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REINFORCED CONCRETE FRAMES STRENGTHENED BY CABLE ELEMENTS UNDER MULTIPLE EARTHQUAKES: A COMPUTATIONAL APPROACH SIMULATING EXPERIMENTAL RESULTS

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Abstract. *The seismic analysis of existing reinforced concrete beam-columns frames that have been damaged due to cyclic imposed deformations and upgraded using diagonal cable elements (tension-ties) is numerically investigated. A double discretization in space by the Finite Element Method and in time by a direct approach is adopted. The unilateral behaviour of the cable elements that undertake only tension stresses is taken into account. A calibration of the numerical approach is achieved in a typical example problem by comparing the computational results with available experimental data from the literature. Application for a typical reinforced concrete frame with only one diagonal tie is also demonstrated.*

1 INTRODUCTION

It is well known that in Greece and in other seismically active countries many existing Reinforced Concrete (RC) frame structures have been designed and constructed using old seismic code provisions. Therefore, reinforcement details of existing RC building are usually inadequate for proper seismic structural behaviour, local and/or global. A typical example of critical seismic behaviour is the area of beam-column connections [1-3]. As concerns the global behaviour for such RC frames structures the need for seismic strengthening often arises. One of the simple, low cost and efficient method for strengthening of RC frames against lateral induced earthquake loading is the use of steel cross X-bracings [4, 5]. Application of this technique is reported, among others, also in Greece to improve seismic performance of existing old pilotis type multi-story RC buildings by strengthening only the ground story [6, 7].

Seismic upgrading of existing RC structures makes use of many and well-known repairing and strengthening techniques [8-11]. The use of cable-like members (tension-ties) instead of steel cross X-bracing can be considered as an alternative strengthening method for inadequate RC frame structures under lateral seismic actions [12,13]. Cable restrainers are also used for concrete and steel superstructure movement joints in bridges [14]. These cable-members (ties) can undertake tension but buckle and become slack and structurally ineffective when subjected to a sufficiently large compressive force. Thus the governing conditions take equality as well as an inequality form and the problem becomes highly nonlinear [15, 16].

This study presents first a numerical approach for the seismic analysis of existing RC beam-column frames that have been strengthened using cable elements. The approach is based on an incremental formulation and uses the Ruaumoko structural engineering software [17]. Damage indices are computed in order the optimum cable-bracing strengthening version to be chosen, especially under multiple earthquakes. Next, a calibration of the approach is realized by using available experimental results. Finally, an application for a simple typical one-bay one-story RC frame strengthened by bracing ties is presented.

2 A COMPUTATIONAL APPROACH

Details of the developed numerical approaches are given in [18], whereas the adopted incremental approach is briefly summarized herein. As usual in Structural Dynamics [19], a double discretization, in space and time, is applied. First, the structural system is discretized in space by using finite elements. Pin-jointed bar elements are used for the cable-elements. The unilateral behaviour of these elements can in general include loosening, elastoplastic or/and elastoplastic-softening-fracturing and unloading - reloading effects. All these characteristics, concerning the cable full constitutive law, as well as other general non-linearities of the RC structure, can be expressed mathematically by using concepts of convex and non-convex analysis [20]. So, for the cable-elements behaviour, the following relation holds:

$$s_i\ (d_i)\ \in\ \hat{\partial}\, SP_i(d_i) \tag{1}$$

where s_i and d_i are the (tensile) force (in [kN]) and the deformation (elongation) (in [m]), respectively, of the i-th cable element, $\hat{\partial}$ is the generalized gradient and SP_i is the super-potential function (Panagiotopoulos [20] and Mistakidis & Stavroulakis [21]).

