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A STOCHASTIC APPROACH FOR OLD RC STRUCTURES STRENGTHENED BY TIES TO PREVENT PROGRESSIVE COLLAPSE UNDER SEISMIC SEQUENCES

Abstract: Old existing industrial reinforced concrete (RC) structures are often subjected to removal of structural elements due to degradation caused by environmental effects. So they are in a risk of progressive collapse. In oder to prevent this risk, a strengthening by cable elements (tension-ties) can be used. The probabilistic analysis of such RC structures under seismic sequences is herein numerically investigated. The unilateral behavior of the cable-elements, which can undertake tension stresses only, is strictly taken into account. Attention is given to uncertainties concerning structural input parameters, common for such old RC structures belonging to built Cultural Heritage. For their treatment, Monte Carlo techniques are applied. The proposed methodology is explained in a numerical example.

Key words: Progressive Collapse, Cultural Heritage RC Structures, Seismic Upgrading by Ties, Seismic Sequences, Monte Carlo methods.

STOHASTIČKI PRISTUP U ANALIZI STARIH AB KONSTRUKCIJA OJAČANIH ZATEGAMA SA CILJEM PREVENCIJE PROGRESIVNOG KOLAPSA NASTALOG USLED NIZA SEIZMIČKIH POTRESA

Rezime: Stare postojeće industrijske armiranobetonske (AB) konstrukcije često su podvrgnute uklanjanju konstruktivnih elemenata zbog degradacije uzrokovane uticajima okoline, zbog čega su u opasnosti od progresivnog kolapsa. Da bi se sprečio ovaj rizik, može se koristiti ojačanje kablovskim elementima (zatezne zatege). Ovde je numerički istražena probabilistička analiza takvih armiranobetonskih konstrukcija izloženim uticaju niza seizmičkih potresa. Strogo se uzima u obzir jednostrano ponašanje kablovskih elemenata, koji mogu da podnesu samo zatezna naprezanja. Pažnja je posvećena nejasnoćama u pogledu ulaznih parametara konstrukcije, uobičajenih za tako stare AB konstrukcije koje pripadaju kulturnom nasleđu. Za njihovo tretman primenjuju se Monte Karlo tehnike. Predložena metodologija je objašnjena na numeričkom primeru.

Ključne reči: progresivni kolaps, AB konstrukcije kulturnog nasleđa, seizmičko poboljšanje stegama, niz seizmičkih potresa, Monte Karlo metode

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1. INTRODUCTION

As well-known, old existing reinforced concrete (RC) structures belonging to built recent Cultural Heritage are often subjected to various environmental actions, e.g. corrosion, earthquakes etc. These actions can cause significant damages resulting into the strength degradation and the reduction of the loads bearing capacity of some structural elements, e.g. columns. For some of these elements is sometimes obligatory to be removed, and so a further reduction of the whole structure capacity is caused, which can lead to a progressive collapse [1].

In order to overcome the risk of the above progressive collapse, and after a structural assessment, a strengthening of the remaining structure is usually suggested. Among the available strengthening methods [2-4], cable-like members (tension-only tie-elements) can be used as a first strengthening and repairing procedure [5]. Cables can undertake tension but buckle and become slack and structurally ineffective when subjected to a sufficiently large compressive force. Thus the governing conditions take an equality as well as an inequality form and the problem becomes a high non-linear one. So, the problem of structures containing as above cable-like members belongs to the so-called Inequality Problems of Mechanics, as their governing conditions are of both, equality and inequality type [6-8]. A realistic numerical treatment of such problems can be obtained by mathematical programming methods (optimization algorithms).

As concerns 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 [5, 9], multiple earthquakes generally require increased ductility design demands in comparison with single isolated seismic events.

Moreover, for the numerical analysis of such old RC structures, many uncertainties for input parameters must be taking into account. These mainly concern the holding properties of the old materials that 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. Therefore, an appropriate estimation of the uncertain input parameters must be performed. For the quantification of such uncertainties, probabilistic methods have been proposed [10, 11].

In the present paper, a numerical approach is presented for the analysis of existing old framed RC buildings, which are strengthened by cable elements in order to avoid progressive collapse under seismic sequences after the obligatory removal of some degraded structural elements. The computational approach is based on an incremental problem formulation. Special attention is given for the estimation of the uncertainties concerning structural input parameters. For this purpose, uncertain-but-bounded input parameters by using upper and lower bounds-estimates [12] are considered and Monte Carlo techniques [13-15] are applied. Damage indices [16] are computed for the seismic assessment of such historic and industrial RC structures. Finally, an application is presented for a simple typical example of an industrial RC frame strengthened by bracing ties after the removal of some ground floor columns.

