

ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ – СОФИЯ

Първа научно-приложна конференция с международно участие
„СТОМАНОБЕТОННИ И ЗИДАНИ КОНСТРУКЦИИ – ТЕОРИЯ И ПРАКТИКА“

22 – 23 октомври 2015

22 – 23 October 2015

First Scientific-Applied Conference with International Participation

“REINFORCED CONCRETE AND MASONRY STRUCTURES – THEORY AND PRACTICE”

ANNUAL OF THE UNIVERSITY OF ARCHITECTURE, CIVIL ENGINEERING AND GEODESY – SOFIA

48 ^{ТОМ}
vol.

2015

св.
fasc. 12 – II

A COMPUTATIONAL APPROACH FOR REINFORCED CONCRETE STRUCTURES STRENGTHENED BY TIES UNDER MULTIPLE EARTHQUAKES

A. Liolios¹, A. Karabinis², A. Liolios³, B. Folic⁴

Keywords: RC building frames, computational structural mechanics, cable-elements strengthening, earthquakes sequences

Research area: structural systems, seismically upgrading technologies

ABSTRACT

A numerical investigation is presented for the seismic response of existing reinforced concrete (RC) structures, which have been damaged due to extreme actions and are seismically upgraded by using cable elements (tension-ties). A double discretization in space by the Finite Element Method and in time by a direct incremental approach, is used. The unilateral behaviour of the cable-elements, which can undertake tension stresses only, is strictly taken into account and results to inequality constitutive conditions. A calibration of the numerical approach is realized in a typical example problem by comparing the computational results with available experimental ones. Finally, using damage indices, the optimal strengthening version of cable-systems is chosen for the case of multi-storey RC frames under multiple earthquakes.

¹ Angelos Liolios, PhD Candidate, MSc, Democritus University of Thrace, Dept. Civil Engineering, Xanthi, Greece, e-mail: aliolios@civil.duth.gr

² Athanasios Karabinis, Prof., Democritus University of Thrace, Dept. Civil Engineering, Xanthi, Greece, e-mail: karabin@civil.duth.gr

³ Asterios Liolios, Prof., Democritus University of Thrace, Dept. Civil Engineering, Xanthi, Greece, e-mail: liolios@civil.duth.gr

⁴ Boris Folic, PhD Candidate, MSc, University of Belgrade, Faculty of Mechanical Enging, Innovation Center, Belgrade, Serbia, e-mail: boris.folic@gmail.com

1. Introduction

Seismic upgrading of existing reinforced concrete (RC) structures makes use of many well-known repairing and strengthening techniques, see e.g. [1 – 3, 6, 9, 12, 29]. One of the simple, low cost and efficient methods for strengthening of existing RC frames against lateral induced earthquake loading is the use of steel cross X-bracings [3, 19, 31]. Application of this technique is reported, among others, also in Greece to improve seismic performance of existing old pilotis type multi-storey RC buildings by strengthening only the ground storey[1].

The use of cable-like members (tension-ties) instead of traditional RC mantles can be considered as an alternative strengthening method for inadequate RC frame structures under lateral seismic actions [19, 31]. As well-known, ties have been used effectively in historic buildings, as well as in monastery and church arches. Besides the usual historic monumental structures (churches, old masonry buildings, etc.), the recent Cultural Heritage includes also existing industrial buildings of reinforced concrete (RC), e.g. old factory premises. As concerns the global behaviour for such RC structures, it often arises the need for seismic strengthening, which must be realized by using materials and methods in the context of the Sustainable Construction [2, 23, 24]. Cable restrainers are also used for concrete and steel superstructure movement joints in bridges [30].

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 both, equality as well as an inequality form, and so the problem becomes a highly nonlinear one [17, 18, 21, 25].

The present study deals first briefly with a numerical approach for the seismic analysis of existing industrial beam-column RC frames that are to be strengthened by cable elements. The approach is based on an incremental formulation and uses the Ruaumoko structural engineering software [4]. Damage indices [13, 22, 26] are computed, for the seismic assessment of historic and industrial structures and in order the optimum cable-bracing strengthening version to be chosen. Next, a calibration of the approach is realized by using available experimental results. Finally, an application is presented for a two-bay two-story RC frame strengthened by bracing ties under multiple earthquakes.

