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Modelling of strengthening of concrete beams with FRP in Ansys software

Modelowanie wzmacniania belek żelbetowych za pomocą FRP w programie Ansys

DOI: 10.15199/33.2022.11.54

Abstract. The purpose of this article is to confirm an accuracy of Cohesive Zone Model (CZM) implemented in Ansys for modelling concrete beams strengthened with fiber reinforced polymer (FRP) tapes. Only mode II of debonding was taken into account, which is sufficient for a case of bent beam strengthened with FRP tape glued to its bottom. Results show satisfying coincidence of used model with experimental data and therefore confirm usefulness of CZM for solving the above mentioned problems.

Keywords: concrete structures; finite elements method; fiber reinforced polymers; Ansys.

Streszczenie. Celem artykułu jest weryfikacja dokładności modelu Cohesive Zone Model (CZM), zaimplementowanego w programie Ansys, w modelowaniu numerycznym belek żelbetowych wzmacnianych taśmami z polimerów zbrojonych włóknami (FRP). Wzięto pod uwagę jedynie postać II utraty przyczepności, co jest wystarczające w przypadku belek zginanych wzmocnionych taśmą przyklejoną do ich spodu. Wyniki pokazują zadowalającą zgodność użytego modelu z danymi eksperymentalnymi i tym samym potwierdzają użyteczność CZM do rozwiązywania ww. zagadnień.

Słowa kluczowe: konstrukcje betonowe; metoda elementów skończonych; polimery wzmacniane włóknami; Ansys.

Strengthening concrete structures with fiber reinforced polymers (FRP) is a popular method of strengthening existing structures. This is mostly due to ease of mounting process, no heavy machinery requirement and almost no change in structure volume and shape [1 – 3]. Yet, there are some disadvantages of this method, too. The most significant are a dependence of strengthening effect on a concrete surface condition and preparation and a debonding phenomenon, which significantly reduces effectivity of this method. There is already a broad set of publications about ways of modelling FRP reinforced concrete beams, to name but a few: [4 – 6].

The purpose of the following paper is to confirm usefulness of the Cohesive Zone Model (CZM) implemented in Ansys software for modelling concrete beams strengthened with fiber reinforced polymer (FRP) tapes, loaded mostly in flexure. Such types of structures exist in most structures, where vertical loads are to be transferred by horizontal elements. Models were developed using Ansys Mechanical module. Experimental data were taken from [7]. Although the research was carried out about 20 years ago, it was chosen as a base due to completeness of its input and output data. Beam BF1 was used for validation of reinforced concrete model. Beam marked BF2 in the thesis was utilized to verify FRP behavior. It is worth mentioning that more effective ways of reinforcing structures with FRP than passive method (e.g. prestressed FRP) are available. But, since the aim of the paper is to verify CZM accuracy, these methods will not be taken into account.

Materials and methods

The analyzed beams were simply supported and subjected to a 4-point bending. A span length was 3,8 meters and the total beam length was 4 meters. A length of the FRP tape itself was 3,66 m. A load was applied vertically downwards. The analysis was controlled by displacement increments. The beam was 200 mm wide and 450 mm in height (see Fig. 1). Static calculations were performed assuming large deflections analysis, taking account for materials nonlinearity.

Concrete compressive strength was tested for each of 9 beams separately at the time of beam test, which was 56 days after pouring. The cylinder strength of concrete for beam BF1 was given as 33,7 MPa, whereas for BF2 it was 36,5 MPa. Concrete was modelled by means of a microplane coupled damage-plasticity model with gradient regularization (MCDPMwGR) described in [8, 9]. Parameters of concrete were determined based on curve fitting for both beams simultaneously. The best fit

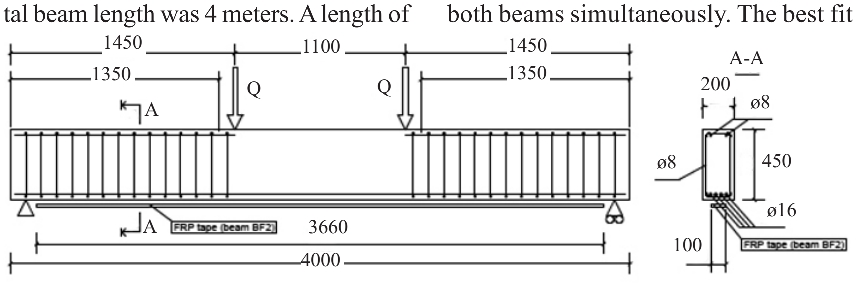

Fig. 1. Geometry and load scheme of analyzed beams
Rys. 1. Geometria i schemat obciążenia analizowanych belek

