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CRITICALITY OF CONTROLLING SEISMIC TORSIONAL RESPONSE IN PLAN UNSYMMETRIC BUILDINGS

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Abstract

Influence of critical system parameters is studied on lateral-torsional coupling of buildings with *unsymmetric stiffness* in plan. Elastic analyses of idealised single storey building (with two degrees of freedom, namely one translation and one rotation) were performed under set of earthquake ground motions; lateral-torsional response of buildings is sensitive to both *structural* and *ground motion* characteristics. Under earthquake shaking,

(1) Dynamic response amplifications are in the ranges *1–20*, depending on whether the ground motion is of *far-field type* or of *near-field type (both fault-normal and fault parallel component)*, respectively; these results are for buildings with eccentricity in the range *0.01B–0.40B*, where *B* is lateral dimension of building measured perpendicular to direction of earthquake; and

(2) Usual code provisions (though conservative for small eccentricity buildings) may not be applicable to large eccentricity buildings. In lightly eccentric buildings, the behaviour of building is different when $\tau<1.0$ and $\tau>1.0$, where τ is ratio of *torsional* and *translational natural periods* of the idealised two degree of freedom model. Influence observed are summarised for *far-field* (usually with high frequency content only) and *near-field* ground motions (usually with dominant low frequency content also) on short and long period large eccentricity buildings:

(a) Buildings with $\tau<1.0$

Response of short period buildings is amplified on both flexible and stiff sides; short period buildings sustain more amplification.

(b) Buildings with $\tau>1.0$

Response of short period buildings is amplified (though lesser than that when $\tau<1$) on flexible and stiff sides; under some ground motions, flexible side response is significantly higher. And, response of long period buildings is amplified on stiff side and de-amplified on flexible side.

Lateral-torsional coupling is present in both *short* and *long* period buildings; the effect is more critical in buildings with large stiffness eccentricity in plan. Hence, seismic design codes should place an upper limit on *torsional eccentricity*.

Keywords: Lateral-torsional coupling; structural and ground motion characteristics; torsional eccentricity.

1. INTRODUCTION

1.1 Torsion

Torsion in buildings depends on *mass* and *stiffness* distribution in plan. Unsymmetric distribution of mass or stiffness causes *torsional eccentricity* in plan. It is measured as the distance between the *center of mass (CM)* of the building plan and the *center of stiffness (CS)* of the lateral structural elements. Under earthquake shaking, eccentricity in plan causes lateral-torsional coupling in building, which induces torsional demand and in turn translation. Thus, altering symmetry of a building results in non-uniform deformation demand in vertical elements resisting lateral loads. Design of these structural elements for increased demands gained importance since 1960s; structural elements along the periphery of buildings are more vulnerable to such demands. Hence. these elements need adequate deformation capacity to resists the additional demand due to torsion [1, 2, 3].

1.2 Behaviour of Large Eccentricity Buildings in Past Earthquakes

Because of necessity, most of buildings lack symmetry in plan, which results in large torsional eccentricity. Past earthquakes showed such buildings vulnerable, because most of them failed in brittle modes. Unsymmetry arises from unsymmetric distribution of *mass, stiffness, strength* or in *combinations*. A swimming pool or water tanks at a corner of building results in *mass* eccentricity in plan, corner structural elements on *heavy mass side* draw lateral-torsional demand, and this leads to brittle collapse (Fig.1.a). Variable column dimensions or provision of structural walls only on one side, or providing lift core on one corner of the building, results in large *stiffness* eccentricity; structural elements on *flexible side* experience more lateral-torsional demand leading to catastrophic failure (Fig.1.b).

Combined unsymmetry in plan due to both mass and stiffness induced large lateral force demand on flexible side elements, where heavy mass is located and collapsed (Fig.2). Buildings with large mass eccentricity, elements located on *heavy mass side* are critical, and buildings with large stiffness eccentricity, elements on *flexible side.* Heavy mass side is analogous to flexible side. Therefore, this study addresses buildings with unsymmetric stiffness in plan. Damages in large eccentricity buildings suggest the necessity to control their torsional response behaviour.

