SCIENTIFIC CONFERENCE
**PLANNING, DESIGN, CONSTRUCTION
AND BUILDING RENEWAL**

**iNDiS 2018
NOVI SAD, 21-23 NOVEMBER, 2018**

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SEISMIC ANALYSIS OF CULTURAL HERITAGE RC STRUCTURES STRENGTHENED BY TIES UNDER UNCERTAINTY DATA

Abstract: The probabilistic seismic analysis of existing Cultural Heritage industrial reinforced concrete (RC) structures, which are strengthened by cable elements (tension-ties), is numerically investigated. Attention is given to uncertainties for the estimation of structural input parameters, common to old RC structures. For their treatment, Monte Carlo techniques are applied. The unilateral behavior of the cable-elements, which can undertake tension stresses only, is strictly taken into account and results to inequality constitutive conditions.

Key words: Cultural Heritage Structures, Seismic Upgrading by Ties, Monte Carlo methods.

ANALIZA SEIZMIČKIH PERFORMANSI AB KONSTRUKCIJA KULTURNOG NASLEĐA OJAČANIH ZATEGAMA U USLOVIMA NEPOUZDANIH PODATAKA

Rezime: U radu je sprovedena numerička analiza postojećih industrijskih armiranobetonskih konstrukcija kulturnog nasleđa, ojačanih kablovskim elementima (zategama), zasnovana na probabilističkoj seizmičkoj analizi. Posebna pažnja je posvećena nepozudanosti prilikom procene ulaznih strukturnih parametara, uobičajenih za stare AB konstrukcije. Za obradu ovih parametara upotrebljene su Monte Carlo tehnike. Ponašanje kablovskih elemenata, koji mogu da prime samo zatežuću silu, strogo je uzeto u obzir i rezultira konstitutivnim uslovima nejednakosti.

Ključne reči: Objekti kulturnog nasleđa, seizmičko ojačanje zategama, Monte Carlo metode

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1. INTRODUCTION

Besides the usual historic monumental structures (churches, old masonry buildings, etc.), the recent built Cultural Heritage includes also old existing industrial buildings of reinforced concrete (RC), e.g. old factory premises [1-3,5]. For their seismic upgrading, many and well-known repairing and strengthening techniques can be used [1-5]. For the recent Cultural Heritage RC buildings, this upgrading must be realized by using materials and methods in the context of the Sustainable Construction [5, 17-19, 26, 32].

One of the simple, low cost and efficient strengthening method is the use of steel cross X-bracings [6-8]. As well-known, ties have been used effectively in old steel bridges, monastery buildings and churches arches [3, 5]. 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 a highly nonlinear one [6-8, 10-17].

Concerning the seismic analysis of such old RC structures, a probabilistic estimation of the input parameters must be realized taking into account a lot of uncertainties. These mainly concern the holding properties of the old materials which had been used for the building of such structures, e.g. the remaining strength of the concrete and steel, as well as the cracking effects etc. [1-4, 22].

On the other hand, for the seismic upgrading of existing RC structures, modern seismic design codes adopt exclusively the use of the isolated and rare 'design earthquake', whereas the influence of repeated earthquake phenomena is ignored. But as the results of recent research have shown [9,13-15], multiple earthquakes generally require increased ductility design demands in comparison with single isolated seismic events. Especially for the seismic damage due to multiple earthquakes, this is accumulated and so it is higher than that for single ground motions.

In this study, a probabilistic numerical approach is presented for the seismic analysis of existing old industrial framed RC buildings. They are elements of the recent built Cultural Heritage and are to be seismically strengthened by cable elements, in order to undertake strong seismic sequences. The computational approach is based on the Monte Carlo methods [27-31] and on an incremental formulation, which uses the Ruaumoko structural engineering software [24]. Damage indices [20, 21] are computed for the seismic assessment and in order the optimum cable-bracing strengthening version to be chosen. Finally, an application is presented for a simple typical example of a three-bay three-story industrial RC frame strengthened by bracing ties under multiple earthquakes.

