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APPLICATION OF A THREE-DIMENSIONAL SEISMIC ASSESSMENT METHOD (3D-SAM) BASED ON AMBIENT VIBRATION TESTS TO FEW BUILDINGS LOCATED IN MONTREAL

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ABSTRACT: Ambient vibration testing applied to building structures is an in-situ modal experiment where low amplitude structural motions are recorded during the building's normal operations or everyday activities. Recorded motions at various points using local sensors are then processed using frequency domain decomposition techniques with a view to extract the essential dynamic properties of the building: mode shapes, natural frequencies and corresponding modal damping ratios. The derived experimental modal properties are used directly as input of the 3D-SAM (three-dimensional seismic assessment method and software), which is based on linear dynamic analysis and calculates the building's global seismic demand parameters such as relative floor displacements, story-drift ratios, floor absolute accelerations for any point on the floors, story shear forces, overturning moments and floor response spectra. All these seismic demands are calculated without the need to make any finite element model of the building, which makes the method very attractive to assess existing buildings. The method is inherently capable of considering torsional behavior in the response prediction and can be used as a seismic assessment tool for irregular buildings. The paper will present a few examples that illustrate the application of this new method for buildings designated as post-critical shelters in the city of Montreal, Canada. Moreover, modification factors for extension of the 3D-SAM method from low vibration excitations to higher levels are introduced.

1. Introduction

Earthquakes cause damages to buildings resulting in hundreds of billions of dollars of economic loss and pose a threat to human lives. These risks are compounded by a growing urban population and an ageing infrastructure that occur both in developed and emerging countries. As governments become aware of these risks, they are budgeting billions of dollars and implementing risk evaluation and mitigation plans before future seismic events occur.

Current detailed seismic evaluation methods for buildings are based on numerical approaches (ASCE 41, FEMA 356, and NIST 2010) that are time consuming and costly, and not necessarily accurate. For example, in order to evaluate a building, an engineering firm needs to collect the building's detailed structural plans, take some in-situ tests to identify material properties, and then build a numerical model of the building using all that information. The process is further complicated by the fact that many older buildings (pre-CAD systems) do not have as-built structural drawings that are up to date with sufficient detailing. Also, buildings may be already damaged and need to be further assessed, some of them are of irregular shape, and also there might be interaction between non-structural components and structural elements, which was ignored at the design stage. Therefore, we saw a need for developing alternative simplified rational seismic evaluation methods for existing buildings, with recognized limitations and range of applicability. This need is particularly important for moderate seismic regions due to the lack of data on recent earthquakes and the scarcity of information, as the existing assessment methods are based on damage observations in high seismicity areas.

The proposed solution is to use low cost in-situ experimental modal tests, owing to advances in sensing techniques and analysing procedures, to derive the essential structural characteristic of the buildings and then use this information for seismic response assessment and prediction of economic losses for slight to moderate damage levels. Nowadays, the most popular experimental modal test for large structures is ambient vibration testing (AVT). Modal parameters such as natural frequencies, damping ratios and mode shapes are derived from AVT by application of well-known frequency domain analysis techniques available in commercial software. AVT is of easy application, a low cost method for large structures and its results were shown to be as reliable and similar to that of forced vibration tests (Brincker et al. 2001, Trifunac 1972, Gilles 2012, Mirshafiei and McClure 2012). The AVT-derived modal properties are used by researchers to calibrate numerical models and then improve the reliability of their seismic response assessment of buildings. However, this calibrated model process is somewhat complex, still requiring a very detailed finite element model (FE model) and in the end some discrepancies remain between the experimental and FE modal parameters, as it is not feasible to calibrate a FE model to 100% of the test results. This added complexity and increase in analysis time partly explain why AVT, sensing techniques and operational modal analysis software are still not that popular among structural engineering firms despite the undisputable added value they provide. In recent years, few researches have proposed simple models to use ambient vibration data directly to assess seismic demands of buildings. These models, strictly applicable only to symmetric structures, have been based on 2D lumped-mass assumption (Michel et al. 2009, and 2012). These models have many important shortcomings that jeopardize the reliability of their results: they assume constant mass for each floor and neglect building torsional behavior and coupling effect of lateral-torsional mode shapes. These shortcomings, inherent to the 2D approach, have prevented the introduction of a comprehensive seismic assessment tool and methodology based on AVT till today.

To address this need for a more realistic method that duly account for non-symmetry and the three-dimensional nature of buildings, a new three-dimensional seismic assessment method and software (3D-SAM) was introduced and verified in Mirshafiei et al. (2015). In this paper, a summary of this novel methodology is presented and illustrated with a building example. Then, the modification factors for extension of the 3D-SAM from small intensity earthquakes to higher excitation levels are introduced. Finally, the application of the 3D-SAM is shown for four building case studies located in Montreal.

2. 3D-SAM

2.1. 3D-SAM summarized description

To our best knowledge, 3D-SAM is the first comprehensive three-dimensional methodology and software based on the observation of real modal properties of a structure obtained from ambient vibration tests and other sensing techniques. The experimental modal properties are combined with building data collected from on-site inspection and the available architectural and structural plans, to provide input to the 3D-SAM method. Each building model can then be subjected to an ensemble of representative ground motion records and its global seismic demand parameters are computed.