(a) *(b)*

Fig. 1 – Damaged buildings due to (a) Large Mass Eccentricity, *Japan earthquake 1978* [4];
(b) Large Stiffness Eccentricity, *Athens earthquake 1999* [5]

Fig. 2 – Damaged building due to mass and stiffness eccentricity *Bam Earthquake, 2003* [6]

1.3 Limit large eccentricity in buildings

To address torsion in building, codes use design eccentricity *(structural and accidental)* and increase horizontal shear demand in structural elements on flexible side. Structural eccentricity accounts for *lateral-torsional coupling* and accidental eccentricity for *uncertainty in mass distribution*. Using equivalent static approach, base shear demand is estimated by shifting *CM* by design eccentricity; it is applicable for regular buildings only. In these lightly eccentric buildings, a constant dynamic amplification factor *(of 1.5)* is specified in code provisions. Otherwise, building codes suggests conducting 3D linear dynamic analysis by shifting *CM* using accidental eccentricity [2]. Use of constant amplification is not applicable in large eccentricity buildings. In large eccentricity buildings, building codes (e.g., Canada, India, and Mexico) suggest 3D dynamic analysis. Some building codes (e.g., UBC, NEHRP, Taiwan, and Iran) suggest equivalent static approach with modified dyamic amplification factor *(ranges from 1 to 3)*, else 3D dynamic analysis is recommended. Considering these, design approaches were proposed by modifying design eccentricity to include dynamic actions. Research focussed on changing design eccentricity based on *elastic* and *inelastic* actions [7,8,9]. Though various approaches were used to modify design eccentricity, the intent was to mitigate the torsional demand. Therefore, critical parameters need to be identified, which influence torsional response of unsymmetrical buildings.

Parametric studies reported in literature showed that responses of unsymmetric buildings are senstive to structural and ground motion characteristics [3, 9, 10, 11]. Though structural parameters are same, torsional behaviour of unsymmetric buildings estimated by various studies showed contradictory results, becasue the studies were limited to selected building configurations; a detailed review to understand the behaviour of unsymmetric buildings considered an idealised *two-element system configuration* [12]. To begin with, a one storey building is considered to predict the system response and not the entire building. The single storey building was torsionally irregular in plan, mainly unsymmetrical due to stiffness. Elastic analysis of idealised single storey building (with two degrees of freedom, namely one translation and one rotation) performed under a suite of earthquake ground motions, showed high dependence on system configuration, and clarified controversies from various studies. Behaviour of small and large eccentricity buildings was examined; large eccentricity buildings showed drastic amplification in response on flexible side. These critical observations suggested that limiting the eccentricity in building is mandatory to control torsional demand on the building.

2. IDEALISED TWO-ELEMENT SYSTEM

All lateral load resisting elements in the *single storey building* is represented by an equivalent two element system; lateral and torsional demands are resisted together by these two elements. The location, number and stiffness of individual resisting elements do not influence the response of this idealised system. These two elements are assumed to have zero out-of-plane stiffness having negligible mass and axial deformations. The floor diaphragm is considered as rigid with uniform mass distribution, and the *CM* is considered as the reference point. Dynamic characteristics of the single storey building are obtained with mass lumped at roof level; translational and torsional stiffnesses are captured by a pair of equivalent lateral load resisting elements that have stiffness unsymmetry. Thus, translational and torsional modes of vibration alone are considered, and hence, the single storey building is idealised as a symmetric two degree of freedom system (Fig.3.a). The behaviour of this idealised system is studied under unidirectional ground motion.

A small eccentricity *e* is introduced by reducing the lateral stiffness of one lateral load resisting element and increasing that of the other element by the same amount, thereby keeping the total lateral stiffness of the system same as that of the symmetric system. Therefore, the centre of stiffness *(CS)* is shifted away from the *CM* resulting in *stiffness eccentric system* (Fig.3.b); the side with lesser element stiffness is called *flexible side* and the other *stiff side*.

