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FINITE ELEMENT ANALYSIS OF BOND BEHAVIOR IN A STEEL REINFORCED CONCRETE STRUCTURE STRENGTHENED CARBON FIBRE REINFORCED POLYMER (CFRP) STRIPS

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Preliminary Note – Prethodno priopćenje

The article deals with the analysis of influence of carbon-fibre reinforced polymer (CFRP) on stress distribution in a steel reinforced concrete beam loaded by four-point bending flexural test. Simulation of the delamination is modelled by FEM with a cohesion zone material model. Distribution of cracks with CFRP strengthening is analysed, too. Finally, the fatigue life tests analysis was executed for the steel specimen (W.Nr. 1.0429 – concrete steel), which was used in the reinforced concrete beam. The fatigue test results are used to plot the fatigue life curve.

Key words: steel, strengthened, polymer strip, stress, finite element method (FEM)

INTRODUCTION

In the past decades, the use of composites for strengthening and repairing concrete structures has gained significant importance in civil engineering [1-3]. There are a large number of new, innovative building materials on the market. In order to avoid a drastic impact of building materials now or in the future, these materials as well as their manufacture and use must comply with the ecological standards. The trend of developing new building materials is not characterised by inventing something new, but rather by improving something long-existing. The aim of this study is to create a model to simulate a four-point bending loading experiment on a reinforced concrete beam with and without carbon-fibre reinforced polymer.

FEM SIMULATION OF A REINFORCED CONCRETE BEAM

Experimental measurements of four-point bending of a reinforced concrete beam were carried out in our laboratory. Figure 1 show that the contact between the load and the beam, as well as the contact between the supports and the beam. The surface representing half profile of the T-beam is divided into smaller areas, borderlines of which will be used later to create a mesh of link/beam elements forming the steel reinforcement. The element Solid65 was used for discretization the steel reinforcement. The dimensions of the full-size beams are 3600 mm x 350 mm x 400 mm and the span between the supports was 3310 mm. Moreover, the lower part of the beam includes a milled groove in the covering layer. The groove is 4 mm wide, 20 mm deep, and 3 000 mm long, positioned symmetrically in relation to the transverse plane of the beam symmetry (Figure 2).

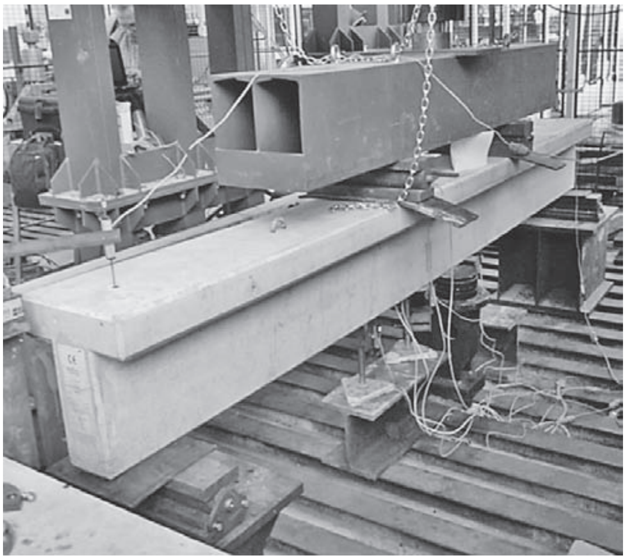

Figure 1 Experimental stand for four-point bending test

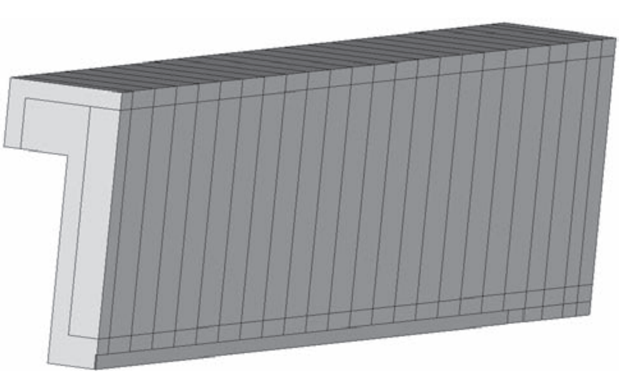

Figure 2 Geometric model of the reinforced concrete beam with a gap or the composite lamella

