Influence of Angle of Incidence in Inelastic Response of an Idealized Single-Story R/C Structural System due to Bi-Directional Ground Motion

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Abstract – *This study examines the influence of angle of incidence in inelastic response of an idealized single-story R/C structural system subjected to bi-directional ground motions. In this work the models have various degree of inelasticity, are subjected to a set of near-fault and far-field ground motion pairs with different characteristics for both the symmetric and asymmetric structural system. It is demonstrated that by applying the bi-directional ground motions only along the principal axis of the building that estimates the critical response of the structural elements due to the variation in any angle of incidence of ground motion in an inelastic sense. The result implies that in accurate estimation of the structural performance by the by the progressive damaging torsional effect in R/C structures. This damaging effect predicted by using the single-storied idealized model that represent the degrading behavior of the R/C load-resisting elements. In this study, the response of flexible and stiff side elements of a structure have been changed due to the variation of critical angle of orientation in an inelastic zone that obtained the maximum critical response in different angles for every 15° interval in anticlockwise sense with the entire 360° orientation of ground motions.*

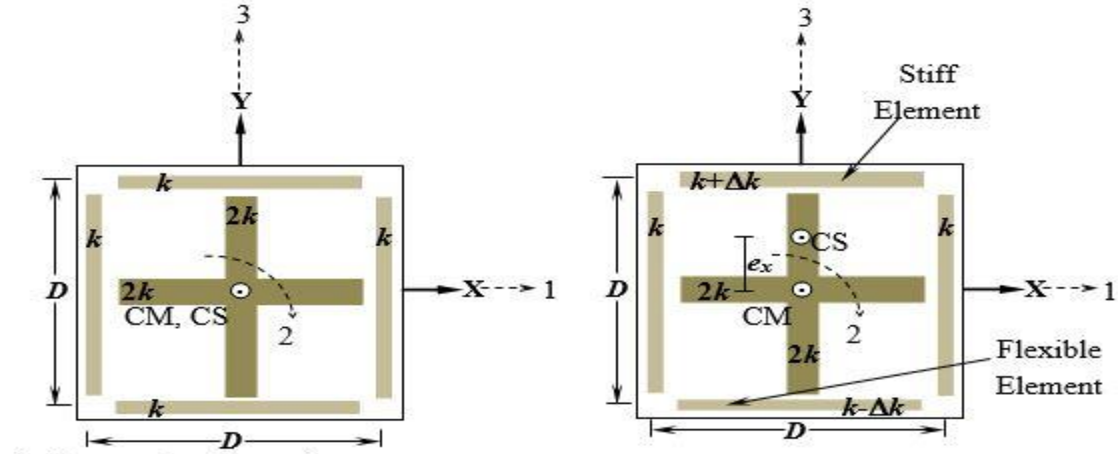
Key Words: **Seismic response, Inelastic response, Near-fault, Far-field, Angle of incidence, Bi-directional, Time period ratio.**

1. INTRODUCTION

The estimation of anticipated seismic damage of structures due to a specific earthquake ground motion is a prime area of research in seismic risk assessment. Generally, buildings are damaged by the dynamic load that destruct the significant life and financial losses. In that case two major requirements that the structural performance and the ground motion intensity initiate to evaluate the structural damage probable of an earthquake. The strong motion database, horizontal directional components of motions are usually applied along the principal axis of structure which are available along orientations of recording for the seismic design of structures. Ground motions deals like a vector formation. It is still unclear that in which particular direction ground motions are attacked on a structure. Therefore, the rotational components are usually neglected whereas the translational parts are given in two horizontal and one vertical direction. Generally, the recording sensors i.e., north-south (N-S) and east-west (E-W) directions are aligned on the principal axis of structure. It implicit the existing of possible different directions of seismic incidence by rotating ground motion pairs. Therefore, this incidence of seismic orientation leads to an increasing the response of structural dynamic. The estimation of maximum seismic response of structure associated to the ground motions excitation using the variation of angle of incidence is already studied by different researcher throughout the globe. One of the valuable investigations into estimated the inelastic response on several engineering demand parameters (EDPs) of single-story asymmetric structural system with the peak inelastic deformation demand due to bi-directional ground excitation displaced that there was not a particular angle of incidence for all maximum EDPs values [1]. Another investigation on a single-story torsionally-stiff symmetric and as well as torsionally-flexible asymmetric system in inelastic response owing to bi-directional near-fault (NF) ground motion makes a critical angle of incidence depending on several engineering demand parameters (EDPs). This study demonstrated that the incidence angle leads maximum displacement of structure depending on fault-normal (FN) and fault-parallel (FP) components of ground motion [2]. Furthermore, the response in nonlinear dynamic analysis of a 3D single-story R/C frames under bi-directional ground motion evaluated that the critical incidence angle of ground motion is more efficient for the design of R/C frame structure [3]. Some researchers [4] have been estimated the response of single-story asymmetric building in inelastic seismic response subjected to bi-directional ground motion demonstrated that the accelerogram while act along the principal axis of the structure, the analysis divulged that the maximum value of damage index does not take place. Also obtained there is not any particular angle of incidence of ground motion that conducts to the maximum values of damage index nevertheless of the seismic intensity level. The significant studies [5] on SDOF system appear to interpret for the near-fault motions that there is no optimum direction for all EDPs at the same time for inelastic behavior. In most of the cases the study is performed by discretizing the structural element finitely. In this backdrop, this study explores to link the idea of angle of incidence under simple bi-directional shaking that achieving the improve estimation of structural response. Using bi-directional approach, each component of a rotated pair applies separately along the principal axes of structure. Due to this application, the observation of response in an inelastic zone is very much critical with the variation of incidence angle. The purpose of this study is to determine the overall response of symmetric and asymmetric structural elements due to bi-directional near-fault (NF) and far-fault (FF) ground motions using the variation of angle of incidence for an inelastic sense. In this way, structural response of an idealized SDOF symmetric and asymmetric systems have been evaluated for the entire 360° orientation of ground motion and presented the critical responses for every 15° interval in anticlockwise sense. The current sagacity in the relevant fields, recognizes the need of conducting bi-directional analysis overall possible incidence angle. The current study requires a considerable computational effort and understanding about the inelastic behavior that interpret of the results derived therefrom are often challenging. The present work also uncovers, for the first time, the existence of a unique orientation where seismic demand caused by bi-directional excitation that estimating the critical response under incidence angle. This has motivated to collectively explore the challenging yet essential issues of seismic demand assessment owing to incidence angle and may be useful for practical purpose. The present study makes some attempt to use a simplified six element systems as discussed in this paper. This simplified model has shear wall type lateral load resisting elements to represent the frames in two principal direction of the building. This shear wall type load resisting elements which actually represented the frame action are not having any capacity of resist in its outer plane action while it can resist the inner plane load. This makes the result very easily understandable and interpretable. With this context the present study is made with the help of a six elements model that is discussed in this following section.

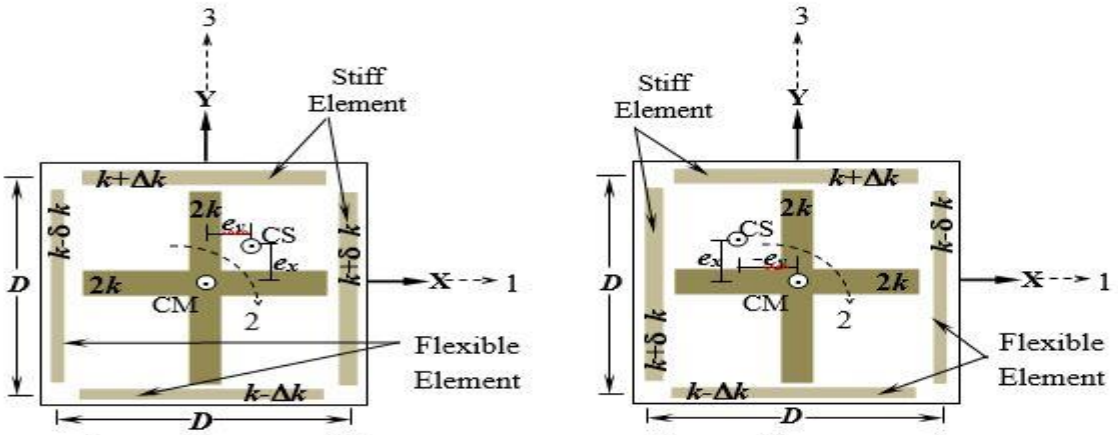
2. IDEALIZED MODEL STRUCTURES

The simplified model even can used to at least to grossly understand the behavior of the effect of angle of incidence. In this study three different type of idealized structural system are represented namely, (a) completely symmetric system, (b) uni-directionally asymmetric system where the asymmetry is caused by the stiffness eccentricity, (c) bi-directionally asymmetric system where the eccentricity is caused by again the stiffness eccentricity. A simplified idealized single-story model as shown in Figure 1 is chosen for analyzing the difference in inelastic response between symmetric and asymmetric buildings influencing incidence angle. The same six-element system was also developed by some researchers in earlier studies [6]. Generally, building structures have load resisting elements scattered over the plan of building. Accepting the same for the purpose of analysis an idealized system of six load resisting elements have been considered with details variation of stiffness distribution. The system has three degrees of freedom and contemplate of a rigid deck supported by three lateral load-resisting structural elements in each of the two translations in two orthogonal directions and one rotational. The frames or walls having strength and stiffness are represented by the lateral load-resisting structural elements in their planes only. The distribution of both the orthogonal directional is perfectly accounted for the reference symmetric system as shown in Figure 1 (a), by assigning stiffness is 2k to the middle element that is 50% of the total stiffness 4k. The remaining 50% is equally distributed between two edge elements thus each of them has stiffness k. For the reference symmetric system, the location of the center of mass (CM) and the center of stiffness (CS) are initially the same. On the other hand, keep in touch on the lateral load resisting edge elements of uni-directionally asymmetric system the eccentricity is initiated by increasing the stiffness of one edge element and decreasing that of the element at the opposite edge by the calculated amount of Δk in case of stiffness eccentric systems as shown in Figure 1 (b). Contrastingly, for the reference asymmetric system the location of the center of mass (CM) initially the same but the center of stiffness (CS) recline at the different eccentric location towards the principal axis of system. The lateral load-resisting edge elements with less stiffness were considered like flexible elements and the opposite edge elements having greater stiffness were represented to as stiff elements. The distance D is same between two extreme lateral load resisting elements in two orthogonal direction. The specific bi-directionally asymmetric system as shown in Figure 1 (c) eccentricity is initiated by increasing the stiffness of one edge element and decreasing that of the element at the opposite edge. The lateral load-resisting edge elements with less stiffness were considered like flexible elements and the opposite edge elements having greater stiffness were represented to as stiff elements. In this system the location of the center of mass (CM) initially the same but the center of stiffness (CS) recline at the different eccentric location. In such bi-directionally asymmetric systems the stiffness eccentricities are symbolized by e_x and e_y that lies between the distance of center of mass (CM) and center of stiffness (CS) with respect to principal axis of system. Distribution of stiffness eccentric condition is balanced for both eccentricities e_x and e_y with the positive sense where center of stiffness (CS) lies in the first quadrant as shown in Fig. 1 (c-i). Another system shows that the negative eccentric sense that is e_x and $-e_y$ where center of stiffness (CS) lies in the second quadrant of the principal axis of the system as shown in Fig. 1 (c-ii). The distance D is same between two extreme lateral load resisting elements in two orthogonal direction. The two possible cases for bi-directionally eccentric system is taken depending on as also found in the previous literature that the combination of eccentricity e_x and eccentricity e_y in different quadrant may alter the result considerably [6]. The stiffness eccentric system is chosen as few literatures in this particular field has only considered asymmetric system for mass eccentricity [6]. Such this study gives an idea about the nature of eccentricity makes any difference or not in the behavior.



a) Symmetric structural system

b) Uni-directionally symmetric structural system



i) e_x positive, e_y positive

ii) e_x positive, e_y negative

c) Bi-directionally asymmetric structural system

Fig. 1. Idealized single-story structural systems.

