Some Issues Related to the Inelastic Response of Buildings Under Bi-Directional Excitation

I.-K.M. Fontara, K.G. Kostinakis & A.M. Athanatopoulou
Aristotle University of Thessaloniki, 54124, Greece

SUMMARY:
The present paper investigates the influence of the orientation of the ground-motion reference axes, the seismic incident angle and the seismic intensity level on the inelastic response of asymmetric reinforced concrete buildings. Nonlinear dynamic analyses of a single-storey reinforced concrete building using ten representative bi-directional ground motions are performed for four different intensity levels: i) real seismic intensity, seismic intensity that causes ii) minor, iii) moderate and iv) severe damage. The ground motions are represented by: a) the recorded accelerograms, b) the corresponding uncorrelated accelerograms, and c) the completely correlated accelerograms. In order to examine the influence of the seismic incident angle, the two horizontal accelerograms of each ground motion are applied along horizontal orthogonal axes forming an angle θ=0°, 10°, 20°, …, …, 350° with regard to structural axes. The results show that the inelastic seismic response depends strongly on the above mentioned parameters.

Keywords: bi-directional excitation, seismic incident angle, inelastic response, intensity level, ground-motion reference axes.

1. INTRODUCTION

Structures under strong earthquakes undergo inelastic behaviour. In order to assess seismic performance the most reliable analytical method is non-linear dynamic analysis. This analysis method has been implemented in modern seismic codes (ASCE 41/06, 2009; EC8, 2003). According to this method a 3D mathematical model of the structure is analysed using simultaneously imposed consistent pairs of ground motion along each of the two horizontal structural axes. Most seismic codes do not clarify if the recorded horizontal components of ground motion or the uncorrelated ones should be used as seismic input. Moreover, the orientation of the recorded accelerograms is arbitrary with respect to the orientation of the building under consideration and the recording axes do not coincide with the building's structural axes. Furthermore the principal axes of ground motion do not coincide with the principal axes of the structure.

Several researchers have investigated the influence of seismic incident angle on elastic as well inelastic structural response. Considering the elastic structural response, analytical formulae for the determination of the critical angle of seismic incidence and the corresponding maximum structural response under three correlated seismic components were developed by Athanatopoulou (2005). Considering the inelastic structural response, MacRae and Mattheis (2000) investigated the influence of angle of incidence on the inelastic behaviour of a three-storey steel frame building subjected to near-fault ground motions. They concluded that the building drifts are dependent on reference axes of the structure. Rigato and Medina (2007) investigated the response of asymmetric and symmetric structures with varying degrees of inelasticity and various natural periods of vibration with regard to the angle of seismic incidence. They observed that the critical angle for a given response quantity varies with fundamental period, model type and level of inelastic behaviour. Moreover, Lagaros (2008) investigated the influence of the incident angle on the results of multicomponent incremental dynamic analysis and demonstrated the need to take into account the randomness of incident angle. It is noted that all the above investigations evaluated the structural response by specific response parameters (e.g. story drift, slab rotation) and they did not examine the influence of the orientation of ground-motion reference axes.

The objective of the present paper is to investigate the influence of seismic incident angle on the damage index of an asymmetric single storey r/c building considering the recorded, the uncorrelated and the completely correlated pairs of accelerograms (orientation of ground-motion reference axes). Furthermore, the influence of seismic intensity level on inelastic structural response over all seismic incident angles is investigated. Nonlinear dynamic analyses using ten bi-directional ground motions for many angles of seismic incidence and four seismic intensity levels are performed and the damage index of the structure is computed.

2. CASE STUDY

2.1. Ground motions

2.1.1. Records selection

A suite of ten pairs of horizontal ground motion records (Table 2.1) is obtained from the PEER strong motion database according to magnitude, closest distance to fault rupture and site class. In particular, the ground motions are selected to fall into the following bins: M_s=[5.7, 7.3], R_{rup}=[9.2, 57.4] and recorded on site class D in accordance to FEMA classification.

2.1.2. Ground-motion reference axes

In most strong motion databases the horizontal components of ground motion are given along the orientation they have been recorded. In other words, the orientation of the recording accelerograms is predetermined by the orientation of the recording instrument which is arbitrary with regard to the unknown principal directions of a forthcoming earthquake. Any rotation of the horizontal accelerograms modifies the values of the acceleration ordinates. Therefore, in order to examine any probable orientation of the recording instrument, the present paper takes into consideration three discrete cases of the horizontal accelerograms; the correlated recorded accelerograms, the corresponding uncorrelated accelerograms and the completely correlated accelerograms.

