SEISMIC PERFORMANCE ASSESSMENT
OF PRECAST ELEMENT CONNECTIONS

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ABSTRACT

In many typical R.C. applications, the reinforcing bars along certain alignments must be maintained continuous. Such continuity is usually obtained through overlapping arrangements and suitable end bents of the bars.
In the more critical contests, like in the case of buildings in seismic areas, more reliable continuity solutions are required. The same holds for blast scenarios. To this purpose a new type of coupling device assuring the bar continuity has been recently proposed. This device is made of a steel external shell, which encloses a certain volume around the bars to be connected. The interstitial volume is filled by VHS Concrete which embeds the bar and assures the continuity with the steel envelope.
To assess the efficiency of this new device, many experimental tests were performed. In particular, it was analyzed the behavior under cyclic loading of columns having different height connected to the foundation structure by these continuity devices and the behavior of a beam-column junction.
This paper presents the analysis for the investigations of the behavior of a precast column having section 0.5 x 0.5 meters and 5 meters high. Both experimental and numerical results are presented with particular attention to the definition of the numerical model.

Keywords: Precast Structures Connections, Splice System, Non Linear Finite Element Analysis, Antiseismic Design.

INTRODUCTION

With more attention given to the seismic challenges, the topic of connections between precast structures is today of considerable interest. Prefabricated buildings have in fast assembly and in cost containment their peculiar qualities; however the structural continuity between the various elements can be a weakness if the building must ensure adequate resistance to horizontal actions. Thanks to the cooperation between experimental and analytical research, some companies can today offer innovative solutions for connecting precast elements. In particular, (Fig.1) an innovative connection system that uses devices to be placed in the casting of prefabricated elements (columns, beams, foundations) is proposed. Through this system, assembly on site is dry, and only after adjustment of the elements it is possible to proceed to the completion of the continuity using a cast of high-performance self-compacting mortar. This system, assures continuity of flexural reinforcement, rapid assembly and low cost of implementation.

To achieve this results several experimental tests developed at the EUCENTRE of Pavia and the Politecnico di Milano have been carried out. These tests have been supported from appropriate analytical and numerical studies developed at University of Rome La Sapienza and the Politecnico di Milano.

In this paper the analytical results and experimental tests on the continuity system designed to establish the connection between a column and its foundation are reported. However, as shown later, this study is only a part of a larger study that includes analysis of the structural elements of different scales (local behavior of the devices and global behavior of the elements) or with different failure mechanisms (shear or flexural failure).

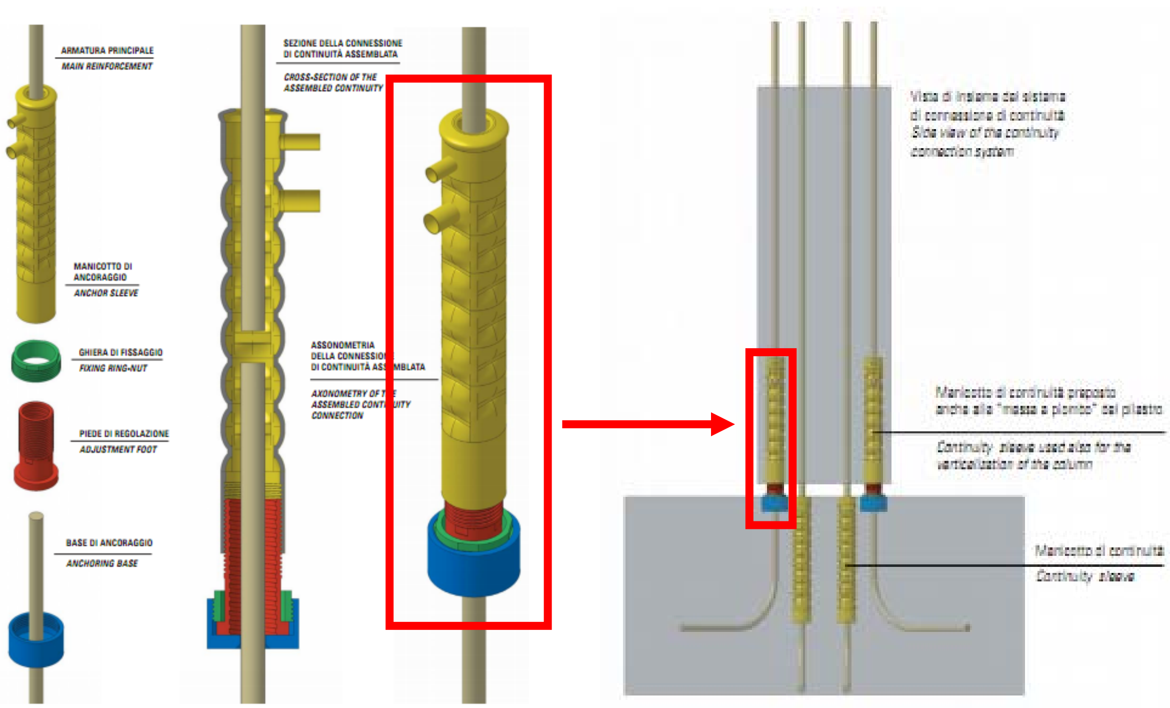


Fig.1. Concept of the connection system.

EXPERIMENTAL PLANNING

The devices presented in this study are proper connecting system between precast elements. They are defined as continuity system and they are conceived with two main functions in mind: 1) in a first step to govern the placement of precast columns; 2) in a second phase to govern the transfer of axial, shear and bending moment from the base of the column to the foundation.

To define the behavior of the continuity system different experimental tests and numerical analyses have been carried out (Fig.2). In particular: at the refined detail level (micro-level) (Fig.3), and at the element scale (meso-level) (Fig.4). In micro level investigation, a single continuity system has been considered under monotonic and cyclic load. At the meso-level, three columns were analyzed to investigate the behavior of the base section under shear and bending load cycles.

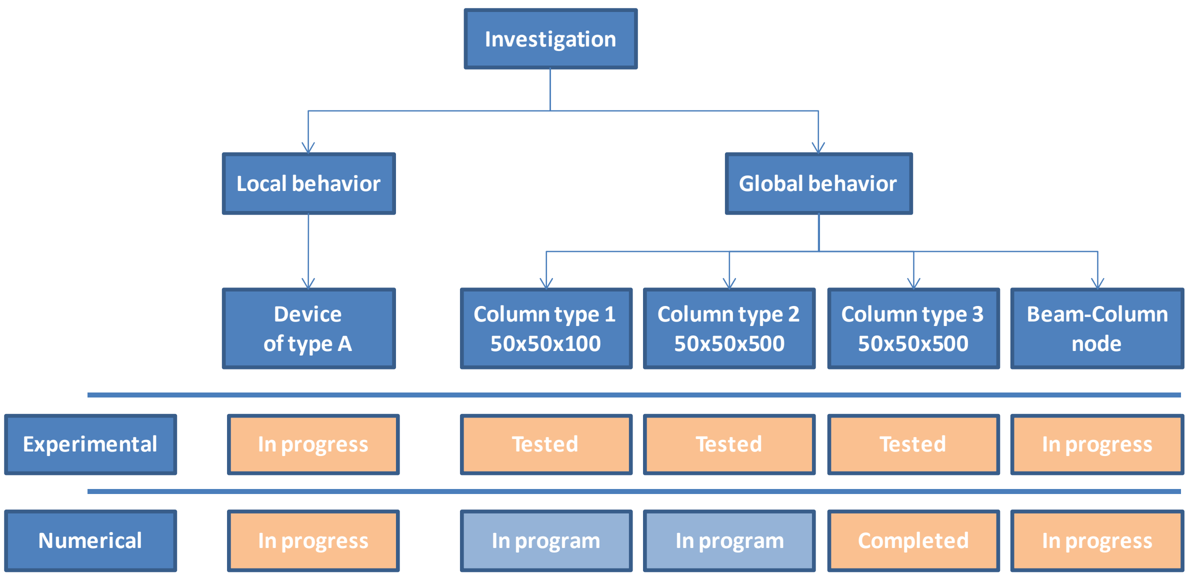


Fig. 2. Tree diagram of the experimental tests.

