REVISITING THE 5% ACCIDENTAL ECCENTRICITY PROVISION IN SEISMIC DESIGN CODES FOR MULTI-STORY BUILDINGS

O.M.O. Ramadan[1], S.S.F. Mehanny[2] and A. Mostafa[3]

[1] *Professor,* [2]*Associate Prof.,* [3] *Graduate Student, Structural Engrg. Dept., Cairo University, Egypt*
E-mail: sameh.mehanny@stanfordalumni.org

ABSTRACT:

The accidental eccentricity provision is revisited in order to evaluate the suitability of its worldwide assumed code value of 5% for multi-story buildings. The question is whether such value realistically models the accidental torsion at any story of a multi-story building irrespective of the number of floors above, or it is just a conservative upper bound that does not mimic the actual response. A series of time history analyses under one horizontal component of a selected ground record is thus performed using Opensees analysis platform on a set of hypothetical three-dimensional reinforced concrete multi-story buildings with a symmetric plan and rigid diaphragms. Eight different buildings in terms of height: 1-, 2-, 3-, 4-, 5-, 10, 15- and 20-story, are studied but with the same geometric layout. Monte Carlo Simulation technique is used to define statistically-independent input random accidental eccentricities at various floor levels by sampling from an assumed Probability Density Function (PDF). Retrieved accidental eccentricities computed from the analyzed models at each floor level that are associated with the maximum story shear at the same floor level are reported. The main results clarify that: (1) the computed accidental eccentricities are highly affected by the number of floors above the floor of interest; and (2) such accidental eccentricity demands are often lower than the typical value of 5% specified in building codes especially for the floors with a larger number of stories (≥5) above.

KEYWORDS: Accidental eccentricity, seismic response, torsion, multi-story buildings, Monte Carlo simulation.

1. INTRODUCTION

Torsion behavior of buildings is considered in several seismic design building codes [1 - 4] through the use of *design eccentricities* which take into account both *intrinsic* and *accidental* sources of torsion. Intrinsic torsion is caused by the unbalance of the theoretical positions of load and resistance centers; or in other words, as a consequence of non-coincident mass and rigidity centers. On the other hand, accidental torsion is due to the random variations of these centers relative to the theoretical positions and to possible ground motion rotational components (i.e., spatial variation of the ground record). In most cases, however, plan dimensions of buildings are small allowing ground rotation effects to be neglected [5] and, therefore, accidental torsion is mainly due to random variations of mass position and/or stiffness of lateral resisting elements.

Hence, it has been traditionally required by all seismic design building codes worldwide to consider the effect of an accidental torsion moment in the design of buildings with non-flexible (i.e., rigid) diaphragms. This additional torsion moment shall be determined by simply assuming the seismic mass to be displaced from the calculated center of mass in each direction a distance equal to what looks like an “ad-hoc” value of 5% [1, 2 and 4] of the building dimension at each story perpendicular to the direction of the seismic design force under consideration. The effect of this imposed shift from the calculated center of mass on the horizontal distribution of story shear among various elements of the vertical lateral-force-resisting system shall be considered in design. This value of 5% adopted by most building codes has been the result of previous extensive analytical studies in the literature to estimate such accidental eccentricity but mainly focusing on one-story building models with a very few exceptions reporting actual eccentricities in some existing buildings. For completeness, it is worth stating that some other few international design codes too conservatively assume the accidental eccentricity to be ±10% of the applicable building dimension [3, 6].

The several theoretical studies in the literature focusing on the design provision of accidental torsion have been carried out to investigate the effect of randomly varying the location of mass and stiffness centers on the seismic response of structural models. Few works have turned to seismic response measurements of symmetric buildings to assess accidental torsion [7, 8]. Results of these works indicate that symmetric buildings are particularly sensitive to accidental torsion.

Recently, within the context of a torsion static design, De la Colina and Almeida [9] performed a probabilistic study, based on Monte Carlo simulations, on accidental torsion but of low-rise buildings only. Five- and seven-story shear building models with rigid floors and bilinear lateral-resisting elements oriented along both perpendicular directions were studied under the effect of two different ground records. The location of the center of mass on each slab, the stiffness values and the yield forces of lateral resisting elements were treated as random variables once considered separately, then simultaneously – but ignoring any correlation among them – in order to investigate their contribution to the total accidental eccentricity/torsion. Results indicated that individual effects of each of the three considered accidental torsion variables are not superimposed when these random variables are concurrently implemented. Results also indicated that the effects of accidental eccentricity decrease downwards for the two studied buildings. No specific values or ranges that could adequately describe such reduction at lower floors have been though reported.