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was ensured by the following set of parameters:

- Over-nonlocal averaging parameter: m = 2,5;
- Tension damage threshold: $\gamma_{t0} = 0$;
- Compression damage threshold: $\gamma_{c0} = 0$;
- Tension cap hardening constant: $R_T = 1$;
- Ratio between the major and minor axes of the cap: R = 1;
- Hardening material constant: D = 0;
- Tensile damage evolution constant $\beta_t = 6000$;
- Compressive damage evolution constant $\beta_c = 0$;
- Nonlocal interaction range parameter c = 2000.

Concrete block was modelled by hexahedral elements CPT215 intendent for coupled problems. Average finite element size was 25 mm. A yield strength of reinforcing steel was taken directly from tensile tests. These values were 560 and 590 MPa for rebars of diameter 8 and 16 mm, respectively. Longitudinal reinforcement in the test beams constituted 4 bottom rebars of 16 mm diameter and 2 top rebars of 8 mm in diameter (see Fig. 1). Transverse reinforcement was in the form of stirrups, 8 mm in diameter, spread with 100 mm space over a 1,25 m length section of the beam measured from the center of support. Model of steel reinforcement bars used 1-dimensional, 2-nodal finite elements, with 1 degree of freedom per node, accounting for longitudinal stiffness only. They were modelled as embedded in concrete, according to Ansys internal routine. Material model for steel was assumed bilinear. Furthermore, isotropic hardening was also defined, based on values defined in Eurocode 2. Young's modulus of reinforcing steel was taken as 200 GPa and a Poisson ratio – 0,3. A modulus of plastic strain of reinforcement (E_T) was determined during model calibration and the best fit was obtained at 24 GPa for bottom and 15 GPa for top reinforcement.

During the test, beamsnamed BF1 and BF2 collapsed under thetotal load (2Q according to Fig. 1) of 144,2 and 185 kN, respectively. At the failure, the beams deflected by 43 and 33 mm, respectively. The geometry and the dimensions of a cross section, as well as the test beam reinforcement distribution, are summarized in Fig. 1.

The Ansys code was used together with Cohesive Zone Model (CZM), for modelling the debonding effect. It uses Alfano and Crisfield model [10] for interface models for the delamination of composites. Debonding model parameters were determined according to [11], since some other papers, e.g. [12] report its accuracy. Fracture energy based approach was adopted. Fracture energy was equal 570 J/m^2, and an ultimate slip (at full debond) is calculated as 0,22 mm.

To be able to properly reflect a behavior of strengthened beam, proper characteristics of both, materials and an interface between them, have to be defined. The stress-strain curves for FRP plates/tapes are known to be linear up to the failure point [12]. Since the ultimate strength of FRP is considerably high, linear elastic material type for it may be easily assumed. Notwithstanding that, a bilinear elastic – perfectly plastic material was assumed. A Young's modulus was taken equal 189 GPa, following results of performed FRP tensile test. Likewise the tensile strength equal 3,2 GPa. The tapes were modelled using 2-dimensional, planar, quadrilateral, 4-node finite elements with 6 degrees of freedom in each node.

Some publications report significant influence of a shear resistance on flexural debonding load-carrying capacity [13]. Accounting for this shear resistance explicitly would be somewhat tedious. Therefore Cohesive Zone Model may be used, where traction-slip relation is established, separately for normal (mode I) and tangential (mode II) directions. It is also possible to include both modes simultaneously (mixed mode). Then a non-dimensional parameter β assigns different weights to the tangential and normal displacement jumps:

$$\lambda = \sqrt{(\delta_n/\delta_n^c)^2 + \beta^2(\delta_t/\delta_t^c)^2} \qquad (1)$$

Where meaning of all symbols is explained in table 1.

Table 1. Cohesive Zone Model parameters
Tabela 1. Parametry Cohesive Zone Model

Meaning	Property
σ_{max}	maximum normal traction
δ_n^c	normal displacement jump at the completion of debonding
τ_{max}	maximum tangential traction
δ_L^c	tangential displacement jump at the completion of debonding
α	ratio of δ_n^* to δ_n^c, or ratio δ_n^* to δ_t^c
β	non-dimensional weighting parameter

Since the interface between the beam and the FRP tape, fixed to the bottom of the beam, is subjected mostly to shear, mode I might be omitted in this case, with no significant accuracy loss. This was verified during performed analyses.