Incremental dynamic equilibrium for the assembled structural system with cables is expressed by the matrix relation:

$$\boldsymbol{M\,\Delta\ddot{u} + C\,\Delta\dot{u} + K_T\,\Delta u = -M\,\Delta\ddot{u}_g + A\,\Delta s + \Delta p} \tag{2}$$

where $\boldsymbol{u(t)}$ and $\boldsymbol{p(t)}$ are the displacement and the load time dependent vectors, respectively, and $\boldsymbol{C(\dot{u})}$ and $\boldsymbol{K_T\,(u)}$, are the damping and the tangent stiffness matrix, respectively. Dots over symbols denote derivatives with respect to time. By $\boldsymbol{s(t)}$ is denoted the cable stress vector satisfying (1). $\boldsymbol{A}$ is a transformation matrix and $\boldsymbol{u_g}$ the ground seismic excitation.

The above relations combined with the initial conditions consist the problem formulation, where, for given $\boldsymbol{p}$ and/or $\boldsymbol{\ddot{u}_g}$, the vectors $\boldsymbol{u}$ and $\boldsymbol{s}$ have to be computed. Regarding the strict mathematical point of view, using (l) and (2), we can formulate the problem as a hemi-variational inequality one by following [20, 21] and investigate it.

For the numerical treatment of the problem the structural analysis software Ruaumoko [17] is used. Here, for the time-discretization, the Newmark scheme is chosen. Ruaumoko uses the finite element method and provides results which concern, among others, the following critical parameters: local or global structural damage, maximum displacements, inter-storey drift ratios, development of plastic hinges and various response quantities, which allow the using of the incremental dynamic analysis (IDA) method [22].

Ruaumoko has been applied successfully for multiple earthquakes concerning the cases of concrete planar frames [16] and RC frames strengthened by cables [18]. It is reminded that multiple earthquakes consist of real seismic sequences, which have been recorded during a short period of time (up to some days), by the same station, in the same direction, and almost at the same fault distance [23].

After the seismic assessment of the existing RC structure, the choice of the best strengthening cable system can be realized by using damage indices [24-29]. In this study the overall structural damage index (OSDI) is used. This parameter summarizes all the existing damages on columns and beams of reinforced concrete frames in a single value, which is useful for comparison reasons [29].

In the OSDI model after Park/Ang [24] the global damage is obtained as a weighted average of the local damage at the section ends of each frame element or at each cable element. The local damage index is given by the following relation:

$$DI_L = \frac{\mu_m}{\mu_u} + \frac{\beta}{F_y d_u} E_T \tag{3a}$$

where: DI_L is the local damage index, μ_m the maximum ductility attained during the load history, μ_u the ultimate ductility capacity of the section or element, β a strength degrading parameter, F_y the yield generalized force of the section or element, E_T the dissipated hysteretic energy, d_u the ultimate generalized displacement.

For the global damage index, which is a weighted average of the local damage indices, the dissipated energy is chosen as the weighting function. So, the global damage index is given by the following relation:

$$DI_G = \frac{\sum_{i=1}^{n} DI_{Li} E_i}{\sum_{i=1}^{n} E_i} \tag{3b}$$

where DI_G is the global damage index, DI_L the local damage index, E_i the energy dissipated at location i and n the number of locations at which the local damage is computed

3 CALIBRATION AND APPLICATION OF THE COMPUTATIONAL APPROACH

3.1 Examined experimental results from the literature

Available experimental results for a simple typical one-bay one-storey RC frame, strengthened with steel cross X-bracing and investigated by Massumi & Tasnimi [4] and Massumi & Absalan [5] are used for the calibration of the presented numerical approach. These results concern two experimental models of reinforced concrete frames, which have been designed on the basis of old traditional codes. The first of them is a bare-frame and the second is the same frame, but strengthened with steel X-bracing.

The single-bay, one-storey frame geometrical and reinforcement details along with the experimental testing procedure are presented in Fig. 1 [4, 5]. The strength class of the used concrete was C25. The steel bracings were squared tubes with section 20 mm × 20 mm, thickness 2 mm and yield strength 240 MPa. During these tests a lateral additive cyclic static load was applied to the storey beam in a displacement-controlled mode [4, 5].