The horizontal accelerograms of a record possess, in general, a random degree of correlation. However, there is a specific set of axes for which the covariance disappears, i.e. the value of the correlation coefficient tends to zero. This set of axes defines the principal axes of the seismic motion along which the accelerograms are considered as uncorrelated. In practice according to Penzien and Watabe model (1975), it is demonstrated that the major principal axis is directed towards the epicenter. The major principal direction is defined with regard to the original orientation by the angle θ_{cr} (Eqn. 2.1) (Fig. 2.1).

$$\tan 2\theta_{cr} = \frac{2 \cdot \sigma_{ij}}{\sigma_{ii} - \sigma_{jj}}$$

$$\sigma_{ij} = \frac{1}{s} \cdot \int_0^s \alpha_i(t) \cdot \alpha_j(t) dt \qquad (2.1)$$

where $\alpha_i(t)$ and $\alpha_j(t)$ are the components in the original (recorded) orientation and s the total duration of the ground motion.

When the correlation coefficient of the horizontal components of the ground motion attains its maximum value, the accelerograms are completely correlated. Completely correlated accelerograms are determined by rotating the uncorrelated accelerograms counterclockwise by an angle θ=45° (Fig. 2.1).

The pairs of the recorded, the uncorrelated and the completely correlated accelerograms are scaled according to the procedure prescribed in ASCE 41-06 so as to match the design spectrum suggested by the Greek Seismic Code.

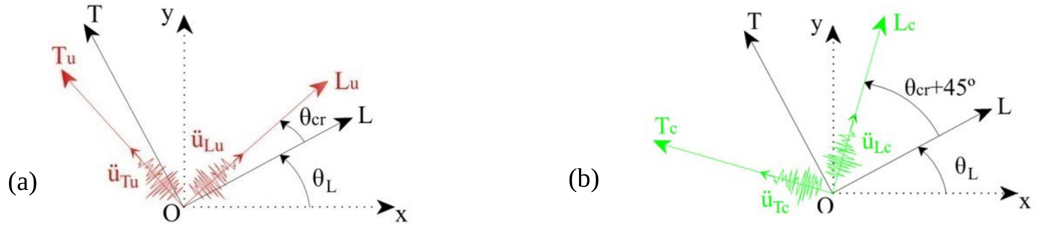


Figure 2.1. (a) Recorded accelerograms along L and T axes and uncorrelated accelerograms along L_u and T_u axes; (b) completely correlated accelerograms along L_c and T_c axes

In Table 2.2 the scale factors corresponding to the recorded, the uncorrelated and the completely correlated accelerograms are presented. In Figure 2.2 the scaled spectra corresponding to the three pairs of the selected ground motions are depicted. Observe that the spectra obtained by the recorded, the uncorrelated and the completely correlated pairs of accelerograms corresponding to the same ground motion are different. Furthermore, we see the great difference among the maximum values of the spectral acceleration corresponding to the three individual pairs of the same ground motion. Moreover we see in Table 2.2 that the scale factors obtained by the recorded, the uncorrelated and the completely correlated components of the same excitation are different.

Table 2.1. Ground motion Records

No	Event	Year	Station Name	Magnitude (Ms)	Closest distance to fault rupture (Km)	Component (deg)
1	Northridge	1994	24303 L.A., Hollywood Storage Bldg.	6.7	25.5	360
						90
2	Northridge	1994	24538 Santa Monica City Hall	6.7	27.6	360
						90
3	Northridge	1994	24087 CDMG Arleta - Nordhoff Fire Sta	6.7	9.2	360
						90
4	Loma Prieta	1989	47381 Gilroy#3, Sewage Treatment Plant	7.1	14.4	0
						90
5	Loma Prieta	1989	58393 Hayward, John Muir School	7.1	57.4	0
						90
6	Loma Prieta	1989	1652 USGS, Aderson Dam (Downstream)	6.9	21.4	270
						360
7	Whittier Narrows	1987	14368 Downey, Country Maintennance	5.7	18.3	180
						270
8	Imperial Valley	1979	5059 El Centro #13, Strobel Residence	6.9	21.9	140
						230
9	San Fernando	1979	135 L. A., Hollywood Storage Bldg.	6.6	21.2	90
						180
10	Landers	1989	23 SCE Coolwater	7.3	21.2	LN
						TR

2.2. Description of investigated building

The single storey reinforced concrete asymmetric building shown in Figure 2.3 is considered in this study. The fundamental period is T=0.3s. The design of the building is performed using the Greek Code for the Design and Construction of Concrete Works on the basis of response values produced by gravity and seismic loads. The seismic analysis is conducted by the response spectrum method using the elastic spectrum suggested by the Greek Seismic Code (EAK) for seismic zone III (0.36g) and site class B, which corresponds to site class D according to FEMA.