2. METHOD OF ANALYSIS

The stochastic approach for the seismic analysis of RC frame-buildings strengthened by ties can be obtained by using Monte Carlo simulations as explained in [10, 11]. For completeness of the present paper, the above approach is herein briefly summarized.

Monte Carlo simulation is simply a repeated process of generating deterministic solutions to a given problem [13-15]. 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 approach are given in [5, 11]. 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. Pin-jointed bar elements are used for the cable-elements. The unilateral behavior 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 [7,8].

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

$$\mathbf{M}\ \Delta\ddot{\boldsymbol{u}}+\mathbf{C}\ \Delta\dot{\boldsymbol{u}}+\mathbf{K}_{\mathbf{T}}\ \Delta\boldsymbol{u}\ =\ \Delta\boldsymbol{p}+\ \mathbf{A}\ \Delta\boldsymbol{s} \tag{1}$$

where ***u(t)*** and ***p(t)*** are the displacement and the load time dependent vectors, respectively, and **C** and $\mathbf{K}_\mathbf{T}$, 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. **A** is a transformation matrix.

The above relations combined with the initial conditions consist the problem formulation, where the vectors ***u*** and ***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 [7,8] and investigate it. For the numerical treatment of the problem, the structural analysis software Ruaumoko [16] is herein used. The seismic assessment of the existing RC structure, as well as of the strengthened by cable-ties system, can be realized by using damage indices [17]. In this study the overall structural damage index DI_G is used.

2.2. Treatment of the stochastic problem by using Monte Carlo simulations

In order to calculate the random characteristics of the response of the considered RC buildings, the Monte Carlo simulation is used in the way developed in [10,111]. As mentioned there, the main element of a Monte Carlo simulation procedure is the generation of random numbers from a specified distribution [13-15]. Systematic and efficient methods for generating such random numbers from several common probability distributions are available. Herein, the random variable simulation is implemented by using the technique of Latin Hypercube Sampling (LHS) see [18,19]. 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

3. NUMERICAL EXAMPLE

3.1. Description of the considered old RC structure under progressive collapse

The old industrial reinforced concrete frame F0 of Fig. 1 is considered to be upgraded by ties in order to avoid progressive collapse when it will be subjected to a multiple ground seismic excitation [9, 24]. This system F0 had been designed and constructed according to old Greek building seismic codes, having initially two more internal columns in the ground floor. These columns are shown as dashed lines and have been removed due to degradation caused by environmental actions. Following [1, 20], the axial loads, which were initially undertaken by these two columns, are now shown as the two applied vertical concentrated loads of 180 kN and 220 kN. The loading system shown in Fig. 1 is the critical one taken into account the “equivalent static” loading according to Greek seismic codes [21].