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MODELLING THE LAMELLA AND ITS BONDING WITH THE CONCRETE

Bonding the lamella with the concrete is modelled using the conta173 contact elements, considering the contact with adhesive bonding (bonded always contact), and using a cohesive material model (CZM – Cohesive Zone Material). We used the data provided by the manufacturer of the glue. We assumed a dominant shear mode of breaking the bonded joint. This material model requires entering τ_{max} = 12 MPa (maximum equivalent contact shear stress), δ_t = 1 mm (tangential displacement after debonding). This value is not stated by the manufacturer and must be obtained through an experiment [4].

In the post-processing, for the contact defined in the above manner, we can evaluate the generally known data, such as contact status, contact gap, contact pressure, as well as the following variables:

DPARAM – debonding parameter – this parameter takes a value from 0 to 1, where the value 1 corresponds with the breaking of the bonded joint, and the value 0 corresponds with the initial unbroken joint,

DTSTARI – the time step at which debonding occurred.

BOUNDARY CONDITIONS

The solution is significantly influenced also by the manner used for the beam positioning modelling. In order to prevent the formation of stress concentrators, we modelled a plane support with a width corresponding to the experiment, and a joint in the support width centre. The above was done using shell elements – shell181. The nodes in the support width centre were removed of all degrees of freedom for displacement, and we retained all degrees of freedom for rotation. Contact with the beam was done using the conta173 and target170 contact elements. A support modelled in this manner has no longer caused the formation of stress concentrators in its vicinity; therefore no cracks occurred in this area [5].

The load acting on the beam in its upper part was created as a quarter of the total force F = 110 kN acting on the small area formed by the experiment requirements. The small area is 150 mm wide and its distance from the beam centre is 500 mm [6].

MATERIAL PROPERTIES

Concrete: the concrete according to STN EN 206-1 was used (Concrete STN EN 206-1-C35/45-Cl0, 04-D_{max}16-S3). The material properties of the concrete are: Young's concrete elasticity modulus E = 34 GPa, ductility stated by the manufacturer ε_{cu} = 0,035, Poisson's rate μ = 0,2, the concrete density ρ = 2 400 kg.m^{-3}.

Steel reinforcement: the concrete steel B500 B according to STN EN 10027 was used: strength R_c = 500 MPa, ultimate tensile strength R_m = 550 MPa, Young's modulus E = 200 GPa, ductility ε = 0,005, Poisson's rate μ = 0,3.

Composite lamella: the simulated composite lamella is made by the BASF company. Its trade name is MBRACE CFK 150/2 000. The composite lamella dimensions are 20 x 1,4 x 3000 mm. For this lamella type, the manufacturer states the Young's modulus larger than 165 GPa, Poisson's number μ = 0,2 and the recommended design tensile strength is 51,8 kN, which means that the uniaxial tension stress is 1 850 MPa at the lamella cross-section of 28 mm^2.

High-strength epoxy glue: to affix the lamella into the groove in the beam we use high-strength epoxy adhesive with a high glass transition temperature for the MBRACE lamella system by BASF, with the trade name MBRACE Laminate Adhesive HT. Its bond strength is >14 MPa, compressive strength is 73 MPa, bending elastic modulus is 4263 MPa, glass transition temperature is ≥ 40°, shrinkage/ expansion is ≤ 0,1 % [5].

ANALYSIS OF THE RESULTS

Figure 3 shows the maximum deflection in the middle of the reinforced concrete beam with a lamella, and it reaches the value w_{max} = 7,57 mm. This value is slightly reduced compared with the model with CFRP lamella [6]. Due to bending, the free end of the beam behind the support is displaced upwards by 0,89 mm. Figure 4 shows the first principal stress in the concrete. This value indicates the sites that are critical for the concrete deterioration due to a high tensile stress, which concrete naturally "does not like". High values are present in the beam lower side. The maximum is reached due to concrete deterioration consideration, and it appears near the steel reinforcement.