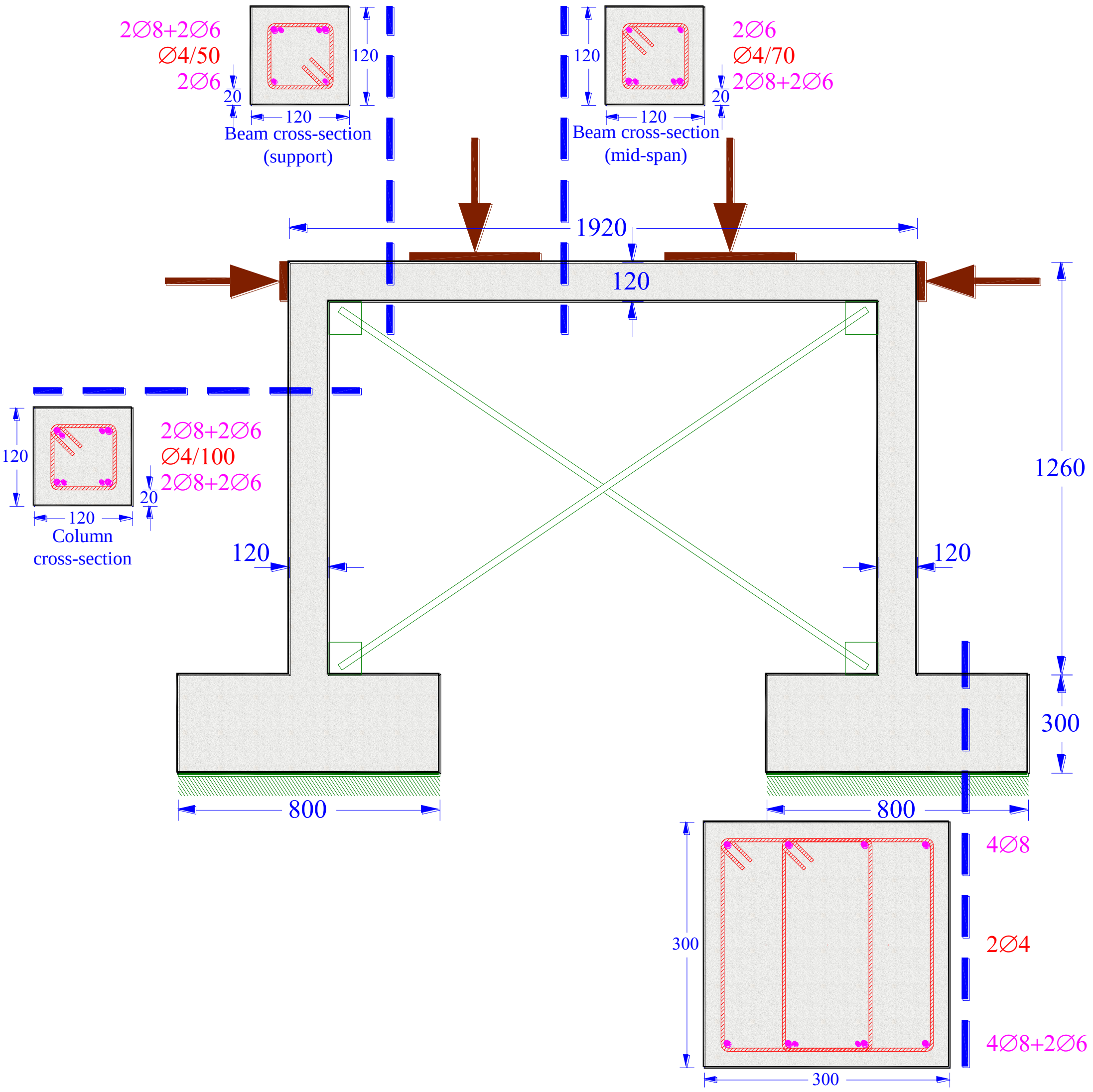


Figure 1. Geometry, reinforcements, strengthening system and test rig of the examined RC frames [4, 5]

