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MEASURING THE DYNAMIC AMPLIFICATION PORTION OF NATURAL TORSION BASED ON THE 3D-SAM METHOD AND SENSING TESTS

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Abstract

16 low to mid-rise irregular buildings located in Montreal, Canada have been tested under ambient vibrations and are analyzed with a novel three-dimensional seismic assessment method (3D-SAM) and software directly based on ambient vibration records. This method performs time-history analysis of the buildings based on their modal properties extracted from sensing tests and input earthquakes without creating a finite element model. Results of this analysis are response histories of resultant forces and twisting moments on each floor. With these results, the dynamic amplification portion of natural torsion of the dataset is calculated and discussed in the paper. The mean value and mean plus one standard deviation of the equivalent measured eccentricities that can represent the dynamic torque acting at the floor centre of mass were shown to be almost 12% and 18% of the plan dimension perpendicular to the direction of the seismic loading, respectively, for the whole database. The proposed methodology is appropriate for large scale assessments of existing buildings, and is applicable to any seismic region of the world. The authors suggest using the same procedure for other cities with different seismicity, to get an estimate range of the dynamic amplification portion of natural torsion of real buildings.

Keywords: 3D-SAM, ambient vibration tests, dynamic amplification portion of natural torsion, irregular buildings, torsion

1. Introduction

Eccentricities between the centres of mass and rigidity at various floor levels in a building cause torsional motion during an earthquake. Seismic torsion leads to increased floor displacements and accelerations at the extremities of the buildings. Structures with non-coincident centres of mass and rigidity are referred to as asymmetric structures and the torsional motion induced by asymmetry is referred to as natural torsion. Asymmetry does in fact exist even in a nominally symmetric structure because of uncertainty in evaluation of the floor centres of mass and rigidity, construction tolerances and variability in the dimensions of structural elements, or lack of precise data on material properties. Moreover, torsional vibration may even result from rotational motion of the ground about the vertical axis. Torsions coming up from undetermined asymmetry and ground rotational motion are together referred to as accidental torsion [1].

In the simplified quasi-static seismic analysis procedure of the National Building Code of Canada (NBC 2010 section 4.1.8.11 [2]) torsional effects are considered by applying torques about a vertical axis at each floor level, derived separately for each of the following load cases considered:

$$T_x = F_x(e_x \pm 0.1D_{nx}) \tag{1}$$

Where F_x is the lateral force at each level and D_{nx} is the plan dimension of the building at each level x perpendicular to the direction of seismic loading being considered. Also, e_x is the natural eccentricity, i.e. that due to the centres of rigidity and mass being at different positions. De La Llera and Chopra [3] have shown that the portion $0.05D_{nx}$ represents accidental torsion; the remainder takes into account natural torsion, including its dynamic amplification.

Moreover, NBC requires three-dimensional dynamic analysis for torsionally sensitive structures, i.e. for which the sensitivity parameter B>1.7 (B is determined as the maximum value of B_x for each level; where $B_x = \frac{\delta_{max}}{\delta_{ave}}$, δ_{max} and δ_{ave} are maximum and average displacements of the building at extreme points of level x, respectively). In the case of dynamic analysis, accidental torsion is accounted by an additional torque equal to $0.1D_{nx}F_x$ instead of $0.05D_{nx}F_x$ to also include dynamic amplification of the static effect of accidental eccentricities.

The NBC provisions for design against torsion are based on studies of the elastic response of torsionally unbalanced buildings to earthquake motion, and to a large extent based on the elastic response of a simple idealized asymmetric single-story building [1, 4]. Therefore, this topic still needs further investigations to consider other effects on torsion such as those due to vertical irregularities and eccentricities in multi-story buildings.

Owing to technological advances in sensing techniques, ambient vibration testing (AVT) has received more attention since the 1990s and has become the most popular method for testing real structures in recent years. AVT is of easy application in large structures, unlike large machinery associated with forced vibration tests, is low cost and its results are reliable. High resolution sensors are now available at relatively low cost and can measure very small ambient accelerations/velocities in buildings.

