Evaluating the Conventional Pushover Procedures for Estimating the Seismic Performance of Steel Plate Shear Walls

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ABSTRACT: The seismic performance demands of steel plate shear wall (SPSW) are estimated through the conventional pushover procedures. Reliability of the pushover analysis is verified through nonlinear time history analysis (NTHAs) on 9-, 6- and 3-story SPSW frames subjected to seven scaled earthquake records according to ASCE/SEI 7-05 provisions. Story drifts, displacements and story shears are the main parameters studied. A relatively accurate estimation is observed by pushover procedures compared to NTHAs. The accuracy of estimation shows an increase with respect to the height.
Keywords: Steel plate shear wall; conventional pushover analysis; nonlinear time history analysis

INTRODUCTION

Significant destructions of buildings during major seismic events showed that the conventional elastic methods of building design are inefficient. These approaches did not provide actual insight of how the structure performs under severe earthquakes. Distinguishing the actual performance of the structure through performance-oriented procedures and guidelines is highlighted in a new design approach termed as Performance-Based Design (Krawinkler et al., 1998).

This new analytical design procedure has two major differences with the conventional perspectives on earthquake engineering: first, the direct connection between designs to structural performance; second, a multiple performance. The performance targets may be a level of stress not to be exceeded a load, a displacement, a limit state or a target damage state (Fajfar, 2000).

The predicted manner to assess the performance of structure subjected to earthquake action is Nonlinear Time History (NTH) analysis. Nonlinear dynamic as the most rigorous analyzing method adopts the combination of ground motion records with a detailed structural model.

This has a relatively low uncertainty. The calculated responses are very sensitive to the characteristics of the individual ground motion used as seismic input; therefore, several analyses are required for applying different ground motion records (Bracci et al., 1997).

Although the NTH analysis is being commonly applied in the theoretical studies, it is time consuming and often difficult to be used by design offices. Hence, it is worth devising a simplified analyzing method for seismic performance evaluation of structures. Nonlinear Static or Pushover Analysis (PA) is competent method for this purpose. Information that is more important could be obtained from the simple and economical PA instead of dynamic analysis.

The Steel Plate Shear Wall (SPSW) is a lateral-load-resisting system that could be analyzed by this method. This system is consisting of vertical steel plate infill connected to the surrounding beams and columns installed in one or more bays at the full height of the structure.

SPSW offer significant advantages over many other structural systems in terms of cost, performance and ease in design. They typically resist lateral loads, primarily through diagonal tension in the web and overturning forces in the adjoining columns. The buildings requiring additional strength and stiffness could be retrofitted by adding steel web plates to the exiting construction.

The objective of this paper is to evaluate the accuracy of the conventional pushover procedures based on FEMA-356 (2000) load patterns and one Single run modal pushover analysis (Shakeri et al., 2010) for estimating seismic performance of typical SPSWs subjected to the different earthquake records. The study subjects are 3-, 6- and 9-story SPSW frames (Memarzadeh et al., 2010) designed according to AISC 341-05 (2005) requirements.

Nonlinear static procedures for seismic demand estimation
Load pattern
There are several procedures that could be adopted for conducting a nonlinear static analysis. While the fundamental procedure for the step-by-step analysis is essentially the same, the procedures vary mostly in the form of lateral force distribution applied to the structural model in each step of the analysis.

FEMA-356 (2000) and similar references recommend the following procedures:
Inverted triangular pattern
A lateral load pattern represented by the following FEMA-356 (2000) equation:

$$F_X = \frac{w_x h_x}{\sum_{x=1}^{n} w_x h_x} V \qquad [1]$$

Where, F_X is the lateral load at floor level x, W_x is the weight at floor level x, h_x is the height from base to floor level x and V is the total lateral load (base shear) to be applied. This load pattern results in an inverted triangular distribution at the height of the building and is normally valid when more than 75% of the mass participates in the fundamental mode of vibration.

Uniform load pattern
A uniform load pattern based on the lateral forces that are proportional to the total mass at each floor level is obtained as follows:

$$F_x = \frac{w_x}{\sum_{i=n}^{n} w_i} V \qquad [2]$$

This pattern is expected to simulate the story shears.

Mode one load pattern
A lateral load pattern proportional to the fundamental mode of modal responses extracted from the Response Spectrum Analysis (RSA) of the building.

A single run story shear-based pushover (SSP) method based on story shear
A vertical distribution pattern proportional to the story shear distribution is calculated through combining the modal responses from response spectrum analyses of the building, which includes sufficient modes to capture at least 90% of the total building mass and using the appropriate ground motion spectrum. For a given mode j, with known frequency or period, the spectral acceleration S_{aj} would be available and this distribution is represented by the following equation (Shakeri et al., 2010):

$$F_{ij} = \Gamma_j \Phi_{ij} M_i S_{aj} \qquad [3]$$

Where, i is the floor number, j is the mode number, Γ_j is the jth mode participation factor, Φ_{ij} is the jth mode value at the ith floor, and M_i is the mass at the ith floor.

