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EFFECTIVENESS OF NEW SENSING-BASED SEISMIC ASSESSMENT METHOD (3D-SAM) IN A TWO-STORY FULL-SCALE SHAKE TABLE TEST

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ABSTRACT

This paper evaluates the accuracy of Sensequake patented methodology for the sensing-based seismic assessment of buildings, 3D-SAM, based on ambient vibration measurements using acceleration and velocity sensors during a shake table test. The proposed method can assess buildings without the need for detailed structural drawings or finite element models. This method was applied to a full-scale, two-story, light wood frame building that was constructed and tested on the NEESWood shake table at the University of Buffalo in 2006. This building was subjected to several earthquake motions and white noise tests were performed before and after each applied earthquake. The authors used the measured ambient vibration data and Sensequake 3D-SAM software to perform modal analysis using the Frequency Domain Decomposition (FDD) in frequency domain, and Stochastic Subspace Identification (SSI) method in the time domain. Using 3D-SAM's proprietary algorithms, the global seismic engineering demand parameters of the building, including the inter-story drift ratios and accelerations, were predicted at all corner locations per floor and for the applied earthquakes solely based on the modal identification results. 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. The results confirm 3D-SAM as a reliable and quick seismic assessment tool for buildings.

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

INTRODUCTION

Wood structures are widely used in single and double-family residences, low-rise commercial and multi-storey residential buildings. The light wood frame is one of the most well known wood-based structural system in North America.

The NEESWood project has developed a seismic design philosophy that will provide the required needs to increase the height of woodframe structures in active seismic zones of the U.S. [1]. This benchmark test represents one unit of a two-story townhouse, with approximately 167 m^2 of living space with an attached two-car garage. The height of the townhouse from the first-floor slab to the roof eaves is 5.5 m and its total weight is approximately 36 tons. The exterior walls of the townhouse test building are covered with 22.225 mm-thick stucco over 11.1125 mm thick OSB sheathed shear walls on the outside and 12.7 mm thick gypsum wallboard on the inside [1].

Five different seismic test phases were considered during the test. The modal properties of the building have been recorded before each seismic level by applying white noise in different directions. In this study, two seismic levels including seismic levels four and five (named according to the NEESWOOD report) were considered in the analysis. Figure 1 shows the details of the structure. In this test, the twin re-locatable, 50-ton, tri-axial shake tables of the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo (UB) have been used [1].

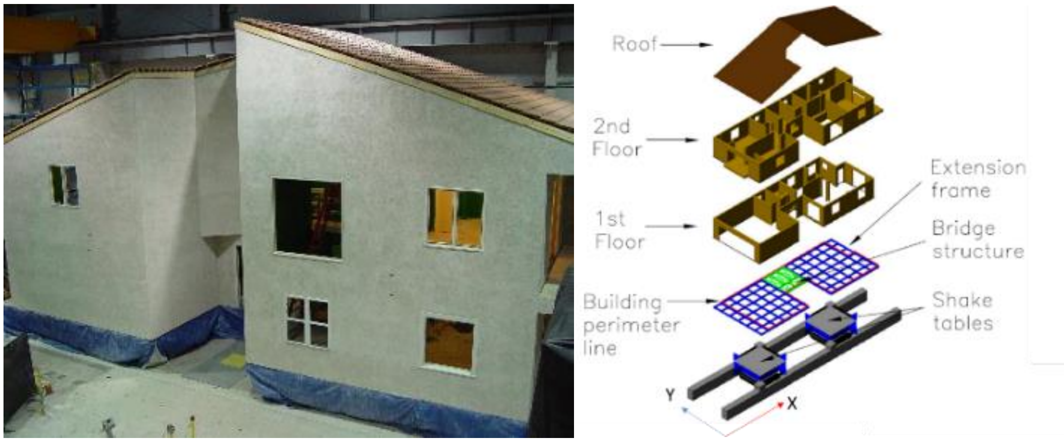

Figure 1. NEESWOOD Two-story, light wood frame details

METHODOLOGY

The patented 3D-SAM methodology

The 3D-SAM method predicts global seismic demands, building response and building performance to future earthquakes based on their in situ derived modal properties (obtained by ambient vibration testing and sensing techniques). The methodology, its inputs, and outputs are illustrated in Figure 2.

