SELECTION OF SECTIONAL FORCES FOR DESIGNING R/C FRAMES ANALYSED BY TIME HISTORY ANALYSIS

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ABSTRACT :

In general the seismic design of R/C structural elements is controlled by the simultaneous action of three response parameters. For example, a column in a 3D frame must be proportioned to resist axial force and bending moments that act simultaneously. For such cases, seismic codes do not provide clear suggestions for the proper combination of sectional forces needed for the calculation of the longitudinal steel reinforcement. The objective of the present paper is the comparative evaluation of eight different methods of selection of the sectional forces needed for the calculation of the longitudinal steel reinforcement in concrete frame elements when the linear response history analysis is used. First, the eight methods are briefly presented. Then, a single-story symmetric building subjected to 15 strong earthquake ground motions is analysed. For each ground motion the longitudinal reinforcement at all critical cross sections is calculated using the eight aforementioned methods. Based on the results of the whole investigation, the following two general conclusions can be drawn: a) The required longitudinal reinforcement is significantly affected by the method used to select the design sectional forces in the frame elements and b) the differences in the results produced by the above methods range between 23% and 300%.

KEYWORDS: Seismic design, time history analysis, R/C buildings, longitudinal reinforcement.

1. INTRODUCTION

According to current seismic code provisions (EC8, FEMA, NEHRP, EAK) one of the methods that can be used for the seismic analysis and design of R/C structures is the linear time history analysis. In this method the seismic action is represented by a pair of horizontal accelerograms (recorded or artificial) and the produced action effects, which are determined by time integration, are then used to calculate the reinforcement steel ratios at every relevant cross section. The application of this method induces many questions regarding, among others, the representative collection and correct scaling of ground motions, the choice of the excitation's incident angle, and the proper (i.e., safe but not too conservative) selection of the frame's sectional forces required for the final design of the R/C frame elements. A review of code provisions regarding the aforementioned aspects reveals that they are lacking the necessary definiteness. Particularly important issues are the right choice of the incident angle and the proper selection of the frame's sectional forces, because both of them strongly affect the response quantities and, consequently, the reinforcement steel ratio.

Concerning the angle of seismic incidence, FEMA356 states that the structural elements of the building "shall be designed for combinations of forces and deformations from separate analyses performed for ground motions in X and Y directions", but does not clearly define how the orientation of the X and Y axes must be chosen. Similarly, neither NEHRP (2003) nor EAK define the orientation of the excitation, whereas EC8 specifies that "the design seismic action shall be applied along all relevant horizontal directions and their orthogonal horizontal directions". Yet, an explicit definition of the "relevant directions" is given only for a specific class of buildings: "For buildings with resisting elements in two perpendicular directions these two directions shall be considered as the relevant directions". Unfortunately, this provision has been proved to be inadequate, because the application of the seismic components along the building's structural axes can lead to significant underestimation of seismic response (Athanatopoulou 2005, Athanatopoulou et al 2005, Athanatopoulou and

Avramidis 2006).
Regarding the combination of sectional forces which should be used for design purposes, none of the seismic codes defines which is the proper (i.e., safe but not too conservative) combination. Most seismic code provisions specify that when three time history data sets are used as seismic input, the maximum value of each response parameter must be used for design, while in case of seven or more time history data sets the average value of each response parameter may be permitted to determine design acceptability.

The objective of the present paper is the presentation as well as the comparative evaluation of eight different methods of selection of the sectional forces needed for the calculation of the longitudinal reinforcement in R/C frame elements within the context of linear response history analysis.

2. CRITICAL ORIENTATION AND MAXIMUM RESPONSE

The structure is subjected to bidirectional horizontal seismic motion consisting of the accelerograms $\ddot{u}_{ag}(t)$ and $\ddot{u}_{bg}(t)$. As the direction of the seismic motion is unknown, they can form any angle θ with the x and y structural axes (figure 1a). We consider two orientations of the seismic excitation:

(i) Excitation ‘α0’: The accelerograms $\ddot{u}_{ag}(t)$ and $\ddot{u}_{bg}(t)$ are applied along the axes x and y, respectively, i.e. the angle of seismic incidence is $\theta=0^o$ (figure 1b). A typical response quantity R is denoted as $R_{,\alpha 0}$.

(ii) Excitation ‘α90’: The accelerograms $\ddot{u}_{ag}(t)$ and $\ddot{u}_{bg}(t)$ are applied along the axes y and x, respectively, i.e. the angle of seismic incidence is $\theta=90^o$ (figure 1c). A typical response quantity R is denoted as $R_{,\alpha 90}$.