In particular, to investigate the flexural mechanism, two full-scale specimens have been designed and built. Both specimens are composed of a column and a foundation connected with continuity system. The column has a square section of 0.5 x 0.5 m and is 5 m height. The vertical reinforcements are different for the two columns, whose reinforcement percentages are respectively equal to 1.70% (for a total of 8Φ26) for the first column and 2.55% (for a total of 12Φ26) for the second column.

In this paper the experimental test and numerical behavior of this second specimen are reported.

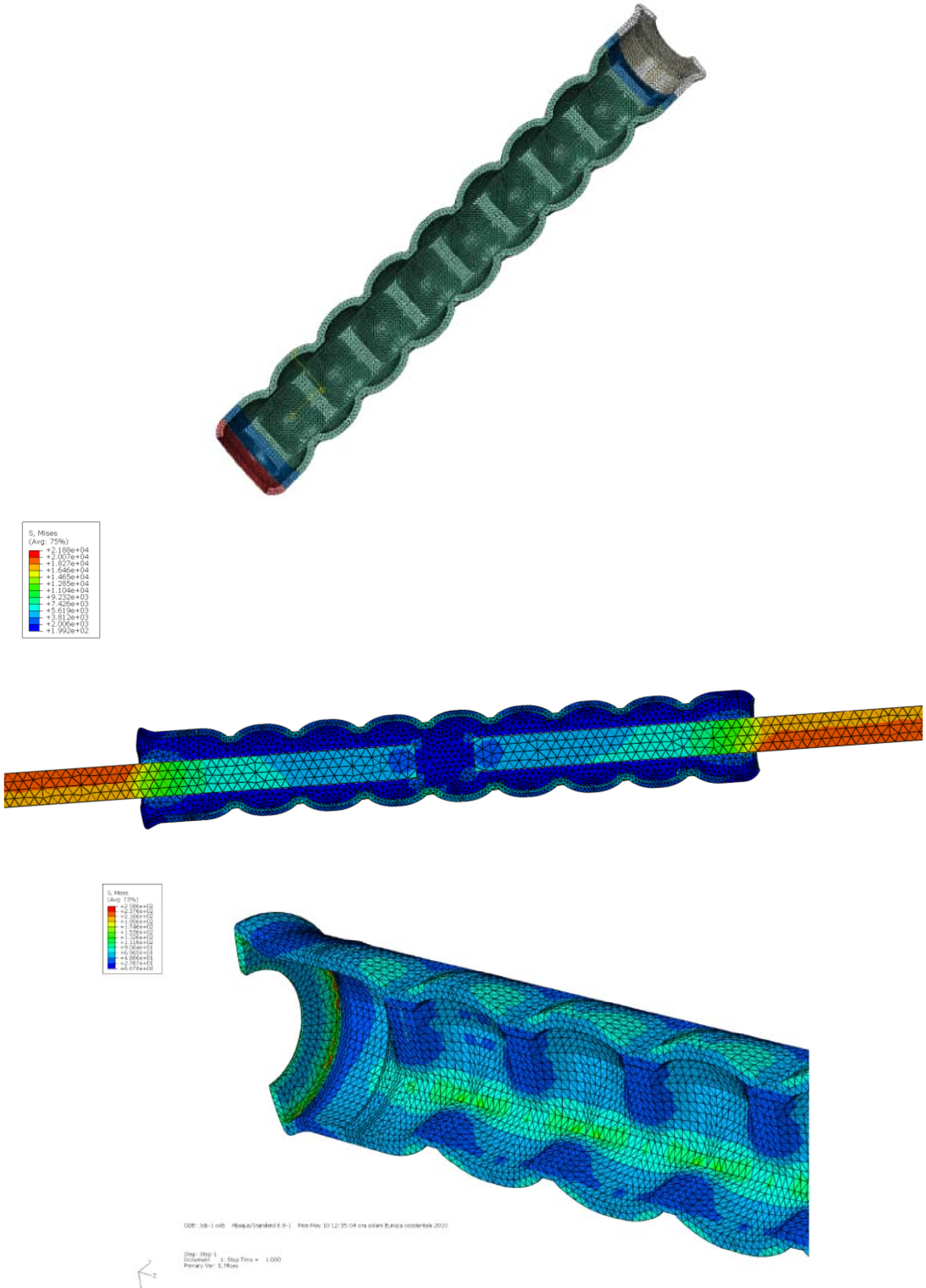


Fig. 3. Connection system, micro-level FE model.

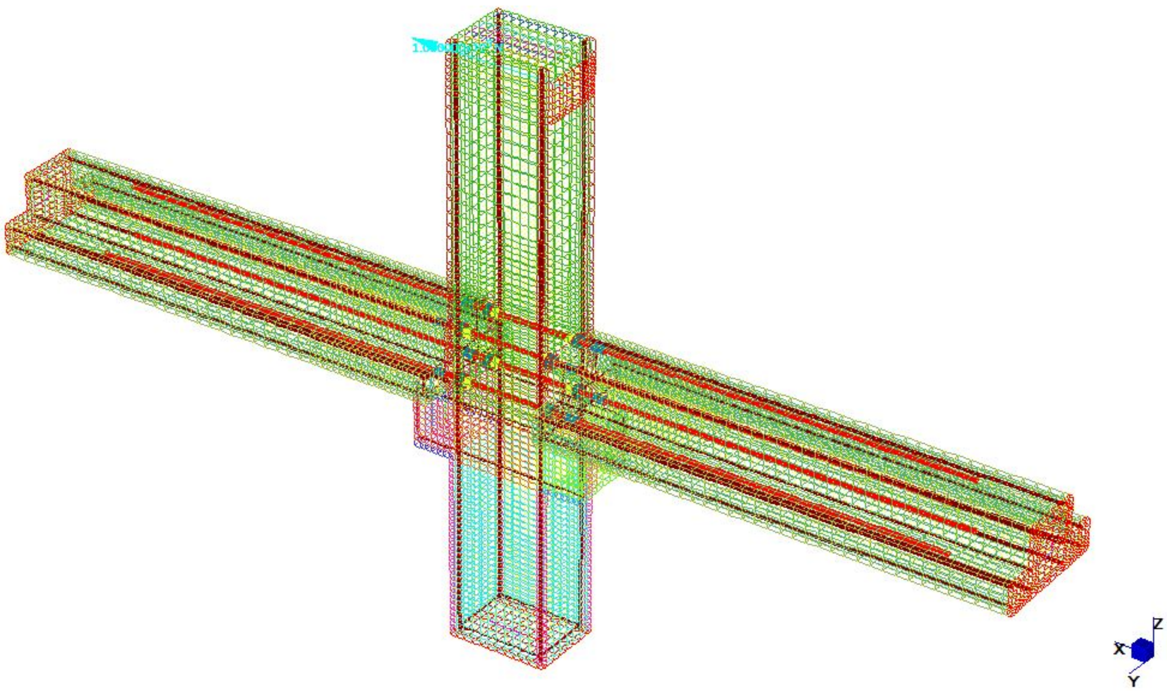


Fig.4. Application of the connection system, meso-level FE model.

EXPERIMENTAL ASSESSMENT

The experimental test consists of a series of the attained horizontal displacements cycles imposed at the top of the column by growing drift at each cycle. The horizontal displacement is imposed in displacement control. In addition at the horizontal displacement a constant axial load of 400 kN is imposed to taking into account the effect of vertical load present in a real building. Fig.5 shows some details of the experimental set.

In order to reproduce the test numerically, one have to know the mechanical properties of materials. In the column there are four different materials: precast column and foundation are made in concrete, between the column and the foundation is placed a high strength mortar to restore the continuity of the concrete section, the reinforcement (bars and stirrups) and the continuity devices are in steel. The values of material strength are derived from laboratory tests and are summarized in Table 1.

Material	Compression strength [MPa]	
Concrete	64.2	
High strength mortar	86.0	
	Yielding stress [MPa]	Ultimate stress [MPa]
Reinforcement bars	450	540
Steel	355	600

Tab. 1. Mechanical properties.

