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Full Length Research Paper

Comparison of improved nonlinear static procedures for spatial steel trusses supported on steel columns

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The most significant expectation for ages has been building structures which are as high as possible, without column and wide-spanned in architecture. Also it is vital to cover these structures as spatial trusses. Similarly; economic, rapid, safe and aesthetical solutions in space systems are possible by spatial steel structures. In last decades, ATC 40, FEMA 273, 274, 356 and recently 440 are the most commonly used resources for seismic analysis procedures enduring with computing in civil engineering. These procedures are defined as displacement based performance analysis. On the other hand, nonlinear static procedures as basic step of these methodologies still have some problems in theoretical background. Some of the researchers are not satisfied with the accuracy of current performance based design methodologies. There are some question marks on how accurate capacity and demand spectrums demonstrate the structural capacity and earthquake demand respectively. In this study, comparison of improved nonlinear static procedures in FEMA- 440 has been made for spatial steel trusses supported on steel columns. For this, numerical models which are set up by taking structural properties of evaluable structures are investigated by using improved nonlinear static procedures which are given in FEMA- 440. Differences and harmonies of methods are still been determined.

Key words: Spatial steel structures, nonlinear seismic procedures.

INTRODUCTION

The determination of the displacement demand of structures subjected to seismic actions is one of the most important steps in performance based design procedures. In last decades, significant progress was made in performance-based engineering methods that rely on non-linear static analysis procedures (NSPs). Nonlinear static procedures are one type of inelastic analysis that can be used to estimate the response of structures to seismic actions. In practice, the current procedures can result in estimates of maximum displacement that are significantly different from one another. The differences between the various approaches relate to the level of detail of the structural model and the characterization of the seismic ground shaking. This is one of the major areas of concern of practicing engineers. Current nonlinear static procedures are Coefficient Method in FEMA-356 (Applied Technology Council, 1996) and Capacity-Spectrum Method in ATC-40 (Federal Emergency Management Agency, 2000; Applied Technology Council, 2005). The two approaches are essentially the same when it comes to generating a “pushover” curve to represent the inelastic force-deformation behavior of a building. They differ, however, in the technique used to calculate the inelastic displacement demand for a given representation of ground motion. Various researchers and practicing engineers have found that in some cases, different inelastic analysis methods give substantially different estimates for displacement demand for the same ground motion and same SDOF oscillator or same building (Chopra and Goel, 2002, 2004, 1999; Chopra et al., 2004; Goel and Chopra, 2004; Aydinoglu, 2003). Recently, a new document was published about nonlinear static procedures. This document has proposed two new procedures instead of Capacity-Spectrum Method of ATC- 40 and Coefficient Method of FEMA-356 (Applied Technology Council, 1996). These new procedures are Displacement Modification and Equivalent Linearization methods (Applied Technology Council, 2005; UBC, 1997).

The Capacity-Spectrum Method and Displacement Coefficient Method rely on different underlying relationships to estimate the response of nonlinear systems based on an elastic response spectrum. The Capacity-Spectrum Method relies on the concept of equivalent linearization while the Displacement Coefficient Method uses R-μ-T relationships. As presented and utilized currently; the graphical characteristics of the two procedures are also different.

However, these differences are not fundamental and results from either approach may be readily transformed into various graphical representations (Kalkan and Kunnath, 2007; Chintanapakdee and Chopra, 2003; Gupta and Kunnath, 2000; Kunnath and Kalkan, 2004; Bozorgina and Bertero, 2004 Fajfar and EERI, 2000 Naeim, 2003; Makowski, 1988). The peak displacement of a nonlinear system is estimated as the intersection of the capacity curve and an elastic response spectrum that is reduced to account for energy dissipated by the yielding structure. The underlying basis of the Capacity-Spectrum Method (CSM) is the concept of an "equivalent linear" system, wherein a linear system having reduced stiffness and increased damping proportional to hysteretic energy, is used to estimate the response of the nonlinear system. The CSM is documented thoroughly in ATC-40 (Applied Technology Council, 1996; Federal Emergency Management Agency, 2000; Applied Technology Council, 2005).

In wide-span structures, spatial steel trusses are preferred instead of classical steel roof constructions. They provide economic solutions in using the wide gaps in diverse geometries passing without columns as indoors. Spatial steel trusses are used in places such as industrial areas, factories, air-plane and helicopter hangars, swimming-pools, sport-centers, storerooms, theateropera saloons, cinemas, stands, shop, school buildings, laboratories and fair-departments and in addition, they are highly economic structures (Ay, 1994; Dikmen and Ay, 2006; Korkmaz et al., 2008; Ay and Durmuş, 2002; Fenkli and Ay, 2004: 24).

On the other hand, some of the researchers are not satisfied with the accuracy of current performance based design methodologies. Therefore, current nonlinear static procedures as basic step of these methodologies still have some problems in theoretical background. In other words, there are some question marks on how accurate capacity and demand spectrums demonstrate the structural capacity and earthquake demand, respectively. For this reason, it is very important that comparison of improved nonlinear static procedures in FEMA- 440 for spatial steel trusses supports the steel columns.