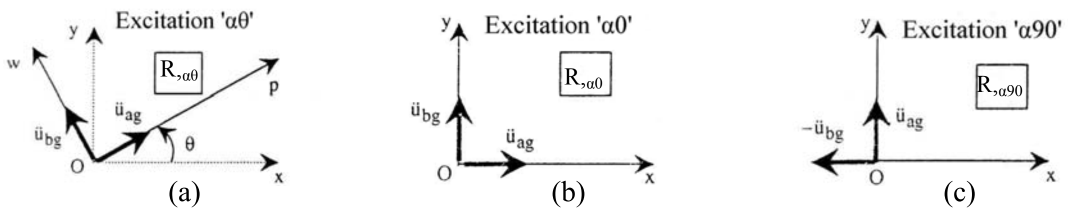

Figure 1 Excitations ‘αθ’ (a), ‘α0’ (b) and ‘α90’ (c)

It has been proved (Athanatopoulou, 2005) that the maximum value of a response parameter for any angle θ of seismic incidence is given, as a function of time, by the relation:

$$R_0(t) = [R_{,\alpha 0}^2(t) + R_{,\alpha 90}^2(t)]^{1/2} \tag{2.1}$$

The plot of the function $\pm R_0(t)$ provides the maximum/minimum value of the required response parameter as well as the time instant t_{cr} at which the maximum/minimum occurs.

$$\max R = +R_0(t_{cr}) \quad \text{and} \quad \min R = -R_0(t_{cr}) \tag{2.2}$$

The corresponding critical angles θ_{cr1} (maximum value) and θ_{cr2} (minimum value) are given by the relations (Athanatopoulou, 2005):

$$\theta_{cr1} = \tan^{-1}\left(\frac{R_{,\alpha 90}(t_{cr})}{R_{,\alpha 0}(t_{cr})}\right) \quad \text{and} \quad \theta_{cr2} = \theta_{cr1} - \pi \tag{2.3}$$

The value of any other response parameter R′ at the time instant t_{cr} for incident angle θ_{cri} (i=1, 2) is computed by the relation:

$$R'(\theta_{cri}, t_{cr}) = R'_{,\alpha 0}(t_{cr}) \cdot \cos\theta_{cri} + R'_{,\alpha 90}(t_{cr}) \cdot \sin\theta_{cri} \tag{2.4}$$

3. METHODS OF SELECTING THE SECTIONAL FORCES

According to methods 3.1, 3.2, 3.3 and 3.4 a response history analysis is performed under bi-directional excitation with the two accelerograms applied along the structural axes of the building ($\theta=0^o$, figure 1b) and the time histories of the response quantities $N(t)_{,\alpha 0}$, $M_\xi(t)_{,\alpha 0}$ and $M_\eta(t)_{,\alpha 0}$ at every cross section are computed.

3.1. Method of Extreme Stresses for Angle α=0º (MS$_{ex}$0)

According to this method the time histories of the normal stresses $\sigma_A(t)_{,\alpha 0}$, $\sigma_B(t)_{,\alpha 0}$, $\sigma_C(t)_{,\alpha 0}$, $\sigma_D(t)_{,\alpha 0}$ at the four corners A, B, C and D of a rectangular cross section are computed. Then, the maximum and minimum values of the stresses, as well as the corresponding time instants t_1 and t_2 are determined. The sectional forces $N(t_i)_{,\alpha 0}$, $M_\xi(t_i)_{,\alpha 0}$ and $M_\eta(t_i)_{,\alpha 0}$ (i=1,2), which correspond to maximum and minimum values of the normal stresses, are considered as the design combinations. Hence, at the four corners of any relevant rectangular cross section the following eight combinations have to be considered (Table 3.1).

Table 3.1 Design combinations for method MS$_{ex}$0

$\max\sigma_{A,\alpha 0}$	$N,_{\max\sigma A,\alpha 0}$	$M_\xi,_{\max\sigma A,\alpha 0}$	$M_\eta,_{\max\sigma A,\alpha 0}$
$\min\sigma_{A,\alpha 0}$	$N,_{\min\sigma A,\alpha 0}$	$M_\xi,_{\min\sigma A,\alpha 0}$	$M_\eta,_{\min\sigma A,\alpha 0}$
$\max\sigma_{B,\alpha 0}$	$N,_{\max\sigma B,\alpha 0}$	$M_\xi,_{\max\sigma B,\alpha 0}$	$M_\eta,_{\max\sigma B,\alpha 0}$
$\min\sigma_{B,\alpha 0}$	$N,_{\min\sigma B,\alpha 0}$	$M_\xi,_{\min\sigma B,\alpha 0}$	$M_\eta,_{\min\sigma B,\alpha 0}$
$\max\sigma_{C,\alpha 0}$	$N,_{\max\sigma C,\alpha 0}$	$M_\xi,_{\max\sigma C,\alpha 0}$	$M_\eta,_{\max\sigma C,\alpha 0}$
$\min\sigma_{C,\alpha 0}$	$N,_{\min\sigma C,\alpha 0}$	$M_\xi,_{\min\sigma C,\alpha 0}$	$M_\eta,_{\min\sigma C,\alpha 0}$
$\max\sigma_{D,\alpha 0}$	$N,_{\max\sigma D,\alpha 0}$	$M_\xi,_{\max\sigma D,\alpha 0}$	$M_\eta,_{\max\sigma D,\alpha 0}$
$\min\sigma_{D,\alpha 0}$	$N,_{\min\sigma D,\alpha 0}$	$M_\xi,_{\min\sigma D,\alpha 0}$	$M_\eta,_{\min\sigma D,\alpha 0}$