3. METHODOLOGY

Achieving the specified end to examine the implications of incidence angle, a brief inspection of the variation of important ground characteristics [7, 8] over orientations may appear useful. In this study, the two bi-directional ground motion components for a particular angle of orientation define by an angle relative to the recorded component is calculated by the matrix transformation by (eq. 1.) used also in previous case studies [7, 8].

$$\begin{Bmatrix} a_{x(\psi)}(t) \\ a_{y(\psi)}(t) \end{Bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{Bmatrix} a_x(t) \\ a_y(t) \end{Bmatrix} \qquad \text{....[1]}$$

Where, $a_x(t)$ and $a_y(t)$ represent the recorded ground motion component at the position of accelerograph towards x and y axis. The same transformed ground motions $a_{x(\Psi)}(t)$ and $a_{y(\Psi)}(t)$ are rotated anti-clockwise by an angle Ψ with regard to the accelerograph in x and y direction. Orientation (Ψ) to mention to the issues related to ground motion along, while incidence angle (θ) is used when response of structure is evaluated illustrated in Figure 2. Accelerogram at an incidence angle of θ on the principal axis of structure is same to the accelerogram acting along the principal axis, but with orientation Ψ = θ in general for our determination.

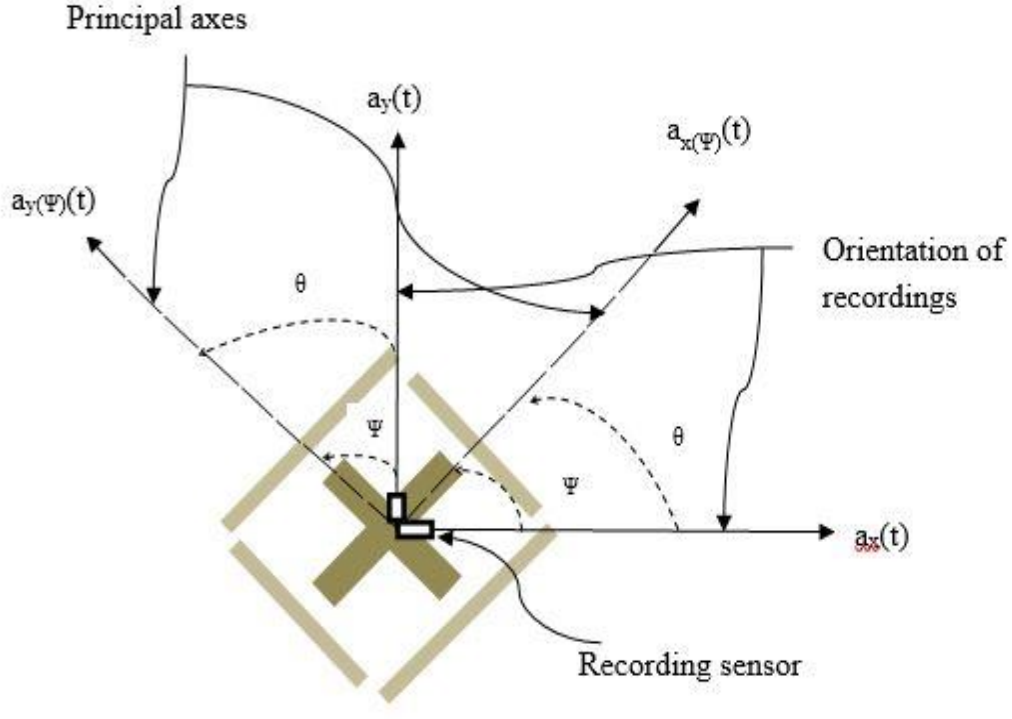


Fig. 2. Correspondence between incidence angle (θ) and orientation of accelerogram (Ψ).

The non-linear equation of motion show in (eq. 2.) is numerically solved in time domain using Newmark's β-γ method and by the by modified Newton-Raphson technique is used for iteration. The Newmark's parameters are chosen as γ = 0.5 and β = 0.25 [6, 10]. Seismosignal V. 5.1.0 – A computer program that constitutes an easy and efficient way for signal processing of strong-motion data [online]; 2018, ed: available from URL: (http://www.seismosoft.com) and by the by added the essential parameters that is moment magnitude, closest site-to-fault-rapture distance, shear wave velocity, mean time period [9]. Using this essential software investigating the ultimate characteristic of ground acceleration motion capacity that has been acted on the structural members.

$$\begin{bmatrix} m & 0 & 0 \\ 0 & mr^2 & 0 \\ 0 & 0 & m \end{bmatrix} \begin{Bmatrix} \ddot{u}_x \\ \ddot{\theta} \\ \ddot{u}_y \end{Bmatrix} + [C] \begin{Bmatrix} \dot{u}_x \\ \dot{\theta} \\ \dot{u}_y \end{Bmatrix} + \{f_s\} = - \begin{bmatrix} m & 0 & 0 \\ 0 & mr^2 & 0 \\ 0 & 0 & m \end{bmatrix} \begin{Bmatrix} \ddot{u}_{gx}(t) \\ 0 \\ \ddot{u}_{gy}(t) \end{Bmatrix} \quad \text{....[2]}$$

Where, r is the radius of gyration of mass of rigid deck; c is damping matrix; u_x, u_y, θ are the translations of the center of mass (CM) along the x and y axis and rotation of CM is horizontal plane respectively and $\ddot{u}_{gx}$ and $\ddot{u}_{gy}$ are ground accelerations along two perpendicular principal axes respectively. For symmetric system the uncoupled torsional effect is negligible.

However, the linear elastic range in

$$\{f_s\} = \begin{bmatrix} 4k & 4ke & 0 \\ 4ke & kD^2 & 0 \\ 0 & 0 & 4k \end{bmatrix} \begin{Bmatrix} u_x \\ \theta \\ u_y \end{Bmatrix} \quad \text{....[3]}$$

4. GROUND MOTION

The two types of synthetic ground motion are used in this present study which are namely near-fault ground motion (NF) and far-field ground motion (FF). Seismic excitations characteristics are realized to depend on the several factors such as magnitude (M_w), distance (r), rupture procedure, travel path from source and local conditions. In this study, we considered a total of thirty ground motions with a range of geophysical parameters that is to say magnitude-distance-soil conditions from Pacific Earthquake Engineering Research Centre 2016 (http://peer.berkeley.edu) to cover a draw up of earthquake scenario of engineering importance. The detail description of the ground motions is shown in Table 1 and Table 2 are representative of near-fault and far-field motions respectively for the purpose of current study analysis.

Near-fault ground motions normally have two components which are one of the components is along the fault and another component is perpendicular to the direction of the fault. This structure existing near the fault irrespective of the principal direction faces the two components whose directions are fixed namely parallel to the fault and perpendicular to the fault. In this context it becomes an important issue to see since the actual direction of the fault difficult to know. However, the orientation of the buildings is made considering the oriented in any direction with respect to the fault. Consequently, this fault normal and fault parallel components generate from the fault movement can adopt the building with any angle of principal of the building. Therefore, the effect of such this variation is needed that buildings with different angle of incidence with respect to the fault parallel and fault normal motions have been studied. Facet of study has been made on this particular aspect however the shake of completeness for the both symmetric and as well as an asymmetric stiffness eccentric system has been studied. The sense in the far-field ground motion instantaneous acceleration vector kept on its direction. It is really very difficult to make any clear-cut conclusion. In spite of the far-field ground motion is used to observe for the variation of angle of incidence. Keeping this mind, the angles are varied with an objective to find out when the maximum response has been obtained with all this parameter.

Table 1: Details of ground motions (NF) used.

Serial no.	Event (Year)	Station	Record ID	Moment magnitude (M_w)	r(km)	Vs30(m/s)	PGA(m/s²)		T_m(s)	
							X - Component	Y - Component	X - Direction	Y- Direction
1	Corinth_ Greece, 1981	Corinth	RSN313	6.6	10.27	361.4	2.32	2.90	0.17	0.14
2	Landers, 1992	Joshua Tree	RSN864	7.3	11.03	379.32	2.68	2.78	0.73	0.78
3	Landers, 1992	Morongo Valley Fire Station	RSN881	7.3	17.36	396.41	2.19	1.61	0.69	0.88
4	Manjil_ Iran,1990	Abbar	RSN1633	7.4	12.55	723.95	5.04	4.87	0.32	0.33
5	Tottori_ Japan,2000	OKY004	RSN3907	6.7	19.72	475.8	8.08	5.28	0.20	0.18
6	Chuetsu-oki_ Japan,2007	Yoshikawaku Joetsu City	RSN4850	6.8	16.86	561.59	4.44	3.08	0.79	0.83
7	Iwate_ Japan,2008	MYG005	RSN5664	6.9	13.47	361.24	5.25	4.37	0.78	1.76
8	Iwate_ Japan,2008	Kurihara City	RSN5818	6.9	12.85	512.26	6.89	4.14	0.39	0.42
9	Chi-chi_Taiwan-03_1999	TCU 129	RSN1023	6.2	10.9	511	9.85	6.12	0.35	0.34
10	Imperial valley-1979	El centro Array#4	RSN179	6.5	7.1	209	4.75	3.63	0.68	1.29
11	Imperial valley-06_1979	El centro Array#6	RSN181	6.5	1.4	203	5.19	3.76	0.66	1.22
12	Imperial valley-06_1979	El centro Array#10	RSN173	6.5	8.6	203	5.19	3.76	0.66	1.22
13	Kocaeli, Turkey_1999	Duzce	RSN1158	7.5	13.5	282	3.06	3.57	0.87	0.50
14	Loma Prieta_1989	Los Gatos - Lexington Dam	RSN3548	6.9	5.5	1070	4.34	4.04	0.89	0.98
15	Denali, Alaska _2002	TAPS Pump Station#10	RSN2114	7.9	2.7	329	3.26	2.92	1.52	1.19

Table 2: Details of ground motions (FF) used.