2. THE PROBABILISTIC COMPUTATIONAL APPROACH

Using Monte Carlo simulations [27,28] the probabilistic approach for the seismic analysis of Cultural Heritage existing RC frame-buildings can be obtained. As well-known (see e.g. [27-31]) Monte Carlo simulation is simply a repeated process of generating deterministic solutions to a given problem. Each solution corresponds to a set of deterministic input values of the underlying random input variables. A statistical analysis of the so obtained simulated solutions is then performed. Thus the computational methodology consists of solving first the deterministic problem for each set of the random input variables and finally realizing a statistical analysis.

2.1. Numerical treatment of the deterministic problem

Details of the developed numerical approaches are given in [6-8, 10-12]. Herein the adopted incremental approach is briefly summarized. A double discretization, in space and time, is applied. The structural system is discretized in space by using finite elements. Pinjointed 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 [15-17].

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

$$\boldsymbol{M}\,\Delta\ddot{\boldsymbol{u}} + \boldsymbol{C}\,\Delta\dot{\boldsymbol{u}} + \boldsymbol{K_T}\,\Delta\boldsymbol{u} = -\boldsymbol{M}\,\Delta\ddot{\boldsymbol{u}}_g + \boldsymbol{A}\,\Delta\boldsymbol{s} + \Delta\boldsymbol{p} \tag{1}$$

where $\boldsymbol{u}(t)$ and $\boldsymbol{p}(t)$ are the displacement and the load time dependent vectors, respectively, and $\boldsymbol{C}(\dot{\boldsymbol{u}})$ and $\boldsymbol{K_T}(\boldsymbol{u})$, 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. $\boldsymbol{A}$ 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 $\ddot{\boldsymbol{u}}_g$, the vectors $\boldsymbol{u}$ and $\boldsymbol{s}$ are to be computed. Regarding the strict mathematical point of view, we can formulate the problem as a hemi-variational inequality one by following [15-17] and investigate it.

For the numerical treatment of the problem the structural analysis software Ruaumoko [3] is used. After the seismic assessment of the existing RC structure, the choice of the best strengthening cable system can be realized by using damage indices [20, 21]. In this study the overall structural damage index (OSDI) is used. In the OSDI model after Park/Ang [20] 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:

$$\mathrm{DI_L} = \frac{\mu_m}{\mu_u} + \frac{\beta}{F_y d_u} E_T \tag{2}$$

where: $\mathrm{DI_L}$ 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:

$$\mathrm{DI_G} = \frac{\sum_{i=1}^{n} \mathrm{DI}_{Li} E_i}{\sum_{i=1}^{n} E_i} \tag{3}$$

where $\mathrm{DI_G}$ is the global damage index, DI_{Li} 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.

2.2. Monte Carlo simulation for the probabilistic problem

In order to calculate the random characteristics of the response of the considered RC buildings, the Monte Carlo simulation is used [25-31]. As mentioned, the main element of a Monte Carlo simulation procedure is the generation of random numbers from a specified distribution. Systematic and efficient methods for generating such random numbers from several common probability distributions are available. The random variable simulation is implemented using the technique of Latin Hypercube Sampling (LHS). The LHS is a selective sample technique by which, for a desirable accuracy level, the number of the sample size is significantly smaller than the direct Monte Carlo simulation.

In more details, a set of values of the basic design input variables can be generated according to their corresponding probability distributions by using statistical sampling techniques. The generated basic design variables are treated as a sample of experimental observations and used for the system deterministic analysis to obtain a simulated solution as in subsection 2.1. is described. As the generation of the basic design variables is repeated, more simulated solutions can be determined. Finally, statistical analysis of the simulated solutions is then performed. The results obtained from the Monte Carlo simulation method depend on the number of the generated basic design variables used.

Such design variables for the herein considered RC buildings are the uncertain quantities describing the plastic-hinges behavior and the spatial variation of input old materials parameters. As regards the random variation of parameters for the old materials, which had been used for the building of old RC structures, their input estimations concern mainly the remaining strength of the concrete and the steel and the elasticity modulus. According JCSS (Joint Committee Structural Safety), see [30], concrete strength and elasticity modulus follow the Normal distribution, whereas the steel strength follows the Lognormal distribution.

Details of the above developed methodology are analyzed in the numerical application of the next section.

3. NUMERICAL EXAMPLE

Figure 1 depicts an old industrial reinforced concrete frame F0 subjected to a multiple ground seismic excitation. A typical list of such earthquakes sequences, which were downloaded from the strong motion database of the Pacific Earthquake Engineering Research (PEER) Center [23], appears in Table 1.