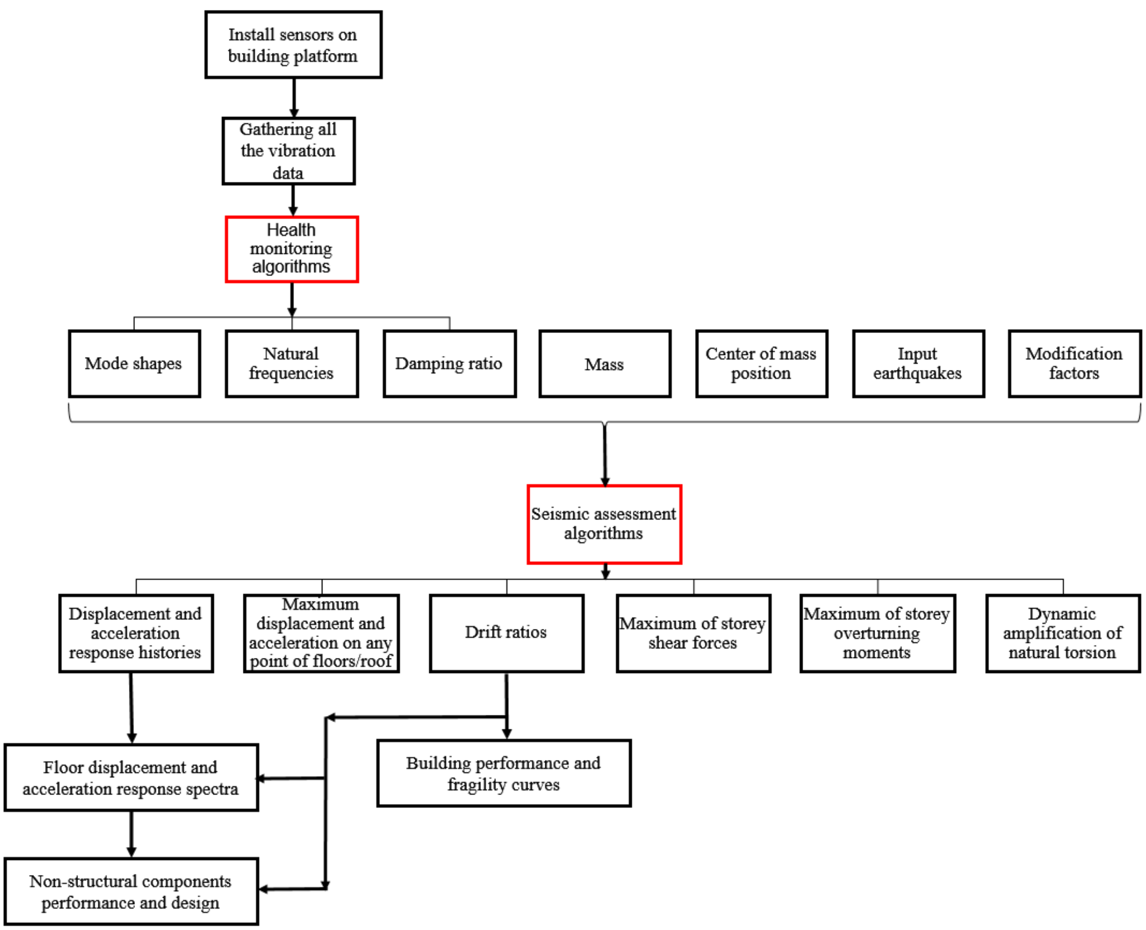

Figure 2. The patented 3D-SAM methodology

By determining the dynamic properties of buildings from ambient vibration tests (AVTs), it is possible to calculate the building seismic response by convolution integrals in the linear range according to classical structural dynamics theory. Unlike previous studies of seismic building evaluation based on AVTs [3, 4] the equation of motion is considered in three dimensions, and earthquake records can be applied in any direction at the building base, that is, three degrees of freedom are assumed for each rigid floor diaphragm including two orthogonal horizontal displacements and one rotational degree of freedom. It is seen in Figure 2 that 3D-SAM is a direct top-to-bottom approach that makes use of the in situ derived modal properties and, therefore, bypasses the need for detailed engineering plans and finite element analysis models. The method is capable of providing the displacement and acceleration response histories at any point and direction on a rigid floor even if a sensor has not been placed exactly at that point during the AVT. This makes the method particularly appealing for irregular and torsional-sensitive buildings. Additional details about 3D-SAM and its verification by comparison with several calibrated finite element models are shown in [5].

Modified three-dimensional seismic assessment method for buildings subjected to moderate to strong earthquake

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 ones, such as low amplitude ambient vibration (PGA < 10^{-5} g). This difference is generally attributed to several factors: (i) the nonlinear behavior of the structural material (such as micro-cracking of the concrete at the foundation or superstructure); (ii) connection slippage (in bolted steel structures and timber structures); (iii) interaction between non-structural and structural elements; and (iv) soil -structure interaction effects [6]. Changes in modal characteristics and the wandering of natural frequencies were also observed in undamaged structures (with slight or non-visible damage) subjected to strong motion [8]. The normal tendency is for natural frequencies to decrease and damping ratios to increase with seismic intensity, while mode shapes are not altered much as long as no localized damage happens.

