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Seismic Assessment of Irregular Low-Rise Buildings Based on a 3-Dimensional Simplified Method

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Abstract: In order to assess the seismic behaviour of existing buildings, a rational yet simple and fast evaluation method is needed. This is particularly important for post-disaster buildings such as emergency shelters and hospitals, for evaluations before or after a seismic event. Current guidelines such as FEMA 154 and NRC 92 propose rapid visual screening methods for the same purpose. However, a more reliable method that could quantify structural seismic demand parameters and provide a better assessment of building performance is still needed for those low-rise buildings with irregularities that may cause torsional effects. In this research, a 3-dimensional simplified assessment method for such buildings is proposed. The method is based on *in situ* building data collected from inspection, information on site conditions, and ambient vibration measurements, therefore reducing the uncertainties related to the modal properties of the building that are otherwise roughly estimated in current assessment methods. It is envisioned that the proposed assessment method may be employed for the evaluation of seismic demand parameters such as relative floor displacements; story drift ratios, floor absolute accelerations and story shear forces. The applicability of the proposed method is demonstrated through an example of a three-storey asymmetric building. The validation of the method using ambient vibration measurements of existing public buildings located in Montreal is under way.

1. INTRODUCTION

Buildings designed before the inception of earthquake-resistant guidelines in design provisions typically suffer damage after strong earthquakes (Bilham 2010). In order to evaluate the safety margin of these potentially damaged buildings, an evaluation of their seismic performance needs to be conducted. Accordingly, the issue of seismic evaluation of existing buildings has become increasingly important in recent decades, especially in the context of performance-based design. Therefore, it is a necessary and good practice to develop seismic evaluation portfolios for important post-disaster buildings such as schools and hospitals. This information will help to assess/predict the building's behavior during any design level earthquake, identify whether it is in need of preventive retrofit, and provide a reference condition to recognize actual damage in the building's lateral force resisting structural system (LFRS) after the occurrence of an earthquake.

Current detailed seismic evaluation methods for buildings are based on linear and nonlinear static and/or dynamic analysis approaches based on modern standards and guidelines (ASCE 41, FEMA 356, and NIST 2010). However, there is uncertainty in the predicted results obtained from the simplified numerical models that are developed in the different approaches. According to a survey conducted in phase I of the ATC-55 project about the application of these assessment methods in structural engineering firms in the United States (FEMA 440), several respondents commented on issues about these methods: their inaccuracy/variability, e.g. different analysis methods lead to significantly different results, the general complexity of these so-called simplified procedures, the sensitivity of the inelastic analysis approaches to assumptions regarding such parameters as initial stiffness, and the invariance of the loading patterns used in nonlinear static analysis procedures. Therefore, there is a need for an alternative simplified and robust seismic evaluation method, with recognized limitations and range of applicability.

This paper discusses a 3-dimensional (3D) simplified seismic assessment method of low-rise buildings based on experimental modal analysis. The proposed method is illustrated with an example of a low-rise irregular building.

The proposed method is tailored to existing buildings for which it is possible to collect real *in situ* data about the geometry, presence of structural irregularities (vertical and or horizontal), and basic dynamic characteristics (modal properties) at ambient vibration levels. Such specific knowledge about the structural characteristics of the building is key to reduce the uncertainty of the model predictions. It is acknowledged that even very sophisticated nonlinear dynamic model predictions, based on sound state-of-the-art theoretical knowledge and reliable numerical procedures, do not have a guaranteed accuracy in the absence of careful model calibration, an important step that is simply not feasible in building design and rather difficult in engineering practice except for buildings of strategic importance. The reduction in the uncertainty associated with the structural building properties is the main advantage of the proposed 3D simplified method compared to other existing analysis procedures. The method enables the evaluation of different engineering demand parameters such as floor displacements; story drift ratios, floor absolute accelerations and story shear forces provided that the building does not behave far into the nonlinear range during and after a design earthquake. This assumption should hold true in post-critical buildings such as those considered in this research as they should have been designed using a large importance factor so as to prevent extensive damage to their LFRS. Moreover, the proposed method has the potential to account for torsional effects in the seismic vulnerability assessment of irregular buildings.

