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Research Paper

Experiment and FEM Modelling of Bond Behaviors between Pre-stressing Strands and Ultra–High–Performance Concrete

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ABSTRACT

The objective of this paper is to investigate the bond properties of prestressing strands embedded in Ultra–High–Performance Concrete (UHPC).The UHPC was made in laboratory using local materials in Vietnam.Its mixture contains: silica aggregates, portland cement PC40, fly ash, silica fume, polycarboxylate superplasticizer and the micro steel fibers.The experimental process is realized on a pull-out test. The volume fraction of micro steel fibers in UHPC was 2%. The prestressing strand with diameters of 15.2mm was considered. The interface shear strength between strand and UHPC is identified based on the results of force and displacement obtained during the pull-out test. The Cohesive Zone Model (CZM) is implemented in finite element model to study this interface behavior. This model described by a piecewise linear elastic law. The CZM's parameters are identified based on experimental results of pull-out test.The numerical studies are used the CZM in ANSYS software. Two numerical tests are realized and compared with experimental results: pull-out test and other test to verify the deflection of I girder due to prestressing force.

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1 Introduction

The shearing stresses at the interfaces between prestressing strands and UHPC are commonly be used to define the strand bond. Under the external loading, the prestressing strands and concrete work together as a composite material via the bond. Thanks to the bond between the interface between two materials, the strand movement is prevented until a bond failure occurrence because of excessive slippage of the prestressing strands. A research conducted by Janney [1] shown that there

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are three mechanisms of bond between the prestressing strands and concrete including adhesion, Hoyer's effect, and mechanical interlock. Adhesion is a chemical mechanism between the strands and concrete. This mechanism no longer contributes to the bond effect if strand slip occurs.

Strand bond is an important parameter so that the pull-out tests have been developed to assess. There are several types of pull-out tests; and one of them is implemented by pulling strands out from a large concrete block [2]. The test was developed to quantify the bond capacity for repeating loadings. Another type of pull-out test, the North Amer-ican Strand Producers (NASP) Bond Test [3], was derived from Post Tensioning Insti-tute (PTI) Bond Test. A special mortar is used in the NASP Bond Test for reducing shrinkage and increasing dimensional stability when comparing to the neat cement mortar used in the PTI Bond Test. The Standard Test for Strand Bond (STSB) has been adopted by American Society for Testing and Materials (ASTM) and is known as the Standard Test Method for evaluating bond of seven-wire steel prestressing strands [4]. The surface condition of prestressing strands was clearly evaluated by the STSB. The pull-out force at the bottom of the prestressing strand is determined when a slip of 0.1 in. (2.5 mm) at the top of the strand is observed. This important value is used to vali-date bonding forces of the strand.

Bond stresses from the given slip is calculated based on the stress – slip model; and this model is a nonlinear structural behavior. Generally, determination of the bond stress in concrete structures is more complicated than other materials. It is difficult to directly measure the bond stress from any types of gauges. Therefore, the bond stress are commonly computed by using the measured slip values combining with the bond stress–slip model analysis. In the Model Code for Concrete Structures 2010 [5], the bond stress–slip model has been well established for non-prestressed reinforcement.

UHPC is a material with the complicated mechanism characteristics. The bond between the prestressing strands and UHPC plays a critical role in the behavior of prestressed UHPC structures. The quantification of bond is very important for designing and calculating this type of structure. The distribution of bond along the prestressing strand will help to determine the transfer length of strands. Accordingly, this research develops a bond stress–slip model between UHPC and strand. The experimentof pull-out test is firstly presented. It allows determining the CZM's parameters. Then, Ansys software was used for modeling and analyzing this bond to verify the bond stress-slip model.

2 Experiment setup

2.1 Materials

The UHPC material is made in the NUCE laboratory [6-8]. Its mixture contains: silica aggregates with a particle size of 300µm; Portland cement PC40 with particle size of 11.4 µm; Fly ash (FA) and silica fume (SF) with a mean particle size of5.83µm and 0.15µm; The content of SiO_2 in SF was 92.3%; Polycarboxylate superplasticizer (PS) with a dry content of 35%; The micro steel fibers (13mm of length and 0.2mm of diameter)uses with a volume fraction of 2%. The UHPC's proportions and its characteristics are shown in Table 1 and Table 2.