3.2 Simulation of the Massumi et al. [4, 5] tests

With respect to aforementioned experimental results, the finite element models related to the unbraced and braced frames are made using Ruaumoko software [17]. The columns and the beam are modeled using prismatic frame elements (Fig. 2). Nonlinearity at the two ends of RC members is idealized using one-component plastic hinge models, following the Takeda hysteresis rule. The effects of cracking on columns and beams are estimated by applying the guidelines of Eurocode 8, part 3 [30] and Greek Retrofitting Code [31]. The stiffness reduction due to cracking results to effective stiffness of 0.450 I_g for the columns and 0.225 I_g for the beam, where I_g is the gross inertia moment of their cross-section. The vertical gravity loads applied on the beam are W = 9 kN.

Cable-elements are used for the steel bracings simulation by applying the bilinear with slackness hysteresis rule [17]. These cable elements have a cross-sectional area F_c = 1.44 cm^2, which is equivalent to the cross-sectional area of steel braces tubes. Yield strength of cable bracings was f_y = 240 MPa, yield strain ε_y = 0.12 %, fracture strain ε_f = 2 % and elasticity modulus E_s = 200 GPa. The cable constitutive law concerning the unilateral (slackness), hysteretic, fracturing, unloading-reloading behaviour, has the diagram depicted in Fig. 3. Ductility index is $\mu = d/d_y$.

The moment versus axial load interaction curves of the cross-section of the beam and the columns of the RC frame used in the analyses are shown in Fig. 4.

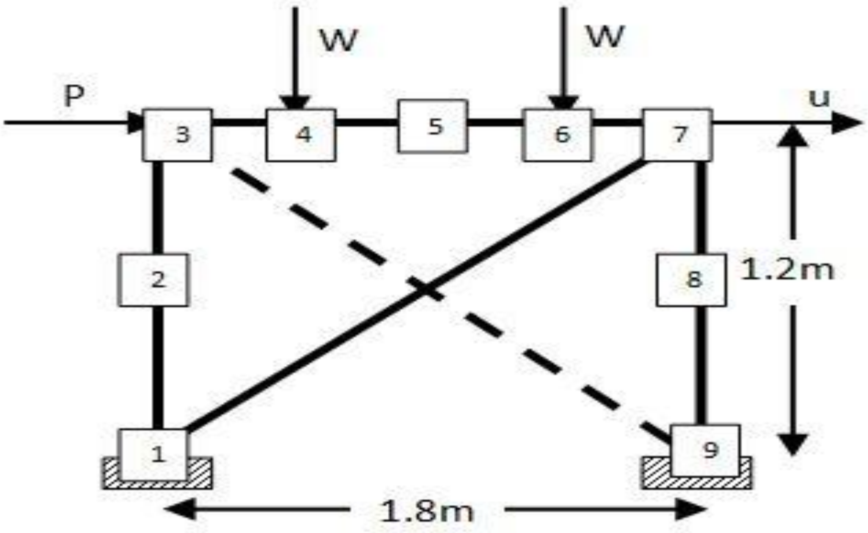


Figure 2. Finite-element discretization of the simulated structural system.