By knowing the dynamic properties of buildings from AVT, 3D-SAM uses time domain convolution (Duhamel integral) to calculate the building seismic response in the linear range. Contrary to previous studies of seismic building evaluation based on AVT, the equation of motion is considered in three dimensions, i.e. three degrees of freedom are assumed for each rigid floor diaphragm including two horizontal displacements and one in-plane rotational degree of freedom. In this way, the coupling effects in sway modes and torsional modes are taken into account. Moreover, as the modal parameters are extracted from the *in-situ* AVM tests, further processing needs to be performed on these complex modal properties before putting them as input for the 3D-SAM; these additional steps are explained in details in Mirshafiei et al. (2015). With all these procedures, the 3D-SAM method produces:

1) displacements and accelerations (relative and/or absolute) at any location and direction on floors and roofs;
2) global seismic demands such as storey shear forces, overturning moments, maximum displacements and accelerations at any floor and location; drift ratios which may lead to development of fragility curve and prediction of building performance for different damage grades;

3) drift ratios and absolute acceleration on each floor that will determine the non-structural performance;

4) displacements and acceleration response spectra for any location on floors which determine the performance of non-structural components;

5) and finally, an estimate of the dynamic amplification portion of natural torsion for each floor.

2.2. Verification of 3D-SAM with one building example

The building used in the verification is located on McGill University downtown campus (Burnside Hall) and was constructed in 1969 with a reinforced concrete shear wall system. It has 13 storeys with a height of about 47 m above ground level; it also has a basement beneath the ground level. A 3D view of the building, a typical floor plan and sensor layout on the floors, FE model and the applied ground motion are shown in Fig. 1. The modal properties of this building were derived via AVT (five lowest frequency modes, work done by Gilles (2012)). The FE model is an equivalent model calibrated with AVT results and is made up of 4 equivalent columns representing shear walls around the building and two equivalent central columns in place of the interior columns and the elevator concrete shaft. Each floor is rigid in plane and the lumped floor masses are assigned to the floor centroids. The model is then subjected to a synthetic horizontal ground motion along its X direction. This record corresponds to a magnitude 6 event compatible with the National Building Code of Canada (NBCC) Uniform Hazard Spectra (UHS) for Montreal according to NBCC 2010. The relative displacement and acceleration time histories of the roof corner joint A and centre of mass C.M. (location shown in Fig. 1b) are compared between the FE model (created in Sap 2000) and the 3D-SAM; the representative graphs are shown in Fig. 2. The graphs show good agreement between the two methods. In fact, if the FE model is fully calibrated to the modal properties derived from AVT, the two approaches will yield the same results. Therefore, the simplified 3D-SAM is a good alternative to linear updated FE models and leads to reliable results without the need for making a numerical model.

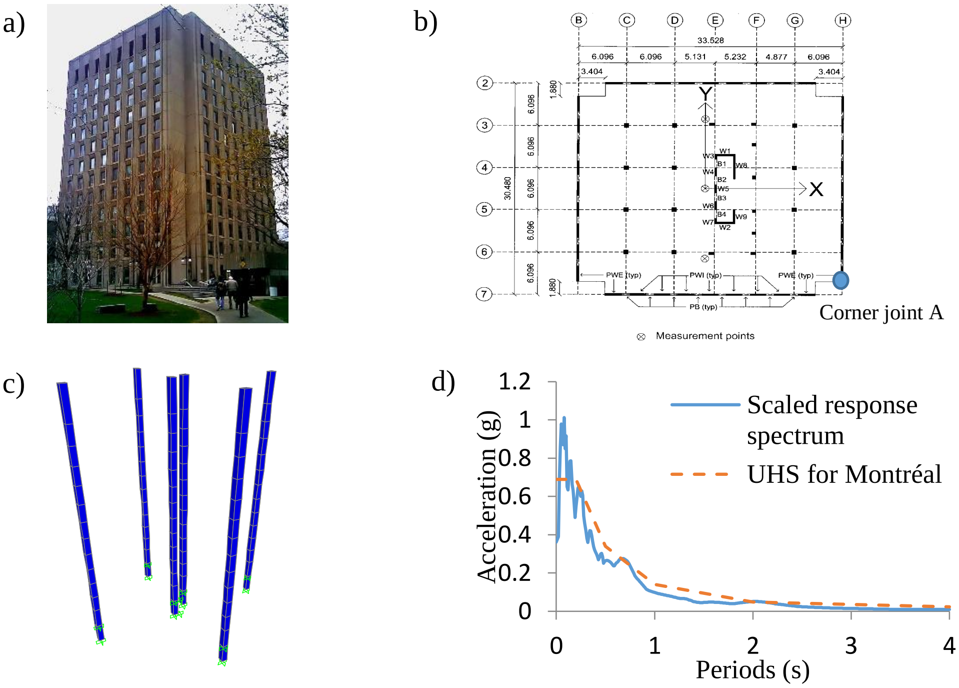

Fig. 1. a) 3D view of the building; b) a typical floor plan and sensor positions; c) 3D view of the equivalent FE model; d) response spectrum of the input ground motion and UHS for Montreal

