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CHOICE OF THE OPTIMAL TIES SYSTEM CONCERNING THE SEISMIC UPGRADING OF RC STRUCTURES UNDER MULTIPLE EARTHQUAKES

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ABSTRACT

The seismic upgrading of environmentally degraded existing reinforced concrete (RC) structures by using ties (cable) elements is numerically investigated. Emphasis is given to select the optimal strengthening version of ties system for the response of such RC structures under multiple earthquakes effects. Damage indices are computed in order to compare these responses before and after the retrofit by cable element strengthening, and so to select the optimum strengthening version. For a typical example problem, the effectiveness of the proposed computational approach is presented.

KEY WORDS. Seismic Upgrading of RC Structures, Environmental Degradation, Strengthening by Cable-braced Systems, Damage Indices, Multiple Earthquakes.

INTRODUCTION

As well-known, for the seismic upgrading of existing reinforced concrete (RC) structures many repairing and strengthening techniques can be used, see e.g. [1-3, 6, 9, 10, 29]. One of the simple, low cost and efficient method for strengthening of existing RC frames against lateral induced earthquake loading is the use of steel cross X-bracings [3, 19, 20, 31]. 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 [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 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, 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 with a numerical approach for the choice of the optimum cable-bracing strengthening version concerning the seismic upgrading of existing beam-column RC frames. The approach is based on an incremental formulation and uses the Ruaumoko structural engineering software [4]. Damage indices [13, 22, 26] are computed, first for the seismic assessment of the existent RC structures and next for the choice of the optimum cable-bracing strengthening version. In an application is presented the case of a two-bay two-story RC frame strengthened by bracing ties under multiple earthquakes.

THE COMPUTATIONAL APPROACH FOR THE OPTIMAL TIES-SYSTEM

Details of the developed numerical approach are given in [12, 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 the cable (ties) elements can in general include loosening, elastoplastic or/and elastoplastic-softening-fracturing and unloading - reloading effects. A piecewise linearized constitutive diagramme (backbone), concerning the constitutive law connecting a generalized force with a generalized displacement, is shown in Fig. 1. All the above behaviour 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].

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

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

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. $\boldsymbol{A}$ is a transformation matrix and $\boldsymbol{u_g}$ the ground seismic excitation.

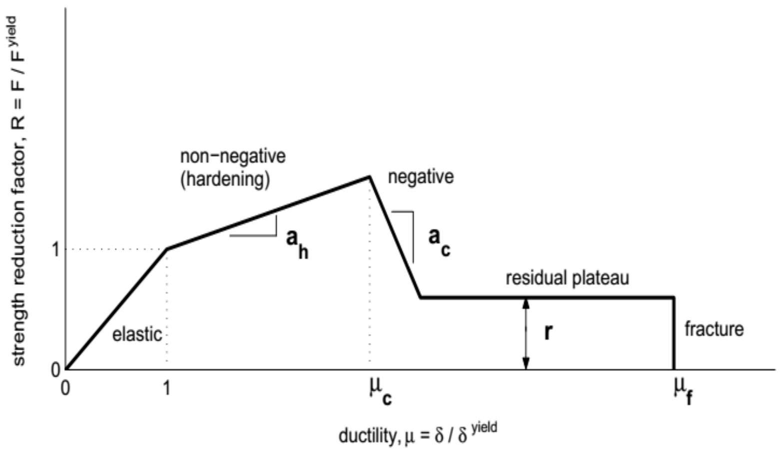

Fig. 1. A piecewise linearized constitutive diagramme (backbone) concerning the constitutive law connecting a generalized force with a generalized displacement [23].

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 $\boldsymbol{s}$ have to be computed. Regarding the strict mathematical point of view, we can formulate the problem as a hemi-variational 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 [23]. In [15,16] a calibration of this code has been realized by using experimental results of [20]. Further, 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:

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

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:

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

where 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.