Therefore, appropriate modification factors can be applied to the modal properties derived by AVT (minute amplitude motion) for an improved prediction of the linear response of the building before the structure reaches a damage state due to strong excitations. Such modification factors can be derived from data collected in buildings equipped with permanent strong-motion instrumentation where the building has not suffered visible structural damage during the strong base motion. After careful review of such buildings in the literature, consisting of 18 buildings listed in [7-15], the following observations are made: (i) 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. As for the seismic assessment and earthquake performance based-design, the floor displacements, drift ratios, and subsequent damage are the key elements, and applying these maximum modification factors to the AVT natural frequencies is considered conservative; (ii) the mode shapes are not changed from ambient to strong vibration levels (before the occurrence of damage); (iii) the internal damping ratio for strong-motion response can be as much as two to four times larger than found using ambient measurements. Consequently, to be conservative and according to the earthquake performance based-design concept mentioned earlier, the damping ratios derived from AVT can be multiplied by the factor 2. The aforementioned are approximate and conservative modifications. As the number of buildings being permanently instrumented is increasing and more data from earthquake events become available, further refined modification factors can be used in 3D-SAM.

3D-SAM modal analysis

3D-SAM software uses the raw vibration data for modal analysis in order to extract the modal properties (frequencies, mode shapes, and damping ratios) to perform the seismic assessment [16]. Three different earthquake motion records with different intensities were considered for seismic evaluation and damage analysis according to NEESWOOD report. In this paper, the results for two seismic levels are discussed (Table1). Seismic levels are named in accordance to the naming reported in the NEESWOOD report. Figure 3 and Figure 4 show the ground motions applied in X-direction for the 1^{st} and 2^{nd} seismic levels. Analysis was done in both X and Y directions; however these two ground motions are shown as examples in this paper.

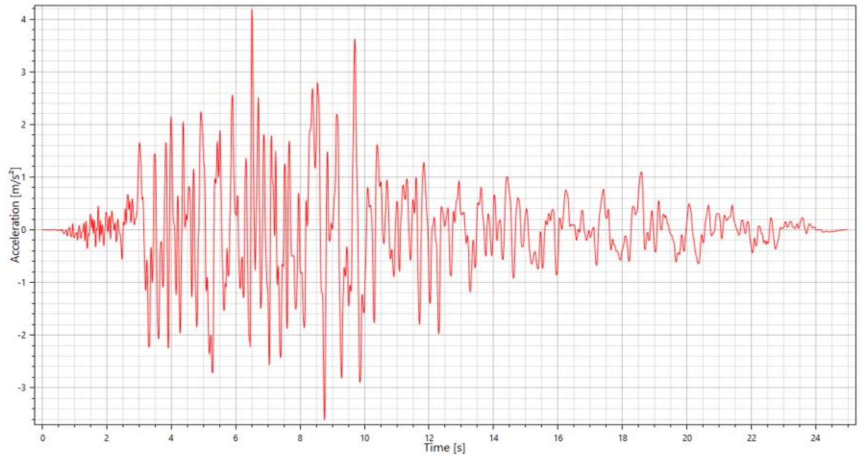

Figure 3: Ground motion applied in X-direction corresponding to the 1st seismic level

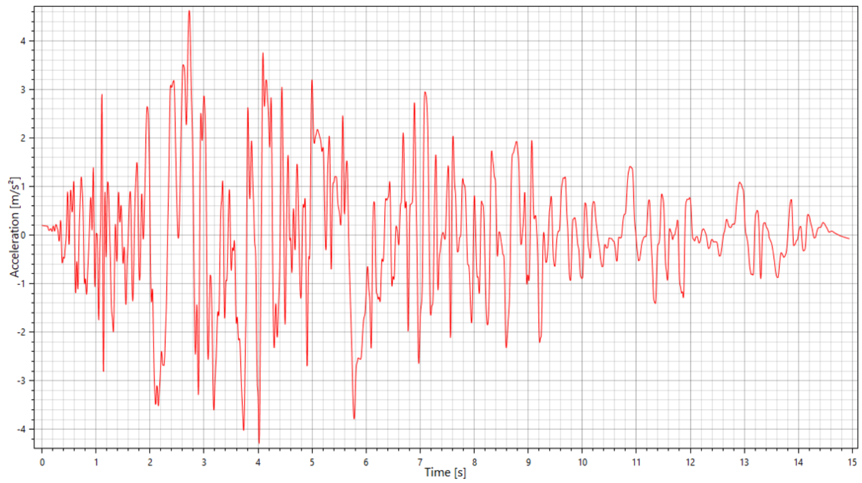

Figure 4: Ground motion applied in X-direction corresponding to the 2nd seismic level

Table1. Properties of applied motion records

Seismic Level	Seismic Test Level	Ground Motions (Northridge 1994)	Hazard Level	PGA (g) East-West direction	PGA (g) North-South direction	PGA (g) Vertical direction
1st	4	Canoga Park	10 % / 50 years	0.43	0.5	0.59
2nd	5	Rinaldi	2 % / 50 years	0.47	0.84	0.85

Since the building has been tested in successive motion records and has been repaired after each seismic level, its condition has contained minor changes. In order to perform the seismic assessment in 3D-SAM, the modal properties of the structure before the applied motion are required. For this purpose, the raw sensing data was collected from the NEESWood database and modal analysis was performed before each motion record. The obtained results were compared with those found in the NEESWood report [1]. Table 2 shows the initial modal properties extracted from 3D-SAM and the modal properties obtained from the NEESWood report.

