. It means that the force obtained from the tests - P_{max} = 77,5 kN equals only 40% of the expected load-bearing capacity.

Fig. 8 shows stress diagrams in the most strenuous stirrups of beam 2. The stresses were calculated on the basis of the strains recorded during the tests. The maximum stresses in the stirrups as measured during the test were: σ_{8bmax}=1052,1 MPa for beam 1 and σ_{9bmax}=1128,5 MPa for beam 2. They were 42% and 45% of the lamella' strength of σ_{max} = 2500 MPa. Considering the fact that the tested beams were deeply cracked in the final phase of the loading, it seems that most of the shear forces were transferred by the lateral reinforcement only.

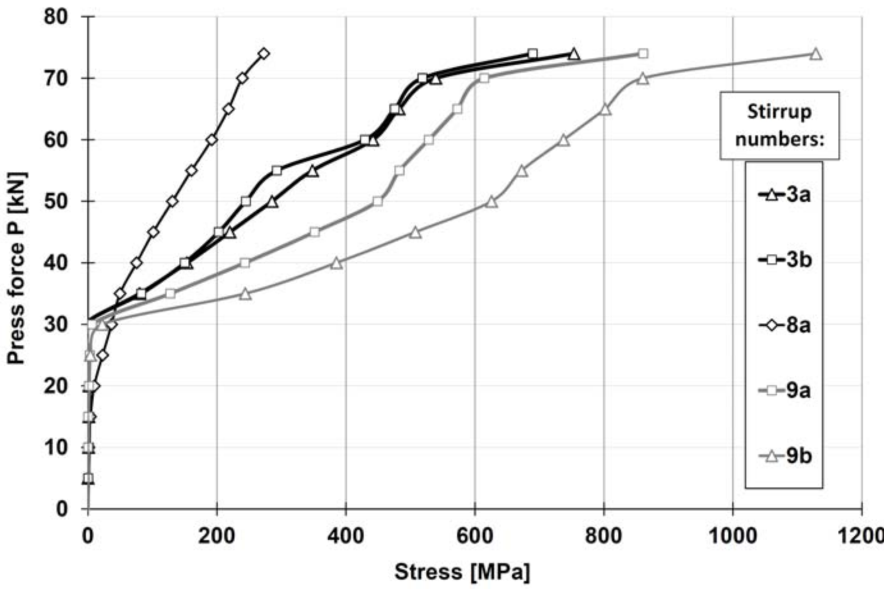

Fig. 8. Stress diagram in chosen stirrups of beam 2

All of the above leads to a conclusion that the reason for the loss of the load bearing capacity for shear was not the loss of the load bearing ability of the stirrups – but the failure of the joint between the stirrups and the main reinforcement. It is apparent in the cracks of both beams that the stirrups were removed from the main reinforcement (Fig. 9). Most probably the failure of the connection was the reason of the distinct cracking sound which was heard during the test of both beams.

Fig. 9. Apparent sliding separation of the neighbouring stirrups from the main reinforcement in beam 1.

Main reinforcement stresses were increasing evenly from the moment of the crack (Fig. 10). Maximum stress in the lamellas in the middle of the span was $\sigma_{6c,max}$ = 905,7MPa for beam 2, which was 36% of the lamella strength. Even increase of the stress in the longitudinal reinforcement indicates a good collaboration of the reinforcement and the concrete. The test confirmed the high effectiveness of covering of the composite reinforcement with sand, for assuring good bond between the concrete and the reinforcement. This was confirmed during the observation of the destroyed beams where the side surface of the lamellas was uncovered.

As for the lateral reinforcement, the good collaboration between the concrete and the reinforcement is proven by the comparison of the reading of the strains in the concrete, as meassured with the extensometer (extensometer bases fixed to the concrete surface) with the readings at strain gauges glued to the surface of the lateral reinforcement lamellas. Figure 11 shows readings from the most strenuous bases 3 and 9 in beam 2, along with the relevant strain gauge readings.