2. The computational approach

Details of the developed numerical approach are given in [17, 18], whereas the adopted incremental approach is briefly summarized herein. A double discretization, in space and time, is applied. The structural system is discretized in space by using frame finite elements [5]. 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 [17, 18, 21, 25].

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

$$\mathbf{M} \Delta \ddot{\mathbf{u}} + \mathbf{C} \Delta \dot{\mathbf{u}} + \mathbf{K}_T \Delta \mathbf{u} = -\mathbf{M} \Delta \ddot{\mathbf{u}}_g + \mathbf{A} \Delta \mathbf{s} + \Delta \mathbf{p}, \quad (1)$$

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

The above relations combined with the initial conditions contain the problem formulation, where, for given \mathbf{p} and/or $\ddot{\mathbf{u}}_g$, the vectors \mathbf{u} and s have to be computed. Regarding the strict mathematical point of view, we can formulate the problem as a hemivariational inequality one by following [14, 21, 25] and investigate it.

For the numerical treatment of the problem, the structural analysis software Ruaumoko [4] is used. Here, for the time-discretization, the Newmark scheme is chosen. Ruaumoko uses the finite element method [5] 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 [11].

Ruaumoko has been applied successfully for earthquakes sequences concerning the cases of concrete planar frames [11] 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 [11, 28].

After the seismic assessment of the existing RC structure [9], the choice of the best strengthening cable system can be realized by using damage indices [7, 13, 22, 26]. 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.

In the OSDI model after Park/Ang [26] 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:

$$DI_L = \frac{\mu_m}{\mu_u} + \frac{\beta}{F_y d_u} E_T, \quad (2)$$

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:

$$DI_G = \frac{\sum_{i=1}^n DI_{L_i} E_i}{\sum_{i=1}^n E_i}, \quad (3)$$

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 of the computational approach

3.1. Investigated experimental results available from the literature

Available experimental results for a simple typical one-bay one-storey RC frame, strengthened with steel cross X-bracing and investigated in [20], have been used for the calibration of the presented numerical approach. For details, see [15, 16].

The geometrical and reinforcement details of the frame along with the experimental testing procedure are presented in Fig. 1 [15, 20]. 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 [15, 20].

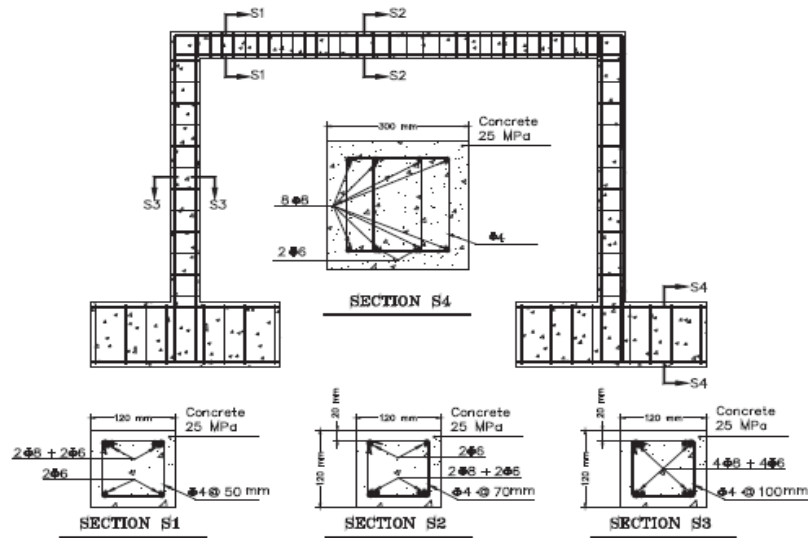


Figure 1. Details of the investigated RC frames (adapted from Massumi et al [20] after permission)