Table 2.2. Scale factors obtained by the recorded, the uncorrelated and the completely correlated accelerograms

No	Earthquake	Accelerograms	scale factor
1	Northridge	Recorded	1.56
		Uncorrelated	1.57
		Completely correlated	1.54
2	Northridge	Recorded	2.01
		Uncorrelated	1.25
		Completely correlated	1.35
3	Northridge	Recorded	1.54
		Uncorrelated	1.63
		Completely correlated	1.60
4	Loma Prieta	Recorded	1.00
		Uncorrelated	1.00
		Completely correlated	1.01
5	Loma Prieta	Recorded	2.96
		Uncorrelated	3.08
		Completely correlated	2.92
6	Loma Prieta	Recorded	1.94
		Uncorrelated	2.06
		Completely correlated	1.94
7	Whittier Narrows	Recorded	2.60
		Uncorrelated	2.46
		Completely correlated	2.58
8	Imperial Valley	Recorded	3.58
		Uncorrelated	3.91
		Completely correlated	3.54
9	San Fernando	Recorded	2.88
		Uncorrelated	3.88
		Completely correlated	2.84
10	Landers	Recorded	1.59
		Uncorrelated	1.60
		Completely correlated	1.57

2.3. Nonlinear dynamic analyses

Nonlinear dynamic analyses have been carried out for ten bi-directional ground motions represented by the aforementioned pairs of accelerograms (recorded, uncorrelated and completely correlated). In order to examine the influence of seismic incident angle, the two horizontal accelerograms are applied along horizontal orthogonal axes forming with the structural axes an angle θ=0°, 10°, 20°, …, …, 350°. The nonlinear analyses are performed by the aid of computer program Ruaumoko 3D (Carr, 2004).