Table 1 - UHPC's proportions

Fiber content	Sand (Kg)	Cement (Kg)	FA (Kg)	SF (Kg)	PS (Kg)	Water (Kg)	Fiber (Kg)
2%	1108	831	166	111	36.9	164	157

Table 2 - UHPC characteristics

Fiber content	Compressive strength f'_c(MPa)	Tensile strength f_t (MPa)	Elastic modulus E (GPa)
2%	120	8	42

The compressive strength of UHPC was estimated base on ASTM C39M [9] for cylinder sample has a diameter of 100 mm and height of 200 mm. The flexural strength is determined based on ASTM C1609M [10] for rectangular sample has a cross-section's dimension of 100x100 mm and length of 400 mm. The elastic modulus of UHPC is identified base on ASTM C469M [11] for cylinder sample with diameter of 100 mm and height of 200 mm. In this study, seven-wire steel strands with nominal diameters of 15.2 mm were used. Those strands were categorized as Grade 270 in ASTM A416 [12] with a tensile strength of 1860 MPa. The details of strand characteristics are shown in the Table 3.

Table 3 - Strand characteristics

Nominal diameter (mm)	Nominal area (mm^2)	Elastic modulus (GPa)	Elongation (%)
15.2	140	200	3.5

2.2 Fabrication of Specimen and test procedure

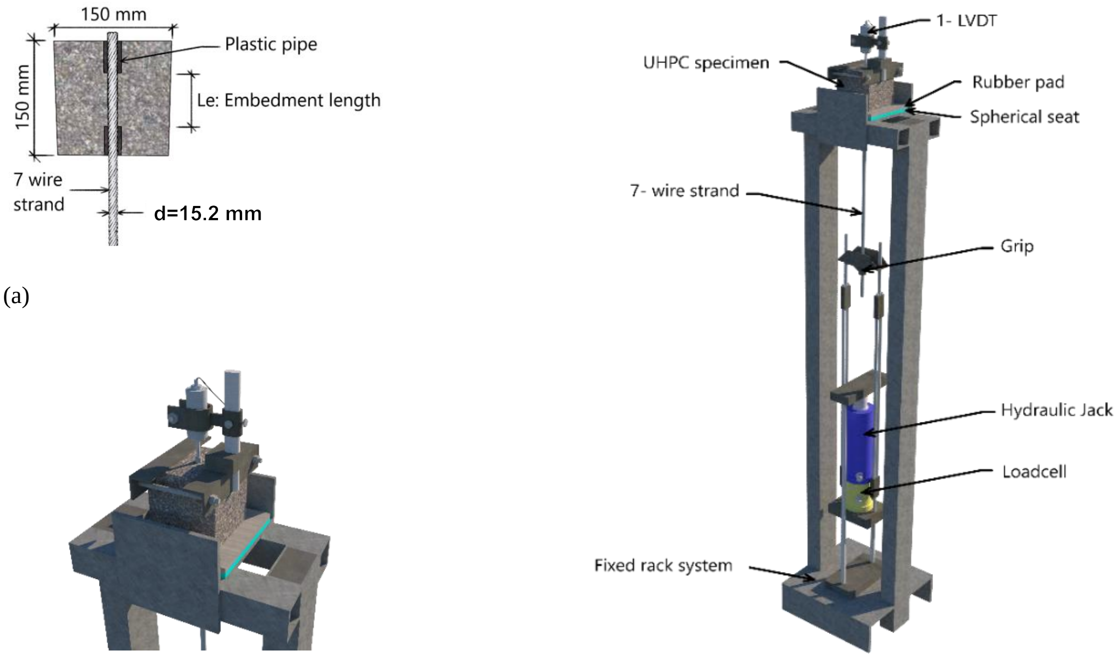
The specimens were manufactured in the laboratory (Figure 1). The pull-out tests were deployed according to the RILEM [13] recommendation for steel reinforcement [14] to evaluate the bond behavior of prestressing strands embedded in UHPC. The pull-out test specimens had a cubic shape geometry with a dimension 150 mm (Figure 2a). Inside these specimens, the embedment length (L_e) equals to five time of the strand diameter (d). In this study, since the strand diameter was 15.2 mm, the embedment length was 76 mm. Two ends of the strand were protected in plastic pipes to disconnect with UHPC (Figure 2a).