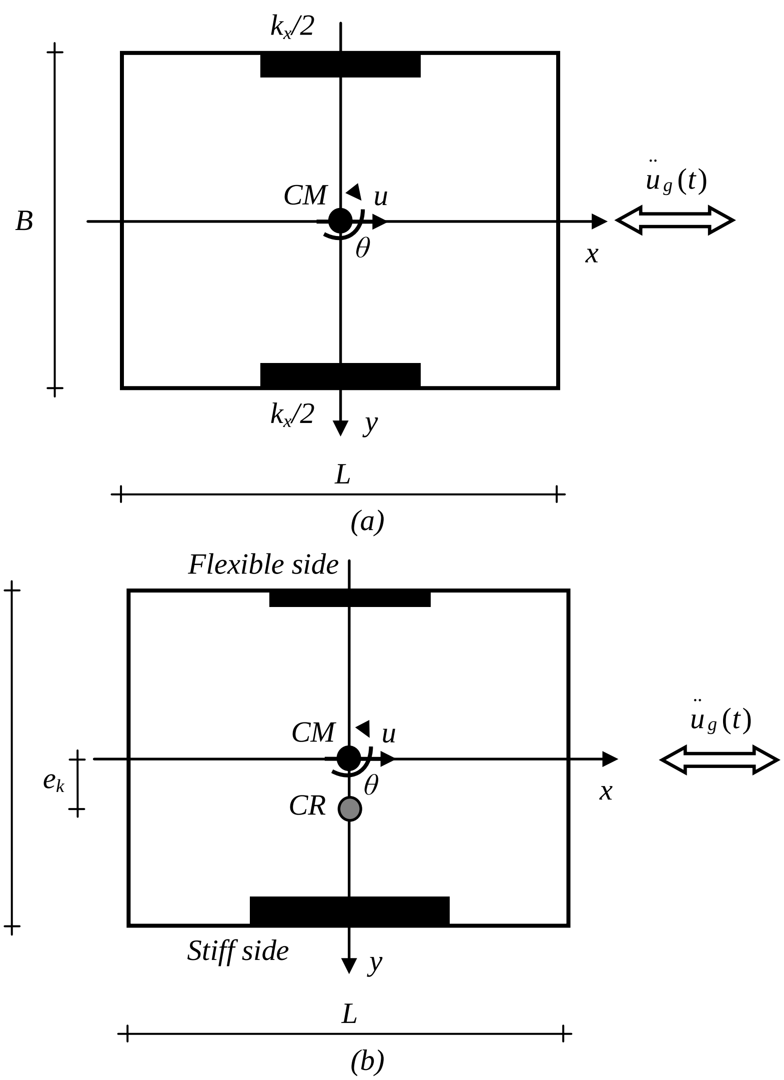


Fig. 3 – Idealised Two-element system: (a) Symmetric building (b) Unsymmetric building

3. PARAMETERS CONSIDERED

Governing equations of dynamic equilibrium of two-element system are written in deformed configuration as:

$$\begin{bmatrix} m & 0 \\ 0 & mr^2 \end{bmatrix}\begin{Bmatrix} \ddot{u}(t) \\ \ddot{\theta}(t) \end{Bmatrix}+\begin{bmatrix} C_x & C_x e_k \\ C_x e_k & C_\theta \end{bmatrix}\begin{Bmatrix} \dot{u}(t) \\ \dot{\theta}(t) \end{Bmatrix}+\begin{bmatrix} K_x & K_x e_k \\ K_x e_k & K_\theta \end{bmatrix}\begin{Bmatrix} u(t) \\ \theta(t) \end{Bmatrix}=-\begin{bmatrix} m & 0 \\ 0 & mr^2 \end{bmatrix}\begin{Bmatrix} \ddot{u}_g(t) \\ 0 \end{Bmatrix} \tag{1}$$

