# COMPARISON OF THE AMBIENT VIBRATION-BASED SEISMIC ASSESSMENT METHOD (3D-SAM) WITH A FIVE-STOREY FULL-SCALE SHAKE TABLE TEST

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## *Abstract*

This paper evaluates the accuracy of the novel approach for seismic assessment of buildings, 3D-SAM, based on ambient vibration measurements using acceleration/velocity sensors in a real shake table test. The proposed method can assess buildings without a need for detailed design documentations or creation of finite element models. This method was applied to the full-scale five-story reinforced concrete building that was built and tested on the NEES-UCSD unidirectional shake table at University of California, San Diego in 2012. This building was subjected to several earthquakes and ambient vibration tests were performed before and after each earthquake. The authors used the measured ambient vibration data in 3D-SAM to perform modal analysis using the Stochastic Subspace Identification (SSI) method in the time domain. Using the proprietary algorithms of 3D-SAM and solely based on the modal identification results, the global seismic engineering demands of the building such as drift ratios and accelerations were predicted at all corner locations per floor and for an applied earthquake. The predicted seismic demands were compared with prescribed HAZUS damage thresholds for a global seismic evaluation and with those of FEMA P-58 for a component-level seismic evaluation. Finally, the predicted damage levels based on the ambient vibration tests and the 3D-SAM methodology were compared with the observed damages from the shake table test as well as a finite element model. The results confirm 3D-SAM as a reliable and quick seismic assessment tool for buildings.

*Keywords: Shake table, Ambient vibration, Seismic evaluation, 3D-SAM, HAZUS, FEMA-P58*

## 1. Introduction

To address the need for understanding the earthquake and post-earthquake fire behavior of buildings and their non-structural components and systems, a highly multidisciplinary project was developed by the University of California, San Diego. In April and May 2012 at the NEES@UCSD facility, the physical phase of testing was executed on a full-scale, five-storey building completely furnished with non-structural components (NCSs). Within the test building, complete egress subsystems, façades, architectural contents, medical equipment, and passive and active fire systems, to name a few, were included [1]. The project, a complete building with non-structural Components and Systems (BNCS), was realized by a unique collaboration between academic, industry and government and hundreds of individuals with expertise in structural and non-structural design, earthquake engineering, and construction and management practices. Three phases of physical testing were executed, subjecting the building to: (i) dynamic motions while isolated at its base, (ii) dynamic motions while fixed at its base, and (iii) live fire tests within select earthquake damaged compartments [2].
In this study, we focus on application of the 3D-SAM™ methodology on seismic and damage prediction of buildings subjected to earthquakes without a need for finite element (FE) models or detailed engineering plans [3]. An earthquake record motion, called CNP100, in fixed-based condition has been considered among the different applied earthquakes. The predicted seismic demands are compared with the measured and finite element model results to evaluate the accuracy of the 3D-SAM methodology. Authors are in the process of performing the same study for stronger earthquakes.

## 2. The 3D-SAM methodology

Our patented technology, 3D-SAM™ (PCT/CA2016/050336), is the first technology and software that can perform both health monitoring and seismic assessments on existing structures based solely on ambient vibration sensing data [3]. This technology is the result of several years of research and development at McGill University and Sensequake, where it has been used to assess many landmark buildings and bridges across Canada [4, 5, and 6].

The 3D-SAM utilizes modal properties, building parameters, its proprietary algorithms and software to predict the building damages due to a future earthquake. The 3D-SAM procedure and its outputs are shown in Fig.1. The detailed process of the 3D-SAM methodology is explained in [5] and [6].

The dynamic building properties extracted from strong-motion records (peak ground acceleration (PGA) > 0.1 g) are expected to be different from those obtained using weak-motion, such as low amplitude ambient vibration (PGA < $10^{-5}$ g). The normal tendency is for natural frequencies to decrease and damping ratios to increase with seismic intensity. Mode shapes are fairly constant as long as no localized damage occurs. Therefore, appropriate modification factors can be applied to the modal properties derived by an ambient vibration test (AVT) to improve prediction of the seismic linear response of the building. Such modification factors have been derived from data collected in buildings equipped with permanent strong-motion instrumentation, which have been subjected to earthquakes in their lifetime [4].