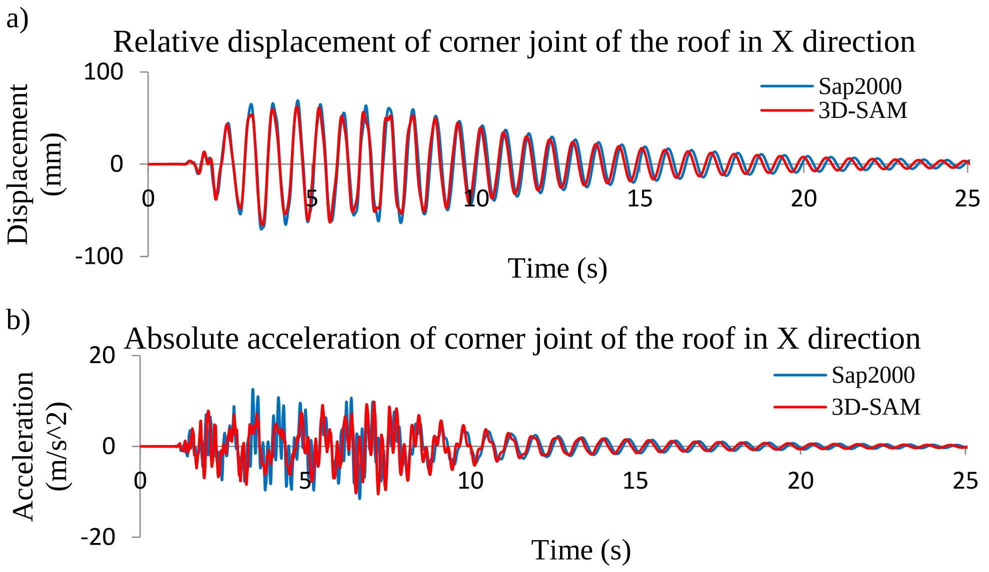

Fig. 2. Comparison between response history analyses of the roof corner joint A by different methods-earthquake is applied in X direction

3. Modified 3D-SAM for higher amplitude motion

Because of the low amplitude range of ambient vibrations (PGA<10^{-5}g), some of the dynamic properties obtained from weak-motion are generally expected to be different from those obtained using strong-motion (PGA>0.1g). This difference has been observed between the ambient vibrations and seismic ground motions (Dunand et al. 2006) and is mostly linked to variations in natural frequencies and damping levels. The change in modal characteristics and wandering of natural frequencies were even observed in undamaged structures (not visible damage) subjected to strong motion (Celebi 2007). The trend is for natural frequencies to decrease and damping ratios to increase with seismic intensity, whereas mode shapes are not significantly affected. To have a correct prediction of the linear response of a structure subjected to a strong earthquake there is a need to have its modal properties for higher vibration levels corresponding to the state of the structure prior to yielding happens. Appropriate modification factors can be derived to relate low vibration modal properties to the properties at higher vibration levels. Such modification factors can be derived based on observations of buildings equipped with permanent strong-motion instrumentation where the building has not suffered from visible structural damage during a strong excitation. After careful review of data for 18 such buildings available in the literature (Dunand et al. 2006, Celebi 2007 and 2009, Carreno and Boroschek 2011), the following observations were made:

1) the strong-motion modal frequencies are decreased by a maximum of 30% and 40% of the corresponding values extracted from ambient vibration records for steel and concrete buildings, respectively;
2) the mode shapes have not changed from ambient to the strong vibration levels (before the occurrence of damage);
3) the overall internal damping observe in for strong-motion response can be 2 to 4 times larger than in ambient measurements.

Based on these general observations, one can apply the appropriate modification factors to the AVT modal properties before inputting them in the 3D-SAM procedure. According to the performance-based design concept and to remain conservative in the assessment of building displacements and drifts, it is suggested that the natural frequencies be decreased by 30% and 40% for steel and concrete buildings, respectively, and that internal damping ratios be multiplied by two. Moreover, the prediction of non-linear seismic demands using linear analysis has been widely used for seismic design as prescribed in codes and for vulnerability assessment. To obtain the best representative linear system at higher shaking levels, the modified modal properties based on the increased natural period and damping ratio suggested above should be used. Therefore, the 3D-SAM application range can further be expanded by use of the equal displacement rule (EDR).

4. Application of 3D-SAM to four case studies

4.1. General

In each case study, ten synthetic records (Fig. 3) are applied to cover the entire frequency range of interest, PGA, magnitude, epicentral distance and duration. The generated records were also scaled up or down to match the UHS of Montreal as closely as possible in different ranges of periods.

The global seismic demand parameters are calculated for all selected ground motions as well as their mean values and standard deviations.