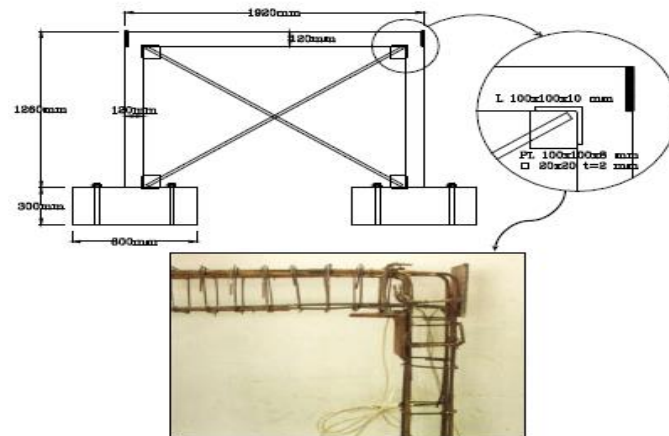


Figure 2. Strengthened RC frame with X-cross bracings and its connection details (adapted from Massumi et al [20] after permission)

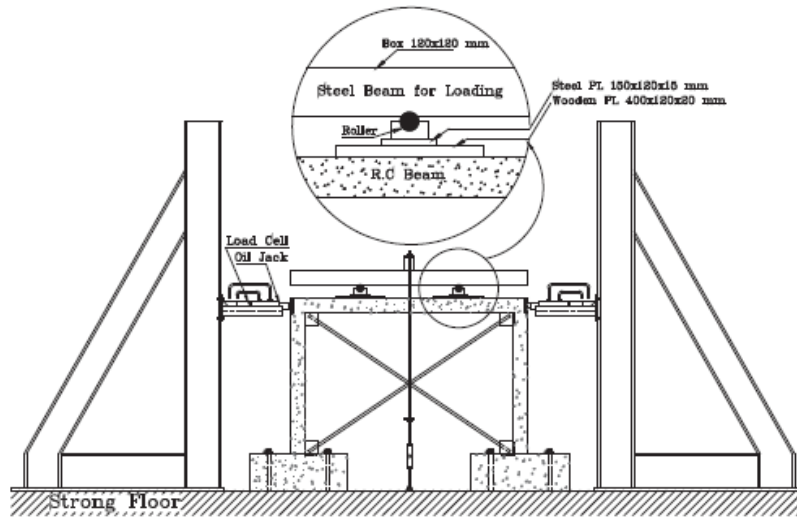


Figure 3. Test setup and loading systems
(adapted from Massumi et al [20] after permission)

3.2. Simulation of the Massumi et al. [20] tests

With respect to aforementioned experimental results, the finite element models related to the unbraced and braced frames are made using Ruaumoko software [4]. The columns and the beam are modeled using prismatic frame elements. Nonlinearity at the two ends of RC members is idealized using one-component plastic hinge models, following the Takeda hysteresis rule. Interaction curves (M-N) for the critical cross-sections of the examined RC frame have been computed. The effects of cracking on columns and beams are estimated by applying the guidelines of Eurocode 8, part 3 [8] and Greek Retrofitting Code (KANEPE) [10]. The stiffness reduction due to cracking [9, 27] 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.

Cable-elements are used for the steel bracings simulation by applying the bilinear with slackness hysteresis rule [4]. These cable elements have a cross-sectional area $F_c = 1.44 \text{ cm}^2$, which is equivalent to the cross-sectional area of steel braces tubes. The cable constitutive law concerning the unilateral (slackness), hysteretic, fracturing, unloading-reloading behaviour, has the diagram depicted in Fig. 4. Ductility index is $\mu = d/d_y$. The loading history of the examined cases (unbraced frame UBF1 and braced frame BF1 [15, 20]) has been simulated as a displacement-controlled multiple earthquake excitation imposed on the top left node C of the frame (see Fig. 1 and Fig. 3).

The analytically derived hysteretic behavioural curves, i.e. diagrams of the load, P , versus to top displacement, u , 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 these figures it is obvious that the computed results are in very good agreement with the experimental data curves.