Definition of structural models

Steel spatial frames on the steel columns are used as closed market area. Different than the residential buildings, snow, wind, and other roof weights are distributed to the foundations through columns. Lateral stability is responded by the columns in such one-story longer spanned spatial systems. Therefore, geometrical properties of roof and columns play an important role in structural behavior.

In the present study, 4 different soil classes were considered. Shear velocities for the soil classes are; 1000, 600, 300 and 150 m/sn for B, C, D, and E soil classes, respectively. Embedment e = 0 and damping is not considered for each model. Design earthquake is selected as an earthquake with exceeded probability of 10% in 50 years. Mapped short-period spectral response Acceleration Ss =1, for 1 s period, Mapped Spectral Response Acceleration at one-second period S1 = 0.4 for 1st earthquake zone and 0.3 for 2nd zone, 0.2 for 3rd zone and 0.1 for 4th zone. Hence, according to Turkish earthquake code (TEC), 4 different earthquake zones and 4 soil classes and 3 different structural models (Figure 1), nonlinear static procedure, were used according to FEMA 440 (Applied Technology Council, 2005). Table 1 presents seismic coefficients according to TEC'07 and UBC'97 (UBC, 1997; Turkish Earthquake Code, 2007).

The selected models in the study were; broken, flat model and vault. The area of the broken model is 48 × 48 m, weight is 1940 kN. The area of flat model is 66 × 53 m and the weight is 750kN. The area of Vault model is 32*48 m and the weight is 410 kN. Minimum column height is 5 m, column sections are HE400A. For steel roof, different types of steel sections were used. Used steel is A36. Earthquake loads were applied for only X direction.

RESULTS

Comparison of base shear, displacements and spectral acceleration graphs for broken model are given in Figures 2, 3 and 4, respectively. Same comparison for flat model can be seen in Figures 5, 6 and 7, respectively. Finally, Figures 8, 9 and 10 display vault model comparison. Tables 2 and 3 showed comparison results for Broken model for X and Y direction, respectively. In Tables 4 and 5, comparison of improved nonlinear static procedures for flat model can be seen for X and Y direction, respectively. Same comparison is given in Tables 6 and 7 for Vault model for X and Y direction, respectively.

CONCLUSION

In this paper, improved nonlinear static procedures according to FEMA 440 are compared for spatial steel trusses placed on steel columns. In the analysis of three structural models, SAP 2000 computer program was performed (Computer and Structures Inc., 2004). Performance points of models Displacement, acceleration, and base shear force were found by using Displacement Modification and Equivalent Linearization methods. Following conclusions were delineated as a result of numerical analysis:

1. In terms of base shear values, in the broken model,

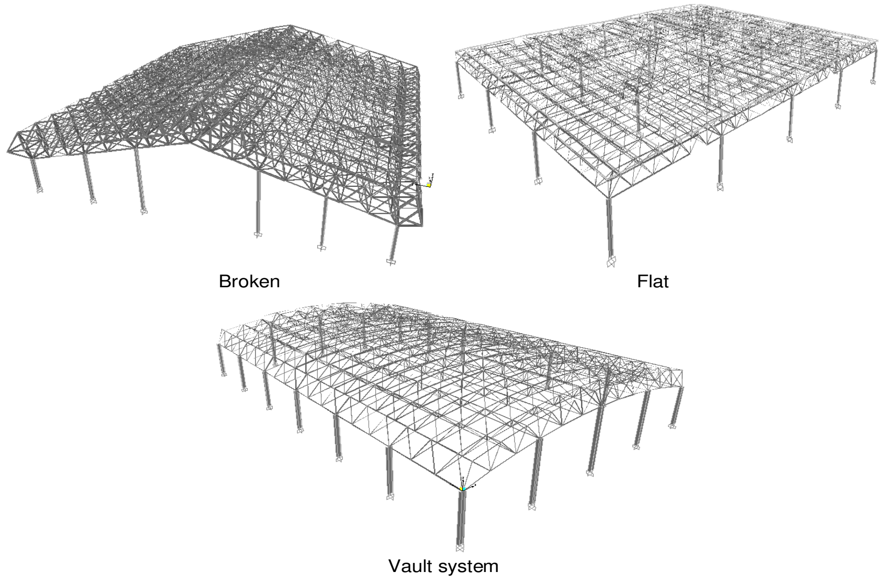


Figure 1. Structural models.

Table 1. Seismic Coefficients C_a , C_v (TEC 2007 -UBC 97) TEC: Turkish Earthquake Code 2007.