There are two types of elements capable of using a CZM material model in ANSYS: Interface elements, based on a traction-separation (sigma-delta) constitutive behavior and occupying a finite thickness between the two surfaces that they join, and Contact elements, which have a zero thickness and can detect contact, separation, penetration and slip between a contact surface and a target surface. In this work, due to negligible thickness of adhesive, the contact elements were used. Due to symmetry, only quarter of the beam was modelled. Fig. 2 presents numerical model.

Results

A failure in the model can be recognized by following debonding which is a failure mode of the beam BF2. Full debonding should appear around maximum deflection, reached during experiment. According to experimental data, at the failure moment, more than a half of the beam length was subjected to full debonding. It may point that the bond was not sufficient. Important finding of the author of the mentioned research was that the most critical bond stresses did not occur in the anchorage zone (the ends of the tape). Knowing all that, one can adjust parameter values to fulfill the-

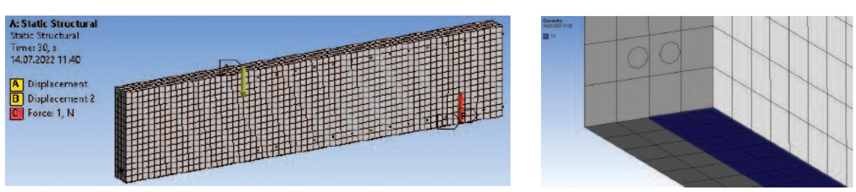

Fig. 2. Numerical model of the (quarter) beam BF2 (with FRP tape)
Rys. 2. Model numeryczny (ćwiartki) belki BF2 (z tasmą FRP)

se conditions. One more condition to be met is a midspan strain of FRP tape, which, in case of beam BF2 was 6,7 mm/m.

Fig. 3 shows comparison of total load (2Q) – mid span deflection between experiment and analysis. Figures 4-10 show strain in FRP, sliding distance, frictional stress, fracture energy, stress in concrete, FRP and steel reinforcement, respectively. All these outputs are captured at ultimate load. The pictures show half length of the tape. Strain in FRP fits perfectly (6,70 vs 6,68 mm/m). Maximum sliding distance equals 0,016 mm and it is located along the edges of the tape. Maximum frictional stress is also distributed near the edges with the top value of little above 5 MPa. Fracture energy (0,075 mJ) indicates reaching maximum tangential traction, which is 5,14 MPa. Maximum compressive stress in concrete reached its compressive strength at the top of the beam, in the vicinity of load application location. This fits experimental observations, as crushing of concrete occurs in corresponding area in tested beam. Fig. 9 shows that there is a huge reserve in FRP strength (1,26 vs 3,2 GPa). It indicates low effectiveness of this method of reinforcing. Fig. 10 indicates reaching yielding by both upper and lower reinforcement, which is also in agreement with experiment.

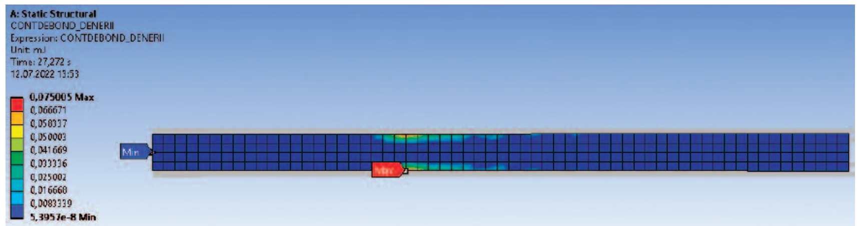

Fig. 7. Debonding fracture energy at ultimate load (half-length of FRP tape)
Rys. 7. Energia pękania związana z utratą przyczepności przy obciążeniu maksymalnym (połowa długości taśmy FRP)