The purpose of AVT is to obtain the in-situ dynamic characteristics of a structure; its natural frequencies, mode shapes and modal damping estimates. Unlike forced vibration testing, the forces applied to the structure in ambient vibration testing are not controlled: The structure is assumed to be excited by wind, traffic, microtremors, and human activities. The measurements (velocities and/or accelerations) are taken for several minutes in the normal operational conditions of the structure, to ensure that all the modes of interest are sufficiently excited. In the modal identification of output-only systems the input loads are unknown and, thus the modal identification has to be carried out based on the responses only.

Although the displacements detected in both ambient and vibration generator tests are very small, vibrator-induced motions may be several orders of magnitude greater than ambient vibrations. However, many studies [5-7] have shown that forced and ambient tests will lead to consistent agreement of modal parameters of the building structure.

In this research, TROMINO® sensors (portable ultra-light seismic noise acquisition system, 1.1 kg per unit) are used to measure ambient vibrations in buildings (http://www.tromino.eu/). Each sensor is equipped with three high gain orthogonal electrodynamic velocimeters (seismic microtremor acquisition), three low gain orthogonal electrodynamic velocimeters (strong vibration acquisition, e.g. traffic on bridges and similar), and three orthogonal digital accelerometers (scale ±5g). In AVT, normally results of the three high gain velocimeters are used, however, it is recommended to keep all the channels active during tests. These sensors use geophones to achieve the very high sensitivity that is needed during ambient vibration tests, cover the frequency range of interest, and have 24 bits analog-to-digital convertors for high resolution and low noise performance of 0.5 µV rms at 128 Hz sampling frequency.

The first step of a successful AVT is to determine the layout of the sensors on building floors and throughout the structure. The main principle in selecting the measuring points is to distribute the sensors in such a way that all the desired mode shapes be derived from the test. Therefore, sensors need to be located in positions that can capture the deformed shapes of a particular mode with the needed resolution. Usually, the number of sensors is less than the number of required measurement nodes (e.g. 6 sensors were available for this study), therefore, several test setups are typically needed to perform AVT in a building. One or two sensors are required to be used as reference sensors; they remain in the same location and are active during all test setups. The other sensors are called roving sensors and are moved from one setup to the next to cover all the desired measurement nodes. The reference sensor needs to be placed in a point where all the desired modes have contribution to the response; i.e. usually on top floors and at corner joints. In fact, the reference sensor acts as the connection point between the different test setups so that at the end of the tests, all the recorded data can be assembled and be representative of the building mode shapes. The duration of data records can have significant effect on the ability and quality of AVT to derive modal properties, and longer acquisition time leads to better results (typically 10 minutes long data records were taken in this study). Moreover, the sampling frequency needs to be selected based on the Nyquist sampling theorem [8] which implies that aliasing (error) caused by discretization of a continuous signal can be avoided if the sampling frequency is greater than twice the maximum component frequency. Hence, in this case the sampling frequency should be at least twice the highest fundamental frequency of interest. For buildings we are typically interested in frequencies below 25 Hz [9], and even much lower (10 Hz maximum) in seismic applications.

Three popular AVT record analysis methods are Frequency Domain Decomposition (FDD) and Enhanced Frequency Domain Decomposition (EFDD) [10, 11] and Stochastic Subspace Identification (SSI). In this research 16 low to mid-rise irregular buildings were tested by AVT and analyzed by these methods and then the best results were chosen as modes shapes, natural frequencies and damping ratios; details of the sensing tests and results are reported in Mirshafiei et. al. [12-14]. It should be mentioned that at least the lowest three natural frequency modes of each tested building were successfully derived by AVT; the third modes were typically torsional. Next, all these buildings were seismically assessed by the 3D-SAM^{TM} method [14-16] and software (Sensequake, 2015 [17]). The 3D-SAM method is summarized in the next section. By application of this method and software, the dynamic amplification portion of natural torsion of the dataset is calculated and reported here.

2. 3D-SAM

3D-SAM is a new three-dimensional seismic assessment method of structures based on their modal characteristics obtained from AVT [14, 15]. This method bypasses the need for a finite element model of the structure and can directly calculate the seismic demands of an existing building. The calculation model is based on the modal properties of the structure as extracted from ambient vibration test records. This approach is therefore capable of assessing buildings without clear blueprints and engineering structural plans.