Here a Single run story Shear-based Pushover (SSP) method is proposed. This proposed procedure considers the contribution of the instantaneous higher modes and the effect of the sign reversal of the modal forces in the higher modes. In this analysis, the story shears associated with each assigned mode are calculated through Eqs. (3) and (4). The story shear associated with each one of the modes is combined through the SRSS rule (Eq. 5) defined as the combined modal story shear. In the calculation of the story shears for each mode by applying Eq. (4), the sign reversal effects of the modal

forces in the upper stories are obtained (Shakeri et al., 2010).

$$SS_{ij} = \sum_{k=i}^{n} F_{kj} \qquad [4]$$

$$SS_i = \sqrt{\sum_{j=1}^{m} SS_{ij}^2} \qquad [5]$$

Where, SS_{ij} is the story shear in level i associated with mode j, SS_i is the modal story shear in level i associated with all the modes considered.
The lateral forces required to generate the combined modal story shears' profile is assumed as the lateral load patterns. The required story forces are calculated by subtracting the combined modal shear forces of consecutive stories, through Eqs. (6) and (7).

$$F_i = SS_i - SS_{i+1} \qquad i = 1,2,3,\cdots,(n-1) \qquad (6)$$

$$F_n = SS_n \qquad i = n \qquad (7)$$

The lateral load pattern is normalized with respect to its total value through Eq. (8).

$$\overline{F}_i = \frac{F_i}{\sum_{i=1}^{N} F_i} \qquad (8)$$

SPSW Structure
The geometry and section properties of the SPSW structures considered in this study are presented in Figure 1. These structures are designed according to AISC 341-05(2005) for the lateral earthquake forces specified by ASCE 7-05 (2005) where equivalent lateral force procedures are applied. The SPSW structures are 3,6 and 9-story 3-bay frames with infill plates in the second bay's panels. The reduced beam section at both ends of HBE is assumed to have two-thirds of the plastic section modulus of the corresponding HBE. The mechanical properties of the structures are presented in the Table1.

Table 1. Mechanical properties of typical bi-linear kinematic hardening model.

E_1	E_2	υ	ρ	F_{yp}	F_{yb}	Failure Criterion
200 (GPa)	200 (MPa)	0.3	7.8 (ton/m^3)	248 (MPa)	345 (MPa)	Von Misses

Here, E, υ and ρ are the Young's modulus, Poison's ratio and density of steel material, and F_{yp} and F_{yb} are the plate and boundary member yield stresses, respectively. All beam and column material properties are the same as the boundary member properties. The beam, column and plate cross sections are presented in Figure 1.
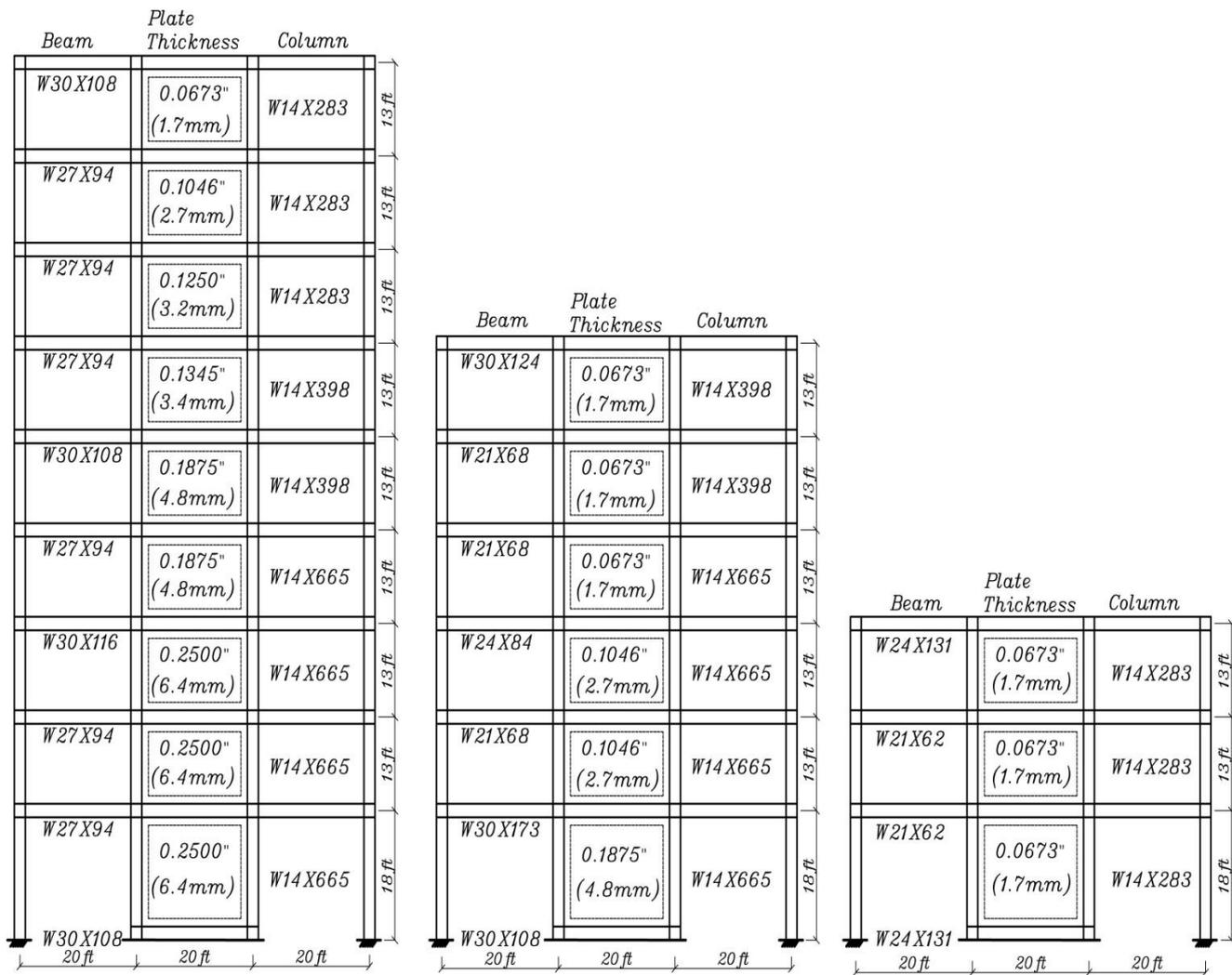
Figure 1. Dimensions and properties of SPSW building (Memarzadeh et al., 2011)

Validation of the finite element model

In order to evaluate the validity of the model, the finite element model of the SPSW structure is subjected to a sinusoidal force at the roof level with a frequency of the first vibration mode for a time interval of 5 seconds.

