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A numerical model for post-tensioned precast beams with unbonded tendons

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Abstract

The modern seismic design of building is concerned with two distinct performance levels: protecting human lives in the case of large earthquakes, and provide structural systems with enhanced functionality by controlling structural damage. A promising resisting structural typology, to limit both generalized cracking as well as residual deformations on structural members, is adoption of unbonded post-tensioned precast concrete beams.

In this paper, a numerical model is presented and compared to experimental results. The model was developed to predict the shear-rotation relationship characteristic of unbonded post-tensioned precast concrete beam-columns connections with due attention to capturing the prestress loss due to cyclic loading.

The model adopts a recently proposed fiber model, developed within the diffuse plasticity approach. Great care has been devoted to selection of material laws for concrete, focusing on the capability to reproduce the gap-opening gap-closing mechanism at the beam-column interface, which is mainly responsible for of the prestress variation and contributes to possible yielding of the prestressing bars at a prescribed levels of column rotation.

The accuracy of the proposed models is illustrated by comparing the predicted behavior in terms of basic mechanical properties, such as shape of the hysteresis, stiffness degradation, failure mode and damage control, with results of recent experiments carried out on cyclically loaded precast beams, post-tensioned using unbonded tendons.

Keywords: precast beam, unbonded tendons, post-tensioning, modelling strategies, fiber elements, Jointed Connections

1. Introduction

The modern seismic design of building is concerned with two distinct performance levels: protecting human lives in the case of large earthquakes, and provide structural systems with enhanced functionality by controlling structural damage. A promising resisting structural typology, to limit both generalized cracking as well as residual deformations on structural members, is adoption of unbonded post-tensioned precast concrete beams.

In this paper, a numerical model is presented and compared with recent experimental results. The model was developed to predict the shear-rotation relationship characteristic of unbonded post-tensioned precast concrete beam-columns connections with due attention to capturing the prestress loss due to cyclic loading. The model adopts a recently proposed fiber model [1], developed within the diffuse plasticity approach. The formulation has been based on adoption of fiber elements to model the behavior of the beam and of elastic-plastic spring/truss elements to model the behavior of tendons. Great care has been devoted to selection of material laws for concrete, focusing on the capability to reproduce the gap-opening gap-closing mechanism at the beam-column interface, which is mainly responsible for of the prestress variation and contributes to possible yielding of the prestressing bars at a prescribed levels of column rotation.

The model developed was implemented inside a research finite element code, in-house developed by one of the authors at Politecnico di Milano. The discretization of the structure is based on the "monolithic beam analogy" [2] concept, and is able to describe the behavior of a precast ductile connection thanks to the presence of a diffused plastic region. As it is well known, several definitions of plastic hinge length are available in the literature, and a tentative one was selected for initial investigation in this work. Tendons were modeled separately with the aim of focusing the attention on the prestressing force-displacement behavior, and on the capability to predict the prestressing loss after a severe earthquake.

The accuracy of the proposed models is illustrated by comparing their behavior with the experimental results obtained from a recent experimental campaign conduced at the Tokyo Institute of Technology during 2014 [3], a good agreement has been reached both in terms of shear-drift behavior and of prestressing force-drift behavior.

2. Jointed connections

Precast structures connections play a crucial role in determining the structural response against an earthquake, as a matter of fact in the case of moment resisting frames is better to concentrate the inelastic action at the beam to column connection aiming to achieve the strong column weak beam mechanism. For precast concrete frame this was traditionally translated in the design concept of trying to create a connection able to provide performances equivalent to that of a monolithic connection in terms of strength and toughness: the emulative connection. This type of connections, however, has not allowed to exploit the full seismic resistance potential of precast structures, for this reason new connections types were researched. Among non-emulative connections there is a special class of dry connections which have emerged as successful, due to their optimal response against earthquakes, this class represent the type of connections investigated in this work: the jointed connections.

The jointed connections make use of unbounded post-tensioned tendons to connect the precast members together, having the advantage of reducing damage, dissipate energy and being self-centering during an earthquake. Figure 1 illustrates a typical sub-assemblage of jointed connection reported in [3.].