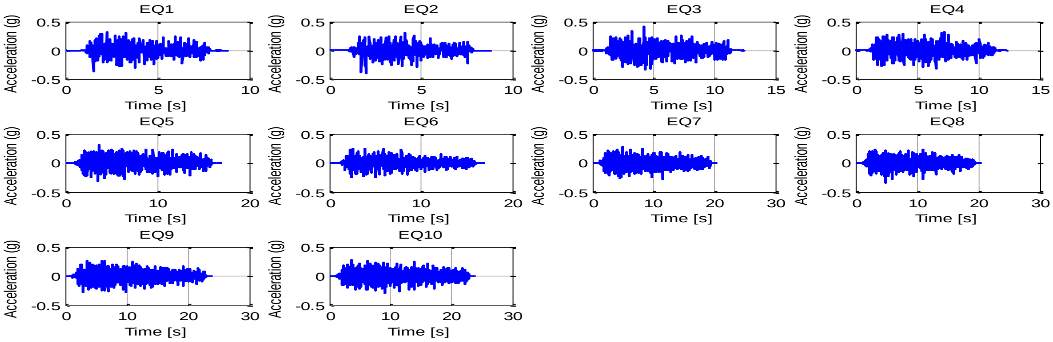

Fig. 3. Ten earthquake records compatible with UHS for Montreal, Canada

4.2. Burnside building

This is the same building used in Section 2.2 for verification of the 3D-SAM. Fig 4. shows some of the important seismic demands obtained from the modified 3D-SAM method when earthquakes are applied in Y direction. Red circles on mean ± sigma graphs show the location of the floors along building height except for shear forces, which are given at half-story heights.

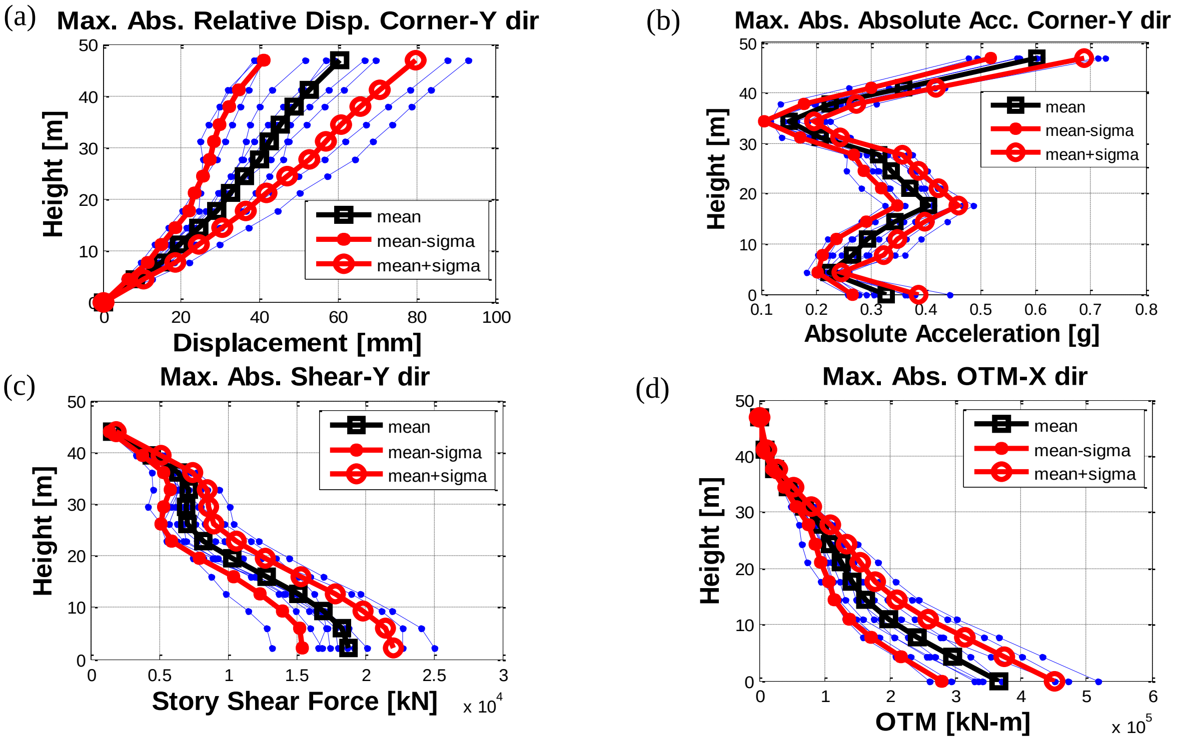

Fig. 4. Maximum seismic demands from 3D-SAM method for Burnside building

4.3. Centre du Plateau

This building was constructed in 1961 with a reinforced concrete moment frame structural system and height of about 13.1 m including one basement floor, 8.4 m above the ground level. A bird's eye view of the building, its floor plans and sensor positions (black dots) are shown in Fig. 5. The building's modal characteristics derived from AVT and analyzed by ARTeMIS™ software are shown in Fig. 6. Then the building is subjected to the ten earthquakes and analyzed by means of the modified 3D-SAM method (Y is aligned N.S. dir., X is aligned E.W. dir. and earthquakes are applied in north-south direction). Fig. 7 shows some of the important seismic demands. The accelerations are calculated in both X and Y directions. By providing the acceleration, response spectra at each floor can be derived and non-structural components can be assessed. Also, with the knowledge of drift ratios between adjacent floors, the building performance and damage state can be predicted. Moreover, in the case of an irregular building 3D-SAM can calculate the dynamic amplification portion of natural torsion on each floor. From Fig. 7 d) it is seen that the dynamic amplification of natural torsion is equivalent to an eccentricity of 10% for this building.