3.2. Method of Extreme Simultaneous Forces for Angle α=0º (MF$_{sim}$0)

According to this method the maximum and minimum values of the response quantities of interest $N(t_i)_{,\alpha 0}$, $M_\xi(t_i)_{,\alpha 0}$ and $M_\eta(t_i)_{,\alpha 0}$ (i=1,2), as well as the simultaneous values of the rest ones are determined. These values can be used for design purposes. Hence, for each cross section the six combinations presented in Table 3.2 have to be considered.

Table 3.2 Design combinations for method MF$_{sim}$0

$\max N_{,\alpha 0}$	$M_\xi,_{\max N,\alpha 0}$	$M_\eta,_{\max N,\alpha 0}$
$\min N_{,\alpha 0}$	$M_\xi,_{\min N,\alpha 0}$	$M_\eta,_{\min N,\alpha 0}$
$N,_{\max M\xi,\alpha 0}$	$\max M_{\xi,\alpha 0}$	$M_\eta,_{\max M\xi,\alpha 0}$
$N,_{\min M\xi,\alpha 0}$	$\min M_{\xi,\alpha 0}$	$M_\eta,_{\min M\xi,\alpha 0}$
$N,_{\max M\eta,\alpha 0}$	$M_\xi,_{\max M\eta,\alpha 0}$	$\max M_{\eta,\alpha 0}$
$N,_{\min M\eta,\alpha 0}$	$M_\xi,_{\min M\eta,\alpha 0}$	$\min M_{\eta,\alpha 0}$

3.3. Method of Extreme Forces for Angle α=0º (MF$_{ex}$0)

According to this method the maximum and minimum (not simultaneous) values of each response parameter are used for design purposes. The design combinations for any relevant cross section are presented in Table 3.3.

Table 3.3 Design combinations for method MF$_{ex}$0

$\max N_{,\alpha 0}$	$\max M_{\xi,\alpha 0}$	$\max M_{\eta,\alpha 0}$
$\max N_{,\alpha 0}$	$\max M_{\xi,\alpha 0}$	$\min M_{\eta,\alpha 0}$
$\max N_{,\alpha 0}$	$\min M_{\xi,\alpha 0}$	$\max M_{\eta,\alpha 0}$
$\max N_{,\alpha 0}$	$\min M_{\xi,\alpha 0}$	$\min M_{\eta,\alpha 0}$
$\min N_{,\alpha 0}$	$\max M_{\xi,\alpha 0}$	$\max M_{\eta,\alpha 0}$
$\min N_{,\alpha 0}$	$\max M_{\xi,\alpha 0}$	$\min M_{\eta,\alpha 0}$
$\min N_{,\alpha 0}$	$\min M_{\xi,\alpha 0}$	$\max M_{\eta,\alpha 0}$
$\min N_{,\alpha 0}$	$\min M_{\xi,\alpha 0}$	$\min M_{\eta,\alpha 0}$

3.4. Method of Maximum Absolute Forces for Angle $\alpha=0^o$ ($MF_{abs}0$)

According to this method the maximum absolute values of the response parameters $N(t)_{,\alpha0}$, $M_\xi(t)_{,\alpha0}$ and $M_\eta(t)$ are used for design purposes. The design combinations for any relevant cross section are presented in Table 3.4.