Using Ruaumoko software [24], the columns and the beams of the frame F0 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 [4, 22]. So, the stiffness reduction due to cracking results to effective stiffness of 0.60 I_g for the external columns, 0.80 I_g for the internal columns and 0.40 I_g for the beams, where I_g is the gross inertia moment of their cross-section.

Concerning the plastic hinges in the end sections of the frame structural elements, a typical normalized moment- normalized rotation backbone is shown in Figure 2, see [25]. This backbone hardens after a yield moment of a_{My} times the nominal, having a non-negative slope of a_h up to a corner normalized rotation (or rotational ductility) μ_c where the negative stifiness segment starts. The drop, at a slope of a_c, is arrested by the residual plateau appearing at normalized height r that abruptly ends at the ultimate rotational ductility μ_u. The normalized rotation is the rotational ductility $\mu=\theta/\theta^{yield}$.

The above six backbone parameters in Fig. 2, namely a_h, a_c, μ_c, r, μ_u and a_{My}= M/M_y are assumed to vary independently from each other according to Normal distribution.

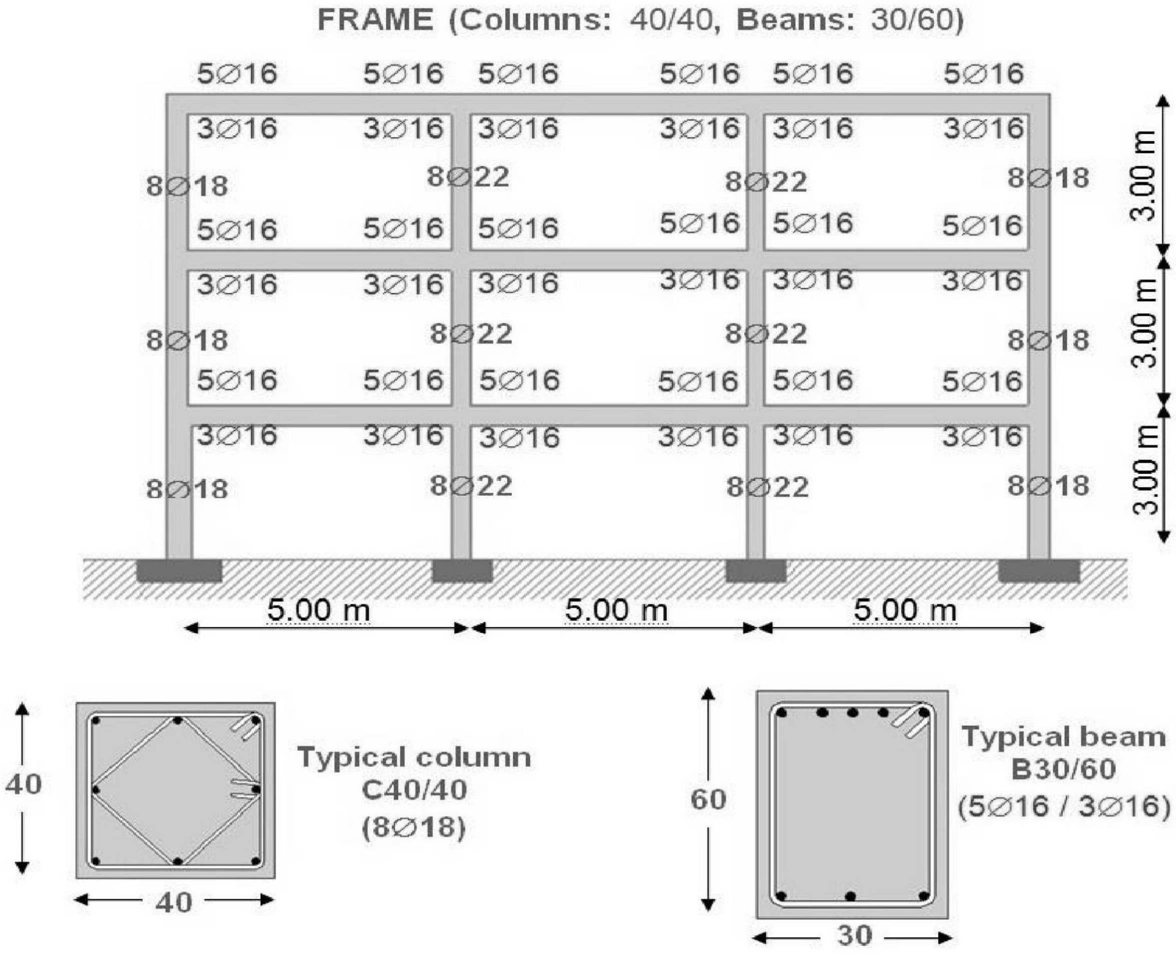

Figure 1. The initial RC frame F0 without cable-strengthening.

Table 1. ***Multiple earthquakes data***

No	Seismic sequence	Date (Time)	Magnitude (M_L)	Recorded PGA(g)	Normalized PGA(g)
1	Coalinga	1983/07/22 (02:39)	6.0	0.605	0.165
		1983/07/25 (22:31)	5.3	0.733	0.200
2	Imperial Valley	1979/10/15 (23:16)	6.6	0.221	0.200
		1979/10/15 (23:19)	5.2	0.211	0.191
3	Whittier Narrows	1987/10/01 (14:42)	5.9	0.204	0.192
		1987/10/04 (10:59)	5.3	0.212	0.200

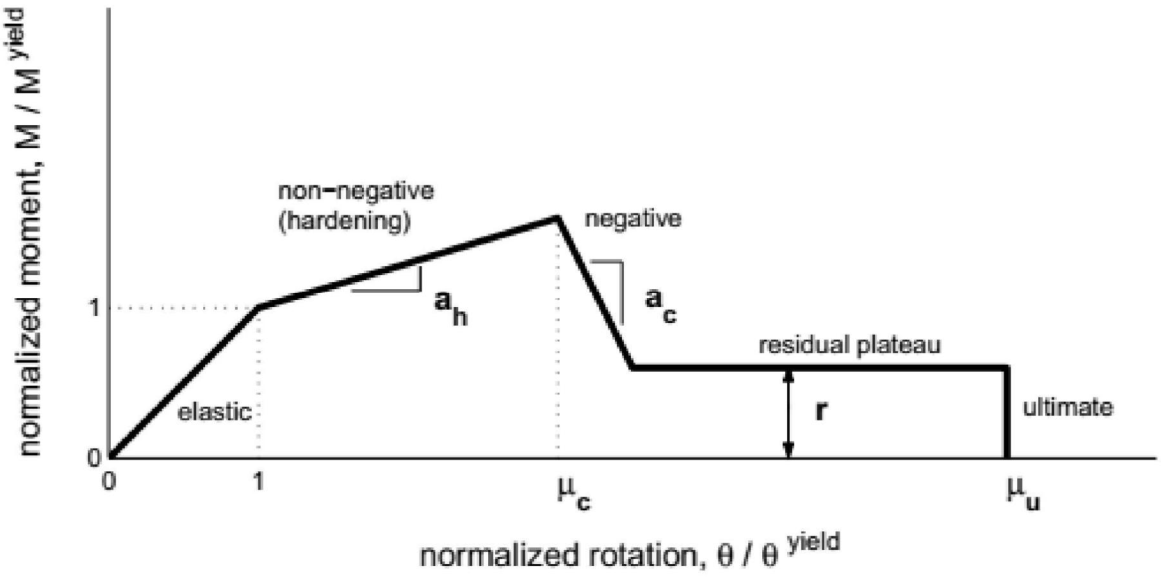

Figure 2. *Constitutive backbone diagramme for normalized moment - normalized rotation in plastic hinges [25].*

The estimated concrete class of system F0 is C12/15 and the steel class is S220. As mentioned, according to JCSS (Joint Committee Structural Safety), see [30], concrete strength and elasticity modulus follow a Normal distribution and the steel strength follows the Lognormal distribution. So the statistical characteristics of the input random variables concerning the building materials are estimated to be as shown in Table 2. The mean/median values of the random variables correspond to the best estimates employed in the deterministic model.