The intent of the system is that the beam and columns should act essentially as rigid bodies and that most of the system deformations take part at the beam-to-column joint, where the end of the beam rocks against the column and a single crack opens. This zone is specifically engineered so that a strong reduction of damage occurs.

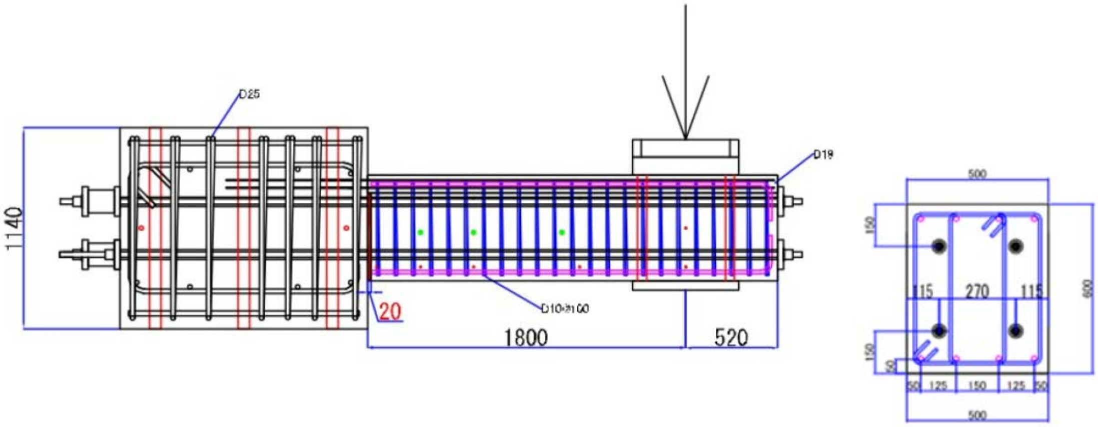

Fig. 1 – Example of beam-column Jointed Connection (member PCa 13 reported in [3])

The post-tensioning steel is designed to remain elastic at all times, this is achieved by debonding it [4] so the strand extension arising from crack opening is distributed over its entire debonded length, which is choose long enough to avoid an excessive pinching of the force deflection hysteresis loops and to minimize prestressing losses. The prestressing force is concentrated in the central region of the beam depth, with no significant penalty ([5], [6]) in terms of flexural strength compared with the same prestress force distributed through the beam depth or concentrated in tendons near the top and bottom beam surfaces.

Jointed connections can be used in Japan, several research programs were developed in the last years to allow the introduction of design provisions related to post-tensioned precast concrete frames with jointed connections. These have permitted the use of precast concrete connections which have been proven to have acceptable levels of strength, rigidity, and ductility on the base of standardized testing. The testing procedures and classifications of the joints are outlined by the Building Center of Japan.

The design of prestressed structural systems composed of ductile connections has been ruled for the first time by the Japanese Building Code. According to the allowed criteria: under Level 1 earthquakes (recurrent period of 50 years), connections among beams and columns have to behave as rigid joints and interfaces among them have to remain in compressive state, while under Level 2 earthquakes (recurrent period of 500 years) and Level 3 earthquakes (recurrent period of 1000 years), the connections can rotate elastically to prevent damage to beams and columns and a maximum drift of 1% and 2%, respectively, is expected for the columns.

At any rate, the tendons should be stretched up to 85% of nominal yielding strength at the prestressing introduction, and then anchored at the end surface of each component. They should not enter the plastic range under Level 2 and Level 3 design earthquake loads. The frictional force produced at the beam to column interface by the prestressing strands has to transmit shearing stress to the column in a traditional anchoring method.

The problem which may arise is that the system would not resist the beams' dead load and other gravitational loads if the prestress forces introduced into the PT steel members strand are not set at some level. For this reason a limit of the 10% for the prestressing loss has been additionally considered by Gioia et al.[3]. Of course the problem may be avoided through the introduction of corbels, but this would complicate construction.