Afterwards SPSW was allowed to vibrate freely. The lateral displacements of some floors for 9 story SPSW are shown in Figure 2 This figure shows a resonance in the first 5 second interval and also decreases the free vibration amplitudes due to the damping function.Some analyses were performed by Memarzadeh et al. (2010) to check the efficiency of the degree of the meshing; where the results confirmed that for the various energy quantities, the shear forces as well as the displacements and accelerations are verified.
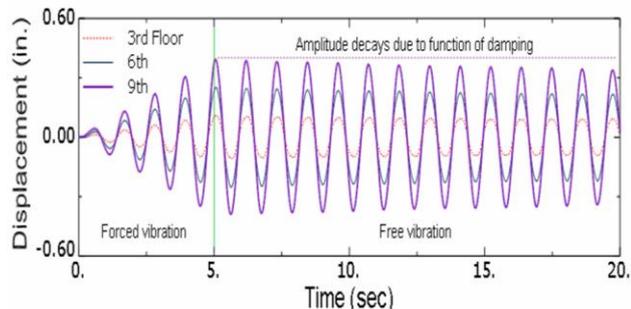
Figure 2. Lateral displacements of floors for 9 story SPSW (Memarzadeh et al., 2010)

Element selection

The "B31" beam element and "S4" shell element are selected for the study from the ABAQUS (2007) library of elements."B31" is a 2-node beam element with linear interpolation formulations in three-dimensional space. This element allows for transverse shear deformation. For this study, the additional flexibility associated with this deformation is ignored. This element uses a lumped mass formulation as well. All beams and columns of the structure are modelled by the beam elements with I-shape cross sections."S4" is a general-purpose 4-node doubly curved shell element, which allows transverse shear deformation.

It uses thick shell theory as the shell thickness increases and becomes discrete Kirchhoff thin shell element as the thickness increases. The transverse shear deformation becomes very small as the shell thickness decreases. This element also uses linear interpolation and accounts for finite membrane strains and arbitrarily large rotations. Totally, 25 section points are specified to be used for integration; 9 points in web, 9 in each flange. The SPSW models are subjected to base earthquake acceleration records to simulate the time history responses of the structures. The analysis utilizes a finite element method involving both material and geometric nonlinearities.

Figure 3 shows Simpson's integration points in an I-shape cross section of a beam element.
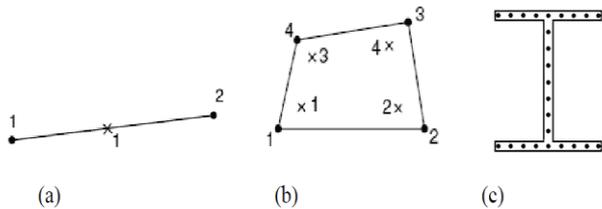
Figure 3. Integration point in (a) "B31" beam element and (b) "S4" shell element (c) I-shape cross section

Ground motion scaling

In order to investigate the accuracy of the selected methods under different ground motions, seven ground motion records are considered for the selected SPSWs.

These records are extracted from the Pacific Earthquake Engineering Research (PEER) site: http://peer.berkeley.edu/smcat.

The International Building Code (IBC) and California Building Code (CBC) require that the earthquake records scaled according to the ASCE 7-05 (2005) provisions. For Time History Analyses (THA) of 3 selected regular SPSW structures, the ground motions are scaled such that the average value of the 5% damped elastic response spectra for a set of scaled motions is not less than the design response spectrum over the period range $0.2T_1$ to $1.5T_1$. Ground motion properties of seven earthquake records and scaled response spectra are presented in Table 2.

Table 2. Ground motion properties

Name	Date	Station	Component (deg)	Vs30(m/s)	PGA	PGV	Soil Type (UBC 1997)	Site Class in NEHRP
Cape Mendocino	4/25/1992	Rio Dell Overpass - FF	270	311.8	0.385	43.920	SD	D
Loma Prieta	10/18/1989	Capitola	0	288.6	0.529	35.001	SD	D
Duzce	11/12/1999	Duzce	180	276.0	0.348	60.024	SD	D
Erzincan	3/13/1992	Erzincan	NS	274.5	0.515	83.956	SD	D
Imperial Valley	10/15/1979	El Centro Array #11	E	196.3	0.364	34.366	SD	D
Northridge	1/17/1994	Pardee - SCE	L	345.4	0.657	75.209	SD	D
Kobe	1/16/1995	Takatori	0	256.0	0.611	127.191	SD	D

The scaled response spectra for each frames is illustrated in Figure 4.
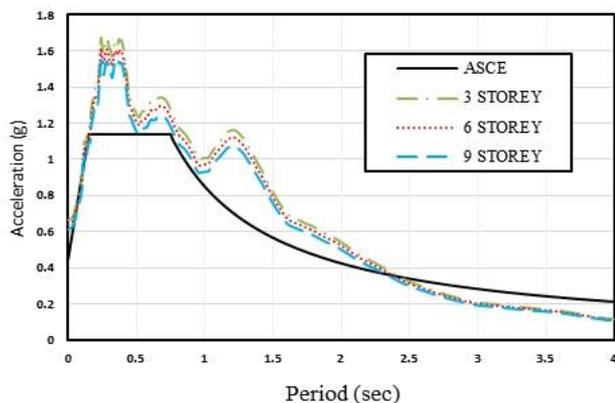
Figure 4. Scaled Response Spectra for each frames

Target displacement evaluation

The target displacements used for the FEMA-356 procedures are determined to estimate the peak roof displacements value for each building through SPSWs which are presented in Table 3.