where m is the mass of the system; r the radius of gyration of mass about *CM*; K_x the lateral stiffness of the systems in x direction; e_k the eccentricity between *CM* and *CS* measured along y direction; K_θ the torsional stiffness of the system about *CM*; $\ddot{u}_g(t)$ the ground acceleration at time t; $\ddot{u}(t)$ and $\ddot{\theta}(t)$ the lateral and torsional accelerations of *CM* relative to the ground, respectively; C_x the translational damping coefficient along x-direction; and C_θ the rotational damping coefficient about the *CM*. Rewriting Eq. (1) in the normalised form, parameters influencing *lateral-torsional response* of RC frame buildings become: *normalised eccentricity ratio (e_k/B), natural period ratio (τ,* depends directly on *aspect ratio, L/B), uncoupled lateral natural period (T_x), damping ratio (ξ),* and *ground motion characteristics*. The first four parameters are of the *structure*, and the last of *ground motion*.

3.1 Structural Parameters

(e_k/B) uses lateral dimension *(B)* between the extreme structural elements, and is varied from 0.01 to 0.40 *(representing small and large eccentricity buildings)*. The *natural periods (T_x)* selected correspond to buildings in *acceleration* and *velocity* sensitive regions of response spectrum. τ projects the *distribution of mass* and *stiffness* in plan; for the two-element system *(constant stiffness distribution)*, τ is dictated by *plan geometry* expressed in terms of plan *aspect ratio (L/B)*. Assuming *rigid floor diaphragm*, *L/B* is restricted to within *1/3 - 3*, and the corresponding range of τ is estimated accordingly. Buildings with large τ *(τ>1)* are said to be *torsionally flexible*, while those with small τ *(τ<1) torsionally stiff system*. *Damping ratio* is taken as *5%* of *critical damping* in each natural modes of vibration of torsionally coupled system (Table 1).

Table 1 – Parameters considered for idealised system

S.No.	Parameter	Ranges Considered
1	Normalised eccentricity ratio *(e_k/B)*	0.0 to 0.4
2	Natural period ratio *(τ)*	0.60 to 1.84 *(L/B = 1/3 to 3)*
3	Natural period *(T_x)*	0.1s, 0.5s, 1.0s, 1.5s, 2.0s
4	Damping ratio *(ξ)*	0.05
5	Ground motions characteristics	Dominant short period content Dominant long period content

3.2 Ground Motion Characteristics

Two different sets of ground motions *(30 each)* are considered (Table 1), to study influences of dominant short period (*or far-field* ground motions) and dominant long period (*or near-field* ground motions) [13,14,15,16]. The ground motions are applied along *x*-direction of idealised two-element system. Factors considered in selection of ground motions are: *magnitude* of earthquake, *distance* from fault, *fault mechanism* and local *soil conditions* [17]. Ground motions recorded at sites farther than *20 km* from fault rupture zone are considered to be *far-field ground motions*. The magnitude ranges from *M6.3* to *M7.3*, since magnitude *<M6* will damage, but may not collapse the buildings. The site-to-source distance varies from *20* to *50 km*. Dominant short period content will affect *short* and *medium period* buildings. Ground motions recorded at sites closer than *20 km* from fault rupture zone are considered as *near-field ground motions*; their magnitude ranges from *M6.2* to *M7.6* and site-to-source distance varies between *0.24* to *17.5 km*. Responses under near-field regions is governed by *magnitude of pulse* and dominant *pulse period*. *Fault-normal* motion contains *large velocity pulse* due to *rupture directivity effect*, and acts normal to strike direction of fault. *Fault-parallel motion* contains *permanent ground displacement pulse* called *fling steps*, which will act parallel to strike direction of fault [18]. Both *fault-normal* and *fault-parallel* motions are used in this study. Presence of *dominant long period content* imposes large demands in *long period* and *tall buildings*. Sometimes, dominant short period content in addition to long period content affects *short*, *medium* and *long period* buildings.

Both near and far-field earthquake records can be scaled for different levels of shaking amplitudes. It helps to identify the damage and economic loss of buildings under different shaking amplitudes [13]. The hard rock *(Type I)* soil is considered. Amplitude scaling of ground motions is employed using the following procedure (Fig.4):

(1) Estimate the response spectrum from individual ground motions *(GM RS);*
(2) Obtain the design response spectrum *(Design RS)* based on *Indian Standards* [19] for specific hazards;
(3) Compare both spectra and estimate scale factor for building with natural period T_x.