3. Experimental tests and related numerical model

Recently, an experimental investigation had been carried out on eight cyclically loaded post-tensioned precast beams using unbonded tendons [3]. The purpose of such research was to examine the basic mechanical properties such as hysteresis, stiffness degradation, failure mode and damage control.

In order to predict the outcome of further tests and to allow for analysis of different testing sequences, a numerical model has been developed to predict the shear-rotation relationship of these types of connections. A sample drawing for this type of beam-column connection is depicted in Fig. 1. The model is focused on capturing the global effects of the cyclic gap-opening at the beam-column interface.

The numerical model has been constructed on the basis of one of the specimen tested during the experimental campaign conduced by Gioia at the Tokyo Institute of Technology, in particular the test of member PCa13 was taken as reference. Figure 2 shows the loading sequence for this member. The PCa13 specimen has a rectangular cross-section (500x600 mm), shear span 1800 mm, and is reinforced with 8D19 mm mild steel bars. Four D32mm tendons provide prestressing by applying 369 kN of post-tension compression axial force, that correspond to axial ratio of 0.25. The values of the material properties adopted in the numerical modelling presented in the next section were derived from experimental values of the same and are: concrete compression strength f_c 35.7 MPa, concrete elasticiy modulus E_c 29900 MPa, yielding strength of the prestress reinforcement f_{yp} 1185 Mpa, elasticity mudulus of the prestress reinforcement E_p 207675 MPa design yield strength of the mild reinforcement f_{yd} 386 MPa, elasticity modulus of the mild reinforcement E_s 186473 MPa.

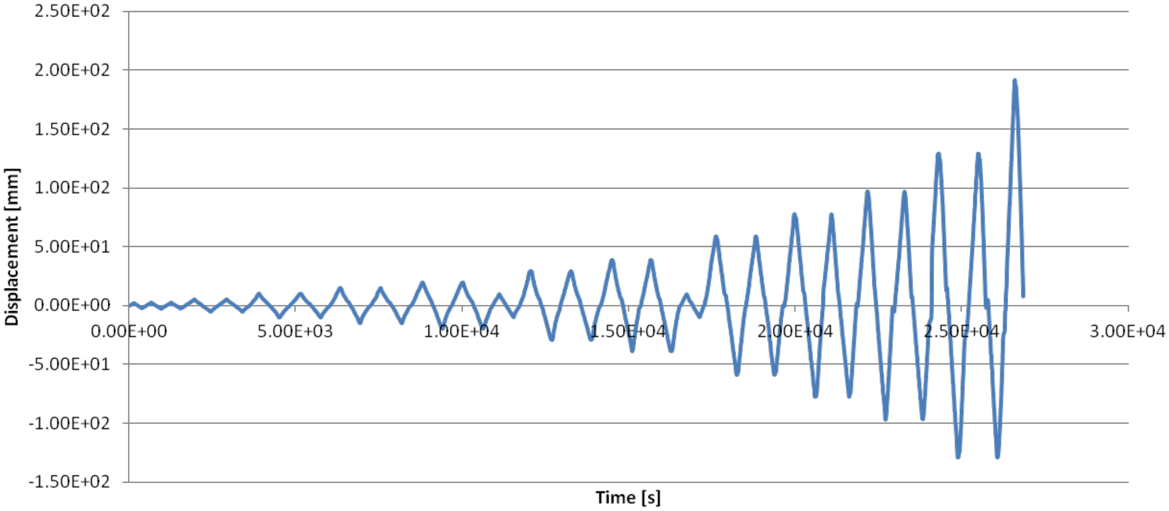

Fig. 2 – Loading program of member PCa13

The numerical model is based on adoption of fiber elements to model the behavior of the beam and of elastic-plastic spring/truss elements to model the behavior of tendons (Fig. 3a).

The fiber element formulation (Fig. 3b) is a recently proposed one by Martinelli [1][8], developed within the diffuse plasticity approach. This formulation is implemented inside the research finite element code, named NonDA (Nonlinear Dynamic Analysis) [7] written in Fortran95, in-house developed by one of the authors at Politecnico di Milano.