(a) (b)

Fig. 1 - (a) Mixing and (b) placing of UHPC mixtures

The pull-out test is realized on 3 specimens. One LVDT is attached at the unloaded (free) end of the strand to measure slip (displacement) (Figure 2b). The force at the loaded end of the strand during pull-out test is determined by one load cell (Figure 2c). The results of force and displacement are saved thanks to DATALOGGER TDS-530. All pull-out test are realized under monotonically increasing loading with a force control rate of 100 N/s (Figure 3).

During pull-out test, the stress is transferred from strand to UHPC material via interface bond. The interface shear stress between strand and UHPC is identified by $\tau=P/(\pi d L_e)$, with P is the force at the loaded end of strand. The bond strength of interface corresponds with maximum value of P. These results obtain by pull-out test is shown on Table 4. The average value of bond strength is 18.28 MPa, corresponding at average displacement value of 3 mm.



(a)

(b) (c)

Fig. 2 - (a) Pull-out test specimen, (b) LVDT at the unloaded end of strand and (c) pull-out test setup.

(a) (b)

Fig. 3 - (a) The pull-out test in lab and (b) the specimen after testing

Table 4 - Experimental results of bond strength between strand/UHPC

Specimen N°	P$_{max}$	Bond strength	
	(N)	τ_{imax} (MPa)	τ_{mean}(MPa)
1	66880	18.44	18.28
2	66330	18.28	
3	**65780**	**18.14**	

3 FEM Modelling

3.1 Element Types

SOLID65 element was used for modelling the UHPC material because it is the 3D solid element with or without reinforcing bars. It can be used for modeling of cracking phenomenon in tension and/or crushing behaviors in concrete structures. Thus, this type of element may be used to model the UHPC structures. In addition, rebars are also embedded inside the SOLID65 element for simulating the interaction between reinforcement and UHPC. The element is defined by eight nodes having three degrees of freedom at each node corresponding to translations in the nodal x, y, and z directions. The rebar specifications can be defined by user [15] (Figure 4). The nonlinear material properties are specified by the authors for the SOLID 65. Moreover, the element is capable to model of cracking (in three orthogonal directions), crushing, plastic deformation, and creep – the featured specifications of the UHPC.

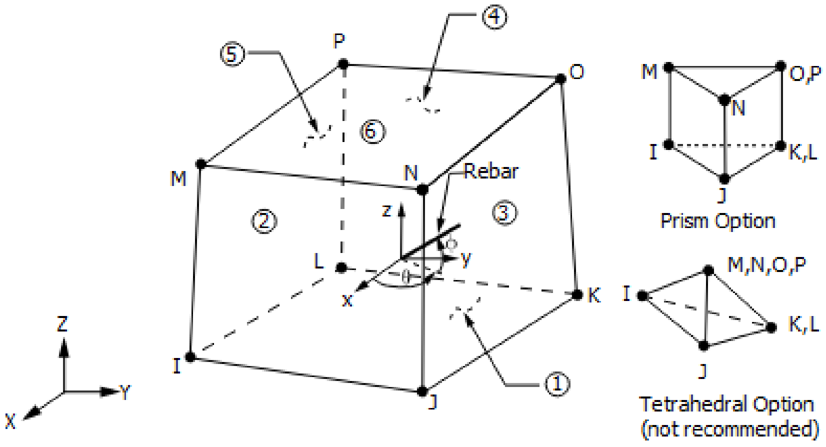


Fig. 4 -SOLID65 3-D Model [15]

The BEAM188 element is used for modelling strands, a slender to moderately stubby/thick beam structures. The Timoshenko beam theory was used for generating this element. Shear deformation effects are also defined in this element. The BEAM188 is a 3-D linear beam element with six degrees of freedom at each node, including translations in x, y, and z directions, and rotations about the x, y, and z directions. The element is suitable for linear, large rotation, and/or large strain nonlinear applications. Furthermore, the stress stiffness terms enable possibility of analyzing flexural, lateral, and torsional stability problems.

