A STOCHASTIC APPROACH FOR HISTORIC RC STRUCTURES STRENGHTENED BY TIES TO PREVENT SEISMIC PROGRESSIVE COLLAPSE

A. Liolios [1], A. Moropoulou [2], K. Liolios [3], D. Partov [4], D. Peidis [5] and B. Folić [6]

1) Democritus University of Thrace, Greece,
2) National Technical University of Athens, Greece,
3) Bulgarian Academy of Sciences, Sofia, Bulgaria,
4) Lyuben Karavelov University (VSU), Sofia, Bulgaria, and
5) Thessaloniki Sochos - Lagkadas Municipality, Greece
6) University of Belgrade
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***Abstract**: Historic 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 seismic progressive collapse. In order to prevent this risk, a strengthening by cable elements (tension-ties) can be used. The probabilistic analysis of such RC structures under critical seismic loading 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**: Historic industrial RC structures, removal of columns, strengthening by ties, Monte Carlo methods.*

1. Introduction

As well-known [1,2], many of old existing industrial reinforced concrete (RC) structures can be considered as elements of the recent built Cultural Heritage. Such historic

[1] Helllenic Open University, School of Science and Technology, Patra, Greece, and Democritus University of Thrace, Xanthi, Greece, e-mails: aliolios@civil.duth.gr, and liolios.angelos@ac.eap.gr.
[2] National Technical University of Athens, School of Chemical Engineering, Athens, Greece, e-mail: amoropul@central.ntua.gr.
[3] Institute of Information and Communication Technologies, Bulgarian Academy of Sciences (BAS), Sofia, Bulgaria, e-mail: kostisliolios@gmail.com.
[4] University of Structural Engineering & Architecture "Lyuben Karavelov" (VSU), Sofia, Bulgaria, e-mail: partov@vsu.bg.
[5] Democritus University of Thrace, Dept. of Architectural Engineering, Xanthi, Greece, and Techn. Staff in Sochos Thessaloniki - Lagkadas Municipality, Greece.
[6] Faculty of Mechanical Engineering, Innovative Centre, Belgrade, Serbia; boris.r.folic@gmail.com

(RC) structures are subjected to various environmental actions, e.g. corrosion, earthquakes etc., which can often cause significant damages. A main such defect is the strength degradation, resulting into a reduction of the loads bearing capacity of some structural elements. For some of such degraded elements is sometimes obligatory to be removed, and so a further reduction of the whole structure capacity is caused, which can lead to progressive collapse [2,16].

After structural assessment, a strengthening of the remaining structure is usually suggested, in order to overcome the above defects. Among the available strengthening methods [3-5], cable-like members (tension-only tie-elements) can be used as a first strengthening and repairing procedure [1, 6]. 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 [6-10]. A realistic numerical treatment of such problems can be obtained by mathematical programming methods (optimization algorithms).

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, e.g. Monte Carlo procedures, see [17-22].

This paper deals with a numerical approach for the stochastic analysis of existing old industrial framed RC buildings, which are strengthened by cable elements in order to avoid progressive collapse [16] after the obligatory removal of some degraded structural elements. The computational approach is based on an incremental problem formulation. 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 reported in [17]. 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, see e.g. [20-22]. 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.

Concerning the numerical treatment of the deterministic problem, a reinforced concrete (RC) framed structure containing cable-like members is considered. For the general analysis of such a structure, see details as described in [1,6,17]. Generally, a double discretization is applied: in space by finite elements and in time by a direct time-integration method. The RC structure is discretized to frame elements with generally non-linear behavior. For the cables, pin-jointed bar elements with unilateral behavior are used. The rigorous mathematical investigation of the problem can be obtained by using the variational or hemivariational inequality concept, see Panagiotopoulos [9]. So, the behavior of the cables and the generally non-linear behavior of RC elements, including loosening, elastoplastic or/and elastoplastic-softening-fracturing and unloading - reloading effects, can be expressed mathematically by the subdifferential relation:

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

Here, for the example case of a typical i-th cable element, s_i and d_i are the (tensile) force and the deformation (elongation), respectively, $\hat{\partial}$ is the generalized gradient and S_i is the superpotential function [9,10].