Table 3. Target Displacement Evaluation

|	3-Story (cm)	6-Story (cm)	9-Story (cm)
Inverted Triangular	14.30	28.21	38.22
Mode One	14.54	27.94	38.40
Uniform	14.54	28.02	35.53
Single Run SSAP	14.81	27.90	39.59

Evaluation of conventional pushover procedures

The conventional pushover procedures are evaluated by comparing the computed roof drift ratio (maximum roof displacement normalized by building height), inter-story drift ratio (relative drift between two consecutive stories normalized by story height) and story shear values to nonlinear time-history results. The time-history results are based on a set of seven scaled records and both the mean THA and four-estimated load patterns are presented in the plots (Figures 5-13).
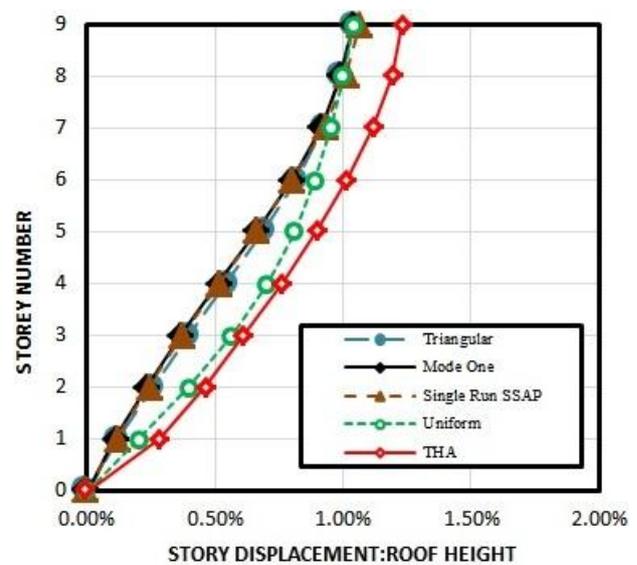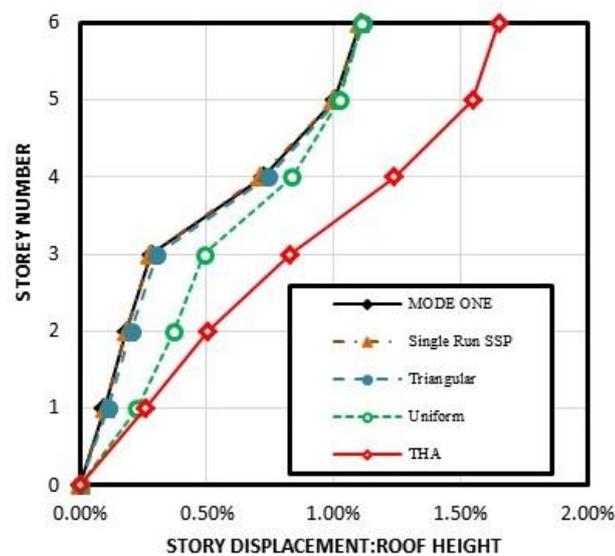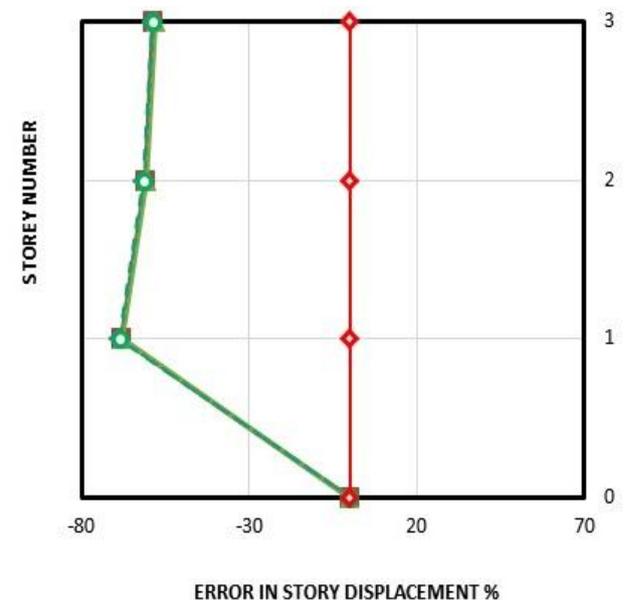