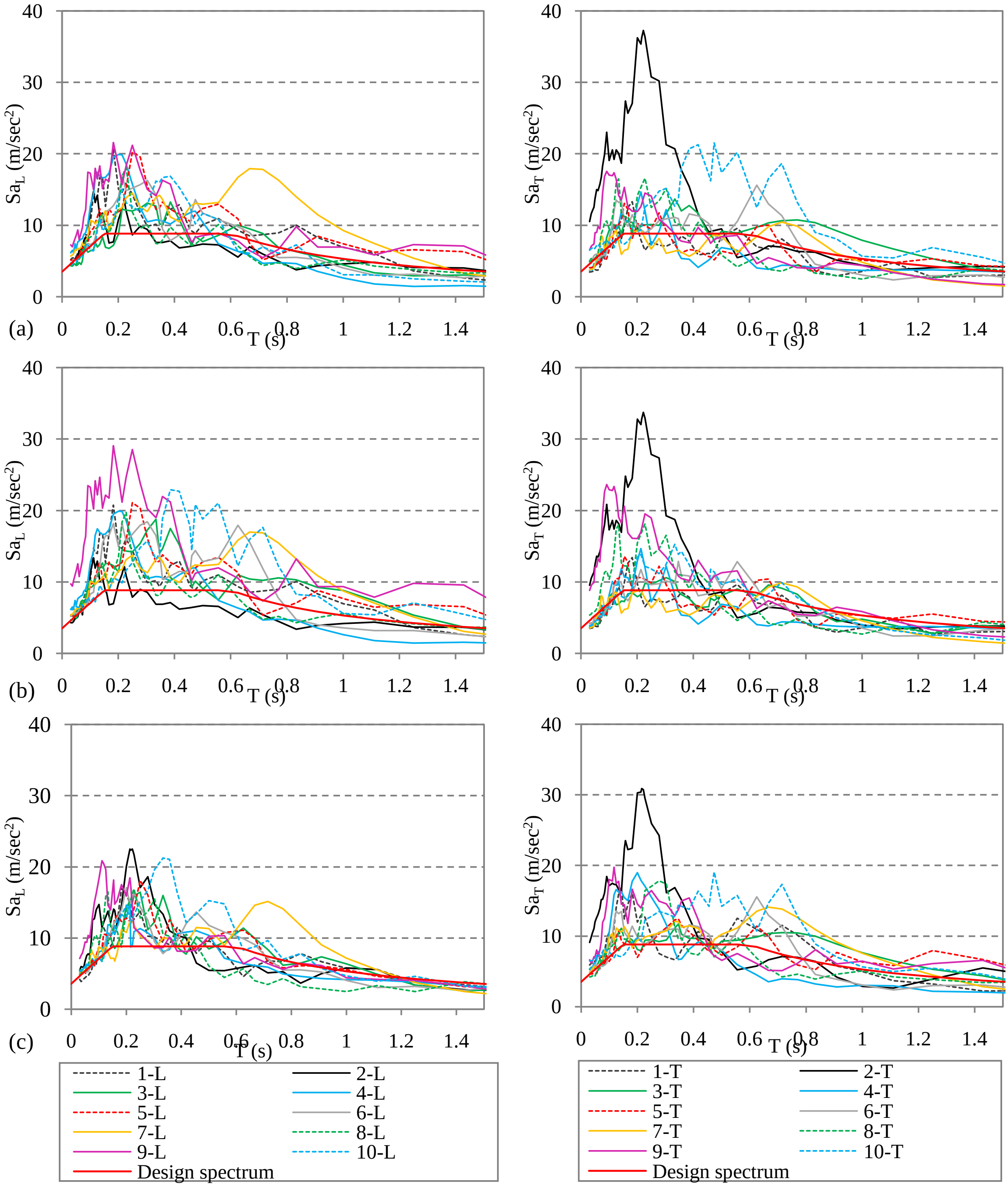


Figure 2.2. Scaled spectra obtained by: (a) the recorded accelerograms (b) the corresponding uncorrelated accelerograms and (c) the corresponding completely correlated accelerograms. Longitudinal (on the left) and transverse (on the right) horizontal component

The evaluation of the inelastic structural response is performed with the aid of damage indices. In general, damage indices estimate quantitatively the degree of seismic damage that a cross-section as well as a whole structure has suffered. A damage index is a quantity with zero value when no damage occurs and equals to 1 when failure or collapse occurs. However, the damage index referring to the whole structure may exceed the value of 1 (Park and Ang, 1985).

In the present paper, the modified Park and Ang (1985) damage index, given by Eqn. 2.2, has been used:

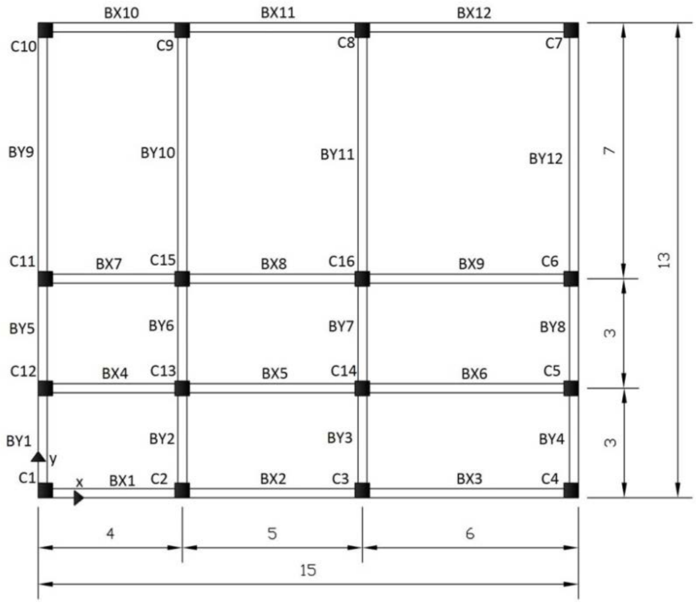
$$DI = \frac{\varphi_m - \varphi_y}{\varphi_u - \varphi_y} + \frac{\beta}{M_y \cdot \varphi_u} \cdot E_T \qquad (2.2)$$

where DI is the local damage index, φ_m the maximum curvature attained during the load history, φ_u the ultimate curvature capacity of the section, φ_y the yield curvature, β a strength degrading parameter, M_y the yield moment of the cross section and E_T the dissipated hysteric energy. Eqn. 2.2 calculates the local damage index (cross-section damage). This research addresses the overall structural damage index (OSDI) computed as the mean value of all local damage indices weighted by the local energy absorptions (Eqn. 2.3).