Site class	UBC: ** TEC: 4 A_0=0,10 n=0.80		UBC : 2B TEC: 3 A_0=0,20 n=0.70		UBC: 3 TEC: 2 A_0=0,30 n=0.65		UBC : 4 TEC: 1 A_0=0,40 n=0.60	
	C_a	C_v	C_a	C_v	C_a	C_v	C_a	C_v
S_B (Z_1)	0.10	0.10	0.20	0.20	0.30	0.30	0.40N_a	0.40N_v
S_C (Z_2)	0.12	0.17	0.24	0.32	0.33	0.45	0.40N_a	0.56N_v
S_D (Z_3)	0.15	0.23	0.28	0.40	0.36	0.54	0.44N_a	0.64N_v
S_E (Z_4)	0.23	0.34	0.34	0.64	0.36	0.84	0.36N_a	0.96N_v

A_0 = Effective Ground Acceleration Coefficient, n: Aproximate values of shear wave velocity reduction factor. Na and Nv:

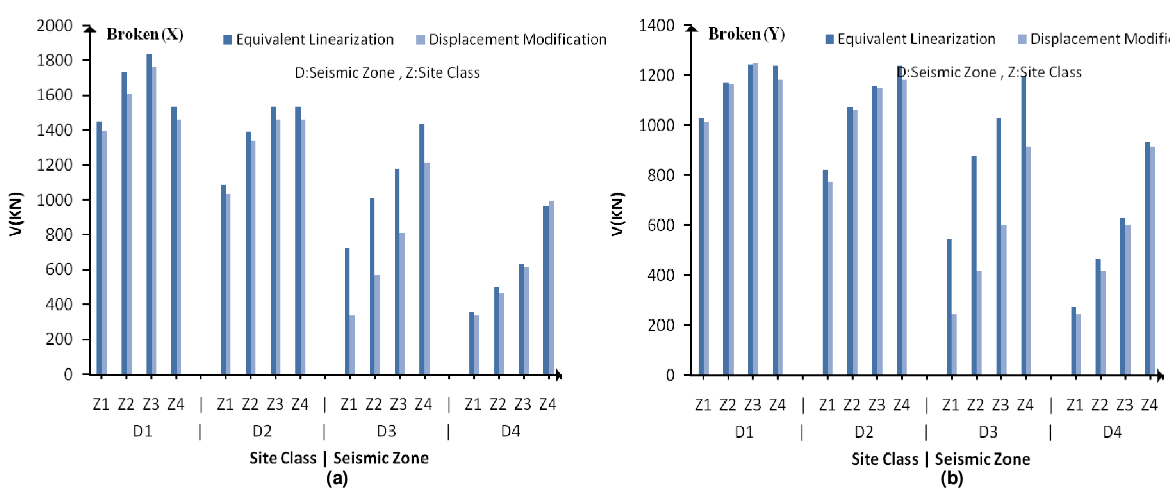


Figure 2. Comparison of base shear for broken model. (a) X direction, (b) Y Direction.

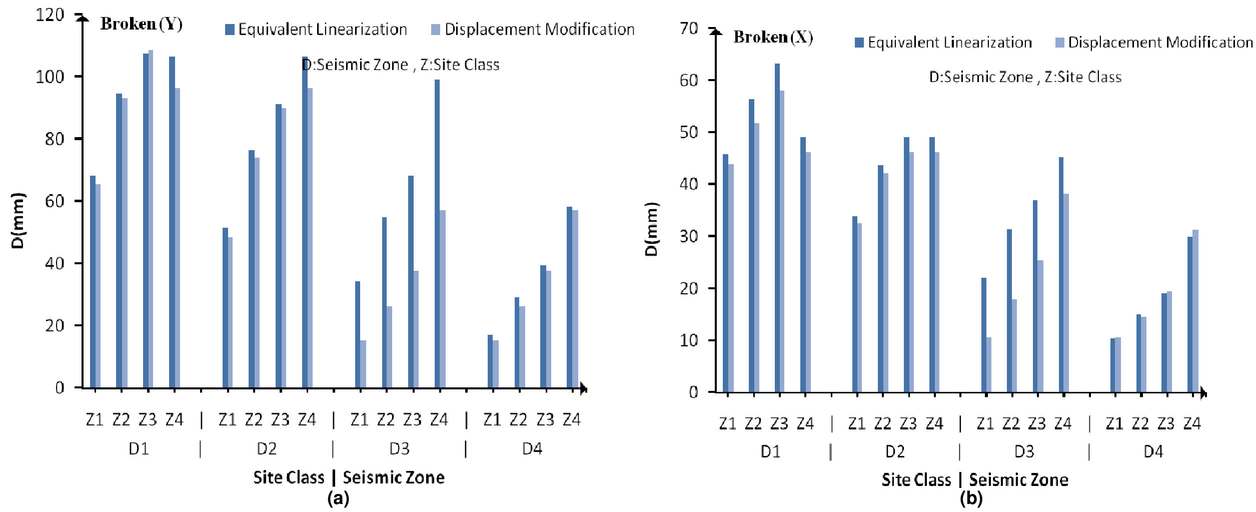


Figure 3. Comparison of displacement for broken model. (a) X direction,(b) Y direction.