Table 3.4 Design combinations for method $MF_{abs}0$

$\max\lvert N_{,\alpha0}\rvert$	$\max\lvert M_{\xi,\alpha0}\rvert$	$\max\lvert M_{\eta,\alpha0}\rvert$
$\max\lvert N_{,\alpha0}\rvert$	$\max\lvert M_{\xi,\alpha0}\rvert$	$-\max\lvert M_{\eta,\alpha0}\rvert$
$\max\lvert N_{,\alpha0}\rvert$	$-\max\lvert M_{\xi,\alpha0}\rvert$	$\max\lvert M_{\eta,\alpha0}\rvert$
$\max\lvert N_{,\alpha0}\rvert$	$-\max\lvert M_{\xi,\alpha0}\rvert$	$-\max\lvert M_{\eta,\alpha0}\rvert$
$-\max\lvert N_{,\alpha0}\rvert$	$\max\lvert M_{\xi,\alpha0}\rvert$	$\max\lvert M_{\eta,\alpha0}\rvert$
$-\max\lvert N_{,\alpha0}\rvert$	$\max\lvert M_{\xi,\alpha0}\rvert$	$-\max\lvert M_{\eta,\alpha0}\rvert$
$-\max\lvert N_{,\alpha0}\rvert$	$-\max\lvert M_{\xi,\alpha0}\rvert$	$\max\lvert M_{\eta,\alpha0}\rvert$
$-\max\lvert N_{,\alpha0}\rvert$	$-\max\lvert M_{\xi,\alpha0}\rvert$	$-\max\lvert M_{\eta,\alpha0}\rvert$

3.5. Method of Extreme Stresses (MS_{ex})

According to this method two response history analyses, under bi-directional excitation for incident angles $\alpha=0^o$ (figure 1b) and $\alpha=90^o$ (figure 1c), are performed. The time histories of the response quantities $N(t)_{,\alpha0}$, $M_\xi(t)_{,\alpha0}$ and $M_\eta(t)_{,\alpha0}$, as well as of $N(t)_{,\alpha90}$, $M_\xi(t)_{,\alpha90}$, $M_\eta(t)_{,\alpha90}$ at any relevant cross section are computed. Then, the time histories of the normal stresses ($\sigma_A(t)_{,\alpha0}$, $\sigma_B(t)_{,\alpha0}$, $\sigma_C(t)_{,\alpha0}$, $\sigma_D(t)_{,\alpha0}$ and $\sigma_A(t)_{,\alpha90}$, $\sigma_B(t)_{,\alpha90}$, $\sigma_C(t)_{,\alpha90}$, $\sigma_D(t)_{,\alpha90}$) at the four corners A, B, C and D of a rectangular cross section are calculated. Finally, using Eqns. 2.1, 2.2 and 2.3, the maximum and minimum values of the stresses, the associated critical incident angles θ_{cr1} and θ_{cr2}, as well as the time instant t_{cr} are determined. The sectional forces corresponding to these maximum and minimum values of normal stresses are used for design purposes. The design combinations for any relevant rectangular cross section are presented in Table 3.5.

Table 3.5 Design combinations for method MS_{ex}

$\max\sigma_A$	$N_{,\max\sigma A}$	$M_{\xi,\max\sigma A}$	$M_{\eta,\max\sigma A}$
$\min\sigma_A$	$N_{,\min\sigma A}$	$M_{\xi,\min\sigma A}$	$M_{\eta,\min\sigma A}$
$\max\sigma_B$	$N_{,\max\sigma B}$	$M_{\xi,\max\sigma B}$	$M_{\eta,\max\sigma B}$
$\min\sigma_B$	$N_{,\min\sigma B}$	$M_{\xi,\min\sigma B}$	$M_{\eta,\min\sigma B}$
$\max\sigma_C$	$N_{,\max\sigma C}$	$M_{\xi,\max\sigma C}$	$M_{\eta,\max\sigma C}$
$\min\sigma_C$	$N_{,\min\sigma C}$	$M_{\xi,\min\sigma C}$	$M_{\eta,\min\sigma C}$
$\max\sigma_D$	$N_{,\max\sigma D}$	$M_{\xi,\max\sigma D}$	$M_{\eta,\max\sigma D}$
$\min\sigma_D$	$N_{,\min\sigma D}$	$M_{\xi,\min\sigma D}$	$M_{\eta,\min\sigma D}$

3.6. Method of Extreme Simultaneous Forces (MF_{sim})

According to this method two response history analyses, for incident angles $\alpha=0^o$ (figure 1b) and $\alpha=90^o$ (figure 1c), are performed. The time histories of the response quantities $N(t)_{,\alpha0}$, $M_\xi(t)_{,\alpha0}$ and $M_\eta(t)_{,\alpha0}$, as well as $N(t)_{,\alpha90}$, $M_\xi(t)_{,\alpha90}$, $M_\eta(t)_{,\alpha90}$ at any relevant cross section are computed. Then, using Eqns. 2.1, 2.2 and 2.3, the maximum and minimum values of the aforementioned response quantities, the associated critical incident angles θ_{cr1} and θ_{cr2}, as well as the time instant t_{cr} are calculated. Finally, using Eqn. 2.4, the simultaneous values of the rest response quantities are calculated. The maximum and minimum values of each response parameter and the corresponding simultaneous values of the rest ones are used for design purposes. The design combinations for any relevant cross section are presented in Table 3.6:

Table 3.6 Design combinations for method MF_{sim}

$\max N$	$M_{\xi,\max N}$	$M_{\eta,\max N}$
$\min N$	$M_{\xi,\min N}$	$M_{\eta,\min N}$
$N_{,\max M\xi}$	$\max M_\xi$	$M_{\eta,\max M\xi}$
$N_{,\min M\xi}$	$\min M_\xi$	$M_{\eta,\min M\xi}$
$N_{,\max M\eta}$	$M_{\xi,\max M\eta}$	$\max M_\eta$
$N_{,\min M\eta}$	$M_{\xi,\min M\eta}$	$\min M_\eta$

3.7. Method of Extreme Forces (MF_{ex})

According to this method the maximum and minimum values of the response quantities $N(t_{cr})$, $M_\xi(t_{cr})$ and $M_\eta(t_{cr})$ are calculated using the procedure presented in section 3.6. These maxima and minima can be used for design purposes. The design combinations for any relevant cross section are presented in Table 3.7.

Table 3.7 Design combinations for method MF_{ex}

maxN	$\max M_\xi$	$\max M_\eta$
maxN	$\max M_\xi$	$\min M_\eta$
maxN	$\min M_\xi$	$\max M_\eta$
maxN	$\min M_\xi$	$\min M_\eta$
minN	$\max M_\xi$	$\max M_\eta$
minN	$\max M_\xi$	$\min M_\eta$
minN	$\min M_\xi$	$\max M_\eta$
minN	$\min M_\xi$	$\min M_\eta$

3.8. Method of 30% Rule (M30)

According to this method two response history analyses, for uni-directional inputs $\ddot{u}_{ag}(t)$ and $\ddot{u}_{bg}(t)$ along the structural axes x and y, respectively are performed. The time histories of the response quantities $N(t)_{,xa}$, $M_\xi(t)_{,xa}$ and $M_\eta(t)_{,xa}$, as well as $N(t)_{,yb}$, $M_\xi(t)_{,yb}$, $M_\eta(t)_{,yb}$ at any relevant cross section are computed and their maximum absolute values are determined. Then the 30% directional combination rule is applied. The design combinations for any relevant cross section are presented in Table 3.8.

Table 3.8 Design combinations for method M30

$\max\lvert N_{,xa}\rvert+0.3\max\lvert N_{,yb}\rvert$	$\max\lvert M_{\xi,xa}\rvert+0.3\max\lvert M_{\xi,yb}\rvert$	$\max\lvert M_{\eta,xa}\rvert+0.3\max\lvert M_{\eta,yb}\rvert$
$\max\lvert N_{,xa}\rvert-0.3\max\lvert N_{,yb}\rvert$	$\max\lvert M_{\xi,xa}\rvert-0.3\max\lvert M_{\xi,yb}\rvert$	$\max\lvert M_{\eta,xa}\rvert-0.3\max\lvert M_{\eta,yb}\rvert$
$-\max\lvert N_{,xa}\rvert+0.3\max\lvert N_{,yb}\rvert$	$-\max\lvert M_{\xi,xa}\rvert+0.3\max\lvert M_{\xi,yb}\rvert$	$-\max\lvert M_{\eta,xa}\rvert+0.3\max\lvert M_{\eta,yb}\rvert$
$-\max\lvert N_{,xa}\rvert-0.3\max\lvert N_{,yb}\rvert$	$-\max\lvert M_{\xi,xa}\rvert-0.3\max\lvert M_{\xi,yb}\rvert$	$-\max\lvert M_{\eta,xa}\rvert-0.3\max\lvert M_{\eta,yb}\rvert$
$0.3\max\lvert N_{,xa}\rvert+\max\lvert N_{,yb}\rvert$	$0.3\max\lvert M_{\xi,xa}\rvert+\max\lvert M_{\xi,yb}\rvert$	$0.3\max\lvert M_{\eta,xa}\rvert+\max\lvert M_{\eta,yb}\rvert$
$0.3\max\lvert N_{,xa}\rvert-\max\lvert N_{,yb}\rvert$	$0.3\max\lvert M_{\xi,xa}\rvert-\max\lvert M_{\xi,yb}\rvert$	$0.3\max\lvert M_{\eta,xa}\rvert-\max\lvert M_{\eta,yb}\rvert$
$-0.3\max\lvert N_{,xa}\rvert+\max\lvert N_{,yb}\rvert$	$-0.3\max\lvert M_{\xi,xa}\rvert+\max\lvert M_{\xi,yb}\rvert$	$-0.3\max\lvert M_{\eta,xa}\rvert+\max\lvert M_{\eta,yb}\rvert$
$-0.3\max\lvert N_{,xa}\rvert-\max\lvert N_{,yb}\rvert$	$-0.3\max\lvert M_{\xi,xa}\rvert-\max\lvert M_{\xi,yb}\rvert$	$-0.3\max\lvert M_{\eta,xa}\rvert-\max\lvert M_{\eta,yb}\rvert$

