COLLAPSE BEHAVIOR OF STEEL BUILDINGS WITH DEEP COLUMNS UNDER HORIZONTAL AND VERTICAL GROUND MOTIONS

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Abstract

With the use of moment frames at only building perimeter, deep, wide-flange steel columns have been widely used in the U.S. seismic zones since the late 1990s. However, their susceptibility to structural instabilities due to vertical ground motions is not yet well understood. To address this shortcoming, the collapse capacity of a four-story steel moment frame with deep columns under horizontal and vertical ground motions is computationally investigated. The employed finite element models are capable of explicitly capturing the full range of instabilities and major collapse mechanisms. By performing incremental dynamic analysis, the simulation results show that the vertical ground motions can not only change the collapse mechanism, but also decrease the collapse capacity of steel moment frames with deep columns, especially when the vertical progressive collapse is the dominated collapse mechanism. As a result, the vertical ground motions should be considered when frames consist of members vulnerable to global buckling and are susceptible to vertical progressive collapse.

Keywords: deep steel columns; frame collapse simulation; vertical ground motions

1. Introduction

Deep, wide-flange steel columns, with a depth of 600 mm or greater, have been widely used in the U.S. seismic zones since the late 1990s due to the use of perimeter moment frames and stringent seismic requirements developed after the 1994 Northridge earthquake. Although their inelastic behavior under combined axial and lateral loadings as well as their influence on collapse responses of frames have been extensively studied [1, 2, 3, 4], the effect of vertical ground motions was not considered in the previous research. As a result, the susceptibility of deep columns to structural instabilities due to vertical ground motions is not yet well understood.

To address this shortcoming, the collapse capacity of a four-story steel special moment frame with deep columns under horizontal and vertical ground motions is computationally investigated. As-recorded horizontal and vertical components of eleven ground motions selected from FEMA P-695 [5] are scaled together in the incremental dynamic analysis (IDA [6]) to assess the collapse capacity. High-fidelity finite element models that can simulate the full range of instabilities in deep columns are employed to capture major collapse mechanisms, including sidesway collapse and vertical progressive collapse. The simulation results are used to assess the effect of vertical ground motion effect on frame responses with deep columns.

2. Prototype Moment Frame

A four-story steel special moment frame (SMF) that consists of deep columns and reduced beam sections (RBS) made of A992 steel is used as the prototype moment frame in this study. The frame, with a seismic design category (SDC) of D_{max}, was designed using the building configuration in [7] per current design codes [8, 9, 10] with the plan view and elevation view shown in Fig. 1(a) and (b), respectively. The frame was designed to carry the seismic force due to the half of the building mass and tributary gravity loads indicated in Fig. 1(a). The lateral bracing of beam-to-column connections satisfies the requirement in [8], i.e. column flanges are laterally braced at the levels of both the top and bottom beam flanges and at only the level of the top beam flanges when the column-beam moment ratios are smaller and greater than 2.0, respectively. The lateral bracing of beam flanges also satisfies the spacing requirements for highly ductile members in [8].The columns are spliced at the third story. More design details can be found in [7].

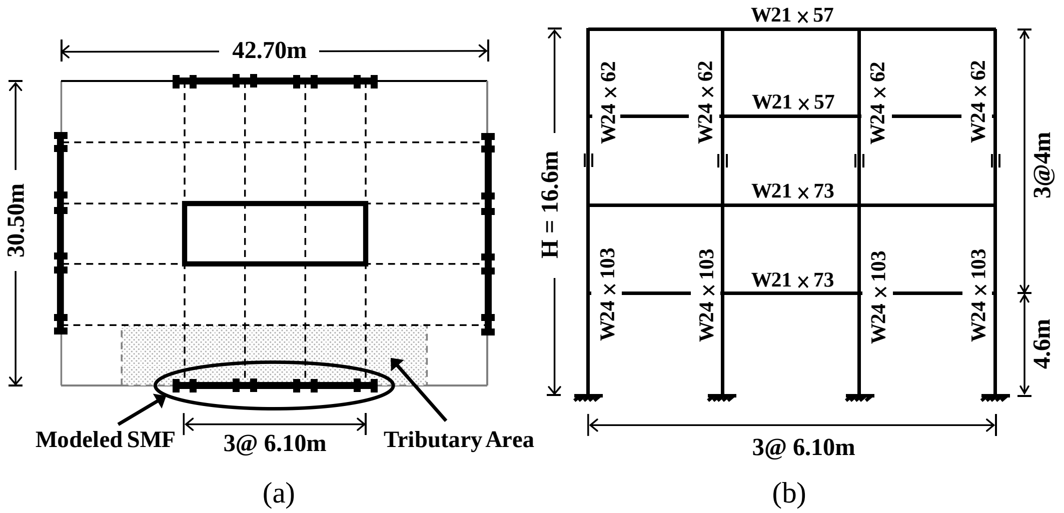


Fig. 1 – (a) Plan view of the four-story building; (b) elevation view of the modeled prototype SMF with member sections listed in English units (in. × lb/ft) [4]