Figure 5.
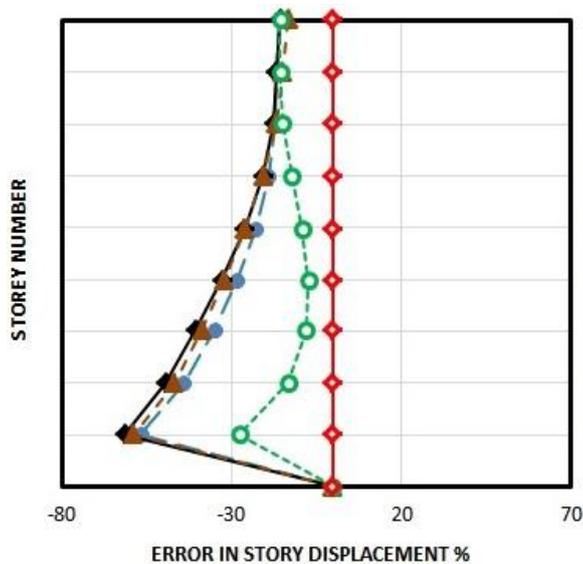
Figure 5. Predicted peak displacement demands and error accrued by NSPs compared to NTH analyses for 9-story SPSW building
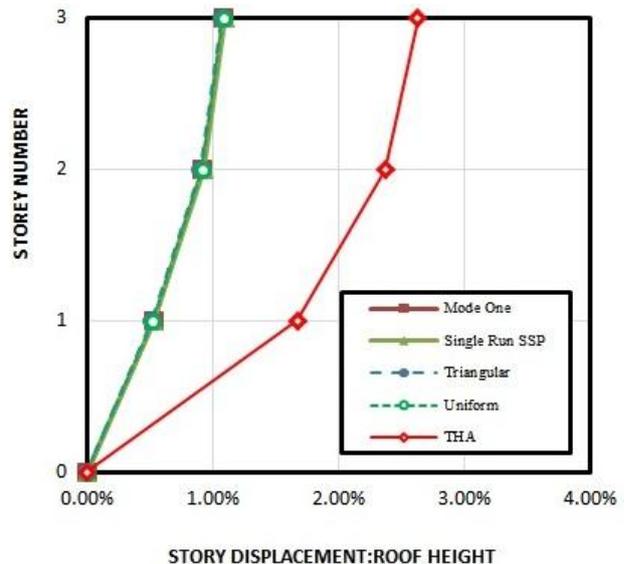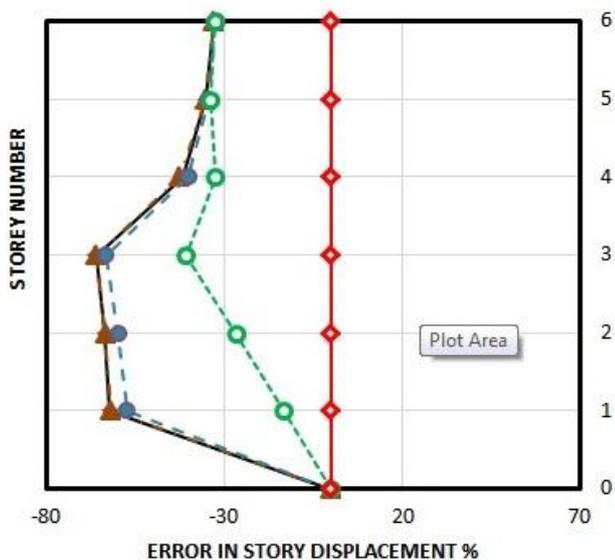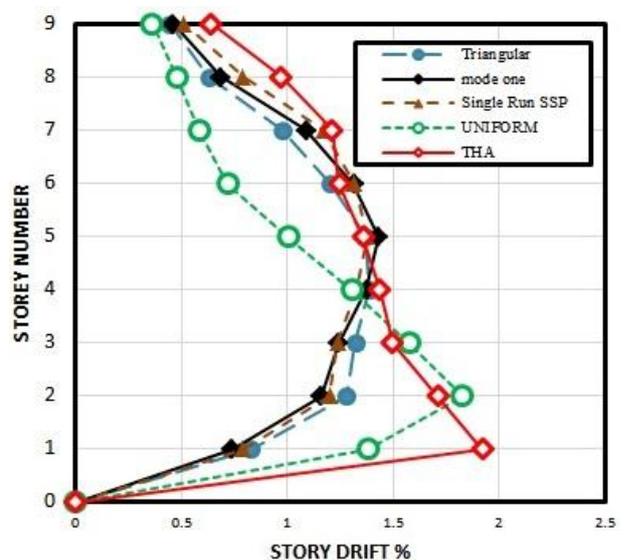

Figure 7.

Figure 6.

Figure 7. Predicted peak displacement demands and error accrued by NSPs compared to NTH analyses for 3-story SPSW building

Figure 6. Predicted peak displacement demands and error accrued by NSPs compared to NTH analyses for 6-story SPSW building
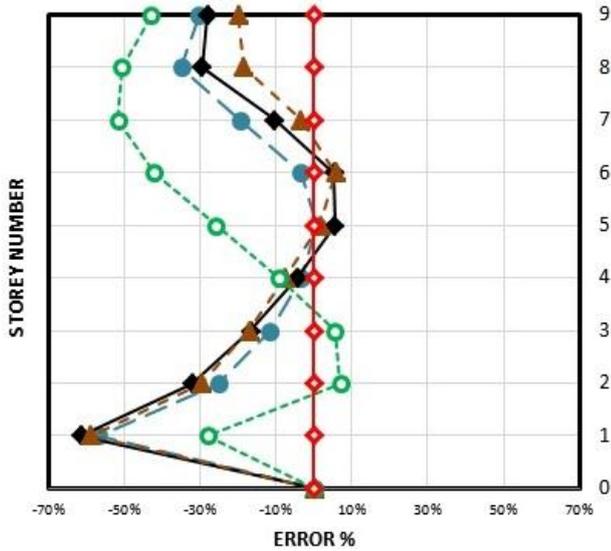

Figure 8.

