Validation of the *2000 NEHRP Provisions*' Equivalent Lateral Force and Modal Analysis Procedures for Buildings with Damping Systems

Oscar M. Ramirez,[a] Michael C. Constantinou,[b] M.EERI, Andrew S. Whittaker,[c] M.EERI, Charles A. Kircher,[d] M.EERI, Martin W. Johnson,[e] M.EERI, and Christis Z. Chrysostomou[f]

Equivalent lateral force and modal analysis procedures for yielding buildings with damping systems were developed, validated, and incorporated in the *2000 NEHRP Provisions*. Key to the implementation of the procedures was the validation process that demonstrated the accuracy of the proposed procedures. The procedures for implementing yielding, viscoelastic, linear viscous, and nonlinear viscous dampers were tested using the results of nonlinear response-history analysis on sample three- and six-story frames and were found to be robust. [DOI: 10.1193/1.1622392]

INTRODUCTION

The 2000 edition of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (BSSC 2001), hereafter referred to as the *2000 NEHRP Provisions*, includes newly developed linear procedures for implementing passive energy dissipation devices in new buildings. Two types of linear procedures are presented: equivalent lateral force (ELF) and modal or response-spectrum analysis (RSA). The development and validation of the analysis methods for buildings with damping systems have been the result of the collective efforts of members of Technical Subcommittee 12 of the Building Seismic Safety Council and researchers at the University at Buffalo. These efforts are described in Ramirez et al. (2000). The companion paper by Whittaker et al. (2003) [this issue, see pages 959–980] describes the evolution of analysis/design procedures for buildings with damping systems, establishes the need for the simplified procedures of the *2000 NEHRP Provisions*, presents in part the equivalent

[a] Professor and Director, Centro Experimental de Ingeniera, Universidad Tecnologica de Panama, Panama, Rep. de Panama
[b] Professor and Chairman, Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY 14260
[c] Associate Professor, Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY 14260
[d] Principal, Kircher & Associates, 1121 San Antonio Rd., Suite D-202, Palo Alto, CA 94303-4311
[e] Principal, ABS Consulting, 300 Commerce Dr., Suite 200, Irvine, CA 92602
[f] Lecturer, Department of Civil Engineering, Higher Technical Institute, 2152 Nicosia, Cyprus

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lateral force and the response-spectrum analysis procedures of the *2000 NEHRP Provisions* and describes the application of these procedures for linear viscous, nonlinear viscous, viscoelastic and hysteretic damping systems.

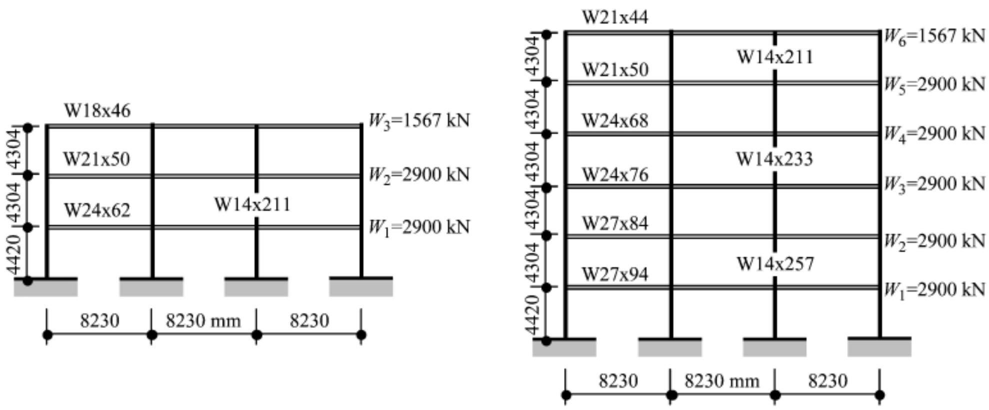
This paper presents some of the validation studies of the *2000 NEHRP Provisions* procedures for buildings with damping systems. The accuracy of the analysis procedures is investigated by comparison with the results of nonlinear response-history analysis. Complete information on the validation studies are presented in Ramirez et al. (2000).

The simplified analyses were performed using the *2000 NEHRP Provisions* ELF and RSA methods except as modified below:

1. In the application of the *2000 NEHRP Provisions*, the load combination factors CF_1 and CF_2 described in Ramirez et al. (2000) were used instead of either of the corresponding factors in ATC (1997) or the force coefficients C_{mFD} and C_{mFV} presented in the *2000 NEHRP Provisions*. This modification is of minor significance in the application of the *2000 NEHRP Provisions* methods of analysis and was made for convenience because it was easier to utilize equations rather than tables when performing spreadsheet analysis.
2. In the application of the *2000 NEHRP Provisions* methods of analysis, the procedures described in the companion paper by Whittaker et al. (2003) for the calculation of the effective damping, the effective period and the added strength and stiffness were followed. The procedures described in the *2000 NEHRP Provisions* are valid for linear viscous damping systems and for viscoelastic and yielding damping systems but are only approximate for nonlinear viscous damping systems.
3. The velocity correction factors presented by Ramirez et al. (2000) were used in selected examples to demonstrate the significance of the correction procedure for multi-degree-of-freedom systems. Such factors are not presented in either the *2000 NEHRP Provisions* or *FEMA-274* (ATC 1997).

One goal of the studies described in both this paper and Ramirez et al. (2000) was to determine whether building frames equipped with dampers could be designed for lower base shear strengths than undamped building frames but achieve similar levels of performance, measured herein using displacements and plastic hinge rotations. The examples presented below involve three- and six-story special steel moment-resisting frame buildings with linear viscous, nonlinear viscous, viscoelastic, and yielding damping systems installed in diagonal or chevron brace configurations. To study the performance of damped building frames with smaller base shear strengths than that required for undamped special moment-resisting frames, termed V in the *1997 NEHRP Provisions* (BSSC 1998), the example frames were designed for a base shear strength in the range of $0.6V$ to V.

The seismic performance of the undamped and damped building frames was studied using nonlinear response-history analysis. Twenty scaled earthquake histories that matched on average a *2000 NEHRP Provisions* response spectrum with parameters $S_{DS}=1.0$, $S_{D1}=0.6$ and $T_s=0.6$ second were used for the analysis. No near-field or soft-



a. Three-story reference frame

b. Six-story reference frame

Figure 1. Reference frame details.

soil histories were included in the set of 20 histories. Ramirez et al. (2000) provides complete information on the histories and scaling procedures used for the analytical studies.