4. APPLICATIONS

A single-storey R/C model building with equal horizontal stiffnesses along the two axes of symmetry x, y is studied (figure 2). The beam and column dimensions, as well as the mass and the material properties are listed in figure 2, where f_c=concrete strength, f_y=yield strength of the reinforcing steel and E_c= the concrete modulus of elasticity. The building was subjected to a set of 15 pairs of horizontal ground motion records (Table 4.1), for which linear time history analyses were conducted. Ground motions were recorded on site class C of FEMA356. The accelerograms were scaled so as to match the elastic spectrum of the Greek Seismic Code according to the procedure suggested in FEMA356. For each ground motion the longitudinal reinforcement steel ratios at every cross section of the building according to EKOS2000 were calculated using the eight methods described in the previous paragraph 3.

The reinforcement steel ratios for every critical cross section of all structural elements under "Loma Prieta" earthquake (Station Number: 58378) are presented in figure 3 (Further results cannot be presented due to space limitations). In order to better quantify the differences among the results produced by the aforementioned eight methods, the relative variation of the method i with regard to method j is defined as:

$$\text{Ratio of relative variation} \quad RV_{i,j} = \frac{A_{s,i} - A_{s,j}}{A_{s,j}} \cdot 100 \tag{4.1}$$

where $A_{s,i}$ *or* ($A_{s,j}$): the required reinforcement area according to method i or (j).

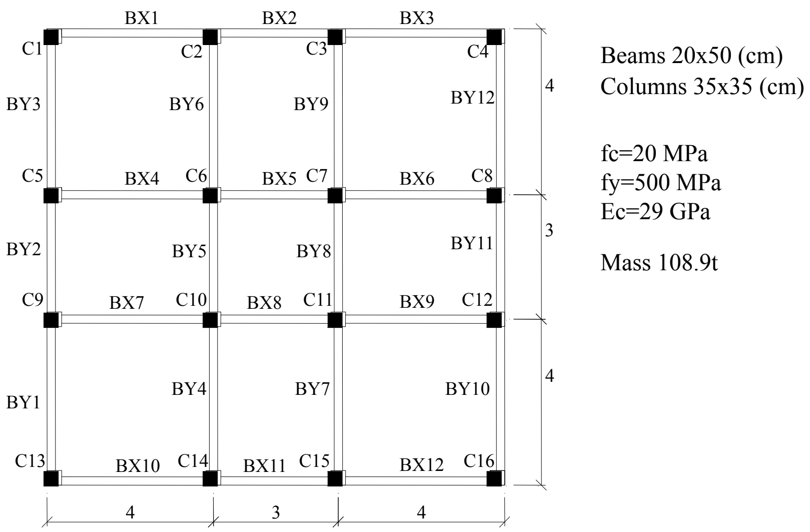

Figure 2 Single-storey symmetric building

Table 4.1 Ground motion records

Date	Earthquake Name	Station Name	Component (deg)	PGA (cm/s^2)	S.F.
15/10/1979	Imperial Valley	5051	315	200.2	1.84
9/2/1971	San Fernando	80053	90	107.9	2.24
9/2/1971	San Fernando	269	21	133.4	2.69
28/6/1992	Landers	12149	0	167.8	1.52
17/10/1989	Loma Prieta	58378	0	153.0	2.36
17/10/1989	Loma Prieta	57383	90	166.9	1.33
17/10/1989	Loma Prieta	58065	0	494.5	0.67
17/10/1989	Loma Prieta	47006	67	349.1	0.52
17/10/1989	Loma Prieta	58135	360	433.1	0.47
17/10/1989	Loma Prieta	58130	90	110.8	2.27
17/10/1989	Loma Prieta	57064	0	121.6	1.86
24/4/1984	Morgan Hill	47006	67	95.0	4.79
17/1/1994	Northridge	23595	90	70.6	3.90
17/1/1994	Northridge	24278	360	504.2	0.50
17/1/1994	Northridge	24271	0	84.9	3.21

The maximum values of the relative variations for all structural elements and ground motions with regard to method MS_{ex} as well as with regard to method $MF_{abs}0$ ($maxRV,_{MSex}$ and $maxRV,_{MFabs0}$ respectively) are presented in Table 5.1. In the same table the average values of the relative variations $RV_{i,j}$ for all structural elements with regard to method MS_{ex} are given as well. The average values were calculated for two cases: (i) when 3 ground motions are considered (Calculation of the maximum values of the reinforcement) and (ii) when 7 ground motions are considered (Calculation of the average values of the reinforcement).