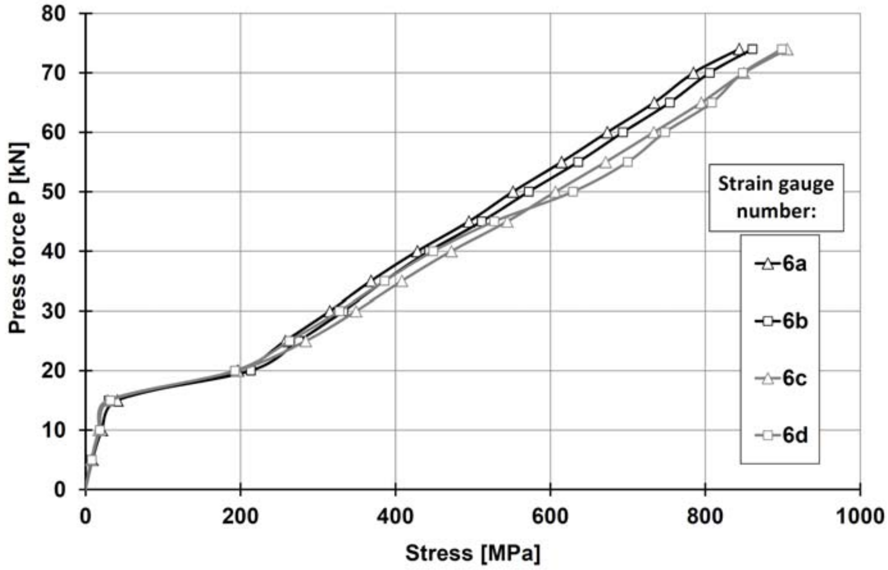

Fig. 10. Stress diagram in the longitudinal reinforcement of beam 2

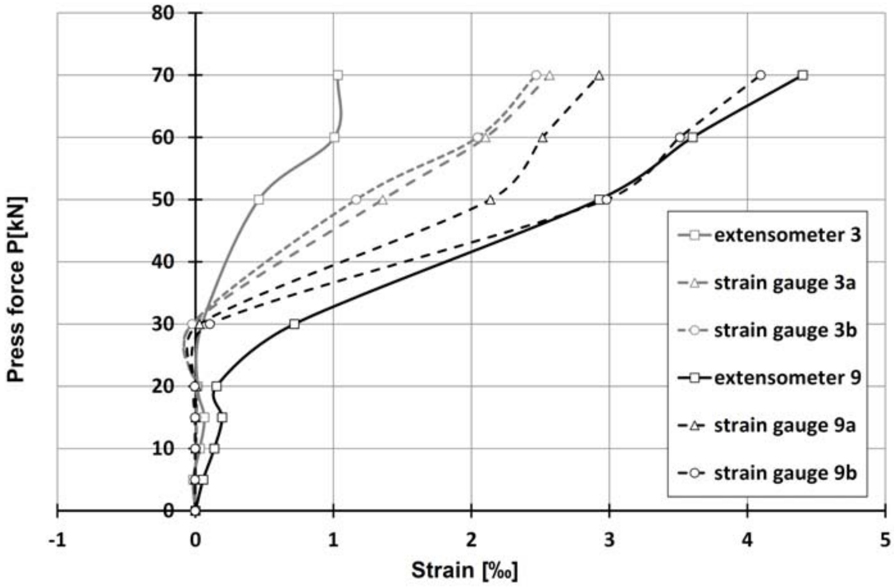

Fig. 11. Comparison of the strains as measured at the extermometers' bases with strain gauge readings for beam 2

Based on the graph above it becomes apparent that both reading methods indicated the appearance of the inclined cracks with the increase of the strains. In case of base 9 and tensometer 9 the readings are almost the same. This confirms the good collaboration between the concrete and the lateral reinforcement. Strains measured at base 3 are lower than the ones read from the strain gauges. The difference may be a result of a different course of the main crack which did not cross base 3, as it did for base 9. The lack of the situation where the extensometer reading was higher than the strain gauges reading confirms that the slide of the vertical reinforcement did not appear.

During the test also displacements were measured in both beams for each phase of the loading. The results are illustrated in Fig. 12. As shown, both beams were behaving similarly with a bi-linear *load – displacement* relationship.

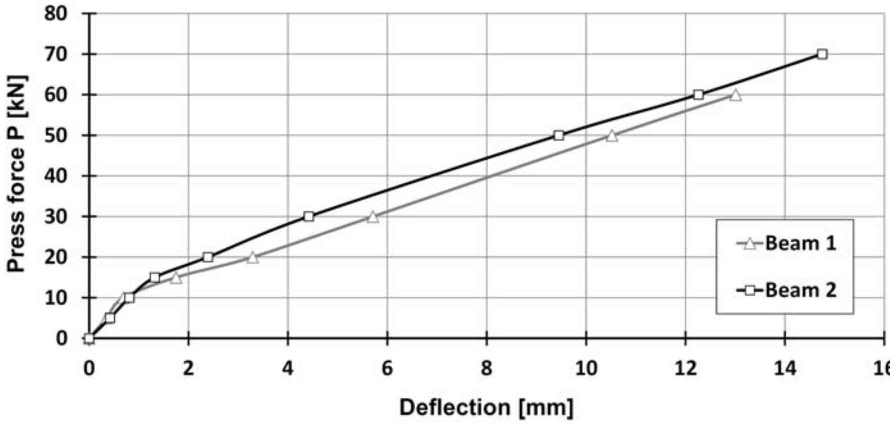

Fig. 12. Deflection diagram of the beams.

