ACCIDENTAL TORSION IN THE MOROCCAN SEISMIC CODE: PARAMETRIC STUDY

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ABSTRACT

Many researchers have studied the natural torsion of buildings subjected to earthquake ground motions, but only a few of them studied the accidental torsion. The increase in response in the flexible and the stiff edges of the building due to accidental torsion is investigated in this study, using both static and time history analyses. The accidental torsion is introduced by the accidental eccentricity provided in the Moroccan seismic code: RPS2000 version 2011. Based on the results of the time history analyses, a new practical method is proposed to assess the maximum increase in response due to accidental torsion. This method is generalized to a certain category of multi-storey buildings and presents the main advantage to avoid performing many extra seismic analyses as required in the current method of the Moroccan seismic code. The new proposed method is limited to the elastic domain to be compliant with the design procedure of the Moroccan seismic code. Further studies have to be performed to assess the efficiency of the elastic seismic design procedure that guaranties that the building will reach the required seismic level of performance by inelastic deformations.

Keywords: Accidental torsion, eccentricity, frequency ratio, earthquake, Morocco.

1. INTRODUCTION

During a ground shaking, the forces applied to the lateral resisting elements of a building are inertia forces. Their resultant passes through the Center of Mass (CM) of the structure. These forces are resisted by the lateral resisting elements via their stiffness. In the elastic range, the resultant of all the resisting forces passes through the Center of Stiffness (CS) or Center of Rigidity (CR), because the force in a resisting plane is proportional to its stiffness. When the CM and the CR are coincident, the structure is referred to as nominally a symmetric-plan building. Otherwise, the distance separating them is defined as static eccentricity (e_s) and the structure is referred to as an asymmetric-plan building. Subjected to a pure translational earthquake ground motion, an asymmetric-plan building is subjected to story torques in addition to shears and overturning moments. Hence, it undergoes a rotational motion in addition to the lateral one. This rotational motion is referred to as natural torsion. It has been proved from real earthquake records of existing nominally symmetric-plan buildings, that the latter category of buildings can also undergo a rotational motion in addition to the lateral one (De la Llera and Chopra, 1994a). The main origins of these rotational vibrations are the discrepancies that exist between the mass, stiffness and strength plan-distributions used in the analysis and the true distributions at the time of the earthquake; and the base rotational motion due to a non-uniform distribution of the ground motion in the space (De la Llera and Chopra, 1994b). To account for the torsional vibrations caused by these uncertainties, an additional eccentricity is introduced in many seismic codes which is referred to as accidental eccentricity (e_{acc}). The rotational motion caused by the accidental eccentricity is referred to as accidental torsion.

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2. DATA

This study is carried out on single storey buildings using the software STructural Earthquake Response Analysis 3D (STERA 3D), elaborated by Dr. Taiki SAITO. Then the results are generalized to a certain category of multistorey buildings. The plan view from one of the studied single stories is presented in Figure 1.

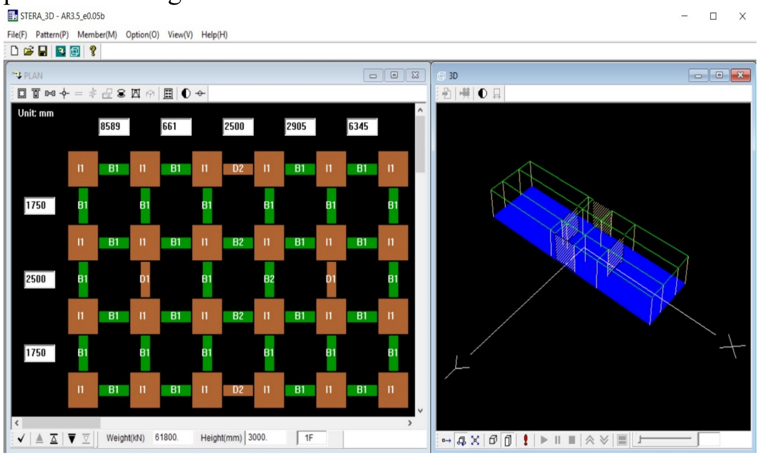


Figure 1. Plan view and perspective of the studied building.

