Performance Based Design of a New Hospital Building in California, U.S.

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SUMMARY:
Performance based seismic design (PBSD) is an alternative to code based approaches to design or evaluation of structures that fail to yield a more direct relationship between a seismic event and the corresponding structural performance of a building; this generally leads to over-conservatism. This paper presents a case study on the alternative procedures used in the performance based design of a new ten story moment frame hospital building in California, U.S. A detailed three-dimensional model of the structure created using *Perform 3-D* explicitly represents the lateral force resisting system's (LFRS) geometry and stiffness, both linear and non-linear, as well as the spatial distribution of mass. The building was analyzed and designed using a 3-D nonlinear response history analysis (NLRHA) procedure based on ASCE 41 with a suite of seven code based ground motion records. A comparison with the results of a nonlinear static pushover procedure (NSP) is presented.

Keywords: Performance Based Seismic Design, Nonlinear Response History Analysis, Pushover, Steel Moment Frame

1. INTRODUCTION

In the last decade, performance based seismic design of structures in high seismic regions has become more commonplace, though not yet ubiquitous, in the building industry. A conceptual framework for performance based design of structures was developed in the NEHRP Prestandard for the Seismic Rehabilitation of Buildings (FEMA 356), and has been adopted, with some modifications, as a design standard for Seismic Rehabilitation of Existing Buildings (ASCE 41).

This paper presents a case study in the PBSD of a new hospital building in California, U.S. The structure's geometry and dynamic characteristics were such that an NSP per ASCE 41 was prohibited. A detailed model of the structure was created using *Perform 3-D* and analyzed using a three dimensional NLHRA based on ASCE 41 and the California Building Code (CBC 2007) utilizing a suite of seven ground motion records. In this paper, results of the NSP are compared with those from the NLRHA.

2. BUILDING DESCRIPTION

The new hospital is ten storeys above grade with two additional basement levels below grade. The building is comprised of a three-story podium housing Diagnostic and Treatment functions (Levels 1-3) with an additional seven storeys of patient services above. The building is irregularly-shaped in plan with orthogonal grids used where possible. The triangular shape necessitates the utilization of three skewed single-bay frames at its corners. The tower is approximately 300 feet by 340 feet in plan up to third floor and reduces to 250 feet by 280 feet above. The primary LFRS for the super-structure consists of special steel moment resisting frames. The primary LFRS for the basement levels are special reinforced concrete shear walls which outline the perimeter of these levels and also retain the soil on grade.

Interstitial floors are employed above Levels 1, 2, 3, 8 and 9 for the purpose of housing and providing maintenance access to above-ceiling infrastructure which includes mechanical, electrical, plumbing, gases, and telecommunications systems required for hospital operations. The interstitial levels are seismically isolated from the main LFRS at these levels, however, they transfer lateral loads via ordinary concentric braced frames to the supporting floor above. Gravity loads are transferred by suspending the framing system from the framing above using HSS hangers. The foundation is a combination of mat, continuous, and isolated spread footings below the basement walls and steel columns.

Architectural rendering of the building is shown in figure 2.1.

Figure 2.1. Architectural rendering of the site

3. DESIGN, MODELLING, AND ANALYSIS

Structural analysis and design are in accordance with the 2007 California Building Code (2007 CBC), which is based on the 2006 International Building Code (IBC 06) with Office of Statewide Health Planning and Development (OSHPD) amendments.

Both NSP and NLRHA procedures are based on ASCE 41. This paper is focused on evaluating the NSP with the NLRHA because of its advantages in reduced computational and post-processing time. A suite of 7 ground motions has been selected for use in the NLRHA procedure as provided by the project Geotechnical Engineer. Selection, rotation, and scaling procedures for the ground motions conform to specific NLRHA requirements.

3.1. Modeling

Using the structural analysis program *Perform 3-D*, a three-dimensional mathematical model of the building that directly incorporates the nonlinear load-deformation characteristics of individual components and elements of the building was developed. All primary lateral-force-resisting elements and designated secondary elements were included in the model to capture the effects of P-Delta. The analysis model was discretized to represent the load-deformation response of each component along its length to identify locations of inelastic action. The force-displacement behavior of all components was explicitly included in the model using full backbone curves that include cyclic strength and stiffness degradation that was calibrated to component testing; these also included residual strength.