It is observed from the literature that most of the probabilistic studies on accidental torsion for symmetric buildings adopt one-story simple models with the exception of that by De la Colina and Almeida [9] who looked at low-rise buildings. Moreover, due to the rather overwhelming computational effort, extensive statistical data manipulation, and computer storage requirement associated with the probabilistic approaches/studies, it is much more common to use simple linear elastic models to capture the global picture of the effects of accidental eccentricities from a design perspective. Accordingly, the authors preferred herein to use linear elastic multistory shear building models, along with the rigid diaphragm assumption, in order to efficiently study in a probabilistic context the overall adequacy of the 5% accidental eccentricity provision for low-, moderate-, and high-rise buildings from a conventional seismic design perspective. The present research is only focusing on the effect of the variation of the location (assumed as a random variable) of the center of mass, assuming mass eccentricities of different floors to be statistically-independent, on the suitability of the code prescribed design values of accidental eccentricities at different floors of multi-story buildings.

2. STRUCTURAL MODELS AND GROUND MOTION CHARACTERISTICS

A set of hypothetical bi-symmetric three-dimensional reinforced concrete multi-story models is considered. Model plan dimensions are defined with a=b=6m where each floor is composed of a single-panel square slab resting on four (250x500mm) perimeter beams that are supported by four corner square columns. The value of seismic mass per unit area was selected to be equal to 225 kg.sec^2/m^3 per floor for all levels, accounting for own weight of structural and non-structural elements including partition walls and flooring. A typical floor height of 3.3m is considered. Eight different buildings in terms of height: 1-, 2-, 3-, 4-, 5-, 10, 15- and 20-story, are investigated but with this same geometric layout. Table 2.1 gives the columns' dimensions for the eight studied buildings. Note that reinforced concrete columns are code-dimensioned for gravity loads only. This hypothetical building layout and other characteristics are representative of typical residential buildings.

Table 2.1 Columns' dimensions for different building models

Building Type	B-NF1 to B-NF5	B-NF10	B-NF15	B-NF20
Columns dimensions (Floors / size,mm)	1-5 / 250x250	1-2 / 350x350 3-5 / 300x300 6-10 / 250x250	1-3 / 400x400 4-7 / 350x350 8-10 / 300x300 11-15 / 250x250	1-3 / 550x550 4-6 / 500x500 7-10 / 400x400 11-16 / 300x300 17-20 / 250/250

B-NF# refers to the Building type with a given Number of Floors per building

Slabs are assumed to be rigid in their plan (i.e., adopting rigid diaphragm assumption) and second-order displacements are ignored in the analysis. Although more realistic models are available to represent building structures, herein a linear elastic shear model is selected because it allows the investigation – in a relatively simple way – of accidental torsion effects on framed multi-story buildings within a probabilistic study context. Analysis has been performed for cracked models, i.e., with cracked moment of inertia, as per ACI-318 [10] recommendations; 0.7 and 0.35 the gross inertia for columns and beams, respectively. A viscous damping is modeled through proportional (Rayleigh) damping, where a damping ratio $\zeta = 0.05$ is considered. This ζ value has been assigned to the initial translational and torsional frequencies for each building model.

The Fault-Parallel (FP) component of the 1978 Tabas earthquake (the largest historic magnitude earthquake of inland Iran) is selected to carry out the analytical/computational study. Figure 1 presents the acceleration time history of the ground record having a Peak Ground Acceleration (PGA) of 0.977g. Figure 2 shows the acceleration response spectrum of the as-recorded Tabas FP component for 5% damping. For analysis purposes, the record has been scaled to a design PGA of 0.15g compatible with the moderate seismic hazard in Cairo-Egypt as per ECP 201 requirements [4]. Work is underway by the authors to study the effect of applying other ground records with different characteristics and frequency contents.

