COLLAPSE SIMULATIONS FOR STEEL STRUCTURES CONSISTING OF SEISMIC AND GRAVITY FRAMES USING FEM MACRO MODELS

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Abstract

Building structures around the world have been designed using various framing methods. In Japan, two-way steel moment frame structure, which is designed as a 3D seismic frame with beams connected to biaxial columns, with moment connections in both directions, is traditionally constructed. In contrast, in the United States and many other countries in high seismic regions, one-way steel moment frame structure, which is designed as independent seismic and gravity frame structure with only a few expensive moment connections in seismic frames, is typically constructed. Structures with these different framing systems are likely to exhibit different seismic response and collapse mechanism when subjected to large earthquake excitation.

In the previous study [1], the adequacy of modeling entire steel moment-resisting frame structures with beam and shell elements is evaluate and seismic analyses are conducted for the 3-story Japanese and U.S.-type steel frame structures. Also, in the precious study [2], the incremental dynamic analyses (IDA) are conduced to evaluate the collapse mechanism and safety margin to complete collapse for these two types of framing systems. It is observed that the 3-story U.S.-type steel frame structure collapses with the initiation of the failure at gravity columns.

In this study, the U.S.-type 3-story and 9-story steel moment-frame structures are analyzed for the NF17/18(45°) ground motions. The maximum SDAs are 5.75% in X-direction and 4.01% in Y-direction in the 3-story structure and the maximum SDAs are 3.60% in X-direction and 4.18% in Y-direction in the 9-story structure. Beams in the seismic frames and gravity columns yield. If gravity columns remain elastic, the continuous column effects [e.g. 3, 4], in which the drift concentration is mitigated by the flexural stiffness of the continuous columns, can be expected. However, if gravity columns yield due to bending moment and axial force, such continuous column effects may not be expected.

The intensity of input ground motions is increased to identify the collapse mechanism including the gravity frames. The U.S.-type 3-story and 9-story steel moment-frame structures are analyzed for the scaled NF17/18(45°) ground motions. It is observed that gravity columns in the 1st-story start to deform locally like buckling in the 3-story structure when subjected to the 1.4 times scaled NF17/18(45°). The maximum SDAs are 7.01% in X-direction and 5.98% in Y-direction. As the intensity of the ground motions, the number of gravity columns which deform locally increases. The 3-story structure collapses with the initiation of the collapse of gravity frames for the 1.7 times scaled NF17/18(45°). The 9-story structure does not collapse for the 1.4 times scaled NF17/18(45°) and the maximum SDAs are 4.56% in the X-direction and 8.13% in the Y-direction. The 1st-story columns in the seismic frames yield at both ends forming a soft-story mechanism. The 9-story structure collapses in the 1st-story for the 1.5 times scaled NF17/18(45°). The seismic frames and gravity frames collapse in the 1st-story almost simultaneously and in a similar manner.

Keywords: Steel moment frame structure; Seismic response; Collapse simulation; Gravity frames

1. Introduction

Typical steel moment-resisting frame structure in Japan is designed so that almost all frames resist vertical and horizontal loading simultaneously connecting all column to beams with rigid connections as shown in Fig. 1. Since columns are subjected to biaxial bending, hollow-square section members are often used for columns. In contrast, typical steel moment-resisting frame structure in the United States and many other countries in seismic regions consists of seismic and gravity frames as shown in Fig. 2. Here, in seismic frames, beams are connected to columns with rigid connections, and in gravity frames, beams are connected to columns with bolts at the web, often modeled by pin connection in practical design.
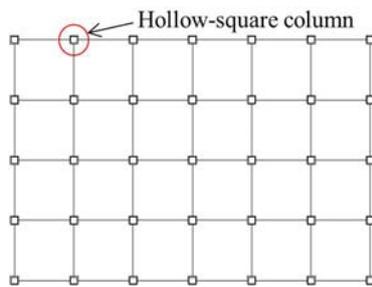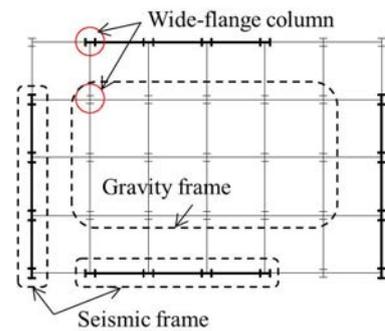

[Beam-column joint]

Fig. 1 Japanese steel structure

Fig. 2 U.S.-type steel structure

MacRae and Mattheis [5], MacRae and Tagawa [6] conducted 3D frame analysis for U.S. and Japanese type steel frame structures. These studies suggested that these different framing systems may exhibit different collapse mechanism. Particularly, Japanese type steel structure may exhibit soft-story mechanism due to biaxial yielding of columns when subjected to severe earthquake [6]. Hasegawa et al. [7] and Kimura [8] conducted 2D frame analysis for Japanese and U.S. type steel frame structures. Tagawa, MacRae and Lowes [9] conducted reliability analysis on U.S. and Japanese type 3-story steel moment-frame structures utilizing simplified models of these structures, which were preferable for conducting reliability evaluation based on many numerical analyses. However, the models used for these previous analyses were relatively simple, utilizing fiber beam-column element and rotational spring to consider plastic hinge. Moreover, floor slab is not modeled. Also, since conventional structural analysis programs, which take the geometric nonlinearity, often referred to as P-Δ effect, assuming small deformation into account, were used, complete collapse behavior was not simulated.