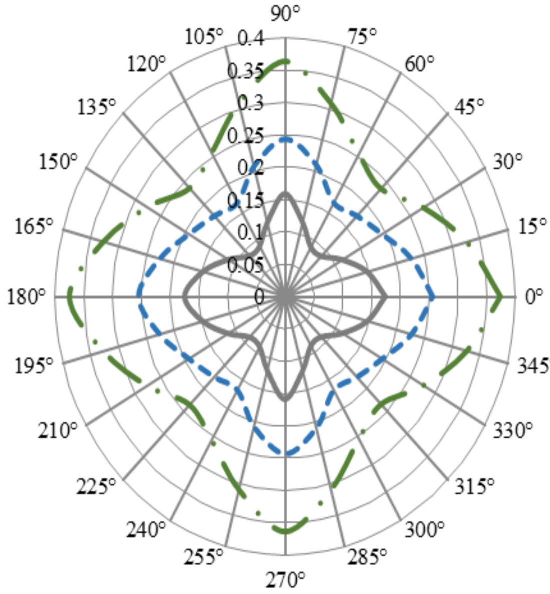
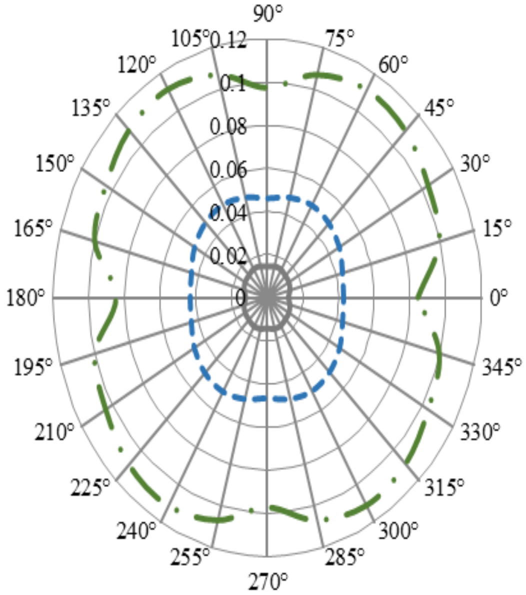
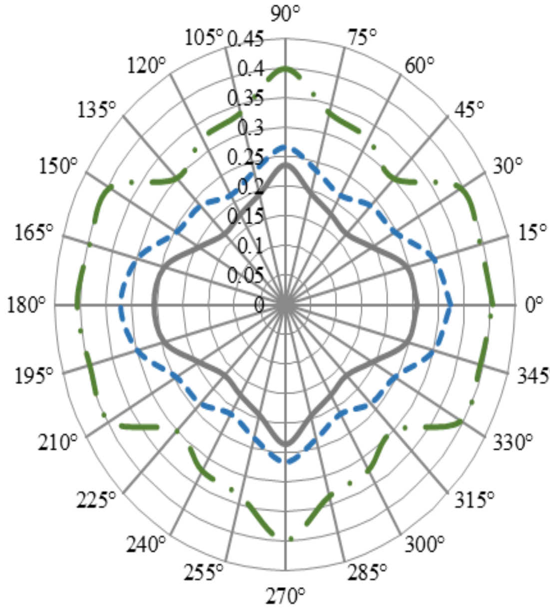
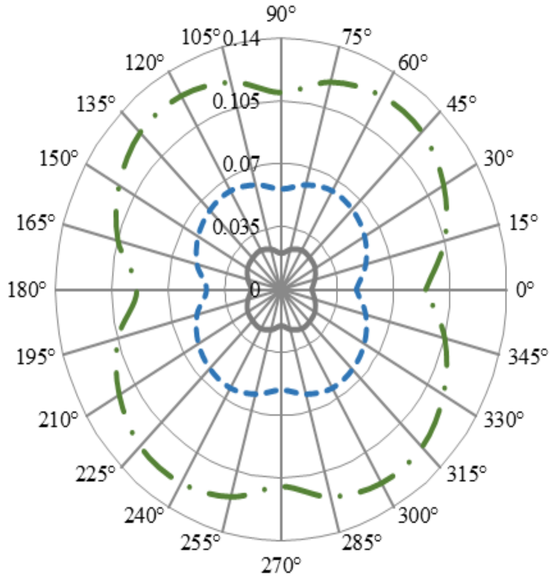
Serial no.	Event (Year)	Station	Record ID	Moment magnitude (M_w)	r(km)	Vs30(m/s)	PGA(m/s^2)		T_m(s)	
							X - Component	Y - Component	X - Direction	Y-Direction
1	Big Bear-01_1992	Featherly Park - Maint	RSN905	6.46	78.91	367.54	0.33	0.37	0.47	0.45
2	Northwest China-01_1997	Jiashi	RSN1748	5.9	24.06	240.09	2.68	2.29	0.22	0.34
3	Northwest China-01_1997	Xiker	RSN1749	5.9	52.36	341.56	0.35	0.43	0.27	0.24
4	Northwest China-02_1997	Jiashi	RSN1750	5.93	37.26	240.09	1.22	1.41	0.33	0.31
5	Northwest China-02_1997	Xiker	RSN1751	5.93	46.24	341.56	0.70	0.73	0.28	0.26
5	Northwest China-03_1997	Jiashi	RSN1752	6.1	17.73	240.09	2.94	2.68	0.36	0.54
7	Northwest China-04_1997	Jiashi	RSN1754	5.8	27.86	240.09	1.84	2.34	0.29	0.36
8	Northwest China-04_1997	Xiker	RSN1755	5.8	40	341.56	1.32	0.82	0.39	0.26
9	Kozani_ Greece-01_1995	Kozani	RSN1126	6.4	19.54	649.67	2.03	1.37	0.28	0.26
10	Hector Mine_ 1999	Anza - Pinyon Flat	RSN1763	7.13	89.98	724.89	0.35	0.26	0.59	0.26
11	Tottori_ Japan_ 2000	SMNH04	RSN3950	6.61	74.62	284.59	0.79	0.80	1.00	1.00
12	Tottori_ Japan_ 2000	SMNH13	RSN3957	6.61	96.93	650	0.55	0.71	1.00	1.00
13	FtPayne_2003	Sewanee	RSN963	4.62	85.04	720	0.03	0.06	0.11	0.10
14	RiviereDuLoup_2005	Presque Isle_ ME	RSN1794	4.65	176.32	665.9	0.12	0.08	0.27	0.22
15	ValDesBois_2010	Pembroke_ ON	RSN4039	5.1	138.29	591	0.18	0.24	0.11	0.11

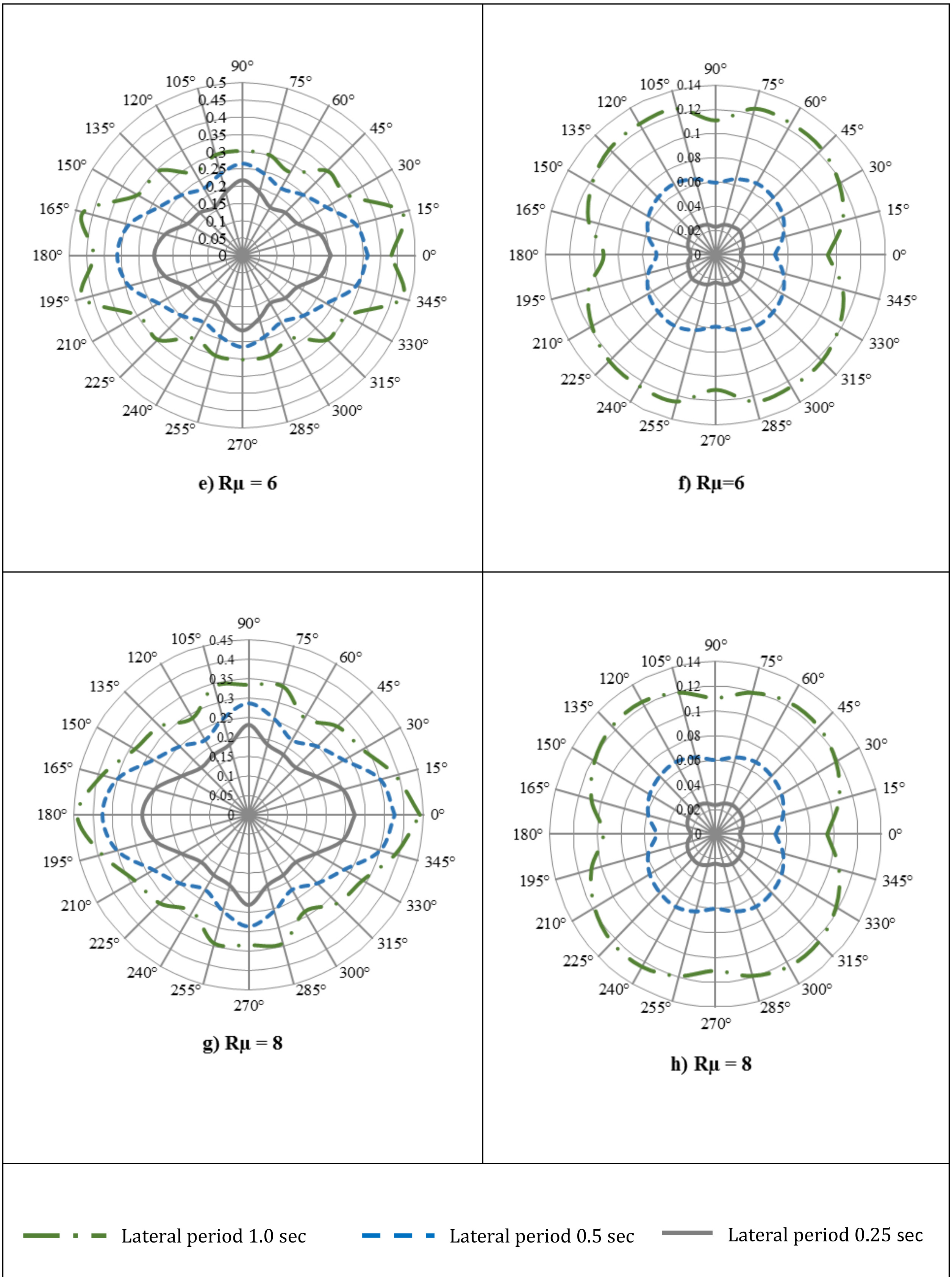
5. SYSTEM PARAMETERS

The variation of maximum displacement response may be influenced by several systems parameters as well as loading considered for valuable conclusions. The primarily considerable two dynamic control parameters namely the lateral natural period (T_x) and the uncoupled torsional-to-lateral period ratio (τ). This lateral periods (T_x) considered for this analysis are 0.25 sec, 0.5 sec and 1.0 sec in short, medium and long period ranges for both symmetric and asymmetric structural systems respectively. On the other hand, for most of the real buildings the values of uncoupled torsional-to-lateral period ratio (τ) are varied within the range of 0.25-2.0 with an interval of 0.05 also used in previous research [6, 10]. Influence the torsional effect for asymmetric system eccentricity is important criteria to observe the critical response of structural elements. Further, the present study attempts to incorporate the analysis of the uni-directional and bi-directional asymmetric system in a feasible range of eccentric variation. In this case study, the three typical eccentric parameters of this system are classified in terms of small, intermediate and large eccentric system as represented as $e/D = 0.05$, 0.1 and 0.2 used in previous literature [6, 10]. Asymmetric systems with stiffness eccentricities is considered only in this present study. The four different values of ductility reduction factor (R_μ) = 1, 4, 6 and 8 are chosen only for symmetric structure whereas standard reduction factor $R_\mu = 4$ select for asymmetric system only. These values are highly recommended from the different codes such as ASCE 7-05 [12] and NEHRP [11].

6. RESULTS AND DISCUSSION

The maximum normalized displacement response is computed and suitably presented for the corners elements as these corner elements are more vulnerable owing to lateral and torsional coupling in asymmetric structure, whereas for symmetric system the response is presented in overall elemental deformation without torsional coupling with critical incidence angle for X and Y directional element. The computation is carried out for three lateral periods like T = 0.25, 0.5 and 1.0 sec are reported for both systems. Fig. [3, 4] represented the normalized maximum displacement response for symmetric system with the variation of different lateral time respect to the response reduction factor (R_μ) = 1, 4, 6, 8 subjected to NF and FF ground motion excitation. On the other hand, also maximum normalized energy dissipation response for symmetric system is shown Fig. [5, 6] with the variation of reduction factor (R_μ) = 1, 4, 6, 8 by different lateral periods subjected to NF and FF ground motion excitation. Results for symmetric system with the variation of angle of incidence of ground motion are shown with different angle of orientation reported in X and Y directional load resisting elements respectively. To gain additional insight, response under bidirectional component is computed for θ varying over 0-360° at an interval of 15°. On the other scenario, maximum normalized displacement response for asymmetric system on unidirectional show in Fig. [7-12] and bidirectional show in Fig. [13-15] eccentric condition is clearly represented with the variation of lateral period where standard reduction factor (R_μ) = 4 considered. In this case, DSPFLX, DSPFLY represent the displacement at flexible side elements in X and Y direction and DSPSTX and DSPSTY represent the displacement at stiff side elements in X and Y direction respectively.