$$OSDI = \frac{\sum_{i=1}^{n}[DI_{col.weighted,i} \cdot (E_{x,col,i} + E_{y,col,i})] + \sum_{i=1}^{m}[DI_{beam,i} \cdot E_{beam,i}]}{\sum_{i=1}^{n}[E_{x,col,i} + E_{y,col,i}] + \sum_{i=1}^{m} E_{beam,i}} \qquad (2.3)$$

where $DI_{col.weighted,i}$ is the energy weighted average of the column damage indices due to both horizontal components of ground motion, $DI_{beam,i}$ the beam damage index, E the dissipated energy and n, m the number of columns and beams respectively. Since the locations having high damage indices will also be the ones which absorb large amounts of energy, the weighted damage index puts a higher weighting on the more heavily damaged members. Thus, to a first approximation, the weighted damage index reflects the state of the most heavily damaged members.

Nonlinear dynamic analyses are conducted for four different seismic intensity levels: a) seismic intensity that causes minor damage, b) seismic intensity that causes moderate damage, c) seismic intensity that causes severe damage and d) real seismic intensity. The first three classifications are determined on the basis of the value of the maximum overall damage index over all seismic incident angles, denoted in the following for brevity as M_{max}OSDIA. For the above three classifications the values of M_{max}OSDIA range approximately from 0 to 0.25, from 0.25 to 0.70 and from 0.70 to 1.00 respectively. To accomplish the four different seismic intensity levels the three pairs of accelerograms are multiplied by an appropriate factor (SF, Table 2.3).



Columns	40/40(cm)
Beams	25/60(cm)
Height	4m
Mass	178.017t
E	29GPa
C20/25 (f_c=20MPa)	
S500 (f_y=500MPa)	

Figure 2.3. Plan view and geometrical properties of the single storey asymmetric building

2.4. Discussion of results

Table 2.3 presents the M_{max}OSDIA for the four seismic intensity levels caused by the recorded, the uncorrelated and the completely correlated pairs of accelerograms.

Table 2.3. M_{max}OSDIA for the four seismic intensity levels

Number of record	Accelerograms											
	Recorded				Uncorrelated				Completely correlated			
		$SF_{rec.}$	Angle (deg)	D		SF_{un}	Angle (deg)	D		SF_{co}	Angle (deg)	D
1	[a]	0.42	30/40	0.08	[a]	0.42	210	0.07	[a]	0.42	260	0.07
	[b]	0.55	250	0.63	[b]	0.55	230	0.70	[b]	0.55	110	0.61
	[c]	0.70	50	0.89	[c]	0.70	70	0.95	[c]	0.70	290	0.78
	[d]	1.00	170	1.09	[d]	1.00	50	1.06	[d]	1.00	110	1.04
2	[a]	0.15	330	0.14	[a]	0.25	70	0.16	[a]	0.25	120	0.21
	[b]	0.20	140	0.66	[b]	0.30	240	0.65	[b]	0.35	290	0.66
	[c]	0.40	40	0.91	[c]	0.37	300	0.95	[c]	0.65	170	0.87
	[d]	1.00	340	1.38	[d]	1.00	210	1.13	[d]	1.00	320	1.15
3	[a]	0.30	330	0.05	[a]	0.30	260	0.11	[a]	0.30	120	0.08
	[b]	0.35	320	0.44	[b]	0.35	270	0.52	[b]	0.35	130	0.47
	[c]	0.50	340	0.86	[c]	0.50	290	0.93	[c]	0.50	250	0.77
	[d]	1.00	130	1.27	[d]	1.00	260	1.13	[d]	1.00	110	1.12
4	[a]	0.40	330	0.15	[a]	0.40	330	0.15	[a]	0.40	20	0.16
	[b]	1.00	330	0.68	[b]	1.00	160	0.67	[b]	1.00	20	0.68
	[c]	1.40	250	0.87	[c]	1.40	340	0.85	[c]	1.40	30	0.86
	[d]	1.00	330	0.68	[d]	1.00	160	0.67	[d]	1.00	20	0.68
5	[a]	0.30	260	0.12	[a]	0.30	70	0.13	[a]	0.30	120	0.11
	[b]	0.70	90	0.61	[b]	0.70	90	0.64	[b]	0.70	310	0.61
	[c]	1.20	100	0.90	[c]	1.00	90	0.88	[c]	1.20	140	0.99
	[d]	1.00	270	0.88	[d]	1.00	90	0.88	[d]	1.00	130	0.88
6	[a]	0.50	40	0.19	[a]	0.50	180/190	0.20	[a]	0.50	220	0.19
	[b]	0.70	60	0.38	[b]	0.70	190	0.43	[b]	0.70	230	0.38
	[c]	1.00	50	0.68	[c]	1.00	350	0.77	[c]	1.00	230	0.70
	[d]	1.00	50	0.68	[d]	1.00	350	0.77	[d]	1.00	230	0.70
7	[a]	0.40	260	0.13	[a]	0.40	280/290	0.10	[a]	0.40	330	0.13
	[b]	0.90	80	0.70	[b]	0.90	110	0.60	[b]	0.90	150	0.65
	[c]	1.10	240	0.80	[c]	1.10	100	0.78	[c]	1.10	330	0.79
	[d]	1.00	250	0.75	[d]	1.00	120	0.75	[d]	1.00	140	0.75
8	[a]	0.30	80	0.13	[a]	0.30	240	0.22	[a]	0.30	280/290	0.16
	[b]	0.60	30	0.62	[b]	0.60	70	0.68	[b]	0.60	120	0.62
	[c]	0.85	320	0.81	[c]	0.85	240	0.87	[c]	0.85	290	0.78
	[d]	1.00	200	0.98	[d]	1.00	250	1.05	[d]	1.00	300	0.96
9	[a]	1.15	260	0.24	[a]	1.16	280	0.25	[a]	1.14	330	0.24
	[b]	2.02	270	0.63	[b]	1.94	290	0.59	[b]	1.99	70	0.61
	[c]	2.59	270	0.80	[c]	2.72	290	0.79	[c]	2.56	320	0.82
	[d]	2.88	250	0.86	[d]	3.88	80	1.20	[d]	2.84	310	0.92
10	[a]	0.30	110	0.22	[a]	0.30	220	0.22	[a]	0.30	270	0.21
	[b]	0.50	310	0.56	[b]	0.50	70	0.60	[b]	0.50	110	0.56
	[c]	0.70	310	0.85	[c]	0.70	240	0.83	[c]	0.70	100	0.83
	[d]	1.00	140	1.15	[d]	1.00	260	1.18	[d]	1.00	130	1.14