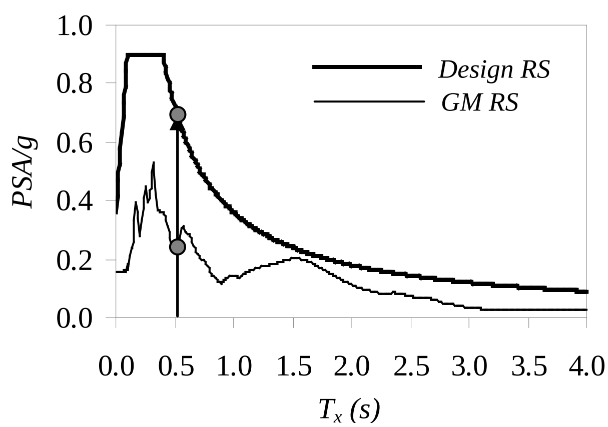


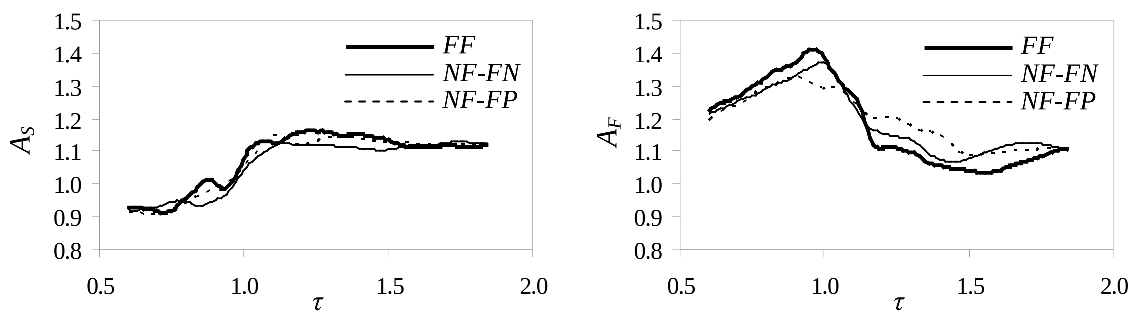
Fig. 4 – Scaling of individual ground motions using Design Response Spectrum

4. BEHAVIOUR OF PLAN UNSYMMETRIC BUILDINGS

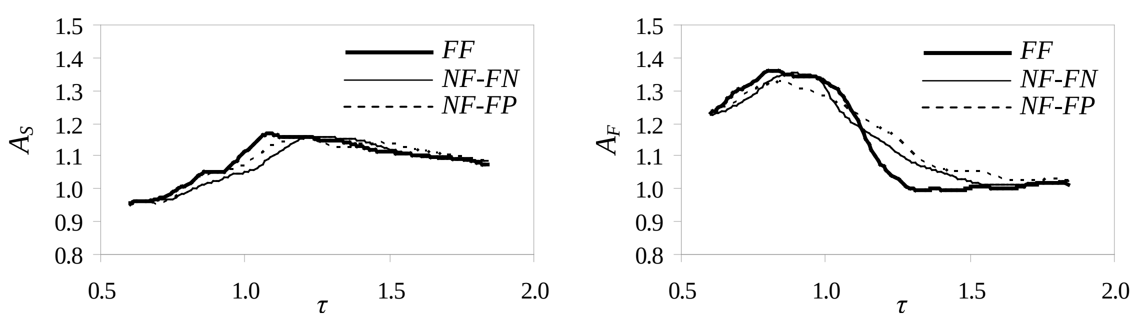
Displacement responses are estimated numerically using *Newmark's γ-β Method* considering *constant acceleration* over the time step; the *Newmark's* parameters are $\gamma=0.50$ and $\beta=0.25$. Element displacement responses are normalised with those of the corresponding symmetric building; helps to identify various parametric influences on lateral-torsional response of unsymmetric buildings. Response amplifications *(A)* in *stiff* (A_S) and *flexible* (A_F) *side* elements of *stiffness unsymmetric buildings* are estimated statistically using *far-field (FF)* and *near-field (NF)* ground motions (considering *fault-normal*, *FN* and *fault-parallel*, *FP*). Normalised displacement responses are insensitive to *scaling of ground motion*, but sensitive to ground motion period content.