Based on the findings, the mode shapes are properly correlated between the NEESWood report and 3D-SAM software. The corresponding mode shapes before any earthquake was applied are shown in Figure 5.

Table 2. Comparison of initial frequencies between 3D-SAM and the NEESWOOD report

Mode	Initial frequency from the NEESWOOD report (Hz)	Initial frequency from the 3D-SAM model (Hz)	Difference (%)
1	3.5	3.5	0.0
2	5.1	5.0	2.0
3	7.9	7.8	1.2

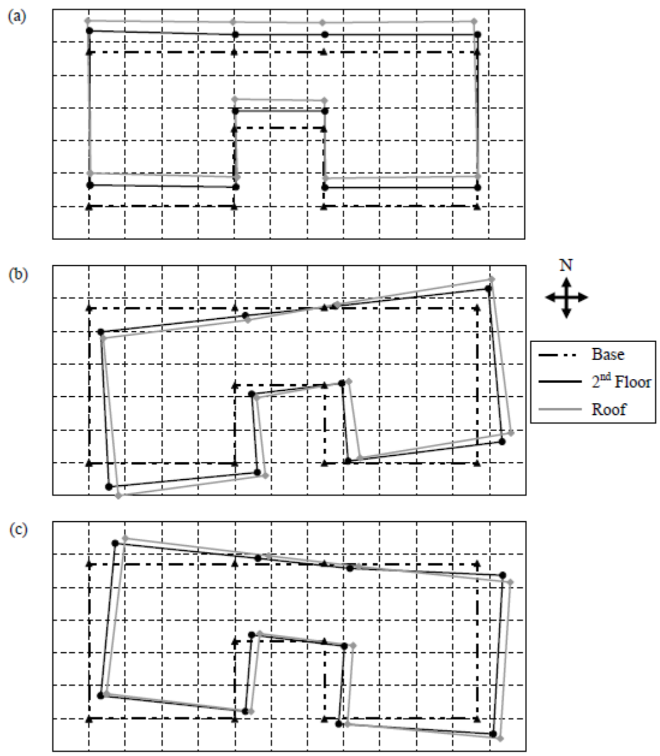

Figure 5. Initial identified mode shapes: (a) Mode 1, (b) Mode 2, (c) Mode 3

The frequency was shown to change after each seismic level. The frequencies are summarized in Table 3 before seismic levels 4 and 5.

Table 3. Modal frequency before seismic levels 4 and 5

Mode	Modal frequency before seismic level 4 (Hz)	Modal frequency before seismic level 5 (Hz)
1	3.1	2.8
2	5.0	5.0
3	7.3	6.9

3D-SAM SEISMIC ASSESSMENT

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

The sensitivity analysis is recommended to see the impact of the modification factor in order to be conservative and obtain the maximum demand. The results of this process are as follows:

- For drift ratios, a sensitivity analysis was conducted on reduction factors of 0%, 10%, 20%, 30%, and 40% for the natural frequencies.
- A sensitivity analysis was conducted on different reduction factors for the acceleration predictions, namely 0%, 10%, 20%, 30%, and 40% in order to reduce the measured natural frequencies.

It should be noted that the acceleration responses have been divided by the proper ductility factors based on ASCE 41-17 which can be used for the future design of retrofit schemes for this building.

To evaluate the accuracy of 3D-SAM's seismic analysis, two common demands of the structure, namely acceleration and drift, were compared for two seismic levels (4 and 5). In terms of the maximum demand values shown in each seismic level below, the earthquakes were applied to both X and Y-directions simultaneously and the demands in both the X and Y-direction are calculated. The maximum is then shown in the outputted plots.

SEISMIC ANALYSIS

First seismic level (Seismic Level 4)

The reduction factors for seismic level 4 are summarized in Table 4.

Table 4. Applied reduction factor in 4th seismic level

	Frequency	Damping ratio	Ductility factor
Drift	40%	2	1
Acceleration	10%	2	1.5

As is mentioned in the NEESWOOD report, "the drift has been generated from the measurements of the linear string potentiometer installed along the north and west side of the townhouse for each seismic test conducted" [1]. In 3D-SAM, the drift will be extracted from each joint. In order to properly compare the output, the maximum drift in each wall has been extracted from 3D-SAM and compared with the relevant value presented in the NEESWood report [1]. Figure 6 shows the drift responses for the fourth seismic level determined from the NEESWood report and 3D-SAM respectively for the 1st level as an example.