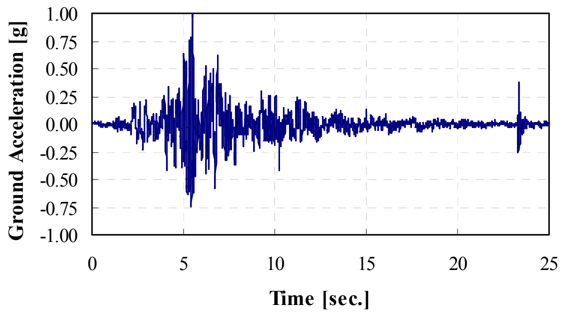

Figure 1. Ground acceleration record for the FP component of Tabas (1978) earthquake.

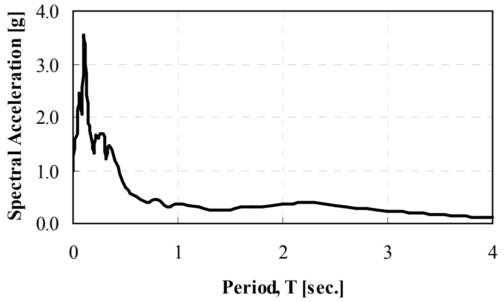

Figure 2. Acceleration Response Spectrum (5% Damping) for the FP component of the Tabas (1978) record.

3. SIMULATIONS AND ANALYSIS APPROACH

The objective of this paper, as mentioned above, is to revisit the accidental eccentricity provision in order to evaluate the suitability of its worldwide assumed code value of 5% for multi-story buildings. It investigates whether such value realistically models the accidental torsion at any story of a multi-story building irrespective of the number of floors above, or it is just a conservative upper bound that does not mimic the actual response. In order to achieve this goal, a series of time history analyses under one horizontal component of a selected *scaled* ground record (Tabas FP component) are performed using Opensees analysis platform [11] on the set of eight hypothetical three-dimensional reinforced concrete multi-story buildings with a bi-symmetric plan and rigid diaphragms as introduced in the previous section. A lumped mass approach is adopted by assigning a given distribution of masses to four different symmetrically located spots within the slab of each floor in such a way to generate a pre-determined random accidental eccentricity at this floor. Monte Carlo Simulation technique is used to define such input random accidental eccentricities at various floor levels (assumed to be statistically-independent) by sampling from an assumed Probability Density Function (PDF). Given the lack of information available in the literature related to the spatial variation of centers of mass on different floors [9], three PDFs have been applied herein, namely: lower triangle, upper triangle, and uniform distribution. The first two distributions are expected to provide very similar, and nearly identical, global [*absolute*] results since generated random accidental eccentricities at different floors are uncorrelated. Each of the three statistical distributions considered for the accidental eccentricity (taken as a random design parameter) has a lower limit of -5% and an upper limit of +5%. A lower limit of 0% eccentricity has been also investigated for a few limited cases for comparison purposes. However, this 0% lower limit may introduce some bias since it implies that the accidental eccentricity, despite being random, always leans to occur in the same direction simultaneously at all floors. Note that a few design codes [2, 4] explicitly require such accidental eccentricity to be considered concurrently in the same direction at all floor levels.

A total of three hundred time history analyses corresponding to 300 samplings of the input random accidental eccentricity for each PDF and for each building are carried out. This is to enable a reasonable statistical analysis for the investigation of the variation of the accidental torsion demand at each floor level up the height of a multi-story building. Retrieved global *absolute* maximum (i.e., the largest value of the 300 resulting maxima of the 300 time history analyses) accidental eccentricities computed from the analyzed models at each floor level that are associated with the maximum story shear at the same floor level are reported. Average values of the 300 maximum accidental eccentricities recovered from the 300 samplings as well as Coefficient of Variations (COV) are also calculated for a comprehensive statistical study and in order to estimate the scatter in the results. In other words, such statistical measures help determining how far the *absolute* global maximum retrieved accidental eccentricity is from the expected average value. Several other statistical measures including resulting maximum accidental eccentricities corresponding to different percentiles are also computed and listed. These percentiles serve as a simple approach to quantify (and visualize) the dispersion in such random variable adopted as a design parameter.