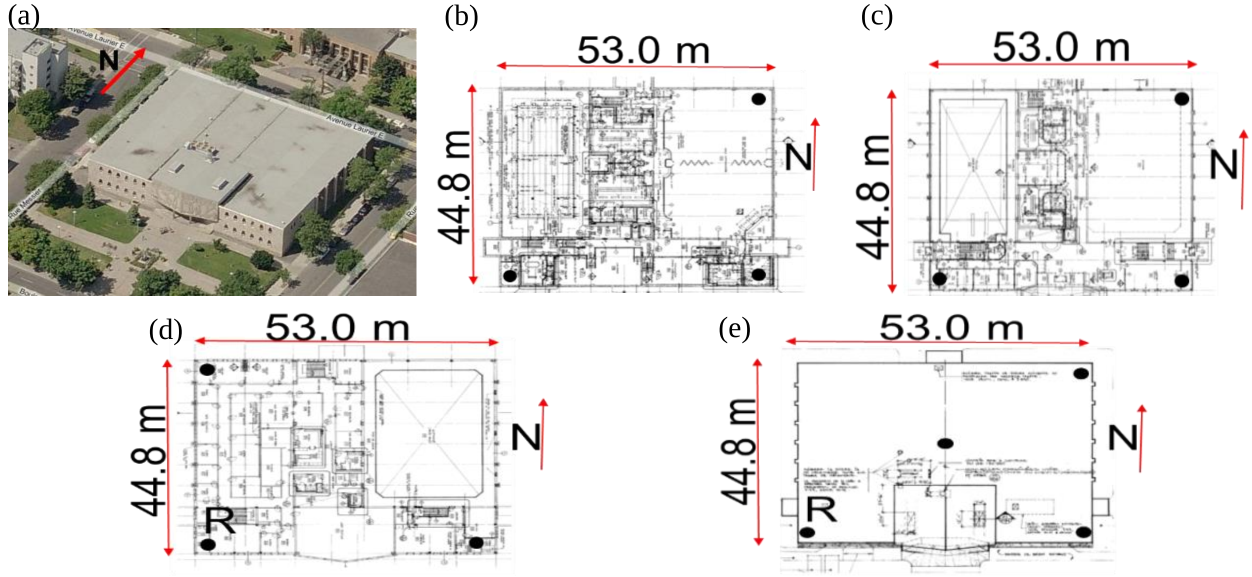

Fig. 5. (a) Bird's eye view; (b) Basement - 4.7 m below ground level; (c) Ground floor; (d) 1st floor- height above ground 4.2 m; (e) Roof - height above ground 8.4 m

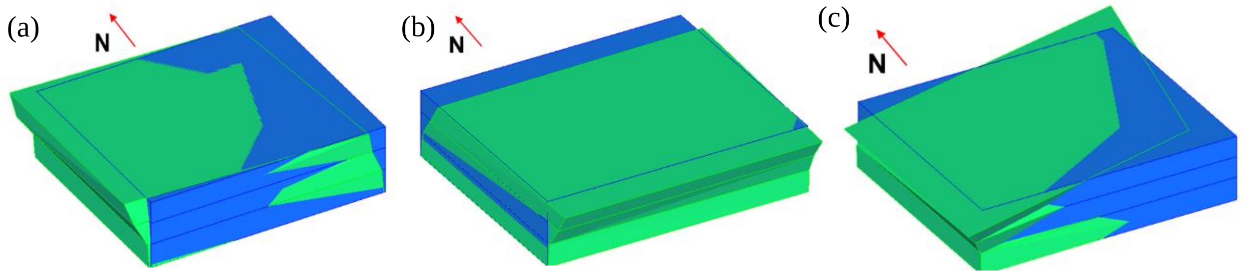

Fig. 6. Mode shapes a) 1st flexural mode N-S dir. (0.23 s, damping ratio=0.017); b) 1st flexural-torsional mode E-W dir. (0.21 s, damping ratio=0.017); c) 1st torsional mode (0.16 s, damping ratio=0.033)