The proposed element is characterized by the way the shear force is obtained, superimposing in the cross-section different shear resisting mechanisms derived starting from the Timoshenko beam theory to describe shear.

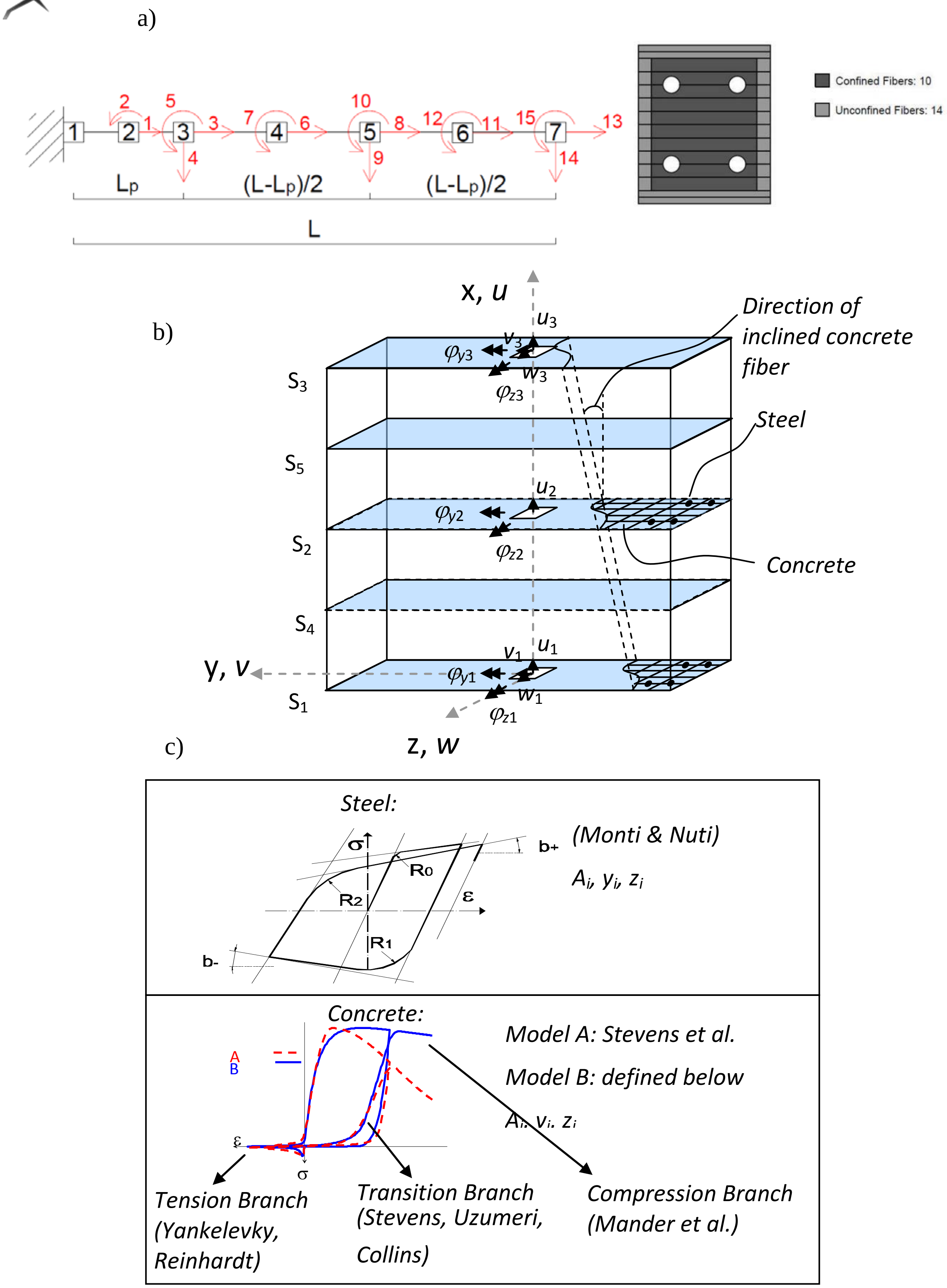

Fig. 3 – a: discretization of the specimen, b: formulation of the finite element, c: material models.