5. CONCLUSIONS

The conclusions derived from the present study are summarized as follows:

- The required reinforcement steel area is significantly affected by the method used to select the design sectional forces in the frame elements. In some structural elements method MF_{ex} led to longitudinal reinforcement which is twice larger than the reinforcement determined by method $MS_{ex}0$ (For example, in column C12 (figure 3) the required reinforcement steel area according to method MF_{ex} is twice larger than the reinforcement steel area determined by method $MS_{ex}0$).

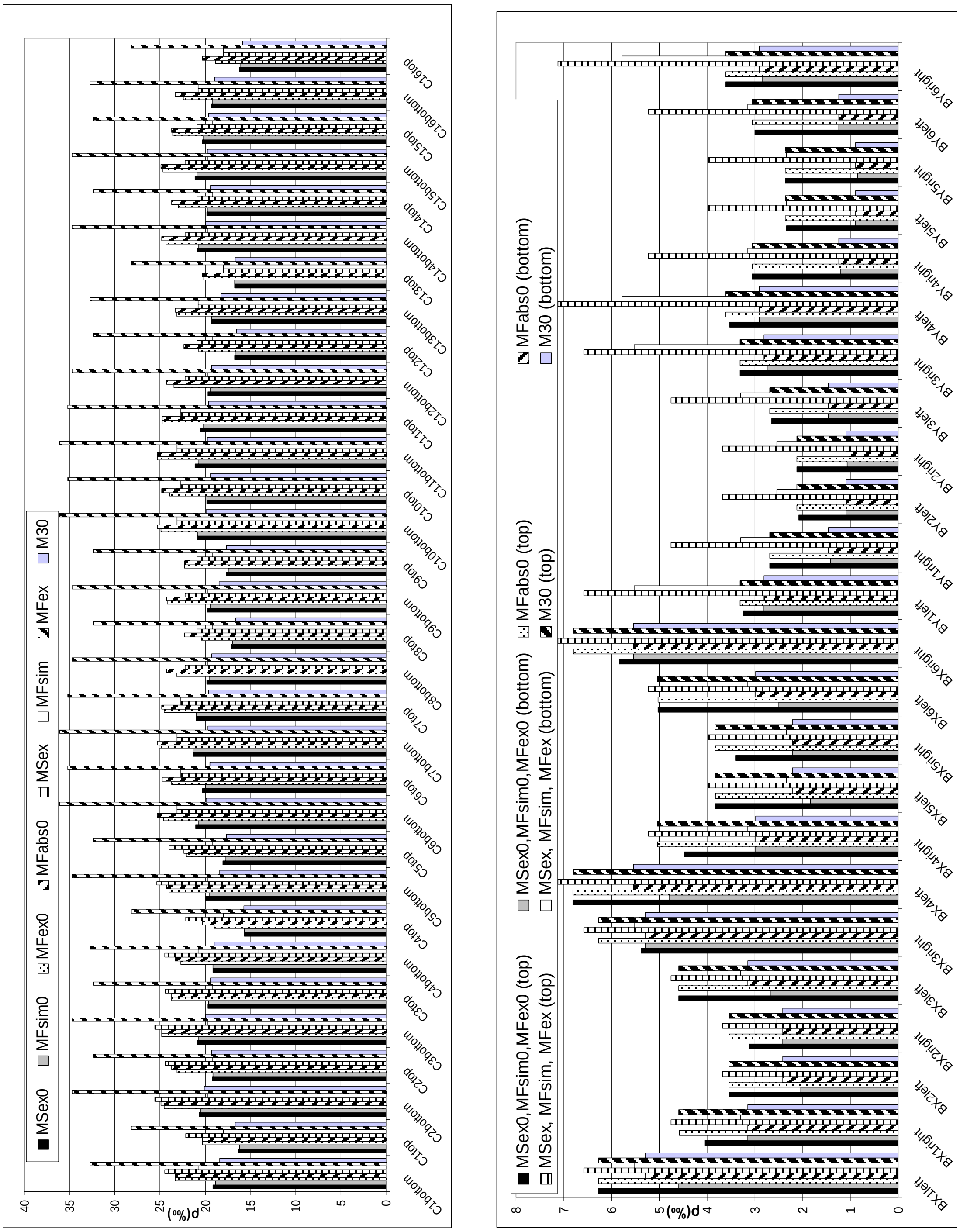

Figure 3 Reinforcement steel ratios for "Loma Prieta" earthquake (Station Number: 58378)