Note that, in the current research, the random eccentricity has been assigned through unbalanced distribution of lumped masses to different building models, with bi-symmetric plan, in only one direction at a time, and not simultaneously in both directions. The ground record is then applied to the three-dimensional model perpendicular to the direction of this assigned random eccentricity.

4. ANALYSIS RESULTS AND DISCUSSIONS

As an example of generated results, Figures 3 and 4 show – for sample floor levels (first and top) – the 300 retrieved *maximum* accidental eccentricities (recovered from B-NF5 model) that are associated with the maximum story shear at the same floor level due to the 300 randomly generated input accidental eccentricity assuming the upper triangle PDF, for -5% and 0% lower limits, respectively. Also reported on the same figures, for comparison purposes, are the associated 300 *input* random eccentricities as per the assumed PDFs. Recovered values of *maximum* accidental eccentricities at bottom floor are observed to be slightly lower than, and fairly different (in terms of scatter around mean values) from, random *input* eccentricities, especially for the PDF with -5% lower limit. The retrieved *maximum* accidental eccentricities are a little larger for the case with 0% lower limit as expected due to inherent bias in the associated assumed input distribution. On the other hand, both *retrieved* and *input* eccentricities are fairly comparable, in terms of maximum value and dispersion, at top of building with the *maximum* retrieved eccentricities scoring higher values than the input eccentricities for a very few number of simulations. This observation particularly occurs for the case of (0%,+5%) upper triangle distribution assumed for the random input accidental eccentricity. Moreover, Figure 5 presents similar data for a few selected floors of the 20-story building (B-NF20) for the upper triangle distribution of the randomly generated accidental eccentricity input. The limits of the PDF distribution assumed to generate the results in Figure 5 are -5% and +5%. It may be easily observed that at the very top of the building, maximum values scored by both *retrieved* and *input* eccentricities are very alike for the upper triangle distribution of the random input. Values of retrieved eccentricities are nevertheless lower for the case of uniform PDF; not presented for space limitations. Note that the upper triangle distribution may be more appealing to rely upon when studying the implications to seismic design schemes/rules since it offers a more conservative design estimate for the accidental eccentricity than the uniform PDF. However, at a few floors from top (starting from about the 16th floor and going downwards) the maximum retrieved eccentricities drastically drop relative to the maximum randomly generated input values. Furthermore, the recovered (from the 300 samplings) eccentricities at these floors are all limited to a very narrow band around the mean of this low retrieved value, i.e., showing a very small dispersion. Wealth of similar results showing comparable trends were generated for other studied buildings and for other PDFs considered in this research, but are not presented herein due to space limitations.

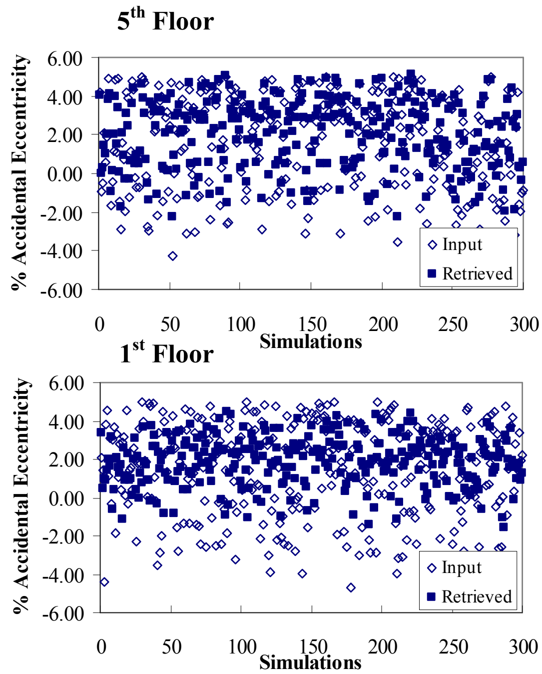

Figure 3. Input versus retrieved eccentricities for 5-story building – Upper triangle PDF (-5% , +5%)