Note that SF_{rec}, SF_{un} and SF_{com} are the appropriate factors by which the recorded, the uncorrelated and the completely correlated accelerograms respectively are multiplied in order to obtain the following four different intensity levels; seismic intensity level that causes: [a] minor damage, [b] moderate damage, [c] severe damage and [d] damage due to real seismic intensity. Figures 2.3, 2.4, 2.5 and 2.6 present the OSDI vs. incident angle for the four levels of seismic intensity under Imperial Valley-No.8 ground motion. The ground motion is represented by the aforementioned three pairs of accelerograms.

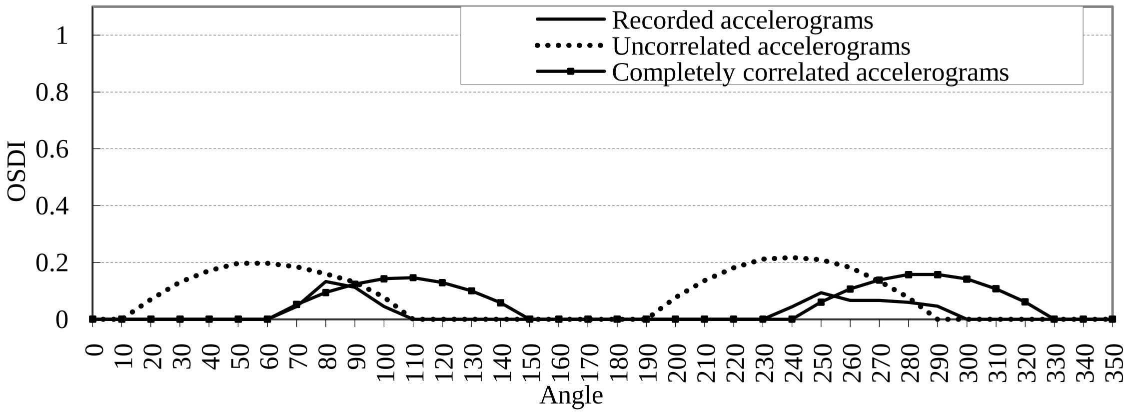


Figure 2.3. The overall damage index vs seismic incident angles for minor structural damage level due to Imperial Valley – No 8 excitation