For the numerical treatment of practical inequality problems, a piece-wise linearization is usually applied to relation (1), see e.g. [5-8]. So, for the case of cables, the unilateral behavior of the i-th cable-element (i = 1,…,N) is expressed by the following relations [7]:

$$e_i\ =\ F_{0i}\ .\ s_i\ +\ e_{i0}\ -\ v_i, \tag{2a}$$

$$s_i\ \geq\ 0\ ,\quad v_i\ \geq\ 0\ ,\quad s_i\, v_i\ =\ 0. \tag{2b}$$

Here e_i , F_{0i}, s_i, e_{i0} and v_i denote the strain (elongation), "natural" flexibility constant, stress (tension), initial strain and slackness, respectively. Relations (2b) consist the Linear Complementarity Conditions (LCC) and express that either a non-negative stress (tension) or a non- negative slackness exists on cables at every time-moment. The above considerations lead to formulate the problem and to solve it at every time-moment as a Linear Complementarity Problem (LCP). The numerical treatment of this LCP is obtained by using optimization methods [1, 6-10].

In an alternative approach, the incremental dynamic equilibrium for the assembled structural system with cables is expressed in matrix form by the equation:

$$\underline{M}.\Delta\underline{\ddot{u}}(t)+\underline{C}.\Delta\underline{\dot{u}}(t)+\underline{K}_T.\Delta\underline{u}(t)=\Delta\underline{p}(t)+\underline{T}.\Delta\underline{s}(t) \tag{3}$$

Here $\underline{u}(t)$ and $\underline{p}(t)$ are the time dependent displacement and the given load vectors, respectively. $\underline{C}$ and $\underline{K}_T(\underline{u})$, are the damping and the time dependent tangent stiffness matrix, respectively. Dots over symbols denote derivatives with respect to time. $\underline{T}$ is a transformation matrix. By $\underline{s}(t)$ is denoted the time dependent cable stress vector with elements satisfying the relations (1)-(2).

The above matrix equation combined with the initial conditions consist the problem formulation, where, for given $\underline{p}(t)$, the vectors $\underline{u}(t)$ and $\underline{s}(t)$ are to be computed. For the numerical treatment of the above problem, the structural analysis software Ruaumoko [11] is herewith used, as described in [5]. When the static case of the problem is only to be investigated, a Dynamic Relaxation approach [12] is appropriately used.

3. Numerical example

The historic industrial RC plane frame structure of Fig. 1 had been initially constructed with two more internal columns in the ground floor, which are shown as dashed lines and have been removed due to degradation caused by environmental actions. Following [16], 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.

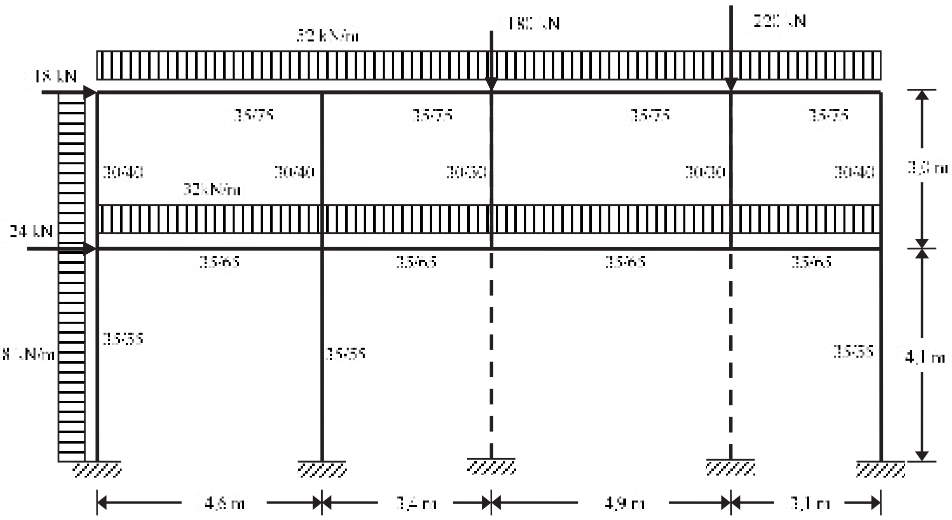

Fig. 1. The initial RC frame F0.