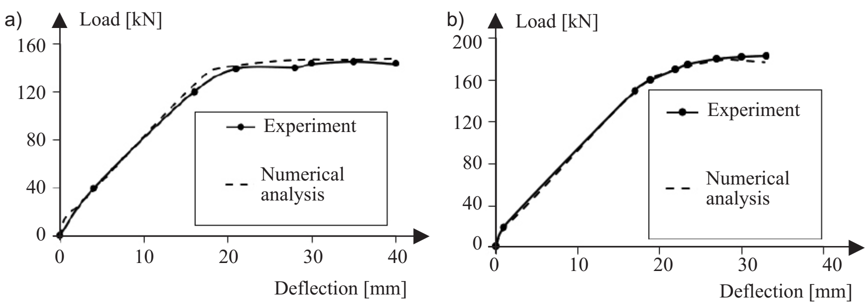

Fig. 3. Comparison of numerical and experimental load-deflection curves of beams BF1 (a) and BF2 (b) taking account of total load (2Q)
Rys. 3. Porównanie krzywych obciążenie-przemieszczenie z obliczeń i eksperymentu belek BF1 (a) i BF2 (b) pod obciążeniem całkowitym (2Q)

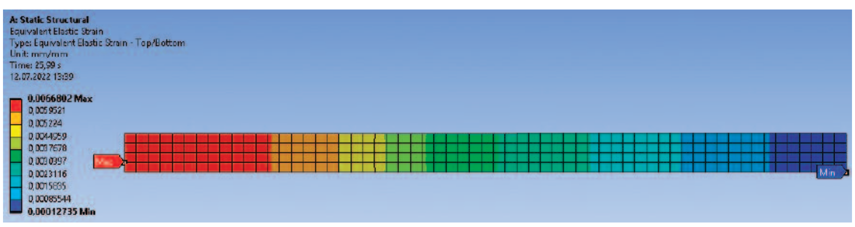

Fig. 4. Ultimate FRP strain (half-length of FRP tape)
Rys. 4. Odkształcenie końcowe FRP (połowa długości taśmy FRP)

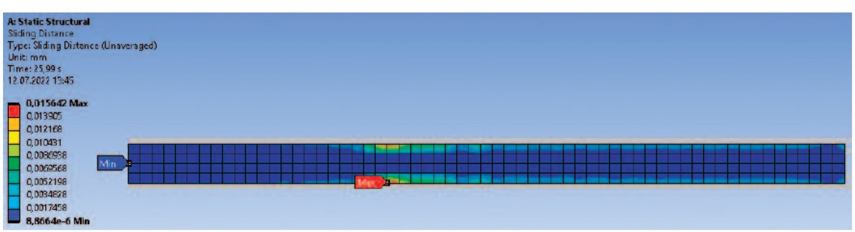

Fig. 5. Sliding distance at ultimate load (half-length of FRP tape)
Rys. 5. Długość poślizgu przy obciążeniu maksymalnym (połowa długości taśmy FRP)

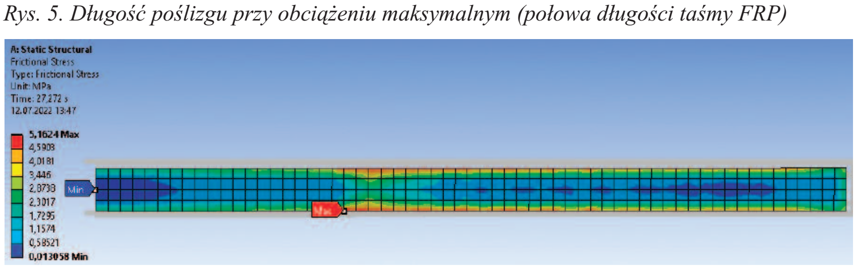

Fig. 6. Frictional stress at ultimate load (half-length of FRP tape)
Rys. 6. Naprężenie od tarcia przy obciążeniu maksymalnym (połowa długości taśmy FRP)

Conclusions and discussion

The article presents an approach to numerical modelling of reinforced concrete beams strengthened with FRP tapes using Ansys software, with its Cohesive Zone Model for composites delamination. Debonding model parameters were determined according to [11].

Output parameters like load-deflection curve, FRP strains, sliding distance, frictional stress, debonding fracture energy, stress in concrete, FRP and steel reinforcement have to be investigated. It was done in the above paper. The basic results, i.e. load-deflection curve and FRP strains are in very good agreement with the experiment. This indicates that CZM might be the right choice when it comes to simulation of beams reinforced with FRP tapes. Nevertheless, verification of one beam is not enough to make general conclusions about the usefulness of the model. But due to limited space, the results of other simulations were not presented here.

