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# TORSION EFFECTS IN BUILDING SEISMIC PERFORMANCE

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The paper considers torsion effects that occur during the building response to seismic action. Computation and parametric analysis are conducted for various values of building eccentricity induced by mass and stiffness variation. Such a model accounts for the actual dynamic effect of accidental eccentricity, usually considered in building design by quasi-static value of the torsion moment. Two types of models are employed to explore dynamic parameters of the building. The models are formed using Wolfram Mathematica software in which the mass and stiffness properties are parametrically related to the basic dynamic characteristics of the building. The commercial software package CSI ETABS ver.17 is used for validation of the model. Seismic performance of the building is evaluated, and the results of the parametric analysis are presented using the shear forces and torsion moment. The analysis showed that the nature of eccentricity has a major influence on distribution of seismic forces due to the torsion.

*Keywords*: Parametric analysis, Eccentricity, Mass variation, Stiffness variation.

## 1 INTRODUCTION

The damage in the structural elements at the building perimeter is usually caused by torsion effects during earthquakes. Torsion response significantly depends on the position of the mass center (CM), stiffness center (CR), and their eccentricity (Anagnostopoulos *et al.* 2013). In some buildings, mass distribution has been modified over time due to changed purpose. The occupants have often removed some of the supporting elements without doing an overall seismic retrofit. Furthermore, local stiffness reduction can be a result of a previous earthquake response that did not endanger overall structural integrity. The result of variation in mass and/or stiffness distribution is the eccentricity (*Ecc*) of CM and CR in each story, which exists even in buildings with a symmetric plan. The design provisions recommend the eccentricity value of 5% of a certain plan dimension (Eurocode 8 2004). Moreover, non-uniform distribution in mass and stiffness causes variation in basic dynamic parameters of a structure, such as its natural periods, mode shapes, mass contribution factors, etc. (Raduka and Nikolic 2010). In this paper, the effect of different mass and stiffness distribution on the torsional response of the building is evaluated through the primary dynamic parameters of the structure.

## 2 MODEL DESCRIPTION

This paper deals with a two-story building (Figure 1) with reinforced concrete walls and columns. The story height is 4 m and the grid dimension is 5 m. Slabs and walls are 15 cm thick except wall A2, which is 30 cm. Columns have 30 cm × 30 cm square cross-section. The building is symmetric regarding the *y*-direction. General position of the mass center (CM) and the rigidity center (CR) eccentricity is shown in Figure 1(a). Seismic action is considered only in the *x*-direction, and it induces translation and torsional response. The building is vertically loaded with self-weight and additional load of $q = 2\ \text{kN/m}^2$. The stiffness of the main structural elements is determined according to the beam theory with elasticity modulus $E = 2.1\times10^7\ \text{kN/m}^2$. Parametric analysis is performed through mass and stiffness variation. Mass is varied using the additional weight according to the scheme shown in Figure 1(a). In order to keep the same mass during the analysis, the load distribution is assigned as $q_1 = (1-a)q$, $q_2 = q$, and $q_3 = (1+3a)q$, in which parameter *a* accounts for uneven mass distribution. The second parametric analysis concerns the change in stiffness of walls A1 and A2 (on both stories) by using parameter *c* that is $k_{\text{A1}}(1+c)$ and $k_{\text{A2}}(1-c)$, where $k_{\text{A1}}$ and $k_{\text{A2}}$ are stiffness of walls A1 and A2, respectively. Since symmetry in mass and stiffness about axis *y* is not perturbed, the *Ecc* of CM and CR is only present in *y*-direction.

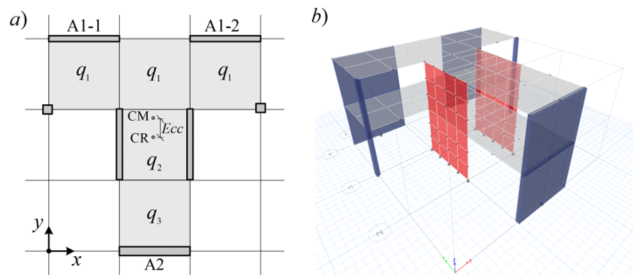


Figure 1. a) Building plan; b) Numerical model in ETABS.