Table 2. Statistical data for the building materials treated as random variables

	Disribution	mean	COV
Compressive strength of concrete	Normal	8.0 MPa	15%
Yield strength of steel	Lognormal	191.3 MPa	10%
Initial elasticity modulus, concrete	Normal	26.0 GPA	8%
Initial elasticity modulus, steel	Normal	200 GPA	4%

After the seismic assessment, the X-cable-braces system F6, shown in Fig. 3, has been proposed in order the frame F0 to be seismically strengthened. For the cable-elements, the bilinear with slackness hysteresis rule of Ruaumoko [24] is used. The cable elements have a cross-sectional area $F_c = 18$ cm^2 and they are of steel class S220. The cable constitutive law concerning the unilateral (slackness), hysteretic, fracturing, unloading-reloading behaviour, has the diagram depicted in Fig. 4. Ductility index is $\mu = d/d_y$.

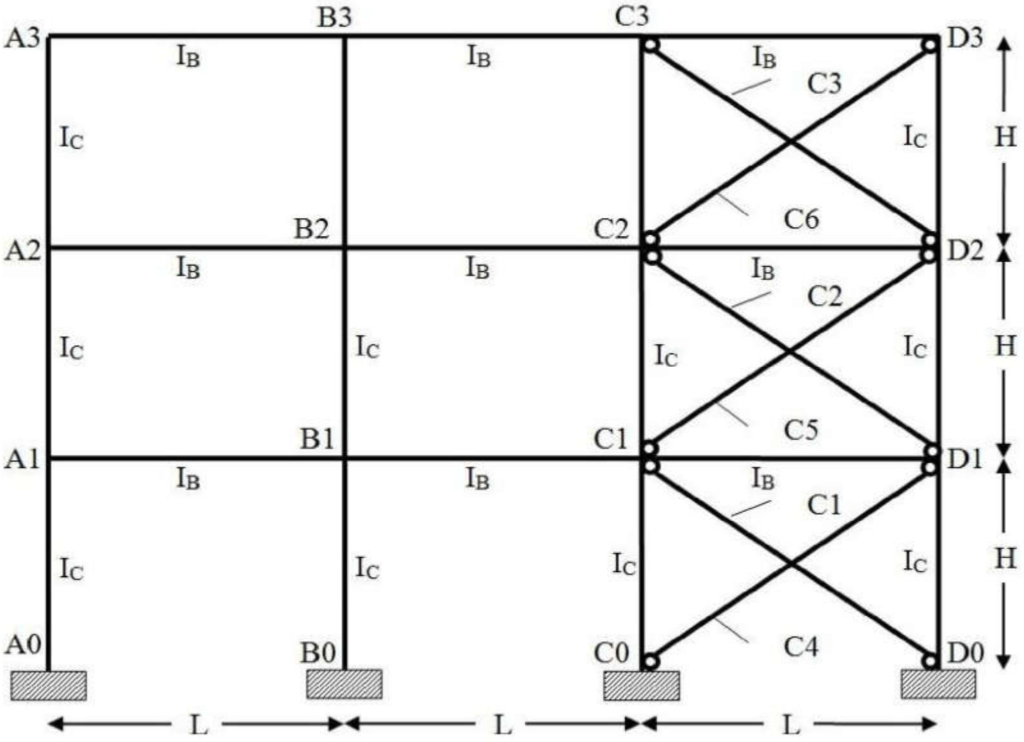

Figure 3. The RC frame F6 with X-bracings cable-strengthening.