2. BACKGROUND AND LITERATURE REVIEW

2.1 Experimental modal analysis

A more detailed description of the experimental modal analysis method and its application towards this research is presented in Mirshafiei and McClure (2012). In summary, the three salient points are as follows:

1) Nowadays, ambient vibration testing (AVT) is a reliable tool to derive modal characteristics of buildings that are far from the onset of collapse i.e. lower-frequency mode shapes, natural frequencies and damping ratio estimates. (Brincker et al. 2001, Hans et al. 2005, Trifunac 1972, Gilles 2011);

2) AVT is used world wide for updating finite element models (Ventura et al. 2001, Yu et al. 2007, Tremblay et al. 2008, Lamarche et al. 2009), structural identification and predicting seismic behavior of buildings (Gilles 2011, Gentile and Gallino 2008, Michel 2008);

3) AVT can be used to identify coupled sway and torsional modes that typically exist in low and mid-rise irregular buildings (Mirshafiei and McClure 2012).

AVT offers the potential to become a powerful instrument of LFRS structural characterization of buildings that truly considers the building as a whole, with its foundation and site conditions, and its architectural components and content.

2.2 Seismic vulnerability assessment of existing buildings

Two principal procedures are typically employed for seismic vulnerability assessment of buildings; one is the vulnerability procedure based on field observations of building performance (and damage) during past earthquakes and the other one is the predicted vulnerability method (Karbassi 2010, Sandi 1982). The former is based on statistics of damages observed by structural engineers on similar building types during post-earthquake reconnaissance visits. It can be combined with the opinion of experts and used to derive damage probability matrices (DPM), which describe the probability that a building type is in a specific damage state for a given level of seismic hazard. This method can be quite reliable if the database is representative of the buildings to be assessed, typically in active seismic urban areas of the world. However, in the absence of sufficient observed data, only the latter procedure that is based on calculations, expert opinions, design specification and detailed modelling can be employed. Subsequently, two popular methods are generally used and they may be seen as complementary: rapid visual screening (RVS) (FEMA 154, NRC 92) and subsequent linear or nonlinear detailed modelling when RVS indicates a significant seismic vulnerability (FEMA 356, FEMA 440, NIST 2010, ASCE 41). The RVS method has been formulated to identify and rank building LFRS that are potentially seismically hazardous in an inventory of buildings. If a building receives a high score, it is considered to have adequate seismic resistance (and lower seismic vulnerability and risk); otherwise, it is flagged for a more detailed evaluation (FEMA 154). To select the appropriate detailed evaluation method, the first decision is whether to adopt the inelastic analysis procedure over the more conventional linear elastic analysis. In general, linear analysis is applicable when the structure is expected to remain nearly elastic for the level of ground motion of interest or when the design is such that the nonlinear response will be rather uniformly distributed throughout the building such that the mode shapes of the damaged building stay similar to those of the building in its usual operational conditions (FEMA 440). However, nonlinear analysis has the potential to provide a better understanding of the performance of buildings at moderate and severe damage levels if the simulation models are calibrated with actual building performance characteristics. There is also a wide selection of methods to conduct a nonlinear analysis such as: detailed time-accurate nonlinear dynamic analysis, simplified nonlinear dynamic analysis with either equivalent (condensed) multi-degree-of-freedom (MDOF) models or single-degree-of-freedom (SDOF) models and nonlinear static procedures (NSPs).

Nonlinear static procedures are popular in engineering practice and two variants are predominantly used. The first type is equivalent linearization techniques that are based on the assumption that maximum total displacement (elastic plus inelastic) of a SDOF oscillator can be estimated by the elastic response of another SDOF oscillator with larger damping and natural period than the original. One of the most well-known forms of the equivalent linearization is the capacity spectrum method (ATC 40). The second type is the coefficient method; i.e. a displacement modification procedure (FEMA 356) that estimates the total maximum displacement of the oscillator by multiplying its elastic displacement response, assuming initial linear properties and damping, with one or more coefficients. The coefficients are usually derived from series of nonlinear response history analysis of oscillators with varying natural periods and strengths. State-of-the-art nonlinear static procedures including the limitations of these methods for seismic evaluation of steel and reinforced concrete structures are summarized in (NIST 2010). The above procedures have recently been improved to take into account the higher mode effects and asymmetric-plan buildings: more advanced methods such as modal pushover analysis and the N2 method have also been developed (Fajfar 2000, Fajfar et al. 2002, Fajfar et al. 2005, Kreslin and Fajfar 2011, Chopra and Goel 2002 and 2004).