REFERENCE AND DAMPED FRAME ANALYSIS AND DESIGN

REFERENCE THREE- AND SIX-STORY FRAMES

Because the vast majority of buildings in the United States are less than six stories in height, three- and six-story frames were selected as reference frames. The reference frames are special steel moment-resisting frames without damping systems. Two perimeter frames are placed along each axis of each building. The buildings are regular in configuration with plan dimensions of 41.15 m by 41.15 m. The assumed occupancy is office space. The three-story building is 13.03 m in height and the six-story building is 25.94 m in height. The reactive weights at each floor level of each building are shown in Figures 1a and 1b. These weights were held constant for all of the damped frames although some minor reduction in reactive weight was achieved with the use of smaller section sizes in the damped frames.

The reference (undamped) frames were designed to meet the minimum base shear and maximum drift limits (0.02 times the story height) of Section 5.3 of the *1997 NEHRP Provisions*. For special steel moment-resisting frames, the *1997 NEHRP Provisions* assign values of 8 to the response modification factor and 5.5 to the deflection amplification factor. The resulting section sizes for the two reference frames are shown in Figures 1a (three-story) and 1b (six-story). One column size was adopted for the three-story frame. Column sizes were changed every second story in the six-story frame. The nominal yield strength of all steel was assumed to be 345 MPa. Torsional effects were not considered in the analysis and design of the reference frames.

For the three-story frame, the weight of structural steel is 215 kN and the fundamental period is 1.07 second as determined by eigenvalue analysis using IDARC2D (Valles et al. 1996). Nonlinear static analysis of the frame predicts a maximum strength of between 2223 and 2775 kN depending on the lateral force distribution used for the analysis: strengths between 1.37 and 1.70 times the minimum strength required by the *1997 NEHRP Provisions*. This substantial increase in strength is associated with having to satisfy of drift limit of 2% of the story height under the design lateral forces.

For the six-story frame, the weight of structural steel is 504 kN and the fundamental period is 1.90 second. Nonlinear static analysis of the frame predicts a maximum strength of between 2748 and 3646 kN depending on the lateral force distribution used for the analysis: strengths between 1.30 and 1.73 times the minimum strength required by the *1997 NEHRP Provisions*.

THREE-STORY AND SIX-STORY FRAMES WITH DAMPING SYSTEMS

Building frames with damping systems may be designed in accordance with the *2000 NEHRP Provisions* for a base shear of not less than $0.75V$, where V is the base shear for the building frame without a damping system. The frames shown in Figures 1a and 1b were redesigned to have base shear strength in the range of $0.6V$ to V, which resulted in different member sections. Damping systems were then added to these frames and proportioned in accordance with the *2000 NEHRP Provisions* to meet the drift criteria. Six frames were designed: five three-story frames with approximate base shear strengths of $0.60V$, $0.75V$, $0.80V$, $0.9V$, and V, and one six-story frame with a base shear strength of approximately $0.75V$. These frames were termed 3S-60, 3S-75, 3S-80, 3S-90, 3S-100, and 6S-75, respectively.

Table 1 summarizes the characteristics of these six frames. Listed in the table are (a) the ratio of the strength of the frame to that of the corresponding reference frame as determined by simple plastic analysis assuming beam-sway mechanisms (see Ramirez et al. for details), (b) the ratio of the weight of the steel sections in the frame to that of the corresponding reference frame, and (c) the ratio of the fundamental period of the frame to that of the corresponding reference frame. The data of Table 1 show that the base shear strengths of the frames with damping systems are substantially lower than the base shear strengths of the reference frames that were designed to meet the drift criteria of the *1997 NEHRP Provisions*.

A total of nine examples utilizing the six frames of Table 1 were analyzed. The frames with the damping systems in these examples are described in Table 2 and illustrated in Figures 2 and 3. Detailed calculations are presented in Ramirez et al. (2000).

NONLINEAR RESPONSE HISTORY ANALYSIS

Nonlinear response-history analysis was performed using IDARC2D (Valles et al. 1996), a program with elements for modeling damping devices. Complete details of the models used for the analysis are presented in Ramirez et al. (2000). The nine example frames listed in Table 2 were analyzed as follows. Example frames 1, 2, 3, 5, 6, 8, and 9 were analyzed for both the design-basis earthquake (DBE) and the maximum considered earthquake (MCE). The DBE set of earthquake histories consisted of the 20-scaled mo-