Recently, due to significant advancement on computational capacity and efficiency, detailed analyses modeling almost all parts of a structure with solid elements to simulate damage and collapse behavior more accurately are conducted [10, 11]. However, computational cost is still expensive modeling with solid elements and may not be suitable for reliability analysis based on many simulations at this moment.

In this study, seismic simulation up to complete collapse is conducted for 3-story and 9-story U.S.-type steel moment-resisting frame structures using macro modeling approach using beam and shell elements, which can consider the composite effects of floor slab explicitly.

2. Modeling, Analysis Method and Ground Motion

In this study, a practical model utilizing beam and shell elements is used for collapse simulation. Shell elements are intended to consider composite effect of beam and shell. General-purpose finite element analysis programs, LS-DYNA [12], are used to conduct nonlinear quasi-static analyses and dynamic time-history analyses with implicit solver option. Geometric nonlinearity is computed using the updated Lagrangian method.

2.1 Beam and Shell Elements

The Hughes-Liu beam element with cross section integration model is used for beam element. The Hughes-Liu beam element is based on a degeneration of the isotropic 8-node solid element [12, 13]. The section division number k is set to 10 for the wide-flange section. Belytschko-Lin-Tsay element [12, 14], which is based on a combined co-rotational and velocity-strain formulation [12, 14], is used for floor slab.

2.2 Modeling of Composite Effect of Floor Slab

Axis line of a girder is located under the centerline of floor slab in steel moment-frame structures as shown in Fig. 3 and then strength and stiffness increase due to the presence of a slab [e.g. 15, 16]. Beam element for a girder is placed under shell element for floor slab and the multiple-point constraint (MPC) condition is applied to connect the nodes of the girder and slab as shown in Fig. 4. The MPC condition keeps the distance between two nodes always constant assuming the plane remaining after deformation. This modeling can consider the composite effects by floor slab such as increase of stiffness and strength explicitly [1].
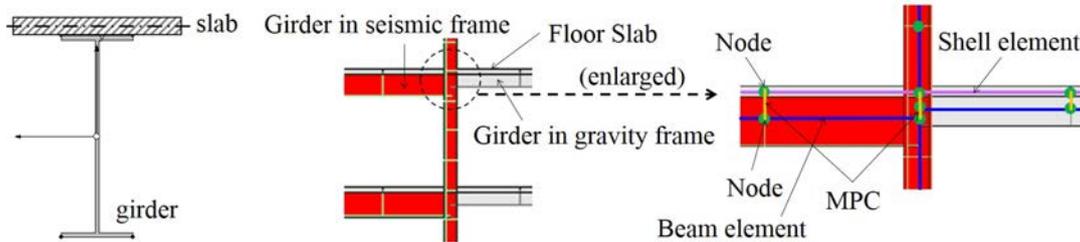

Fig. 3 – Girder under slab   Fig. 4 – Modeling with shell and MPC to consider composite effect

2.3 Analyzed Structures

Analysis models with the number of nodes and elements for the U.S.-type 3-story and 9-story steel moment-frame structures are shown in Fig. 5. The pre-Northridge 3-story and 9-story steel moment-frame structures designed in the SAC steel project [17] are used as a reference. Some minor modifications are made from the original SAC structures, such that the original 9-story structure has an underground story whereas that story is omitted in the model used in this study. Lists of member size are given in Table 1. Wide-flange section columns and beams are used. Each beam element for columns and girders is divided in 8 and each edge of floor slab is divided in 8 according to the division of adjacent girders. Pin connections between beams and columns in gravity frames are modeled by providing the moment release condition at beam ends.

The elastic modulus is 205 kN/mm^2 is for steel and 11.25 kN/mm^2 for concrete. The density is $7.85 \cdot 10^3$ kg/m^3 for steel and $2.4 \cdot 10^3$ kg/m^3 for concrete. The thickness of floor slab is 150 mm. To consider the dead load (96 psf = 4596 N/m^2) and live load (20 psf = 958 N/m^2), the density of concrete is increased by 1.572 times. Yield stress of steel columns and beams is set to 345 N/mm^2 and 248 N/mm^2, respectively. The Mises yield surface and combined isotropic and kinematic hardening model is applied to steel constitutive law. The hardening parameter is set to 0.3 (0: kinematic, 1.0: isotropic hardening) and the post-yield tangent stiffness ratio is set to 0.03. Rayleigh damping ratio of 2% at the 1st-mode natural period and at T=0.2 sec [17] is used.