Figure 8. Predicted peak inter-story drift demands by NSPs compared to NTH analyses for 9-story SPSW building
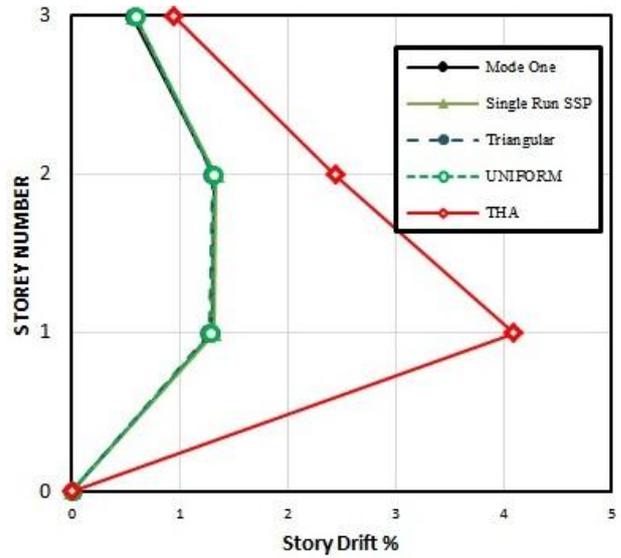
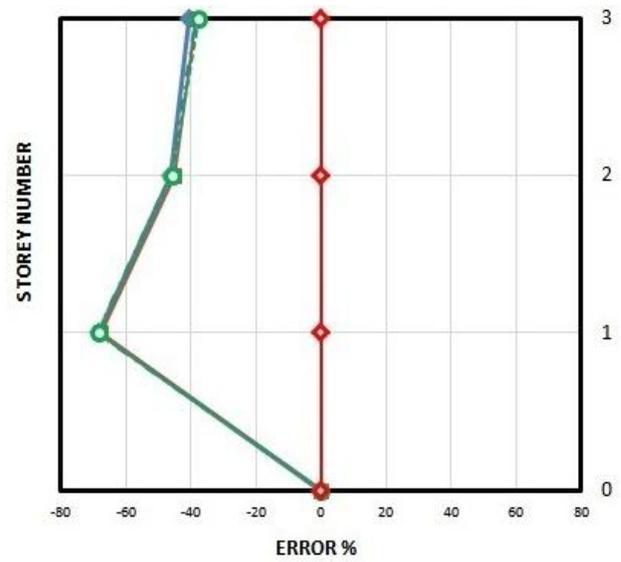**Figure 10.**
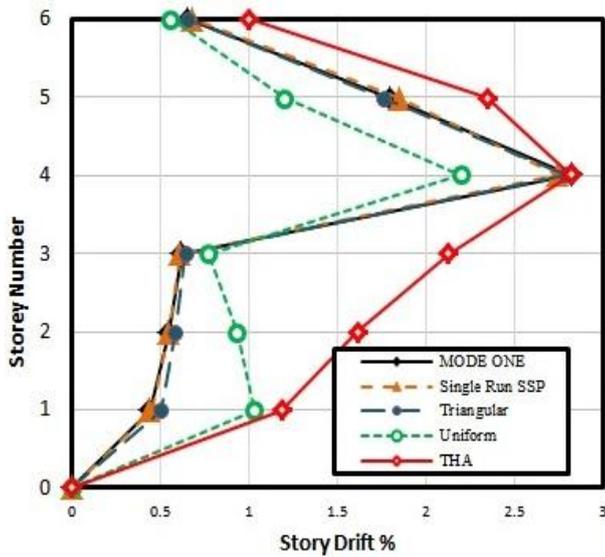
Figure 9.

Figure 10. Predicted peak inter-story drift demands by NSPs compared to NTH analyses for 3-story SPSW building
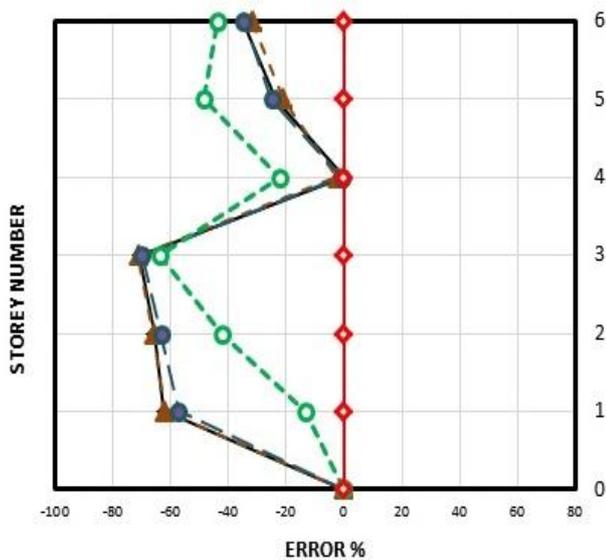

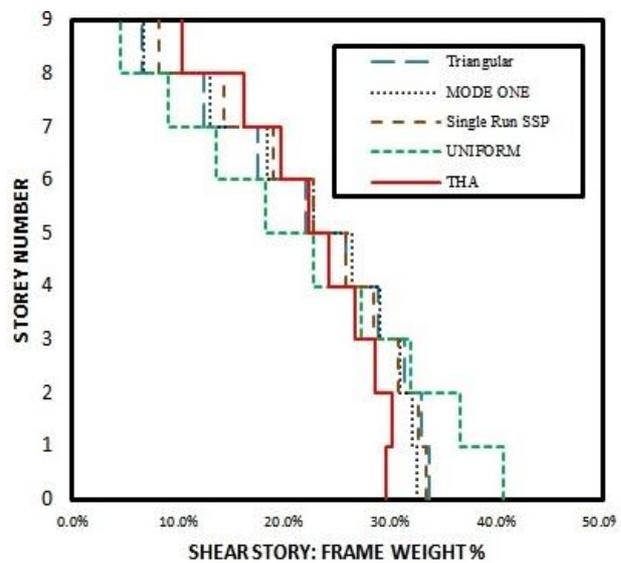**Figure 9.** Predicted peak inter-story drift demands by NSPs compared to NTH analyses for 6-story SPSW building
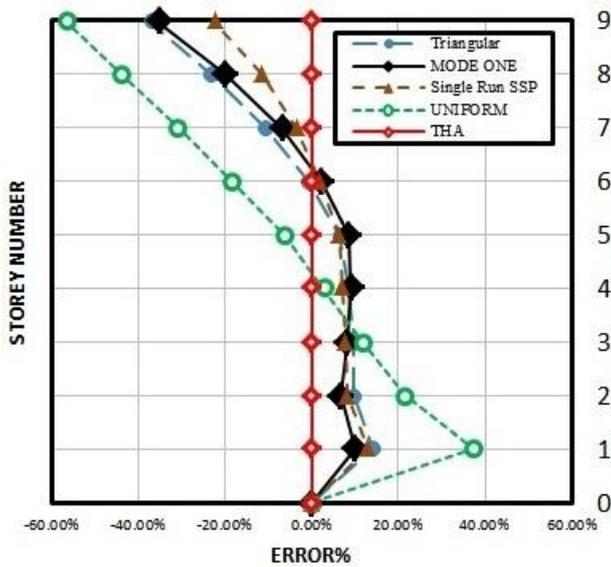

Figure 11.