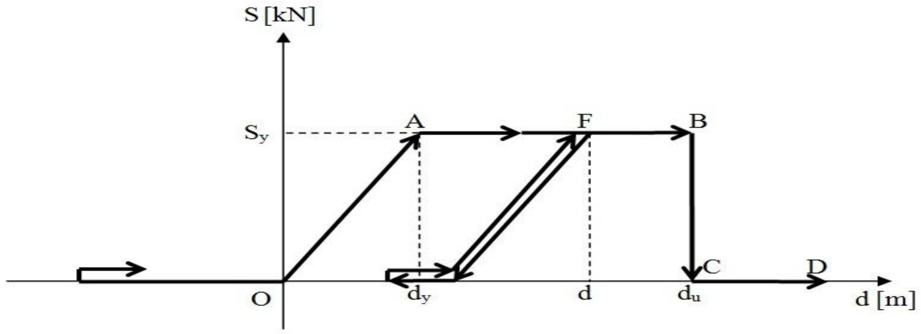
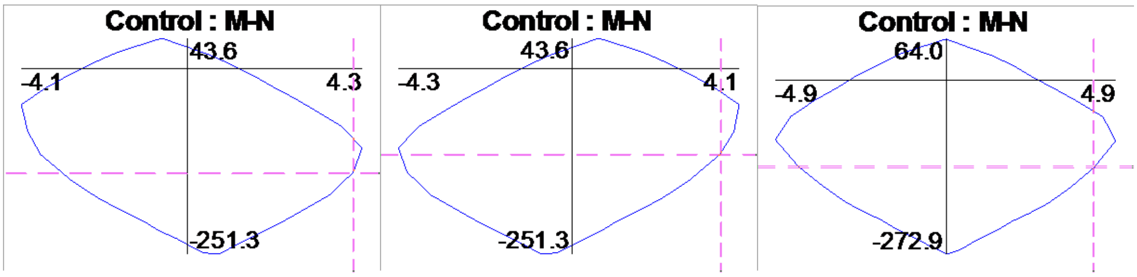


Figure 3. Constitutive law of the cable-elements.



Beam cross-section at support *Beam cross-section at mid-span* *Column cross-section*

Figure 4. M-N interaction curves for the cross-sections of the examined RC frame (in kNm and kN).

The loading history of the examined cases (unbraced frame UBF1 and braced frame BF1 [4, 5]) has been simulated as displacement-controlled multiple earthquake excitation imposed on the top left node 3 of the frame (Fig. 2). This loading simulation had full loading steps with maximum displacements ±5, ±10, ±15, ±20, ±25 and ±30 mm for the unbraced frame, whereas for the X-braced frame the loading steps had maximum displacements ±2.5, ±5.0, ±7.5, ±10, ±12.5 and ±15 mm.

The analytically derived diagrams of the load, P, versus top displacement, u, hysteretic behavioural curves for the unbraced (bare) frame and the X-braced frame are shown in Figs. 5 and 6, respectively, and compared with the experimentally obtained ones. From the comparisons in these figures it is obvious that the computed results are in very good agreement with the experimental data curves.

Some representative results of the numerical simulation are also presented in the Table 1. In the table column (2) the Global Damage Index DI_G and in column (3) the Local Damage Index DI_L for the bending moment at the left fixed support A of the frame are given (see also Fig. 2). Further, in the table column (4) the developed maximum horizontal top force P_{top} is also given.