Table 1. Characteristics of example frames exclusive of the damping systems

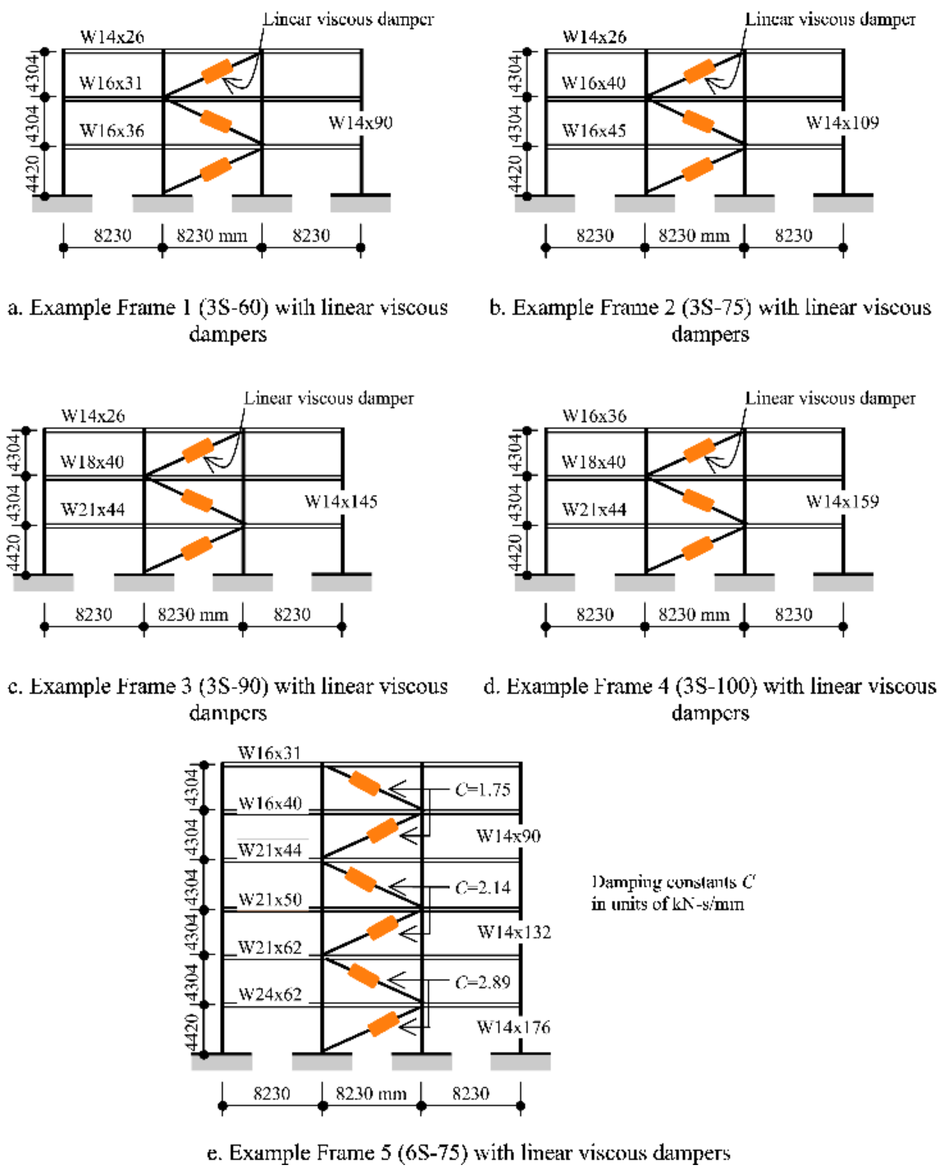
Frame	Strength ratio	Weight ratio	Period ratio
3S-60	0.44	0.52	1.66
3S-75	0.55	0.57	1.48
3S-80	0.59	0.57	1.42
3S-90	0.66	0.70	1.29
3S-100	0.73	0.76	1.24
6S-75	0.58	0.60	1.37

tions noted above and described in Ramirez et al. (2000) and in the companion paper by Whittaker et al. (2003). The amplitudes of the DBE acceleration histories were multiplied by 1.5 to establish the MCE histories: the inverse of the process adopted in the *2000 NEHRP Provisions* to generate a DBE spectrum from an MCE spectrum. Peak response quantities were obtained for each history and values are presented in the tables below for minimum, maximum, mean (μ), and $\mu+1\sigma$ responses. Example frames 2 and 4 were analyzed to assess the degree of inelastic action in frames with and without damping systems. Frame 7 was analyzed for MCE shaking only.

Table 2. Properties of the example frames

Example Frame	Frame	Damping System[1]	EVD[2]	Damper Properties[3]
1	3S-60	LV	10%	C=0.8 kN-s/mm all stories
2	3S-75	LV	10%	C=0.9 kN-s/mm all stories
3	3S-90	LV	10%	C=1.0 kN-s/mm all stories
4	3S-100	LV	20%	C=2.14 kN-s/mm all stories
5	6S-75	LV	10%	See Figure 3e for details
6	3S-80	NLV	10%	C=14.5 kN-(s/mm)$^{0.5}$ all stories
7	3S-80	NLV	20%	C=32 kN-(s/mm)$^{0.5}$ all stories
8	3S-75	VES	8.5%	3M ISD110; A=626330 mm^2, h=140 mm
9	3S-75	TMY	-	b=305 mm, h=457 mm, t=25 mm, F_y=248 MPa

1. LV=linear viscous; NLV=nonlinear viscous with a velocity exponent of 0.5; VES=viscoelastic solid; TMY=triangular metallic yielding.
2. EVD=equivalent viscous damping ratio; damping ratio calculated assuming elastic response
3. See Ramirez et al. (2000) for complete details.



a. Example Frame 1 (3S-60) with linear viscous dampers

b. Example Frame 2 (3S-75) with linear viscous dampers

c. Example Frame 3 (3S-90) with linear viscous dampers

d. Example Frame 4 (3S-100) with linear viscous dampers

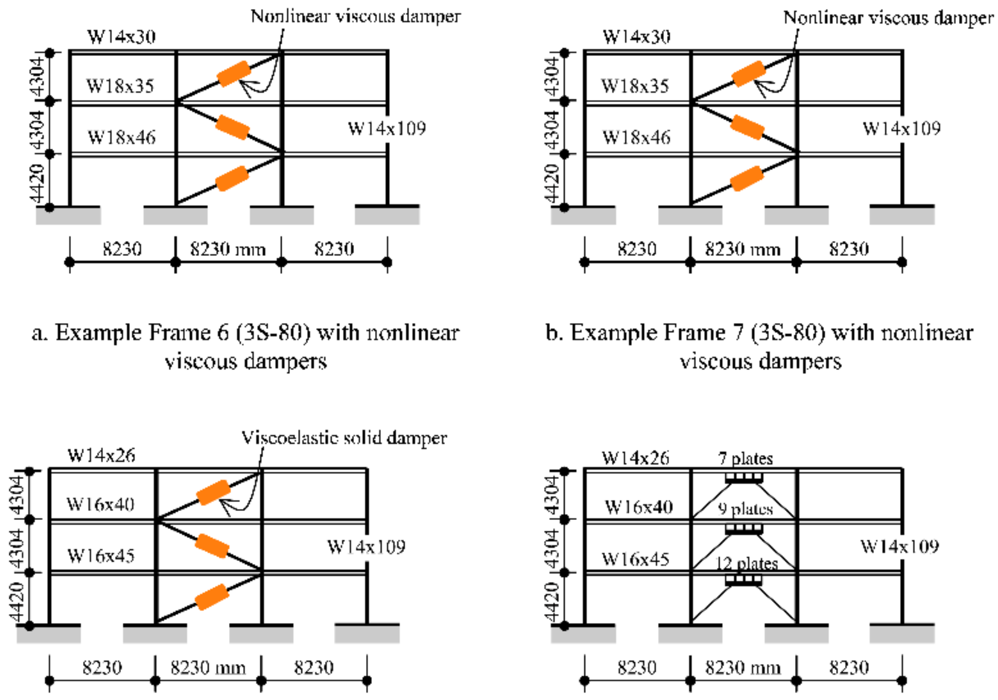
e. Example Frame 5 (6S-75) with linear viscous dampers

Figure 2. Details of example frames 1 through 5 (all braces TS 8×8).