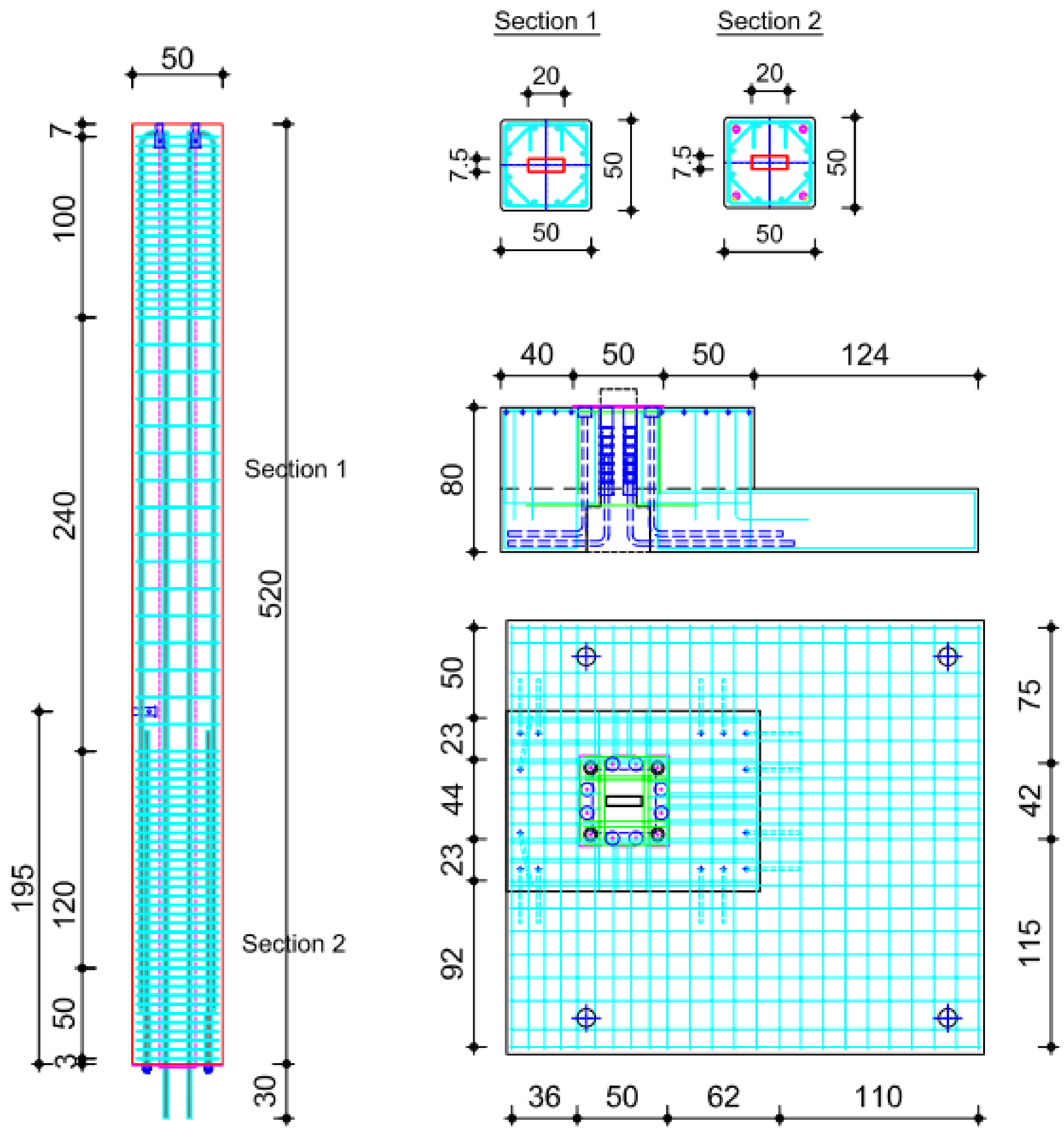


Fig.5. Geometrical details of the column and of the foundation (dimensions are in cm).

The column was subjected to a series of complete cycles of horizontal displacement with a drift ratio ranging between 0.4% to 4.5%. At last three load-unload cycles from 3% to 7% of drift was employed to reach the failure of the column.

In Fig.6 the results of the experimental test was shown in terms of curve shear base reaction – horizontal displacement.

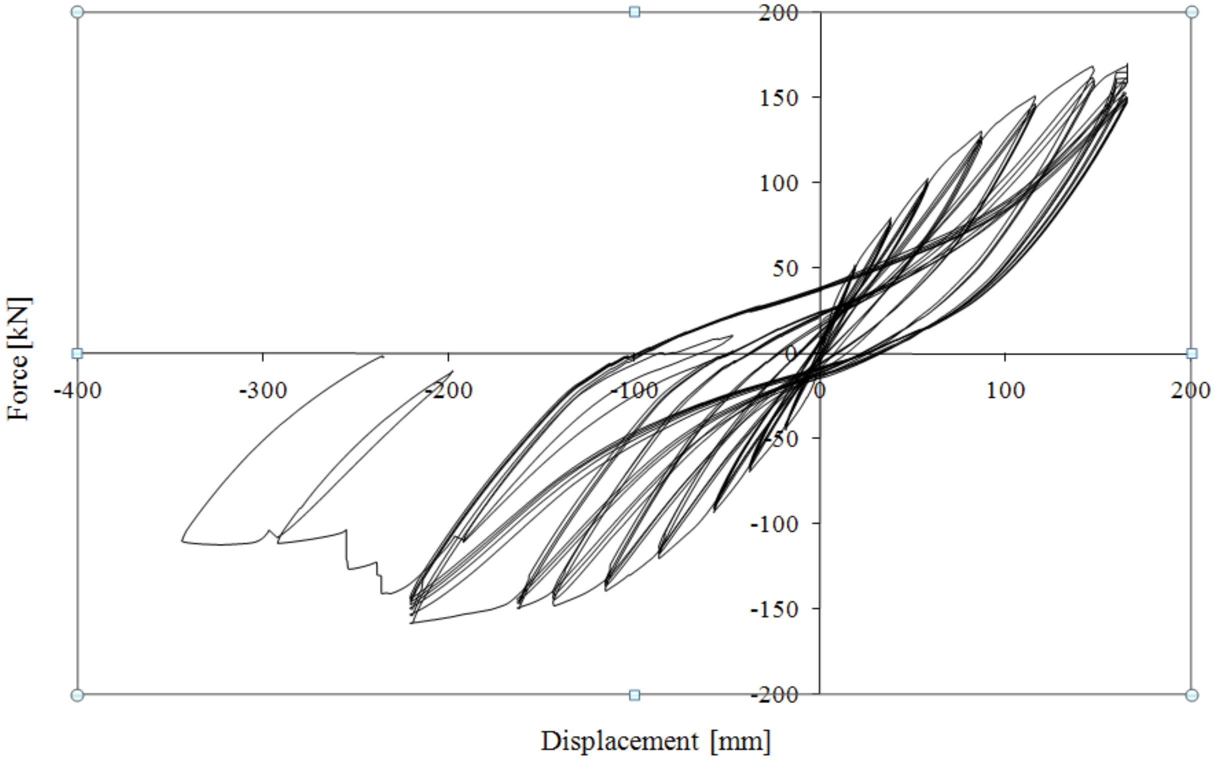


Fig.6. Experimental result in terms of shear [kN] – top displacement [mm] diagram.

NUMERICAL MODELING

GEOMETRICAL DESCRIPTION

As shown from the Figure 7, the numerical model involves the whole column and a part of the foundation. The discretization of a part of the foundation was considered necessary both to adequately represent the deformation of the base and to include in the model a proper discretization of the continuity system. The problem of flexural is symmetrical; it was decided to model numerically only half column. The symmetric part of the element was simulated using appropriate restraints.

The section of the precast column was modeled taking into account the longitudinal hole (75 x 200 mm) necessary for the passage of the pre-stressing cable to give the axial load to the column. A layer of mortar was modeled between the column and the foundation. Its dimensions were taken, according to the design, more than the size of the column. This detail has been accurately modeled to take into account any confinement effect.

The geometrical discretization of the column was performed by solid hexahedral and tetrahedral finite elements (C3D8R and C3D4 in ABAQUS environment [1]). These last were used only in parts of the foundation, where the geometry of the continuity system required a more irregular discretization. The reinforcement bars and the stirrups were modeled with truss elements (T3D2 in ABAQUS environment).