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

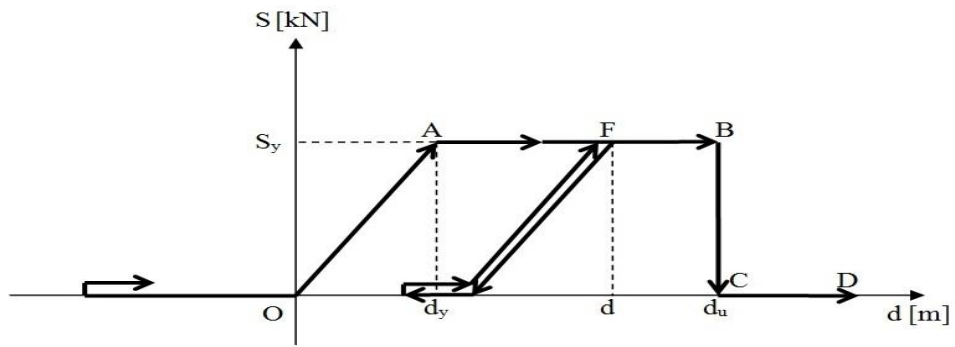


Figure 4. Constitutive law of the cable-elements

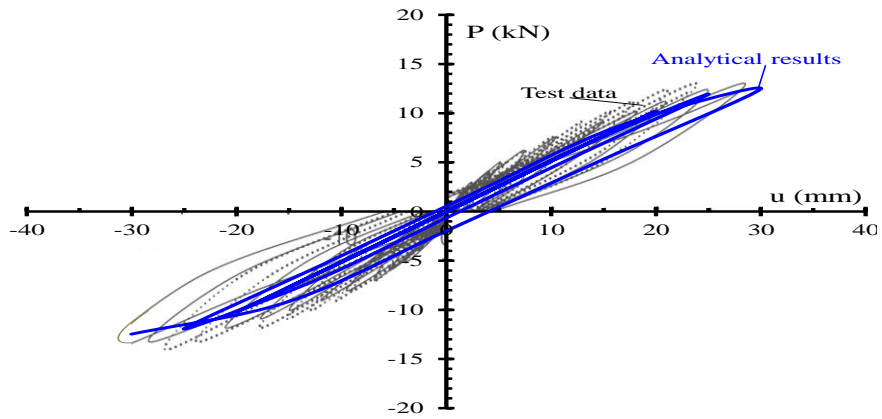


Figure 5. Computational [15, 16] and experimental [20] load versus displacement hysteretic behavioural curves for the examined unbraced RC frame

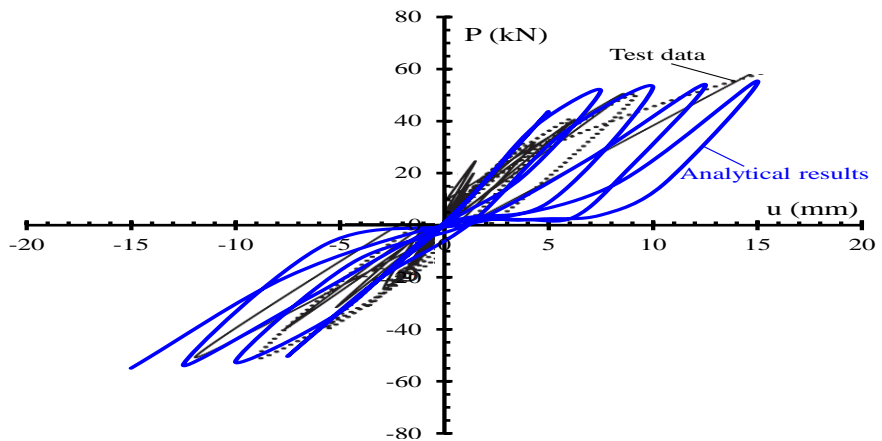


Figure 6. Computational [15, 16] and experimental [20] load versus displacement hysteretic behavioural curves for the examined X-cable braced RC frame

Table 1. Representative quantities for the unbraced and braced frames

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

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 [9, 27, 29] and the damage indices are minimized.

4. Numerical example

This example has been investigated in Ref. [18], and concerns the industrial reinforced concrete frame F0 of Fig. 7 subjected to a multiple ground seismic excitation, received from PEER database [28]. For the various example details see [18].