Firstly, the model adopts a uni-axial constitutive relation for concrete, associated to a rotation of the principal direction of the compressive stress during the analysis to account for the arch action. The fibers may become, thus, non normal to the cross-section. Secondly, the so called Mörsch's truss shear resisting mechanism is also explicitly modeled on the basis of a local mechanical model.

Furthermore, the shear and flexural behavior are coupled. For the computation of the shear force resultant a distinction is made for the contributions of the concrete above and below the neutral axis, since it is assumed that different mechanisms are involved. Compression concrete above the neutral axis participates to the arch action, while concrete below the neutral axis to Mörsch's truss.

Material nonlinearity has been represented by cyclic constitutive relationships for concrete and steel (see Fig. 3c). Great care has been devoted to the selection of material laws for concrete, focusing on the capability to reproduce the gap-opening gap-closing mechanism at the beam-column interface, which is mainly responsible for of the prestress variation and contributes to possible yielding of the prestressing bars at a prescribed levels of column rotation. The uniaxial stress-strain model by Mander et al [10] has been adopted to simulate the compression behavior of concrete, supplemented by the one proposed by Yankelevsky and Reinhardt [11] to model and reproduce the nonlinearity which occurs when the fiber is under tension. Experimental evidence (as shown in Fig. 4) shows that the surface at the beam-end is not plane. Consequently, stresses will be generated during alternate cycling since the two end-surfaces do not come perfectly into contact again once initially separated. Such stresses have to be taken in account to improve the agreement between the experimental and analytical result during unloading and reloading phases. The concrete struts in the Mörsch's truss follow instead the material model by Stevens et al. [12]. The cyclic behavior related to the possible presence of mild steel reinforcement adopts to the Monti and Nuti [13] constitutive model. Tendons were instead modeled separately as elastic-plastic, with the aim of focusing the attention on the prestressing force-displacement behavior, and on the capability to predict the prestressing loss after a severe earthquake. Further details on the element capabilities can be also found in [14] and [15].

The discretization of the structure (see Fig. 3a) is based on the length of the plastic hinge. As it is well known, several definitions of plastic hinge length are available in the literature, and a the one by Priestley and Park [9] ($L_p = 0.08l + 6d_b$) was selected for initial investigation, it amounts to 260 mm. The position of the plastic hinge has been offset into the columns of $6d_b$, similarly to what would happen for strain penetration of anchored mild steel.

4. Results of the numerical models

The accuracy of the proposed models is illustrated by comparing their behavior with results of the experiments in [3].

Figure 5 depicts the experimental and numerical response in terms of shear force-beam tip deflection. Experimental and analytical responses indicates that stable hysteresis loops are achieved. As shown in Fig. 5, the shear force – beam tip displacement is well reproduced in terms of shapes of the hysteresis loops, maximum positive and negative force (the numerical test was displacement controlled as the experimental one), initial stiffness, stiffness at the beginning of the unloading phases and, for most of the analysis, also for residual displacement at complete unloading (i.e. residual drift). For the larger rotations (that correspond to drifts of 2.0% - 3.0%) the model points out little strength degradation between successive cycles to a given drift level. The maximum shear is reached with an error of about 10%.

Time-histories of the post-tensioning force are depicted in Fig. 6, Fig. 7 respectively for one of the tendons in upper part and in the lower part of the cross-section. A very good match can be appreciated for both tendons and, although more complicated rules are available for steel, the simple elastic-plastic one herein adopted was sufficient to simulate the post-tensioning force over the whole loading history. These good results, allow for the use of the proposed modelling technique for estimating the loss of prestress in this type of connections.