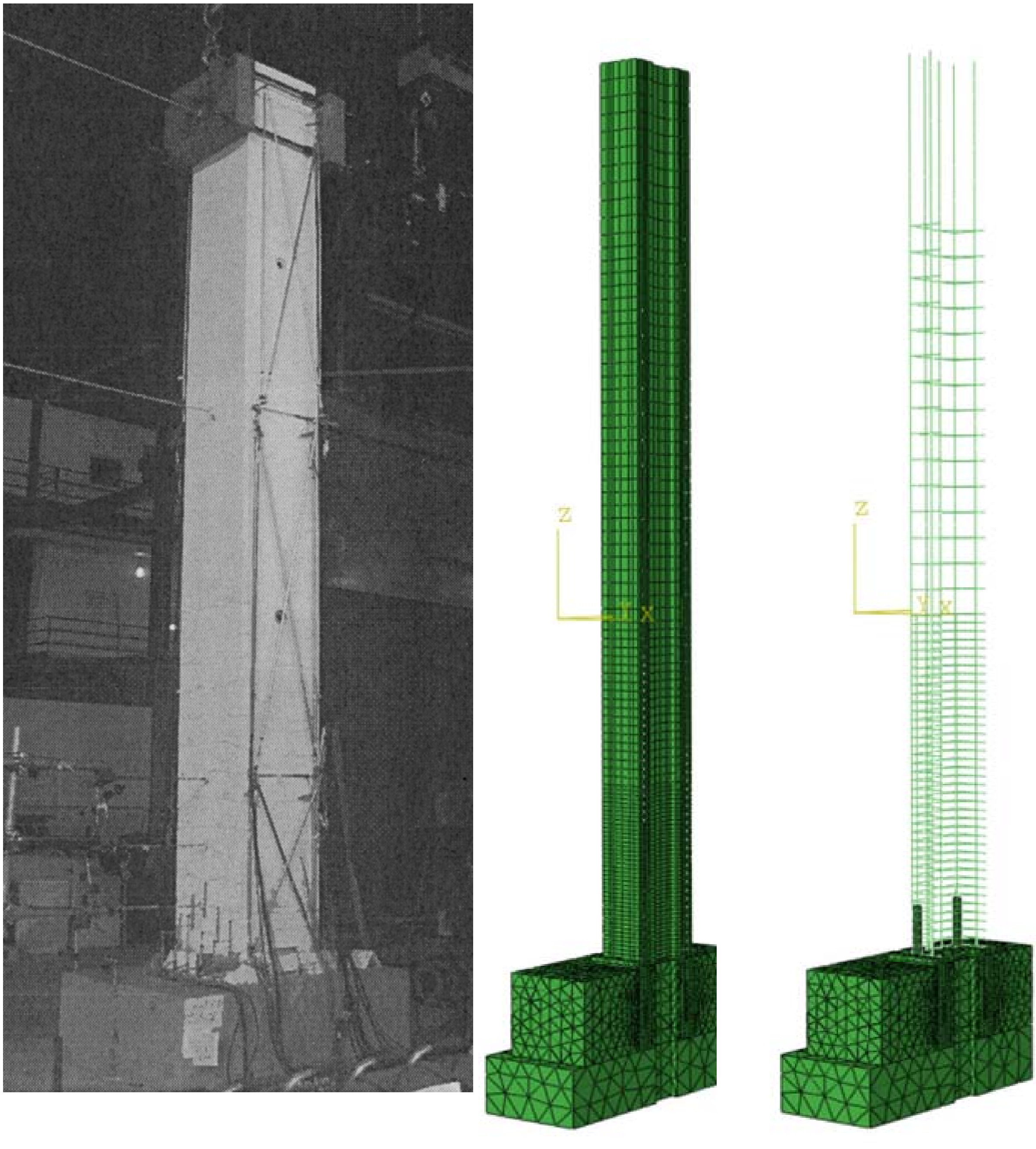


Fig.7. Picture of the column (a) and numerical model: mesh of the concrete (b) and discretization of the reinforcements and stirrups (c).

Fig.8 shows the development of longitudinal reinforcement and the discretization of the stirrups inside the section. All the geometrical quantities were assumed according to the detailed design. In the bottom part of the column, the overlap mechanism was modeled introducing in the model all the reinforcements in which the tension must be transferred.

Instead, in the top part of the column, as the constitutive model of the concrete is kept elastic linear; the stirrups were not modeled because considered unnecessary to mechanical behavior of the element.

Particular attention was given to modeling the connection between the precast column and the foundation. The continuity system uses two devices: the device type A, placed inside the column and the device type B, located within the foundation (Figures 8-9-10). Both the devices are modeled using shell elements (S4 and S3 in ABAQUS environment). Fig.8 shows these elements placed inside the concrete.

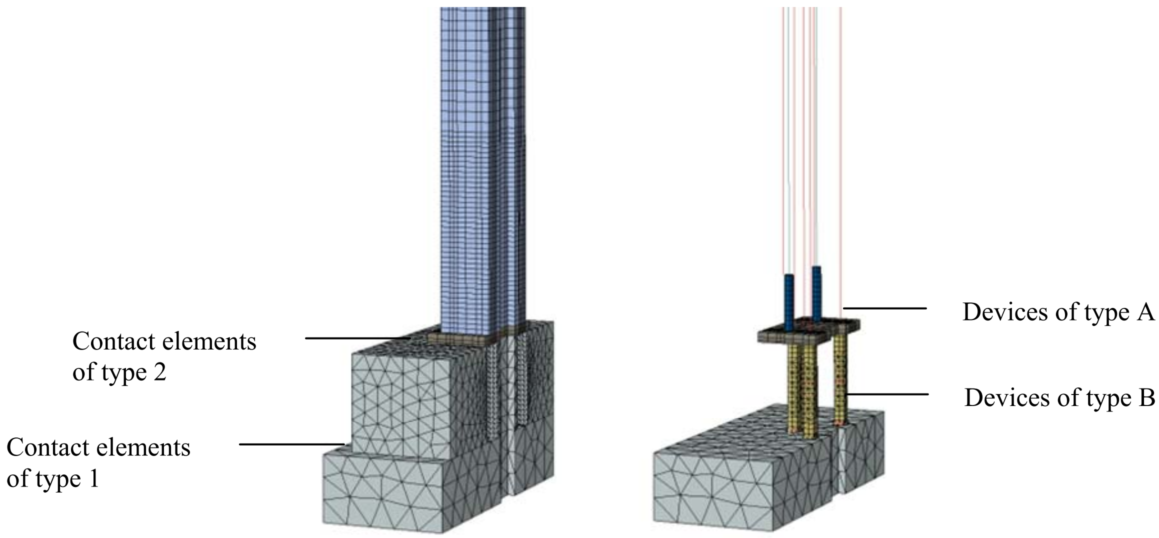


Fig.8. Location of elements of the continuity system.

The device of type A is a transfer device in which the bars are screwed to its ends. The connection is very strong because the tension present in the first bar is converted to tension into the device by a shear mechanism on the thread, and then in tension into the second bar. The mechanism has been modeled numerically with a direct connection between the bars to the device through the introduction of diagonal fictitious elements present only at the ends of the device (Fig.9).

In this way the bars are aligned with the axis of the device and the tension are transferred through a shear mechanism, as experimentally evidence. The device was modeled with an octagonal section that is a right balance between the approximation of the circular geometry and the computational cost required to the local refinement.

The element of type B is a less rigid connection. The steel bars passing in axis to the device and transmit the axial force to the mortar through internal mechanisms of adhesion and shear. Through the formation of compressed struts, the mortar put in tension the device and the action is transmitted to a second bar or diffused in the surrounding concrete. The diffusion mechanisms and the formation of the compression strut are emphasized by the corrugated shape of the lateral walls of the device.