X- Directional Element	Y- Directional Element
 a) Rµ = 1	 b) Rµ = 1
 c) Rµ = 4	 d) Rµ = 4



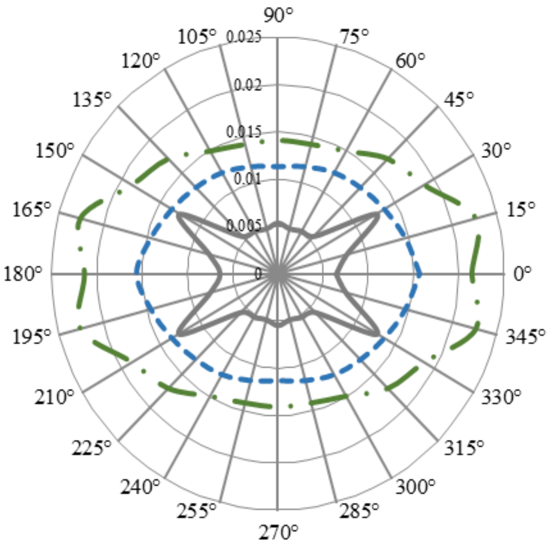
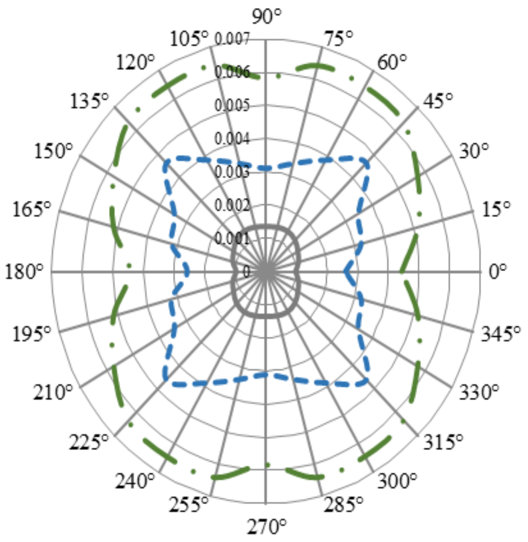
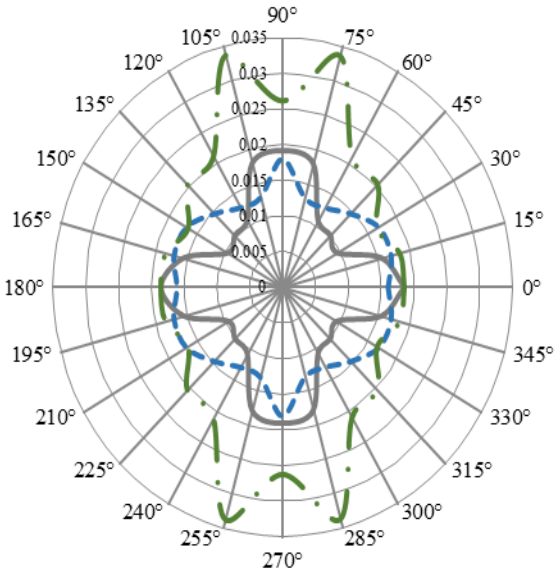
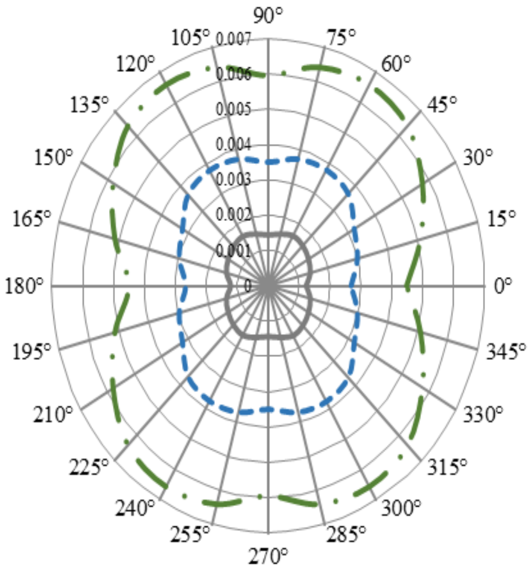
e) Rμ = 6

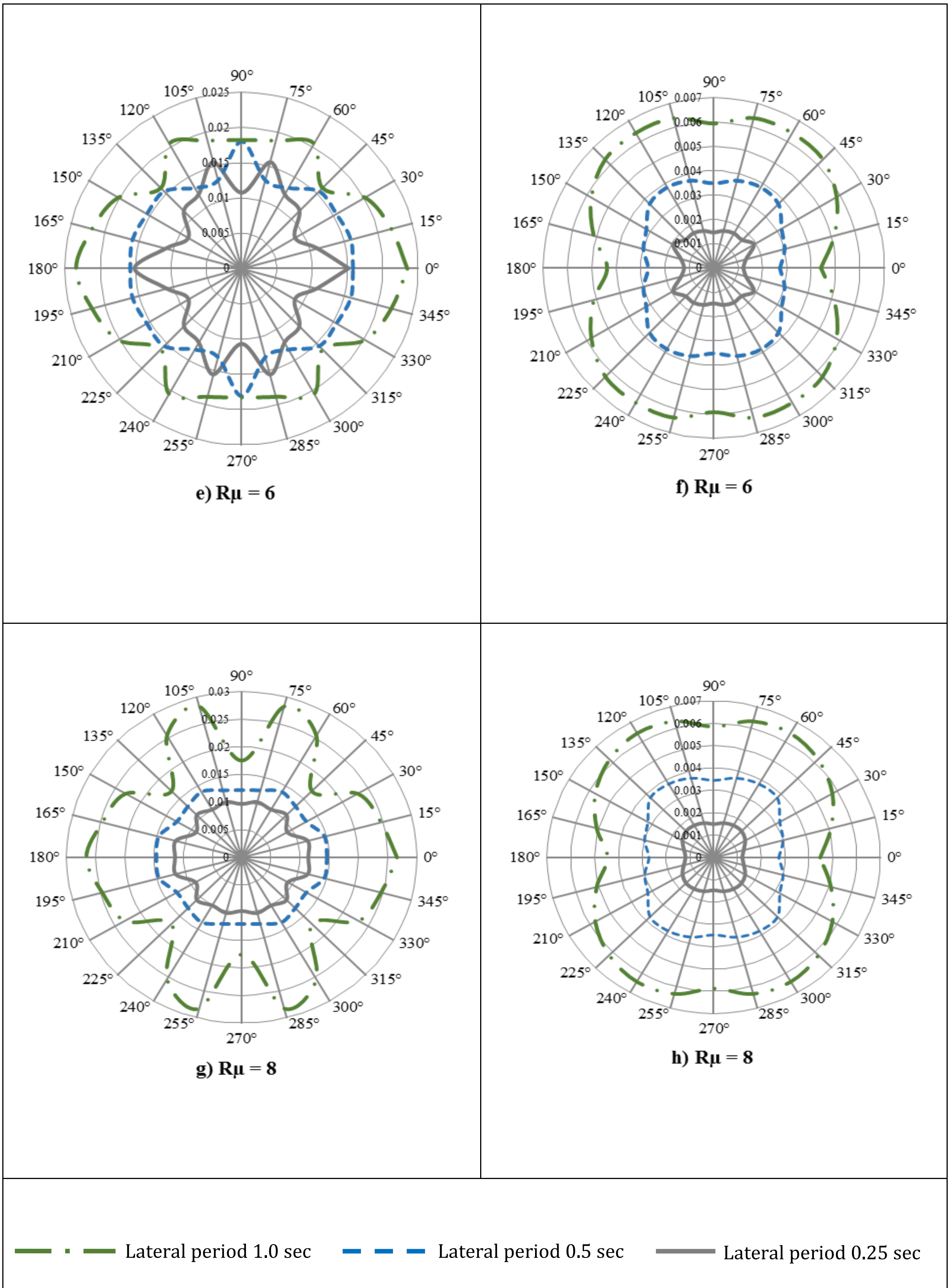
f) Rμ=6

g) Rμ = 8

h) Rμ = 8

Fig. 3. Normalized maximum displacement response for symmetric system due to NF ground motions.

X- Directional Element	Y- Directional Element
 a) $R\mu = 1$	 b) $R\mu = 1$
 c) $R\mu = 4$	 d) $R\mu = 4$



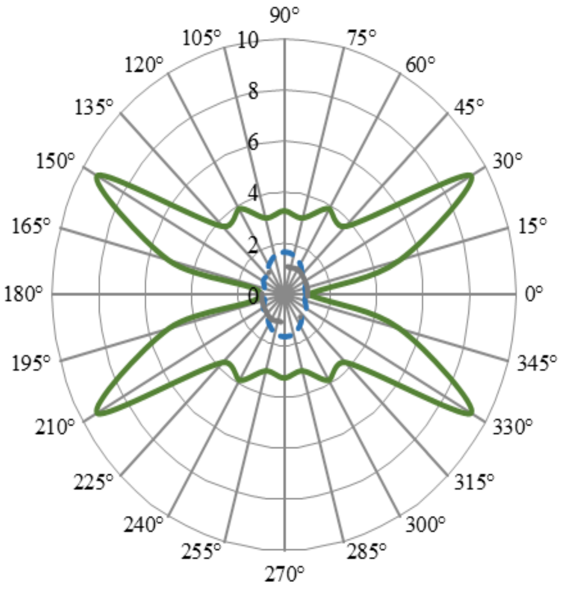
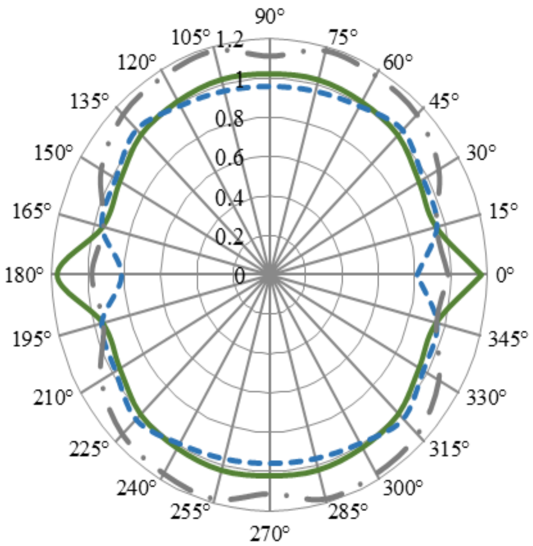
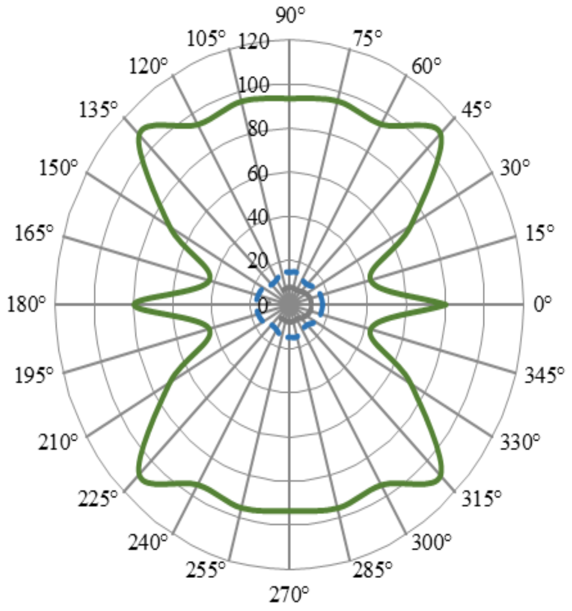
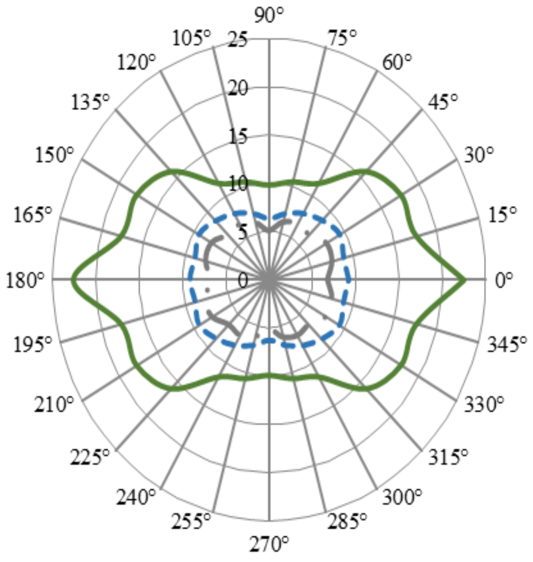
e) Rμ = 6