4.1 Small Eccentricity Buildings

Lateral-torsional responses of small eccentricity buildings show lesser amplification *(except at* $\tau\sim1$*)*. Behaviour is different when $\tau<1$ and when $\tau>1$; *flexible side* governs, when $\tau<1$, and *stiff side*, when $\tau>1$. Also, there is strong coupling at $\tau\sim1$ between lateral and torsional modes [e.g., 9,10,11]. With strong modal coupling and dominant short or long period ground motion content, element displacement responses are highly amplified around $\tau=1$. Maximum amplifications in response due translation and rotation will not happen at the same value of τ; but, their combined maximum are seen to occur near $\tau=1$. Moreover, response amplifications on flexible and stiff sides are highly dependent on ground motion period content. To reduce amplification on *stiff side* $(\tau>1)$, stiffening the stiff side element will increase further the stiffness eccentricity, which is not practically advisable; therefore, one should avoid $\tau\geq1$. Therefore, in small eccentricity buildings, in addition to e_k/B *ratio*, influence of τ must be considered to control torsional response (Fig.5).



(a) $T_x = 0.5s$

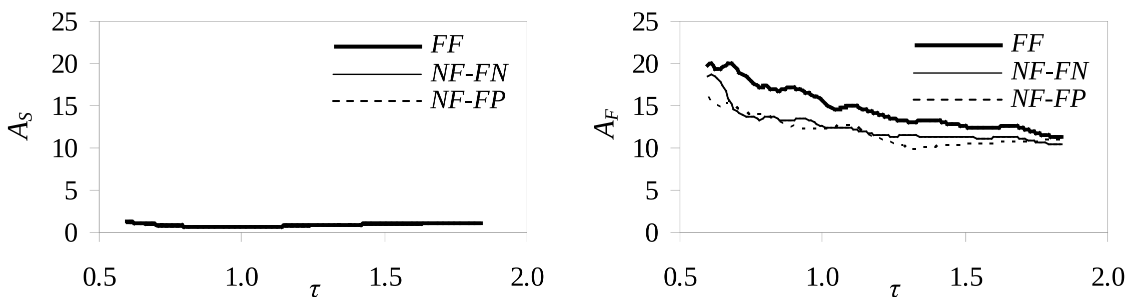


(b) $T_x = 2.0s$

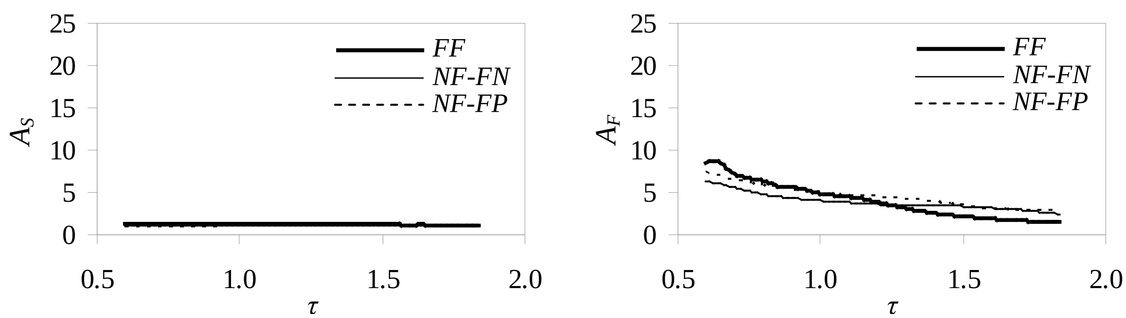
Fig. 5 – Behaviour of small eccentricity buildings: $e_k/B = 0.05$, $\xi = 0.05$