By extracting the dynamic properties of buildings from AVT, it is possible to calculate the building seismic response by convolution integral in the linear range according to classical structural dynamics theory. The 3D-SAM method predicts global seismic demands and response histories of buildings to any number of input earthquakes. The whole process of the method, its inputs and outputs are illustrated in Fig.1. It should be mentioned that depending on the seismic demand parameter and the intensity of the considered earthquakes, appropriate modification factors are applied to the modal properties derived from AVT [14] to extrapolate the response beyond ambient motion levels. These modification factors were derived from data collected on buildings with permanently instrumented sensors that had been subjected to moderate to strong earthquakes and have also been tested previously by AVT. Therefore, this method can be used to calculate seismic demands for buildings even when subjected to the design level earthquakes, provided that adequate response modification factors are used and the structure suffers no collapse.

The various outputs of the 3D-SAM method are determined from the calculated relative displacement vectors at the center of mass on each floor. By assuming rigid in-plane movement of each floor, relative displacement vectors can be obtained at any floor location including building corners. Absolute accelerations are estimated by taking the second time derivative of relative displacement vectors and adding the ground acceleration [15].

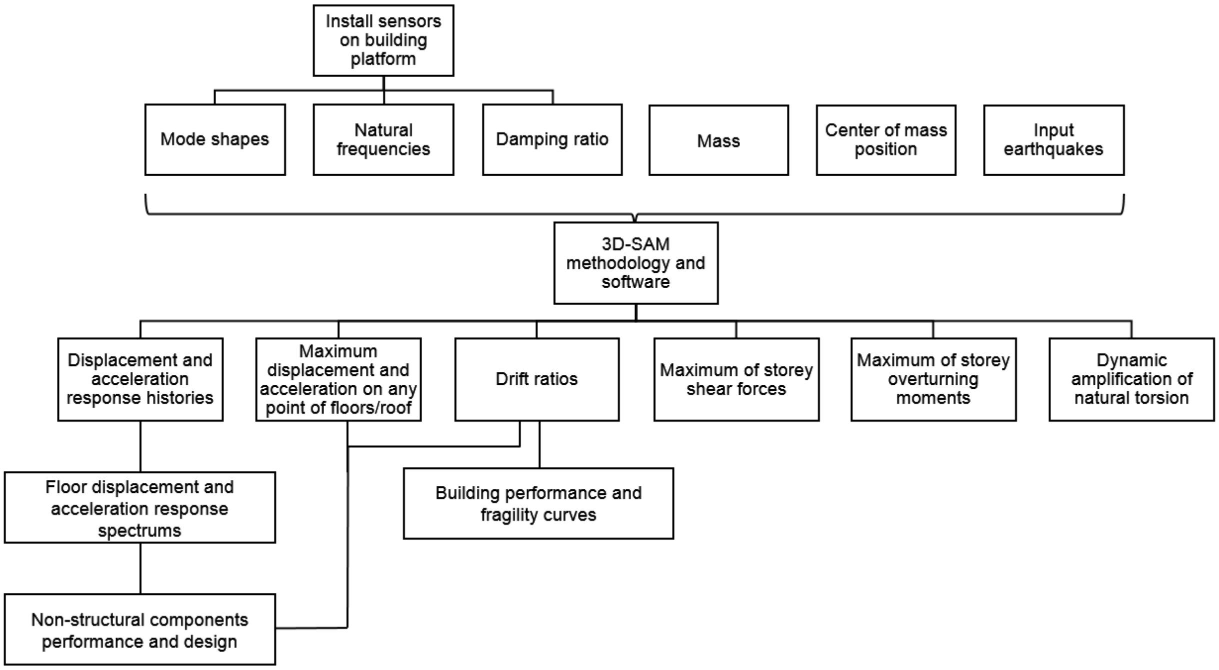

Fig. 1 - 3D-SAM methodology, corresponding inputs and outputs [14]

3. Dynamic amplification portion of natural torsion

Multiplying the horizontal components of absolute acceleration of the floor center of mass by the floor mass, the inertia forces at each floor are computed which leads to the determination of story shear forces and overturning moments. Finally, the second time derivative of the angular displacement at the center of mass yields the angular acceleration "α". The moment of inertia of each floor, I_o, about the vertical axis through the center of mass multiplied by "α" yields the resultant torque at center of mass. This torque divided by the inertia force leads to the additional eccentricity that represents the dynamic amplification portion of natural torsion.