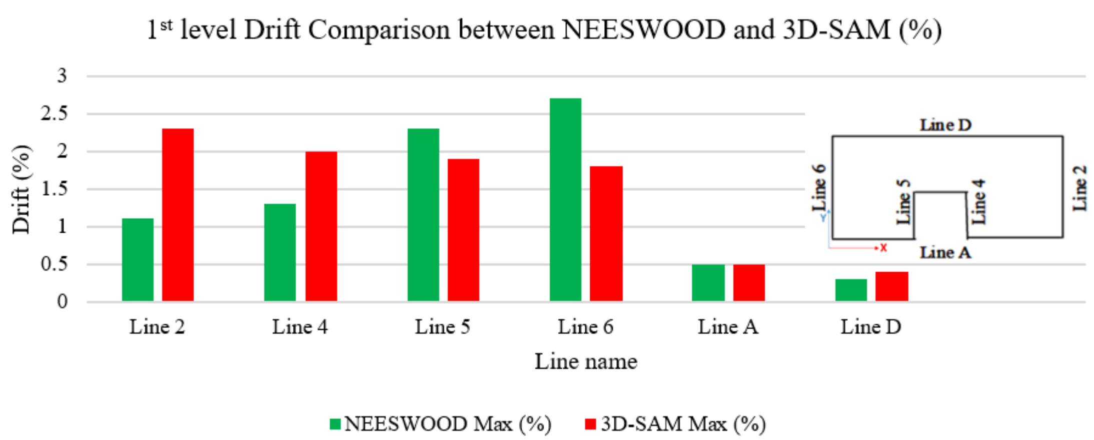

Figure 6. Drift seismic response in NEESWood and 3D-SAM after 4th seismic level in the 1st

The acceleration responses were compared at different joints. Figure 7Figure 9 shows the acceleration responses for the fourth seismic level determined from the NEESWood report and 3D-SAM respectively for both levels.

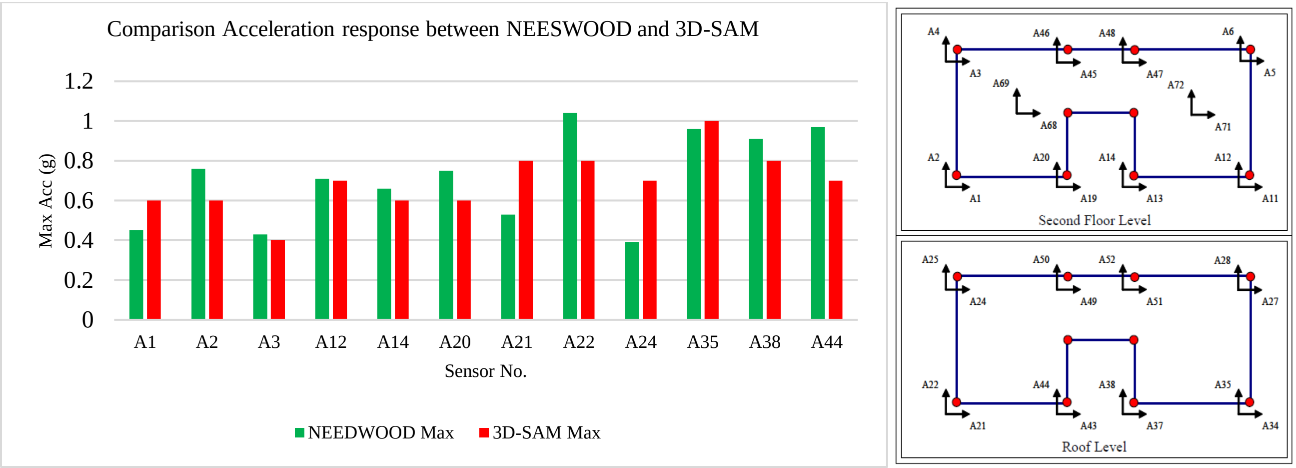

Figure 7. Seismic level 4: (a) Maximum acceleration response from the NEESWOOD report and 3D-SAM and (b) sensor locations

The comparison between 3D-SAM and NEESWOOD report shows that the mean values of the drift ratio and acceleration are very close. The mean drift ratio obtained by 3D-SAM is slightly higher than that reported in the NEESWOOD report, with differences of only 0.11% and 0.02% for Level 1 and Level 2, respectively. Similarly, the mean acceleration values reported by 3D-SAM are also very close to those in the NEESWOOD report. The comparison is shown in Table 5 and *Table 6*.

Table 5. Comparison between the mean value of the drift ratios predicted by 3D-SAM and the measured values reported in the NEESWOOD report on both levels, the first seismic level

Level	NEESWood (%)	3D-SAM (%)
Level 1	1.37	1.48
Level 2	0.95	0.97

Table 6. Comparison between the mean value of the accelerations predicted by 3D-SAM and the measured values reported in the NEESWOOD report on both levels, the first seismic level

Level	NEESWood (g)	3D-SAM (g)
Level 1	0.60	0.58
Level 2	0.79	0.77

Second seismic level (Seismic Level 5)

In general, the building at the second seismic level had suffered minor to moderate structural damage and, therefore, according to ASCE 41-17, a ductility factor of 1.5 was used to reduce the linear acceleration levels. The reduction factors for seismic level 5 are summarized in Table 7.

Table 7. Applied reduction factor in 5th seismic level

	Frequency	Damping ratio	Ductility factor
Drift	30%	2	1
Acceleration	10%	2	1.5

The same steps as those followed for the first seismic level are taken to obtain the acceleration and drift ratios for the second seismic level. The final mean values of the predicted drift ratio and acceleration obtained using 3D-SAM are compared with the measured values reported in the NEESWOOD report, as shown in Table 8 and Table 9.