PRESENTATION AND INTERPRETATION OF RESULTS

ACCURACY OF THE SIMPLIFIED NEHRP PROCEDURES

Response data are presented for representative cases in Tables 3 through 15. Complete details are presented in Ramirez et al. (2000). Included in the tables are (a) peak interstory drifts, (b) peak interstory velocities (for the viscous dampers only), (c) peak



a. Example Frame 6 (3S-80) with nonlinear viscous dampers

b. Example Frame 7 (3S-80) with nonlinear viscous dampers

c. Example Frame 8 (3S-75) with viscoelastic solid dampers

d. Example Frame 9 (3S-100) with metallic yielding dampers

Figure 3. Details of example frames 6 through 9 (all braces TS 8×8).

damper forces, (d) story shear forces at the time of maximum drift, and (e) maximum story shears (that include including the viscous force as appropriate). Data are presented for the equivalent lateral force (ELF) and response-spectrum analysis (RSA) methods of the *2000 NEHRP Provisions* and for the nonlinear response-history analysis. Included in the presentation of the ELF and RSA results are data for two characterizations of the higher-mode periods, namely, T_m and $T_m\sqrt{\mu}$, where T_m is the period in mode m from eigenvalue analysis (taken as the residual mode period for the ELF) and μ is the ductility demand calculated from the analysis of the first mode response.

Evaluation of the data presented in Tables 3 through 15 led the authors to the following conclusions:

1. The ELF method tends to overestimate and underestimate the damper forces and frame-member actions in the lowest and upper stories, respectively. These differences are caused primarily by the contribution of the residual mode to the total response. The residual mode shape has a substantial component associated with the displacements of the lower floors of the building and resembles the second mode of vibration but with substantially larger modal displacements in the lower floors and a larger modal weight.

Table 3. DBE analysis of Example Frame 1 (3S-60) with a linear viscous damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1,2] using T_m ELF	RSA	Higher modes using $T_m\sqrt{\mu}$ ELF	RSA	Nonlinear response-history analysis Min.	μ	$\mu+1\sigma$	Max.
Story drift (mm.)	3	95	98	96	102	45	86	109	119
	2	119	114	120	114	47	102	131	151
	1	80	71	82	72	29	68	92	122
Interstory velocity (mm/sec)	3	367,**364**	509,**441**	355,**362**	524,**461**	263	456	568	690
	2	458,**454**	365,**394**	443,**451**	372,**400**	233	445	558	625
	1	405,**359**	290,**277**	383,**354**	298,**285**	153	329	429	520
Damper force (kN)	3	261,**259**	361,**313**	252,**257**	372,**327**	188	326	406	492
	2	325,**322**	259,**280**	314,**320**	264,**284**	166	317	398	446
	1	287,**255**	206,**197**	272,**251**	211,**202**	109	235	306	371
Story shear at max. disp. (kN)	3	510	642	492	588	325	481	609	734
	2	853	864	849	860	511	894	1045	1272
	1	1306	1221	1267	1172	743	1093	1245	1316
Max. story shear (kN)	3	572,**566**	727,**706**	551,**548**	685,**664**	363	567	701	849
	2	938,**941**	933,**939**	932,**937**	930,**936**	562	987	1165	1286
	1	1338,**1328**	1246,**1243**	1291,**1198**	1201,**1198**	807	1314	1563	1795

1. ELF = equivalent lateral force procedure; RSA = response-spectrum analysis
2. Values in bold are results using the revised velocity correction factors of Ramirez et al. (2000)

2. The use of $T_m\sqrt{\mu}$ instead of T_m for calculating higher-mode response contributions produces marginally improved predictions of total response compared with the average results of the nonlinear response-history analysis.
3. The two simplified procedures generally predict conservative estimates of story drift that fall consistently between the μ and $\mu+1\sigma$ results of the nonlinear response-history analysis.
4. The use of pseudo-velocity correction factors of Ramirez et al. (2000) improves the predictions of interstory velocity and damper forces as can be seen in Tables 3 and 4. Although the improvement is not significant, the correction is simple to implement and as such its use is warranted.
5. The accuracy of the predictions of key design parameters such as the peak damper force and the maximum base shear force by the two simplified methods varies considerably among the selected examples. Table 16 summarizes these predictions for MCE shaking. However, the results of the simplified analyses are generally within 30% of the average of the results of nonlinear response-history analysis and as such are acceptable for simplified methods of analysis. The pre-

Table 4. MCE analysis of Example Frame 1 (3S-60) with a linear viscous damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1,2] using T_m ELF	RSA	Higher modes using $T_m\sqrt{\mu}$. ELF	RSA	Nonlinear response-history analysis Min.	μ	$\mu+1\sigma$	Max
Story drift (mm.)	3	145	149	149	159	67	124	164	207
	2	181	174	186	174	70	142	191	244
	1	121	108	129	111	44	107	154	210
Interstory velocity (mm/sec)	3	497,**494**	725,**619**	452,**484**	704,**636**	395	605	741	919
	2	620,**616**	461,**514**	563,**604**	491,**533**	319	590	728	835
	1	580,**509**	397,**376**	503,**491**	396,**387**	224	484	633	808
Damper force (kN)	3	353,**351**	515,**440**	321,**344**	499,**452**	282	431	529	656
	2	440,**437**	327,**365**	400,**429**	349,**379**	227	421	519	596
	1	412,**362**	282,**267**	357,**348**	281,**275**	160	345	451	577
Story shear at max. disp. (kN)	3	645	871	575	629	347	547	683	796
	2	893	917	872	894	725	985	1145	1503
	1	1616	1458	1455	1218	912	1212	1355	1507
Max. story shear (kN)	3	729,**720**	993,**958**	646,**648**	781,**755**	461	694	833	1004
	2	1021,**1026**	1011,**1022**	993,**1006**	997,**1007**	839	1155	1317	1505
	1	1652,**1633**	1482,**1475**	1455,**1451**	1260,**1258**	1143	1610	1881	2176

1. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis
2. Values in bold are results using the revised velocity correction factors of Ramirez et al. (2000)

dicted responses of the simplified methods deviate most from the average results of the nonlinear response-history analysis for the six-story moment-resisting frame.