4.2.2 Large Eccentricity Buildings

In large eccentricity buildings, responses are highly amplified, since lateral-torsional coupling manly arises from *large eccentricity* ratio $e_k/B=0.4$. Mostly, flexible side dominates the torsional response. Hence, design decision should be made based on flexible side. Observation are summarised from far-field and near-field ground motions responses on short and long period large eccentricity buildings. In buildings with τ<1.0, response of short period buildings is amplified on both flexible and stiff sides, and long period buildings sustain lesser amplification. In buildings with τ>1.0, response of short period buildings is amplified lesser than when τ<1 on flexible and stiff sides. Short period (stiffer) buildings with large eccentricity show drastic amplification in response ~*20*, whereas long period (flexible) buildings with large eccentricity show amplification in response ~*9*. Thus, amplification in response in large eccentricity buildings can be reduced only by *limiting stiffness eccentricity* (Fig.6).



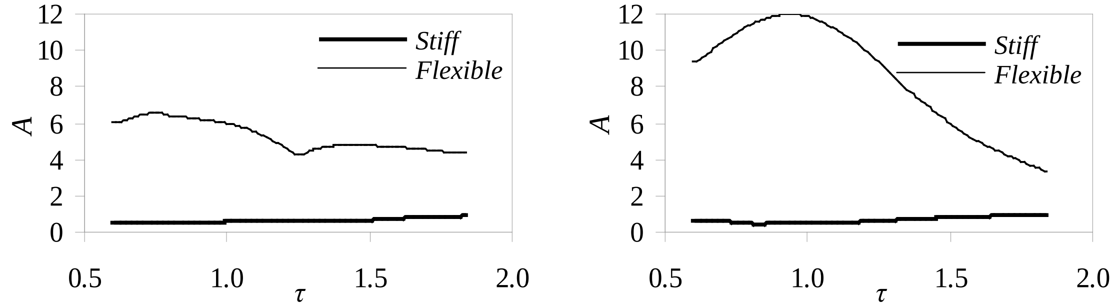
(a) T_x *= 0.1s*



(b) T_x *= 2.0s*

Fig. 6 – Behaviour of large eccentricity buildings: $e_k/B = 0.40$, $\xi = 0.05$

In limited cases of ground motions, long period large eccentricity buildings show more amplification than short period large eccentricity buildings *(due to dominant long period content)*. For example, amplification in response under *Nepal Earthquake*, having *dominant long period content*, was obvious through this study (Fig.7). Sometimes, in long period large eccentricity buildings, response amplified on flexible side and de-amplified on stiff side, when τ<1 and when τ>1 (as noticed in *small eccentricity buildings*). For example, response of a long period large eccentricity building under *Loma Prieta Earthquake (Redwood city)* having *dominant short period content* was witnessed in this study (Fig.8). Thus, ground motion period content plays a vital role in amplifying flexible and stiff side displacement response. Ground motion characteristics may not be known precisely; therefore, *limiting stiffness eccentricity* in buildings is mandatory.



(a) T_x = 0.5s *(b) T_x = 2.0s*

Fig. 7 – Large eccentricity building response under *Nepal Earthquake, 2015 (dominant long period content)*: $e_k/B = 0.40$, $\xi = 0.05$.

(a) $e_k/B = 0.05$ *(b) $e_k/B = 0.40$*

Fig. 8 – Large eccentricity building response under *Loma Preita Earthquake, 1989 (dominant short period content)*: T_x = 1.5s, $\xi = 0.05$

4.2.3 Summary and Design Implications

For constant value of damping *(5% of critical damping)*, response amplification increases with increase in e_k/B. Maximum response amplification on flexible side is around *~1.2* for $e_k/B=0.02$, *~1.4* for $e_k/B=0.05$, *~20* for $e_k/B=0.40$. Maximum response amplification on stiff side is around *~1.1* for $e_k/B=0.20$, *~1.17* for $e_k/B=0.05$, *~1.34* for $e_k/B=0.40$. Therefore, constant amplification factor *(i.e., 1.5)* specified in code provisions for equivalent static approach are applicable *only* for small eccentricity buildings, and not for large eccentricity buildings. Hence, *limiting stiffness eccentricity* in code provisions is mandatory.