NUMERICAL EXAMPLE

The reinforced concrete frame F0 of Fig. 2.A. is of concrete class C40/45, has dimensions L = 7 m and h = 3.5 m and was designed according to Greek building codes and to current European seismic codes [8-10]. The beams are of rectangular section 30/60 (width/height, in cm) and have a total vertical distributed load 30 KN/m (each beam). The columns have section dimensions, in cm: 40/40.

The frame was initially constructed without cable-bracings. Due to various extremal actions (environmental etc.), corrosion and cracking has been taken place, which has caused a strength and stiffness degradation. The so resulted reduction for the section inertia moments was estimated [15, 27] to be 20% for the internal columns, 40% for the external columns and 60% for the beams, providing the effective stiffness. Three cable-bracing systems, shown in Figs. 2.B,C,D, have been proposed and investigated in order the optimal one to be

chosen. The first system, denoted as F1, has two descending diagonal cable-elements. The second, denoted as F2, has X-bracing diagonal cable-elements. The third, denoted as F3, has inverted V bracing diagonal cable-elements.
The cable elements have a cross-sectional area $F_c = 18\ cm^2$ and they are of steel class S220 with yield strain $\varepsilon_y = 0.11\ \%$, fracture strain $\varepsilon_f = 2\ \%$ and elasticity modulus $E_c = 200$ GPa. The cable constitutive law, concerning the unilateral (slackness), hysteretic, fracturing, unloading-reloading etc. behavior, is depicted in Fig. 3.

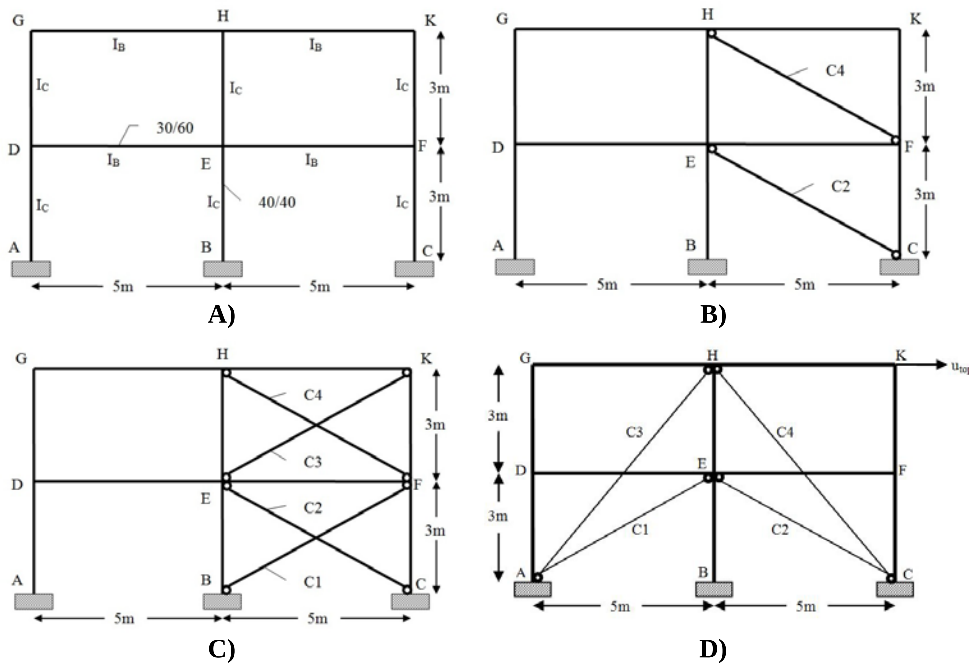

Fig. 2. Numerical example: A) The two-bays two-storey RC frame F0, B) The F1 two-ties-system, C) The F2 four-ties-system X, D) The F3 four-ties-system inverted V.

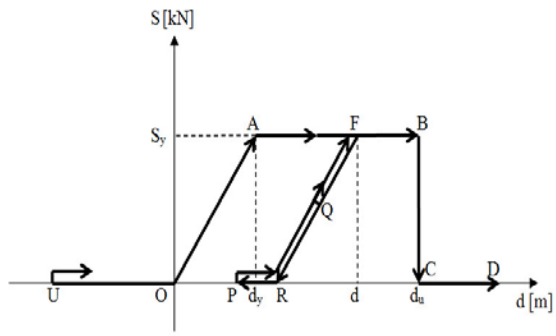

Fig. 3. The constitutive law for the unilateral behavior of the cable-elements.