During modelling some important findings were noticed:

■ Adjusting debonding parameters in numerical model does not change the load-deflection curve significantly. That means, following load-deflection curve alone cannot be used to calibrate numerical model using CZM for debonding. One must observe other output parameters like FRP strains, sliding distance,

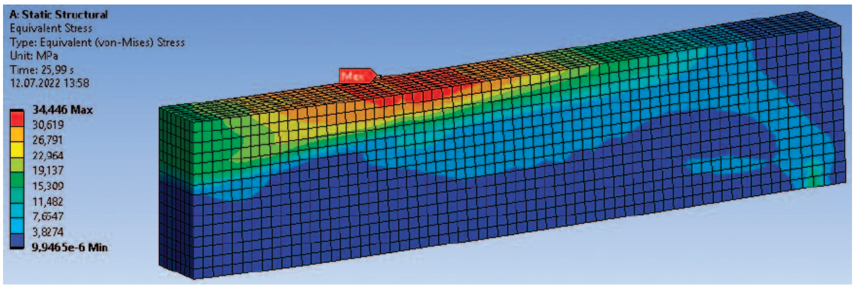

Fig. 8. Equivalent von-Mises stress in concrete at ultimate load (half-length of the beam)
Rys. 8. Naprężenie równoważne von-Misesa w betonie przy obciążeniu maksymalnym (połowa długości taśmy FRP)

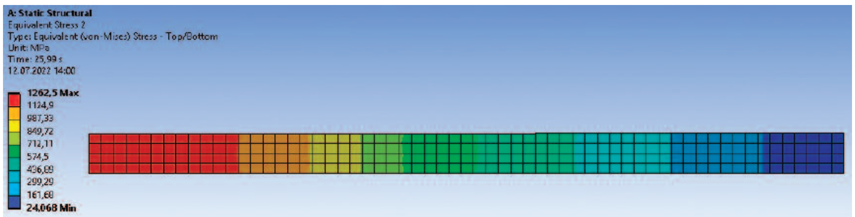

Fig. 9. Equivalent von-Mises stress in FRP at ultimate load (half-length of FRP tape)
Rys. 9. Naprężenie równoważne von-Misesa w FRP przy obciążeniu maksymalnym (połowa długości taśmy FRP)

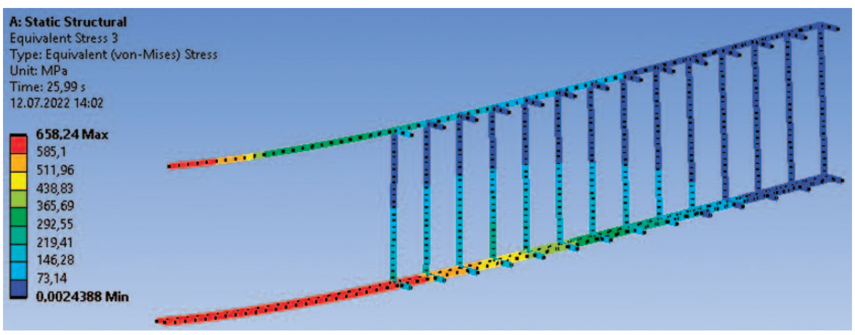

Fig. 10. Equivalent von-Mises stress in steel reinforcement at ultimate load (quarter of the beam)
Rys. 10. Naprężenie równoważne von-Misesa w zbrojeniu stalowym przy obciążeniu maksymalnym (połowa długości taśmy FRP)

frictional stress and/or debonding fracture energy.

■ High values of artificial damping may influence results significantly, so it should be kept at the lowest possible level to retain highest result accuracy.

■ Assuming high ultimate displacement jumps cause higher relative displacements in the model.

■ debonding parameters of CZM in Ansys do not influence the results significantly. It means that debonding model assumed is of secondary importance.

■ There is no full control over debonding behavior of the FRP-concrete interface in Alfano and Crisfield model [10], since only two parameters can be explicitly defined. To have the full control, at least three parameters are required.

There are numerous papers about numerical modelling of RC beams strengthened with FRP. The conclusions are often coincident with the conclusions extracted from this research. For example [14] also concluded that ultimate response assuming perfect bond does not differ from assumed bond-slip relationship. Also [15] successfully used mixed coupling model for simulation of delamination of FRP together with discrete crack model for concrete.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Przyjęto do druku: 07.10.2022 r.