The model explicitly represented the LFRS geometry, member sizes and spatial distribution of mass. Rooftop structures, including the elevator machine room roof, and the Heli-stop were applied as lumped masses and were not explicitly modeled. Individual non-linear frame elements included the frame moment connections, frame columns and frame beams. The component gravity loads were included in the model for combination with lateral loads. For this study, the 3-D nonlinear model is used for both NSP and NLRHA procedure. P-Δ effects were considered for both procedures.

For clarity, only earlier ETABS model as shown in figure 3.1 is presented to show the geometry of the building. A typical floor plan is shown in figure 3.2 with the main LFRS frame layout.

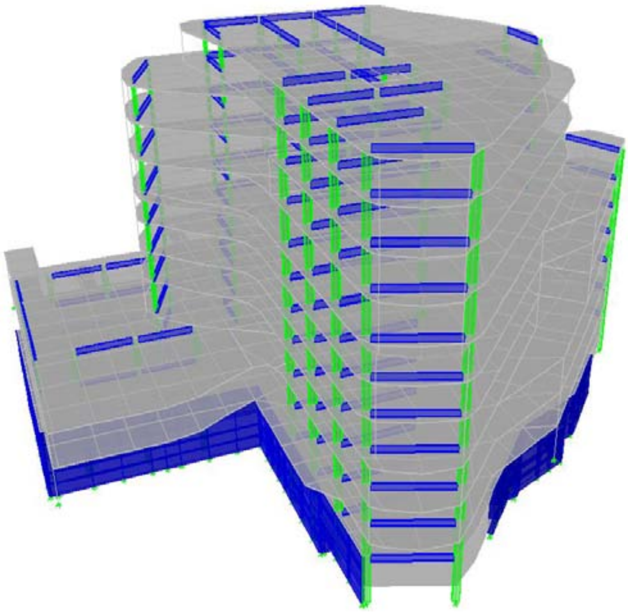

Figure 3.1. 3-D view of early ETABS model

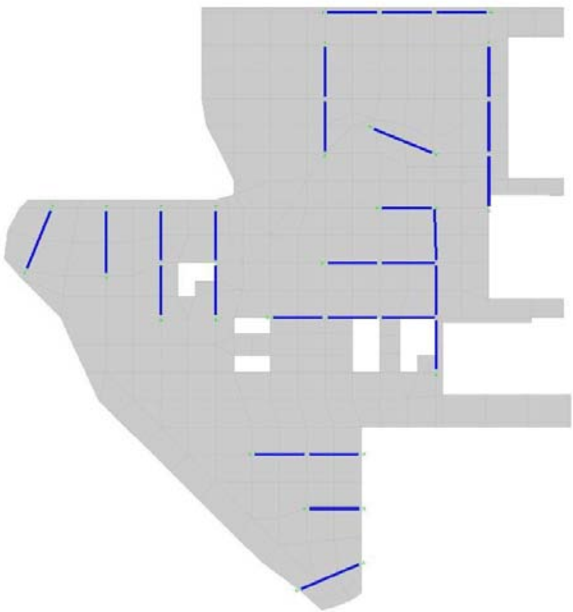

Figure 3.2. Typical floor plan

3.2. Pushover analysis

The NSP is a nonlinear static procedure in which a lateral load pattern corresponding to the anticipated inertial load profile is applied to the structure and then incrementally increased until the structure reaches the target displacement or collapses. Due to its conceptual simplicity and computational attractiveness as compared to NLRHA, pushover analysis has been gaining popularity as a tool for seismic design and performance evaluation of structures.

The lateral load patterns are intended to represent and bound the distribution of inertia forces of the structure during the earthquake. A carefully selected lateral load pattern will provide useful insight into the response of the structure. It is evident that the distribution of inertia forces for the structure will change continually during an earthquake due to the nonlinearity of the structure. The basic assumptions for using an invariant lateral load pattern are that the distribution of inertia forces will be reasonably constant throughout the earthquake, and the maximum responses will be comparable to those expected in the earthquake.

In addition to first mode lateral load patterns, a modal lateral load pattern using SRSS considering more than 90% mass participation was utilized to consider high mode effects. This modal lateral load pattern captures more accurately other building irregularities in mass and stiffness.