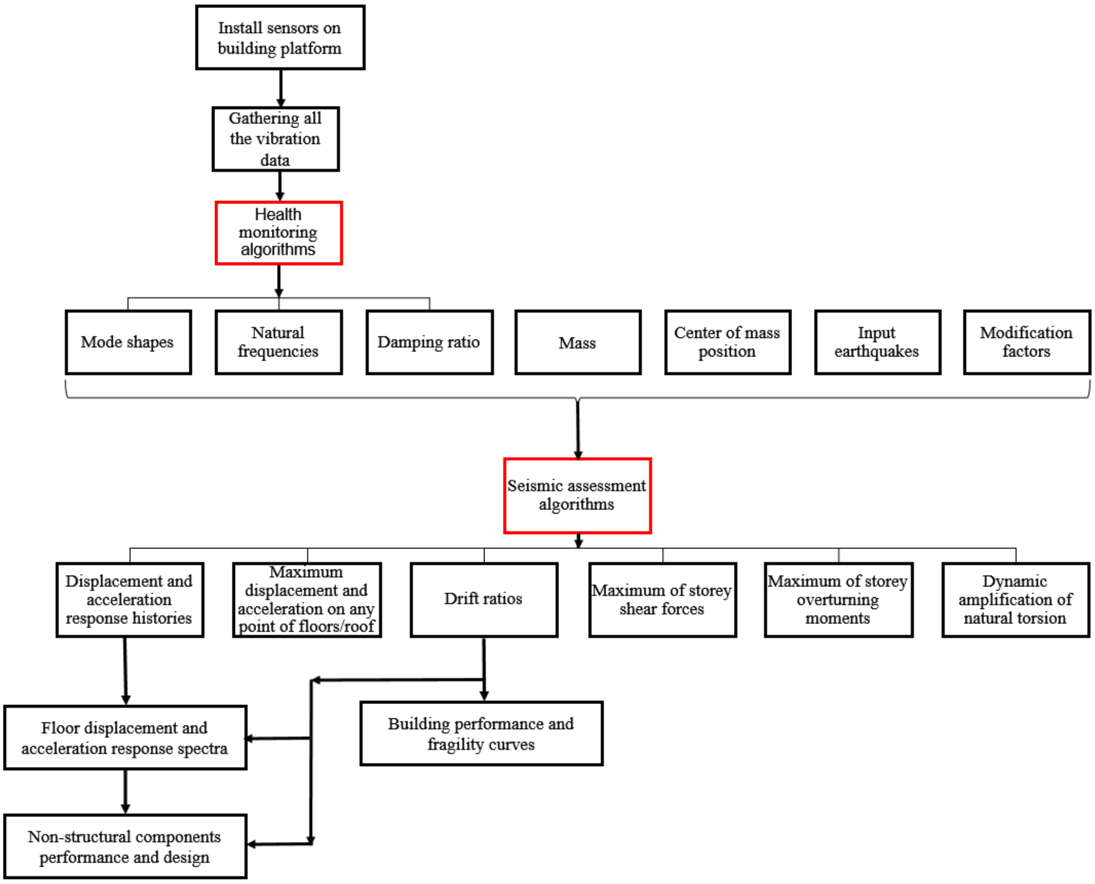



Fig. 1 – The patented 3D-SAM technology

## 3. 3D-SAM modal analysis

The 3D-SAM software used the raw data for modal analysis in order to extract the modal properties (incl. frequency, mode shape and damping ratio) to perform the seismic assessment. Table 1 shows the first seven frequencies extracted in 3D-SAM and compares them with the BNCS report [2]. It can be seen that the errors in frequency are very small. Mode shapes and damping ratios were in agreement as well.