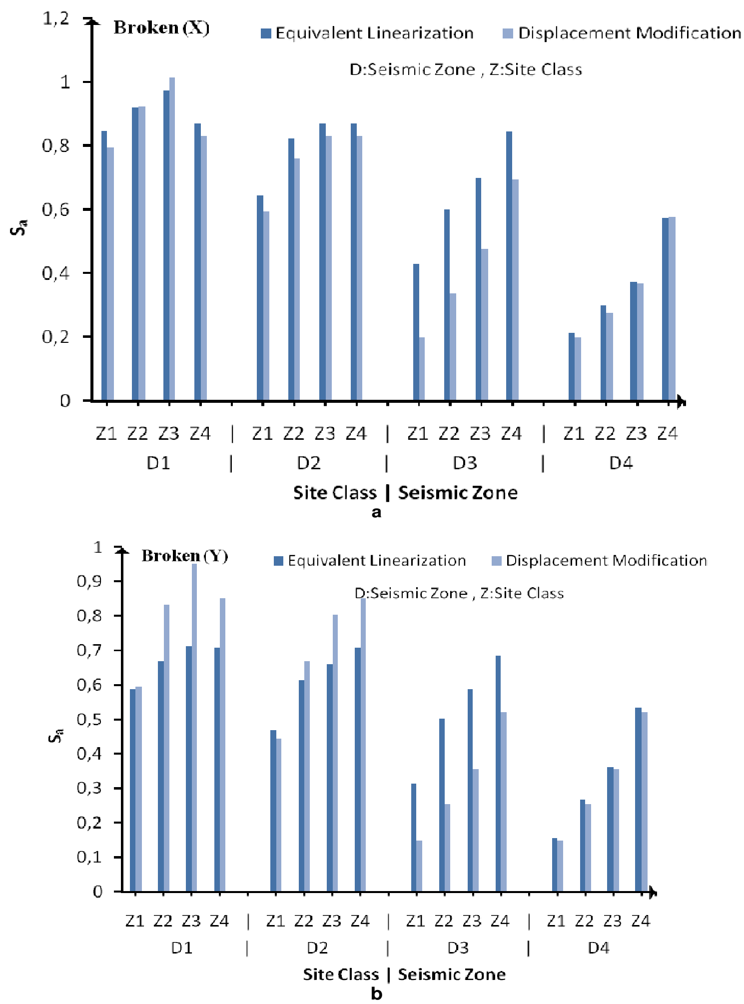


Figure 4. Comparison of spectral acceleration for broken model direction. (a) X direction,(b) Y direction.

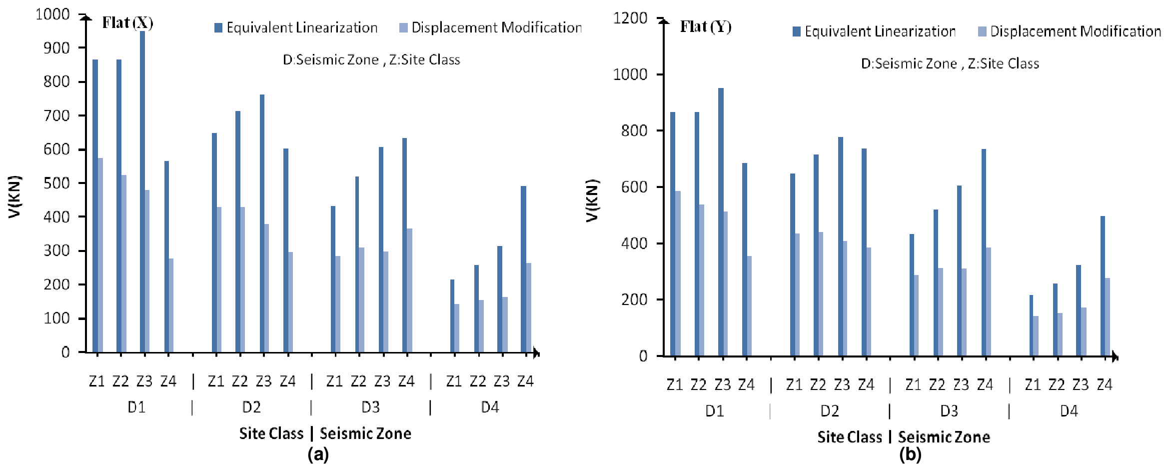
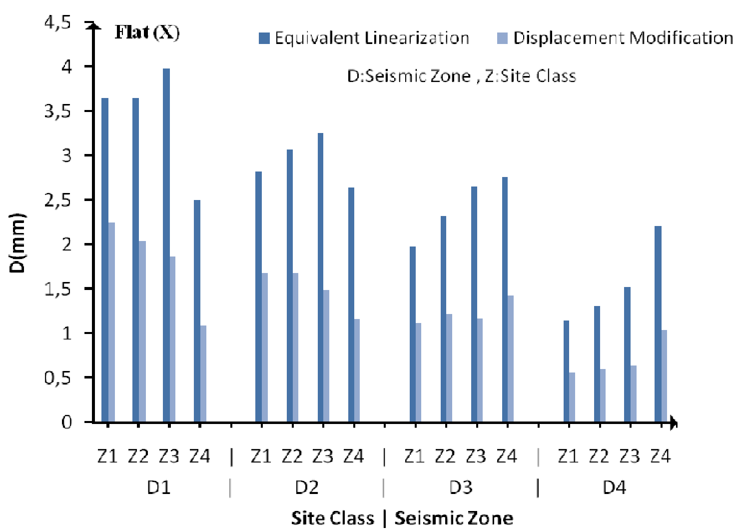