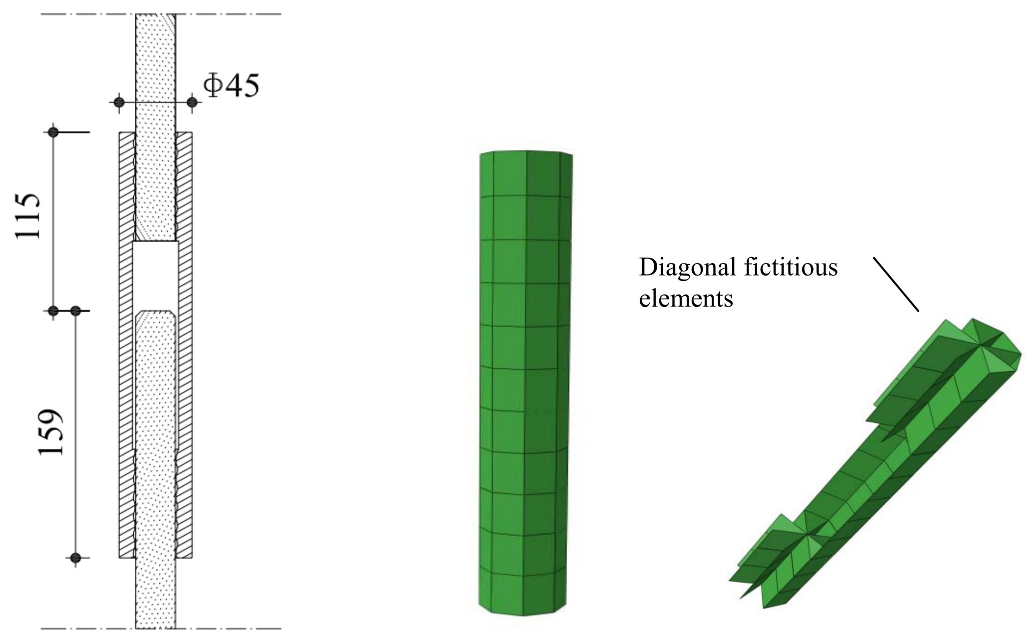


Fig.9. Device of type A. Geometric details and numerical model.

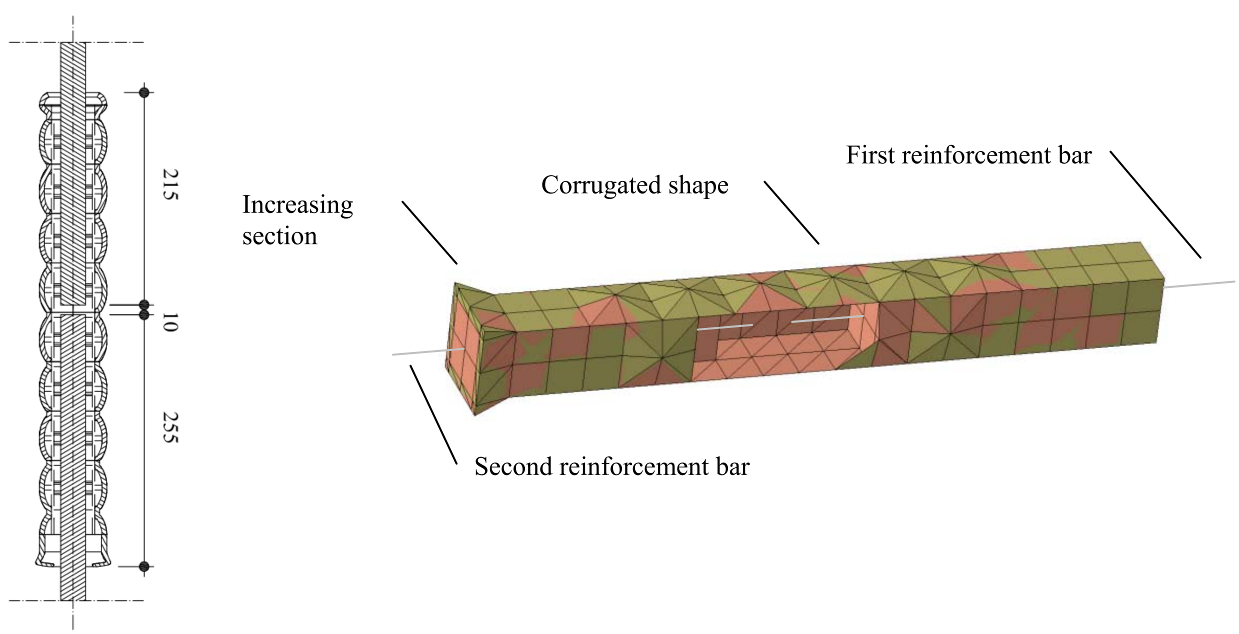


Fig.10. Device of type B. Geometric details and numerical model.

Since this mechanism of transfer appears to be quite complex, it was decided to model the device pointing out the features of the real geometry. In particular, it has been modeled both the device and the inside mortar. The walls of the device are modeled using shell elements with three or four nodes (S4 and S3 in ABAQUS environment) based on real geometry, for the inside mortar solid elements (C3D8R and C3D4 in ABAQUS environment) were used. In this way, the numerical model is able, although consider a meso-level, to put in evidence locally the individual mechanisms of load transfer.

Furthermore, the numerical model includes two types of contact elements, positioned as shown in Fig.8. The type 1 is used only by the numerical point of view to connect two parts of the model with non-conforming discretization. An elastic contact between the parties is generated by the contact element in order to simulate the continuity between the parties. Instead, the second type of element is used to reproduce the physical behavior of a discrete crack at the base of the column that has occurred during the tests and which has influenced the measurements of displacement. This type of element reproduces a behavior with elastic law in compression and in shear while no strength is assumed in tensile.

Moreover in order to assess the local behavior of the connection system (type B), used to coupling precast concrete elements, a detailed model of this particular connection with a non-linear Finite Element Analysis (FEA) is carried out.

As introduced above, the connection is made putting the extremity of the two steel bars to join, in to a corrugated steel tube, and filling with a self-compacting high resistance mortar (about 80 N/mm^2 of compressive resistance). One of the corrugated steel tube extremities has a camber, to improve the adherence with the external concrete. Referring to the steel tube, the connection system, object of this study, have a total length of 485 mm, the internal diameter of 60 mm and the external diameter of 70 mm, instead the two bars have a diameter of 26 mm. The corrugations are impressed on four sides along the length of the tube.

The FEA consist in a static monotone traction test of the two bars coupled by the connection system, the yielding of the steel bars before the failure of the mortar filling is the expected positive response of the test. It is possible highlighted three principal parts of the finite element model: i) the connection system (corrugated tube), ii) the mortar inside the connection system (filling), and iii) the two steel bars. For all these parts the mesh is composed by linear tetrahedral elements.

The computational codes utilized to perform that simulation are "Solid Work" and "NeiNastran": these tools are coupled together in a platform called "NeiFusion". Therefore the geometry of the connection system (type B) is made by "Solid Work", instead the finite element mesh and the solution is carried out by "NeiNastran" [2].

MATERIAL

The column is composed of three materials: concrete, mortar and steel. The concrete is modeled using two different constitutive models. A linear elastic law is used at the top of the column and in foundation where experimentally there were no cracks. Most of the column is modeled in non-linear field using damage concrete plasticity.

The concrete damaged plasticity model is based on the assumption isotropic damage and is designed for applications in which the concrete is subjected to arbitrary loading conditions.

The model takes into consideration the degradation of the elastic stiffness induced by plastic straining both in tension and compression. It also accounts for stiffness recovery effects under cyclic loading [3-9].

The same material law is assigned to the mortar while a plastic bilinear hardening is used to modeling the behavior of the steel.

Special attention is devoted to avoid mesh dependency [10].