According to the design code [2] the maximum allowed deflection for the beams with a span up to 6 m is $a_{lim} = l_{eff}/200$. Based on this the maximum deflection for the tested beams is:

$$a_{lim} = l_{eff}/200 = 2400/200 = 12 \text{ mm.}$$

Therefore the maximum allowed deflection was achieved for both beams even before the loss of load bearing capacity with the loading force P between 50 kN and 60 kN. This equalled to 81% for beam 1 and 76% for beam 2, of the load bearing capacity as achieved in the test.

The width of the cracks was not investigated as part of the test. However it can be estimated based on the readings taken at the bases of the extensometer. The maximum strain readings were achieved at base 9 in both tested beams. A distinct increase of the strains in these bases was associated with the widest inclined crack from shear which passed through them. Therefore it seems that the strains at the bases closely reflect the width of the cracks which pass through them. Fig. 13 presents the strains as described above.

It should be noted that the durability of the FRP reinforcement is much different from the durability of the steel. As for that the expectations for the width of the cracks which are applied to the composites should differ from the ones for the reinforced concrete. Therefore (following the US design code [3]) there are two allowed crack levels agreed: w_{lim}=0,7 mm inside the buildings and w_{lim}=0,5 mm on the outside. Table 1 shows that beam 1 surpassed the above criteria with the loading force of

P=50 kN. Beam 2, which was cracking more evenly, satisfied both of the criteria within all spectrum of the loads until the total loss of the load-bearing capacity.

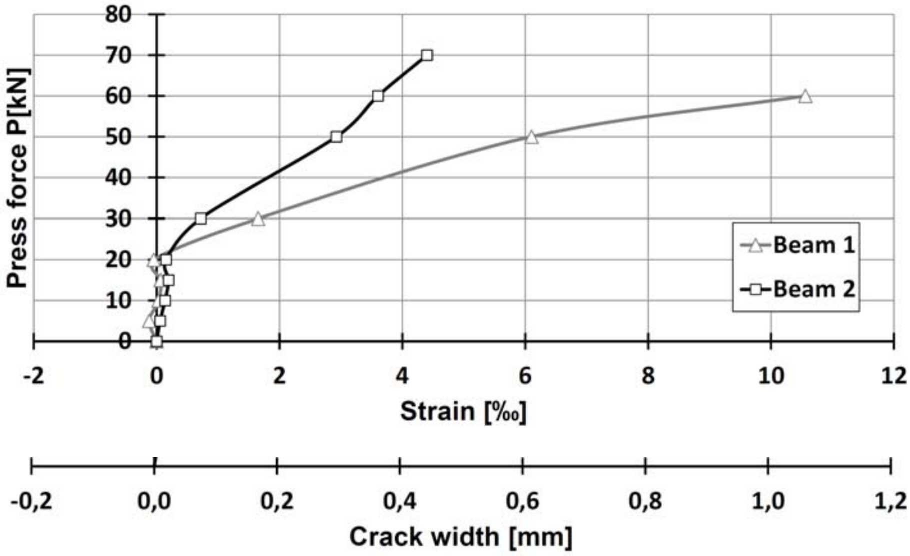

Fig 13. Strains at extensometer base No 9 and the corresponding width of the inclined cracks.

5. Conclusions

Based on the tests on the behaviour of the concrete beams reinforced with the CFRP lamellas following conclusions were made:

- the full capacity of the lateral CFRP reinforcement for shear was not achieved in the tested beams, because of the loss of the adherence of this reinforcement with the longitudinal reinforcement (the failure of the connection between the lateral and longitudinal lamellas);
- high effectiveness of covering of the CFRP reinforcement with the sand, for enhancement of the bond between the concrete and the reinforcement was confirmed; neither lateral nor longitudinal reinforcement shifted in any of the beams;
- rapid mechanism of destruction of the beams reinforced with the composite materials was confirmed; For safety reasons this should be taken into account using the appropriate safety factors;
- maximum acceptable deflections were achieved only in the final stage of the experiment, with the 76% to 81% of the achieved testing load bearing capacity;
- beam 2 shown a small width of the crack, compliant with the codes, until the total loss of the load bearing capacity; this is considered as a satisfying result;

- the main flaws of the CFRP lamella reinforcement are: labour consumption in preparation of the reinforcement, low load bearing capacity at the reinforcement joints.

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