EXTENT AND PATTERNS OF DAMAGE

The *2000 NEHRP Provisions* allow the strength of a building frame to be reduced substantially below that of an undamped frame if damping systems are added to the frame. Compare the reference frame of Figure 1a (without damping devices) to the damped frame of Figure 2a (with a linear viscous damping system). These two frames meet the drift criteria of both the *1997 NEHRP Provisions* and the *2000 NEHRP Provisions*. As noted in Table 1, the frame with the damping system (3S-75) has a base shear strength (calculated by plastic analysis using a pattern of lateral loads proportional to the first mode shape) that is 55% of that of the frame without the damping system.

The pattern of plastic hinge formation and some key response quantities were investigated in (a) the three-story reference frame of Figure 1a, (b) the three-story, 3S-75 frame with linear viscous damping system (Example Frame 2, Figure 2b), and (c) the three-story, 3S-100 frame with linear viscous damping system (Example Frame 4, Figure 2d). Note that 3S-75 just meets the drift criteria of the *2000 NEHRP Provisions*

Table 5. DBE analysis of Example Frame 2 (3S-75) with a linear viscous damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1] using T_m		Higher modes using $T_m\sqrt{\mu}$		Nonlinear response-history analysis			
		ELF	RSA	ELF	RSA	Min.	μ	$\mu+1\sigma$	Max.
Story drift (mm.)	3	88	89	88	91	39	82	104	114
	2	104	99	105	100	40	92	120	137
	1	71	62	72	63	25	63	85	103
Interstory velocity (mm/sec)	3	391	490	383	516	250	447	543	610
	2	464	371	454	375	228	442	545	604
	1	411	281	396	291	133	322	409	469
Damper force (kN)	3	312	391	305	411	199	357	434	487
	2	370	296	362	299	182	353	436	483
	1	328	224	316	232	106	257	327	375
Story shear at max. disp. (kN)	3	585	696	574	677	360	556	695	840
	2	1046	1059	1043	1056	560	1055	1246	1458
	1	1506	1424	1482	1408	694	1339	1568	1699
Max. story shear (kN)	3	663	791	650	783	378	650	792	887
	2	1139	1137	1136	1135	606	1182	1400	1464
	1	1552	1458	1522	1442	800	1577	1897	2095

[1]. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

whereas case 3S-100 is a stronger and highly damped frame: a frame that is more representative of a design for substantial improvement of performance. The three frames were analyzed using the scaled Northridge Century earthquake history that is described in Ramirez et al. (2000): a DBE-type history that produced responses in the frames that were similar to the average responses calculated using the 20 scaled motions described above. Analyses were performed for this DBE history and an MCE history, which was the DBE history scaled in amplitude by a factor of 1.5.

Figures 4 through 6 below present the results of these analyses. Each figure identifies the seismic excitation (DBE or MCE), presents key response quantities such as maximum interstory drift ratios, roof displacements, base shear forces (including the damping component) and plastic hinge rotations, and the location and sequence of the formation of plastic hinges. Comparing the performance of the frames in both the DBE and MCE shaking:

1. The maximum DBE drift for the reference frame equals 0.028, which exceeds the *NEHRP Provisions* limit of 0.02. This is not surprising because the *NEHRP Provisions* consistently underestimate the maximum inelastic drift by the ratio of R/C_d, which is equal to 1.46 (=8/5.5). If the drift limit of 0.02 is factored up by 1.46, the resulting drift ratio is 0.029 and quite similar to the calculated maximum of 0.028.

Table 6. MCE analysis of Example Frame 2 (3S-75) with a linear viscous damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1] using T_m ELF	RSA	Higher modes using $T_m\sqrt{\mu}$ ELF	RSA	Nonlinear response-history analysis Min.	μ	$\mu+1\sigma$	Max.
Story drift (mm.)	3	132	133	134	143	58	118	156	179
	2	156	149	159	150	59	131	166	187
	1	106	94	112	96	37	96	133	176
Interstory velocity (mm/sec)	3	525	686	486	723	374	597	725	875
	2	623	461	577	483	341	587	719	771
	1	587	376	521	395	199	464	596	717
Damper force (kN)	3	419	547	388	577	299	477	579	699
	2	497	368	460	385	272	469	575	616
	1	468	300	416	315	159	370	476	573
Story shear at max. disp. (kN)	3	710	907	654	753	476	639	784	978
	2	1074	1104	1061	1087	831	1183	1340	1592
	1	1788	1630	1662	1482	1040	1487	1720	2254
Max. story shear (kN)	3	818	1042	753	924	564	777	915	1088
	2	1214	1210	1195	1199	907	1379	1580	1684
	1	1846	1664	1692	1527	1198	1917	2242	2519

[1.] ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

2. Frame 3S-75 (Figure 5) that just meets the drift criteria of the *NEHRP Provisions* exhibits smaller drifts, smaller plastic hinge rotations and substantially smaller base shear forces than the undamped reference frame.
3. The maximum DBE and MCE roof displacements in the highly damped Frame 3S-100 (Figure 6) are substantially smaller than those in lightly damped 3S-75. However the performance of 3S-100 as measured in terms of drift ratios, maximum plastic hinge rotations and maximum base shear forces is only marginally better than that of 3S-75.
4. Moment-frame buildings designed with damping systems to meet the minimum criteria of the *2000 NEHRP Provisions* perform comparably to or better than buildings designed without damping systems to meet the minimum strength and drift criteria of the *1997 NEHRP Provisions*. Moreover, buildings with damping systems offer the distinct advantage of lower base shear forces than conventional buildings without damping systems for similar levels of performance.