The normalized pushover profiles are shown in figure 3.3. It is obvious from the figure that higher mode effects contribute significantly to this structure's response.

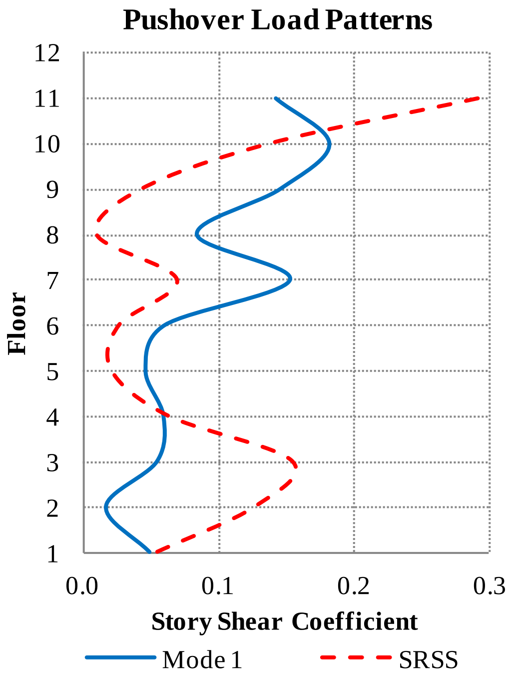

Figure 3.3. Normalized pushover load patterns

The control node used is at the roof center of mass. The nonlinear force-displacement relationship between the base shear coefficient and control node reference-drift coefficient for the pushover analyses under varying lateral load patterns are shown in figure 3.4. The base shear coefficient is calculated as the ratio of base shear to building weight. The reference drift coefficient is the ratio of the actual reference drift of the control node to the code drift limit. The plot implies that the structure has greater strength under the modal lateral load pattern that that utilizing first mode patterns; this is apparent for both directions, however the discrepancy is relatively small.

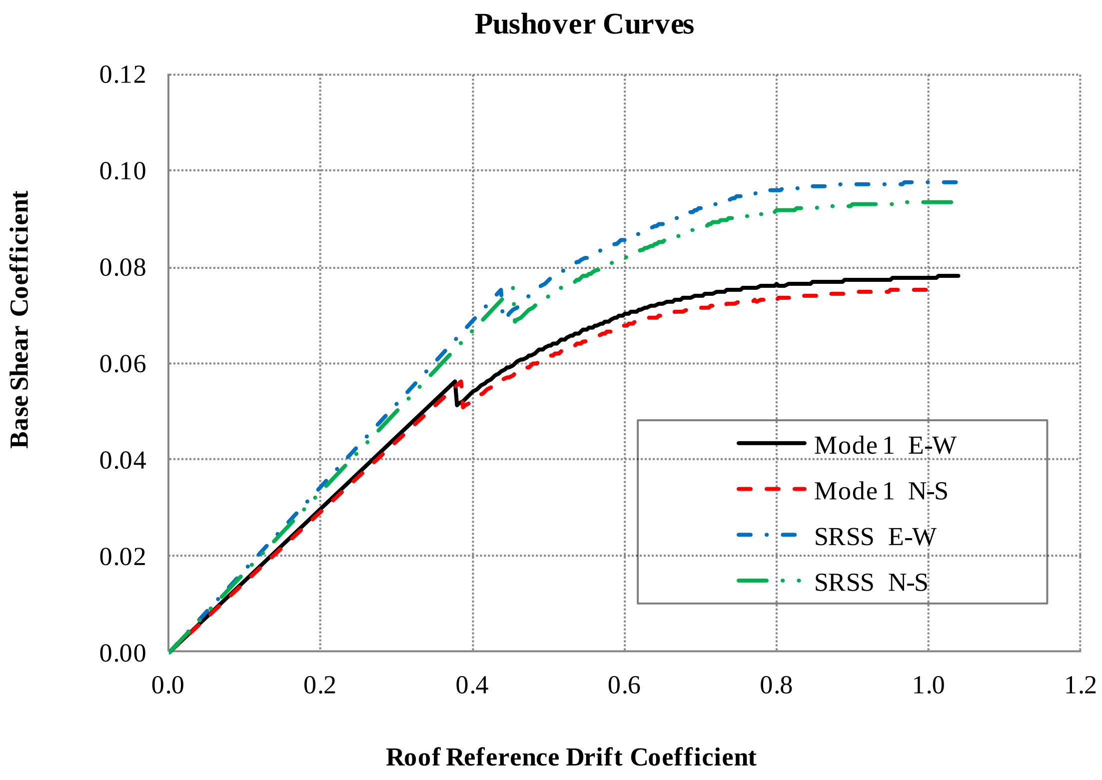

Figure 3.4. Pushover curves for main directions

Target displacement for each corresponding pushover curve is calculated using Coefficient Method as described in ASCE 41.