Due to removal of the above two columns, and after structural assessment [15] and in order to prevent 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. In the so formulated system, it is wanted to be computed which of the cables are activated and which are not, under the considered critical static loading of Fig. 1. This critical loading takes into account extreme seismic load effects according to current Greek Codes, see KANEPE [18].

Using Ruaumoko software [11], the columns and the beams of the frame are modeled by prismatic frame RC elements. The concrete class is estimated to be C12/15. The effects of cracking on columns and beams are estimated by applying the guidelines of [1-4, 13]. 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.

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 [11]. Concerning the constitutive diagram of plastic hinges, a typical normalized moment-normalized rotation backbone [14] is shown in Fig. 3.

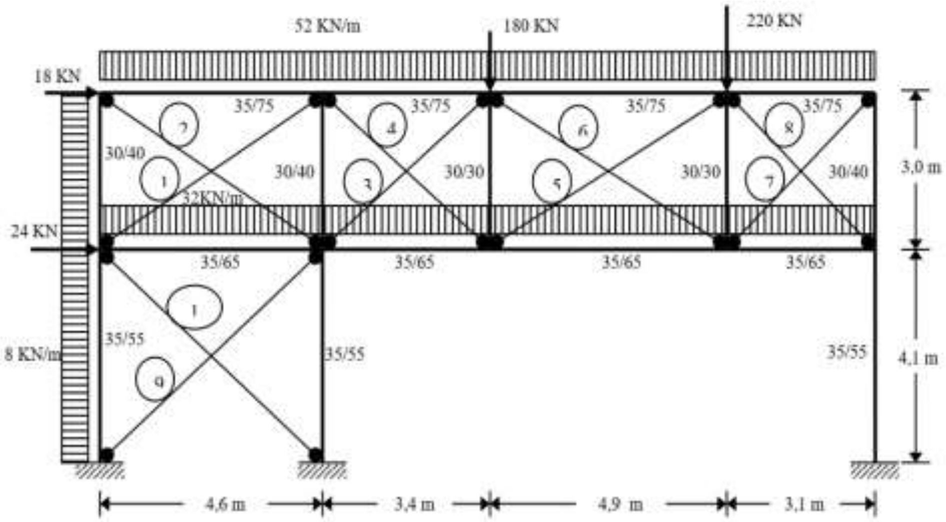

Fig. 2. The RC frame F1 (or F2) strengthened by 10 cables.

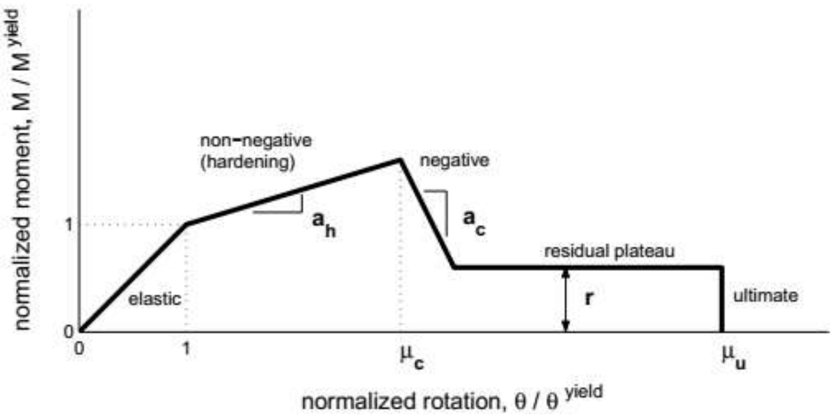

Fig. 3. Constitutive backbone diagramme for normalized moment - normalized rotation in plastic hinges [14].

The strengthening cable members have a cross-sectional area F_r = 10 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. hysteretic behavior, has the diagram depicted in Fig. 4.

Considering input-parameters uncertainty, according to JCSS (Joint Committee Structural Safety), see [18-20], 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, correspond to the best estimates employed in the deterministic model according to Greek code KANEPE [18].