CONCLUSIONS

Moment-frame buildings with and without damping systems were analyzed and designed using the simplified ELF and RSA procedures of the *2000 NEHRP Provisions*. The resultant designs were evaluated by response-history analysis with twenty scaled

Table 7. DBE analysis of Example Frame 5 (6S-75) with a linear viscous damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1] using T_m ELF	RSA	Higher modes using $T_m\sqrt{\mu}$ ELF	RSA	Nonlinear response-history analysis Min.	μ	$\mu+1\sigma$	Max.
Story drift (mm.)	6	53	64	53	67	26	41	50	61
	5	79	84	79	85	38	65	84	106
	4	85	85	85	85	41	75	101	127
	3	86	85	86	85	39	73	100	131
	2	71	71	71	72	31	59	80	107
	1	68	41	70	41	18	34	44	56
Interstory velocity (mm/sec)	6	132	348	130	349	99	190	234	265
	5	196	299	193	293	131	243	294	316
	4	212	248	209	251	142	255	315	355
	3	215	222	211	226	138	272	341	423
	2	177	198	174	197	126	259	337	433
	1	345	147	325	148	83	183	250	339
Damper force (kN)	6	205	540	201	542	153	295	364	411
	5	304	464	299	454	204	377	456	490
	4	403	471	396	476	270	485	598	675
	3	407	421	400	428	262	516	649	804
	2	454	508	446	505	323	662	863	1109
	1	884	376	832	378	212	469	640	869
Max. story shear (kN)	6	427	736	414	705	222	334	390	408
	5	967	1069	945	1025	536	756	862	888
	4	1321	1338	1306	1326	751	1056	1198	1352
	3	1499	1543	1498	1538	867	1268	1429	1495
	2	1742	1769	1725	1743	987	1579	1813	1868
	1	2369	1861	2271	1818	1102	1948	2293	2416

[1]. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

earthquake histories that matched on average a *2000 NEHRP Provisions* response spectrum with parameters S_{DS}=1.0, S_{D1}=0.6 and T_s=0.6 second were used for the analysis. No near-field or soft-soil histories were included in the set of 20 histories. As such, the results of the study are strictly only valid for moment-frame buildings on rock and firm-soil sites.

The two simplified methods of the *2000 NEHRP Provisions* were validated by the studies reported in this paper and in Ramirez et al. (2000). The simplified methods produced estimates of peak displacements, peak velocities, and peak accelerations (including the viscous component) that were in good overall agreement with the average of results of nonlinear response-history analysis. Although the simplified methods are not

Table 8. MCE analysis of Example Frame 5 (6S-75) with a linear viscous damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1] using T_m		Higher modes using $T_m\sqrt{\mu}$		Nonlinear response-history analysis			
		ELF	RSA	ELF	RSA	Min.	μ	$\mu+1\sigma$	Max.
Story drift (mm.)	6	79	97	80	105	36	53	65	77
	5	118	126	119	130	59	88	112	138
	4	128	128	129	129	67	106	141	173
	3	129	127	130	128	62	107	146	184
	2	107	107	108	108	47	90	124	161
	1	101	62	111	63	26	56	81	110
Interstory velocity (mm/sec)	6	171	513	160	485	133	249	302	325
	5	254	424	238	393	188	319	383	410
	4	275	336	258	332	197	346	425	480
	3	278	291	260	299	203	380	480	584
	2	230	266	215	257	172	374	490	617
	1	512	207	424	202	124	278	372	497
Damper force (kN)	6	265	795	248	753	206	386	469	505
	5	394	657	369	610	292	495	594	636
	4	522	637	489	629	374	657	808	911
	3	528	552	494	566	385	722	911	1109
	2	589	681	551	658	441	957	1253	1580
	1	1312	530	1086	518	319	711	953	1271
Max. story shear (kN)	6	527	1042	461	871	294	399	457	492
	5	1130	1321	1015	1124	701	897	1007	1092
	4	1459	1493	1376	1407	967	1236	1366	1481
	3	1550	1643	1539	1604	1116	1489	1641	1733
	2	1894	1950	1801	1817	1357	1937	2137	2281
	1	3052	2116	2568	1888	1655	2592	3002	3455

1. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

error free, they are simple to apply, converge systematically and produce results of sufficient accuracy for the purpose of design. The greatest differences occurred in the analysis of the three-story frame.

Moment-frame buildings on rock or stiff soil sites with damping systems designed to meet the minimum strength and drift criteria of the *2000 NEHRP Provisions* performed comparably to, or better than, conventional buildings without damping systems. Buildings with damping systems can be designed for a lower base shear force than conventional buildings without damping systems for similar performance. Although the minimum design base shear force for a damped building is 75% of that of the corresponding conventionally framed building, the analysis results presented in this paper suggest that the minimum percentage could be lowered further.

Table 9. DBE analysis of Example Frame 6 (3S-80) with a nonlinear viscous damping system

Response quantity and level/story		2000 NEHRP Provisions: Higher modes[1] using T_m		Higher modes using $T_m\sqrt{\mu}$		Nonlinear response-history analysis			
		ELF	RSA	ELF	RSA	Min.	μ	$\mu+1\sigma$	Max.
Story	3	87	88	88	92	39	80	104	119
drift	2	103	96	104	96	40	86	114	131
(mm.)	1	72	61	75	62	22	58	79	99
Interstory	3	440	559	433	597	254	484	600	664
velocity	2	520	382	511	388	232	441	546	595
(mm/sec)	1	489	311	477	327	141	311	398	449
Damper	3	268	300	266	312	216	299	333	350
force	2	291	261	289	262	207	285	317	331
(kN)	1	286	225	281	230	161	240	271	288
Story shear	3	659	803	650	789	422	671	849	1032
at max. disp.	2	1100	1112	1098	1110	676	1108	1311	1507
(kN)	1	1682	1560	1662	1547	689	1420	1679	1819
Max. story	3	752	889	703	846	446	738	905	1042
shear	2	1223	1229	1166	1173	697	1225	1446	1578
(kN)	1	1757	1633	1702	1585	779	1617	1945	2100

[1]. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

Table 10. MCE analysis of Example Frame 6 (3S-80) with a nonlinear viscous damping system