However, all the above methods have uncertainties in regard to numerical models and approaches; moreover, due to the lack of good quality drawings and unrecognized true behavior of connections and elements of the building, the creation of an accurate finite element model remains difficult for assessing existing buildings. Even though the effects of modeling uncertainties can be quantified with rigorous probabilistic analysis, the variability of their predicted results remains an issue in practical applications.

2.3 Seismic vulnerability assessment using ambient vibration data

Boutin et al. and Hans et al. (2005, 2008), respectively, have shown that Timoshenko cantilever beam modelling was suited for describing the sway response of regular symmetric concrete moment frame and shear buildings and the model results were consistent with experimental modal characteristics obtained from AVT. Then, for a given LFRS based on this beam model, a so-called seismic integrity threshold was calculated which indicates the onset of structural damage: the building LFRS is predicted to remain elastic below this threshold, and by using linear dynamic analysis based on first-mode response, the story-drift ratios for elastic response were calculated. However, the simple model is applicable only to symmetric structures and shear-dominant LFRS buildings

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Michel et al. in 2008 have discussed the evaluation of the building stiffness from the AVT modal parameters and story-drift ratios. For calculating the lateral building stiffness, 2D lumped-mass shear beam models have been considered since they have low computational cost and apply to a large set of buildings. Elastic motion of buildings under moderate earthquakes was computed by modal superposition analysis. However, in this research, constant mass has been assumed for each floor, and the building torsional behaviour and coupling effects of modes have been neglected. Moreover, building motion was decomposed into the two main horizontal directions (longitudinal and transversal, assumed principal) and then the response was calculated. In a later study, Michel et al. (2009 and 2011) have used linear modal analysis to calculate fragility curves for the slight damage grade from modal parameters extracted from ambient vibration tests for 60 buildings in the city of Grenoble (France). Damage level was defined in terms of story-drift ratio (see HAZUS: NIBS 2003) corresponding to different grades of damage and for different LFRS. Therefore, fragility curves were developed, expressing the conditional probability P[D=j│i] that a building will exceed a given damage state j for a prescribed level of ground shaking i. However, this improved method still has the same shortcomings as mentioned above; i.e. it ignores the possible variation of the mass at each floor, and the torsional effects. Also, the limits of applicability of this method are not clearly established. Therefore, there is a need for introducing a more general three-dimensional method which will address these shortcomings.

3. SEISMIC ASSESSMENT OF BUILDINGS BASED ON the 3D SIMPLIFIED METHOD

This section discusses a simplified assessment method for evaluation of existing buildings based on extracted modal parameters from AVT. Lower frequencies, mode shapes and damping ratios are derived from experimental modal analysis. Based on these data, simplified 3D models of buildings are generated. Eventually, each building is subjected to an ensemble of ground motions and its different response indicators based on linear modal analysis theory are computed. The results of the analysis are predictions of building response parameters (global displacements, e.g. roof or other reference points, story drift ratios, story forces, and base shear) that are subsequently used to predict building performance based on acceptance criteria as defined in FEMA 356.

Having extracted the dynamic building characteristics from AVT, it is possible to calculate the building seismic response by time domain convolution (Duhamel integral) in the linear range. Unlike previous studies of seismic building assessment based on AVT, the building inventory used in this work is comprised of low-rise buildings of complex geometry (community centers, with swimming pools and gymnasia) that usually do not possess symmetric plans; even building shapes that look symmetric in geometry have eccentricities between their center of mass and center of rigidity at different floor levels. Therefore, the separation of the seismic motion into the two principal building directions is not strictly possible and coupling effects in sway modes and torsional modes should also be taken into account that were neglected in previous studies. Subsequently, the equation of motion is considered in three dimensions. In this case, 3N degrees of freedom (N is the number of stories) are considered; three degrees of freedom are assumed for each rigid floor diaphragm including two horizontal displacements and one rotational degree of freedom, as shown on Figure 1:

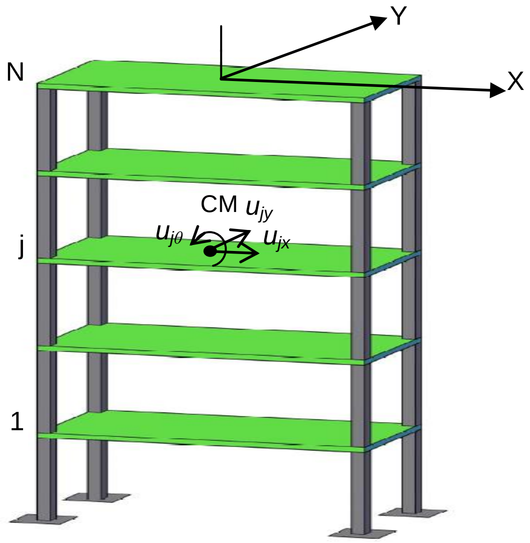

Figure 1: Schematic view of a building with 3N degrees of freedom for the 3D simplified assessment method

From classical linear structural dynamics (Chopra, 2007) the equations of motion with the assumption of seismic force in x direction are as follows:

[1] $[\boldsymbol{M}]\{\ddot{\boldsymbol{u}}\} + [\boldsymbol{C}]\{\dot{\boldsymbol{u}}\} + \{\boldsymbol{K}\}\{\boldsymbol{u}\} = -[\boldsymbol{M}]\begin{Bmatrix}\mathbf{1}\\ \mathbf{0}\end{Bmatrix}\ddot{u}_{gx}(t)$

Where

$[\boldsymbol{M}] = \begin{bmatrix}\boldsymbol{m} & \mathbf{0}\\ \mathbf{0} & \boldsymbol{I_O}\end{bmatrix} \qquad \{\boldsymbol{u}\} = \begin{Bmatrix}\boldsymbol{u_x}\\ \boldsymbol{u_y}\\ \boldsymbol{u_\theta}\end{Bmatrix}$

$\boldsymbol{u_x} = \{u_{1x}\ u_{2x}\ \ldots\ \ u_{Nx}\}^T \quad \boldsymbol{u_y} = \{u_{1y}\ u_{2y}\ \ldots\ \ u_{Ny}\}^T \quad \boldsymbol{u_\theta} = \{u_{1\theta}\ u_{2\theta}\ \ldots\ \ u_{N\theta}\}^T$

$\boldsymbol{m}$ is a diagonal sub-matrix of order 2N, with diagonal values of m_j, the mass lumped at the j th floor diaphragm; $\boldsymbol{I_O}$ is a diagonal sub-matrix of order N with diagonal values of I_{Oj}, the moment of inertia of the j th floor about the vertical axis through the center of mass; $\mathbf{1}$ and $\mathbf{0}$ are vectors of dimension N and 2N with all elements equal to 1 and zero, respectively.

It is emphasized that this model would not be suitable for buildings with flexible in-plane roof systems and/or flexible floors where the distribution and magnitude of floor inertia forces is affected by the in-plane flexibility, the flexible diaphragm working as a series system with the main LFRS of the building. However, AVT can be used to assess such effects with a distributed measurement grid on the flexible floor/roof surface.

The relative displacement vector $\{\boldsymbol{u}\}$ of all the stories of the model forced into vibration by ground motion can be written in modal coordinates $\{\boldsymbol{q}\}$ that uncouple the equations of motion by use of the expansion theorem:

(2) $\{\boldsymbol{u}\ (\boldsymbol{t})\} = [\emptyset]\{\boldsymbol{q}\ (\boldsymbol{t})\}$
(3) $\boldsymbol{q}\ (\boldsymbol{t}) = \{q_1\ q_2\ \ldots\ \ q_n\}^T$
(4) $\forall\ i \in [1, n] \qquad q_i(t) = \frac{-P_i}{\omega_i'}\int_0^t \ddot{u}_{gx}(\tau)e^{-\zeta_i\omega_i(t-\tau)}\sin\left(\omega_i'(t-\tau)\right)d\tau$