The system is a reinforced concrete structure formed by a grid of identical columns and two different types of shear walls. During all the study, the structure remains nominally symmetric in the X direction, and the location of the shear walls in the Y direction is controlled to produce the target static eccentricity. The floor is considered rigid with a uniform distribution of the mass.

Because of the unavailability of the earthquake records in Morocco, artificial earthquake ground motions were generated with compatibility with the design spectrum proposed in the Moroccan Seismic Code. Table 1 summarizes the five seismic waveforms used in this study and Figure 2 shows an example of the generated ground motions and its compatibility with the design spectrum of the Moroccan Seismic Code.

Table 1. Generated artificial earthquake ground motions.

Artificial Earthquake Ground Motion (GM)	Nº GM
Al Hoceima (random phase)	1
Al Hoceima (El Centro phase)	2
Al Hoceima (Kobe phase)	3
Agadir (random phase)	4
Rabat (random phase)	5

Three target spectra were considered: Al Hoceima city, Agadir city and Rabat the capital. Two phases are used: The Kobe phase and the El Centro phase. A third case is added by considering a random phase and multiplying the seismic wave by Jennings Envelope.

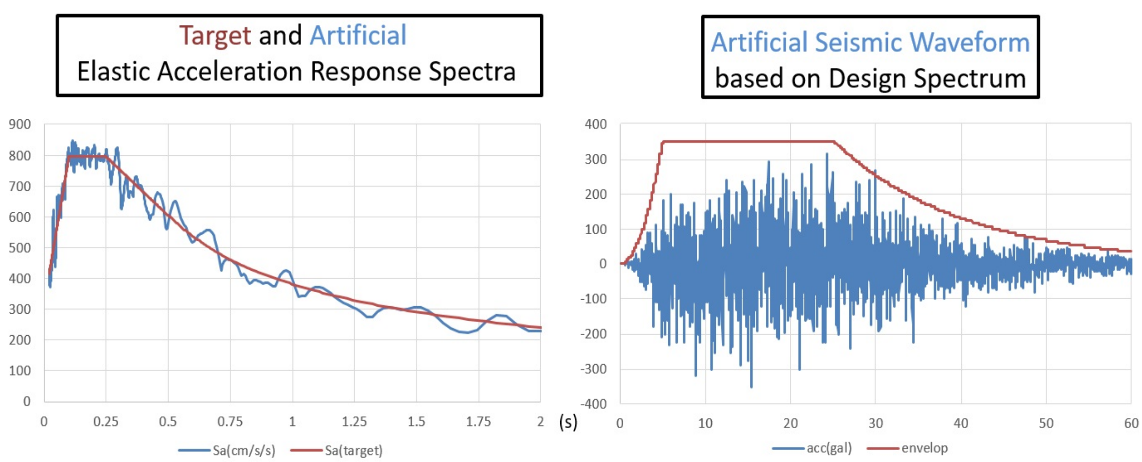


Figure 2. Artificial earthquake ground motion GM1 (Al Hoceima city).

3. THEORY AND METHODOLOGY

3.1. Theory

The ratio of the uncoupled circular frequencies of the model building is referred to as the parameter Ω, and it’s given by equation (1). It’s the main parameter that controls the increase in response due to torsion. The response of the building subjected to an earthquake ground motion can be expressed by equation (2):

$$\Omega = \frac{\omega_\theta}{\omega_y} = \frac{1}{r}\sqrt{\frac{k_\theta - k_y . {e_s}^2}{k_y}} \tag{1}$$

$$\begin{pmatrix} \ddot{u_y} \\ r\ddot{u_\theta} \end{pmatrix} + \omega_y^2 \begin{bmatrix} 1 & \frac{e_d}{r} \\ \frac{e_d}{r} & \Omega^2 + \left(\frac{e_d}{r}\right)^2 \end{bmatrix} \begin{pmatrix} u_y \\ r u_\theta \end{pmatrix} = -\begin{pmatrix} \ddot{u_{gy}} \\ 0 \end{pmatrix} \tag{2}$$

where ω_y and ω_θ are the uncoupled circular frequencies of the building, k_y is the lateral stiffness in the Y direction, k_θ is the rotational stiffness around the CM, e_s is the static eccentricity in the Y direction, u_y and u_θ are respectively the translation in Y direction and the rotation around the vertical axis Z through the CM, r is the mass-radius of gyration, e_d is the design eccentricity, and u_{gy} is the ground displacement in Y direction.