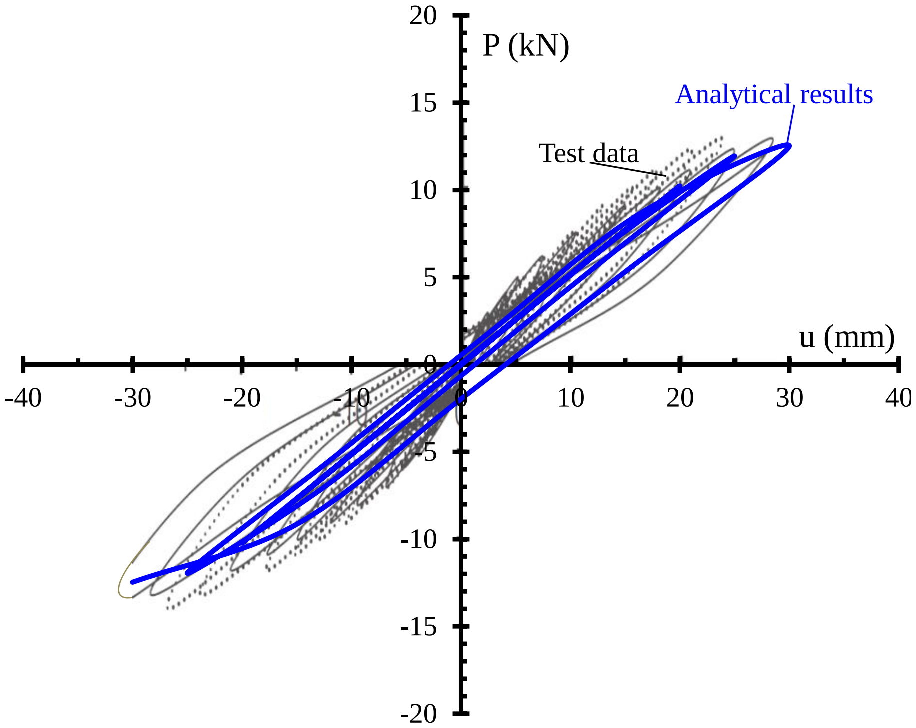


Figure 5. Analytical and experimental [4, 5] load versus displacement hysteretic behavioural curves for the examined unbraced RC frame.

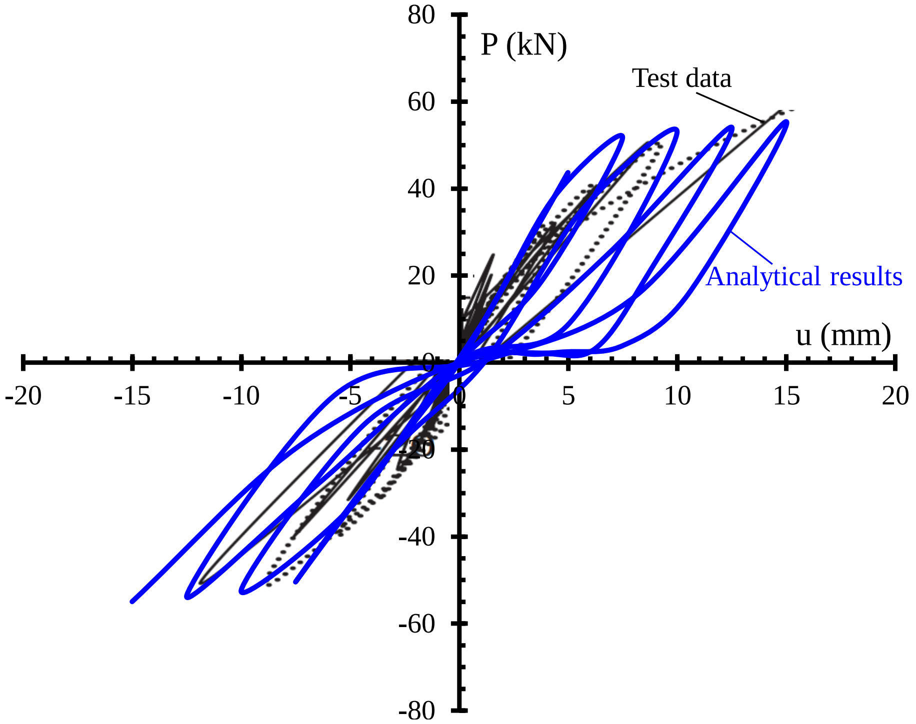


Figure 6. Analytical and experimental [4, 5] load versus displacement hysteretic behavioural curves for the examined X-cable braced RC frame.

FRAME	DI_G	DI_L	P_{top} [kN]
(1)	(2)	(3)	(4)
Unbraced	0.098	0. 201	12.52
X-braced	0.001	0.001	55.40

Table 1. Representative response quantities for the unbraced and braced frames

The table values indicate, as expected, that cable-strengthening reduces the damage indices and increases the global horizontal frame resistance approximately 4.4 times; P_{max} = 12.52 kN for the unbraced frame, whereas P_{max} = 55.40 kN for the cable-X-braced frame. The frame-stiffness of the cable-strengthened RC frame is also increased as in infilled RC frames [32] and the damage indices are minimized. Similar concluding remarks hold for multi-story and multi-bay real praxis RC frames as investigated in [18]. Therein is shown that a further improvement of the seismic behaviour of the initial frames can be obtained by trying various cable-bracing schemes and by realizing a parameter sensitivity analysis concerning the cable characteristics.