Response quantity and level/story		2000 NEHRP Provisions: Higher modes[1] using T_m		Higher modes using $T_m\sqrt{\mu}$		Nonlinear response-history analysis			
		ELF	RSA	ELF	RSA	Min.	μ	$\mu+1\sigma$	Max.
Story	3	136	138	141	155	61	124	162	183
drift	2	160	150	167	150	62	131	173	199
(mm.)	1	112	94	124	100	31	94	134	173
Interstory	3	620	813	586	918	406	686	856	1064
velocity	2	732	492	691	529	354	614	752	840
(mm/sec)	1	725	436	671	485	205	468	603	720
Damper	3	316	367	307	397	273	356	397	443
force	2	343	294	334	301	255	336	372	394
(kN)	1	359	265	340	279	194	294	334	364
Story shear	3	840	1095	791	938	440	719	930	1223
at max. disp.	2	1138	1165	1125	1152	943	1218	1341	1432
(kN)	1	2098	1861	1985	1696	894	1547	1771	1912
Max. story	3	930	1178	847	1010	614	909	1093	1328
shear	2	1279	1293	1207	1226	990	1446	1629	1827
(kN)	1	2166	1927	2025	1741	1187	1937	2239	2445

[1]. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

Table 11. MCE analysis of Example Frame 7 (3S-80) with a nonlinear viscous damping system

Response quantity and Nlevel/story		*2000 NEHRP Provisions* Higher modes[1] using T_m		Higher modes using $T_m\sqrt{\mu}$		Nonlinear response-history analysis			
		ELF	RSA	ELF	RSA	Min.	μ	μ+1σ	Max.
Story	3	106	108	108	116	42	75	97	115
drift	2	125	118	127	118	53	100	132	148
(mm.)	1	87	74	91	77	36	79	109	132
Interstory	3	508	660	483	729	235	453	566	655
velocity	2	599	435	569	448	298	520	635	745
(mm/sec)	1	572	363	530	392	214	412	535	623
Damper	3	634	724	621	767	462	641	717	770
force	2	689	614	674	619	520	686	759	822
(kN)	1	688	537	656	556	440	611	697	752
Story shear	3	717	913	683	861	382	613	833	1298
at max. disp.	2	1114	1139	1105	1130	1014	1350	1561	1845
(kN)	1	1815	1673	1737	1619	1343	1732	1907	2165
Max. story	3	1003	1192	884	1099	510	784	934	1087
shear	2	1480	1476	1355	1358	1133	1570	1778	2007
(kN)	1	2051	1885	1905	1774	1466	2172	2487	2646

1. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

Table 12. DBE analysis of Example Frame 8 (3S-75) with a viscoelastic damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1] using T_m		Higher modes using $T_m\sqrt{\mu}$		Nonlinear response-history analysis			
		ELF	RSA	ELF	RSA	Min.	μ	μ+1σ	Max.
Story	3	76	78	76	80	41	94	123	139
drift	2	98	94	98	94	42	94	122	143
(mm.)	1	71	64	72	65	25	59	79	105
Interstory	3	375	485	372	507	275	493	611	725
velocity	2	482	401	479	407	241	440	539	574
(mm/sec)	1	430	315	425	324	132	308	395	495
Damper	3	391	464	393	492	240	466	592	718
force	2	504	432	506	436	215	432	538	575
(kN)	1	424	324	427	334	120	296	385	462
Story shear	3	653	786	646	775	156	866	1128	1316
at max. disp.	2	1273	1293	1272	1292	707	1267	1522	1752
(kN)	1	1773	1693	1758	1685	751	1407	1705	2045
Max. story	3	716	853	710	847	532	963	1173	1367
shear	2	1354	1361	1352	1360	753	1405	1672	1769
(kN)	1	1818	1732	1804	1725	922	1642	1977	2231

1. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

Table 13. MCE analysis of Example Frame 8 (3S-75) with a viscoelastic damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1] using T_m ELF	RSA	Higher modes using $T_m\sqrt{\mu}$ ELF	RSA	Nonlinear response-history analysis Min.	μ	$\mu+1\sigma$	Max.
Story drift (mm.)	3	114	117	116	128	62	132	177	210
	2	147	140	150	141	63	130	169	196
	1	106	96	112	100	37	90	123	158
Interstory velocity (mm/sec)	3	515	691	490	768	411	678	838	1048
	2	662	527	630	559	357	580	711	801
	1	615	430	570	465	198	445	576	738
Damper force (kN)	3	558	671	560	799	285	625	724	627
	2	718	603	721	632	343	550	669	711
	1	616	460	620	508	178	430	564	675
Story shear at max. disp. (kN)	3	802	1036	764	936	711	1066	1266	1392
	2	1424	1465	1415	1455	1036	1479	1680	1787
	1	2155	2005	2064	1927	1098	1548	1735	1916
Max. story shear (kN)	3	891	1130	851	1050	782	1224	1433	1645
	2	1541	1557	1527	1548	1129	1655	1888	2035
(kN)	1	2215	2053	2125	1986	1381	2007	2326	2664

1. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

Table 14. DBE analysis of Example Frame 9 (3S-75) with a yielding damping system

Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1] using T_m ELF	RSA	Higher modes using $T_m\sqrt{\mu}$ ELF	RSA	Nonlinear response-history analysis Min.	μ	$\mu+1\sigma$	Max.
Story drift (mm.)	3	100	107	105	119	55	106	129	155
	2	119	112	124	113	48	95	123	147
	1	82	72	93	76	41	68	91	121
Max. story shear (kN)	3	855	1041	855	1041	735	1111	1330	1408
	2	1351	1361	1351	1361	1125	1638	1922	2235
	1	2165	1952	2165	1952	1722	2030	2214	2422

1. ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

Table 15. MCE analysis of Example Frame 9 (3S-75) with a metallic yielding damping system

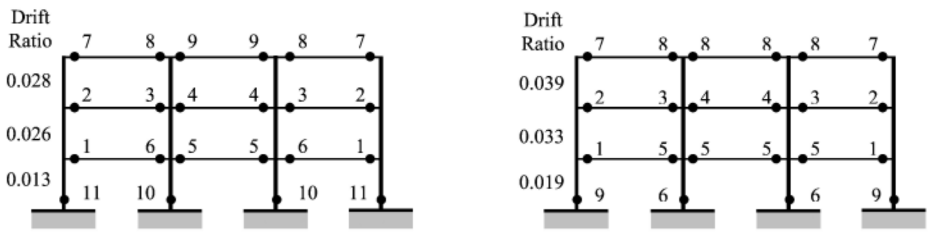
Response quantity and level/story		*2000 NEHRP Provisions* Higher modes[1] using T_m		Higher modes using $T_m\sqrt{\mu}$		Nonlinear response-history analysis			
		ELF	RSA	ELF	RSA	Min.	μ	$\mu+1\sigma$	Max.
Story drift (mm.)	3	150	160	166	200	75	157	200	235
	2	178	168	197	170	78	142	190	228
	1	123	109	157	121	47	104	146	195
Max. story shear (kN)	3	1102	1417	1102	1200	957	1318	1546	1647
	2	1413	1434	1413	1434	1510	1845	2101	2434
	1	2731	2342	2731	2122	1939	2217	2418	2738