3.3. Nonlinear response history analysis

The building was analyzed using a three dimensional NLHRA based on ASCE 41 using seven orthogonal pairs, fault normal and fault parallel, of representative near fault ground motion records that were spectrally matched to the site's target spectra at 5 percent damping. Two ground motion intensities were investigated: Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) representing 475 and 2475 year return earthquakes respectively. All response parameters were extracted directly from each of the response histories and their maxima were averaged per codified procedures. Since the numerical model accounts directly for geometric and material nonlinearities the internal forces will are reasonable approximations of those actually expected during a real event. Diaphragm flexibility and multidirectional effects were also considered in the analyses and modelling.

4. RESULTS AND EVALUATION

NLRHA has traditionally been regarded as the most rigorous method for estimating the response of a structure to a particular seismic event. The method has been widely accepted as the benchmark for seismic structural analysis. Results of both pushover analysis and NLRHA are presented in this section. The overall pushover analysis procedure will be evaluated for analyzing a high building with irregularities.

4.1. Target displacement

The target displacement (TD) as defined in ASCE 41 is intended to represent the actual maximum displacement likely to be experienced by the yielded structure during a particular event. Several methodologies, alternative to those presented in ASCE 41 have been researched because the accuracy of its determination is critical for effectiveness of the NSP. This is because it is the basis from which all other parameters: member forces, drifts, and displacements are derived when evaluating conformance to the performance objectives. For a hospital structure these are Immediate Occupancy (IO) and DBE and Life Safety (LS) at MCE.

Target reference drift coefficients for the NSP using the aforementioned lateral load patterns in both directions for DBE and MCE spectra are presented in table 4.1. Corresponding NLRHA maximum drift coefficients are also listed for comparison. The roof target reference drift coefficient is calculated as ratio of reference drift to code design drift.

It is observed that the NSP demonstrates fairly good estimation of target displacement for DBE responses when compared to the NLRHA. However, it overestimates target displacements at MCE by as much as 33.3%. In general, the NSP using modal lateral pattern provides a closer match to the NLRHA than that using the first mode lateral pattern.

Table 4.1. Roof Target Reference Drift Coefficients

TD	DBE			MCE		
	Mode 1	SRSS	NLRHA	Mode 1	SRSS	NLRHA
E-W	0.54	0.50	0.47	0.50	0.47	0.38
error	*15.7%*	*6.5%*		*33.3%*	*23.6%*	
N-S	0.51	0.48	0.47	0.48	0.45	0.39
error	*9.3%*	*2.4%*		*24.8%*	*16.2%*	

4.2. Structural element response

To benefit from the post processing features in *Perform 3-D*, *Limit States* were defined for every element modeled. These correspond to varying levels of real damage in structures. ASCE 41's acceptance criteria tables correlate these damage states to the allowable thresholds as defined in this consensus document. Usage ratios (UR) as defined in *Perform 3-D* represent a pseudo demand-capacity ratio as a percentage of the allowable deformation limits specified in ASCE 41.

Usage ratios for key structural elements are presented in table 4.2 including moment frame beam hinge rotation, column axial force, and interstitial level brace axial force.

The table illustrates that the NSP correlates well with the NLRHA when comparing frame column and brace axial forces. Beam hinge rotations on the other hand deviate significantly from the NLRHA. For this structure this suggests that while the NSP is reliable estimating demands on force controlled elements like the frame columns and braces, the simplifications inherent in the procedure fall short of reasonably estimating demands on deformation controlled elements as seen for moment frame beam hinge rotations.