As can be seen the overall structural damage index depends on the seismic incident angle. For instance, for real seismic intensity some incident angles produce OSDI≈0.55 and some others produce OSDI values up to 1.0. This is true for the three individual pairs of Imperial Valley – No 8 excitation (Fig. 2.6). It is worth mentioning that for the majority of the incident angles the three individual pairs of accelerograms (recorded, uncorrelated and completely correlated) corresponding to the same excitation produce different values of overall structural damage index. Moreover, observe that the critical incident angle (i.e. the angle that yields the maximum damage index) is different for the various seismic intensity levels under the same pair of accelerograms. Moreover it is different for the three pairs of accelerograms corresponding to the same ground motion. As illustrated in Figure 2.4 for the recorded and the completely correlated pairs of accelerograms and for moderate seismic intensity level the angle that causes maximum OSDI is 30° and 120° respectively. However, these orientations cause little damage (OSDI≈0.38 and 0.32 respectively) under the uncorrelated accelerograms.

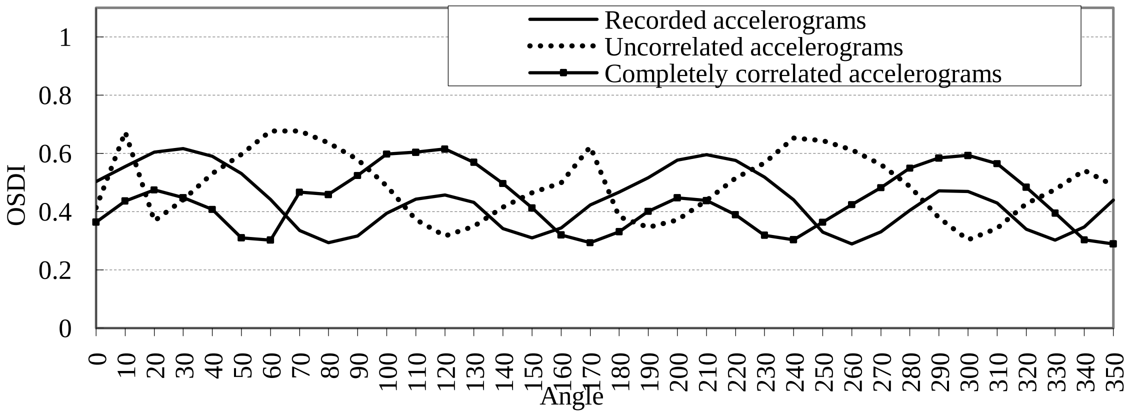


Figure 2.4. The overall damage index vs seismic incident angles for moderate structural damage level due to Imperial Valley – No 8 excitation

Another important observation is that the critical angle does not coincide with the principal axes of the building (incident angles θ=0° and θ=90°).

Also we see that the overall structural damage index depends on the pair of accelerograms used as seismic input. Observe that the M_{max}OSDIA produced by the recorded, the uncorrelated and the completely correlated accelerograms is different (Figs 2.5 and 2.6). Furthermore, note that the three pairs of accelerograms can cause different extent of structural damage for the critical angle of seismic incidence. For example, the values of M_{max}OSDIA for Northridge – No 3 excitation are 0.86, 0.93 and 0.77 for severe damage level under the recorded, the uncorrelated and the completely correlated pairs of accelerograms respectively (Table 2.3). Also the OSDI for severe damage level under the Imperial Valley – No 8 excitation ranges between 0.42 and 0.81 for the recorded, 0.45 and 0.87 for the uncorrelated and from 0.41 to 0.78 for the completely correlated pair of accelerograms (Fig. 2.5).