For each of the 16 cases considered here, ten earthquakes are applied along two orthogonal axes independently; i.e. E_x is a base motion along the x direction and E_y is a base motion along the y direction. Each building is subjected to an ensemble of ten synthetic earthquakes (response spectra are shown in Fig. 2 and based on a study by Assi [18]) compatible with Montreal's uniform hazard spectrum of moderate seismicity, and covering the appropriate frequency range of interest, peak ground acceleration, magnitude, epicentral distance and duration. Details and characteristics of these buildings can be found in [12-14].

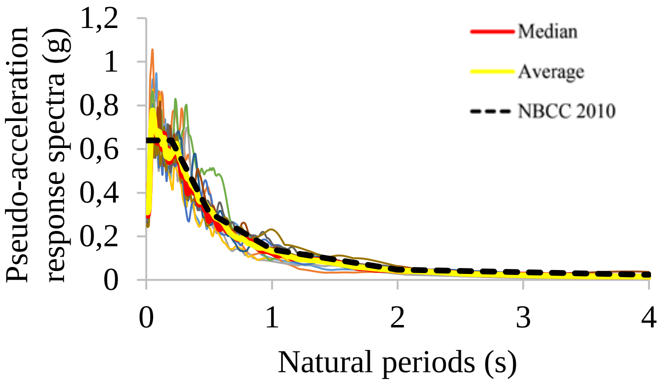

Fig. 2 - Pseudo-acceleration response spectra of the synthetic earthquakes compatible with UHS of Montreal (NBCC 2010 [2])

Owing to building asymmetry, horizontal inertia forces exist in both orthogonal directions even if the earthquake is applied along one direction. Therefore, considering the torque from the 3D-SAM analysis, the following definitions are used to determine the additional eccentricity that can replicate the dynamic amplification portion of natural torsion on the center of mass of each floor, see Fig.3a:

The instantaneous eccentricity is obtained by the ratio of the total torque and the total horizontal inertia force, calculated on each floor and for each time step during an earthquake record; the mean value for the total analysis time is reported as “ecc”. Moreover, the components of this eccentricity are reported as “ecc_x” and “ecc_y” along the x and y axes with the same approach, Fig.3b. To conveniently report and compare the eccentricities, they are divided by the building plan dimension perpendicular to the direction of the seismic loading being considered, and are expressed in percentage in Fig. 4.