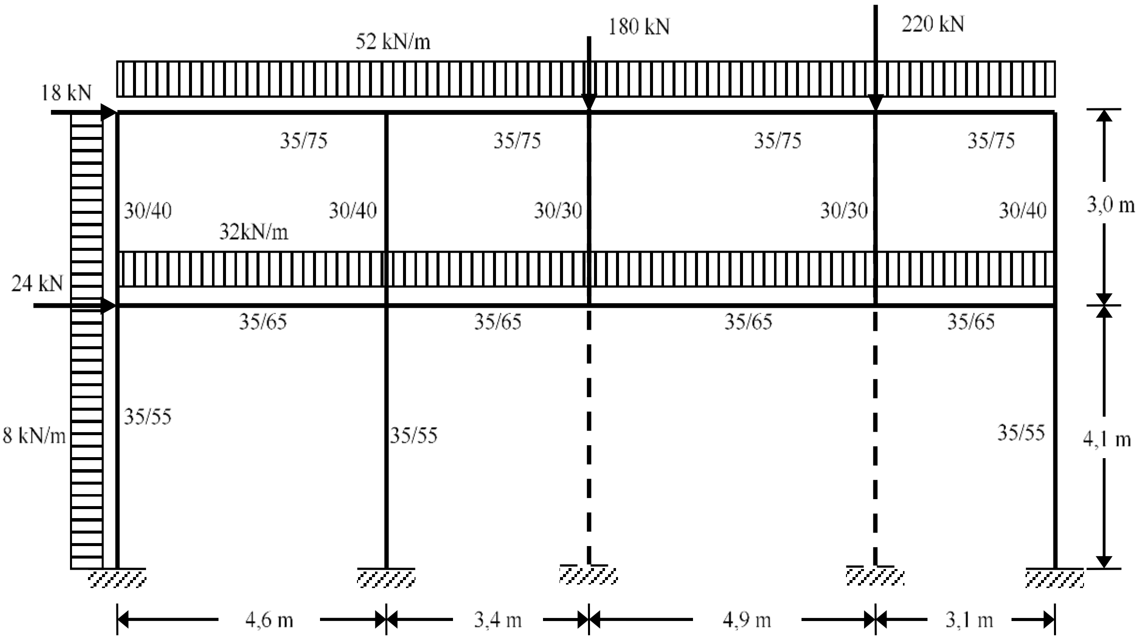

Figure 1 – System F0: The initial RC frame (without cables-strengthening).

Due to removal of the above two columns, the behavior of the horizontal beams connected with them changes drastically: These beams are not working further as “continuous beams”, although they had been designed and constructed as such ones. So, after a structural assessment by a “push-over” methodology [3,16] of the system F0 under the shown critical loading system, it is computed that the global damage index DI_G has a value greater than one. Thus it is concluded that the initial RC frame F0 of Fig. 1 is under a significant risk for a progressive collapse by the shown critical loading. Obviously, this holds even more when seismic events and/or seismic sequences are activated.

In order to prevent such a progressive collapse, the initial RC frame F0 of Fig. 1 is strengthened by ten (10) steel cables (tension-only tie-elements) as shown in Fig. 2. These strengthening cable members have a cross-sectional area F_r = 15 cm^2 and are of steel class S1400/1600 with elasticity modulus E_s = 210 GPa. The cable constitutive law concerning the unilateral (slackness), hysteretic, fracturing, unloading-reloading etc. behavior, has the diagram depicted in Fig. 3.

Due to various extreme actions (environmental etc.), corrosion and cracking has been taken place, which has caused a strength and stiffness degradation estimated by in-situ investigations. The effects of cracking on columns and beams are simulated by applying the guidelines of [2,21,22]. So, the stiffness reduction due to cracking results to effective stiffness with mean values 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.

Using Ruaumoko software [16], the columns and the beams of the frame are modeled by prismatic frame RC elements. Nonlinearity at the two ends of the RC frame structural elements is idealized by using one-component plastic hinge models, following the Takeda hysteresis rule [16]. Interaction curves (M-N) for the critical cross-sections of the examined RC frame have been computed. The Ruaumoko Bi-linear with slackness hysteresis element is used for the simulation of the cable (tension-only) elements.

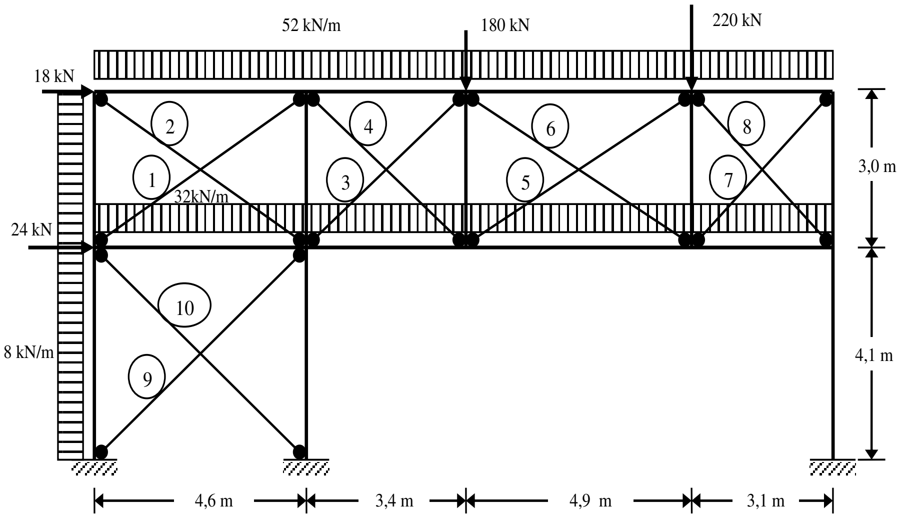

Figure 2 – System F10: The RC frame strengthened by 10 cables-tension ties.