## 2.1 Simplified Mathematical Model

The simplified 6 DOF model with two horizontal translations and rotation about the vertical axis in the CM of each story is formed using mathematical software Wolfram Mathematica (WM model). Stiffness of the walls takes into account shear and flexural deformations, and the local stiffness matrix can be seen in Eq. (1):

$$k = \begin{bmatrix} \dfrac{12\,EI_w\,GA\,(3\,EI_w + GA_w\,h^2)}{36\,(EI_w)^2\,h + 60\,EI_wGA_w\,h^3 + 7\,(GA)^2\,h^5} & \dfrac{-6\,EI_w\,GA_w\,(6\,EI_w + 5\,GA_w\,h^2)}{36\,(EI_w)^2\,h + 60\,EI_wGA_w\,h^3 + 7\,(GA)^2\,h^5} \\ \dfrac{-6\,EI_w\,GA_w\,(6\,EI_w + 5\,GA_w\,h^2)}{36\,(EI_w)^2\,h + 60\,EI_wGA_w\,h^3 + 7\,(GA)^2\,h^5} & \dfrac{12\,EI_w\,GA\,(3\,EI_w + GA_w\,h^2)}{36\,(EI_w)^2\,h + 60\,EI_wGA_w\,h^3 + 7\,(GA)^2\,h^5} \end{bmatrix} \quad (1)$$

where *A* and $I_w$ are area and moment of inertia of a cross-section, *h* is the story height and *G* and *E* are shear modulus and modulus of elasticity, respectively. Columns are modeled as frame elements considering flexural deformations.

## 2.2 Software Generated Model and Verification

The numerical model of the building is created using software package CSI ETABS ver.17 (2018). Rigid diaphragms are defined for slabs in each story, and the story total mass is reduced to CM. ETABS models are used only for verification of models created in Wolfram Mathematica. Several models with different values of parameters *a* and *c* are obtained. No significant differences in basic building characteristics (Table 1) were noticed, so the WM model is used for further detailed parametric analysis.

Table 1. Values of basic building characteristics for the initial model (*a*=0*, c*=0).

| | Story | Mass ton | Inertia Moment ton-m² | XCM m | YCM m | XCR m | YCR m | EccY |
|---|---|---|---|---|---|---|---|---|
| ETABS model | Story2 | 95.7679 | 3432.29 | 7.500 | 9.035 | 7.500 | 7.548 | -1.486 |
| | Story1 | 95.7679 | 3432.29 | 7.500 | 9.035 | 7.500 | 7.534 | -1.500 |
| WM model | Story2 | 95.7592 | 3427.96 | 7.500 | 9.035 | 7.500 | 7.512 | -1.523 |
| | Story1 | 95.7592 | 3427.96 | 7.500 | 9.035 | 7.500 | 7.507 | -1.528 |

Table 2. Dynamic properties of initial model (*a* = 0 and *c* = 0).

| Mode | ETABS model | | | | WM model | | | |
|---|---|---|---|---|---|---|---|---|
| | T (s) | Mx | My | MRz | T (s) | Mx | My | MRz |
| 1 | 0.116 | 0 | 0.833 | 0 | 0.117 | 0 | 0.828 | 0 |
| 2 | 0.087 | 0.755 | 0 | 0.076 | 0.086 | 0.752 | 0 | 0.075 |
| 3 | 0.062 | 0.076 | 0 | 0.755 | 0.062 | 0.075 | 0 | 0.752 |
| 4 | 0.029 | 0 | 0.167 | 0 | 0.028 | 0 | 0.172 | 0 |
| 5 | 0.021 | 0.153 | 0 | 0.016 | 0.021 | 0.157 | 0 | 0.016 |
| 6 | 0.015 | 0.016 | 0 | 0.154 | 0.015 | 0.016 | 0 | 0.157 |

The dynamic properties, natural periods and modal mass contribution factors in *x*, *y*, and rotation about *z*-axis, respectively, are also compared for the initial model (*a* = 0 and *c* = 0) and displayed in Table 2. It can be noticed that there are only minor differences in dynamic parameters values.