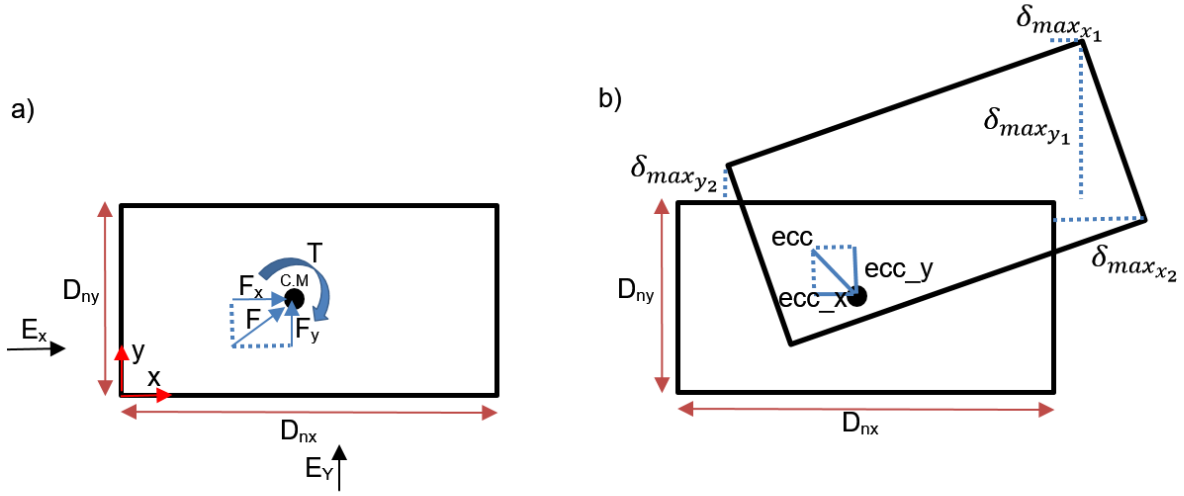

Fig. 3 - a) Total inertia force, F, its components, F_x and F_y, and the torque, T, generated at a floor centre of mass; b) Eccentricities that can represent the dynamic amplification portion of the natural torsion [14]

The different defined eccentricities are calculated for each earthquake and for each floor. Next, mean eccentricity values are calculated from the response to the ten base motion for each building and each floor. In total 104 eccentricity values are found for the whole database (all buildings and all floor and roof levels). Moreover, $B_x = \frac{\delta_{max_{y_1}}}{(\delta_{max_{y_1}}+\delta_{max_{y_2}})/2}$ and $B_y = \frac{\delta_{max_{x_1}}}{(\delta_{max_{x_1}}+\delta_{max_{x_2}})/2}$ (Fig.3b) were obtained from the response time histories and all the eccentricities were plotted against average of (Bx, By) and are shown in Fig. 4. The definitions for B parameters are similar to those exist in literature and seismic design guidelines such as the NBC code. As described previously, for irregular buildings and dynamic analysis inertia forces exist in both x and y directions even though earthquakes are applied along one direction. Therefore, in this study the eccentricities are plotted against average of (Bx, By).

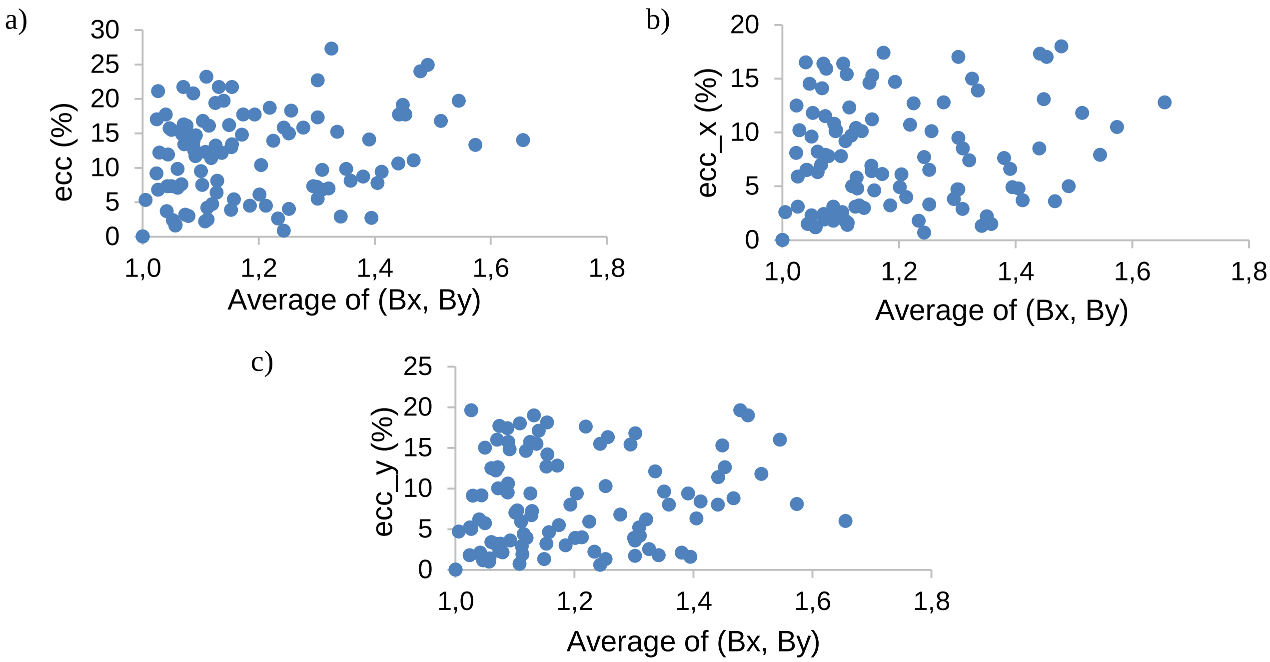

Fig. 4 - Different defined equivalent eccentricities for the dynamic amplification portion of natural torsion for 16 irregular buildings located in Montreal