The systems F0, F1, F2 and F3 of Fig. 2 are considered to be subjected to a multiple ground seismic excitation, presented and discussed in the papers [11,18]. The complete list of these earthquakes was downloaded from the strong motion database of the Pacific Earthquake Engineering Research (PEER) Center [28], and appears in Table 1. The strong ground motion database consists of five real seismic sequences, which have been recorded during a short period of time (up to three days), by the same station, in the same direction, and almost at the same fault distance. E.g for Coalinga, July 1983, they are two events, E_1 with PGA=0.605 g and E_2 with PGA=0.733 g). By PGA is denoted the peak ground acceleration in gravity acceleration units (g=9.81 m/sec^2).

Table 1. Sequential earthquakes data

N	Seismic sequence	Station	Comp	Date (Time)	Magn. (ML)	Record. PGA(g)	Norm. PGA
1	Mammoth Lakes	54099 Convict Creek	N-S	1980/05/25 (16:34)	6.1	0.442	0.200
				1980/05/25 (16:49)	6.0	0.178	0.081
				1980/05/25 (19:44)	6.1	0.208	0.094
				1980/05/25 (20:35)	5.7	0.432	0.195
				1980/05/27 (14:51)	6.2	0.316	0.143
2	Chalfant Valley	54428 Zack Brothers Ranch	E-W	1986/07/20 (14:29)	5.9	0.285	0.128
				1986/07/21 (14:42)	6.3	0.447	0.200
3	Coalinga	46T04 CHP	N-S	1983/07/22 (02:39)	6.0	0.605	0.165
				1983/07/25 (22:31)	5.3	0.733	0.200
4	Imperial Valley	5055 Holtville P.O.	HPV	1979/10/15 (23:16)	6.6	0.221	0.200
			315	1979/10/15 (23:19)	5.2	0.211	0.191
5	Whittier Narrows	24401 San Marino	N-S	1987/10/01 (14:42)	5.9	0.204	0.192
				1987/10/04 (10:59)	5.3	0.212	0.200

Representative results of the numerical investigation are presented in Table 2. In column (1), Event E_1 corresponds to Coalinga seismic event of 0.165 normalized PGA of Table 1 and Event E_2 to 0.200 normalized PGA. The sequence of events E_1 and E_2 is denoted as Event (E_1+ E_2). In column (2) the Global Damage Indices and in column (3) the Local Damage Index DI_L for the bending moment at the left fixed support of the frames are given. Finally, in the column (4), the maximum horizontal top displacement u_{top} (absolute value) is given.

As the table values show, multiple earthquakes generally increase, in an accumulative way, the response quantities. Based on the values of the horizontal top displacement $u_{top} = u_2^{(A)}$, and of the Global Damage Indices, it can be concluded that the optimal global strengthening version is that one F3 of Fig. 2.D.

Table 2. Representative response quantities for the frames F0, F1, F2 and F3.

FRAMES	EVENTS	DI_G	DI_L	u_{top} [10^2cm]
(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
F1	Event E_1	0.133	0.185	1.715
	Event E_2	0.256	0.354	3.149
	Event (E_1+ E_2)	0.317	0.385	3.813
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
F3	Event E_1	0.054	0.009	1.069
	Event E_2	0.082	0.128	1.313
	Event (E_1+ E_2)	0.085	0.137	1.314

CONCLUDING REMARKS

The choice of the optimal ties-strengthening system for an existing RC structure can be obtained by the herein presented numerical approach. This approach can be used also for the parametric investigation of the inelastic seismic behaviour under multiple earthquakes sequences of existing RC systems, environmentally degraded and strengthened by cable elements. The unilateral behaviour of cable-elements and other non-linearities of the RC elements are strictly taken into account. As the results of a numerical example have shown, the optimal strengthening version of cable-bracings can be decided by computing necessary damage indices.

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