## 3 PARAMETRIC ANALYSIS RESULTS

Parametric analysis is conducted to investigate the effects of torsion during the seismic performance of the studied building. In the first group of models, only the mass is varied using parameter *a*. Therefore, in this case, the CR remains in the same place and the change of *Ecc* is achieved by different positions of the CM. In the second group of models, the CM remains in the same place while the CR changes positions. The initial coordinates of CM, CR, and eccentricity are given in Table 1. The linear variation of parameters *a* and *c* controls the eccentricity *Ecc*. The special case with no eccentricity is achieved for the mass parameter *a* of approximately 0.95 and for the stiffness parameter *c* of approximately 0.2. As can be seen in the diagrams, smaller changes in stiffness have a stronger effect on the *Ecc* compared to the changes in mass distribution (Figure 2).

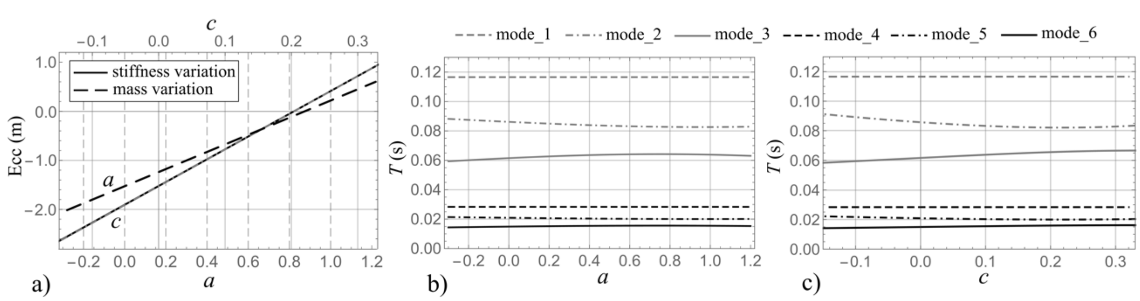


Figure 2. a) Building *Ecc* for different values of parameters *a* and *c*; b) periods by mass variation (a); c) periods by stiffness variation (c).

The basic dynamic parameters used in the parametric analysis will be briefly described here. The spatial distribution vector **s** of effective earthquake forces is defined by the summation of modal inertia force distributions $\mathbf{s}_n$ as can be seen in Eq. (2):

$$\mathbf{s} = \mathbf{m}\,\boldsymbol{\iota} = \sum_{n=1}^{N} \mathbf{s}_n = \sum_{n=1}^{N} \frac{L_n}{M_n} \mathbf{m}\,\phi_n \tag{2}$$

where $L_n = \phi_n^T \mathbf{m}\,\boldsymbol{\iota}$ is load participation factor of *n*-th mode, $\boldsymbol{\iota}$ is influence vector of ground motion, **m** is mass matrix of the system, and $\phi_n$ *n*-th eigenvector. $M_n$ represents the generalized mass of *n*-th mode. The modal mass contribution factor is $L_n^2 / M_n$ and by multiplying this value with the ground acceleration amplitude, the base shear force for the *n*-th mode is derived (Chopra 2001).

Although simple, this model represents a realistic structure made up of a wall system where the effects of a seismic excitation on the structural response can be analyzed. In order to obtain the internal forces and displacements of the structure, and due to the variability in response spectrum shapes with respect to local conditions, a uniform spectral acceleration amplitude in the *x*-direction is considered for all system modes.

## 3.1 Basic System Properties

The period values are shown in Figure 2(b) and 2(c), while the modal mass contribution factors for each type of parametric analysis are shown in Figure 3. It can be seen that periods slightly change with the variation in eccentricity. Also, it can be noticed that the 1st and 4th mode correspond to the translation in *y*-direction and they are independent of other modes. For the 2nd and 5th mode, translation in *x*-direction is dominant, while the 3rd and the 6th are dominantly torsional modes. The coupling between translation *x* and torsion mode may be observed. As expected, for the decrease in *Ecc*, the modal mass contribution factor of the 2nd mode is increasing to the maximum value of 84% for the case without *Ecc* and the contribution of torsional 3rd mode also disappears (Figure 3(a)). In Figure 3(c), the maximum values of modal mass contribution factors to moment of torsion may be observed in the case without eccentricity, while the contribution of the translational mode to rotation disappears. As a result, these two modes become independent.