3.2. Methodology

Three different static analyses are needed to calculate the increase in displacement in the flexible edge ($I_{f,st}$), respectively in the stiff edge ($I_{s,st}$), for a specific model building. Figure 3 highlights the three analyses with three different colors: black color for the 1st seismic analysis using only the static eccentricity as a design eccentricity (the effect of the accidental torsion is not included), red color for the 2nd seismic analysis with the CM shifted by $0.5e_s + 0.05b$ to the flexible side, and green color for the 3rd seismic analysis with the CM shifted by 0.05b to the stiff side. By the 1st analysis (black color), the displacements in Y direction $U_{y,f}$ and $U_{y,s}$ respectively in the flexible and the stiff edge are determined. These latter displacements do not include the effect of the accidental torsion. The 2nd analysis (red color) produces the greatest displacement in the flexible edge $U^*_{y,f}$ including the effect of the accidental torsion. The 3rd analysis (green color) produces the greatest displacement in the stiff edge $U^*_{y,s}$ including the effect of the accidental torsion. Finally, the ratios of these 4 determined displacements are calculated to get the investigated parameters $I_{f,st}$ and $I_{s,st}$.

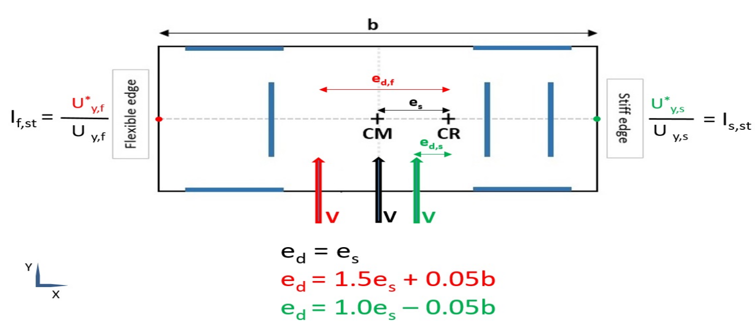


Figure 3. Calculation of the investigated parameters by the static analysis.

Three different time history analyses are needed to calculate the increase in displacement in the flexible edge ($I_{f,dy}$), respectively in the stiff edge ($I_{s,dy}$) for a specific model building. Figure 4 highlights the three analyses with three different colors: black color for the 1st seismic analysis using only the static eccentricity as a design eccentricity (the effect of the accidental torsion is not included), red color for the 2nd seismic analysis with the CM shifted by 0.05b to the flexible side, and green color for the 3rd seismic analysis with the CM shifted by 0.05b to the stiff side. By the 1st analysis (black color), the maximum displacements in Y direction $U_{y,f}$ and $U_{y,s}$ respectively in the flexible and the stiff edges are determined. These latter displacements do not include the effect of the accidental torsion. By the 2nd analysis (red color), the maximum displacements in Y direction $U^*_{y,f}$ and $U^*_{y,s}$ respectively in the flexible and the stiff edges are determined, whose displacements include the effect of the accidental torsion (e_{acc}=-0.05b). By the 3rd analysis (green color), the maximum displacements in Y direction $U^*_{y,f}$ and $U^*_{y,s}$ respectively in the flexible and the stiff edges are determined, whose displacements include the effect of the accidental torsion (e_{acc}=+0.05b). Finally, the maximum ratios of these 6 determined displacements are calculated to get the investigated parameters $I_{f,dy}$ and $I_{s,dy}$.

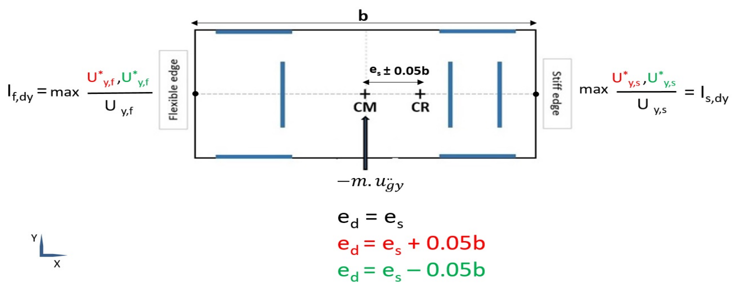


Figure 4. Calculation of the investigated parameters by time history analysis.