Due to the lamella groove, and the lamella with a high elasticity modulus, concentration of stresses occurs near the original beam/groove interface. The maxi-

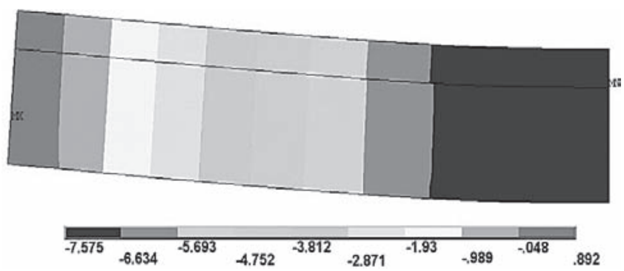

Figure 3 Displacement of the reinforced concrete beam with a lamella

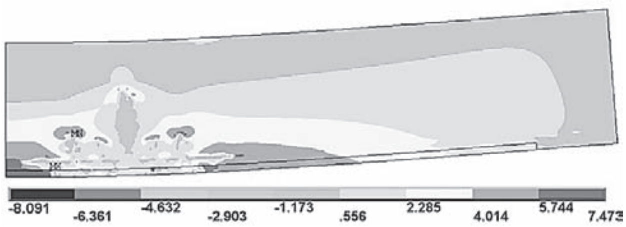

Figure 4 First principal stress in the concrete

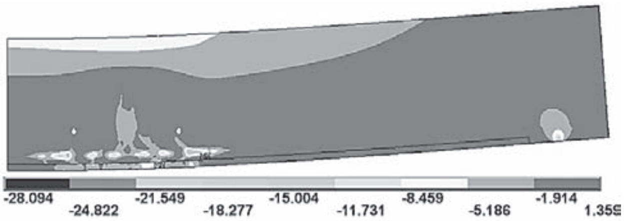

Figure 5 Third principal stress in the concrete

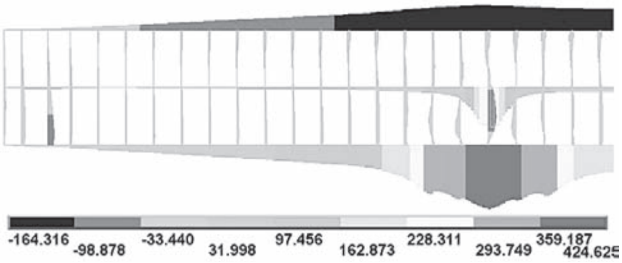

Figure 6 Axial stresses in the concrete beam reinforcement

mum value dropped and moved to this area from the steel reinforcement site.

Figure 5 shows the third principal stress in the concrete. This value shows the areas where concrete crushing might occur in case of exceeding the concrete compressive strength.

The maximum reached value is - 28,1 MPa is below the used concrete compressive strength, therefore there should be no crushing.

The stress value was higher compared to the previous case and, like in the first principal stress, the value moved from the steel reinforcement to the site of the lamella groove [6].

The course of axial stresses in the reinforcement is shown in Figure 6. As we can see, compressive stress occurs in the upper part of the reinforcement. The maximum compressive stress emerged near the action of the loading pressure, and the compressive stress value in the reinforcement reached the value $p_{max,steel}$ = 164,32 MPa. The maximum tensile stress emerged in the bottom part of the steel reinforcement, at the site under the loading force, and its value reached $\sigma_{tmax,steel}$ = 424,63 MPa. This value is lowered compared with the model without the composite reinforcement, but it is still near the value of the yield strength R_c.

Figure 7 shows the pink-coloured cracks formed in the concrete as a result of exceeding the concrete tensile strength. These cracks occur around the T-shaped steel stirrups.

The shape and length of cracks has changed significantly compared with the case without a lamella. Although there is still one significantly long crack at the site under the acting load, other cracks are of approximately the same length.