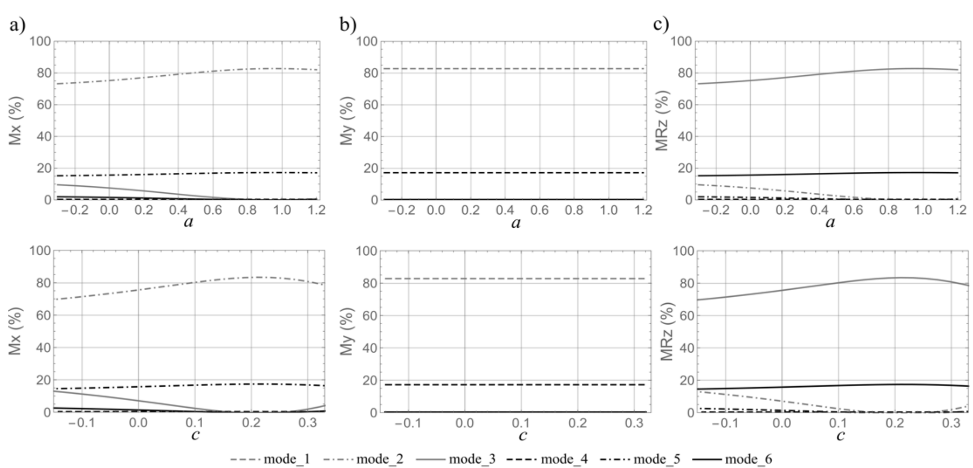


Figure 3. Modal mass contribution factors for translations and rotation.

The higher modes (5 and 6) show the same trend as the corresponding lower modes, but accounting for significantly smaller participating mass.

### 3.2 Analysis of System Forces

Further parametric computations are performed using the spectral analysis with the uniform spectral acceleration value for the 2nd mode. The spectral acceleration load with the value of the ground acceleration of approximately 0.6 g. is applied. This value corresponds to the bearing capacity of the critical wall, which is 500 kN for wall A1 and 800 kN for wall A2. Accordingly, the value of horizontal base shear force to reach the elastic limit for mass variation model BS is 960 kN (for $a = 0.95$) and for stiffness variation model, the BS is 986 kN (for $c = 0.20$). Due to the extensiveness and quantity of data, only the most important results for each mode are presented. The focus is on the modes contribution to total shear forces. The sum of BS is constant because of uniform spectral acceleration assumption.

In the Figure 4(a) it can be noticed that the influence of the 2nd mode (translation) on the BS decreases, while the influence of the 5th torsional mode increases for the larger value of eccentricity. The influence of the 5th higher translational mode remains almost the same. The base moment of axis *z*, which equals to zero for all modes when there is no eccentricity, is shown in Figure 4(b). In every other case, the 2nd and 5th mode are coupled.

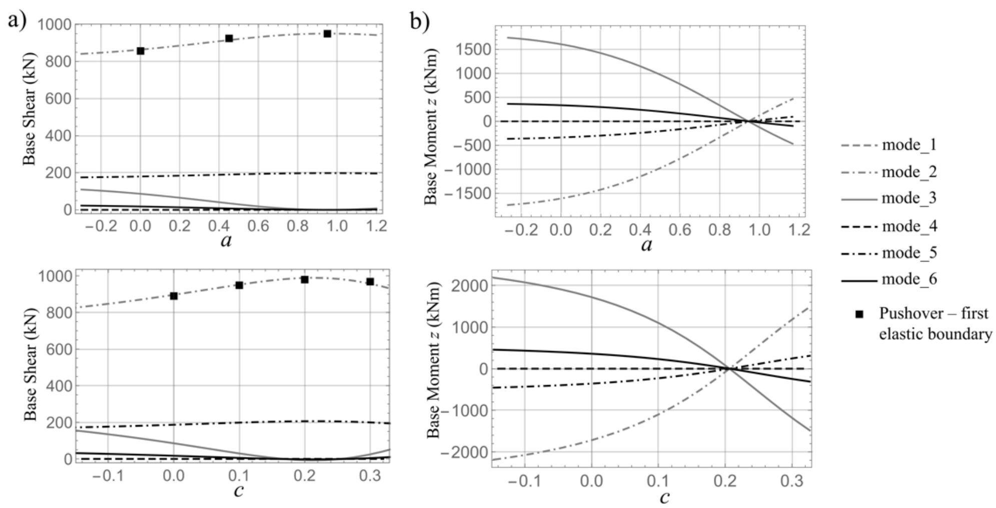


Figure 4. a) Base Shear and b) Base Moment *z*.