3.3 Application for the case of one-tie braced frame

Based on the previous calibration of the numerical procedure and in order to clarify the unilateral behaviour of the cable-elements and their effects on the structural response the same RC frame of Fig. 1 is examined using only one tension-tie as shown in Fig. 7. The loading history had the same full loading steps as for the X-braced frame, i.e. the loading steps had maximum displacements ±2.5, ±5.0, ±7.5, ±10, ±12.5 and ±15 mm. The relevant analytically obtained load versus top displacement hysteretic behavioural curve is shown in Fig. 8. As this figure shows, when the loading is in the direction CD, the cable is activated and the system stiffness is increasing. On the contrary, when the loading is in the inverse direction DC, then the cable becomes slack and so inactivated, and the system stiffness is decreasing and approaching the one of the bare RC frame.

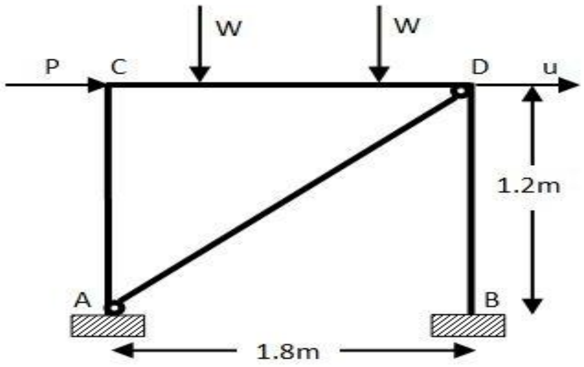


Figure 7. The one-tie braced RC frame

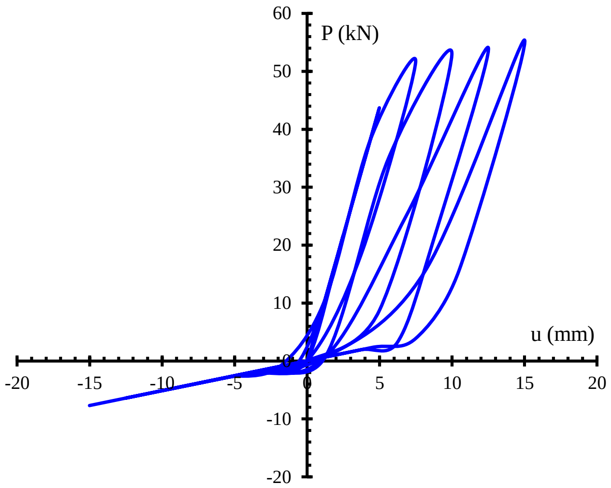


Figure 8. Computed load-displacement hysteretic behaviour for the one-tie braced RC frame

4 FUTURE EXPERIMENTAL WORK

Unbraced and cable braced RC frames have already been constructed and planned to be tested in Reinforced Concrete Laboratory of Democritus University of Thrace under lateral cyclic loading in order to experimentally investigate the effectiveness of the examined strengthening technique in large-scale RC frame (see also Fig. 9).