- Methods $MS_{ex}0$, $MF_{sim}0$ and M30 led to the smallest longitudinal reinforcement steel ratios at columns (-29.40%, -29.40%, -30.15% and -37.70%, -37.50%, -38.56% regarding the required reinforcement steel ratios determined by methods MS_{ex} and $MF_{abs}0$ respectively).
- Methods $MF_{ex}0$ and $MF_{abs}0$, which are considered to be the most compatible with current seismic code provisions, led for the columns to larger (+37.50%) and for the beams to smaller reinforcement steel ratios (-78.78%) than the required reinforcement determined by method MS_{ex}.
- Methods which do not take the critical incident angle into account ($MS_{ex}0$, $MF_{sim}0$, $MF_{ex}0$ and $MF_{abs}0$) led to

significantly smaller reinforcement steel ratios in beams than the reinforcement determined by the MS_{ex} (-78.78%).

- The average relative variations RV with regard to method MS_{ex} are not significantly affected by the number (3 or 7) of the ground motions used in analysis (Table 5.1).

It must be pointed out, that the above conclusions are, at present, restricted to the studied building. For generalized conclusions further investigation is needed.

Table 5.1 Maximum variations

Maximum relative variations with regard to method MS_{ex}										
	Columns							Beams		
Method	$MS_{ex}0$	$MF_{sim}0$	$MF_{ex}0$	$MF_{abs}0$	MF_{sim}	MF_{ex}	M30	$MS_{ex}0$, $MF_{sim}0$, $MF_{ex}0$	$MF_{abs}0$	M30
$maxRV,_{MSex}$	-29.40	-29.40	37.51	37.51	-23.20	68.31	-30.15	-78.78	-75.00	-76.31
Maximum relative variations with regard to method $MF_{abs}0$										
Method	$MS_{ex}0$	$MF_{sim}0$	$MF_{ex}0$	MS_{ex}	MF_{sim}	MF_{ex}	M30	$MS_{ex}0$, $MF_{sim}0$, $MF_{ex}0$	MS_{ex}, MF_{sim}, MF_{ex}	M30
$maxRV,_{MFabs0}$	-37.70	-37.50	-12.33	-27.28	-35.30	57.85	-38.56	-29.67	299.90	0.18
Average relative variations RV with regard to method MS_{ex}										
Method	$MS_{ex}0$	$MF_{sim}0$	$MF_{ex}0$	$MF_{abs}0$	MF_{sim}	MF_{ex}	M30	$MS_{ex}0$, $MF_{sim}0$, $MF_{ex}0$	$MF_{abs}0$	M30
3 motions	-17.80	-17.30	-1.63	0.41	-6.52	51.02	-13.71	-31.33	-29.38	-28.00
7 motions	-11.20	-12.11	9.75	12.77	-4.76	55.99	-13.00	-34.63	-29.24	-26.22

REFERENCES

Athanatopoulou, A.M. (2005). Critical orientation of three correlated seismic components. *Engineering Structures* **27:1**, 301-312.

Athanatopoulou, A.M., Tsourekas, A. and Papamanolis, G.. (2005). Variation of response with incident angle under two horizontal correlated seismic components. *Earthquake Resistant Engineering Structures V*, Skiathos, Greece, 183-192.

Athanatopoulou, A.M., Avramidis, I.E. (2006). Effects of seismic directivity on structural response. *The Second fib Congress*, Naples, Italy, paper ID 8-15.

Eurocode 8. (2003). Design of structures for earthquake resistance, Part 1: General Rules, Seismic Actions and Rules for Buildings, European Committee for Standardization.

EKOS 2000. Greek Code for the Design and Construction of Concrete Works, Greek Ministry of Environment, Planning and Public Works, Greece.

EAK 2003. Greek Code for Earthquake Resistant Design of Structures, Ministry of Environment, Planning and Public Works, Greece.

FEMA 274. (1997). Commentary on the guidelines for the seismic rehabilitation of buildings, Federal Emergency Management Agency.

FEMA 356. (2000). Prestandard and commentary for the seismic rehabilitation of buildings, Federal Emergency Management Agency.

FEMA 440. (2004). Improvement of nonlinear static seismic analysis procedures, Federal Emergency Management Agency.

NEHRP (FEMA 450). (2003). Recommended provisions for seismic regulations for new buildings and other structures, Federal Emergency Management Agency.

SAP2000. Integrated Finite Element Analysis and Design of Structures, Computers and Structures, Inc., Berkeley, California, USA.