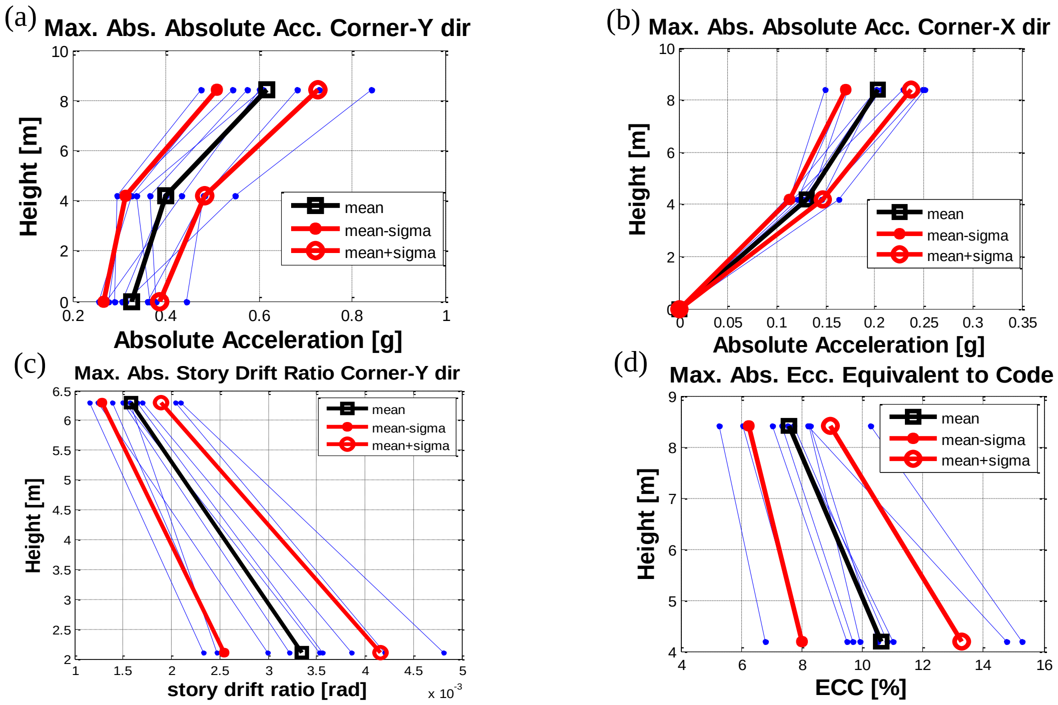

Fig. 7. Maximum seismic demands from 3D-SAM method for Centre du Plateau

4.4. Centre Roger Rousseau

This community centre is a single building constructed in 1976 with braced steel frame structural system and height of about 7.9 m above the ground level. A bird's eye view of the building, a typical floor plan and sensor locations, and the four derived modal properties from AVT are shown in Fig. 8.

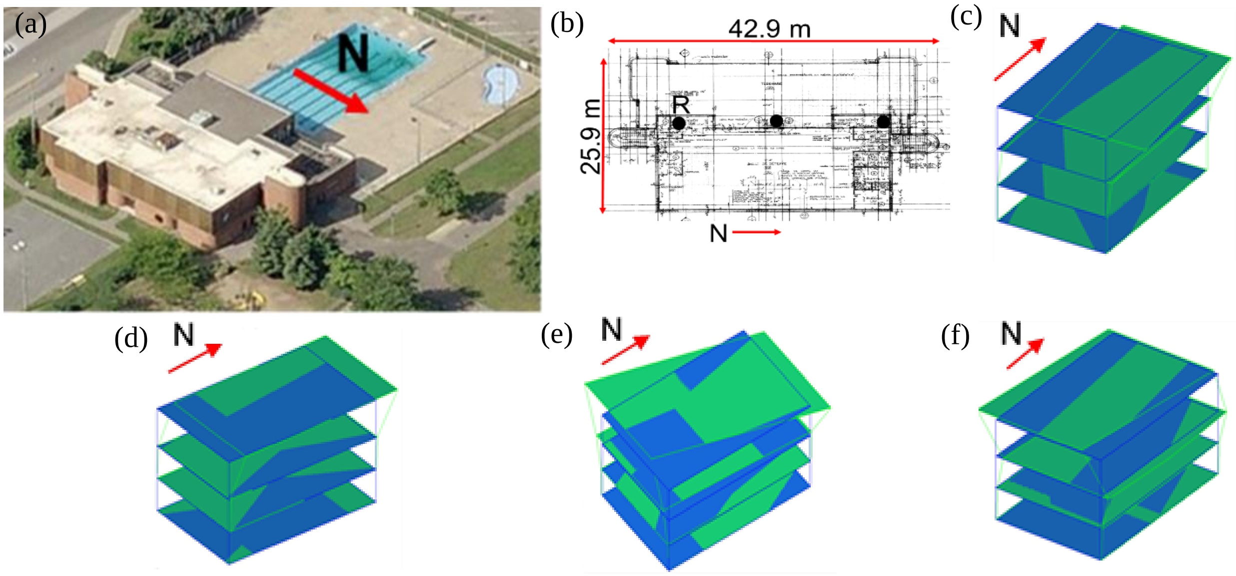

Fig. 8. (a) Bird's eye view; (b) Typical floor plan and sensor positioning; (c) 1st flexural-torsional mode E-W dir. (0.18 s, damping ratio=0.06); (d) 1st flexural-torsional mode N-S dir. (0.13 s, damping ratio=0.02); (e) 1st torsional mode (0.09 s, damping ratio=0.016); (f) 2nd flexural-torsional mode E-W dir. (0.08, damping ratio=0.01)

The building is subjected to the ten earthquakes in NS direction and analyzed with the modified 3D-SAM method; some of the derived seismic demands are shown in Fig. 9.