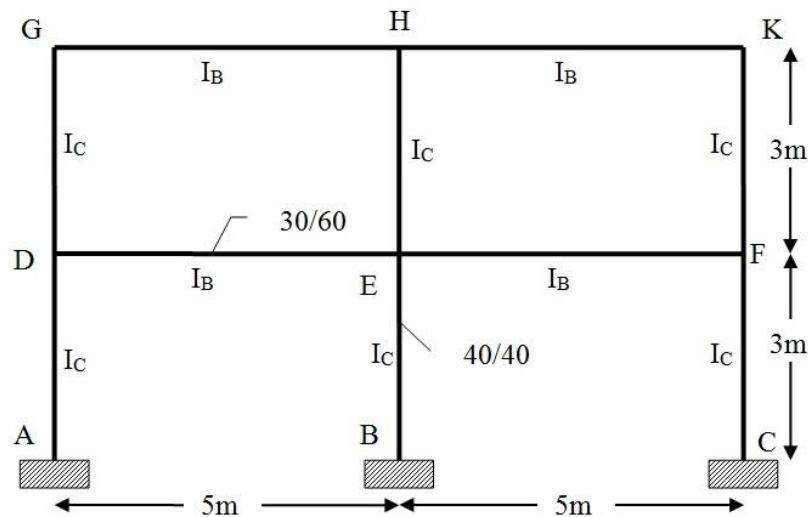


Figure 7. System F0: the industrial RC frame without cable-strengthening

After the seismic assessment [9], the X-cable-bracings system, shown in Fig. 8, has been proposed as the optimal one in order the frame F0 to be seismically upgraded. The cable elements have a cross-sectional area $F_c = 18 \text{ cm}^2$ and they are of steel class S220. Concerning the Coalinga case of seismic sequence [11, 28], some representative results are shown in Table 2.

In column (1) of the Table 2, the Event E_1 corresponds to Coalinga seismic event of $0.605g$ PGA, and Event E_2 to $0.733g$ PGA, ($g = 9.81\text{m/sec}^2$). The sequence of events E_1 and E_2 is denoted as Event ($E_1 + E_2$). In table column (2) the Global Damage Indices DI_G and in column (3) the Local Damage Index DI_L for the bending moment at the left fixed support A of the frames are given. Finally, in the column (4), the absolutely maximum horizontal top displacement u_{top} is given.

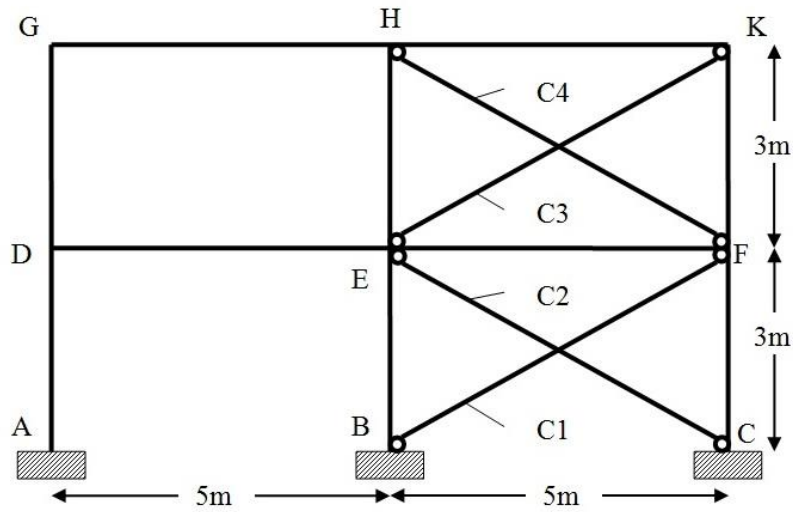


Figure 8. System F2: the industrial RC frame cable-strengthened with x-bracings

Table 2. Representative response quantities for the systems F0 and F2

SYSTEM	EVENTS	DI_G	DI_L	u_{top} [cm]
(0)	(1)	(2)	(3)	(4)
F0	Event E_1	0.134	0.179	2.227
	Event E_2	0.301	0.474	3.398
	Event $(E_1 + E_2)$	0.334	0.481	3.410
F2	Event E_1	0.068	0.007	1.126
	Event E_2	0.097	0.136	1.447
	Event $(E_1 + E_2)$	0.108	0.154	1.471

As the values in the above Table 2 show, multiple earthquakes generally increase response quantities, especially the damage indices. On the other hand, the strengthening of the frame F0 by X-bracings (system Frame F2 of Fig. 8) improves the response behaviour, e.g. u_{top} is reduced from 3.410 cm to 1.471 cm.