Figure 5. Comparison of base shear for flat model. (a) X direction, (b) Y direction.



a. X direction

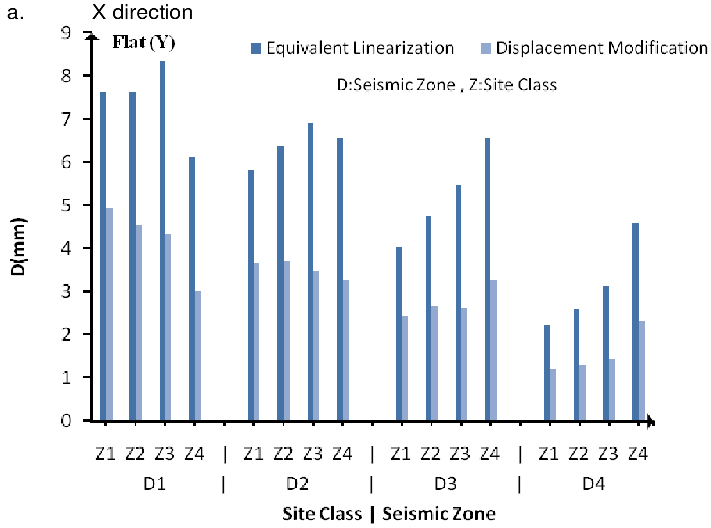
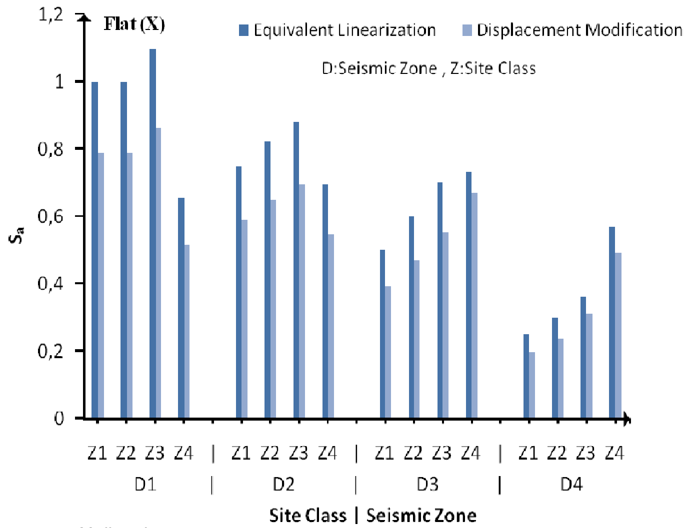
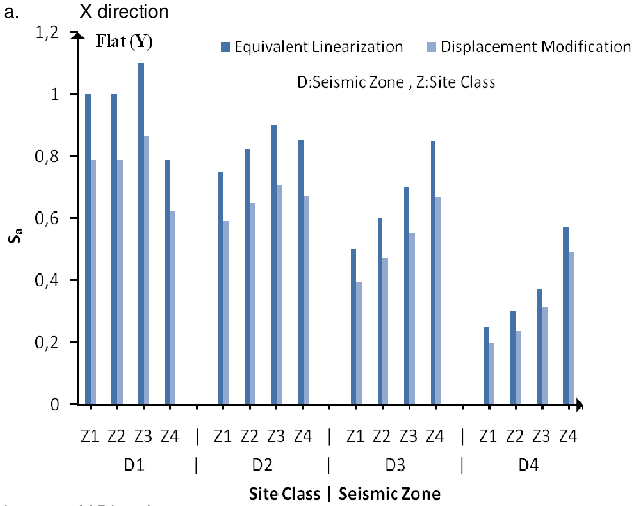