3. Finite Element Modeling

The detailed finite element model of the frame was modeled and analyzed in LS-DYNA [11] using the explicit scheme to obtain the collapse response. The frame model was discretized using fully integrated shell elements and connected to a leaning column to simulate the P-Delta effect due to the gravity loads applied to gravity frames, as shown in Fig. 2. The frame was assumed fully fixed at the base, and the lateral bracing was achieved by restraining out-of-place displacements at key nodes that satisfy the requirements in [8] as described in Section 2. A mass-proportional damping of 2.5% is assumed at the first mode period, and artificial geometric imperfections are not included to avoid favoring pre-determined instability behavior. The horizontal and vertical periods of vibration of the frame are 1.67 s and 0.11 s, respectively. More details about the employed finite element modeling approach, which has been validated in [12], can be found in [4].

To signal sidesway collapse (SC), two criteria are used in this study to reduce the computational effort required in the explicit scheme: (1) story drift ratio exceeds 10% and (2) story drift ratio increases 2% or more during the 10 second window immediately after the time needed for the Arias intensity [13] to reach 95% (i.e. t_{IA}=95%). For vertical progressive collapse (VC), the deformed shape of the frame is combined with the axial force responses of columns to determine the occurrence of instability and loss of axial capacity of columns as well as frame failure, as can be seen in Fig. 3.

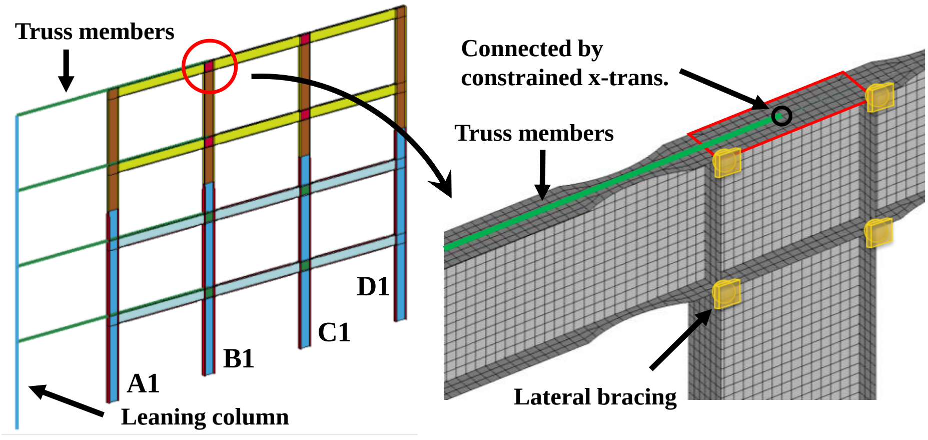


Fig. 2 – Finite element model of (a) the four-story SMF; and (b) beam-to-column connections [4]

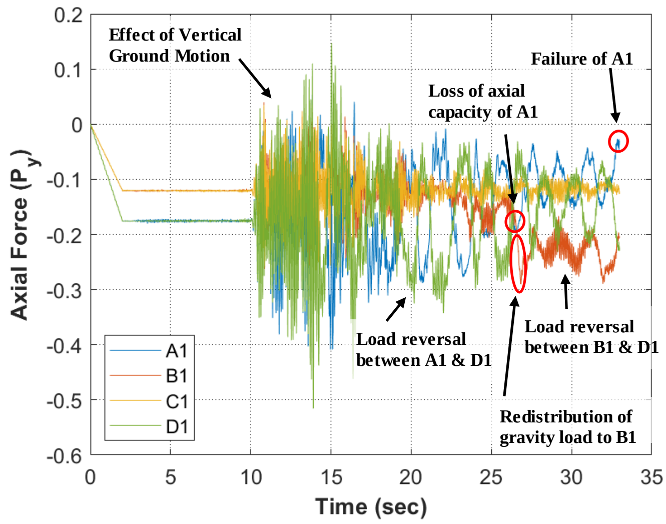


Fig. 3 – Axial force responses of 1st-story columns of studied four-story SMF subject to Duzce/BOL000 and Duzce/BOL-UP components with S_{ah} = 0.80g for Duzce/BOL000

4. Simulation Results

Eleven ground motion records selected from the Far-Field ground motion record set in FEMA P-695 [5] are used in this study to investigate the effect of vertical ground motions on the collapse response of the four-story SMF with deep columns. The considered horizontal and vertical components of each record are listed in Table 1 and scaled up together in the incremental dynamic analysis (IDA) to maintain the as-recorded characteristics. Based on the collapse criteria defined in Section 3, the spectral accelerations with 5% damping ratio at vibration periods of scaled components that induce frame collapse (i.e. $S_{ah,C}$ and $S_{av,C}$), maximum story drift ratio at collapse ($SDR_{max,C}$), and dominated collapse mode for each record are listed in Table 2 for the cases with and without vertical ground motions.