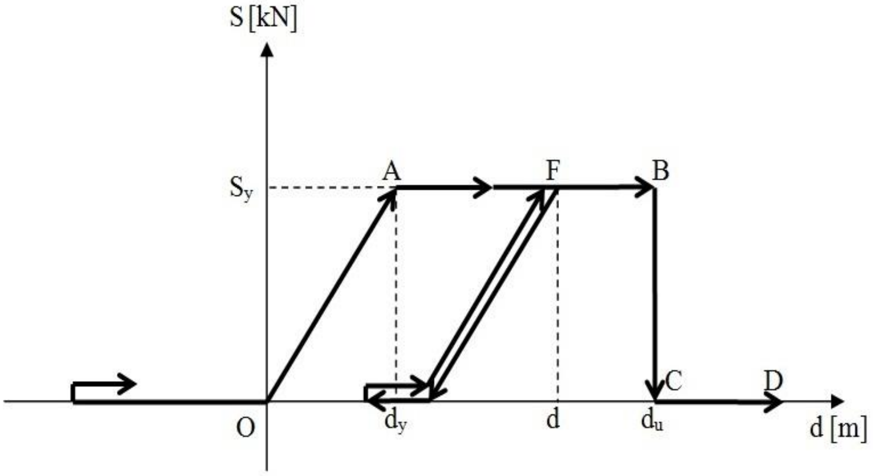

Figure 3 – The diagram for the constitutive law of cable-elements.

The concrete class of initial frame is estimated to be C12/15. According to JCSS (Joint Committee Structural Safety), see [23], 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 1. By COV is denoted the coefficient of variation. The mean⁄median values of the random variables, computed by using upper and lower bounds-estimates [12], correspond to the best estimates employed in the deterministic model according to Greek code KANEPE [21].

Table 1 – Statistical data for the building materials treated as random variables

	Distribution	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%

3.2. Seismic Sequences Input and some Representative Probabilistic Results

In Table 2 three typical real seismic sequence are reported, which have been downloaded from the strong motion database of the Pacific Earthquake Engineering Research (PEER) Center [24], see also [5].

The system F10 with cable elements of Fig. 2 is considered herein indicatively to be subjected to the Coalinga seismic sequence of the Table 2.

Table 2 – 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

The application of the proposed numerical procedure by using 250 Monte Carlo samples gives the following representative results concerning some dynamic response characteristics:

In column (2) of the Table 3, the Event E_1 corresponds to Coalinga seismic event of 0.605g PGA, and Event E_2 to 0.733g PGA, ($g=9.81m/sec^2$). 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 columns (5) and (6) the mean value and the coefficient of variation COV of the absolutely maximum vertical displacement U_{y180}, (under the concentrated load of 180 kN, see Fig. 2), respectively, are given.

As the table values show, multiple earthquakes generally increase, in an accumulative way, the response quantities, e.g. critical vertical displacements and damage indices. On the other hand, the strengthening of the frame F0 by X-bracings (system Frame F10 of Fig. 3) improves the response behaviour. So, the values of the Global Damage Indices DI_G show that the progressive collapse has been avoided.

Next, for the sequence of events E_1 and E_2, i.e. Event (E_1+ E_2), the following mean-value results for the maximum response tension are computed for the critically active cable-elements of the stress vector $\underline{s}$, where: $\underline{s} = [S_1, S_2, \ldots, S_{10}]^T$:

$S_1 =$ 3.68 kN, $S_4 =$ 530.73 kN, $S_7 =$ 498.87 kN, $S_9 =$ 31.84 kN.

The relevant mean coefficient of variation is COV=22.47%.

Obviously, by a suitable parametric investigation concerning the characteristics of the cable-elements (sectional area F_r, etc.), a further improved behavior and improved upgrading of the initial structure F0 can be obtained.

Table 3 – Representative probabilistic dynamic response quantities for the system F10

SYSTEM	EVENTS	DI_G		U_{y180} [cm]	
		Mean value	COV	Mean value	COV
(1)	(2)	(3)	(4)	(5)	(6)
F10	Event E_1	0.137	17.4%	-1.42	14.8%
	Event E_2	0.194	18.3%	-1.73	16.4%
	Event $(E_1 + E_2)$	0.257	19.7%	-1.87	18.7%

4. CONCLUDING REMARKS

The herein presented computational approach can be effectively used for the probabilistic numerical investigation of the seismic inelastic behaviour of old RC framed structures strengthened by cable elements in order to prevent progressive collapse. This is proven by the results of a typical numerical example concerning the seismic response of a system subjected to multiple earthquakes. The probabilistic treatment of the uncertain-but-bounded input parameters is effectively realized by using Monte Carlo simulation.

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