Table 4.2. Building Structural Elements Usage Ratios

UR	DBE			MCE		
	Mode 1	SRSS	NLRHA	Mode 1	SRSS	NLRHA
Beam Hinge LS	0.24	0.09	0.23	0.83	0.44	0.53
error	*5.6%*	*-61.2%*		*57.6%*	*-16.9%*	
Column Axial	0.47	0.47	0.45	0.52	0.54	0.48
error	*3.8%*	*3.4%*		*8.2%*	*12.2%*	
Brace Axial	0.43	0.41	0.53	0.49	0.50	0.58
error	*-19.4%*	*-22.0%*		*-16.0%*	*-14.3%*	

4.3. Story drift

Story drift is defined as the difference in lateral deflection between two adjacent stories. For deformation controlled structural elements (i.e. frame joints) and non-structural elements (interior partitions and building façade for example) adequately predicting story drifts is critical in evaluating a structure's performance and determining its adequacy as compared to the stated objectives. Story drift coefficient results for the three methodologies investigated are presented in figures 4.1 and 4.2 for the building's principal directions. The story drift coefficient is calculated as ratio of story drift to code design drift.

The structure was optimized utilizing the NLRHA as such the story drift profiles show consistent story drift coefficients along the height of the structure. By varying the beam-column combinations the designed structure exhibits desirable uniform yielding at all levels especially under MCE level earthquakes when the structure is expected to undergo the most ductility demand.

Compared to NLRHA results, NSP analyses using first mode lateral load pattern tends to overestimate the story drifts at mid to lower floors and underestimate the story drifts at higher floors. Modal NSP analyses show better overall building story drift profile shapes, especially for MCE level earthquakes. Considering the building's height and the existence of several vertical and plan irregularities, it is not surprising that first mode NSP does not adequately predict the building's behaviour. Conversely, when higher modes effects are included as in the modal NSP comparable story drift profiles to the NLRHA are observed. Still the procedure tends to slightly underestimate the absolute value of the story drifts along the height of the building at the DBE level. This result is slightly counter-intuitive and warrants further investigation.