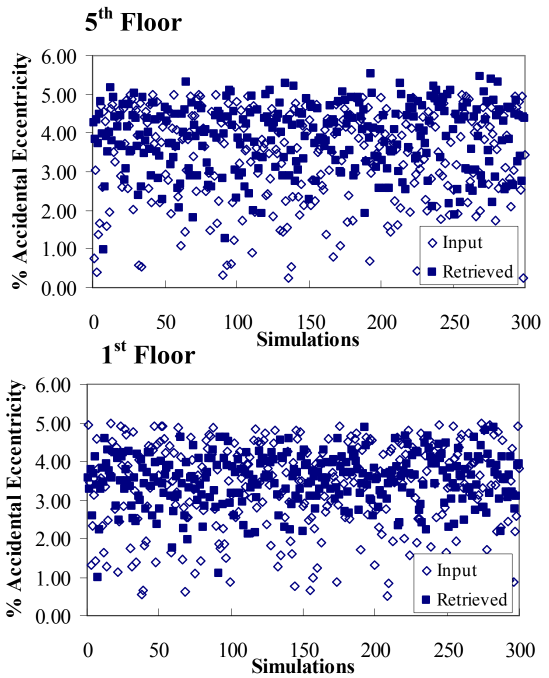

Figure 4. Input versus retrieved eccentricities for 5-story building – Upper triangle PDF (0% , +5%)

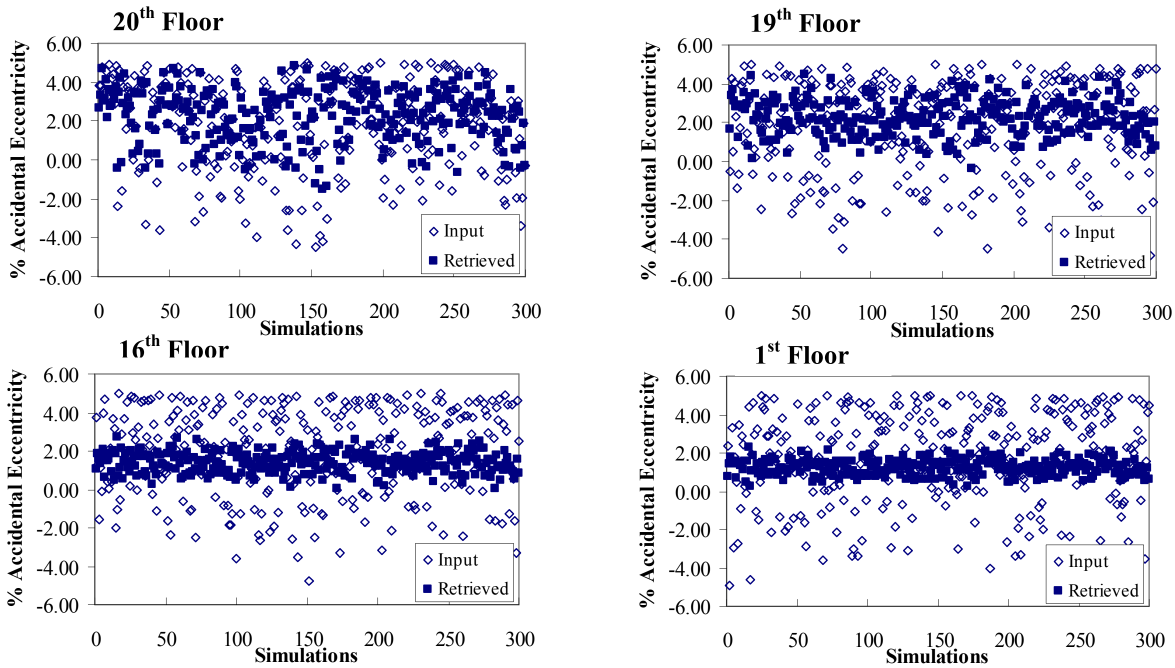

Figure 5. Input versus retrieved eccentricities for 20-story building – Upper triangle PDF (-5% , +5%)