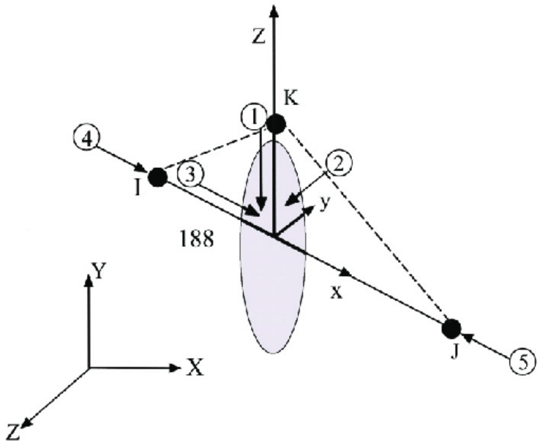


Fig. 5 - BEAM188 3-D Linear Finite Strain Beam Model [13]

3.2 Cohesive Zone Model (CZM)

The Cohesive Zone Model (CZM) is used to model the interfaced bond between strands and UHPC. The main advantages of the CZM is to represent the physical property of the interface, particularly, in fracture mechanics behavior [16], [17].

CZM model in pull-out test, the shear cohesive stress is expressed as a function of the tangential displacement (Figure 6). These values are identified by experiment of pull-out test (see Table 4).

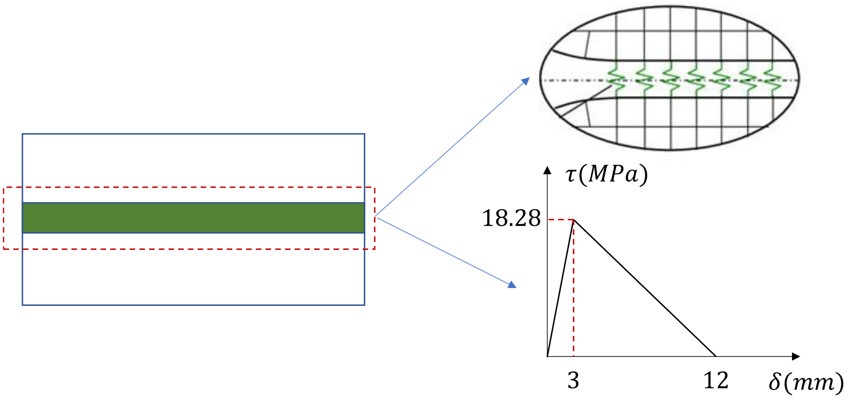
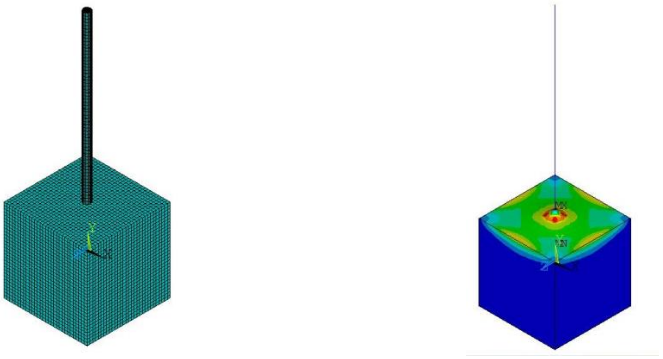


Fig. 6 - Cohesive zone model to model interface behavior between strand/UHPC

3.3 Numerical results

In FEM, the CZM is implemented at interface strand/UHPC to model the bond behavior. CZM's parameters is shown on Figure 6. The interface strength during the pull-out test obtains in FEM is 19.2 MPa. It is well converged with the experimental result (18.28 MPa). The pull-out test in FEM at initial state and loading state is presented on Figure 7.

In other modeling, the CZM model is used at interface prestressing strand/ UHPC to model an I-shape girder UHPC was cast with lengths of 6.3 m. The girder is used two 15.2 mm diameters prestressing strand without reinforcement steel. These detail dimensions of girder were shown as Figure 8. The upward deflection of girder due to prestressing force for experiment is 11 mm (Figure 9a). This deflection obtains thanks to the bond between strand and UHPC. This upward deflection value is 11.19 mm in FEM using CZM model (Figure 9c). A good comparison value is obtained between experiment (11 mm) and modeling (11.19 mm).