Figure 6. Comparison of Displacement for Flat Model Y a ,b Direction



a. X direction



b. Y Direction

Figure 7. Comparison of Spectral Acceleration for Flat Model

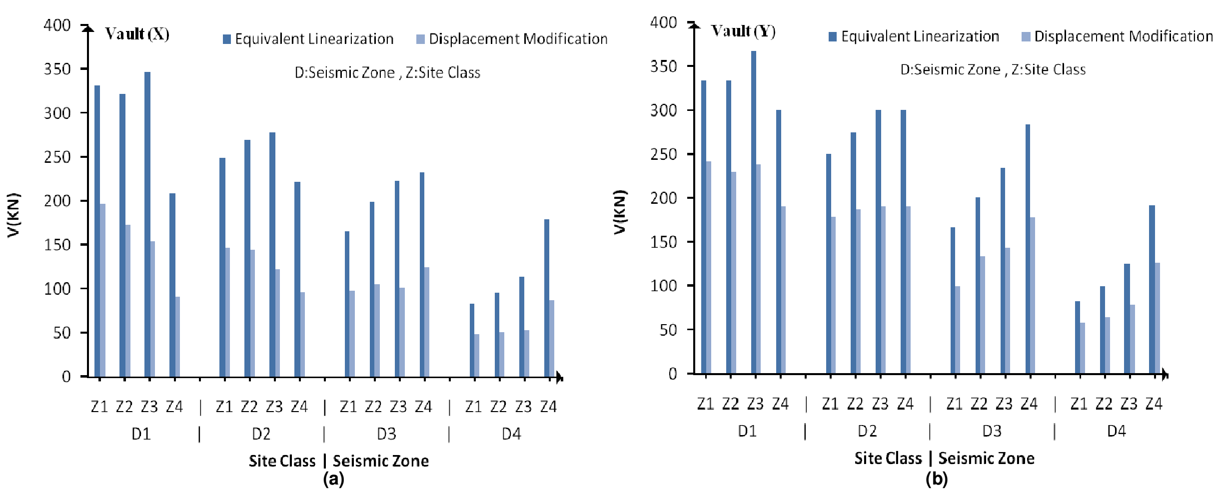


Figure 8. Comparison of base shear for vault model. (a) X direction, (b) Y direction.

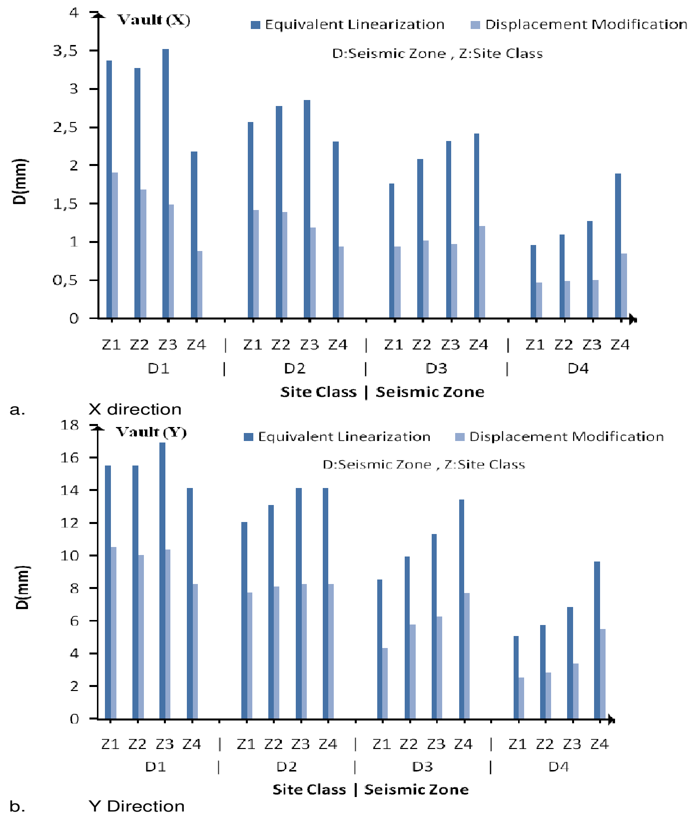


Figure 9. Comparison of Displacement for Vault Model

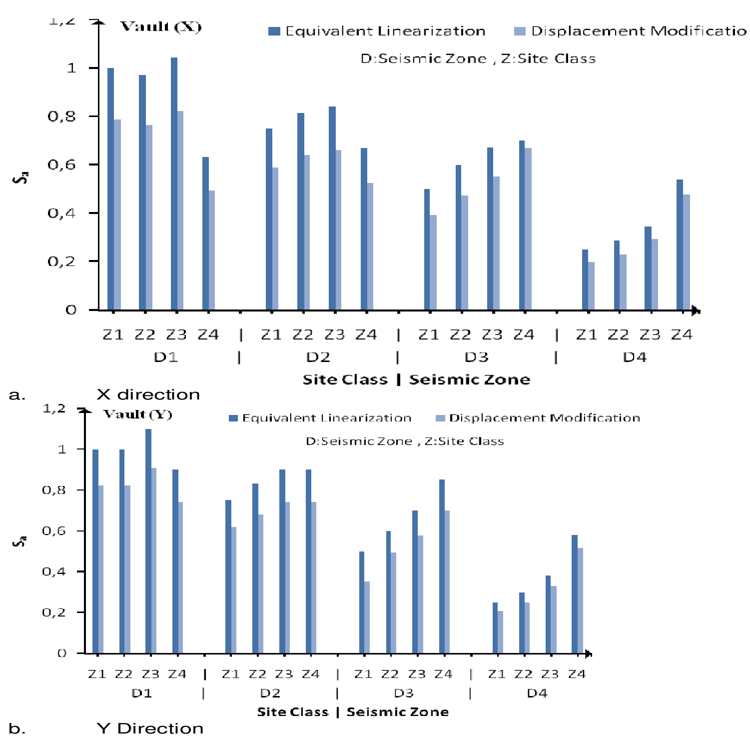


Figure 10. Comparison of Spectral Acceleration for Vault Model

Table 2. Broken (X) comparison of improved nonlinear static procedures (FEMA 440).