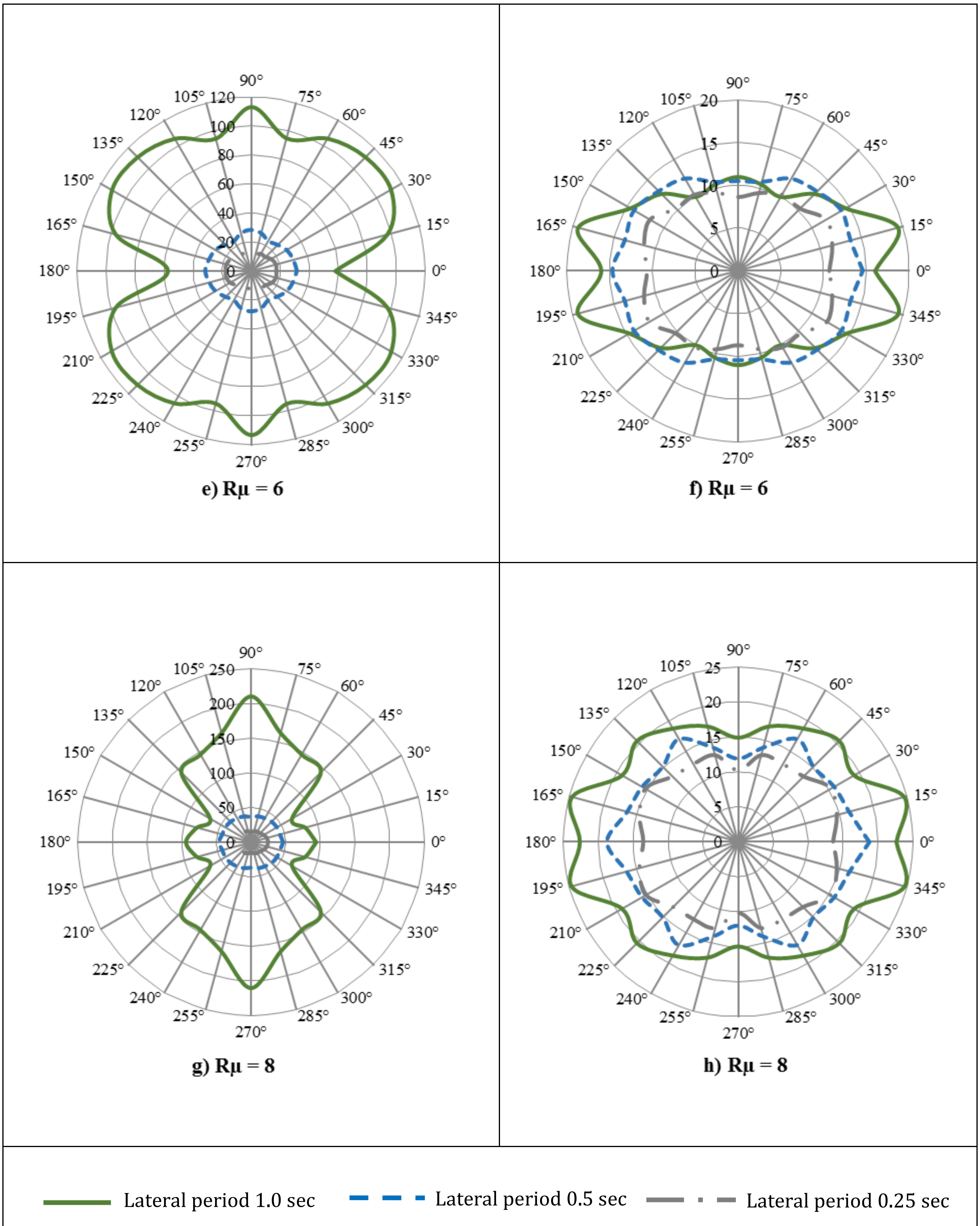
f) Rμ = 6

g) Rμ = 8

h) Rμ = 8

Fig. 4. Normalized maximum displacement response for symmetric system due to FF ground motions.

X- Directional Element	**Y- Directional Element**
 a) Rμ = 1	 b) Rμ = 1
 c) Rμ = 4	 d) Rμ = 4



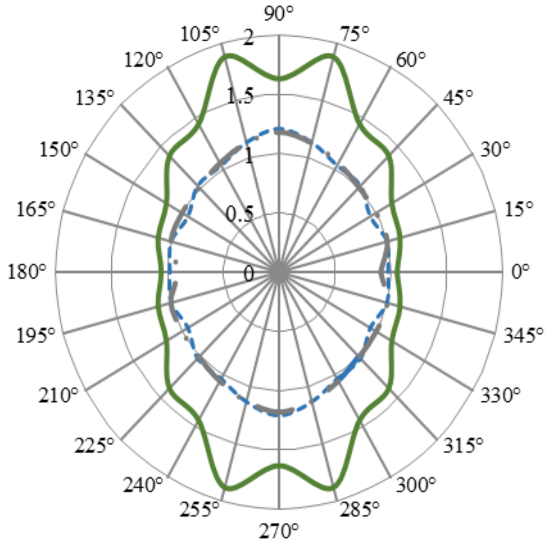
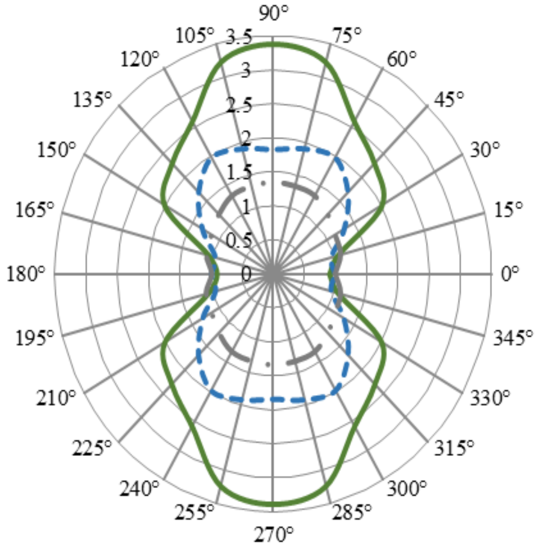
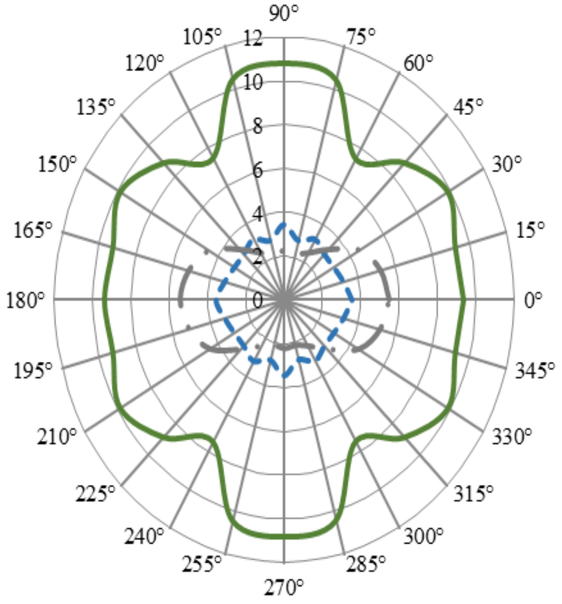
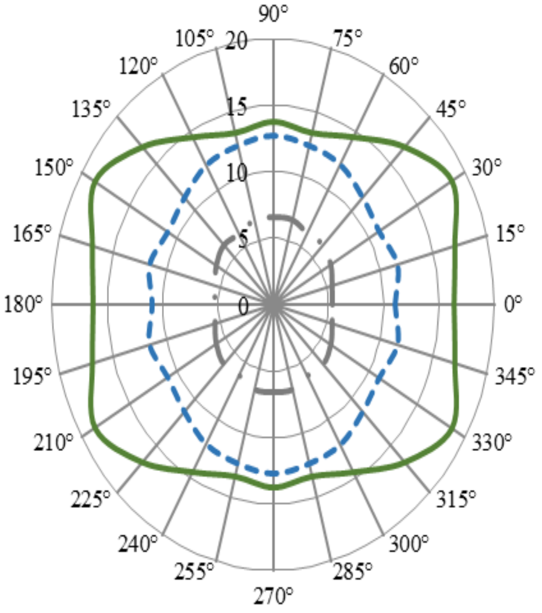
e) Rμ = 6

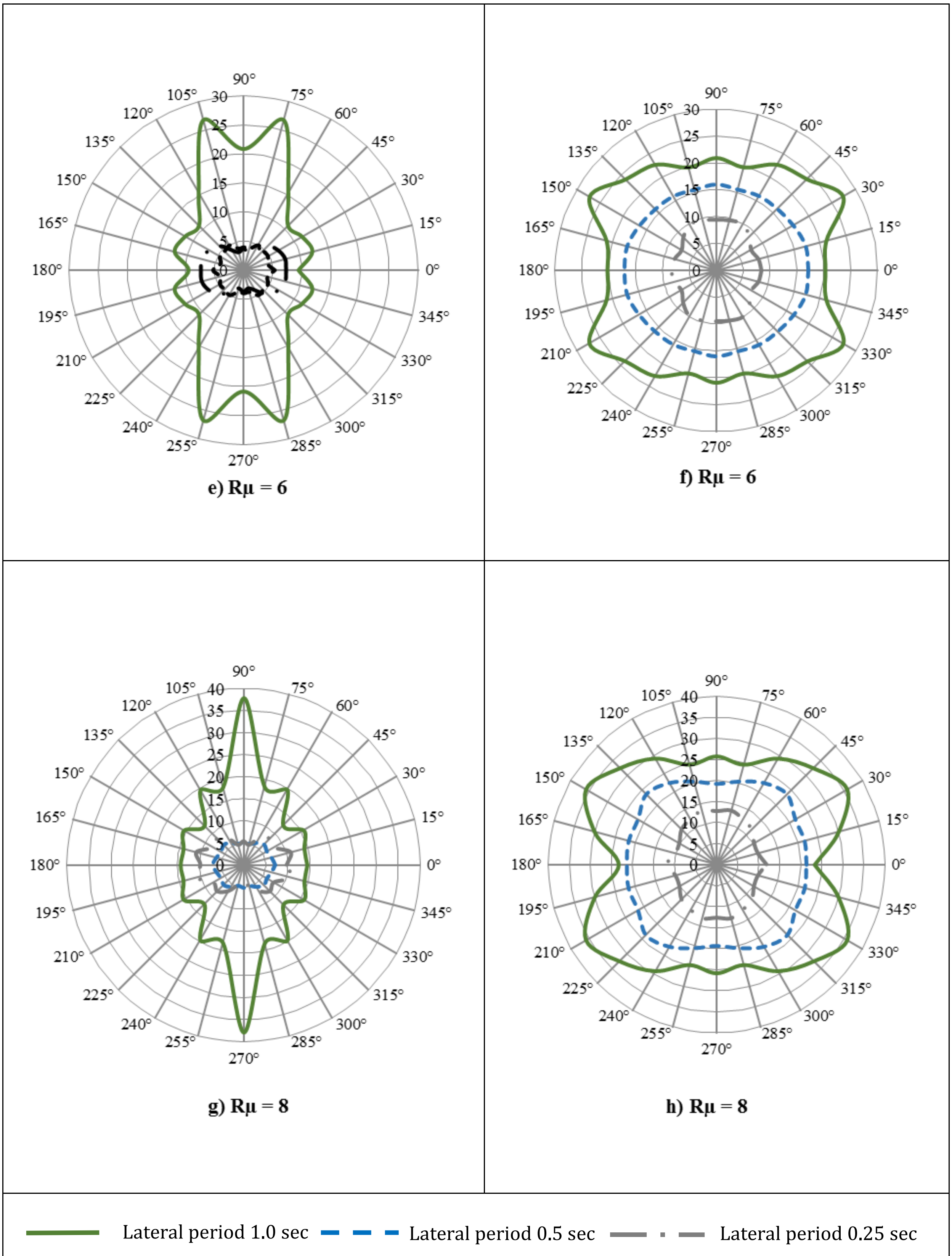
f) Rμ = 6

g) Rμ = 8

h) Rμ = 8

Fig. 5. Maximum normalized energy dissipation response for symmetric system due to NF ground motions.