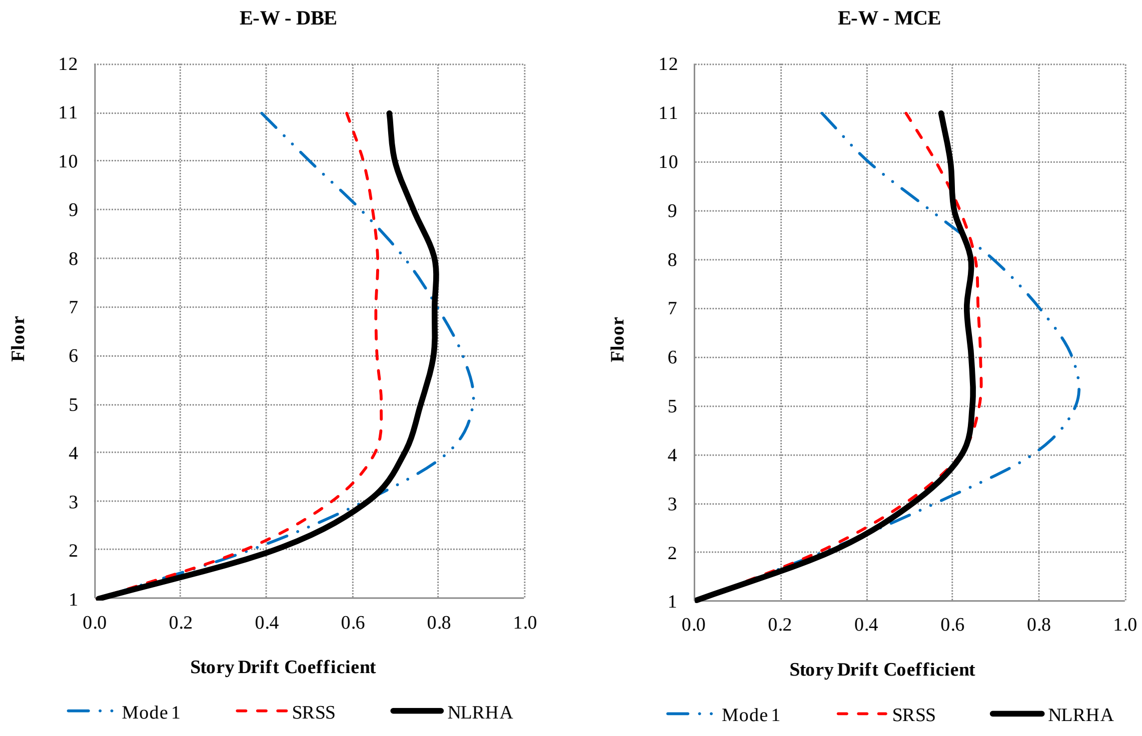

Figure 4.1. East west direction story drift coefficients

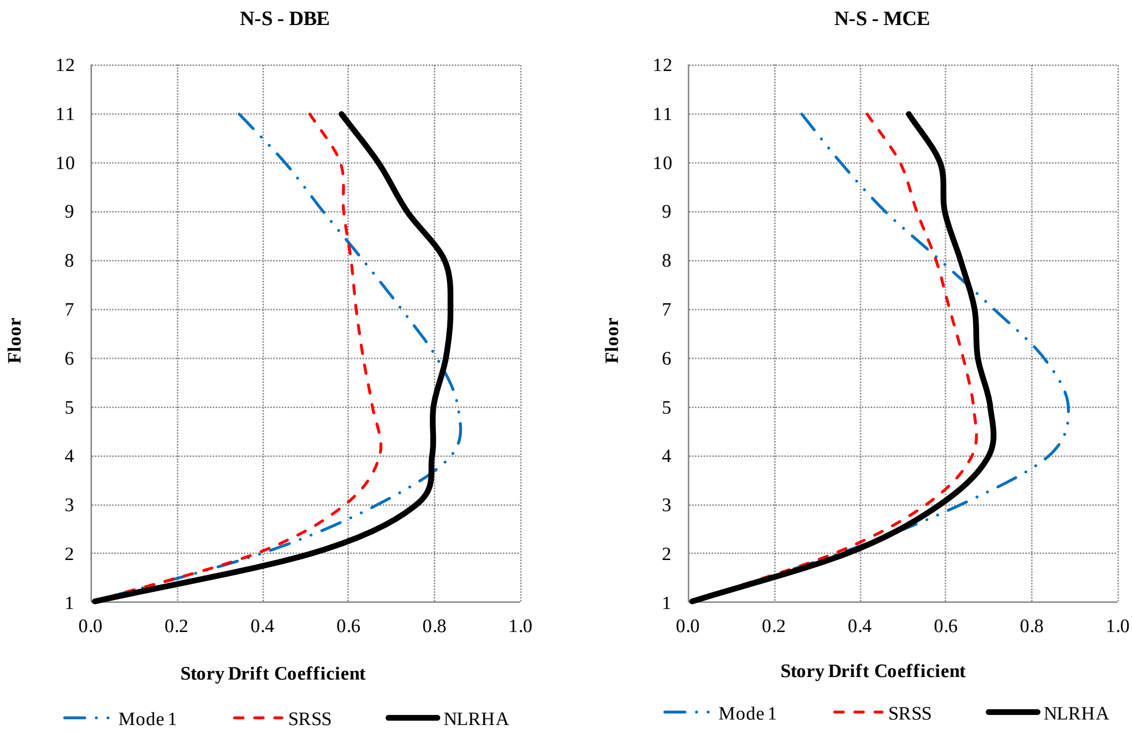

Figure 4.2. North south direction story drift coefficients

5. CONCLUSION

This paper presents a case study of a performance based design of a new hospital building in California, U.S. Both NSP and NLRHA procedures based on ASCE 41 were utilized to analyze and compare the most relevant building response parameters. The results for this real structure appear to validate previous research and literature on the same topic. Some of these conclusions are:

- NSP procedure demonstrates good estimation of target displacement for DBE responses, however it overestimates target displacement for MCE responses by as much as 33.3% in this particular case.
- Results suggest that NSP is capable of providing good estimation for component actions with limited ductility demands such as column and brace axial forces but may not be for component actions with larger ductility demands such as moment frame beam hinge rotations.
- Modal NSP is superior to the NSP using first mode lateral load profiles when comparing building story drift profile shapes with the NLRHA; this is especially the case at MCE level.
- For flexible structures, taking into account the higher mode effects using modal NSP provides better overall estimation of response than first mode NSP.
- Understanding the advantages of each of the methodologies allows their effective use in gaining insight to likely building behaviour and performance than either of the methodologies can individually thereby allowing for a more robust structural design.

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