Equation 4 gives the response in the generalized (modal) coordinates using Duhamel integral (time domain convolution) with $\omega_i' = \omega_i\sqrt{1-\zeta_i^2}$ the damped angular frequency and $P_i = \{\phi_i\}^T[\boldsymbol{M}]\begin{Bmatrix}\mathbf{1}\\ \mathbf{0}\end{Bmatrix} / (\{\phi_i\}^T[\boldsymbol{M}]\{\phi_i\})$ the participation factor of mode i (n=number of modes derived from AVT; N=number of stories). $\phi, \zeta\ and\ \omega$ are the n modal parameters of the building extracted from AVM tests (three-dimensional mode shapes and corresponding natural frequencies and approximate viscous damping ratios).

Making use of the AVT extracted 3-D mode shapes and their corresponding frequencies, each building model can be analyzed for an ensemble of ground motions scaled to the uniform hazard spectrum for location under study. The relative displacement vectors at center of mass on each floor are calculated, and assuming rigid in-plane movement of each floor, the relative displacement vectors can be obtained at any floor location, especially at building corners. The rest is identical to other assessment methods: story-drift ratios are calculated and compared with the prescribed design limits (for example $0.01h_s$ according to NBCC 2010 for post-disaster buildings, h_s is the story height, or with limits found in FEMA 356 for different performance levels). Moreover, taking the second time derivative of relative displacement vectors and adding the ground acceleration, absolute acceleration are estimated at the center of mass on each floor. After multiplying the horizontal components of absolute acceleration of each floor by its mass, the inertia force at each floor is computed and then summation of all will result in total base shear. It should be stated that P-Delta effects are not considered as part of this method, although a more precise estimate of sway displacements at corner columns can contribute to a rough assessment not currently possible with 2-D methods.

In the following section, the 3D simplified approach is applied to a benchmark building. Validation of the method with a data base of irregular buildings is currently being done at McGill University.

4. VALIDATION OF THE 3D SIMPLIFIED METHOD FOR THE BENCMARK BUILDING

An example of a 3-story irregular building is assessed by the 3D simplified method and the results are compared with a detailed linear model using SAP2000 (computers and Structures, 2009). The building is located in Montréal and is asymmetrical with respect to the north-south direction. The LFRS comprises a reinforced concrete moment frame and six concrete shear walls. The plan view and three-dimensional elevation view of the building are shown in Figure 2. Three degrees of freedom are defined at the center of mass on each floor and a lumped mass/inertia is assigned to each DOF.

The model is subjected to a synthetic horizontal ground motion along its asymmetric direction Y. This ground motion has been adopted from a study done by Assi (2006). This record corresponds to a Magnitude 6 event, epicentre distance of 30 km, duration of 8.89 s, return period of 2500 years and scaled appropriately to be compatible with the NBC Uniform Hazard Spectra (UHS) for Montréal according to NBCC 2005 (the hazard has been slightly reduced for Montreal in the 2010 edition of NBC). The scaled response spectrum of this ground motion compared with UHS is shown in Figure 3.