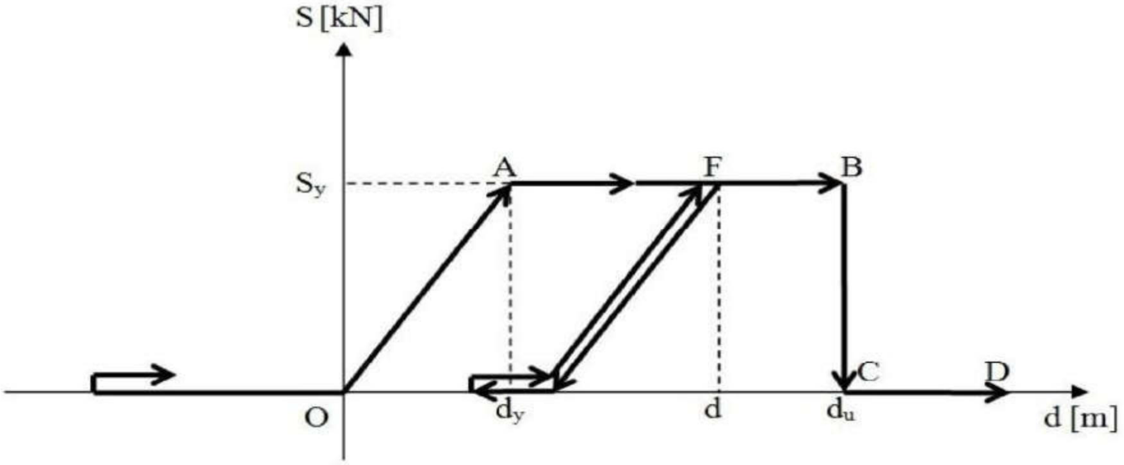

Figure 4. Constitutive law of the cable-elements.

Concerning the Coalinga case of seismic sequence, representative results are shown in Table 3. In column (2), Event E_1 corresponds to Coalinga seismic event of 0.605g PGA, and Event E_2 to 0.733g PGA. The sequence of events E_1 and E_2 is denoted as Event (E_1+E_2). In the table column (3) the mean value and in column (4) the coefficient of variation COV of the Global Damage Indices DI_G are given. Similarly, in the column (5) and in the column (6) the mean value and the coefficient of variation COV of the absolutely maximum horizontal top roof displacement u_{top}, respectively, are given.

As the values in the Table 3 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 F6 of Fig. 4) improves the response behaviour by reducing the peak values.

Table 3. Representative response quantities for the frames F0 and F6

SYSTEM	EVENTS	DI_G		u_{top} [cm]	
		Mean value	COV	Mean value	COV
(1)	(2)	(3)	(4)	(5)	(6)
F0	Event E_1	0.178	15.9%	2.56	13.8%
	Event E_2	0.448	14.8%	3.54	12.4%
	Event (E_1+ E_2)	0.487	16.4%	4.97	14.2%
F6	Event E_1	0.122	15.2%	1.28	13.8%
	Event E_2	0.331	13.7%	2.04	12.7%
	Event (E_1+ E_2)	0.348	16.8%	2.48	14.2%

4. CONCLUDING REMARKS

The herein presented computational approach can be effectively used for the probabilistic numerical investigation concerning the seismic inelastic behaviour of Cultural Heritage industrial RC frames strengthened by cable elements and subjected to multiple earthquakes. As in a numerical application has been shown, the probabilistic estimation of the uncertain input parameters is effectively realized by using Monte Carlo simulation.

REFERENCES

[1] Fardis, M.N., (2009). *Seismic design, assessment and retrofitting of concrete buildings, based on EN-Eurocode 8*. Springer, Berlin.

[2] Penelis G. Gr., & Penelis Gr. G. (2014). "*Concrete Buildings in Seismic Regions*". CRC Press.

[3] Dritsos, S.E., (2001). *Repair and strengthening of reinforced concrete structures* (in greek). University of Patras, Greece.

[4] Eurocode 8 (CEN 2004). Design of structures for earthquake resistance, Part 3: Assessment and Retrofitting of buildings, (EC8-part3), EN 1998-3, Brussels.

[5] Asteris, P. G. & Plevris, V. (Eds.), (2015). *Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures.* IGI Global.

[6] Liolios Ang. & C. Chalioris, (2015). "*Industrial reinforced concrete buildings strengthened by cable elements: A numerical investigation of the response under seismic sequences*", In: Moropoulou A. (Editor), Proc. Scientific Conference on "Scientific Support for decision-making on sustainable and compatible materials and interventions for the preservation and protection of Cultural Heritage", Thalis Project, NTUA, Athens, pp. 244-257.

[7] Liolios, Ang. (2018). *Cultural Heritage RC Structures Strengthened by Ties under Seismic Sequences and Uncertain Input Parameters: A Computational Approach*. In: Moropoulou A. (Edit.), Proceedings of the 1st International Conference TMM_CH: Transdisciplinary Multispectral Modelling and Cooperation for the Preservation of Cultural Heritage, 10-13 October 2018, Athens, Greece (will be published by Springer, Dec. 2018).