For design purposes, we may be generally more interested in reporting absolute (i.e., overall or global) maximum value of the 300 retrieved accidental eccentricities at each floor level. However, associated notion of scatter of these 300 recovered values may be of some importance in order to assess the global picture and to avoid erratic values, if any. Such erratic values, in statistical terms, refer to *outliers*, or individual observations that are significantly larger or smaller than the rest of the sample data points. A simple approach to introduce information about the dispersion in recovered *maximum* eccentricities is to compute different values corresponding to different percentiles. Sample percentiles are computed by counting data previously sorted in ascending order. Retrieved *maximum* eccentricity values corresponding to sample percentiles of 10%, 50% (i.e., counted median), 90% and 100% (which is basically the overall absolute maximum value) are reported in Figure 6 for selected buildings under investigation. From this figure, one can easily notice the reduction in the maximum retrieved eccentricity at lower stories relative to top stories of a given building, along with higher dispersion (i.e., scatter) in these recovered values at high floors relative to bottom ones. However, such reduced scatter in retrieved eccentricities at lower stories is only taking place for medium- to high-rise buildings (i.e., B-NF10, B-NF15, and B-NF20). Conversely, for low-rise buildings such as B-NF5, the scatter in retrieved floor eccentricities, at different levels, looks very comparable. It is also important to highlight the bulge in the distribution of retrieved maximum eccentricities for B-NF20 occurring between the 5th and 8th floors. This anomaly is in contrast with the rather constantly climbing trend of the distribution of retrieved maximum eccentricities up the height generally observed for other investigated (lower) buildings. It may be directly associated with significant contribution from higher vibration modes for the case of the 20-story building as may be intuitively expected.

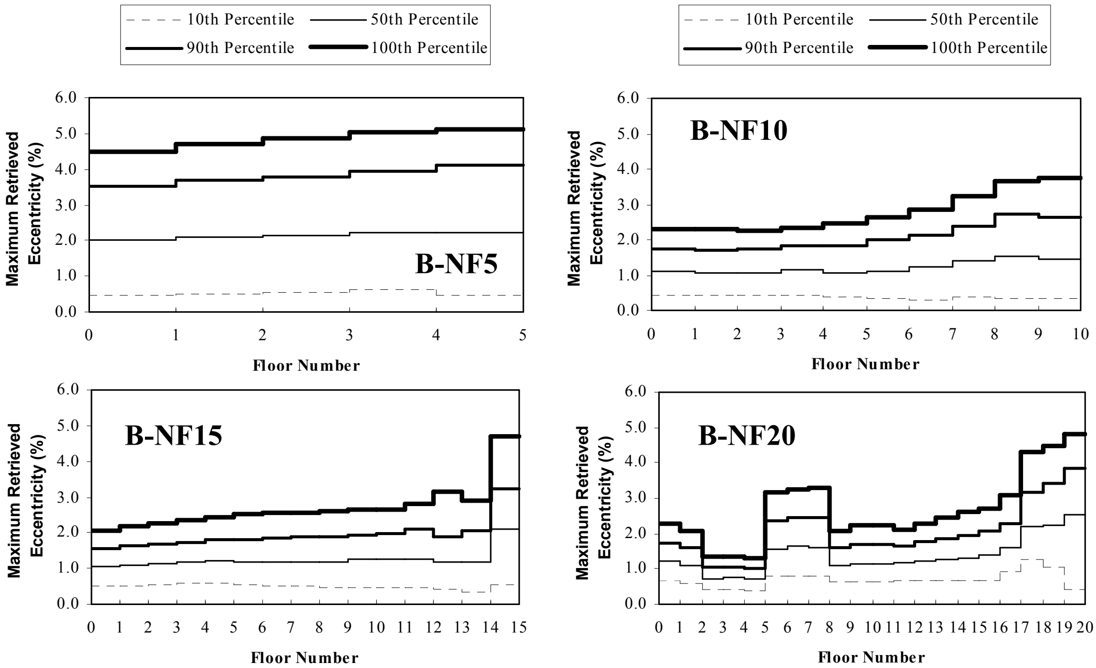

Figure 6. Percentiles of retrieved accidental eccentricities at different floors for some selected buildings – Case of upper triangle PDF (-5% , +5%).

