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EFFECT OF FIBER REINFORCED POLYMER SHEETS ON WEB-SHEAR CAPACITY OF HOLLOW CORE SLABS

BY

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Abstract. The prestressed hollow core slabs are among the most common load bearing precast concrete elements in the world. They are widely used in floors and roofs of office, commercial, residential and industrial buildings. In this research, a finite element numerical model is presented to study the behaviour of the prestressed hollow core slabs reinforced using an innovative application of Fiber Reinforced Polymers on the internal surface of the slab's voids. Fiber Reinforced Polymer (FRP) composites are widely used for strengthening concrete structures due to many advantages over conventional retrofitting techniques. In order to emphasize the performance of this strengthening method, I- shaped single web beams cut longitudinally from the full width slab were analysed. This study is conducted using the Finite Element Method implemented in the Abaqus software. 3Dfinite elements and the damage plasticity model were used for the concrete regions, 2- node truss elements for the prestressing reinforcement and 8- node quadrilateral in- plane general-purpose continuum shell element for the FRP sheets. Numerical results are summarized in terms of: load-deflection behaviour, failure load and crack pattern.

Keywords: Precast prestressed hollow core slabs; FRP strips; Shear behaviour; Strengthening effectiveness.

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1. Introduction

The prestressed hollow core (PHC) slabs are frequently used products of the precast industry with wide applications in building construction, particularly as floor and roof structural elements (Brunesi *et al*., 2015). Advantages such as short construction time, high quality level and substantial reduction of self-weight are attainable and they can cover large spans, up to 20 m. The prefabricated units can be manufactured by various methods, for example slip-forming, wet casting, or extrusion on long-line prestressing beds. The technique of extrusion on long prestressing beds is becoming more and more used. Traditional vibrator concrete compacting systems have been replaced by extruders, which use the shear compacting principle. Shear compacting allows the use of low slump concrete, which can reduce curing time, save cement, and improve slab quality (Yang, 1994). The units, saw-cut to the desired length from long continuous strips, usually consist of plain concrete with several pretensioned strands. It is too difficult for the technique of extrusion to add shear reinforcement. The strands, which are tensioned in the casting beds before the casting and curing of concrete, are anchored in the hardened concrete by bonding after the saw-cutting of the units (Girhammar and Pajari, 2008).

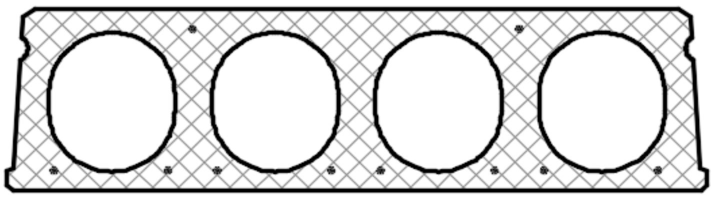

Fig. 1 – Cross-section of a four voids precast hollow-core slab.

During last decades, externally bonded Fiber Reinforced Polymer (FRP) composite sheets have been successfully applied in the retrofitting of reinforced concrete elements, especially in the case of beams and slabs (Sas, 2011). Precisely, the performance of strengthening the shear capacity of reinforced concrete beams and slabs using externally bonded FRP sheets was validated by several experimental studies. It has been demonstrated that reinforced concrete beams and slabs strengthened in shear using FRP strips showed up to 60% increase in the shear capacity over the un-strengthened slabs (Dhara *et al.*, 2015). A number of parameters were observed to substantially influence the consolidation method and these are the orientation of FRP sheets with the longitudinal axis of the element, the bonding surface and bonding agent, type of FRP sheets, thickness of FRP and the width of the strengthened zone (Wu, 2015). Nonetheless, the efficiency of FRPs has been demonstrated also on the structural behaviour of PHC slabs strengthened in flexure (Elgabbas *et al.*, 2009). Most of these recent studies have focused on ways to enhance the leading factor affecting flexural strengthening performance: the bond between prestressing strands and concrete (Hosny *et al.*, 2006).