X- Directional Element	**Y- Directional Element**
 a) Rμ = 1	 b) Rμ = 1
 c) Rμ = 4	 d) Rμ = 4



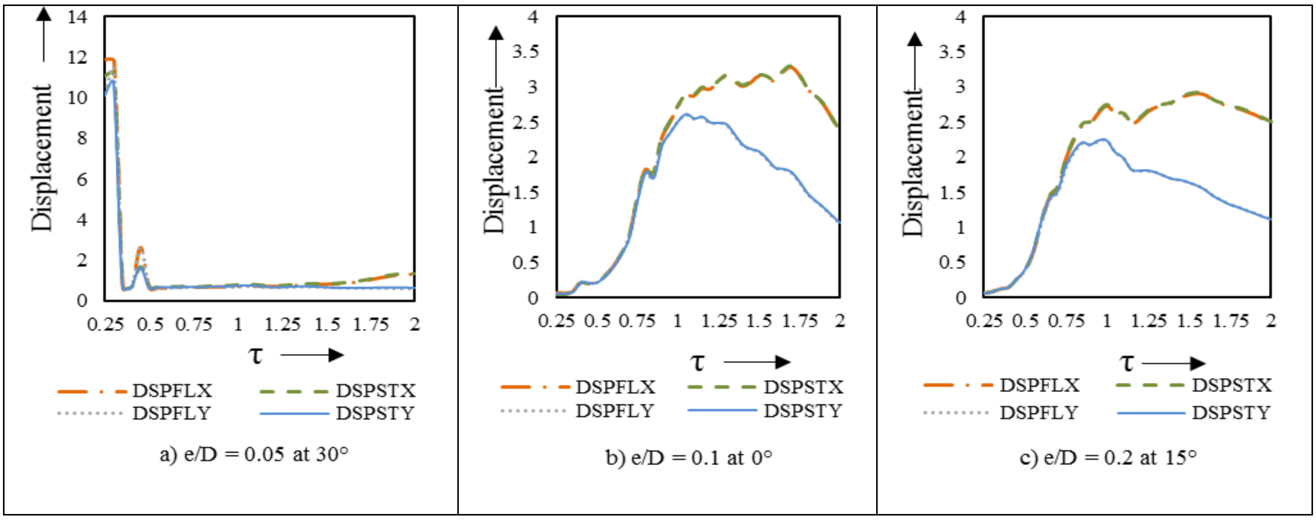
e) Rμ = 6

f) Rμ = 6

g) Rμ = 8

h) Rμ = 8

Fig. 6. Maximum normalized energy dissipation response for symmetric system due to FF ground motions.

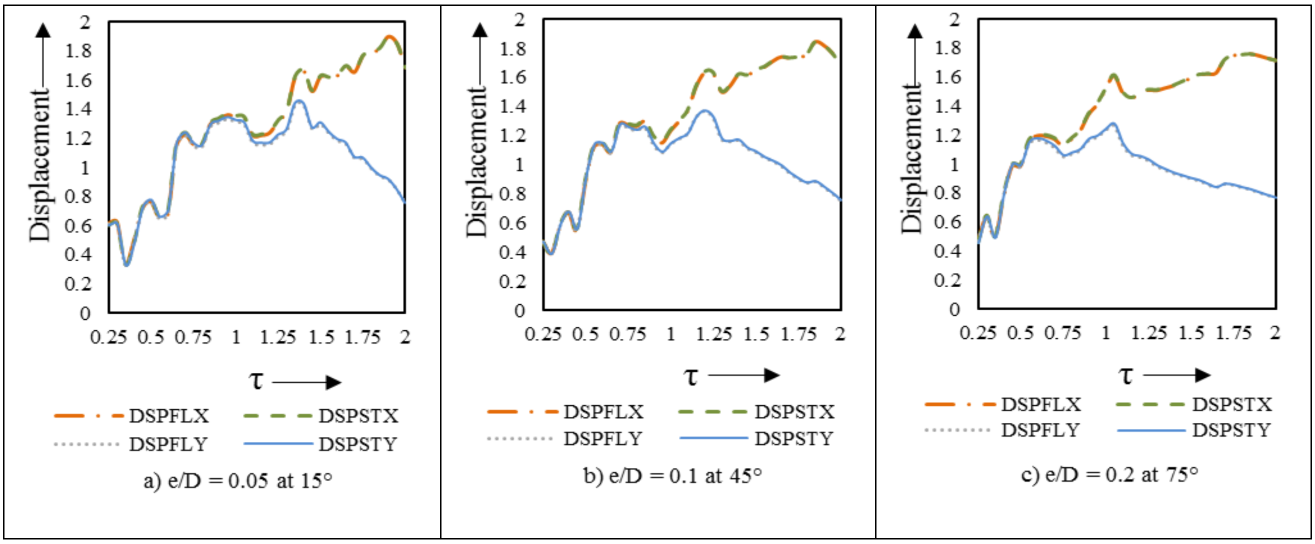


a) e/D = 0.05 at 30°

b) e/D = 0.1 at 0°

c) e/D = 0.2 at 15°

Fig.7. Maximum normalized displacement response for uni-directional eccentricity due to NF motion when lateral period 0.25 sec and Rμ = 4.

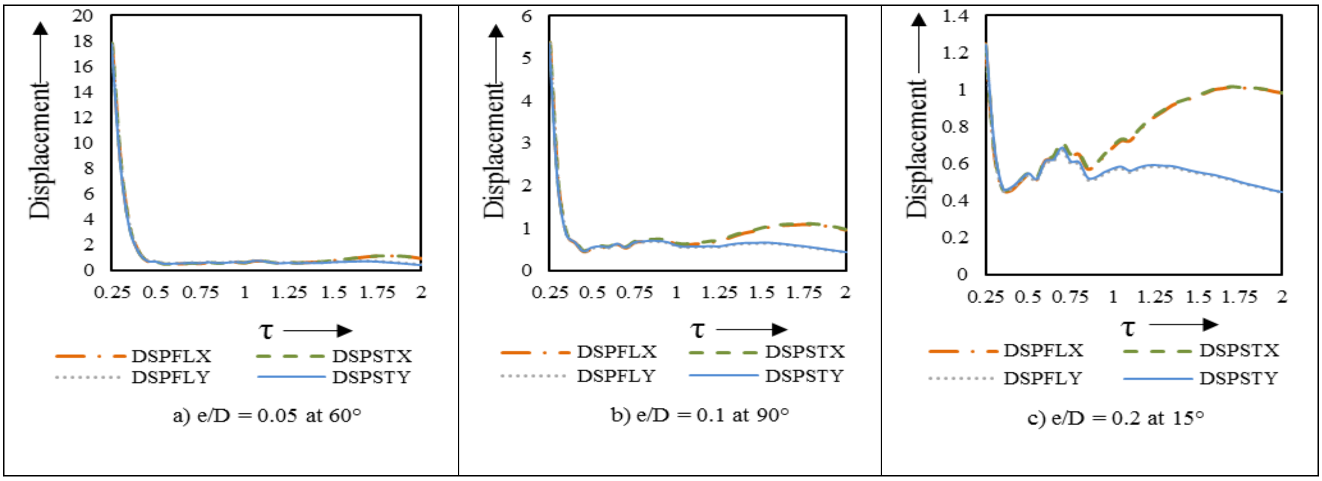


a) e/D = 0.05 at 15°

b) e/D = 0.1 at 45°

c) e/D = 0.2 at 75°

Fig.8. Maximum normalized displacement response for uni-directional eccentricity due to NF motion when lateral period 0.5 sec and Rμ = 4.

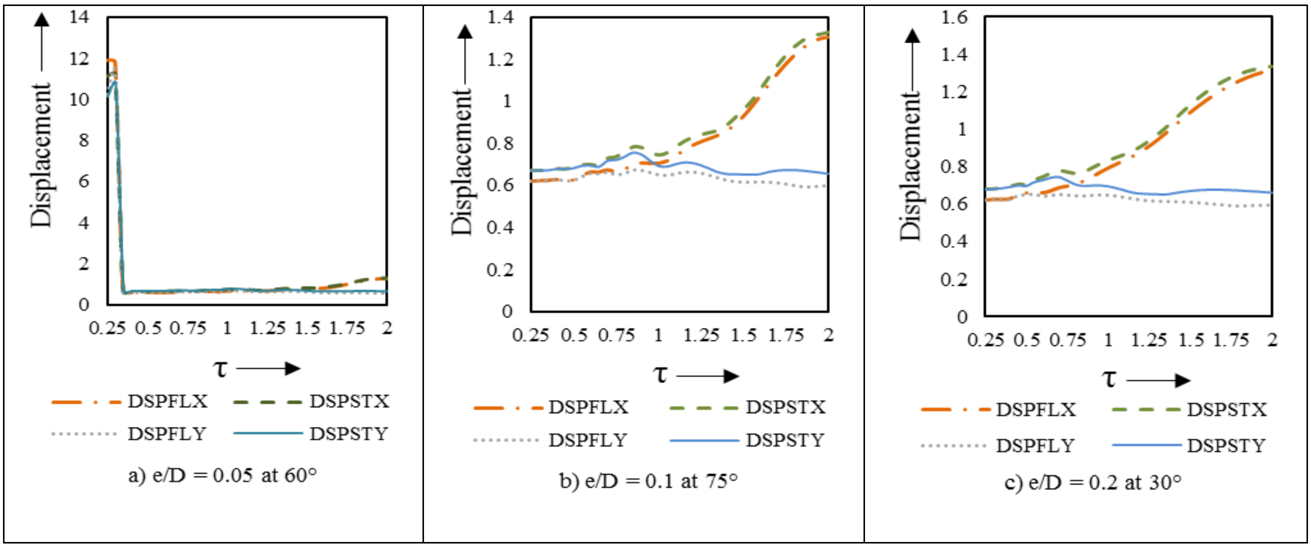


a) e/D = 0.05 at 60°

b) e/D = 0.1 at 90°

c) e/D = 0.2 at 15°

Fig.9. Maximum normalized displacement response for uni-directional eccentricity due to NF motion when lateral period 1.0 sec and Rμ = 4.

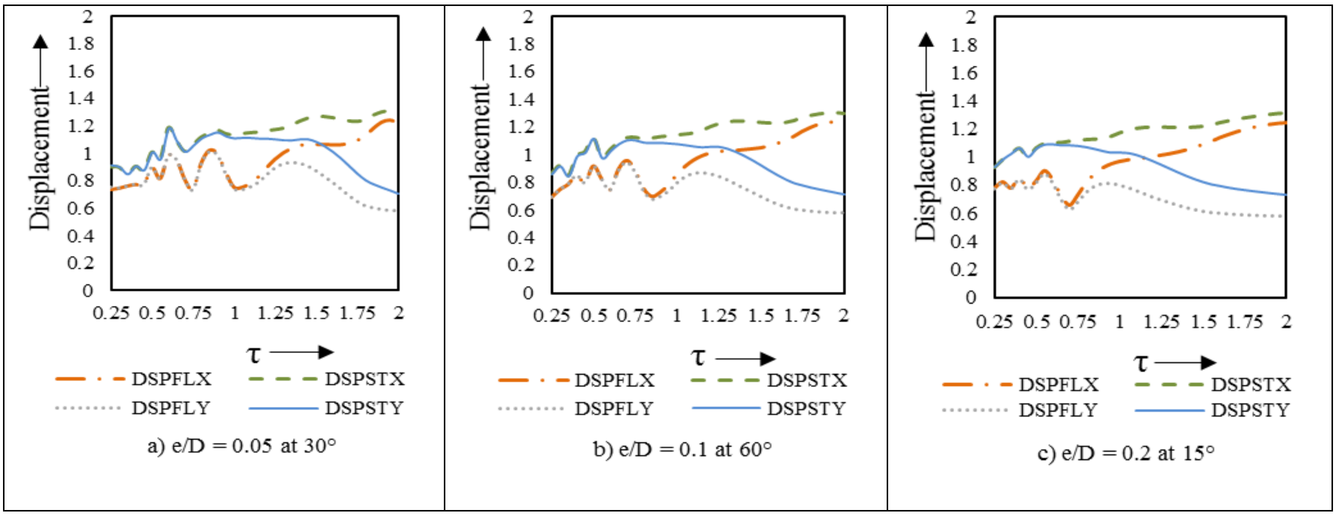


a) e/D = 0.05 at 60°

b) e/D = 0.1 at 75°

c) e/D = 0.2 at 30°

Fig. 10. Maximum normalized displacement response for uni-directional eccentricity due to FF motion when lateral period 0.25 sec and Rµ = 4.