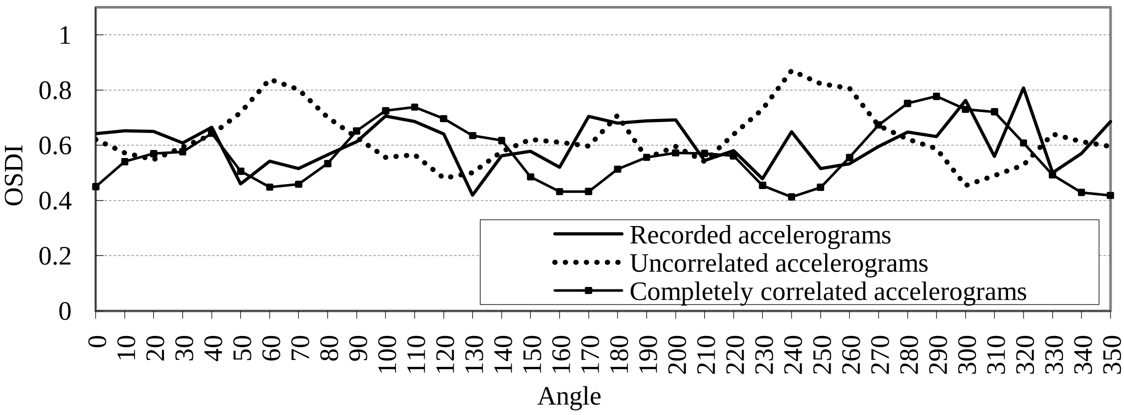


Figure 2.5. The overall damage index vs seismic incident angles for severe structural damage level due to Imperial Valley – No 8 excitation

Moreover, observe that under No 10 excitation for severe damage level the recorded accelerograms cause maximum value of M_{max}OSDIA, while under No 6 excitation the uncorrelated and under No 5 excitation the completely correlated accelerograms cause the maximum value of M_{max}OSDIA (Table 2.3). Under No 5 excitation for moderate damage level the uncorrelated accelerograms cause M_{max}OSDIA while for severe damage level the complete correlated accelerograms cause M_{max}OSDIA. Consequently, any of the three individual pairs of accelerograms considered in this study has the potential to maximize the overall structural damage index. This is true not only for different ground motions but also for different intensity levels of the same ground motion.

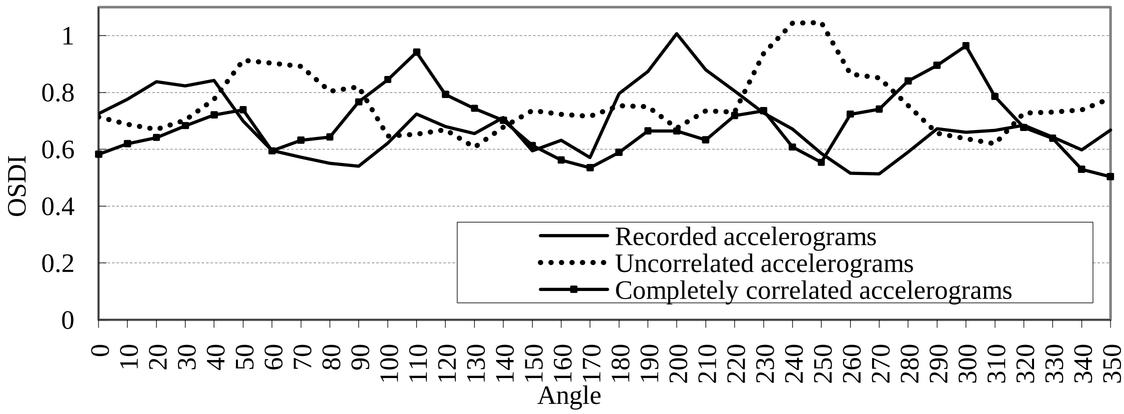


Figure 2.6. The overall damage index vs seismic incident angles for real seismic intensity under Imperial Valley – No 8 excitation

3. CONCLUSIONS

The present paper investigates the influence of the orientation of the ground-motion reference axes, the seismic incident angle and the seismic intensity level on the inelastic response of an asymmetric single storey reinforced concrete building. Nonlinear dynamic analyses under ten representative bi-directional ground motions for four different intensity levels and for many seismic incident angles are performed. The ground motions are represented by: a) the correlated recorded accelerograms, b) the corresponding uncorrelated accelerograms and c) the completely correlated accelerograms. For the examined building and the earthquake records used the following conclusions are drawn:

- The response spectra obtained by the recorded, the uncorrelated and the completely correlated accelerograms corresponding to the same ground motion are different. Therefore the scale factors determined by the recorded, the uncorrelated and the completely correlated accelerograms of the same excitation are different.
- The inelastic seismic response depends on the seismic incident angle as well as the orientation of the ground-motion reference axes.
- The maximum value of the overall structural damage index does not occur when the accelerograms act along the structural axes.
- The incident angle that causes maximum value of the overall damage index varies with the ground motion intensity level.
- The three individual pairs of the same excitation (recorded, uncorrelated and completely correlated) can cause different level of structural damage (different value of OSDI) for the critical angle of seismic incidence.
- Any individual pair of accelerograms (recorded, uncorrelated and completely correlated) has the potential to maximize the overall structural damage index. This is true not only for different ground motions but also for different intensity levels of the same ground motion.

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