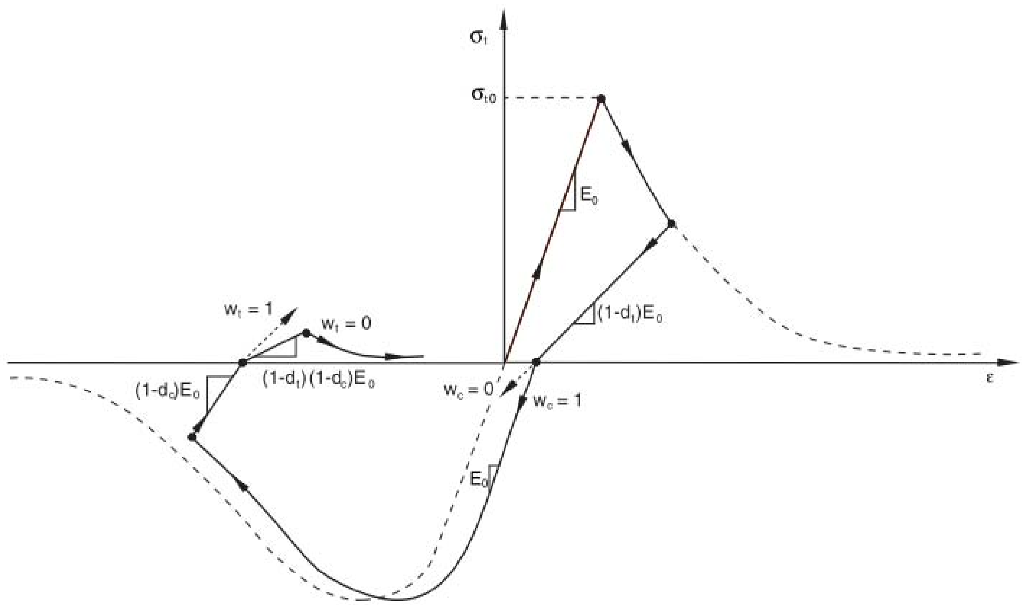


Fig.11. Stress-strain diagram for the concrete with the plasticity-damage model used in ABAQUS [9].

About the local behavior simulation of the connection system, the material adopted for the bars are composed by a standard Italian B450C steel for concrete reinforcements; the elastic modulus (E_s) and the Poisson coefficient are 206000 N/mm^2 and 0.3 respectively, the Von Mises failure criteria for ductile material is adopted, the ideal yielding tension is 450 N/mm^2, and the unidirectional behavior law is bilinear with a plastic stiffness of 20600 N/mm^2. Transversal total sectional area of the tube is about double of the transversal sectional area of the bar (A_b), therefore steel yielding is not expected, consequently the corrugated tube's steel have an elastic behavior, with an elastic modulus of 206000 N/mm^2.

The filling, as previously stated, is a self-compacting high resistance mortar, the elastic modulus and the Poisson coefficient are assumed equal at 30000 N/mm^2 and 0.2 respectively, the Drucker and Prager failure criteria is adopted, the cohesion is estimated equal at 10 N/mm^2, instead the angle of shear resistance is valued equal at 40°, and the unidirectional behavior law is bilinear with a plastic stiffness of 3000 N/mm^2.

NUMERICAL ASSESSMENT AND COMPARISON WITH EXPERIMENTAL TEST

BEHAVIOR UNDER MONOTONIC LOADING HISTORY

Based on the experimental results obtained during the cyclic test, it is possible to trace an envelope curve of the cycles and take it as an approximate curve of the monotonic response. This curve is plotted in Fig.11 and can be used to obtain a first evaluation of the accuracy of the numerical model and to identify some parameters of non-linear law.

Fig.12 shows that the numerical model is able to provide reasonably good response both in terms of ultimate strength and deformability. Regarding the deformation, the numerical analysis shows that the presence in the model of a discrete crack at the base of the column (between the column and the foundation) is required to achieve, on a structural element, the stiffness measured experimentally.

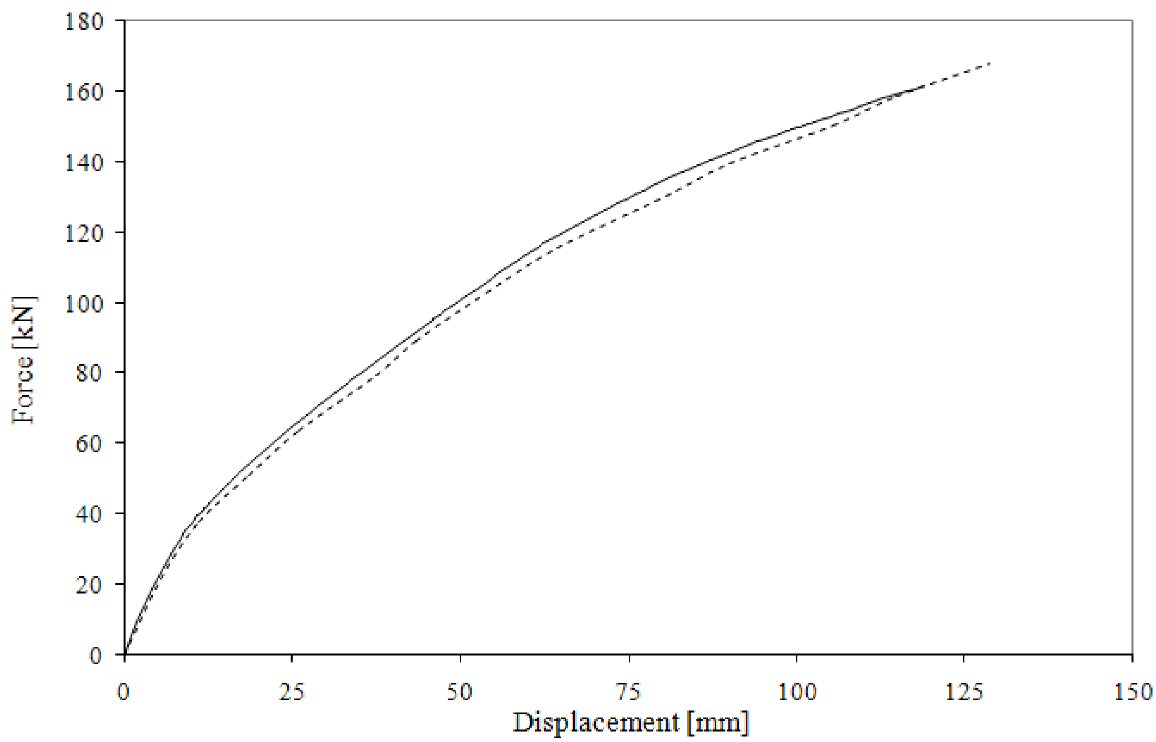


Fig.12. Curve displacement at the column top vs. shear base. Comparison between experimental measurements (dotted line) and numerical evaluation (continued line).

Fig.13 shows the detail, in amplified scale, of the displacement in the discrete crack. Due to the rigid rotation of the column, the little vertical displacement present at the base section cause a relevant horizontal displacement at the top of the column. For this reason the presence of the discrete crack was necessary to reproduce the structural behavior of the element with good accuracy.

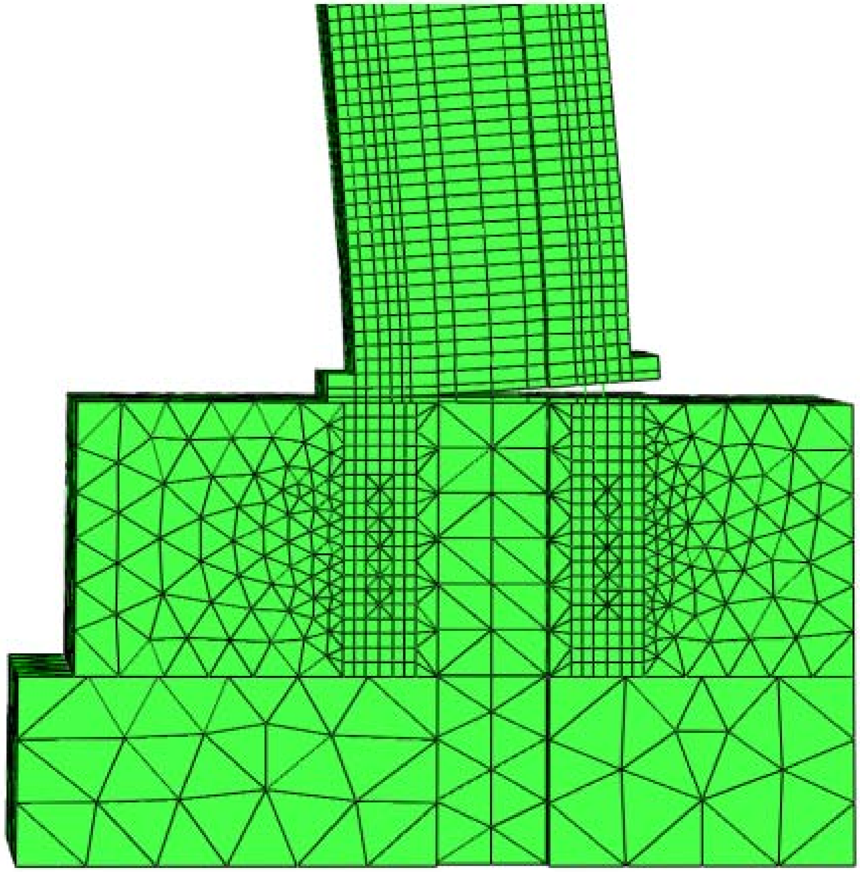


Fig.13. Details of the opening of the crack in the base section.