5. Concluding remarks

As it has been shown in the numerical example, the herein presented computational approach can be effectively used for the numerical investigation of the seismic inelastic behaviour of industrial RC frames strengthened by cable elements and subjected to multiple earthquakes. Further, computed damage indices can be used in order an optimal cable-bracing scheme to be selected among investigated alternative ones.

LITERATURE

1. *Antonopoulos, T. A., Anagnostopoulos, S. A. and Tsirlis, F. N.* (2008). Evaluation of the seismic performance of old reinforced concrete buildings with an open ground storey, simple retrofitting solutions. Proc. 3rd Greek Conference on Earthquake Engineering and Engineering Seismology, 2061, Athens, Greece, (in greek), 2008.
2. *Asteris, P. G. & Plevris, V.* (Eds.). (2015). “Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures”. IGI Global, 2015.
3. *Bertero, V. V. and Whittaker, A. S.* (1989). “Seismic upgrading of existing buildings”, 5as Jornadas Chilenas de Sismología e Ingeniería Antisísmica, 1, 27 – 46.
4. *Carr, A. J.*, (2008). “RUAUMOKO – Inelastic Dynamic Analysis Program”. Dep. Civil Engineering, University of Canterbury, Christchurch, New Zealand, 2008.
5. *Chopra, A. K.* (2007). “Dynamics of Structures: Theory and Applications to earthquake Engineering”, Pearson Prentice Hall, New York.
6. *Dritsos, S. E.* (2001). “Repair and strengthening of reinforced concrete structures” (in Greek). University of Patras, Greece.
7. *Elenas, A., Liolios, Ast., Vasiliadis, L., Favvata, M. and Liolios, Ang.* (2012). Seismic intensity parameters as damage potential descriptors for life-cycle analysis of buildings. IALCCE 2012: Proc. Third Int. Symp. Life-Cycle Civil Engineering, Vienna, Austria, October 2012, CRC Press, Taylor & Francis, London.
8. *Eurocode 8* (CEN 2004). Design of structures for earthquake resistance, Part 3: Assessment and Retrofitting of buildings, (EC8-part3), EN 1998-3, Brussels.
9. *Fardis, M.N.*, (2009). “Seismic design, assessment and retrofitting of concrete buildings: based on EN-Eurocode 8”. Springer, Berlin.
10. *Greek Retrofitting Code-(KANEPE)* (2013). Greek Organization for Seismic Planning and Protection (OASP), Greek Ministry for Environmental Planning and Public Works. Athens, Greece, 2013. (In Greek): www.oasp.gr.
11. *Hatzigeorgiou, G. and Liolios, Ast.* (2010). Nonlinear behaviour of RC frames under repeated strong ground motions. Soil Dynamics and Earthquake Engineering, vol. 30, 1010 – 1025, 2010.
12. *Karayannis, C. G., Chalioris, C. E. and Sirkelis, G. M.* (2008). Local retrofit of exterior RC beam–column joints using thin RC jackets-An experimental study. Earthquake Engineering & Structural Dynamics, 37(5), 727-746.
13. *Ladjinovic, Dj. & Folic, R.* (2004). Application of improved damage index for designing of earthquake resistant structures. In: Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada (Paper No. 2135, pp. 1 – 15).
14. *Liolios A.* (2000). An inequality numerical modeling for the seismic analysis of monumental complexes and masonry structures: The Hagia Sophia case. In: Moropoulou A., Erdik M. et al (Sci. Eds.), PACT, J. Eur. Study Group on Phys., Chem., Biol. and Math. Techniques Applied to Archaeology, v. 59 (2000), pp. 65 – 74.
15. *Liolios Ang.* (2015). A computational investigation for the seismic response of RC structures strengthened by cable elements. In: M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.), Proceedings of COMPDYN 2015: Computational Methods in Structural Dynamics and Earthquake Engineering, 5th ECCOMAS Thematic Conference, Crete Island, Greece, 25–27 May 2015, Vol. II, pp. 3997 – 4010.