2. Finite Element Modelling of the I-Shaped Single Web Beam

With the focus on examining the usefulness and efficiency of this new procedure regarding the enhancement of ultimate shear capacity and failure modes, the technique was applied to I-shaped single web beams cut longitudinally from the full PHC slabs, which can be considered as single web hollow core slabs (Wu, 2015). This research is part of an ample experimental and numerical programme of full scale PHC slabs externally retrofitted by FRP strips bonded along the full perimeter on both sides of the specimens. In order to understand the behaviour of full scale PHC slabs, this paper focuses on the numerical modelling validation of Wu's I-shaped single web beams, longitudinally cut out from PHC slabs, as shown in Fig. 2.

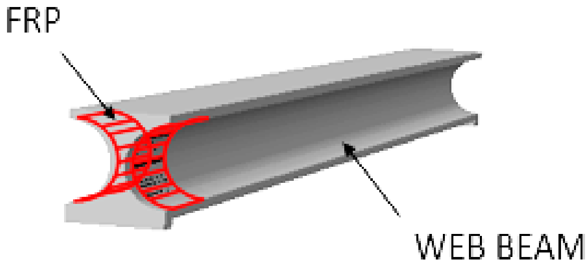

Fig. 2 – Single web hollow core unit strengthened with FRP sheets.

Regardless the fact that experimental data is compulsory in understanding the behaviour of this strengthening system, analytical and numerical solutions are also needed to further comprehend and estimate the failure modes and behaviour of the strengthened element. Numerical modelling of FRP-strengthened features means a tremendous challenge since aspects such as: loading sequence, construction process, nonlinear material behaviour, crack propagation and residual stresses may have a remarkable influence on the results obtained in such a manner.

2.1. Material Constitutive Behaviour

The choice of a proper concrete constitutive model plays a major role in the finite element simulation process. In ABAQUS, the software used for the numerical analysis in the present study, there are two concrete constitutive models: concrete smeared cracking model and concrete damage plasticity model

(Lubliner *et al.*, 1989). The last-mentioned one will be adopted in the current work to predict the constitutive behaviour of concrete. In this approach, it is assumed that compressive crushing and tensile cracking are the main failure mechanisms of concrete (Lee and Fenves, 1998). These phenomena are the result of microcracking, which can be interpreted as a local damage effect controlled by a yield function, which determines their onset and evolution. Specific details of the mathematical implementation of these ideas are given by Lubliner and by Lee and Fenves.

In the concrete damage plasticity model, it is assumed that the failure mechanisms of concrete material are primarily due to tensile cracking and compressive crushing (Bazant, 1986). The two variables: $\tilde{\varepsilon}_t^{pl}$ (the equivalent tensile plastic strain) and $\tilde{\varepsilon}_c^{pl}$ (the equivalent compressive plastic strain) define the evolution of yield or failure. Furthermore, it may be considered that the uniaxial tensile and compressive response of concrete is characterized by damage plasticity, as illustrated in Figs. 3 and 4.

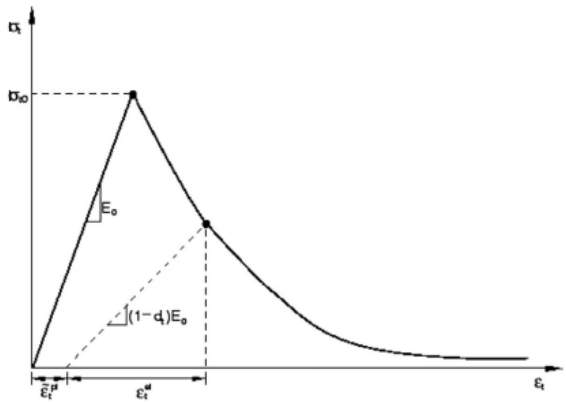

Fig. 3 – Response of concrete to uniaxial loading in tension. Tension $\sigma - \varepsilon$ curve.