The comparison of the mean values of the drift ratio and acceleration obtained by 3D-SAM and NEESWOOD reports shows that the results are generally close. The mean values of the drift ratio obtained by 3D-SAM are higher than those reported in the NEESWOOD report by 0.40% and 0.35% for Level 1 and Level 2, respectively. Additionally, the mean acceleration values reported by 3D-SAM are very similar to those in the NEESWOOD report, with only a 0.01g difference for Level 1, and a 0.11g difference for Level 2.

Table 8. Comparison between the mean value of the drift ratios predicted by 3D-SAM and the measured values reported in the NEESWOOD report on both levels, the second seismic level

Level	NEESWood (%)	3D-SAM (%)
Level 1	1.93	2.33
Level 2	1.18	1.53

Table 9. Comparison between the mean value of the accelerations predicted by 3D-SAM and the measured values reported in the NEESWOOD report on both levels, the second seismic level

Level	NEESWood (g)	3D-SAM (g)
Level 1	0.85	0.88
Level 2	1.07	1.18

DAMAGE ANALYSIS

Damage analysis is performed using two distinct approaches: a global-based assessment that evaluates the building globally per floor/story using HAZUS [19] and a component-based approach which assesses the building components individually per floor using FEMA P-58 [20]. Figure 8 shows the procedure from modal analysis to seismic assessment and damage analysis.

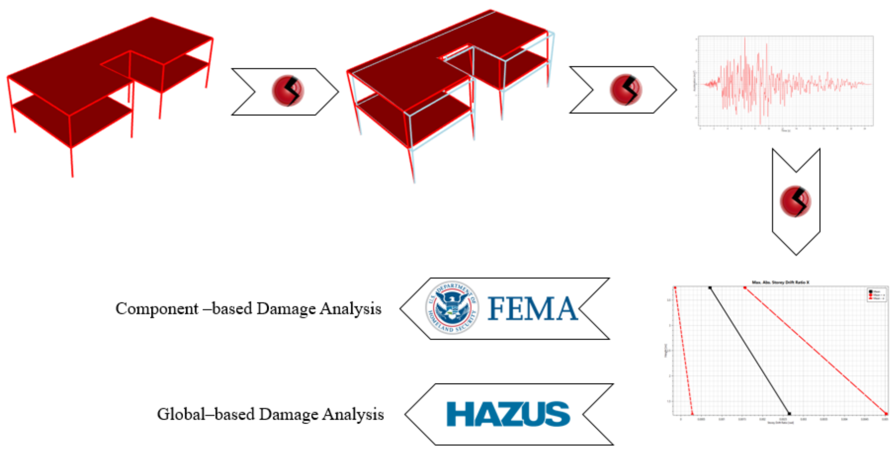

Figure 8: Modal analysis, seismic assessment and damage analysis procedure

Global-based damage analysis

Based on FEMA-154 [21], the building is considered to be a light wood frame structure (W1). By comparing the seismic demands predicted by 3D-SAM and the HAZUS fragility curves (Figure 9), probability of damage was calculated for each level for both drift and acceleration-sensitive components. The global damage levels are classified in four categories: slight, moderate, extensive, and complete. Structural damages are defined as follows:

- Slight Structural Damage: Small plaster or gypsum-board cracks at corners of door and window openings and wall ceiling intersections; small cracks in masonry chimneys and masonry veneer.
- Moderate Structural Damage: Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
- Extensive Structural Damage: Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “room-over-garage” or other “soft-story” configurations; small foundations cracks.
- Complete Structural Damage: Structure may have large permanent lateral displacement, may collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load resisting system; some structures may slip and fall off the foundations; large foundation cracks. Approximately 3% of the total area of W1 buildings with complete damage is expected to be collapsed [19].

Figure 10 summarized the damage probabilities for structural components for both levels based on drift values using the fragility curve. It should be noted that average (mean) of demands of each level is considered for global damage analysis.

As it is shown, the drift-sensitive structural components would most-likely suffer from moderate damage level in level 1 and level 2 which would lead to large plaster or gypsum-board cracks at the corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys. This description matches the observed structural damage including the permanent differential movement of adjacent panels; sheathing pull-out at wall corners; major cracking and splitting of sill and top plates; crushing of GWB at wall corners; tape cracking of GWB; significant crack propagation around garage wall; cracking of stucco on door and window openings; cracking and spalling of stucco at the corners of the structure [1].