For a conclusive study, COV, being a more comprehensive statistical parameter than just simple percentiles, is also computed to quantify total dispersion (i.e., scatter) in the retrieved *maximum* accidental eccentricities for different studied PDFs and buildings. However, COV values are presented in a comparative or relative format (designated herein by γ_{COV}) in Figure 7 dividing COV of the retrieved maximum eccentricities by COV of randomly generated input accidental eccentricities. It may be observed from the figure that the scatter in the retrieved eccentricities is always significantly less than that in the input randomly generated eccentricities, especially for higher buildings. For example, γ_{COV} takes values between about 0.25 and 0.45 for all stories of B-NF15, and between about 0.4 and 0.6 for all stories of B-NF5. The substantial reduction in the dispersion of the output eccentricities recovered from torsion response demands from THAs relative to the input eccentricities is a result of the integration of the equation of motion. The integration operation, as expected, generally smoothens up the scatter in any response parameter relative to its input counterpart. Figure 7 also presents other statistical measure – still given in a dimensionless (relative) format – for B-NF5 and B-NF15 as sample investigated buildings. It is γ_{max}, referring to the overall maximum retrieved eccentricity divided by the corresponding overall maximum input eccentricity at different stories. It may be identified that the global retrieved maximum eccentricity at all floors for the two buildings is always less than the maximum input random value ($\gamma_{max} < 1$), again with the highest observed γ_{max} occurring at top stories. However, for low-rise buildings (e.g., B-NF5), γ_{max} values reside in a very small range (between 0.9 and 1.0) at all floors, while for high-rise buildings (e.g., B-NF15), γ_{max} values are spread over a wide range from about 0.4 at bottom of the building up to about 1.0 at top story. This observation implies that for design purposes one would assume same accidental eccentricities to be considered at all floors for a low-rise building. On the other hand, a smart distribution for imposed design accidental eccentricities should be recognized for high-rise buildings assigning higher values to top stories relative to bottom ones. It is also worth mentioning that statistical observations emphasize the fact that recommended design accidental eccentricities should rather be reliably based on either the overall maximum retrieved value (not the average) or at least a value corresponding to an appropriate conservative percentile such as the 84th percentile or larger. Such decision must rely on detailed calculations studying required confidence intervals and specific inherent design code strategy for provided reliability of designed structures.

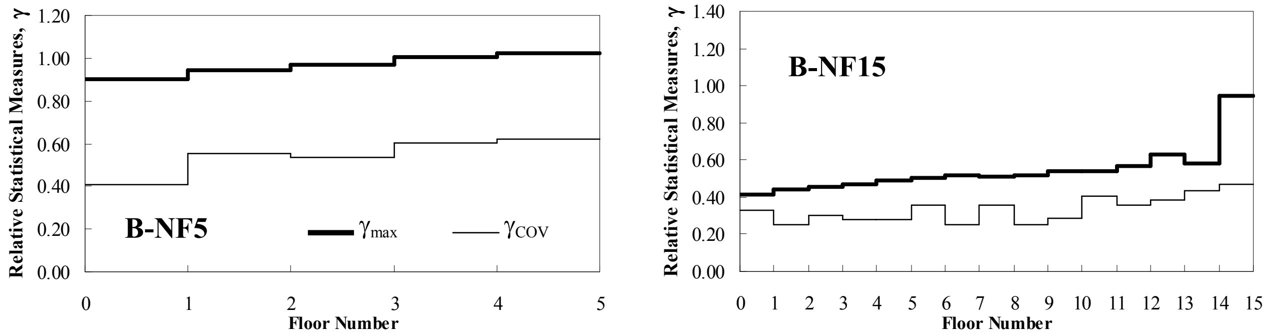

Figure 7. Relative statistical measures, γ, at different stories for B-NF5 and B-NF15 buildings – Case of upper triangle PDF (-5% , +5%).

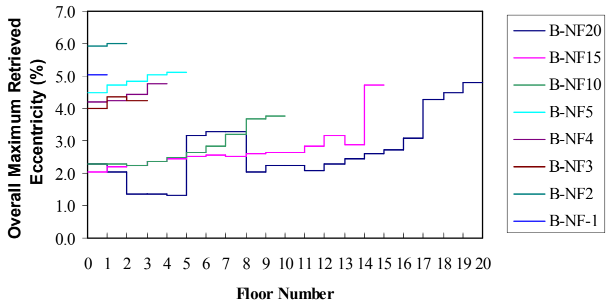

Figure 8. Building Spectrum Curves (BSC) for overall maximum retrieved accidental eccentricity – Upper triangle PDF (-5% , +5%).