Table 1 – Components of ground motion records used in this study

Record No.	**Event**	**Component**	
		Horizontal	Vertical
1	Northridge, 1994	MUL009	MUL-UP
2	Northridge, 1994	LOS000	LOS-UP
3	Duzce, 1999	BOL000	BOL-UP
4	Hector Mine, 1999	HEC000	HECVER
5	Imperial Valley, 1979	H-DLT262	H-DLTDWN
6	Imperial Valley, 1979	H-E11140	H-E11-UP
7	Kobe, 1995	NIS000	NIS-UP
8	Kobe, 1995	SHI000	SHI-UP
9	Kocaeli, 1999	DZC180	DZC-UP
10	Kocaeli, 1999	ARC000	ARCDWN
11	Landers, 1992	YER270	YER-UP

Table 2 – Collapse assessment parameters of the studied SMF under different components applied

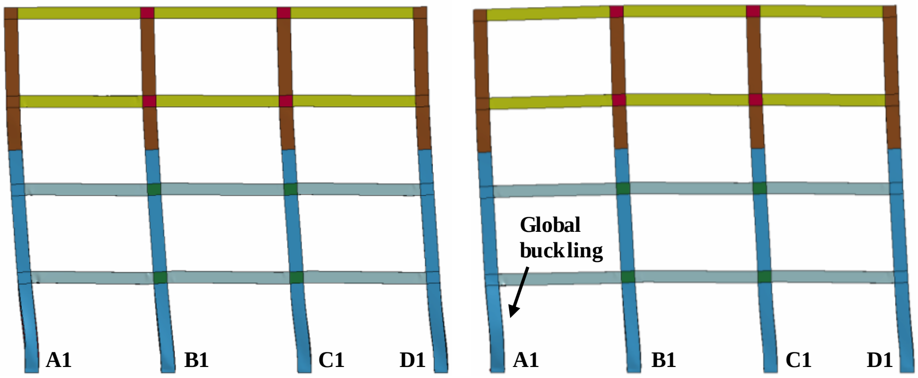
Record No.	**Horizontal Component Only**			**Horizontal + Vertical Components**			
	$S_{ah,C}$ (g)	$SDR_{max,C}$ (%)	Collapse Mode	$S_{ah,C}$ (g)	$S_{av,C}$ (g)	$SDR_{max,C}$ (%)	Collapse Mode
1	1.45	7.9	SC	1.29	1.88	5.3	VC
2	0.78	8.5	SC	0.80	1.64	8.8	SC
3	0.83	4.3	VC	0.80	1.46	4.4	VC
4	0.82	7.8	SC	0.77	1.79	4.8	VC
5	0.57	6.0	VC	0.56	0.85	5.1	VC
6	0.95	8.1	SC	0.96	1.19	7.8	SC
7	0.45	6.7	SC	0.45	1.91	6.8	SC
8	0.36	7.0	SC	0.36	0.32	7.1	SC
9	0.45	10.0	SC	0.47	1.87	10.0	SC
10	0.51	7.8	SC	0.50	1.74	7.2	SC
11	1.03	8.0	SC	1.06	0.89	8.0	SC

Note: SC = sidesway collapse; and VC = vertical progressive collapse.

As can be seen from Table 2, the consideration of vertical ground motion effect does not significantly affect the parameters associated with collapse, $S_{ah,C}$ and $SDR_{max,C}$, for most records except records No. 1, 3, and 4, whose $S_{ah,C}$ are decreased by 4% to 11%. The common ground of these three records is that they all induce vertical progressive collapse when the vertical component is applied. Of particular concern is that, for records No. 1 and No.4, the effect of vertical ground motion is able to change the collapse mode from SC to

VC (see Fig. 4) and greatly reduces frame ductility (i.e. $SDR_{max,C}$) by 35% (see Table 2). As shown in Fig. 4(b), with the vertical component applied, A1 column suffered from severe global buckling and axial shortening at a small drift of 5%. The minor vertical motion effect for record No. 5 is due to the fact that the S_{av} of its vertical component is small.