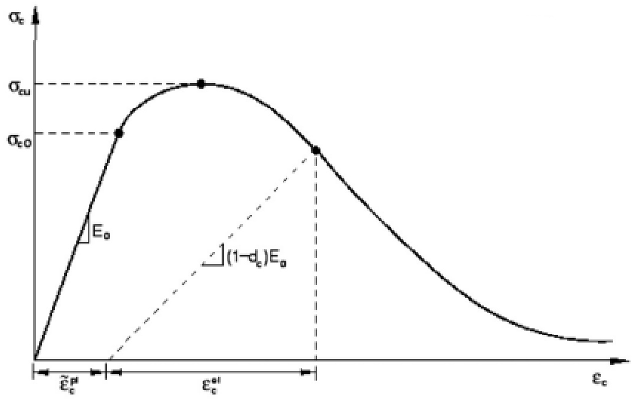

Fig. 4 – Response of concrete to uniaxial loading in compression.

The constitutive relationship of reinforcement has to include the three significant stages: elastic, yielding and hardening stage. The prestressing strand in hollow-core slabs corresponds to high strength steel which does not present an apparent yield phase. This type of stress-strain relation may be outlined by the dual slash- curve model (Yu, 2002) shown in Fig. 5. This formulation includes the following parameters: modulus of elasticity (E_{steel}), Poisson's ratio (n) and ultimate strength of prestressing steel (f_{cu}).Segment 'ab' on the stress-strain curve represents the softening stage: σ_a, σ_b, ε_a and ε_b are the stresses and strains at points 'a' and 'b'.

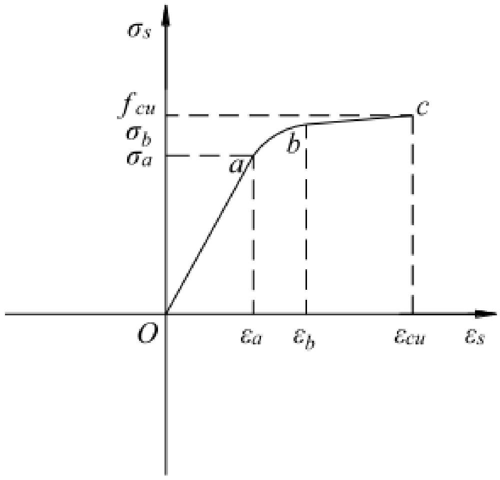

Fig. 5 – Stress-strain curve for steel strand.

The behavior of FRP is approximated by using a brittle cracking model and is assumed to be linear up to when the failure strain (ε_{ult}) is reached, as shown in Fig. 6 (Coronado and Lopez, 2006). At this point, a crack develops and the material losses all its load-carrying capacity (Tao and Chen, 2015). The parameters demanded by this formulation are the modulus of elasticity (E_{FRP}), Poisson's ratio (n) and failure strain (ε_{ult}).

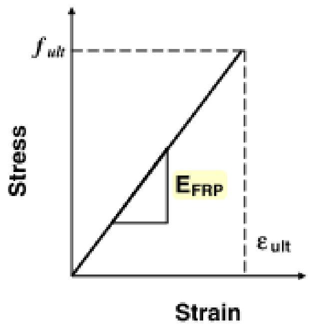

Fig. 6 – Stress-strain curve for FRP.

2.2. Model Geometry

Figs. 7 and 8 highlight a 3D view of the finite element's model geometry for the control web beam and the retrofitted one.

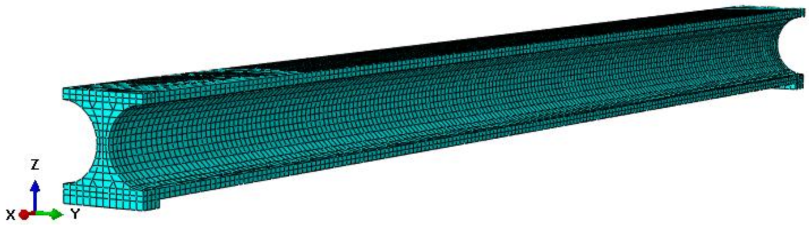

Fig. 7 – Control web beam.