4. RESULTS AND DISCUSSION

4.1. Design envelopes

The new proposed method to evaluate the effect of the accidental torsion is based only on the results of the time history analysis, which is considered more reliable than the static analysis because it represents the true behavior of the building under earthquake ground motions. It has been proved that the greater the aspect ratio is, the greater is the increase in edge displacements. Hence, the aspect ratio is fixed to 3.5, which is the highest value permitted for regular buildings in the Moroccan Seismic Code. The target spectrum does not affect on the investigated parameters, which are normalized displacements, as long as the analysis is limited to the elastic range. More than 2000 time history analyses have been performed by changing the parameter Ω (from 0.7 to 1.6), the uncoupled lateral period T_y (from 0.2s to 2.0s), the phase (El Centro, Kobe, Random) and the static eccentricity e_s (0.00b, 0.05b, and 0.09b). Envelopes of the final results are proposed for each value of static eccentricity and both edges. Figures 5 and 6 summarize the proposed design envelopes.

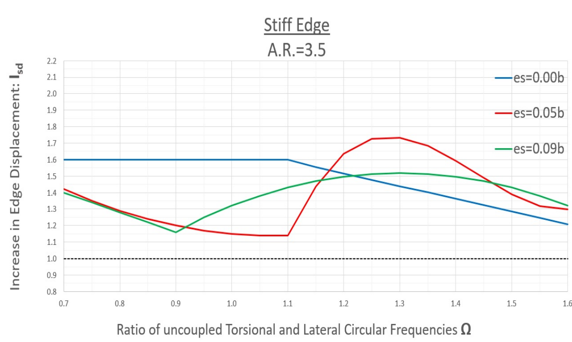


Figure 5. Design envelopes for the stiff edge

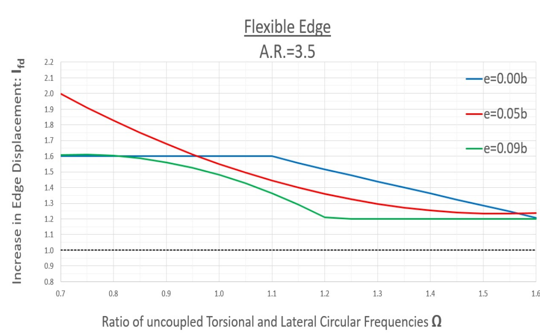


Figure 6. Design envelopes for the flexible edge

4.2. New Proposed Method

To improve the torsional provisions on the Moroccan seismic code RPS2000 Version 2011, a new practical method is proposed to evaluate the effect of the accidental torsion. The main advantage is to avoid performing many extra seismic analyses as required in the current version of the code, which is time-consuming and cumbersome. The new method is so far applied only to regular multi-storey buildings, and it's summarized in the following steps:

- ✓ Do the linear seismic analysis without considering the accidental eccentricity.
- ✓ Determine the equivalent single degree of freedom (Ω_{equi}, $e_{s,equi}$).
- ✓ Determine I_{fd} and I_{sd}, respectively for the increase in the flexible and stiff edges due to accidental torsion using the design envelopes (Figures 5 and 6).
- ✓ Calculate the increase in displacement of any resisting element due to accidental torsion, using only its distance from the center of rigidity (Figure 7).

Flexible side: $$I(x) = 1 + \frac{x}{d_{fe}} \times (I_{fd} - 1)$$

Stiff side: $$I(x) = 1 + \frac{x}{d_{se}} \times (I_{sd} - 1)$$

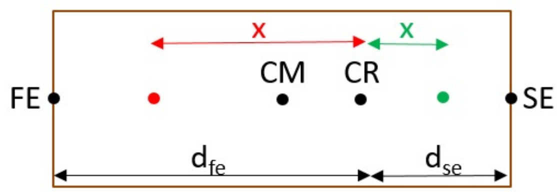


Figure 7. The Distance of resisting elements from the CR.

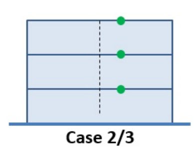
- ✓ Amplify the element forces obtained in the first step by the calculated increase in displacement.