Fig. 4 – End-section of the beam, after testing

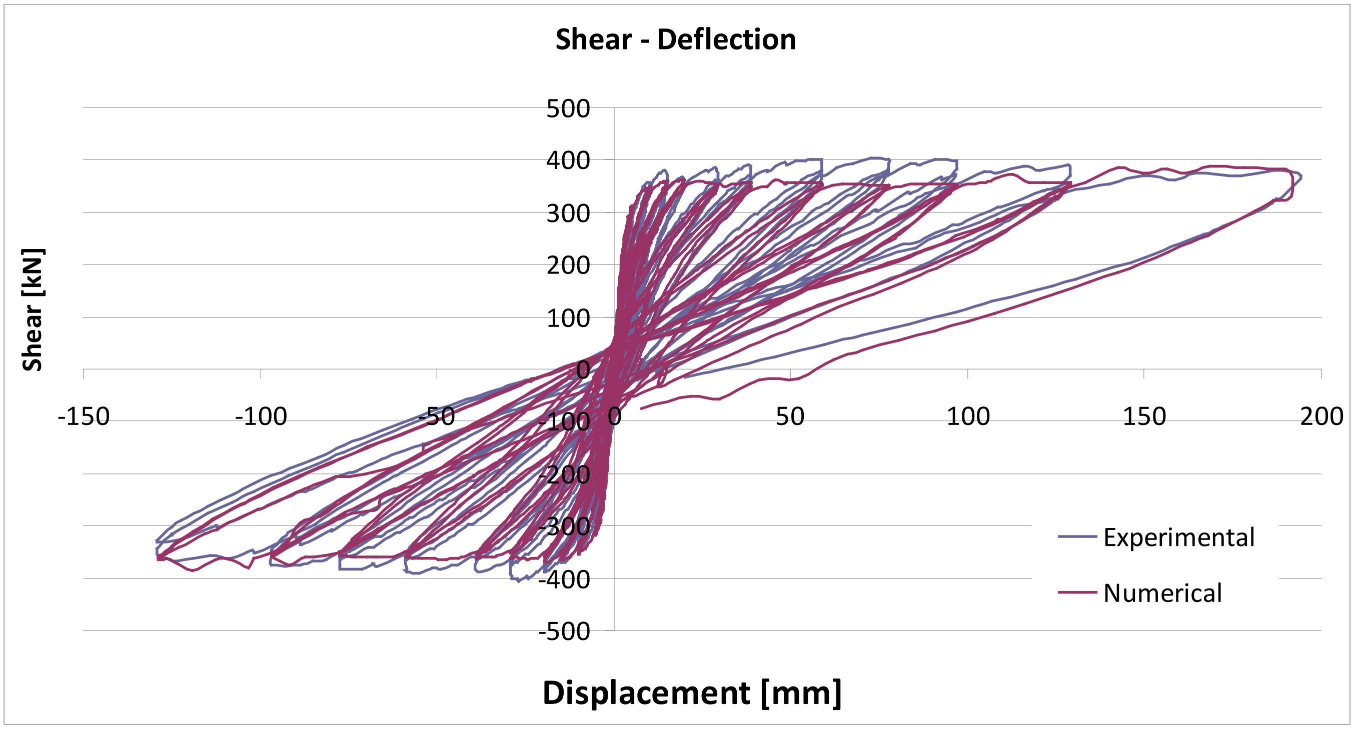

Fig. 5 – Experimental and numerical response in terms of shear force-beam tip deflection for specimen PCa13