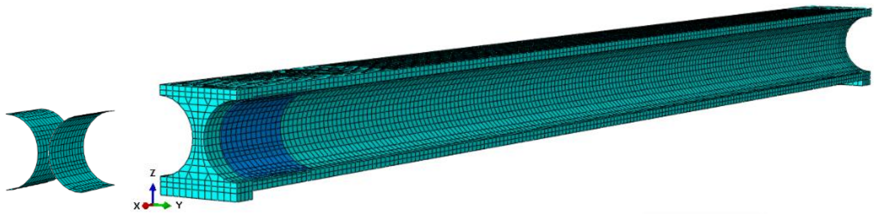

Fig. 8 – Retrofitted web beam.

The boundary conditions for the support plates are pin support on the loading side of the model (the nodes on the bottom face of the support plate are constrained in the x, y and z directions) and roller support on the other side (the nodes on the bottom face of the support plate are constrained only in the y and z directions), as shown in Fig. 9.

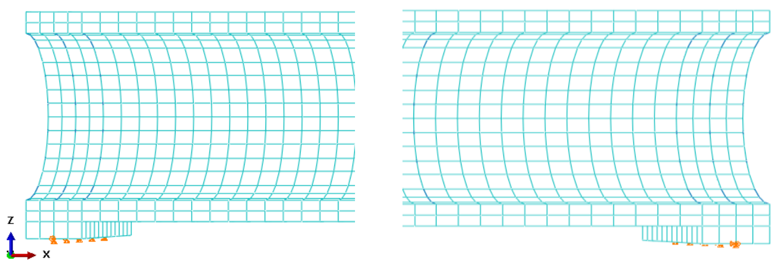

Fig. 9 – Boundary conditions.

The Riks Wempner method (or the arc length method) is adopted in this finite element modelling for solving nonlinear equilibrium equations. The nonlinear analysis in the present study is accomplished in two steps. In the first step, prestress in the tendons is introduced with 'predefined field' option. The second step consists in the applying of self-weight as a uniform load on the element and additionally, in the gradual applying of a line load in the vertical direction for the determination of shear failure (Wu, 2015).

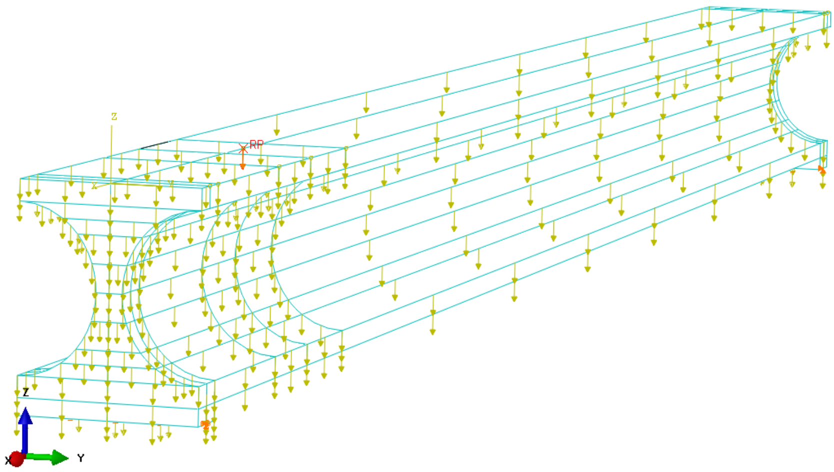

Fig. 10 – Self-weight+concentrated force in step 2 of the analysis.

2.3. Finite Element Modelling Validation

The results in this research are correlated with data extracted from an experimental study undertaken at the University of Windsor, Canada, by Yuanli Wu. A total of sixteen I-shaped single web beams, cut from full PHC slabs, were tested in the experimental program abovementioned: a series of 8 specimens with 1 prestressing strand web beams (corresponding to low prestressing hollow core slabs) and a second series of 8 specimens with 2 prestressing strand web beams (corresponding to medium prestressing elements).

Fig. 11 illustrates the FEM results for load-deflection behavior and demonstrates the fact that the numerical simulation was able to predict the ultimate loading capacity, ductility and FRP retrofitting effect, due to the good correlation between data from FEM and experimental tests. The load-deflection relationship represents an important assessment criterion for a finite element model efficiency because it defines the overall behavior of specimens during the experimental test. It is concluded that the pattern of both curves is similar, that they present acceptable initial stiffness, ultimate failure load, deflection and the same developing trend. It can be noticed a large nonconformity (around 20%) in the post-elastic domain, due to the insufficient data regarding the elements' material behaviour in experimental setup.