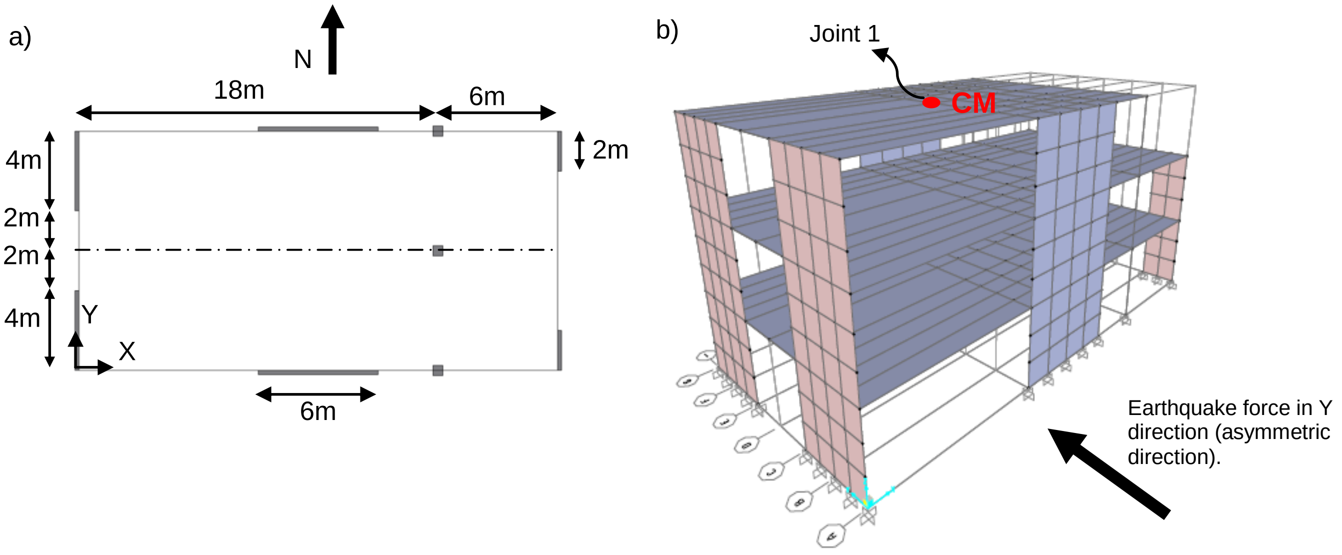

Figure 2: Case study of irregular building: a) plan view; b) 3D view

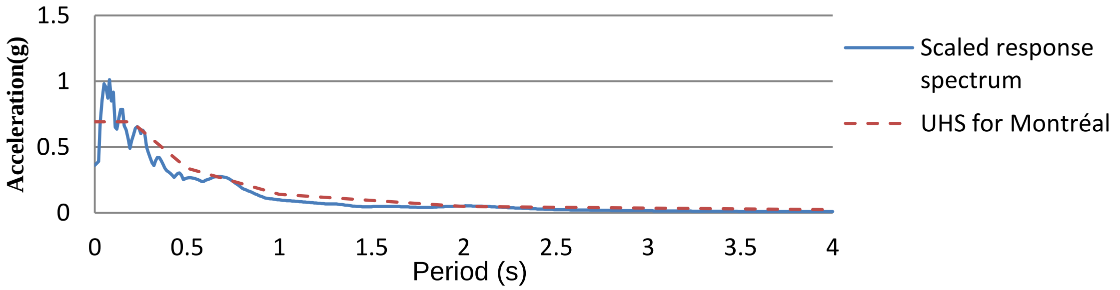

Figure 3: Comparison between scaled response spectrum of input ground motion and UHS for Montréal

Mode shapes and frequencies of all nine modes of this irregular building are computed using SAP 2000. The periods of the first three modes are found to be 0.23, 0.17 and 0.11, respectively. The first mode is flexural-torsional mainly in Y direction; the second mode is flexural in X direction (owing to symmetry), and the third mode is torsional.

A Matlab routine is written for computing the modal displacements and accelerations at the center of mass based on the 3D simplified method. The main input parameters are: the earthquake acceleration record, mass, angular frequency, damped angular frequency, damping, unitary and modal matrices. The main outcomes are displacement and acceleration histories of all the pre-defined degrees of freedom at the center of mass of each rigid floor and ultimately the modal participation factors. In this verification example, the mode shapes of the building are derived directly from SAP2000 (computers and Structures, 2009), however, in the field investigated cases this input data is provided from the ambient vibration tests. Figures 4 and 5 show a comparison of relative displacements and absolute acceleration demand parameters at the center of the mass of the third floor of the benchmark building, between the 3D simplified method and the direct linear modal superposition analysis from the SAP2000 model.

These results illustrate the accuracy of the 3D simplified method since the results are almost identical. Other engineering demand parameters may be computed such as story-drift ratios, story forces, and base shear. The next step will be to further verify the proposed approach with data from ambient vibration tests (AVT) from actual buildings. This effort is currently under way.