Table 1. 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%

The application of the proposed numerical procedure by using a pseudo Dynamic Relaxation approach [12] and 250 Monte Carlo samples, gives the following mean-value results for the cable-elements:

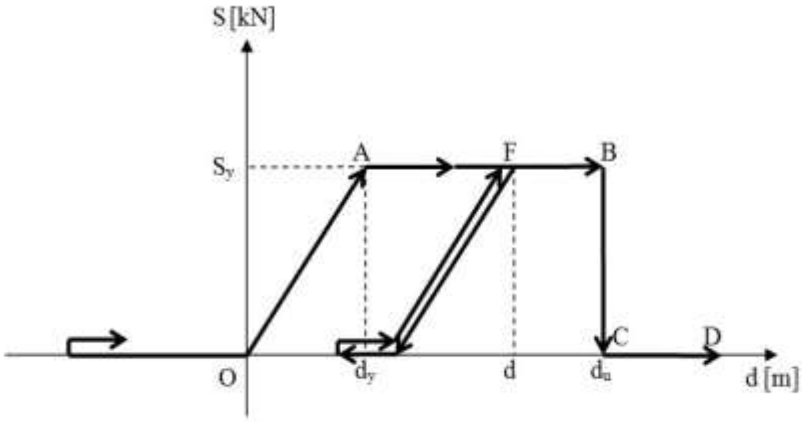

Fig. 4. Constitutive law of the cable-elements.

a. The mean values of the slackness of the no activated cable-elements are:
$v_1 = 0.848*10^{-3}$ m, $v_3 = 10.321*10^{-3}$ m, $v_5 = 1.082*10^{-3}$ m,
$v_8 = 9.564*10^{-3}$ m, $v_{10} = 1.652*10^{-3}$ m.
b. The elements of the stress vector $\underline{s}$, where: $\underline{s} = [S_1, S_2, \ldots, S_{10}]^T$, are computed to have the following mean stress-values (in kN) for the non-active cables:
$S_1 = S_3 = S_5 = S_8 = S_{10} = 0.0$,
whereas for the active cables, the tension-values are:
$S_2 =$ 10.17 kN, $S_4 =$ 346.04 kN, $S_6 =$ 18.84 kN,
$S_7 =$ 342.08 kN, $S_9 =$ 25.81 kN.

The relevant mean coefficient of variation is COV=21.84%.

Thus, cables 2,4,6,7 and 9 are the only ones which have been activated, appearing non-zero tension. The other cables 1,3,5,8 and 10 cannot contribute to the system resistance under the given loads of Fig. 1.

Obviously, by parametric investigation of the characteristics of the cable-element (sectional area, elasticity modulus etc.), a parametric upgrading investigation of the strengthened structure can be obtained in order to avoid collapse. Such a parametric investigation is shown indicatively in the Table 2. This investigation concerns the response of the initial frame-structure F0 without cables ($F_r = 0$ cm^2) and when it is strengthened by cable members having a cross-sectional area either $F_r = 5$ cm^2 (frame F1) or $F_r = 10$ cm^2 (frame F2). By U_{y180} and U_{y220} are denoted the node vertical displacements under the single concentrated loads of 180 kN and 220 kN, respectively, (see Fig.1). M_1 and M_2 are the maximum bending moments of the first and the second floor-beams, respectively, between the deleted columns. By COV in % is denoted the coefficient of variation. The reduction of mean response values due to cable-strengthening is remarkable.

4. Concluding remarks

A computational stochastic approach has been presented, which can be effectively used for the numerical investigation concerning the inelastic behaviour of historic existing RC framed-structures subjected to removal of some degraded structural elements and strengthened by cable elements. By parametric investigation of the characteristics of the cable-elements (sectional area, elasticity modulus etc.), the required upgrading of the remaining structure in order to avoid collapse can be obtained.

Table 2. Comparison of response representative mean-values of the initial frame F0 and the strengthened frames F1 and F2.

Frame	Cables cross-section	S_4 [kN]	S_7 [kN]	U_{y180} [cm]	U_{y220} [cm]	M_1 [kNm]	M_2 [kNm]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
F0	$F_r = 0\ cm^2$	0.00	0.00	-2.46	-2.59	307.91	402.64
	COV [%]	0	0	22.1	22.1	21.8	21.8
F1	$F_r = 5\ cm^2$	272.11	268.65	-1.67	-1.70	218.22	290.98
	COV [%]	24.7	24.7	22.8	22.8	23.7	23.7
F2	$F_r = 10\ cm^2$	401.30	412.89	-1.26	-1.27	174.59	236.37
	COV [%]	22.4	22.4	23.4	23.4	20.8	20.8

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