Seismic zone	Site class	Equivalent linearization			Displacement modification		
		V (kN)	D (mm)	S_a	V_y (kN)	D_y (mm)	S_a
D1	Z1	1450.68	45.84	0.848	1397.95	43.95	0.795
	Z2	1732.98	56.45	0.918	1610.75	51.85	0.923
	Z3	1837.64	63.26	0.975	1763.91	58.12	1.015
	Z4	1534.91	49.01	0.869	1462.69	46.29	0.830
D2	Z1	1088.62	33.91	0.646	1037.38	32.53	0.595
	Z2	1390.96	43.72	0.825	1341.09	42.10	0.761
	Z3	1534.91	49.01	0.869	1462.69	46.29	0.830
	Z4	1534.91	49.01	0.869	1462.69	46.29	0.831
D3	Z1	725.75	22.13	0.430	336.21	10.54	0.199
	Z2	1011.58	31.41	0.600	572.33	17.95	0.338
	Z3	1180.18	36.88	0.700	812.11	25.46	0.477
	Z4	1436.13	45.29	0.845	1219.53	38.24	0.695
D4	Z1	362.87	10.35	0.215	336.21	10.54	0.199
	Z2	505.79	14.99	0.300	466.66	14.63	0.277
	Z3	632.24	19.10	0.375	620.01	19.44	0.369
	Z4	969.43	30.04	0.575	995.84	31.22	0.577

Table 3. Broken (Y) Comparison of Improved Nonlinear Static Procedures (FEMA 440).

Seismic zone	Site class	Equivalent linearization			Displacement modification		
		V (kN)	D (mm)	S_a	V_y (kN)	D_y (mm)	S_a
D1	Z1	1027.67	68.06	0.589	1013.91	65.55	0.595
	Z2	1173.48	94.59	0.671	1164.62	92.98	0.833
	Z3	1245.53	107.71	0.712	1249.77	108.48	0.952
	Z4	1238.32	106.39	0.708	1183.32	96.39	0.852
D2	Z1	822.67	51.36	0.471	774.39	48.36	0.446
	Z2	1073.48	76.40	0.615	1060.77	74.08	0.670
	Z3	1155.38	91.30	0.661	1148.73	90.09	0.804
	Z4	1238.32	106.39	0.708	1183.33	96.39	0.852
D3	Z1	548.44	34.21	0.314	243.61	15.21	0.149
	Z2	877.51	54.79	0.503	419.92	26.23	0.253
	Z3	1027.67	68.06	0.589	602.48	37.63	0.357
	Z4	1198.46	99.14	0.685	915.68	57.19	0.521
D4	Z1	274.22	17.06	0.157	243.61	15.21	0.149
	Z2	466.18	29.06	0.267	419.92	26.23	0.253
	Z3	630.71	39.36	0.361	602.48	37.63	0.357
	Z4	932.35	58.23	0.534	915.68	57.19	0.521

results of each method are close to each other. For theother models, a significant difference is observed. This shows that structural geometry is one of the important parameters.

Table 4. Flat (X) comparison of improved nonlinear static procedures (FEMA 440).

Seismic zone	Site class	Equivalent linearization			Displacement modification		
		V(kN)	D(mm)	S_a	$V_{y(}$(kN)	D_y(mm)	S_a
D1	Z1	866.26	3.65	1.00	576.14	2.25	0.788
	Z2	866.26	3.65	1.00	523.37	2.04	0.788
	Z3	951.36	3.98	1.098	480.05	1.87	0.865
	Z4	566.32	2.50	0.654	278.51	1.09	0.515
D2	Z1	649.70	2.82	0.750	430.32	1.68	0.591
	Z2	714.67	3.07	0.825	429.57	1.68	0.650
	Z3	764.25	3.26	0.882	380.88	1.49	0.695
	Z4	602.68	2.64	0.696	297.11	1.16	0.548
D3	Z1	433.13	1.98	0.500	285.70	1.12	0.394
	Z2	519.76	2.32	0.600	310.35	1.21	0.472
	Z3	606.38	2.65	0.700	299.02	1.17	0.552
	Z4	635.00	2.76	0.733	366.28	1.43	0.670
D4	Z1	216.57	1.14	0.250	142.26	0.56	0.197
	Z2	259.88	1.31	0.300	153.80	0.60	0.236
	Z3	314.34	1.52	0.363	164.48	0.64	0.309
	Z4	492.52	2.21	0.569	265.81	1.04	0.492

Table 5. Flat (Y) comparison of improved nonlinear static procedures (FEMA 440).