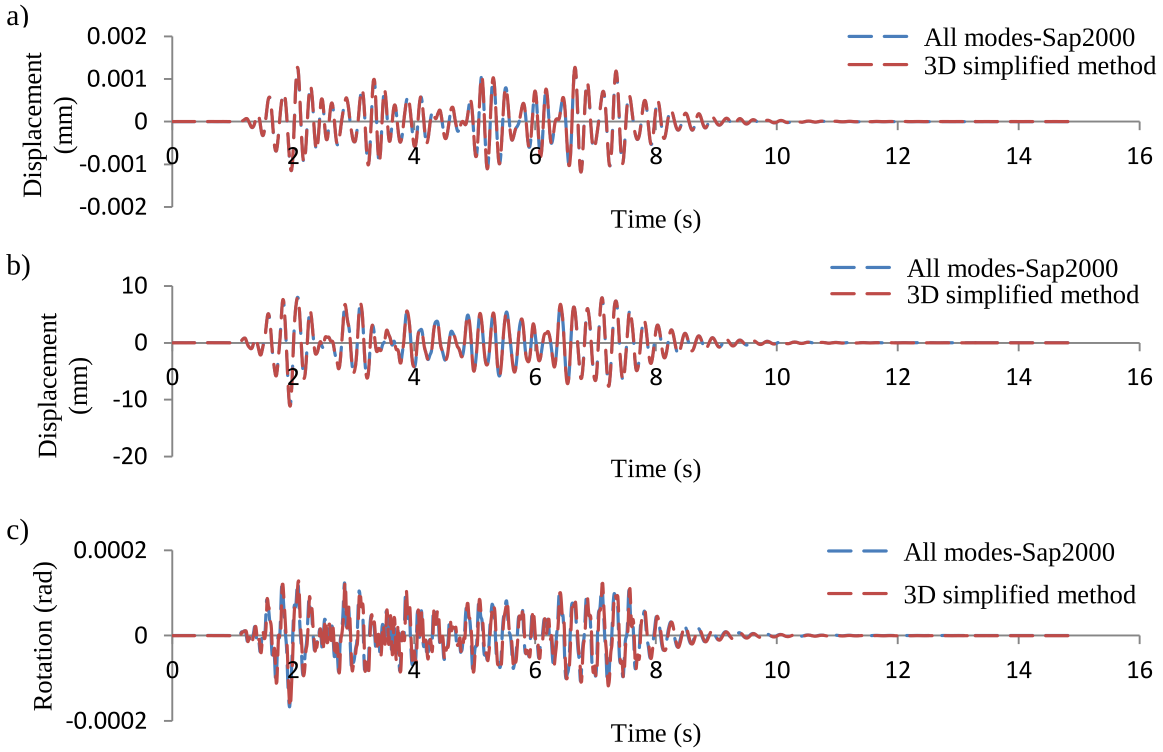

Figure 4: Comparison of relative displacement demands between Sap2000 and 3D simplified method at joint 1 (Earthquake in Y direction): a) Relative displacement in X direction b) Relative displacement in Y direction c) Relative rotation