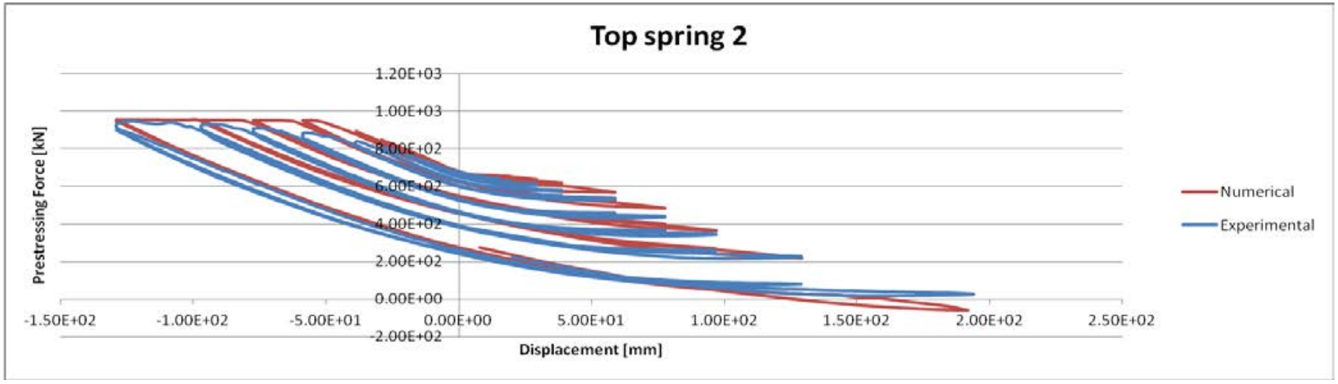

Fig. 6 – Experimental and numerical histories of the post-tensioning force of the tendons in the upper part of the cross-section of specimen PCa13

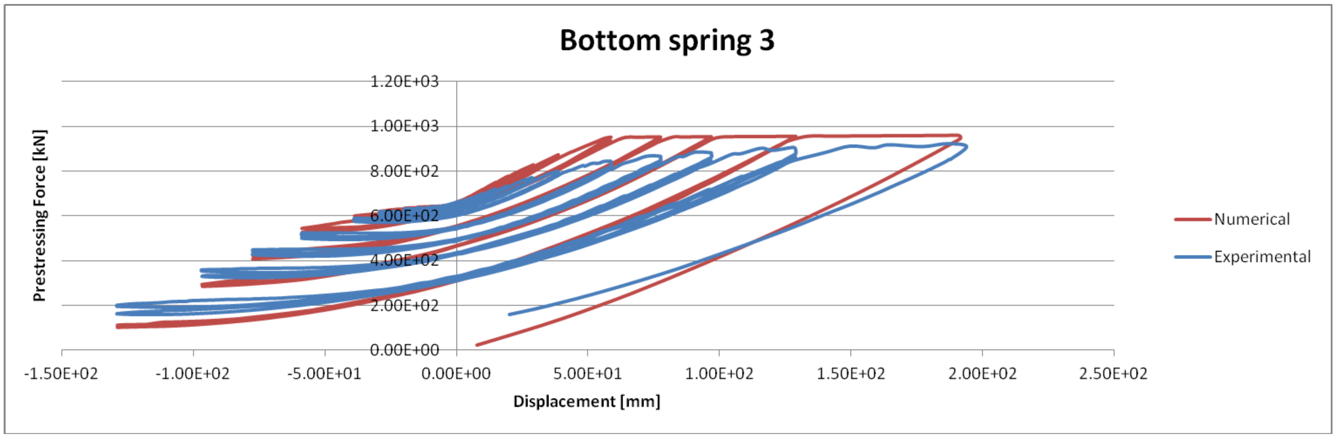

Fig. 7 – Experimental and numerical histories of the post-tensioning force of the tendons in the lower part of the cross-section of specimen PCa13

5. Conclusions

The paper presents a numerical model of unbonded post-tensioned precast concrete beam-columns connections. The aim is to capture not only the general feature of the cyclic response of this type of connections, but also to predict local effects such as the loss of prestress due to the cyclic loading pointed out by experimental tests. The model adopts a recently proposed fiber model and its results are compared to experimental ones.

Experiments and numerical results confirm that the loss of prestress is not only related to the prescribed level of beam-column rotation, but also to the gap-opening gap-closing mechanism at the beam-column interface. This was reproduced in the numerical model, within a smeared crack approach, by adoption of a material law for concrete that include a model for crack opening/closing.

The good accuracy of the proposed models, assessed by comparing the predicted behavior in terms of basic mechanical properties, such as shape of the hysteresis, stiffness degradation, failure mode and damage control, with results of physical tests, suggest these type of models, and the modelling technique here presented, can be used for estimating the prestress loss in this type of connections with reasonable errors.

6. Acknowledgements

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