Short period buildings *(stiff buildings)* show more response amplification compared to long period buildings *(flexible buildings)* owing to presence of dominant short period content in selected ground motions. Also, too much *stiffening of large eccentricity buildings* does not reduce response amplification; stiffening structural elements to *reduce stiffness eccentricity* will reduce response amplification. Thus, response amplification in unsymmetric buildings depends on e_k/B and not on *total lateral stiffness (K_x)*. Hence, it is more necessary to reduce stiffness eccentricity than increasing lateral stiffness of the building. Alternately, short period buildings should be designed using *higher amplification factor* in *design eccentricity* expression specified in codes. Observed response using idealised two-element system is highly dependent on the system configuration; it is more pronounced in large eccentricity buildings than in small eccentricity buildings.

Table 2 – Summary of *various parametric influences* in small and large eccentricity buildings

S.No.	Small Eccentricity Buildings	Large Eccentricity Buildings	Inference for design
1	Small eccentricity buildings show *lesser amplification* in response (~*1.4* for $e_k/B=0.05$)	Large eccentricity buildings show *more amplification* in response *(~20* for $e_k/B=0.40$)	Avoid *large eccentricity* in buildings.
2	Behaviour of *small eccentricity building* is different, when $\tau<1$ and $\tau>1$; flexible side governs, when $\tau<1$, and stiff side, when $\tau>1$.	Mostly flexible side governs the torsional response (all ranges of τ); *stiff side* shows *less* response (maximum ~*1.34*). Therefore, limit flexible side response.	Therefore, *limiting* e_k/B is mandatory.
	Response is highly amplified for τ~*1*. Also, for $\tau>1$, stiffening stiff side is not applicable. A limit should be proposed for τ to *subside* response amplification.	Sometimes, similar behaviour *(as small eccentricity buildings)* is observed from individual ground motion response, in *flexible* large eccentricity buildings and occasionally in *stiff* large eccentricity buildings, when ground motion has *dominant short* or *long period* content.	Therefore, *limiting* τ is mandatory in small eccentricity buildings.
3	Small eccentricity buildings (either stiffer or flexible buildings) show more or less similar amplification.	*Stiffer* large eccentricity buildings show more amplification (~*20*); *flexible* large eccentricity buildings show comparatively lesser amplification (~*9*).	Therefore, *limiting stiffness eccentricity* is mandatory.
		Stiffer buildings with large eccentricity show more amplification than flexible buildings with large eccentricity, when ground motion has dominant short period content.	Therefore, limit *stiffness eccentricity* than *increasing lateral stiffness.*
		In few cases *(Nepal Earthquake)*, *flexible* large eccentricity buildings will show more amplification (~12) than *stiffer* large eccentricity buildings (~7), when ground motion has dominant long period content.	
4	Amplification factor specified in code provisions may be applicable. But, must consider influence of τ.	Amplification factor specified in code provisions is not applicable.	Hence, limit e_k/B and τ through code provisions.

5. CONCLUSIONS

Lateral-torsional response in unsymmetric plan buildings is extremely dependent on structural and ground motion characteristics. In small eccentricity buildings, responses are amplified near τ~1, where the modes are highly coupled; amplification in response is very less compared to large eccentricity buildings.

Lateral-torsional coupling is present in both short and long period buildings; effect is more in buildings with large stiffness eccentricity in plan. Though design of critical lateral load resisting elements requires more attention, controlling additional lateral-torsional demand alone will help avoid undue damage or collapse. Ground motion characteristics may not be predicted precisely, but play a vital role in amplifying response. Also, increase in total lateral stiffness in such buildings drastically amplifies the response. In addition, constant amplification factor specified in code provisions are not applicable to buildings with large stiffness eccentricity. Hence, seismic design codes must consider placing an upper limit on plan eccentricity.

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