Figure 11. Predicted Shear Story by NSPs compared to NTH analyses for 6-story SPSW building

Figure 13.

Figure 12.

Figure 12. Predicted Shear Story by NSPs compared to NTH analyses for 6-story SPSW building

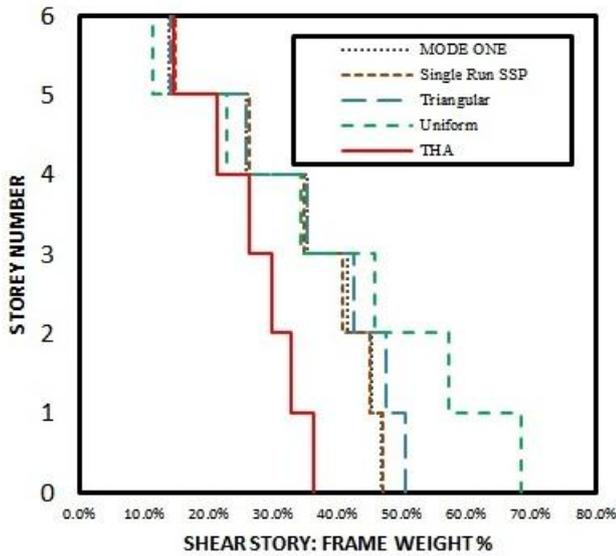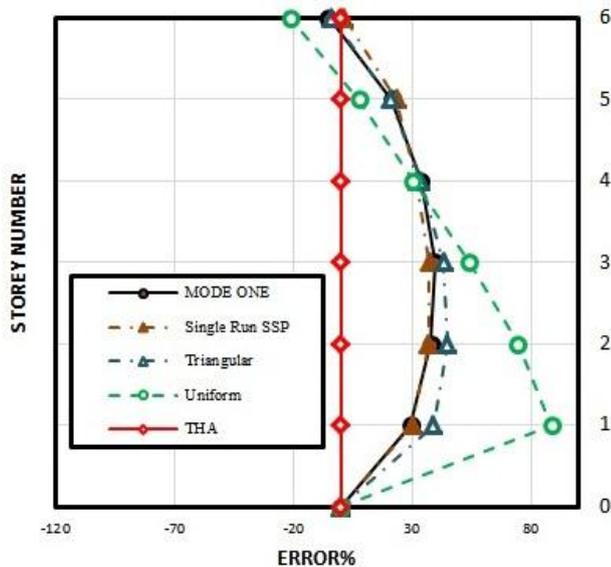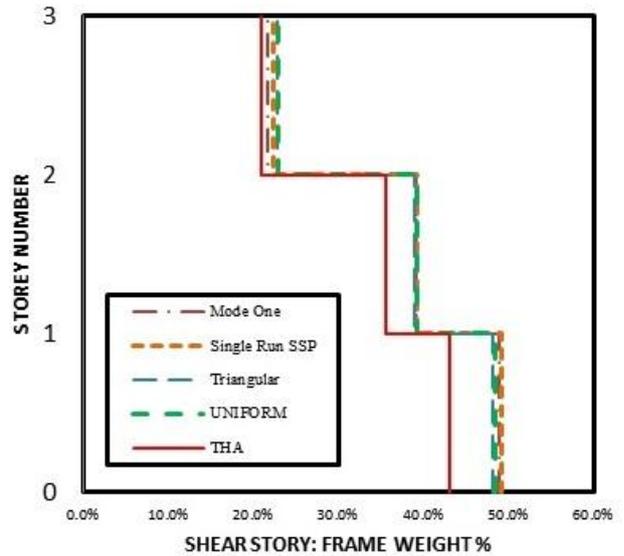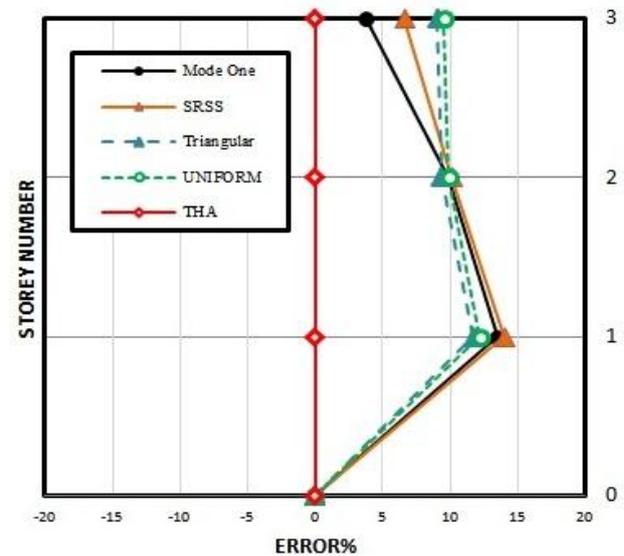**Figure 13.** Predicted Shear Story by NSPs compared to NTH analyses for 3-story SPSW building