(a) (b)

Fig. 7 -The pull-out test in FEM at (a) initial state and (b) loading state

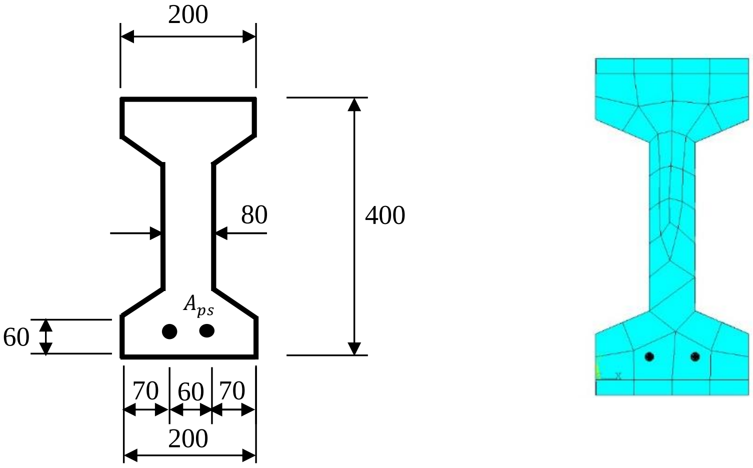
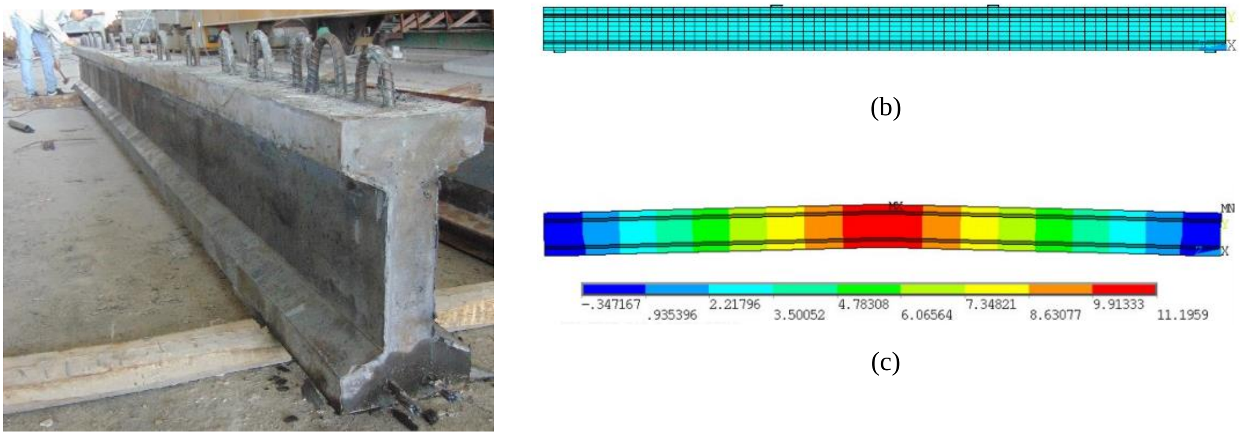


Fig. 8 - Cross section of I girder



(b)

(c)

(a)

Fig. 9 - (a) Experimental and (b) numerical modellingofI-girder, (c) upward deflection after cutting the prestressing strand

4 Conclusion

In this study, the bond properties of prestressing strands embedded in UHPC is investigated. The bond behavior is identified by the pull-out test. The volume fraction of micro steel fibers in UHPC is 2%. The prestressing strand with diameters of 15.2mm was considered. The Cohesive Zone Model (CZM) is used to model the interface bond between strand/UHPC. CZM's parameters is identified based on experimental results from pull-out test. First numerical modeling is realized on pull-out test. The interface strength obtains in FEM (19.2 MPa) is well converged with the experimental result (18.28 MPa). Second modeling used CZM model to verify the upward deflection after cutting the prestressing strand of I-girder. A good comparison value is obtained between experiment (11 mm) and modeling (11.19 mm). So, CZM model is promising way to model the interface between strand and concrete. It is able to model the transfer of stress from strand to concrete, or the interface bonding, debonding.

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