[1.] ELF=equivalent lateral force procedure; RSA=response-spectrum analysis

Table 16. Summary of key analysis results

	Frame	Example Frame 2			Example Frame 5[2]			Example Frame 6		
	Method[1]	ELF	RSA	NRHA	ELF	RSA	NRHA	ELF	RSA	NRHA
Response quantity	Drift (mm)	156	149	131	118 129 107	126 128 107	88 107 90	160	150	131
	Damper Force (kN)	497	547	477	394 528 1312	795 637 681	495 722 957	359	367	356
	Base Shear (kN)	1846	1664	1917	3052	2116	2592	2166	1927	1937
	Frame	Example Frame 8			Example Frame 9					
	Method	ELF	RSA	NRHA	ELF	RSA	NRHA			
Response quantity	Drift (mm)	147	140	132	178	168	157			
	Damper Force (kN)	718	671	625	Not applicable					
	Base Shear (kN)	2215	2053	2007	2731	2342	2217			

[1.] ELF=equivalent lateral force; RSA=response-spectrum analysis; NRHA=nonlinear response history analysis
[2.] Three sets of results presented for the six-story frame because damper sizes changed every two stories.



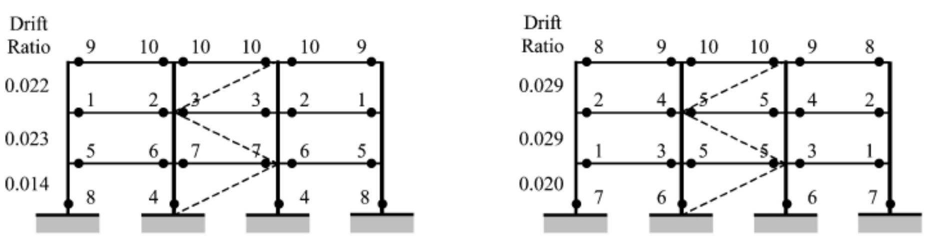
$\Delta_{roof} = 277$ mm; $\theta_p^{max} = 0.0121$ rad; $V_{max} = 3206$ kN

a. DBE responses

$\Delta_{roof} = 378$ mm; $\theta_p^{max} = 0.0191$ rad; $V_{max} = 3335$ kN

a. MCE responses

Figure 4. DBE and MCE response of reference three-story frame.



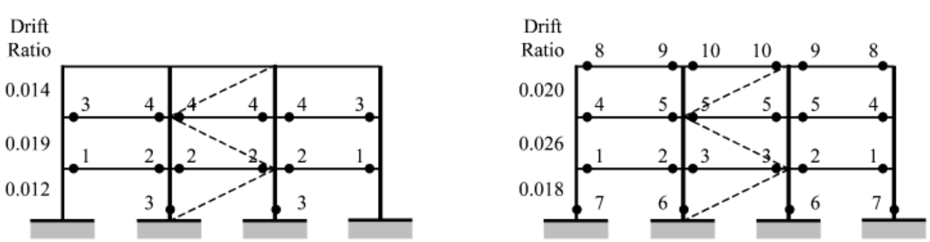
$\Delta_{roof} = 240$ mm; $\theta_p^{max} = 0.0094$ rad; $V_{max} = 1782$ kN

a. DBE responses

$\Delta_{roof} = 312$ mm; $\theta_p^{max} = 0.0156$ rad; $V_{max} = 1964$ kN

a. MCE responses

Figure 5. DBE and MCE response of Frame 3S-75.



$\Delta_{roof} = 183$ mm; $\theta_p^{max} = 0.0078$ rad; $V_{max} = 2272$ kN

a. DBE responses

$\Delta_{roof} = 261$ mm; $\theta_p^{max} = 0.0153$ rad; $V_{max} = 2660$ kN

a. MCE responses

Figure 6. DBE and MCE response of Frame 3S-100.

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REFERENCES

Applied Technology Council (ATC), 1997. *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* and *NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings*, 1997 Edition, Report Nos. *FEMA-273* and *FEMA-274*, prepared for and published by the Federal Emergency Management Agency, Washington, D.C.

Building Seismic Safety Council (BSSC), 1998. *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, 1997 Edition, Part 1—Provisions, Part 2—Commentary, Report Nos. *FEMA-302* and *FEMA-303*, prepared for and published by the Federal Emergency Management Agency, Washington, D.C.

Building Seismic Safety Council (BSSC), 2001. *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, 2000 Edition, Part 1—Provisions, Part 2—Commentary, Report Nos. *FEMA-368* and *FEMA-369*, Federal Emergency Management Agency, Washington, D.C.

Ramirez, O. M., Constantinou, M. C., Kircher, C. A., Whittaker, A. S., Johnson, M. W., Gomez, J. D., and Chrysostomou, C. Z., 2000. *Development and Evaluation of Simplified Procedures for Analysis and Design of Buildings with Passive Energy Dissipation Systems, MCEER Report 00-0010, Revision 1*, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York, Buffalo, NY, 470 pp.

Valles, R. E., Reinhorn, A. M., Kunnath, S. K., Li, C., and Madan, A., 1996. *IDARC2D Version 4.0: A Computer Program for the Inelastic Damage Analysis of Buildings, NCEER Report 96-0010*, National Center for Earthquake Engineering Research, University at Buffalo, State University of New York, Buffalo, NY

Whittaker, A. S., Constantinou, M. C., Ramirez, O. M., and Johnson, M. W., 2003. Equivalent lateral force and modal analysis procedures of the *2000 NEHRP Provisions* for buildings with damping systems, *Earthquake Spectra* **19** (4), 959–980. [this issue]

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