16. *Liolios Ang. & Const. Chalioris* (2015). Reinforced concrete frames strengthened by cable elements under multiple earthquakes: A computational approach simulating experimental results. In: Proc. of 8th GRACM International Congress on Computational Mechanics, Volos, 12 – 15 July 2015. (<http://8gracm.mie.uth.gr/Papers/Session%20D3-B1/A.%20Liolios.pdf>)
17. *Liolios, Ang., Chalioris, C., Liolios, Ast., Radev, S. and Liolios, K.* (2012). A Computational Approach for the Earthquake Response of Cable-braced Reinforced Concrete Structures under Environmental Actions. Lecture Notes in Computer Science, LNCS, vol. 7116, pp. 590 – 597, Springer-Verlag, Berlin Heidelberg.
18. *Liolios, Ast., Liolios, Ang. and Hatzigeorgiou, G.* (2013). A numerical approach for estimating the effects of multiple earthquakes to seismic response of structures strengthened by cable-elements. *Journal of Theor. Appl. Mechanics*, 43(3), 21 – 32.
19. *Markogiannaki, O. & Tegos, I.* (2011). Strengthening of a Multistory R/C Building under Lateral Loading by Utilizing Ties. *Applied Mechanics and Materials*, vol. 82, 559 – 564.
20. *Massumi, A. and Absalan, M.* (2013). Interaction between bracing system and moment resisting frame in braced RC frames. *Archives of Civil and Mechanical Engineering*, 13(2), 260 – 268.
21. *Mistakidis, E. S. and Stavroulakis, G. E.* (1998). Nonconvex optimization in mechanics. Smooth and nonsmooth algorithmes, heuristic and engineering applications. Kluwer, London.
22. *Mitropoulou, C. C., Lagaros, N. D. and Papadrakakis, M.* (2014). Numerical calibration of damage indices. *Advances in Engineering Software*, 70, 36 – 50.
23. *Moropoulou, A.* (2009). Current Trends towards the Sustainable Construction. The Relation between Environment and Concrete. In: Technical Chamber of Greece – TEE (ed.), Proceedings, 16th Hellenic Concrete Conference, Cyprus, 2009.
24. *Moropoulou A., Bakolas A., Spyrakos C., Mouzakis H., Karoglou A., Labropoulos K., Delegou E. T., Diamandidou D., Katsiotis. N. K.* (2012). NDT investigation of Holy Sepulchre complex structures. in: V. Radonjanin, K. Crews, (eds), Proc. of Structural Faults and Repair 2012, Proceedings in CD-ROM
25. *Panagiotopoulos, P. D.* (1993). Hemivariational Inequalities. Applications in Mechanics and Engineering. Springer-Verlag, Berlin, New York, (1993).
26. *Park, Y. J. and A. H. S. Ang* (1985). Mechanistic seismic damage model for reinforced concrete. *Journal of Structural Division ASCE*, vol. 111(4), 722 – 739.
27. *Paulay T., M. J. N. Priestley,* (1992). *Seismic Design of Reinforced Concrete and Masonry Buildings.* Wiley, New York.
28. *PEER* (2011). Pacific Earthquake Engineering Research Center. PEER Strong Motion Database. <http://peer.berkeley.edu/smcat>.
29. *Penelis G. Gr., & Penelis Gr. G.* (2014). *Concrete Buildings in Seismic Regions.* CRC Press.
30. *Priestley, M. J. N., Seible, F. C. and Calvi, G. M.* (1996). *Seismic Design and Retrofit of Bridges.* John Wiley & Sons, Inc.
31. *Tegos, I., Liakos, G., Tegou, S., Roupakias, G. and Stilianidis, K.* (2009). An alternative proposal for the seismic strengthening of existing R/C buildings through tension-ties. TEE Proceedings, 16th Hellenic Concrete Conference, Cyprus, 2009 (in Greek).

**ОСИГУРЯВАНЕ НА ПОЖАРНИ
ВЪЗДЕЙСТВИЯ**

FIRE RESISTANT DESIGN