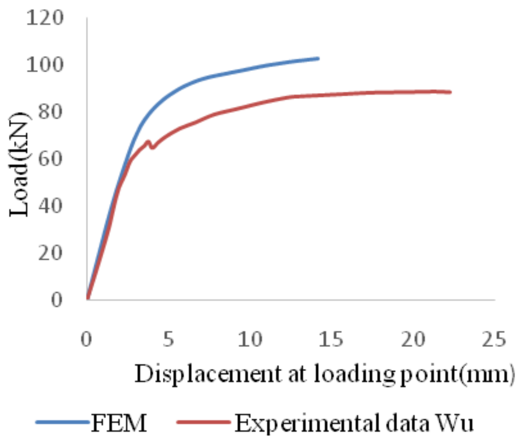

Fig. 11 – Load-deflection behavior.

Furthermore, the distribution of the Von Misses stresses results is shown in Fig. 12. The tensile region increases from the middle to both sides along the FRP vertical fiber direction and the most effective working area is in the middle region of FRP sheets.

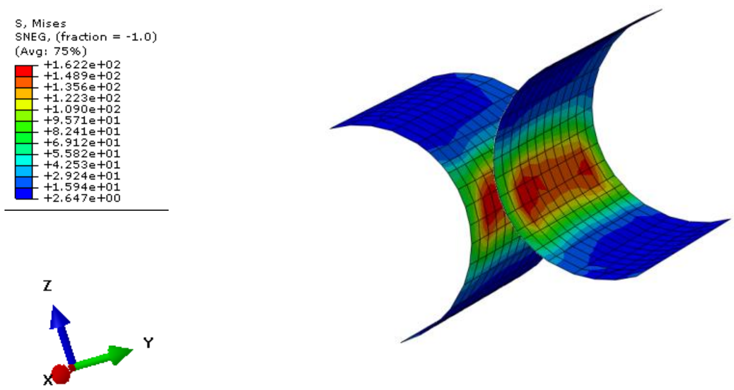

Fig. 12 – The distribution of Von Misses stresses in FRP sheets.

3. Conclusions

The finite element analysis undertaken in this paper using the ABAQUS software can simulate the shear behaviour of FRP retrofitted I-shaped single web beam with an acceptable accuracy. The predicted load-deflection relations are in unison with the corresponding experimental data. The damage-plasticity model can adequately approximate the concrete behaviour in the plastic domain. The experimental programme mentioned in this paper proved that the shear capacity of web beams strengthened by FRP sheets is considerable increased, compared to the not retrofitted specimens. It is predictable that the suggested approach would also be efficient when applied to the full width hollow core slabs, an analysis that is currently under work using numerical analysis and experimental testing.

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EFECTUL POLIMERILOR ARMAȚI CU FIBRE ASUPRA REZISTENȚEI LA FORFECARE A FÂȘIILOR PREFABRICATE CU GOLURI

(Rezumat)

Fâșiile prefabricate cu goluri din beton precomprimat reprezintă unele din cele mai des utilizate elemente portante din beton. Acestea sunt întrebuințate la planșee și acoperișuri pentru clădiri de birouri, spații comerciale, ansambluri rezidențiale sau industriale. În cadrul acestei cercetări este prezentat un model numeric care studiază comportarea fâșiilor cu goluri consolidate printr-o tehnică inovatoare ce constă în aplicarea polimerilor armați cu fibre pe suprafața internă a golurilor. Polimerii armați cu fibre sunt materiale compozite folosite în mare măsură pentru reabilitarea structurilor din beton datorită avantajelor pe care le au față de metodele tradiționale de consolidare. Pentru a accentua eficiența acestei tehnici, s-au analizat grinzi de tip I care au fost secționate longitudinal din fâșia întreagă. Acest studiu s-a făcut cu programul de element finit Abaqus. Rezultatele numerice obținute au fost detailate în ceea ce privește comportarea forță-deplasare, forța de cedare și harta fisurilor.