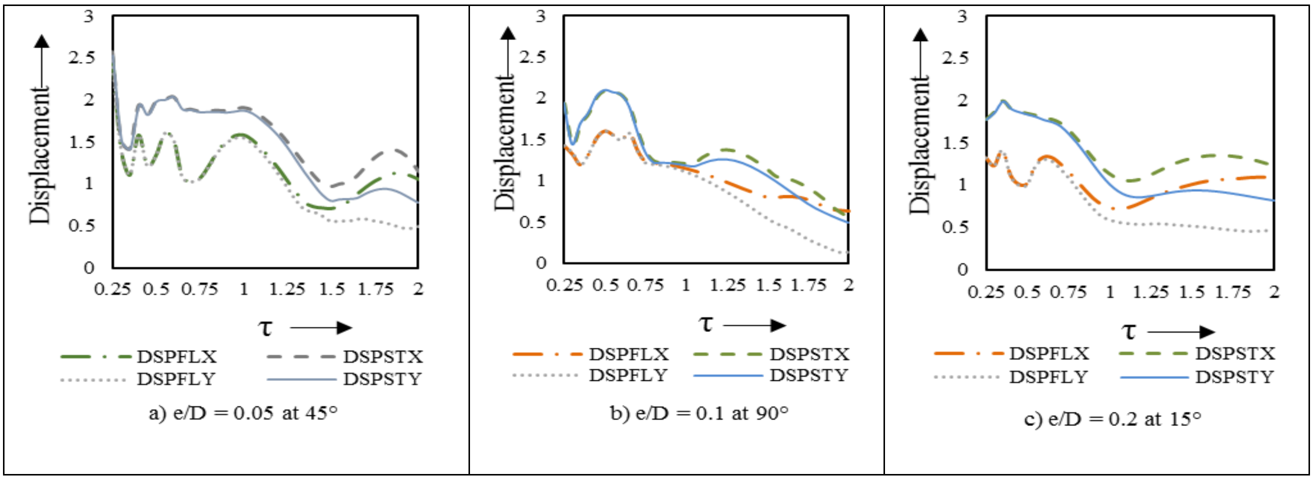


a) e/D = 0.05 at 30°

b) e/D = 0.1 at 60°

c) e/D = 0.2 at 15°

Fig. 11. Maximum normalized displacement response for uni-directional eccentricity due to FF motion when lateral period 0.5 sec and Rµ = 4.

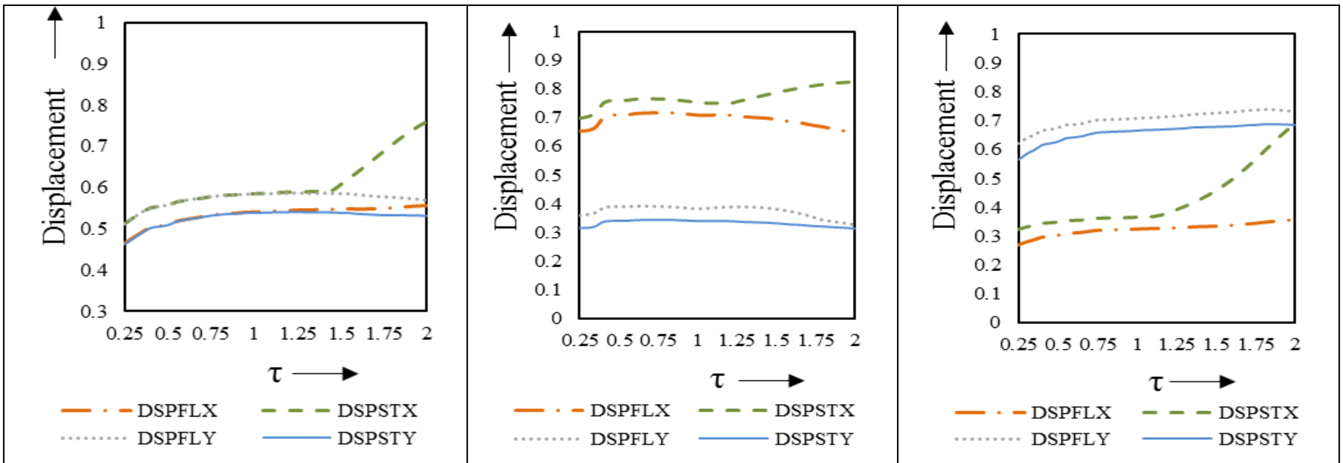


a) e/D = 0.05 at 45°

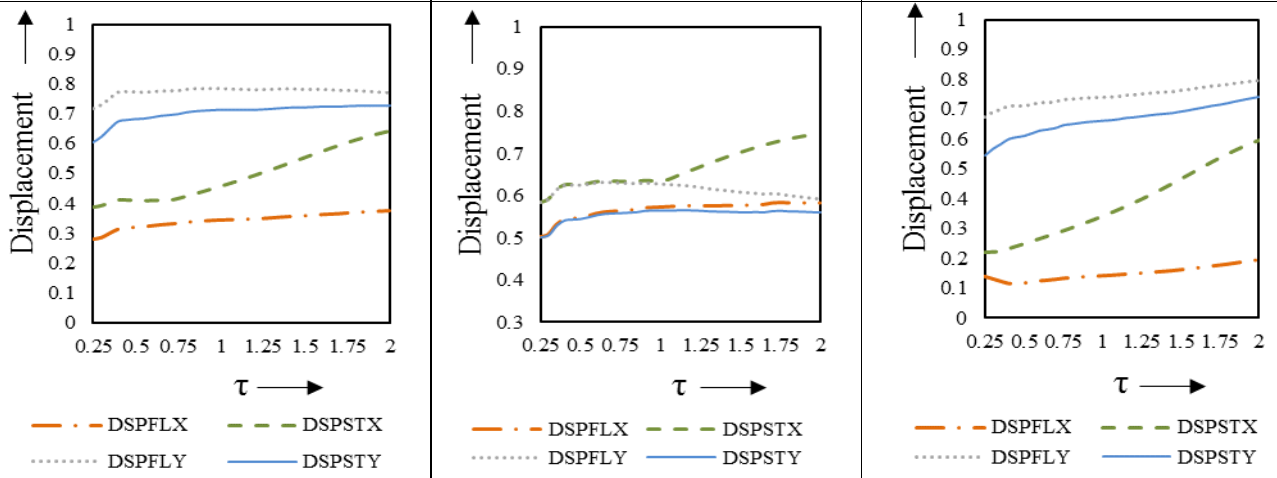
b) e/D = 0.1 at 90°

c) e/D = 0.2 at 15°

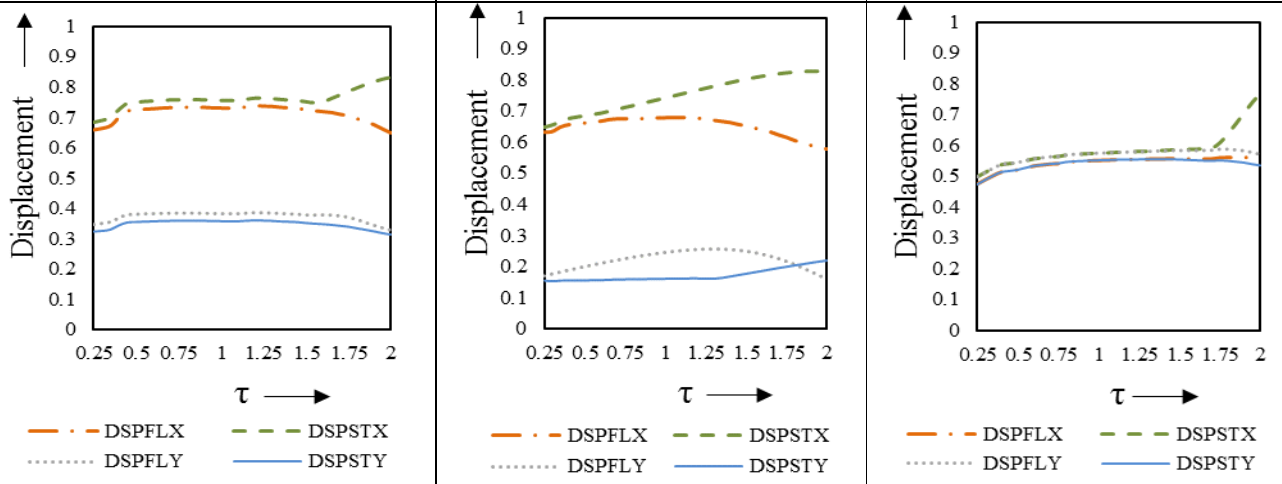
Fig.12. Maximum normalized displacement response for uni-directional eccentricity due to FF motion when lateral period 1.0 sec and Rµ = 4.



a) $e_x/D = 0.1$, $e_y/D = 0.1$ at 30° b) $e_x/D = 0.1$, $e_y/D = 0.2$ at 45° c) $e_x/D = 0.1$, $e_y/D = 0.05$ at 15°

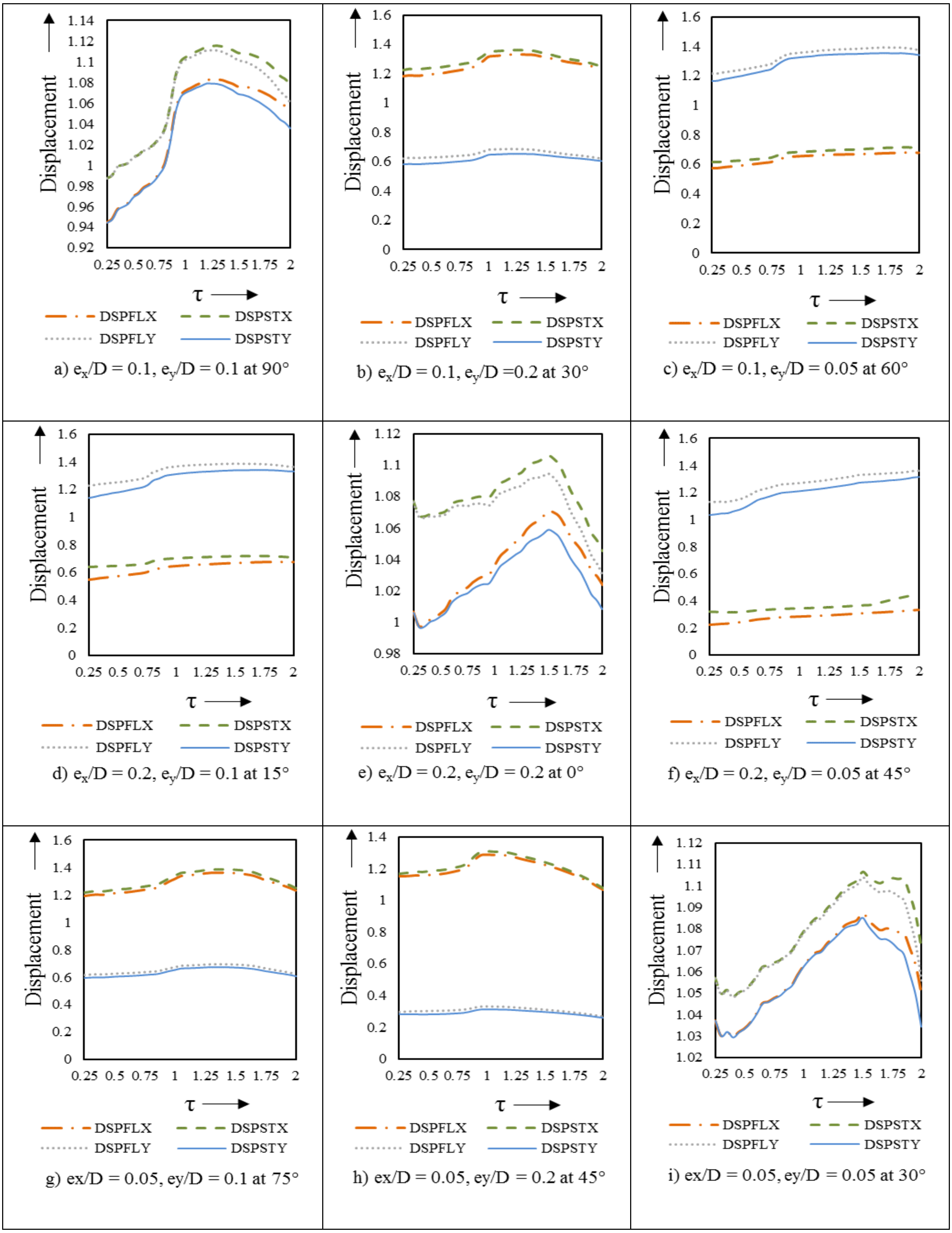


d) $e_x/D = 0.2$, $e_y/D = 0.1$ at 60° e) $e_x/D = 0.2$, $e_y/D = 0.2$ at 90° f) $e_x/D = 0.2$, $e_y/D = 0.05$ at 0°



g) $e_x/D = 0.05$, $e_y/D = 0.1$ at 30° h) $e_x/D = 0.05$, $e_y/D = 0.2$ at 75° i) $e_x/D = 0.05$, $e_y/D = 0.05$ at 45°