Table 1 – Comparison of frequency between 3D-SAM and BNCS report

| Mode name | Frequency (Hz) in BNCS Report | Frequency (Hz) in 3D-SAM | Difference (%) |
|---|---|---|---|
| **1 - L** | 1.35 | 1.31 | ~ 3% |
| **1 - T+To** | 1.69 | 1.71 | ~ 1.2% |
| **1 - To** | 2.28 | 2.25 | ~ 1.3% |
| **2 - L** | 5.79 | 5.73 | ~ 1% |
| **2 - L+To** | 6.31 | 6.42 | ~ 1.7% |
| **2 – To** | 9.33 | 9.44 | ~ 1.2% |
| **3 – L** | 10.40 | 10.70 | ~ 3% |



## 4. Seismic Assessments

We used the main characteristics of the structure derived by 3D-SAM software and other parameters of the building such as the floor and roof mass, the position of the center of mass, the floor heights, the floor dimensions and the chosen earthquake motions to generate the global earthquake assessment demands [3]. Our technology predicts how the building will behave in the event of an earthquake. The 3D-SAM can calculate the relative displacement and absolute acceleration response histories of any point on a floor/roof in a specified direction, the drift ratios between floor levels, the storey shear forces and the overturning moments. Additionally, 3D-SAM calculates the response histories for any desired earthquake and location on the floors. Fig.2 shows the applied earthquake motion in this study.

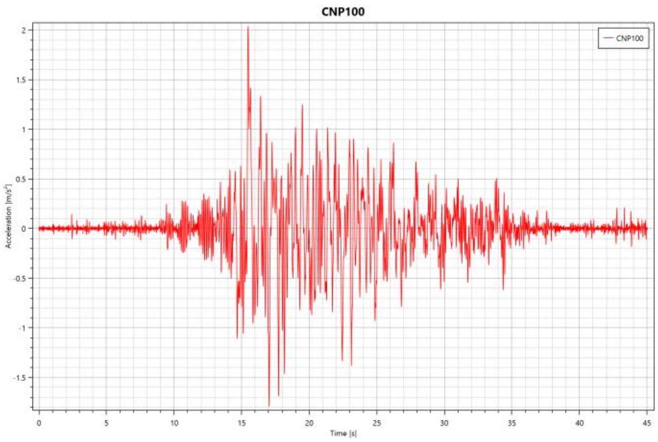
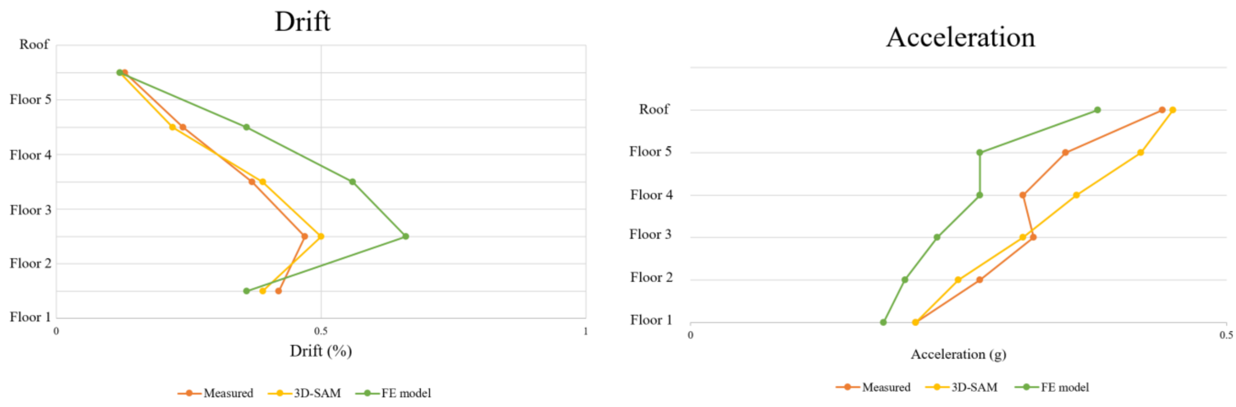



Fig. 2 – Applied Earthquake motion record

In order to evaluate the accuracy of the 3D-SAM seismic demand predictions, the FE model [7], real measured, and 3D-SAM results are compared. Fig.3 shows the comparison between measured, FE model and 3D-SAM seismic evaluation of the building for the two common Engineering Demand Parameters (EDPs): drift and acceleration. The 3D-SAM's seismic response is much better correlated with the measured response when compared to the FE Model for both demand parameters.