Figure 5(a) and 5(b) show the shear force of the wall A1 and A2 in the ground story decomposed by the vibration modes. The trend in shear force variation is similar for changing both parameters (*a* and *c*) and it is associated with eccentricity. Also, increasing the eccentricity in the positive direction generates a lower shear force on wall A1 and larger force on wall A2 for dominant modes. The influence of the torsional 3rd mode is very significant for wall A2 when the eccentricity increases in a negative direction. The influence of the translational mode is maximal in the case with no eccentricity, which is very favorable for the evaluation of the total force by using modal combination rules instead of dynamic analysis. Total forces in walls A1 and A2, obtained by CQC modal combination, are presented in Figure 5(c) for both parameters.

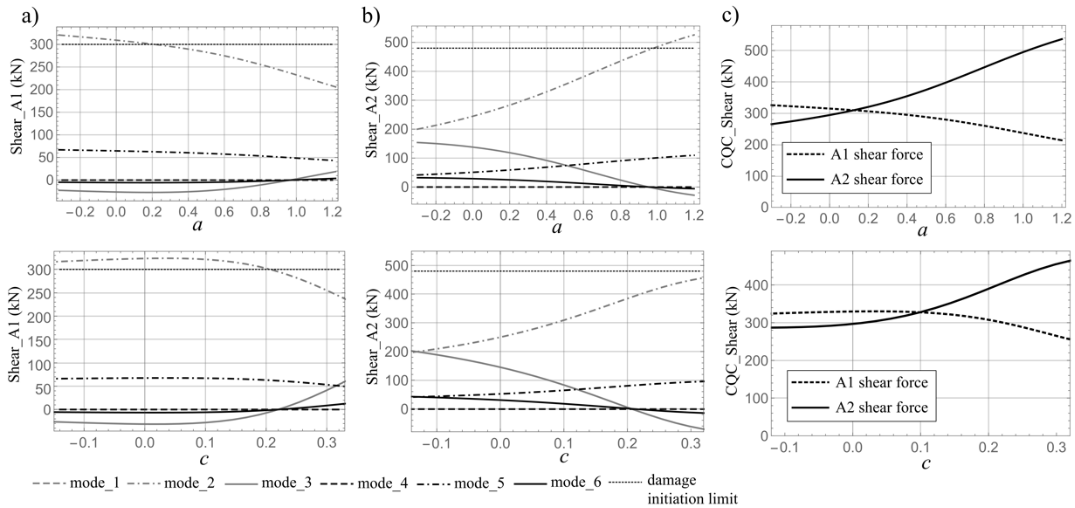


Figure 5. a) wall A1 shear force; b) wall A2 shear force; c) total forces in walls obtained by CQC.

## 4 CONCLUSION

Generally, it can be concluded that a decrease of eccentricity causes the separation of torsional and translational modes, which is favorable. More reliable results are obtained for computations using only translational components, which have a higher participation factor (simplified 2D models or pushover analysis). However, the influence of dominant torsional modes is a higher for larger values of the eccentricity, which can significantly affect the shear force in walls.

It is interesting to observe the variation of shear force in the wall A1 due to different eccentricity sources. When the parameter *a* decreases with the change of mass distribution, there is a trend of a slight increase in the shear force, whereas, in the case of a decrease in parameter *c* in the distribution of stiffness, the shear force does not tend to increase and remains approximately uniform (Figure 5(c), second diagram). The reason for this lies in the nature of the eccentricity (mass or stiffness). Unequal mass distribution causes the center of mass to change position, and thus the position of the resultant, while the stiffness of the system does not change. In the case of stiffness variation, not only the center of stiffness changes, but also the stiffness of individual walls, which results in an additional redistribution of internal forces within the system.

Finally, it is shown that any kind of structural change in mass or stiffness can have a critical influence on building torsional response during an earthquake. Further studies on mechanisms that induce eccentricity should be researched and discussed.

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