It is seen in Fig. 4 that contrary to the static seismic analysis of a one story building where eccentricity is increased as B parameter is increased, in the dynamic seismic analysis of different buildings the eccentricities are scattered in relation to the defined parameter $(B_x+B_y)/2$; the same trend was observed for other defined combinations of B_x and B_y. This is expected as during the course of the dynamic response history analysis for a particular floor of one case study, there may be a large dynamic torque and a small inertia force at C.M that leads to a larger needed equivalent eccentricity to accommodate such a torque, however, this may not be the case for another case study with the same $(B_x+B_y)/2$. Therefore, it is suggested that not to use the sensitivity parameter B definition to consider torsional effects in the dynamic analysis.

Finally Table 1 summarizes the range of the calculated eccentricities from the whole dataset, as an indication of the expected range of the dynamic amplification portion of natural torsion. These results are valid for the seismicity level corresponding to Montreal, Canada and cannot be extrapolated to other seismic regions without proper validation. As explained before, torsion in the seismic analysis is resulted from natural and accidental torsion and their corresponding dynamic amplifications. Therefore, it is suggested that in the dynamic seismic analysis of finite element models the equivalent floor eccentricity of the dynamic amplification portion of natural torsion at center of mass be computed and compared with the reported measured ones from this study; i.e. based on this study it is recommended not to have less than 12% of equivalent eccentricity for the dynamic amplification portion of natural torsion at center of mass. The measured eccentricities from this study based on ambient vibration tests serve as a reference and basis to improve the finite element models and dynamic seismic analysis.

Table 1 - Equivalent floor eccentricities of the dynamic amplification portion of natural torsion of 16 buildings in Montreal

	ecc (%)	ecc_x (%)	ecc_y (%)
Mean	11.7	7.7	8.2
Mean+sigma	18.1	12.7	13.9
Median	12.2	7.0	7.1

4. Conclusions

In this research 16 irregular buildings subjected to ambient vibration tests were analyzed by the new 3D-SAM method and software that provide seismic demands and time history analysis of a building directly based on its modal properties derived from AVT. By using this approach, additional eccentricities equivalent to the dynamic amplification portion of natural torsion were calculated and reported on each floor of buildings subjected to ten earthquakes compatible with seismicity of Montreal, Canada. The mean value and mean plus one standard deviation of these measured equivalent floor plan eccentricities were shown to be as large as 12% and 18% of the plan dimension perpendicular to the direction of the seismic loading, respectively, for the whole dataset. The measured eccentricities from this study based on ambient vibration tests serve as a reference and basis to improve the finite element models and dynamic seismic analysis. Therefore, it is suggested that in the dynamic seismic analysis of finite element models the equivalent floor eccentricity of the dynamic amplification portion of natural torsion at center of mass be computed and compared with the reported measured ones from this study; i.e. based on this study it is recommended not to have less than 12% (more conservative 18%) of equivalent eccentricity for the dynamic amplification portion of natural torsion at center of mass.

Even though the measured dynamic amplification portions of natural torsion reported in this research are related to the dynamic seismic analysis and cannot directly be compared with the provisions of the equivalent static method of design guidelines, however, results of this study suggest that the 5% equivalent plan eccentricity to consider dynamic amplification portion of natural torsion commonly used in seismic design guidelines for non-torsionally sensitive buildings is low and further investigation in this topic is recommended. Therefore, the dynamic amplification portion of natural torsion can be significant for low-rise irregular buildings and needs to be considered properly in seismic analysis.

Similar work can be carried out on buildings located in other cities and areas of different seismicity to get estimates of the dynamic amplification portion of natural torsion based on real building dynamic properties. This type of research can provide insight into seismic torsional effects in buildings, a complex parameter that has not been extensively studied yet.

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