While the vertical motion effect is negative for records that induce VC, the effect can be slightly positive for records that cause SC with an increase about 3% in $S_{ah,C}$, see records No. 2, 9, and 11 in Table 2. The different effects above can be discerned from the axial force responses in columns, as shown in the Fig. 5. Although the vertical component of the record No. 2 (Fig. 5b) caused a higher axial force in the exterior column, the column experienced a much longer high axial force due to the vertical component of the record No. 4 (Fig. 5d). It is suggested that the effect of vertical ground motions is small and can be positive due to column stretches when the duration of high axial force is short. Otherwise, the effect is detrimental and can even change the collapse mode.



(a) (b)

Fig. 4 – Collapse mode of the studied SMF subject to record No. 4. (a) SC when subject to HEC000 with S_{ah} = 0.83g; and (b) VC when subject to HEC000 and HECVER with S_{ah} = 0.77g

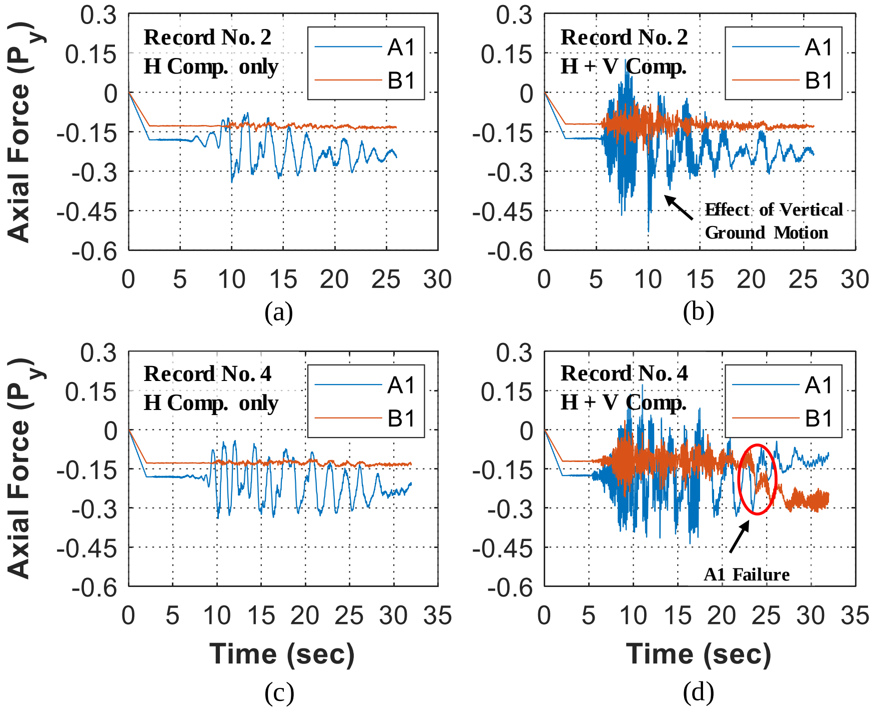


Fig. 5 – Axial force responses of 1st-story exterior (A1) and interior (B1) columns of the studied SMF subject to (a) LOS000 with S_{ah} = 0.79g; (b) LOS000 and LOS-UP with S_{ah} = 0.81g; (c) HEC000 with S_{ah} = 0.83g; and (d) HEC000 and HECVER with S_{ah} = 0.77g

5. Conclusions

The effect of vertical ground motions on the collapse response of a four-story steel SMF with deep columns is investigated using high-fidelity finite element simulations. Eleven ground motion records are employed in the incremental dynamic analysis to assess the collapse capacity of the SMF. The simulation results suggest that when the vertical ground motion causes a fluctuation of high axial forces in deep columns for a long duration, the columns may suffer from early global buckling, resulting vertical progressive collapse and great reduction in frame ductility. On the other hand, the influence of a short duration of such fluctuation on the frame collapse capacity is small and even positive due to column stretches. As a result, the effect of vertical ground motions should be considered for structures with members vulnerable to global buckling.

Above findings are obtained from the specific frame with limited number of simulations and modeling assumptions. More ground motion records and frame configurations are needed to generalize the findings. The author is also currently working on evaluating the collapse behavior of space frames with deep columns to fully consider the effect of vertical motions and out-of-plane displacements on stability of deep columns.

6. Acknowledgements

This work was supported by the National Taiwan University and Taiwan Ministry of Science and Technology grant number 109-2222-E-002-001-MY2. Any opinions, findings, conclusions, and recommendations expressed in this paper are those of the author and do not necessarily reflect the views of the sponsor.

7. References

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