(a) (b)

Fig. 3 – Comparison of EDP between measured, FE model and 3D-SAM a) Drift b) Acceleration



## 5. Damage Analysis

Damage analysis is performed using two different approaches: a global-based assessment that evaluates the building globally per floor/storey using HAZUS [8] and a component-based approach which assess the building components individually per floor using FEMA P-58 [9].

### 2.2.1 Global-based damage analysis

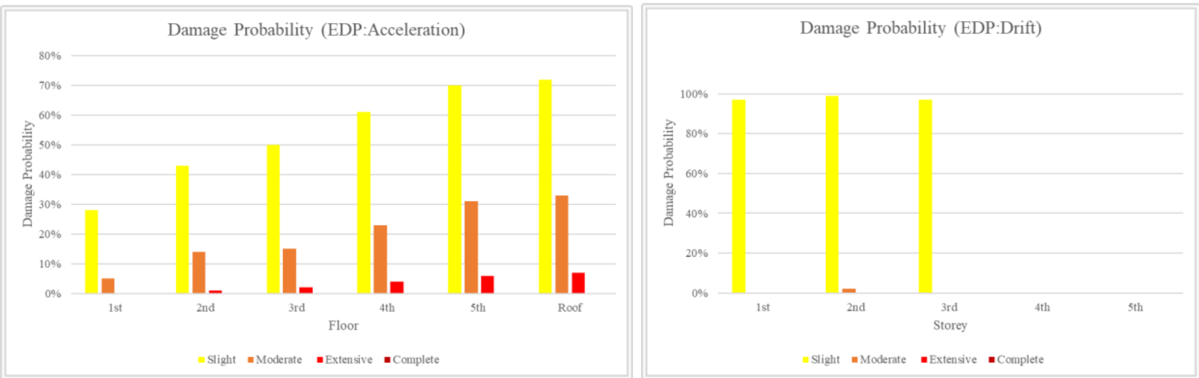
Based on FEMA-154 [10], the building is considered a concrete shear wall (C2). By comparing the seismic demands predicted by 3D-SAM and HAZUS fragility curves, probability of damage was calculated for each floor for both drift and acceleration sensitive components (Fig.4). The global damage levels have been classified in four categories: slight, moderate, extensive and complete. Structural damages are defined as follows:

Slight Structural Damage: diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at few locations.

Moderate Structural Damage: most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded yield capacity indicated by larger diagonal cracks and concrete spalling at wall ends.

Extensive Structural Damage: most concrete shear walls have exceeded their yield capacities; some walls have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement or rotation of narrow walls with inadequate foundations. Partial collapse may occur due to failure of non-ductile columns not designed to resist lateral loads.

Complete Structural Damage: structure has collapsed or is in imminent danger of collapse due to failure of most of the shear walls and failure of some critical beams or columns. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the total area of C2 buildings with complete damage is expected to be collapsed [8].




(a) (b)

Fig. 4 – Global-based damage probability in different floor/storey according to fragility database provided in HAZUS a) Acceleration b) Drift

As shown in Fig. 4a, the acceleration-sensitive components (non-structural components) mainly suffer from slight damages in fist three floors and slight to moderate damages in floor 4 to floor 6. The drift-sensitive components (structural components) suffer from slight damages (Fig. 4b). The definition of damage levels for three non-structural components based on Hazus are described in Table 2.



Table 2 – Description of some of non-structural components in different damage levels