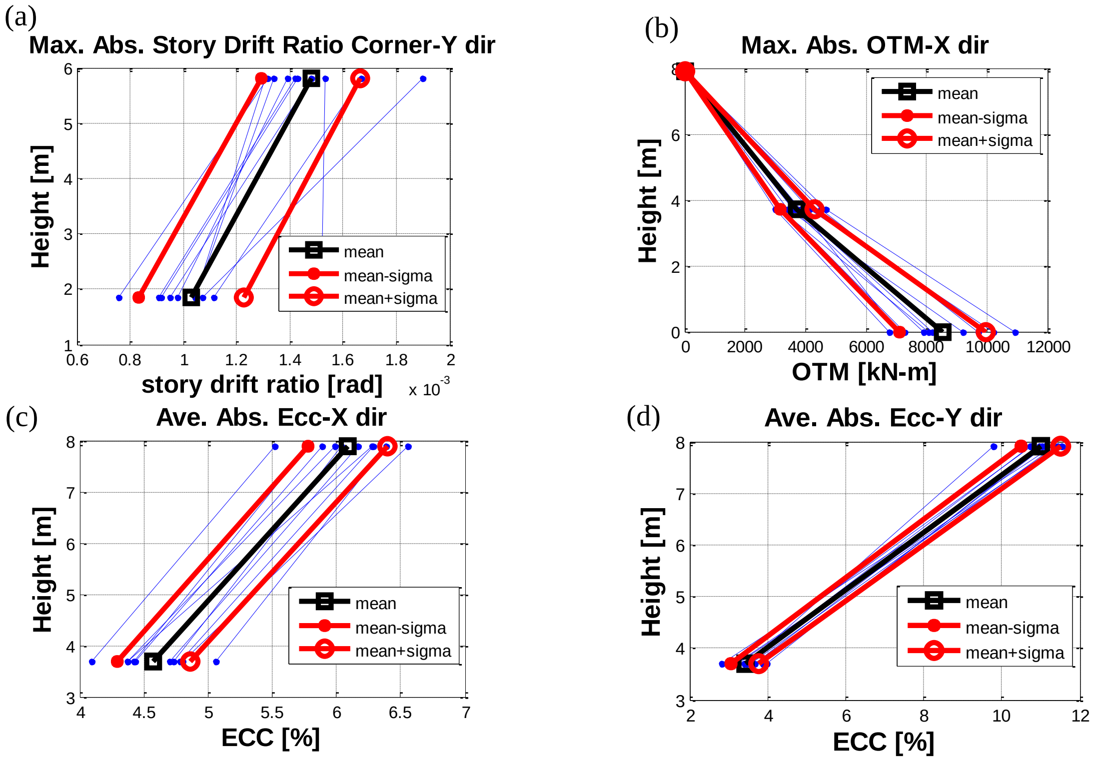

Fig. 9. Maximum seismic demands from 3D-SAM method for Centre Roger Rousseau

4.5. Centre Roussin

This community center was constructed in 1964 with reinforced concrete moment frame and height of 17.1 m including one basement floor, and 13 m above the ground level. A bird's eye view of the building, a typical floor plan and sensor locations, and the derived 6 modes from AVT are shown in Fig. 10. Some of the important seismic demands of the building derived by modified 3D-SAM are shown in Fig. 11.

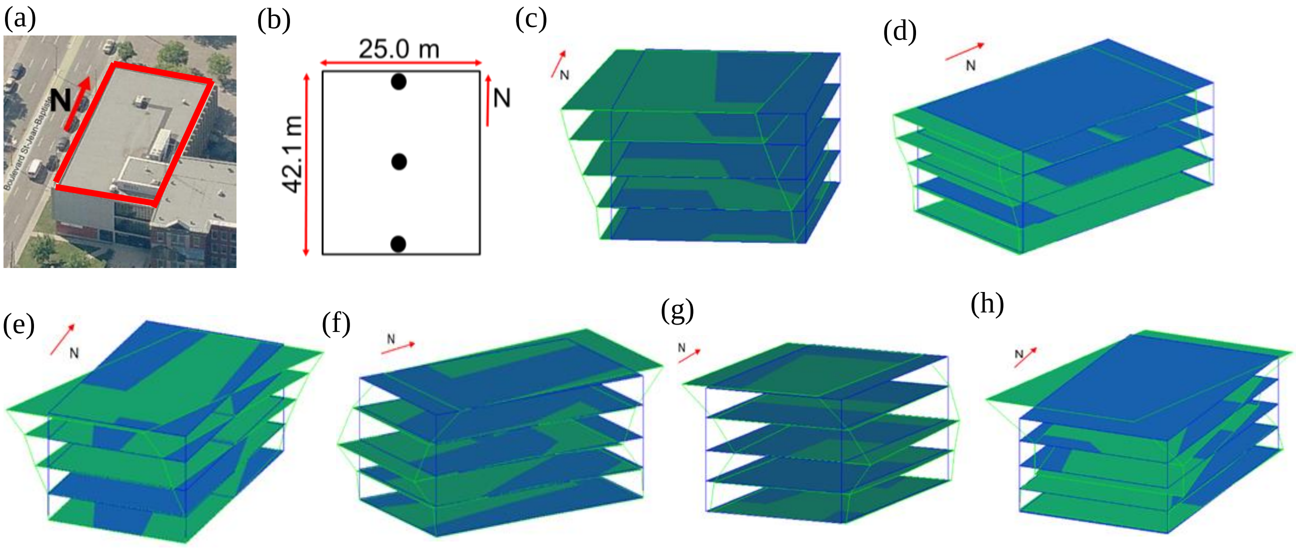

Figure 10. (a) Bird's eye view; (b) A typical floor plan; (c) 1st flexural-torsional mode E-W dir. (0.38 s, damping ratio=0.041); (d) 1st flexural mode N-S dir. (0.38 s, damping ratio=0.040); (e) 1st torsional mode (0.23 s, damping ratio=0.030); (f) 2nd flexural mode N-S dr. (0.13 s, damping ratio=0.020); (g) 2nd flexural mode E-W dir. (0.12 s, damping ratio=0.023); (h) 2nd torsional mode (0.1 s, damping ratio=0.010)