The Error Prediction of Total Model

In order to compare the accuracy of the different NSPs parameters, the following error index is introduced by Lopez-Menjivar and Pinho (2004), which is applied in this study:

$$ERORR_{(NSPs)} = 100 \times \sqrt{(\frac{1}{n}) \times \sum_{i=q}^{n} (\frac{NSP_{Parameters} - THA_{parameters}}{THA_{parameters}})^2} \qquad [9]$$
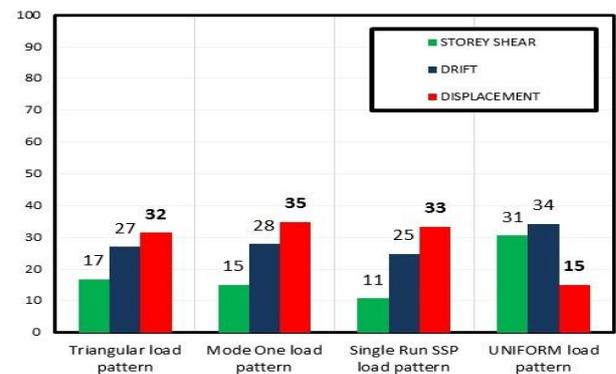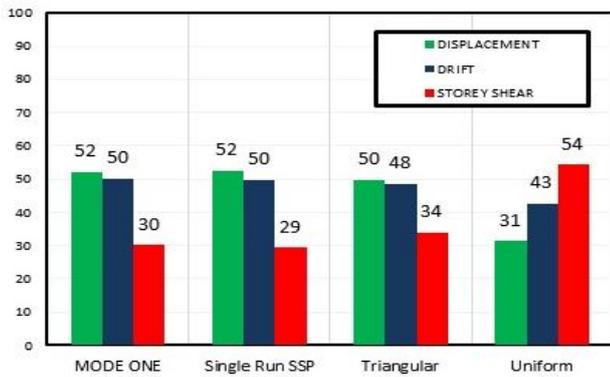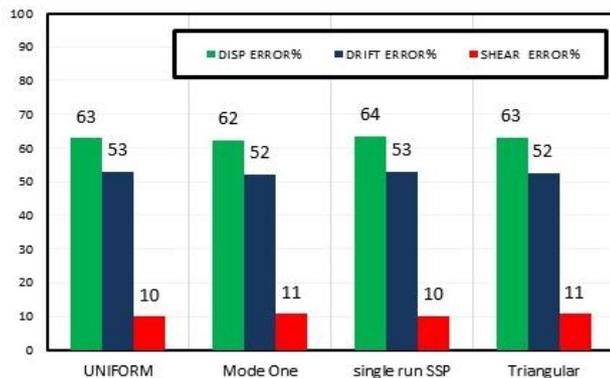

Figure 14. Comparison of the accuracy of the different NSPs parameters for 9-story SPSW building, using an error index defined by Eq. (9)

Figure 15. Comparison of the accuracy of the different NSPs parameters for 6-story SPSW building, using an error index defined by Eq. (9)

Figure 16. Comparison of the accuracy of the different NSPs parameters for 3-story SPSW building, using an error index defined by Eq. (9)

RESULTS AND DISCUSSION

The floor displacements, story drift ratios and story shear with respect of SPSWs are estimated through conventional nonlinear static pushover analysis in this article. As seen in the Figure 5 the peak floor displacement is estimated accurately by Uniform Load Pattern for 9-story SPSW while this method is not applicable for estimating inter-story demand for the same model. Single Run SSP method is an accurate method for estimating story shear demand of 9-story SPSW model, due to participation of the higher modes of structure in this method (Figure 11).

In addition, for estimating the inter-story drift of 9-story SPSW model, this is the most accurate method. In general, according to Figure 12 if the objective is to estimate the floor displacements, story drift ratios and story shear for 9-story SPSW, all through one method, Single Run SSP is the best-suggested method.

The peak floor displacement with a relatively accuracy is estimated by Uniform Load Pattern for 6-story SPSW building but this pattern is not applicable method for estimating inter story drift and story shear for both the 3-story and 6-story SPSWs. As seen, Single Run SSP is a relatively accurate method for the estimating seismic performance of mid-rise SPSW buildings (Figure 15). However, none of these load patterns is capable of estimating the floor displacements and story drift ratios for 3-story SPSW as accurate as possible (Figure 16).

All Figures in this article, illustrate a more vivid conception of the 3 discussed parameters.

CONCLUSION

The following conclusions are obtained from the accuracy assessment of conventional nonlinear static procedures in estimating the seismic demands of SPSW buildings using seven sets of intense ground motions. These conclusions are based on a comparison of NSP estimates of seismic demands and the corresponding values determined by THA for 3, 6, and 9-story SPSW buildings, designed to meet seismic code criteria:

• The equivalent bilinear SDF systems for 9-story SPSW, determined from nonlinear static procedures can estimate the peak roof displacement quite accurately in comparison with the peak roof displacement from THA method, while this is not applicable for 3 and 6-story SPSW models

• The story drift demands are calculated through Single Run SSP and three other conventional load patterns to correspond with THA results. The higher modes extracted from Single Run SSP procedure in the response to 3, and 6-story SPSW buildings, are general have no statistical significant, so the first mode by itself may be relatively adequate for mode one load pattern for low-rise and mid-rise SPSWs

• The degree of precision of all procedures suggested in estimating the maximum story drift and roof displacement in mid-rise and low-rise models across all stories is generally low; however, the degree of precision of these procedures in estimating peak story drift at an individual story can be applicable for certain cases. All of the adopted procedures provide similar results in practice; while, the Uniform Load Pattern is slightly simpler and more practical than other load patterns

• It is found that, the degree of precision in estimating floor displacements, story drift ratios and story shear of SPSWs estimated with conventional nonlinear static pushover analysis for high-rise model is great.

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