Seismic zone	Site class	Equivalent linearization			Displacement modification		
		V(kN)	D(mm)	S_a	$V_{y(}$(kN)	D_y(mm)	S_a
D1	Z1	866.26	7.63	1.00	584.82	4.93	0.788
	Z2	866.26	7.63	1.00	538.88	4.54	0.788
	Z3	952.89	8.35	1.10	513.52	4.33	0.866
	Z4	685.03	6.12	0.791	356.10	3.00	0.623
D2	Z1	649.70	5.83	0.75	434.73	3.66	0.591
	Z2	714.67	6.37	0.825	439.80	3.71	0.650
	Z3	779.64	6.91	0.900	410.53	3.46	0.709
	Z4	738.34	6.56	0.852	386.62	3.26	0.672
D3	Z1	433.13	4.03	0.500	287.26	2.42	0.394
	Z2	519.76	4.75	0.600	315.41	2.66	0.472
	Z3	606.38	5.47	0.700	311.82	2.63	0.552
	Z4	736.32	6.55	0.850	385.46	3.25	0.670
D4	Z1	216.57	2.23	0.250	142.36	1.2	0.197
	Z2	259.88	2.59	0.300	154.75	1.30	0.236
	Z3	324.85	3.13	0.375	171.77	1.45	0.315
	Z4	498.10	4.57	0.575	275.91	2.32	0.493

2. For Broken model, base shear, displacement and acceleration values were in harmony. However, in the other axis (Y axis), especially for the 3rd earthquake zone, this harmony dissolves. This shows that earthquake zone

Table 6. Vault (X) comparison of improved nonlinear static procedures (FEMA 440).

Seismic zone	Site class	Equivalent linearization			Displacement modification		
		V(kN)	D(mm)	S_a	$V_{y(}$(kN)	D_y(mm)	S_a
D1	Z1	331.84	3.37	1.00	196.72	1.91	0.788
	Z2	322.22	3.28	0.971	172.96	1.68	0.765
	Z3	346.62	3.52	1.045	154.31	1.49	0.823
	Z4	208.99	2.19	0.630	90.90	0.88	0.496
D2	Z1	248.88	2.57	0.750	146.76	1.42	0.591
	Z2	269.99	2.78	0.814	144.20	1.39	0.641
	Z3	278.63	2.86	0.840	122.63	1.19	0.662
	Z4	221.78	2.31	0.668	96.67	0.94	0.527
D3	Z1	165.92	1.77	0.500	97.32	0.94	0.394
	Z2	199.01	2.09	0.600	105.62	1.023	0.473
	Z3	222.89	2.32	0.672	101.43	0.98	0.552
	Z4	232.61	2.42	0.701	124.21	1.203	0.670
D4	Z1	82.96	0.97	0.250	48.40	0.47	0.197
	Z2	96.00	1.10	0.289	50.42	0.49	0.228
	Z3	114.65	1.28	0.346	53.08	0.51	0.294
	Z4	179.51	1.90	0.541	87.48	0.85	0.478

Table 7. Vault (Y) comparison of improved nonlinear static procedures (FEMA 440).

Seismic zone	Site Class	Equivalent linearization			Displacement modification		
		V(kN)	D(mm)	S_a	$V_{y(}$(kN)	D_y(mm)	S_a
D1	Z1	334.04	15.54	1.00	241.78	10.52	0.825
	Z2	334.04	15.54	1.00	230.52	10.03	0.825
	Z3	367.44	16.93	1.10	238.60	10.38	0.907
	Z4	300.64	14.15	0.90	190.15	8.27	0.742
D2	Z1	250.53	12.06	0.75	179.08	7.80	0.619
	Z2	275.59	13.11	0.83	187.54	8.16	0.681
	Z3	300.64	14.15	0.90	190.15	8.28	0.742
	Z4	300.64	14.15	0.90	190.15	8.28	0.742
D3	Z1	167.02	8.58	0.50	99.72	4.34	0.352
	Z2	200.43	9.97	0.60	133.96	5.83	0.495
	Z3	233.83	11.37	0.70	143.98	6.27	0.578
	Z4	283.94	13.45	0.85	178.39	7.76	0.701
D4	Z1	83.51	5.10	0.25	57.94	2.52	0.207
	Z2	100.21	5.80	0.30	65.39	2.85	0.247
	Z3	125.27	6.84	0.38	78.95	3.44	0.330
	Z4	192.07	9.63	0.58	127.25	5.54	0.516

is one of the important parameters.
3. For Flat vault models, each result is significantly different.
4. Support conditions on top of the columns for spatial

structures were found very effective in earthquake behavior of the systems. Further research is necessary for this part.

As a result of the study, structural geometry, earthquake zone and soil class affect the analysis results in each method. Results with Displacement Modification and Equivalent Linearization defined in FEMA are different for each type of structural systems. Therefore, when designing these types of structures, designers should be aware of the structural details such as geometry, structural type and support conditions.

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