[8] Liolios, Ang., Moropoulou, A., Partov, D., Folic,B. & Lios Ast. (2015). *Cultural Heritage RC Structures strengthened by Cable Elements under Multiple Earthquakes.* In:

Radonjanin V., Folic R. and Ladinovic D. (eds.), Proceedings of the Intern. Scientific Conference iNDiS 2015.

[9] 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.

[10] 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 Int. Congress on Computational Mechanics*, Volos, 12 July – 15 July 2015

[11] 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, 25–27May 2015, Vol. II, pp. 3997- 4010.

[12] Liolios Ang., Chalioris C., Liolios K. . and Folic B. (2012). *Strengthening by cable-bracings of reinforced concrete structures: A numerical approach*. In: Radonjanin V., Folic R. and Ladinovic D. (eds.), Proceedings of the Intern. Scientific Conference iNDiS 2012, pp. 130-136.

[13] Liolios Ast., Hatzigeorgiou G. and Liolios Ang., (2012). *Effects of multiple earthquakes to the seismic response of structures*, Building Materials and Structures Journal, vol. 55, no. 4, pp. 3-14.

[14] 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 Theoretical and Applied Mechanics*, 43(3), 21-32.

[15] Mistakidis, E.S. and Stavroulakis, G.E., (1998). Nonconvex optimization in mechanics. Smooth and nonsmooth algorithmes, heuristic and engineering applications. Kluwer, London.

[16] Panagiotopoulos, P.D., (1993). *Hemivariational Inequalities. Applications in Mechanics and Engineering*. Springer-Verlag, Berlin, New York, (1993).

[17] Leftheris, B., Stavroulaki, M. E., Sapounaki, A. C., & Stavroulakis, G. E. (2006). Computational mechanics for heritage structures. WIT Press, 2006.

[18] 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.

[19] Moropoulou, A., Labropoulos, K. C., Delegou, E. T., Karoglou, M., & Bakolas, A. (2013). "Non-destructive techniques as a tool for the protection of built cultural heritage". Construction and Building Materials, 48, 1222-1239.

[20] 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.

[21] 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).

[22] Paulay T. and M.J.N. Priestley, (1992), "*Seismic Design of Reinforced Concrete and Masonry Buildings*", Wiley, New York.

[23] PEER (2011). Pacific Earthquake Engineering Research Center. *PEER Strong Motion Database*. http://peer.berkeley.edu/smcat..

[24] Carr, A.J., (2008). *"RUAUMOKO - Inelastic Dynamic Analysis Program"*. Dep. of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

[25] Vamvatsikos, D., & Fragiadakis, M. (2010). *Incremental dynamic analysis for estimating seismic performance sensitivity and uncertainty*. Earthquake engineering & structural dynamics, 39(2), 141-163

[26] Spyrakos C.C. and Maniatakis Ch.A. (2006). *"Retrofitting of a Historic Masonry Building",* 10th National and 4th International Scientific Conference on Planning, Design, Construction and Renewal in the Construction Industry (iNDiS 2006), Novi Sad, 22-24 November 2006, 535-544.

[27] Ang, A. H., & Tang, W. H. (1984). *Probability concepts in engineering planning and design, vol. 2: Decision, risk, and reliability*. New York: Wiley.

[28] Kottegoda, N., & Rosso, R. (2000). Statistics, probability and reliability for civil and environmental engineers. McGraw-Hill, London.

[29] Dimov, I. T. (2008). Monte Carlo methods for applied scientists. World Scientific.

[30] JCSS. *Probabilistic Model Code*-Part 1: Basis of Design (12th draft). Joint Committee on Structural Safety, March 2001. Available from: http://www.jcss.ethz.ch/.

[31] Papadrakakis, M., & Stefanou, G. (Eds.). (2014). *Multiscale modeling and uncertainty quantification of materials and structures.* Springer, Berlin.

[32] Kurtović-Folić Nadja, (2018), *Built heritage subjected to earthquake disasters and their mitigation*, In: Partov, D., Zareva-Peeva T., Stoynova I. (eds.), Proceedings of the XVIII Anniv. Intern. Scient. Conf. 'Construction and Architecture", VSU'2018, Sofia, Bulgaria.