In Figure 8 we can see the DPARAMJ and DPARAMI values that indicate the probability of adhesion loss of the glue and the lamella.

The maximum value is cca 0,94, which represents a 94 % probability of adhesion loss. According to the DTSTARI value, this should occur in the last, 9th loading step, at the site filled with red.

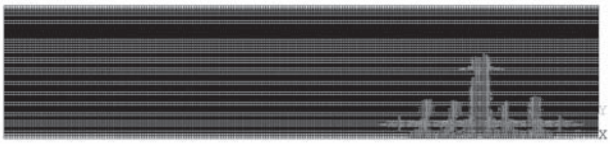

Figure 7 Depiction of cracks in the concrete

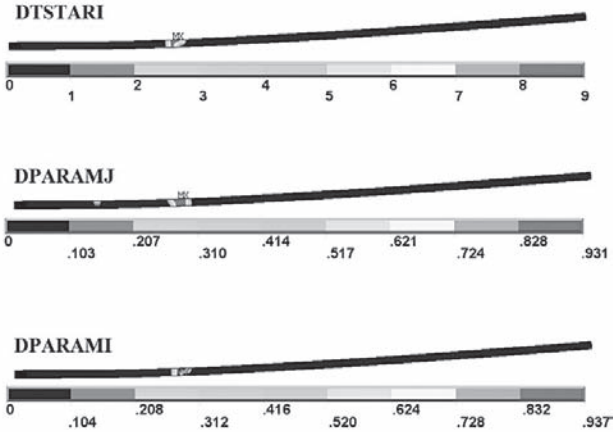

Figure 8 The probability of adhesion loss with loading steps

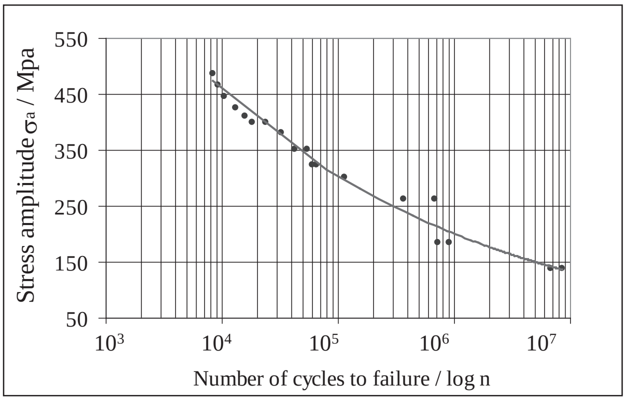

Figure 9 Wöhler curve of 1.0429 steel (bending)

Finally we carried out low-frequency fatigue tests on the W. Nr. 1.0429 steel to determine fatigue life in the low-cycle fatigue domain. We gradually tested the specimen bars in a multiaxial test device for a single-axis type of loading, which was done at provided air-cooling. The resulting number of cycles prior to fracture, frequency of the fatigue loading, and the eccentric deviation setting value were entered into a worksheet. Figure 9 shows the measured values at low-frequency experimental testing, processed in a regression analysis [7-10].

CONCLUSIONS

The results obtained show that the use of the above-mentioned composite lamella changes the stress distribution in the concrete matrix as well as in the steel reinforcement. This is manifested by the reduction in the maximum stress values in the tensile domain for both the concrete and the reinforcement, and in case of the concrete also by increased maximum compression stresses, which is favourable for concrete. The maximum bending (deflection) values are very similar in the two cases. It also results from the data obtained that there will be no adhesion compromise between the concrete and the lamella (the maximum value is 94 % of the bond ultimate shear strength), but there will occur delamination in the concrete. The shape and size of the cracks in the concrete have changed as well. Based on the values measured in fatigue tests, the fatigue strength can be approximately determined at the number of cycles prior to fracture N_f = 1.107. Hence, the fatigue life of the tested material of concrete (reinforcing) steel could be around 110 MPa.

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Note: The responsible translator for the English language is Janka Súkeníková, Sarja, Žilina, Slovakia