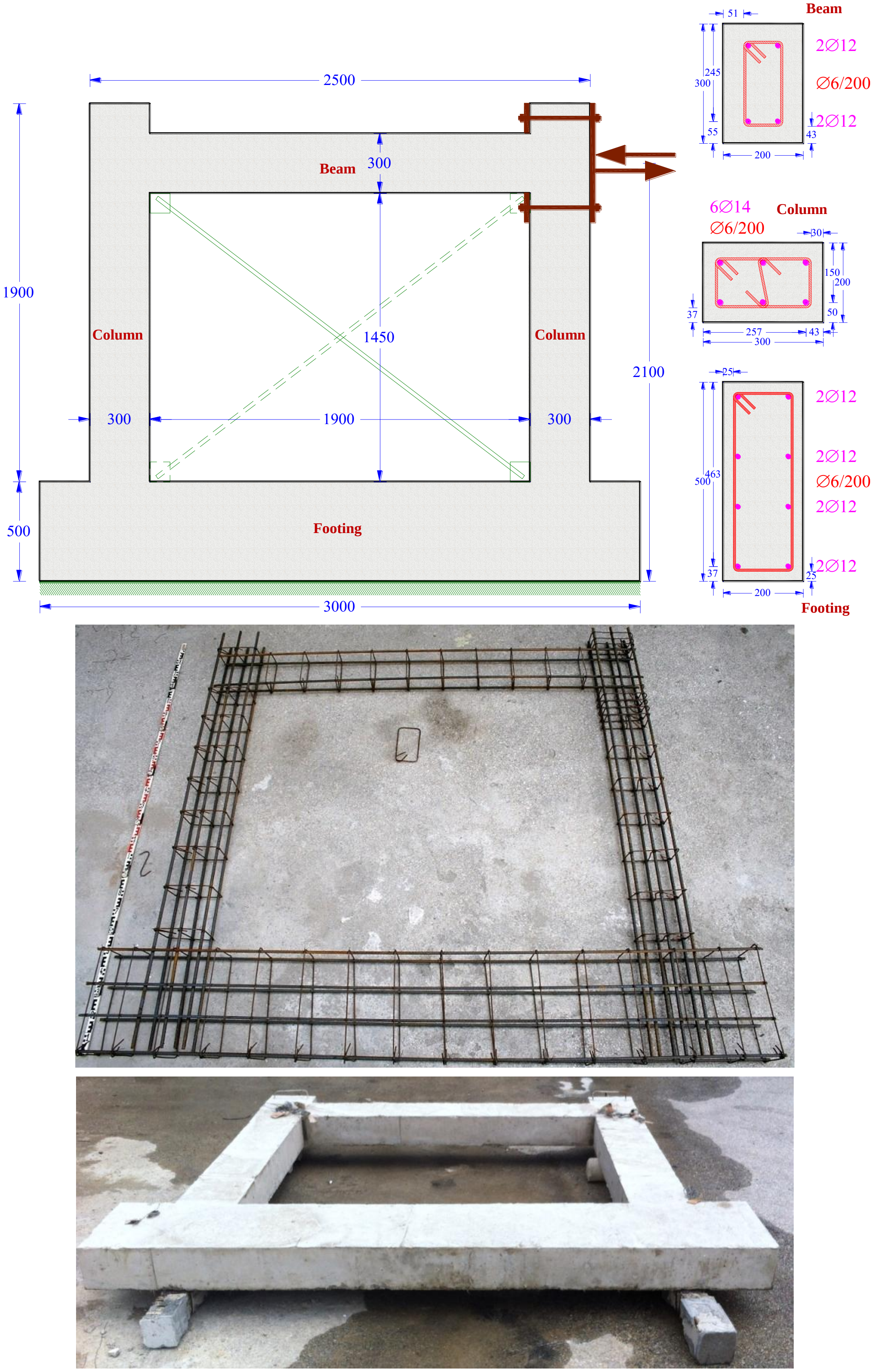


Figure 9. Characteristics of the large-scale RC frames that have been constructed and planned to be tested in Reinforced Concrete Laboratory of Democritus University of Thrace.

5 CONCLUDING REMARKS

The seismic inelastic behaviour of planar RC frames strengthened by cable elements can be numerically investigated by the herein presented numerical approach. This approach has been calibrated by using available experimental results concerning the case of a single-bay one-storey RC frame subjected to a cyclic lateral loading in displacement-controlled mode.

First results indicate that the presented computational approach could effectively be used for the seismic assessment and strengthening of existing RC frame structures by cable-elements. On the basis of computed damage indices an optimal cable-bracing scheme can be selected among investigated alternative ones by realizing a parameter sensitivity analysis concerning the cable characteristics. Unbraced and cable braced large-scale RC frame have already been constructed and planned to be tested in lateral cyclic deformations in order to experimentally investigate the aforementioned parameters.

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