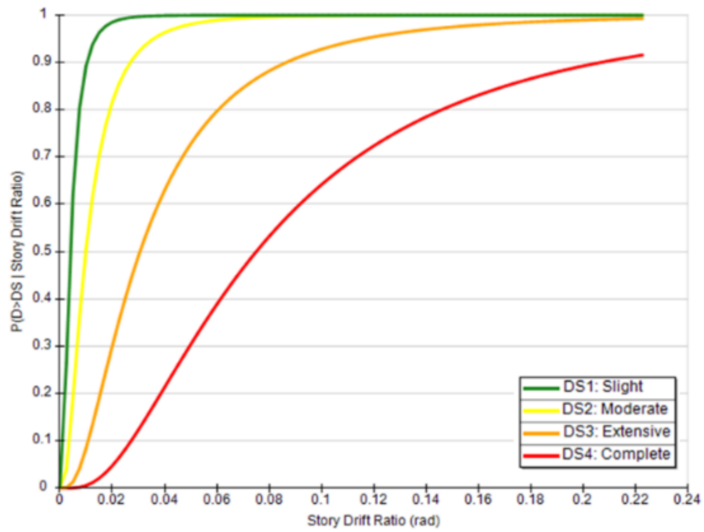

Figure 9. Fragility Curve for structural components in W1 type buildings

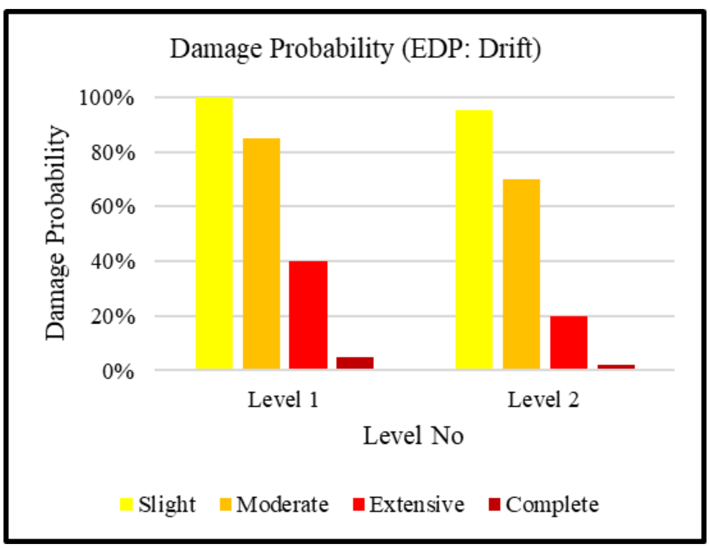

Figure 10: Global-based damage prediction based on HAZUS, structural components.

Non-structural components would most likely suffer extensive damage on both levels. Considered non-structural components in this analysis are partition walls, suspended ceilings, and exterior wall panels. Description of damage states for these components can be found in [19].

Component-level damage analysis

The component-level assessment is based on the 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 different levels based on the predicted seismic demands from 3D-SAM.

The first considered component is the framed wood walls with structural panel sheathing and stucco. The predicted drift ratio used for damage analysis of this component is 3.5%, while the measured drift ratio based on the NEESWOOD report is 2.9%. Description of damage states and predicted damage probabilities for this component are given in Table 10.

Table 10. Description of damage states defined for exterior wood walls and the predicted probability of damage.

Damage	Damage Description	Damage Probability
DS1	Cracking of stucco.	100%
DS2	Spalling of stucco, separation of stucco and sheathing from studs.	100%
DS3	Fracture of studs, major sill plate cracking.	80%

Figure 11 gives an example of calculation of damage probabilities using the FEMA P-58 fragility curves and the predicted seismic demand from 3D-SAM. According to this analysis, cracking and spalling of stucco is the most probable damage state which matches the observed damage indicated in NEESWOOD report (Figure 12).

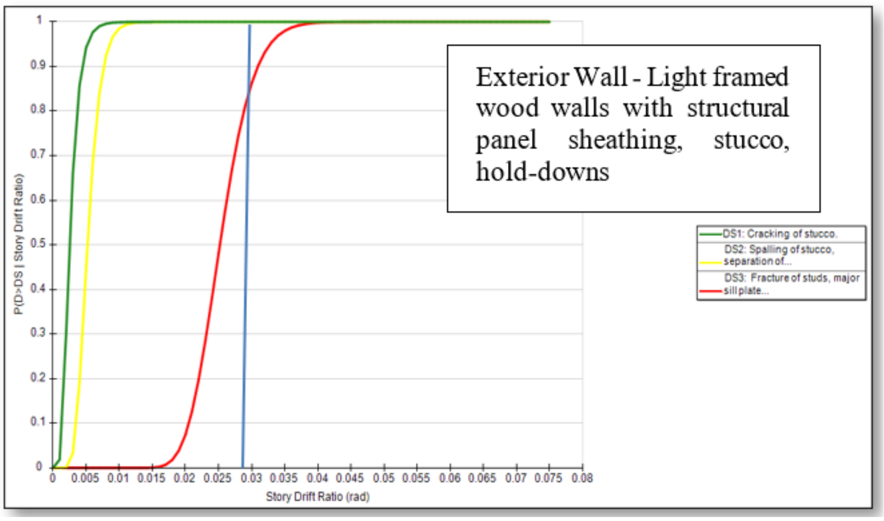

Figure 11: Intersection of the seismic demand with the fragility curves defined for Light framed wood exterior walls to identify damage probabilities.