Fig. 13. Maximum normalized displacement response for bi-directional eccentricity due to NF ground motions when lateral period 0.25 sec and Rμ = 4.



a) $e_x/D = 0.1$, $e_y/D = 0.1$ at 90°

b) $e_x/D = 0.1$, $e_y/D = 0.2$ at 30°

c) $e_x/D = 0.1$, $e_y/D = 0.05$ at 60°

d) $e_x/D = 0.2$, $e_y/D = 0.1$ at 15°

e) $e_x/D = 0.2$, $e_y/D = 0.2$ at 0°

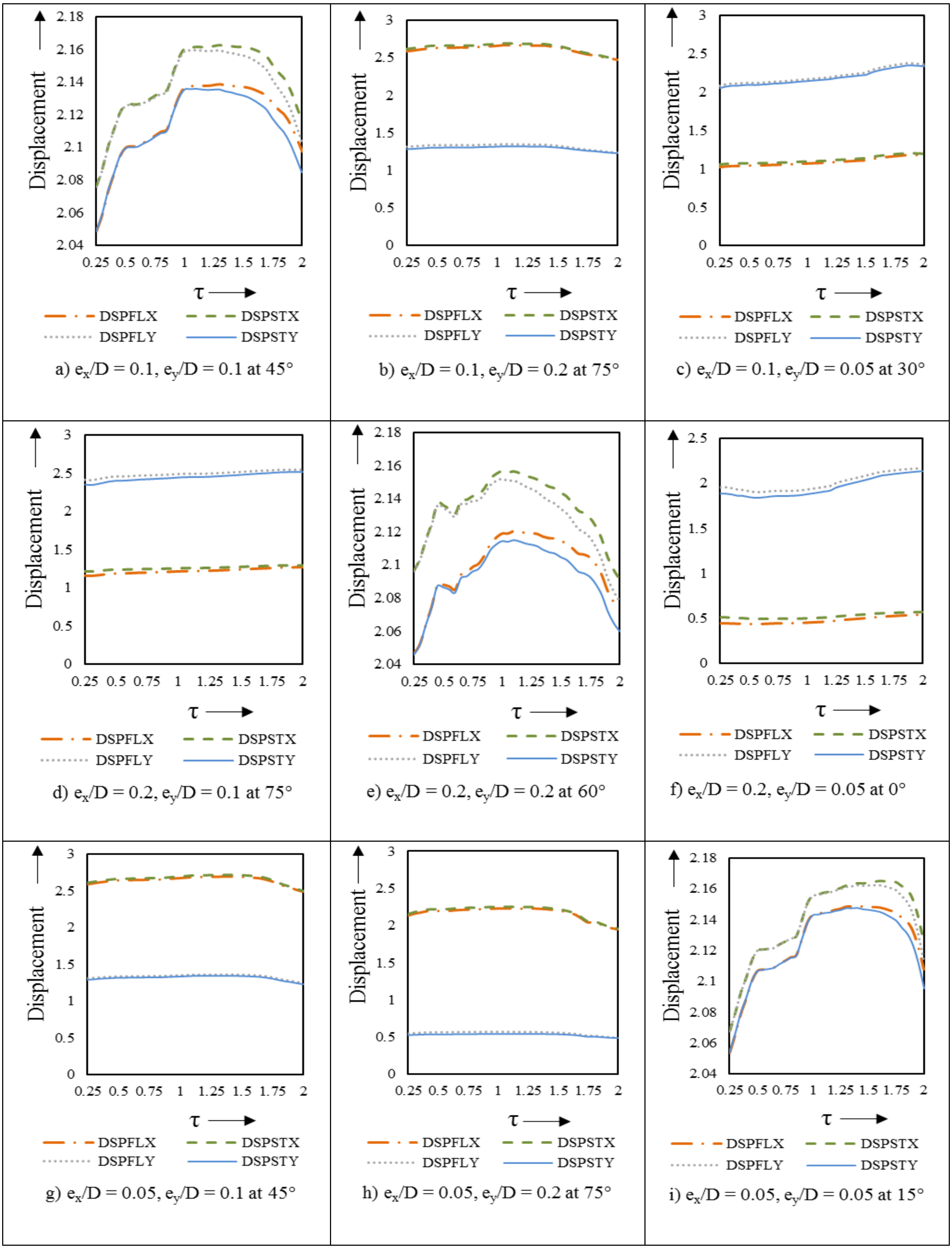
f) $e_x/D = 0.2$, $e_y/D = 0.05$ at 45°

g) ex/D = 0.05, ey/D = 0.1 at 75°

h) ex/D = 0.05, ey/D = 0.2 at 45°

i) ex/D = 0.05, ey/D = 0.05 at 30°

Fig. 14. Maximum normalized displacement response for bi-directional eccentricity due to NF ground motions when lateral period 0.5 sec and Rμ = 4.



a) $e_x/D = 0.1$, $e_y/D = 0.1$ at 45°

b) $e_x/D = 0.1$, $e_y/D = 0.2$ at 75°

c) $e_x/D = 0.1$, $e_y/D = 0.05$ at 30°

d) $e_x/D = 0.2$, $e_y/D = 0.1$ at 75°

e) $e_x/D = 0.2$, $e_y/D = 0.2$ at 60°

f) $e_x/D = 0.2$, $e_y/D = 0.05$ at 0°

g) $e_x/D = 0.05$, $e_y/D = 0.1$ at 45°

h) $e_x/D = 0.05$, $e_y/D = 0.2$ at 75°

i) $e_x/D = 0.05$, $e_y/D = 0.05$ at 15°

Fig. 15. Maximum normalized displacement response for bi-directional eccentricity due to NF ground motions when lateral period 1.0 sec and Rμ = 4.

The response of all elements is studied to develop a physical understanding to the behavior of the unidirectional and bidirectional asymmetric system that is plotted at ordinate and uncoupled torsional to lateral period ratio (τ) at abscissa. The overall response for both unidirectional and bidirectional eccentric condition for asymmetric structural system shows the maximum response with respect to the critical incidence angle that is varied in an eccentric condition. The response of unidirectional eccentric condition represents due to NF and FF ground motion whereas bidirectional eccentric condition reported owing to only NF ground motion for better estimation of structural elemental deformation in a critical incidence angle. To study this aspect, the maximum normalized elemental response is plotted along with flexible and stiff side showing mean + standard deviation, as shown in Fig. [3-15] for both structural systems. For symmetric system, the maximum displacement response is carried out for X directional element lies 0.4 times for NF and 0.03 times for FF ground motion whereas for Y directional element it lies 0.12 times for NF and 0.006 times for FF ground motion, show in Fig. [3, 4]. Furthermore, the maximum energy dissipation response is carried out for X directional element lies about 200 times for NF and 37 times for FF ground motion whereas for Y directional element it lies 15 times for NF and 26 times for FF ground motion. This response is satisfied for different critical angle of orientation in higher level of inelasticity show in Fig. [5, 6]. On the other side, for asymmetric structural system maximum displacement response for unidirectional eccentric condition for e/D = 0.05 carried maximum response for both stiff and flexible side elements in X and Y direction subjected to NF and FF ground motion with the variation of different maximum incidence angles, where Rμ = 4 show in Fig. [7-12]. Furthermore, response for bidirectional eccentric condition for different eccentric combination represent the higher response in stiff and flexible side elements in X and Y direction due to NF and FF ground motion with different maximum critical orientation, where Rμ = 4 show in Fig. [13-15]. These two eccentric combinations are clearly plotted with respect to the lateral to torsional time period ratio that enhance maximum credible damage of structural elements with orientation of ground motion excitation on a structure. The results are shown in a higher response of different angle of orientation at θ variation.

7. CONCLUSIONS

The resent investigation analyzes by influencing the angle of incidence in inelastic response of an idealized single-story R/C structural system owing to bidirectional ground excitation. Thus, it is considered to be a traditional approach appropriate for design guideline also verified of a structural performance. The results are estimated by rotating the ground motion around the structure over 360° orientation and the critical response evaluated under every 15° interval. Identification of such orientations have shown for improving execution of the inelastic seismic performance. This investigation has been conducted to the following conclusions.

1. In the case of symmetric structural system, we measure structural response in terms of displacement and hysteretic energy dissipation due to bidirectional excitation may considerably change with orientations. There is clearly demonstrated that the angle of incidence mostly important for bidirectional analysis which is essential for practical purpose and design section of structure. To gain additional insight, the response under bidirectional shaking is quadrant wise repetitive and relatively different for all values of θ. The response due to bidirectional shaking may closely be estimated for appropriate angle of incidence that is most preferred considerably angle of incidence.

2. On the other side, for asymmetric structural system when ground motion is subjected to assault on a structure, the response of flexible and stiff side elements is higher in inelastic zone with various eccentric condition that is influenced by the uncoupled torsional effect. The performance of stiff and flexible side elements is differed with increasing the seismic inelasticity. From this particular way, we clearly underestimated that the incidence angle has another impact even for which vulnerability may cause due to high magnitude of earthquake.

3. In the bird's eye observation that the response for symmetric system may be underestimated by more then 50% for NF and 40% for FF ground motion components respectively. Moreover, for asymmetric system with uni-directional eccentric condition it carries 55% for FF and 57% for NF ground excitation respectively. Asymmetric system with bi-directional eccentric condition it leads 70% for NF and 64% for FF ground motion respectively. The incidence angle leads to the maximum deformation differs with the reduction factor values used in the design process of a building. These visions lucidly demonstrated that there is no specific particular orientation for any structures which can affect the structure more vulnerable.

Thus, the present paper may be of help in the process of response analysis of the built or to-be-built structures in the event of any anticipated earthquake and believe to be new. Safety level of the structures undergoing seismic excitation without collapse may be assessed to plan for the post-earthquake strategy. Such a structure serve various functional and architectural requirements causes due to plan and interconnected activities leads to the additional vulnerability of system due to external loads. Furthermore, the sensitivity of the bi-directionally attacking forces executed more seismic deterioration than uni-directional effect of such systems. This present paper may prove useful to provide broad guidelines to address all essential issues and to highlight the needs of investigating the same in further details. These results can, therefore, help to evaluate the retrofitting assessment due to additional strength demand. These findings point out the limitation of current codes developed primarily on research in this particular aspect that employed the incidence angle phenomenon. Hence, this interesting study may be extended to a various model of SDOF and MDOF asymmetric structural system due to bi-directional shaking for obtaining further insight.

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