| | Slight | Moderate | Extensive | Complete |
|---|---|---|---|---|
| Partition walls | A few cracks are observed at intersections of walls and ceilings and at corners of door openings. | Larger and more extensive cracks requiring repair and repainting; some partitions may require replacement of gypsum board or other finishes. | Most of the partitions are cracked and a significant portion may require replacement of finishes; some door frames in the partitions are also damaged and require re-setting. | Most partition finish materials and framing may have to be removed and replaced; damaged studs repaired, and walls be refinished. Most door frames may also have to be repaired and replaced. |
| Suspended ceiling | A few ceiling tiles have moved or fallen down. | Falling of tiles is more extensive; in addition the ceiling support framing (T-bars) has disconnected and/or buckled at few locations; lenses have fallen off of some light fixtures and a few fixtures have fallen; localized repairs are necessary. | The ceiling system exhibits extensive buckling, disconnected t-bars and falling ceiling tiles; ceiling partially collapses at few locations and some light fixtures fall; repair typically involves removal of most or all ceiling tiles. | The ceiling system is buckled throughout and/or fallen and requires complete replacement; many light fixtures fall. |
| Exterior wall panels | Slight movement of the panels, requiring realignment. | The movements are more extensive; connections of panels to structural frame are damaged requiring further inspection and repairs; some window frames may need realignment | Most of the panels are cracked or otherwise damaged and misaligned, and most panel connections to the structural frame are damaged requiring thorough review and repairs; few panels fall or are in imminent danger of falling; some window panes are broken and some pieces of glass have fallen. | Most panels are severely damaged, most connections are broken or severely damaged, some panels have fallen and most are in imminent danger of falling; extensive glass breakage and falling. |

Based on the BNCS report and damage observation, the structural and non-structural components suffered from minor damages after this earthquake record. The result of global assessment based on the 3D-SAM methodology has predicted the slight and slight to moderate damage levels which are consistent with the real observation from the shake table test.

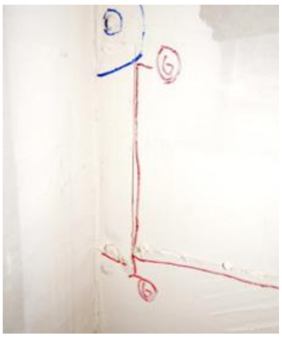
### 2.2.2 Component-based damage analysis

Component assessment is based on FEMA P-58 database for all available components. Each component has its own fragility curve which has been used to find its damage level for in different floors based on the predicted seismic demands from the 3D-SAM. Results of the comparison between the predicted and observed damages are shown for few components.

According to the BNCS report [2], after this motion record, the joint tape cracks grew noticeably longer and wider (Fig. 5a), and gypsum board crushing occurred around the elevator door openings (moderate) at level 5 (Fig. 5b). Predicted damages using FEMA P-58 and 3D-SAM for this component are shown in Table 3.





(a)

(b)

Fig. 5 – Partition wall damage (a) joint tape cracks around the corner of stair well at Storey 2 (DS-I), and (b) gypsum board crushing around the elevator door opening at Storey 5 (DS-II).

Table 3 – Damage analysis of partition walls based on FEMA P-58

| Damage state of partition walls | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Storey 1 | | | Storey 2 | | | Storey 3 | | | Storey 4 | | | Storey 5 | | |
| Damage Observation | Minor | | | Minor | | | Minor | | | Moderate | | | Moderate | | |
| Damage prediction (FEMA P-58) | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 |
| | 27% | 0% | 0% | 50% | 1% | 0% | 27% | 0% | 0% | 0% | 0% | 0% | 2% | 0% | 0% |

DS1: Screw pop-out, cracking of wall board, warping or cracking of tape, slight crushing of wall panel at corners
DS2: Moderate cracking or crushing of gypsum wall boards (typically in corners). Moderate corner gap openings, bending of boundary studs.
DS3: Buckling of studs and tearing of tracks. Tearing or bending of top track, tearing at corners with transverse walls, large gap openings, and walls displaced.

Table 3 shows the DS1 damage state has been predicted by FEMA P-58, a minor damage which matches with the observations in the first three stores. However, the other two storeys were predicted with almost no damage based on FEMA P-58 drift-based fragility curve, despite having suffered from moderate damage in reality. This shows that the damage on storeys 4 and 5 was due to high acceleration levels and an acceleration-based fragility curve should be used to evaluate the partitions located in these storeys.