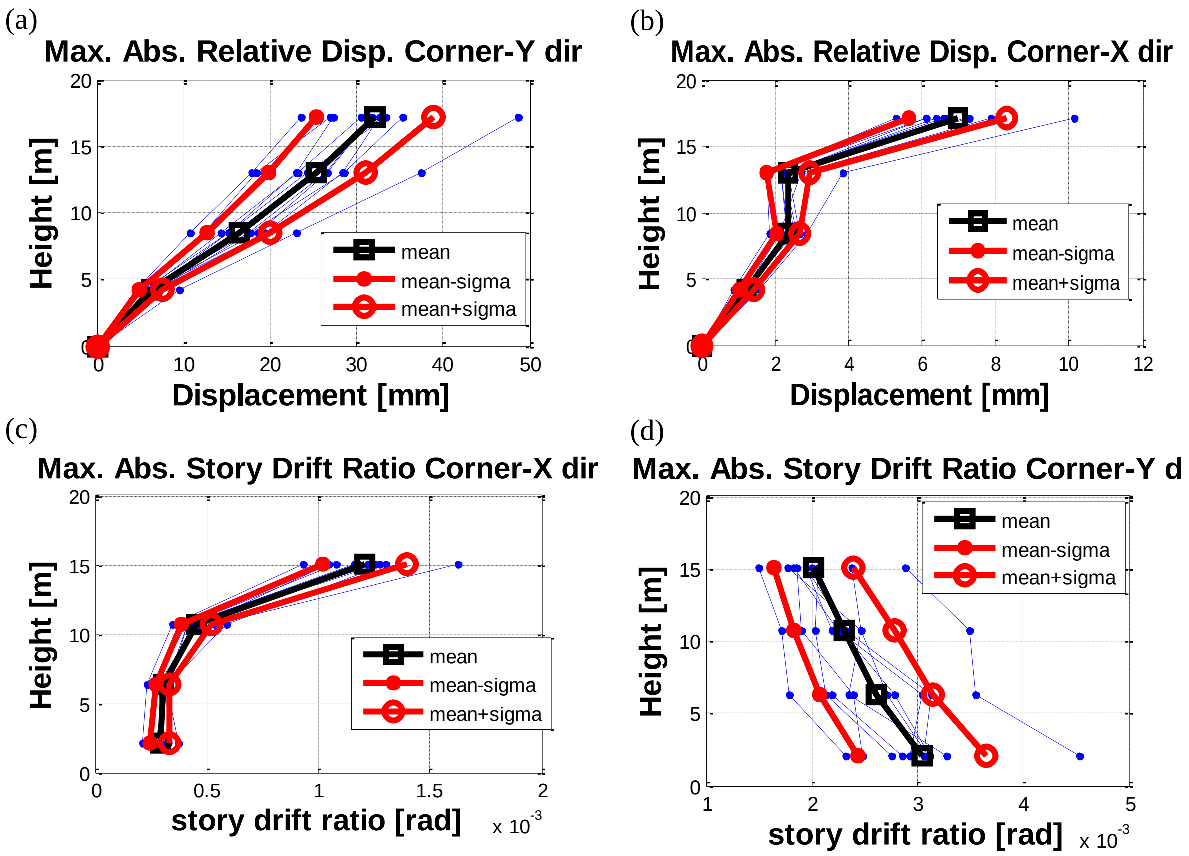

Fig. 11. Maximum seismic demands from 3D-SAM method at a corner joint for Centre Roussin

5. Conclusion

In this paper a simplified 3-dimensional seismic assessment method directly based on ambient vibration testing, 3D-SAM, is briefly presented and verified for a high rise building located in Montreal. The 3D-SAM methodology and software calculate response histories of relative displacements and absolute accelerations at any location and direction on the building floor as well as the following seismic demands: maximum relative floor displacements, story drift ratios, floor absolute accelerations, story shear forces, overturning moments and dynamic amplification portion of natural torsions. All these demand parameters are calculated for any selected number of ground motions (can be applied in any direction) along with their mean and standard deviations. The calculated absolute accelerations on each floor can be used to find response spectra (see companion paper by Asgarian et al.) that lead to prediction of non-structural component seismic performance. Moreover, drift ratios and displacements of the corner joints can be a good indicator of the building performance for an eventual design-level earthquake and the subsequent damage states. Application of the 3D-SAM was demonstrated with four post-disaster buildings located in Montreal. Moreover, appropriate modification factors for further expansion of the 3D-SAM application from weak to the stronger ground motions were proposed. It is emphasized that the method does not require the creation of any detailed FE model and is solely based on modal properties of the current condition of buildings derived from ambient vibration tests. The 3D-SAM method is a more efficient and accurate tool for building seismic response prediction if compared to the current use of linear calibrated finite element methods based on experimental modal analysis. The method calculates the seismic demands directly from experimental modal characteristics of the building.

6. Acknowledgements

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