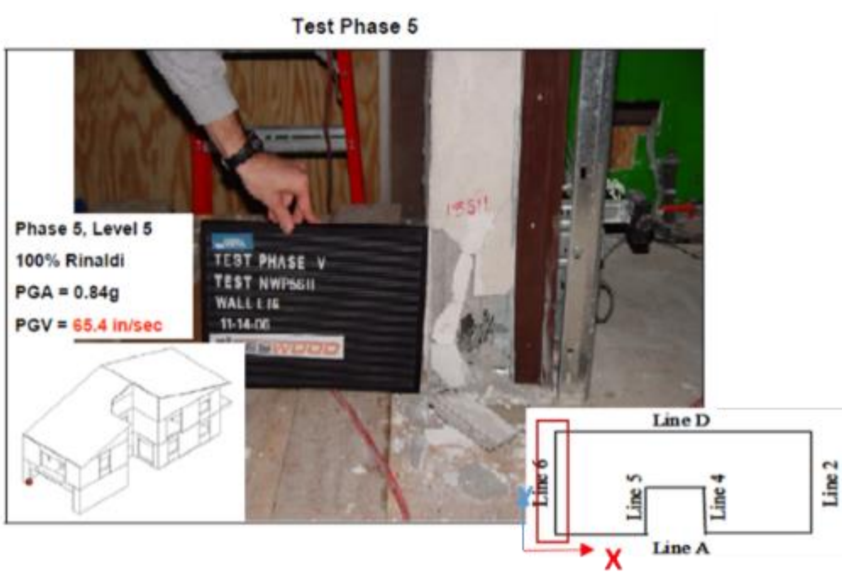

Figure 12: Observed cracking and spalling of stucco

The second considered component is unsecured fragile objects on shelves with unknown restraints. The predicted acceleration used to for damage analysis of this component is 1.8g. Description of damage states and predicted damage probabilities for this component are given in Table 11. The fragility curve used to predict the probability of damage for this component is given Figure 13. According to the NEESWOOD report for this component, it was observed that the fragile objects on shelves have fallen. This is in line with damage prediction based on 3D-SAM results as a 100% probability of exceeding this damage state was predicted.

Table 11. Description of damage states defined for exterior wood walls and the predicted probability of damage

Damage	Damage Description	Damage Probability
DS1	Object falls off shelf or shelf overturns and object breaks or object breaks within cabinet	100%

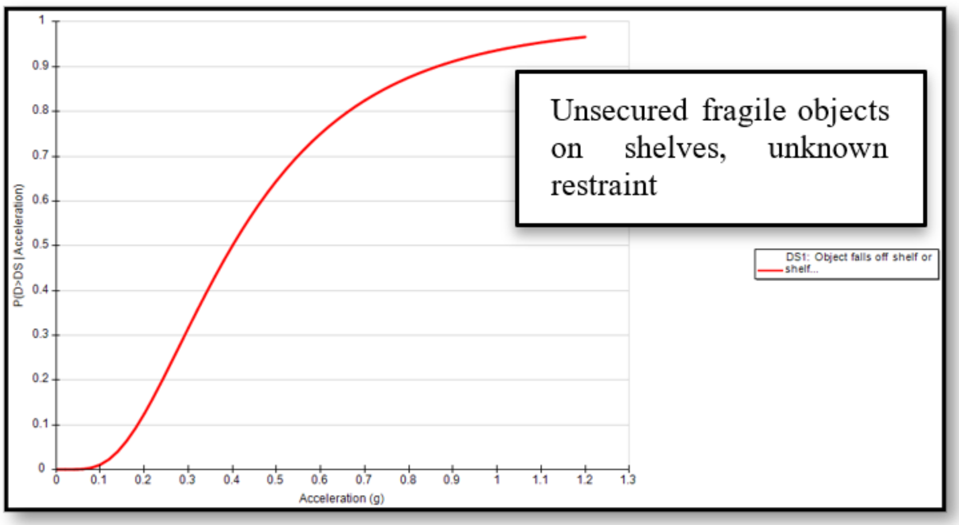

Figure 13. Fragility curve given in FEMA P-58 for Unsecured fragile objects on shelves with unknown restraints.

CONCLUSIONS

In conclusion, the extracted modal properties from 3D-SAM were in accordance with the NEESWOOD database. The initial modal analysis comparison shows the results have been correlated with NEESWood output completely. In seismic analysis, the seismic demands have been matched with NEESWood report in three chosen seismic levels. Regarding the damage analysis, the global assessment using HAZUS predicted the observed damage for both the structural and non-structural components. In addition, the component-based assessment using FEMA P-58 is well-correlated with the observed damages for a great majority of the components on different levels. In summary, the novel 3D-SAM methodology solely based on ambient vibration data, matches with real values in order to the applied earthquake record for both the modal analysis and the predicted seismic demands (drift and acceleration) and the results are in agreement with the real seismic demands and observed damages.

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