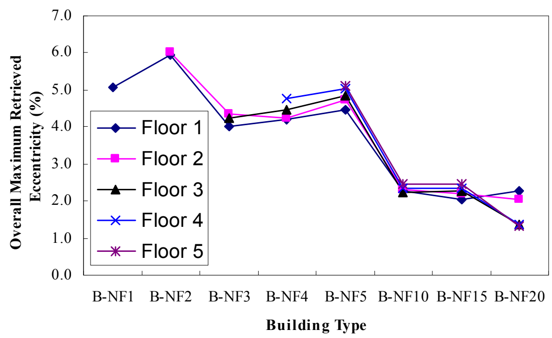

Figure 9. Sample Floor Spectrum Curves (FSC) for overall maximum retrieved accidental eccentricity – Upper triangle PDF (-5%, +5%).

It has been also found very appealing and illustrative, from a design perspective, to present the above statistical results in the following format: (1) Building Global Maximum Eccentricity *Spectrum* Curve; and (2) Floor Global Maximum Eccentricity *Spectrum* Curve. The title of these curves refers to the "loose" definition of the term *spectrum* meaning sweeping full band or range of a given parameter. The Building Spectrum Curve (BSC) gives, for each considered PDF, the overall absolute expected *maximum* eccentricity at each floor level of this building of interest. On the other hand, and for a complete visualization of the problem, the Floor Spectrum Curve (FSC) presents, again for each considered PDF, overall absolute expected *maximum* eccentricity at the given floor of interest for different studied buildings (B-NF1 to B-NF20). These spectra may generally be generated for the different percentiles mentioned above. They are however presented in this paper only for the 100th percentile (i.e., overall absolute maximum retrieved eccentricity) for illustration purposes. Figure 8 gives BSC for all investigated buildings for the upper triangle PDF as an example. Data in these curves show that the global (i.e., overall) maximum retrieved accidental eccentricity at all floors of low-rise buildings (up to 5 stories) may be reasonably and conservatively assumed in the order of 5% as per most seismic design codes. It is also clear that the retrieved accidental eccentricity decreases downwards, i.e., with more stories included above the story of interest. Same trend is clearly observed for higher buildings (B-NF10 to B-NF20) with the overall maximum retrieved eccentricity generally assuming lower values than the limiting code-prescribed design accidental eccentricity. This emphasizes previous observations that are stated above supported by results and figures. Same tendency of results takes place for both upper triangle and uniform PDFs but with the latter showing slightly lower retrieved eccentricity values as expected by intuition. This is due to intrinsic bias of the former PDF towards higher input accidental eccentricities and consequently larger recovered eccentricities. To complete the whole picture, sample FSCs are given in Figure 9 for a few selected floors for the different studied buildings, corresponding to the upper triangle PDF. Same trend highlighted before regarding distribution of overall maximum retrieved accidental eccentricities up the height of buildings may be again inferred from Figure 9.

5. CONCLUSIONS

The main results presented above clarify that (1) the computed (*retrieved*) accidental eccentricities (i.e., demand) at each floor level are affected by the number of floors above the floor of interest; and that (2) such accidental eccentricity demands are often lower than the typical value of 5% specified in building codes for the floors with a larger number of stories above. The paper thus addresses the community of seismic design codes developers promoting to include such conclusions in the updates of current versions of seismic design provisions. The main recommendation worth to be implemented is to relax (i.e., to prescribe a value less than 5%) the required accidental eccentricity for the determination of the design accidental torsional moment, and hence the distribution of the associated story shear among the various lateral-resisting elements, in the lower stories of multi-story buildings. Adopting the design value of 5% at all floors is kept for low-rise buildings (up to 5 floors) for conservatism. However, for higher buildings, it is initially proposed to assign a design accidental eccentricity of 5% to the upper quarter of the building, a value of 3% to the middle half, and a value of 2% to the lower quarter.

To conclude, the research presented herein is a benchmark and a preliminary step in this critical design subject of accidental eccentricity for multi-story buildings typically empirically dealt with. Further effort, looking at different buildings layouts, other ground records, and introducing uncertainty in the stiffness of various lateral resisting elements is yet to be spent prior to largely adopt the proposed design values or to extrapolate them to higher structures. However, trends of results showing that the accidental eccentricities and hence the accidental torsional demands decrease downwards in multi-story buildings are believed to remain valid.

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