Table 4 – Damage analysis of Beam Column Joints based on FEMA P-58

| Damage state of Beam Column Joints | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Storey 1 | | | Storey 2 | | | Storey 3 | | | Storey 4 | | | Storey 5 | | |
| Damage Observation | The minimal damage has been observed after this motion. | | | | | | | | | | | | | | |
| Damage prediction (FEMA P-58) | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 |
| | 0% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

DS1: Beams or joints exhibit residual crack widths > 0.06 in. No significant spalling. No fracture or buckling of reinforcing.
DS2: Beams or joints exhibit residual crack widths > 0.06 in. Spalling of cover concrete exposes beam and joint transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcing.
DS3: Beams or joints exhibit residual crack widths > 0.06 in. Spalling of cover concrete exposes a significant length of beam longitudinal reinforcement. Crushing of core concrete may occur. Fracture or buckling of reinforcing requiring replacement may occur.



Table 4 shows the comparison between observation and predicted damage in Beam Column Joint component. Table 4 indicates that the minimal damage observation in all storeys is well correlated with the predicted 'no damage' by FEMA P-58.

The comparison between the precited and observed damages for the shear wall component is shown in Table 5. The observed damage shows minimal damage in all storeys which is well correlated with no damage predicted by FEMA P-58.

Table 5 – Damage analysis of Shear wall based on FEMA P-58

| Damage state of Shear wall | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Storey 1 | | | Storey 2 | | | Storey 3 | | | Storey 4 | | | Storey 5 | | |
| Damage Observation | The minimal damage has been observed after this motion. | | | | | | | | | | | | | | |
| Damage prediction (FEMA P-58) | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 | DS1 | DS2 | DS3 |
| | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

DS1: Spalling of cover, vertical cracks greater than 1/16 inch.
DS2: Exposed longitudinal reinforcing.
DS3: Core concrete damage, buckled reinforcing, fractured reinforcing, shear failure, web failure, bond slip.

Table 6 shows the comparison of unsecured components on the 2nd floor with observation. The observed damage shows small movement damage in the 2nd floor which is correlated with the predicted 'small damage' by FEMA P-58. Table 7 indicates the comparison between secured equipment in 2nd floor. The observed damage shows limited movement damage in the 2nd floor which is correlated with the predicted 'no damage' by FEMA P-58.

Table 8 shows the comparison between the predicted damage and observation for the fire sprinkler. The observed damage shows minimal damage in all floors which is correlated with 'almost no damage' predicted by 3D-SAM.

Table 6 – Damage analysis of unsecured equipment on the 2nd floor based on FEMA P-58

| Damage state of unsecured equipment at floor 2 | |
|---|---|
| Damage Observation | Small movement of equipment |
| Damage prediction (FEMA P-58) | DS1 |
| | 18% |


DS1: Falls, does not function.

Table 7 – Damage analysis of secured equipment at floor 2 based on FEMA P-58

| Damage state of secured equipment at floor 2 | |
|---|---|
| Damage Observation | Movement within limits imposed by restrains |
| Damage prediction (FEMA P-58) | DS1 |
| | 0% |


DS1: Falls, does not function.



Table 8 – Damage analysis of fire sprinkler based on FEMA P-58

| | Damage state of Fire Sprinkler | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Damage Observation | Floor 1 | | Floor 2 | | Floor 3 | | Floor 4 | | Floor 5 | | Roof | |
| | The minimal damage has been observed after this motion. | | | | | | | | | | | |
| Damage prediction (FEMA P-58) | DS1 | DS2 | DS1 | DS2 | DS1 | DS2 | DS1 | DS2 | DS1 | DS2 | DS1 | DS2 |
| | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 0% | 1% | 0% |

## 6. Conclusion

In conclusion, the extracted modal properties from the 3D-SAM were in great match with the BNCS result. The 3D-SAM seismic demands show a closer match with the measured outputs compared to the FE model for the applied earthquake motion record. In damage analysis, the global assessment using HAZUS correlates well with the observed damage in structural and non-structural components. In addition, component-based assessment using FEMA P-58 is well-correlated with the observed damages for most of the components on different floors. In summary, the novel 3D-SAM methodology, solely based on ambient vibration data, has performed much better than the finite element model for the applied earthquake record for both modal analysis and predicted seismic demands (drift and acceleration) and the results are very close to the real seismic demands and observed damages.

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