An example of three storey building has been studied to show how the new proposed method to account for the influence of the accidental torsion can be used by practitioner engineers, and to highlight its advantages with respect to the one proposed in the Moroccan seismic code. Three earthquake ground motions are considered. The increase in edge displacement of each storey calculated by the current method of the Moroccan Seismic Code (27 dynamic analyses for each ground motion) and the maximum increase in edge displacement calculated by the proposed method (only one seismic analysis for each ground motion) are summarized in Figure 8. The increase in edge displacement, calculated by the proposed method is equal to 1.5, whereas the maximum value from the current method of the Moroccan Seismic Code is estimated at 1.4816. This example shows how practical and how accurate is the proposed procedure.

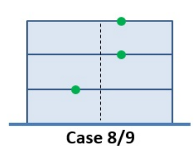
Increase in edges displacement due to accidental eccentricity: e_{acc}=0.05b

Current method of the Moroccan seismic code
(**27** dynamic seismic analyses /GM)

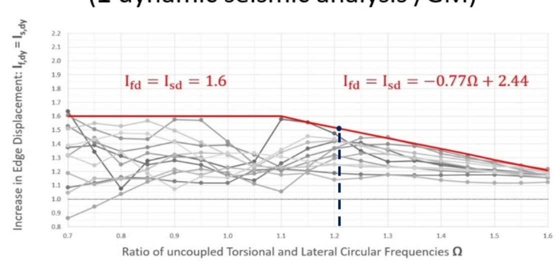
Story	Increase in edge displacement		
	GM1	GM2	GM3
3	1.3662	1.4095	1.4537
2	1.3649	1.3895	1.4656
1	1.3615	1.3706	1.4816



Story	Increase in edge displacement		
	GM1	GM2	GM3
3	1.3749	1.3871	1.4107
2	1.3684	1.3647	1.4180
1	1.3531	1.3369	1.4202



New proposed method
(**1** dynamic seismic analysis /GM)



$\Omega = 1.21$

Increase in edge displacment = 1.5

Figure 8. Increase in edge displacements of a regular three storey building

5. CONCLUSIONS

The investigation of the increase in edge displacements due to torsion has led to the following conclusions:

- ✓ Many parameters influence the increase in edge displacements due to the accidental torsion. The circular frequency ratio Ω is the most significant. For values of Ω greater than 1.1, the building is considered torsionally stiff, and the total response is mainly due to the lateral movement rather than the torsional one. For small values of Ω, let's say less than 1.1, the building is torsionally flexible and the influence of the torsional motion becomes significant.
- ✓ The increases calculated by the equivalent static method and the time history analysis are different, which means that the torsional provisions of the Moroccan and other worldwide seismic codes have to be revised.
- ✓ The increases in the stiff and the flexible edges are different because the torsional movement in the first one is opposite to the lateral one, whereas they are complementary in the flexible edge.
- ✓ Nominally symmetric-plan buildings are more sensitive to the introduction of the accidental eccentricity, and the resulting increase in edge displacements can reach 1.6 in some cases.
- ✓ The new proposed method to improve the torsional provisions of the Moroccan seismic code is based on design envelopes. This method can quickly and easily evaluate the maximum increase in edge displacements due to accidental torsion.

6. RECOMMENDATION

The proposed design envelopes are obtained from results of buildings with an aspect ratio of 3.5 and three different static eccentricities (0.00b, 0.05b, and 0.09b). Hence, these results cover all the regular buildings as defined in the Moroccan seismic code, but not always accurate (especially if the aspect ratio is small). A Similar procedure of determining the design envelopes has to be done for buildings with other values of the aspect ratio and the static eccentricity, to increase the accuracy of the results and to expand its use to all categories of buildings. An analytical study is to be performed to generalize the results of the one-story building to all types of multi-storey buildings. A stiffness proportional damping matrix is considered in this study. The contribution of the higher modes of vibration, thus the results, can change if other type of damping matrix is to be considered.

This study is performed in the elastic domain to be compliant with the Moroccan seismic code. The efficiency of this design procedure is to be assessed by studying the effect on the ductility on the torsional response and by performing nonlinear time history analyses.

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