BEHAVIOR UNDER CYCLIC LOADING HISTORY

Fig.14 shows the load history. The displacement values were taken from the experimental data and correspond to a drift of 0.4%, 0.8%, 1.2%, 1.8%, 2.4%, 3.0%, 3.5%, and 4.5%. In Fig.15 the imposed displacement is plotted as a function of time analysis. Clearly, in a static analysis this variable has no physical meaning and only serves to order the loading history.

Fig.16 shows a picture of the base of the column after the experiment, while Figure 17 shows the area most damaged at the end of the numerical analysis. Note in both cases, the extended damaged area with the presence of major cracks at the base of the column. From Fig.17 it is also possible to see the cracks that occur inside the column in the contact zone between steel elements (device of Type A) and the concrete of the column. These devices, because of their position, trigger the major cracks in the column. From the Fig.17, it is possible to notice an internal damage in the area of the overlap of the longitudinal bars. Presumably, this damage had little influence in the global response of the column.

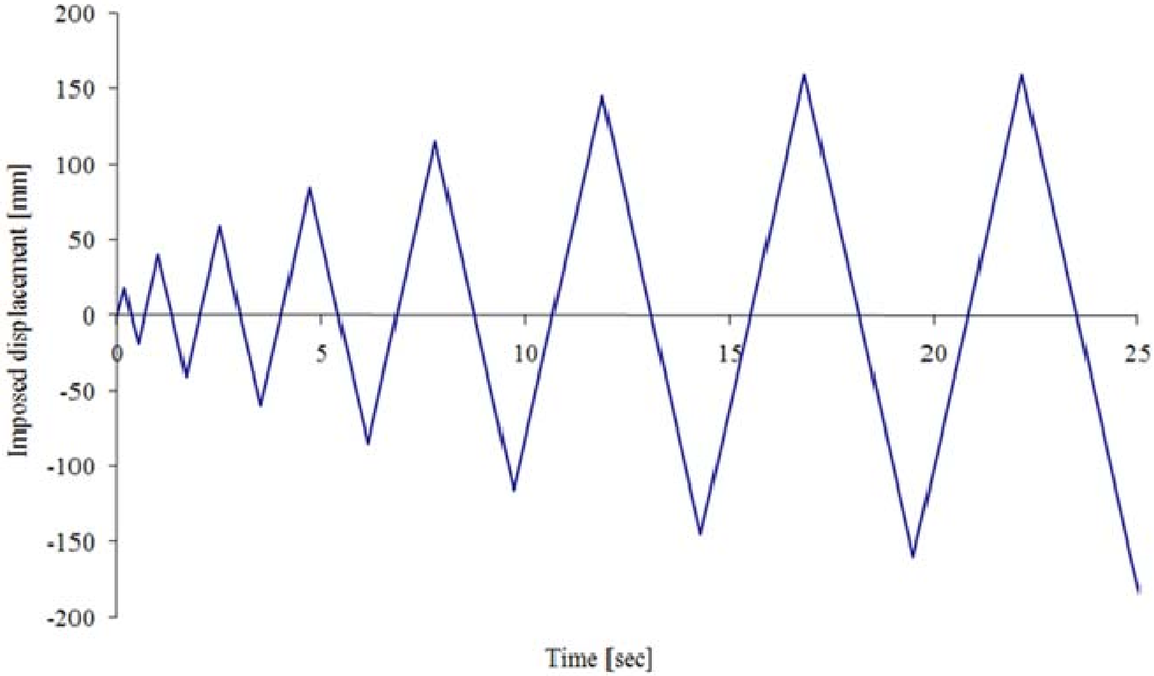
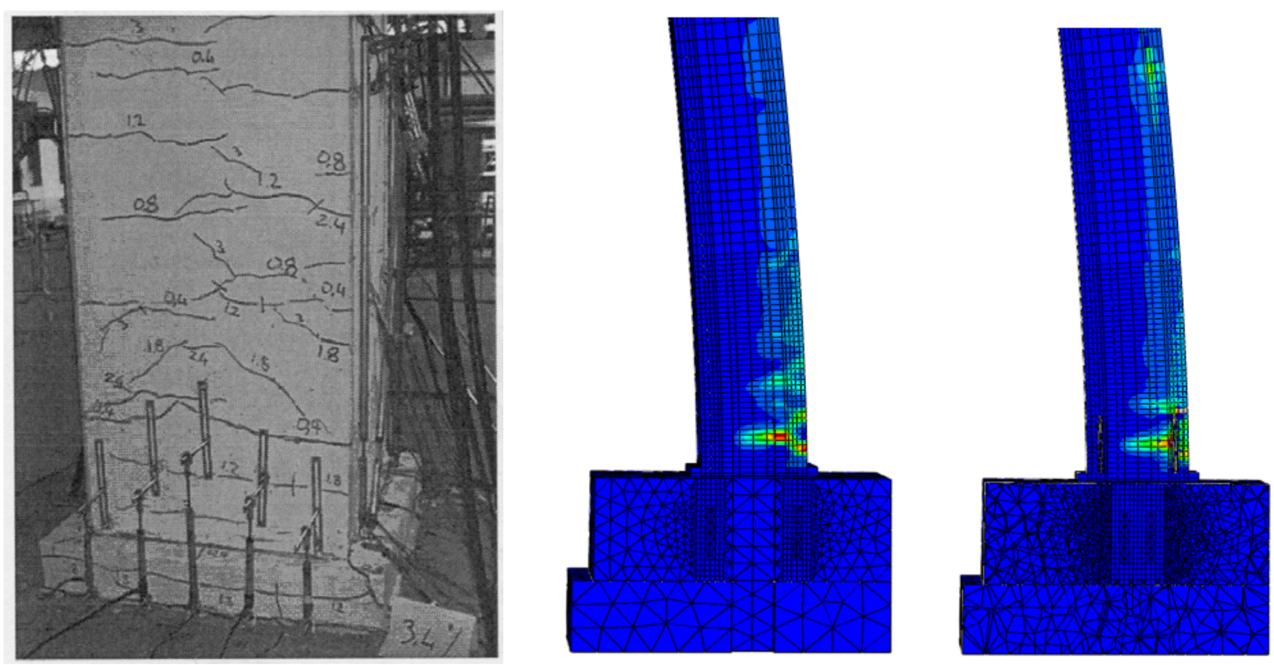


Fig.14. Load history for cyclic analysis.



(a) (b) (c)

Fig.15. Cracks at the end of the experimental test (a) and cracks occurring in the numerical analysis in the middle section (b) and in the section of the longitudinal bars (c).