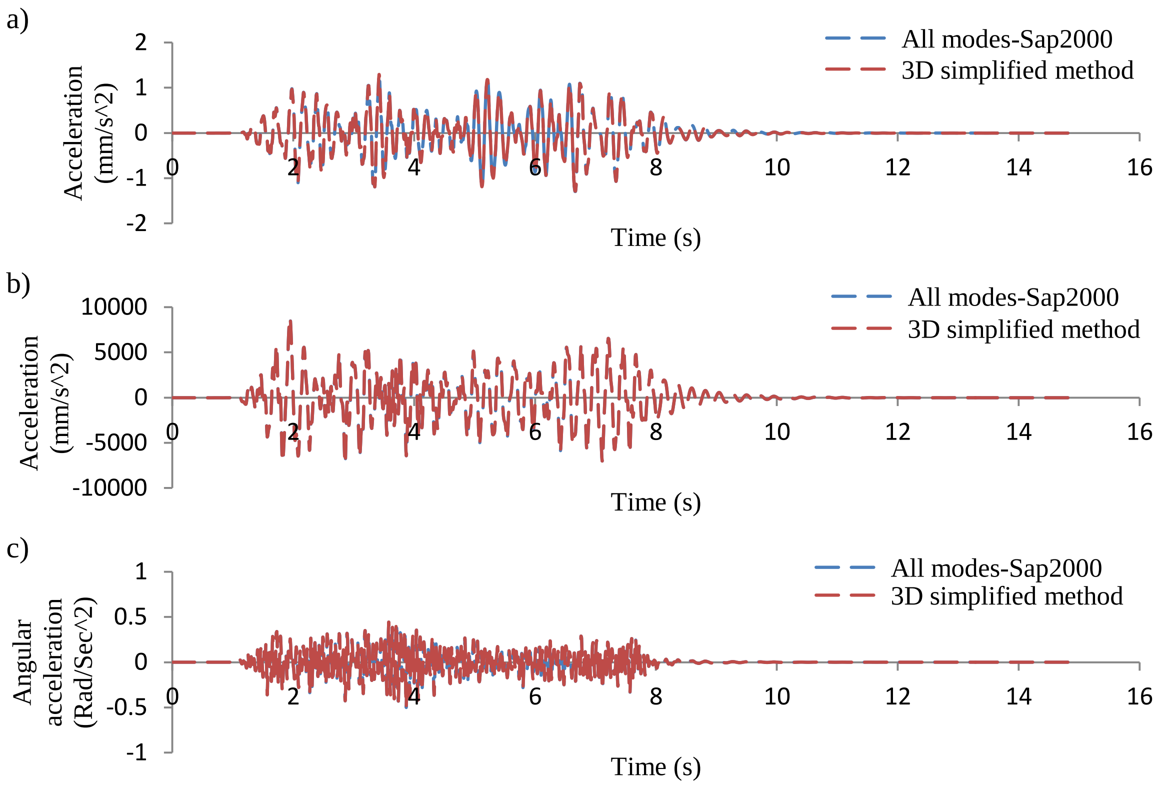

Figure 5: Comparison of absolute acceleration demands between Sap2000 and 3D simplified method at joint 1 (Earthquake in Y direction): a) Absolute acceleration in X direction b) Absolute acceleration in Y direction c) Angular acceleration

Usually, only the first few modes are derived from AVT for low-rise buildings. Therefore, the effects of the truncated modal superposition will be reflected in the 3D simplified method. To get an idea of these effects, four different scenarios were investigated on the benchmark building for two earthquake directions: modal analysis considering only the 1st mode (combined sway and torsion), first two modes, first three modes and all modes. Consequently, relative displacements and absolute accelerations in X and Y directions for these four different cases are calculated at the center of mass and corners of each floor. In summary the following conclusions are observed: 1) as expected the relative displacements are dominated by the 1st mode (sway coupled with torsion) and they are predicted relatively well at the center of mass and corner joints in the loading direction or perpendicular to the direction of earthquake. Consideration of coupling flexural and torsional effects in irregular buildings (obtained from the AVT 3D extracted modes) is the main advantage of the proposed approach, which is capable of predicting relatively good approximations of the displacement demands of buildings subjected to moderate excitations causing only slight damage. Absolute acceleration predictions in direction of earthquake loading are very accurate based on the fundamental mode response while predictions in the perpendicular direction are not accurate enough for the corner joints; accelerations of the corner joint of the 3rd floor evaluated with complete modal superposition are almost three times larger than those obtained with the lowest three modes. This issue becomes more important for mid and high-rise buildings, but higher frequency modes are also easier to identify by AVT in such buildings.

5. CONCLUSION

In this paper, a 3-dimensional simplified seismic assessment method for buildings with rigid floor/roof diaphragms is proposed and illustrated with an example of a three-story irregular building. The main novelty of the method is that it is based on in situ data collected from buildings (i.e. building inspection, information on site conditions, drawings and ambient vibration measurements). In particular extracted 3D mode shapes and natural frequencies allow consideration of flexural/torsional coupled response. Validation of the method with a database of several low-rise irregular buildings in Montreal is underway.

Preliminary results indicate that the proposed procedure could yield reasonable predictions of seismic displacements in irregular buildings under moderate earthquakes. Prediction of accelerations is more challenging as they are more affected by higher frequency modes than displacements, and at the same time higher modes are more difficult to extract from AVT in low-rise buildings than in medium-high rises.

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