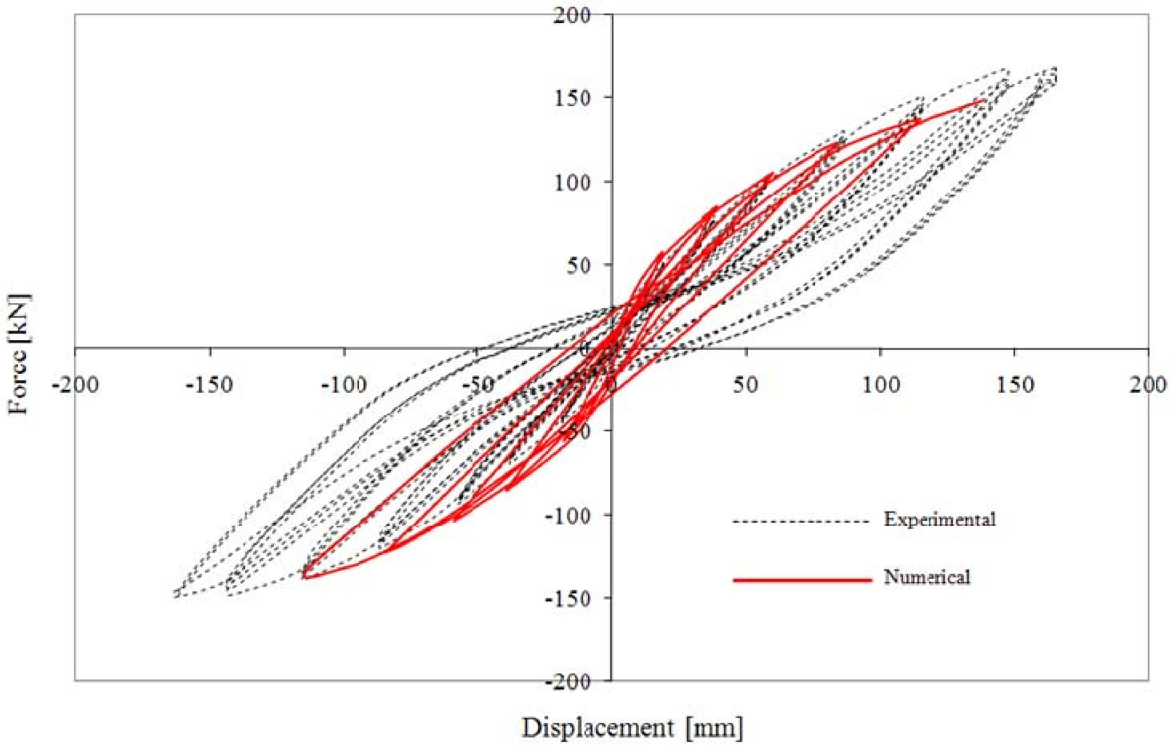


Fig.16. Diagram of shear at the base of the column vs. top displacements.

From the point of view of the numerical analysis, the column gives the maximum strength between the fifth and sixth cycle (between 2.4% and 3% drift). Figure 15 shows the comparison between the numerical results and the experimental results in terms of curve displacement at the top vs. shear base. From the numerical analysis, the failure of the column occurs after the fifth cycle, with a drift between 2.4% and 3%.

The collapse of the column is caused from the tensile failure of the reinforcements outside the anchorage device above the foundation block. This failure occurs in correspondence with the discrete crack modeled with contact elements in correspondence of the base of the column. There were no failure in bars in other positions and even failure by crushing into concrete or mortar.

TRACTION TEST OF THE CONNECTION SYSTEM

Concerning the traction test of the connection system (type B), the expected yielding value of the bars (F_{by}) is 238'000 N; by F_{by} the elastic response (d_y) of the connection system is computed. The result of the traction test (considering the non-linear behavior of the materials) is shown in Figure 16, that curve is normalized by F_{by} and d_y, for the force and displacement respectively. Instead in Figure 17, the Von Mises stress are depicted for both the steel corrugated tube and the two bars; the crossing of the yielding threshold (450 N/mm^2) is well visible in the two bars, instead in the tube the maximum tensions are moderate (about one half of the bar's max stress).

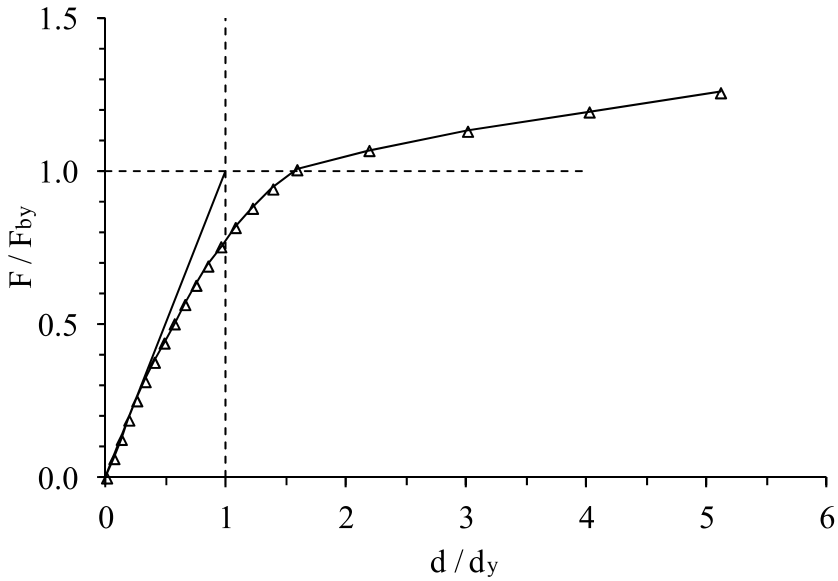


Fig.17. Axial displacement vs. axial reaction of the connection system.

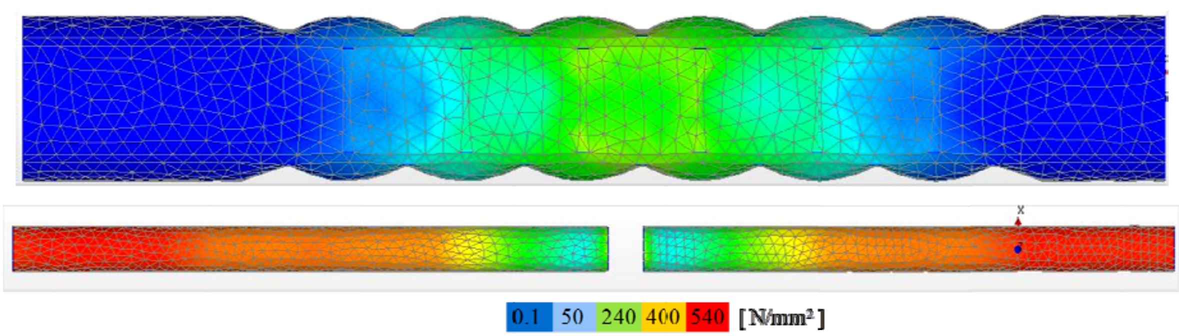


Fig.18. Von Mises stress on the bars and on the corrugated tube, for a traction of 300000 N, (stress in N/mm^2).

The mortar of filling not fail before the steel yielding threshold, and this is the main positive result of that FEA traction test; however the connection system (type B) show a non-linear behavior since 0.5 F_{by}. Possible future analysis about this kind of connection system can be: i) an high velocity rate load traction test for study the connection system versus stress due to blast loads, and ii) study the shear capacity.

CONCLUSION

Structural continuity is an important issue with regard to the strength of connections between precast elements. In this paper the mechanical behavior of a column connected to a foundation through a system of devices is examined from the experimental and the numerical point of view. In particular, it performs a finite element modeling able to reproduce both the global behavior of the structure and some local aspects.

To develop the numerical analysis is used ABAQUS software modeling the nonlinear behavior of concrete and mortar using Concrete Damage Plasticity model. The devices and reinforcements bars are modeled by a bilinear plasticity model. The comparison with the experimental results shows a good agreement for the first five cycles of the load history.

Concerning the local behavior of the connection system (type B), a monotonic traction test is been simulated using NeiFusion software; a detailed geometry of the system is been meshed and a non linear constitutive law of the material is been adopted. The full load capacity of the bars are developed without the failure of the filling mortar, therefore the connection system is well performing because a brittle failure do not occurs.

The present study represents an intermediate step of a larger study in which the connecting devices will be analyzed in detail. In addition, other failure mechanisms will be investigated for the node column-foundation or beam-column. Ultimate goal of the whole study is the demonstration of the efficiency of the continuity system in question, demonstrating the fully equivalence between the behavior of a P.C. structure and a similar R.C. structure.

Other aspects are under study: specific attention is devoted to the increase on structural integrity obtainable with the adoption of this kind of connections. In particular, the configuration with double layer of connections (at the top and the bottom of the beam) can accommodate the moments connected with the loss of intermediate support due to failure of the column. Moreover further testing is needed to gain statistical data validating this connection in seismic conditions.

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