3-story
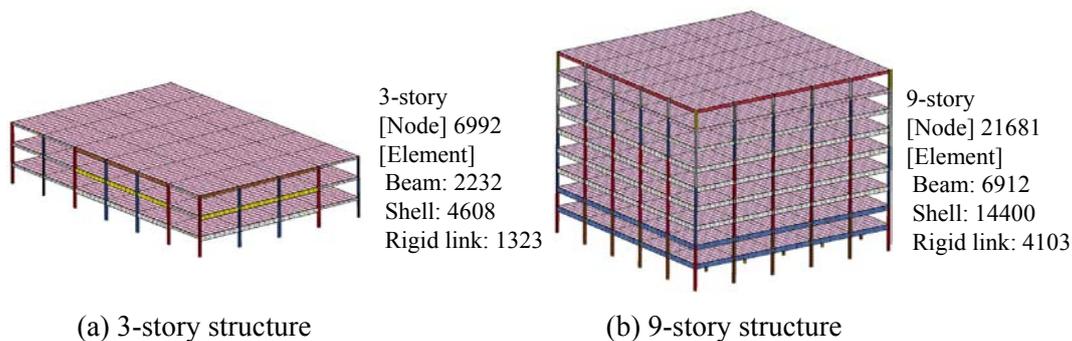[Node] 6992
[Element]
 Beam: 2232
 Shell: 4608
 Rigid link: 1323

9-story
[Node] 21681
[Element]
 Beam: 6912
 Shell: 14400
 Rigid link: 4103

(a) 3-story structure   (b) 9-story structure

Fig. 5 – Analysis models

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Table 1 Member lists

(a) 3-story structure

[Seismic frame]

	Column		Beam
	exterior	interior	
3/roof			W24x68
2/3	W14x257	W14x311	W30x116
1/2			W33x118

[Gravity frame]
Column: W14x68
Beam: W18x35 (except roof), W16x26(roof)

(b) 9-story structure

[Seismic frame]

	Column		Beam
	exterior	interior	
9/roof	W14x233	W14x257	W24x68
8/9	W14x257	W14x283	W27x84
7/8	W14x257	W14x283	W30x99
6/7	W14x283	W14x370	W36x135
5/6	W14x283	W14x370	W36x135
4/5	W14x370	W14x455	W36x135
3/4	W14x370	W14x455	W36x135
2/3	W14x370	W14x500	W36x160
1/2	W14x370	W14x500	W36x160

[Gravity frame]

	Column		Beam
	Below penthouse	Others	
9/roof	W14x61	W14x48	W16x26
8/9	W14x90	W14x82	W18x35
7/8	W14x90	W14x82	W18x35
6/7	W14x120	W14x109	W18x35
5/6	W14x120	W14x109	W18x35
4/5	W14x159	W14x145	W18x35
3/4	W14x159	W14x145	W18x35
2/3	W14x211	W14x193	W18x35
1/2	W14x211	W14x193	W18x35

2.4 Ground Motions

The X-directional and Y-directional accelerations of the ground motions used are plotted in Fig. 6. These are originally from the NF17 and NF18 ground motions [18], which were used for the SAC steel project, and modified so that the attacking angle [5, 6] relative to the X- and Y-direction of the structures is 45 degrees. The set of these ground motions is referred to as NF17/18(45°). Displacement and acceleration response spectra of NF17/18(45°) in the X- and Y-directions are shown in Fig. 7.
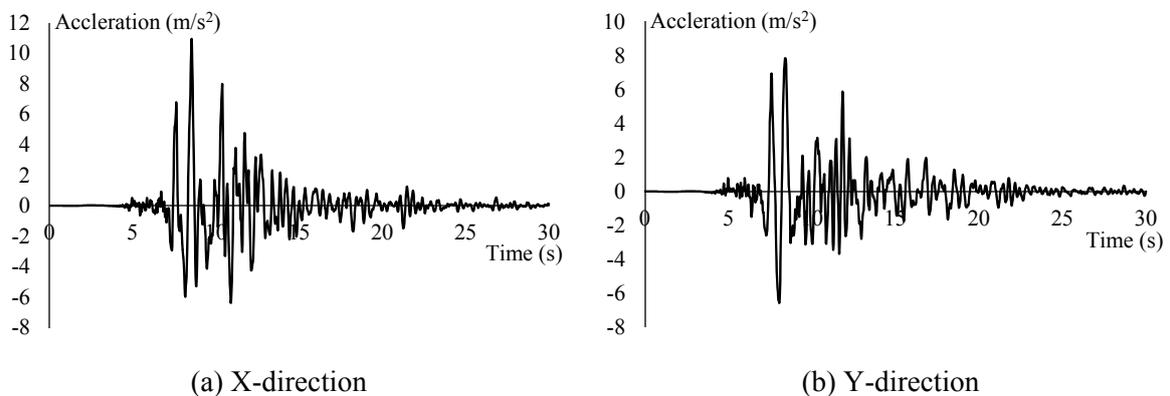

(a) X-direction

(b) Y-direction

Fig. 6 – Ground motions (NF17/18(45°))
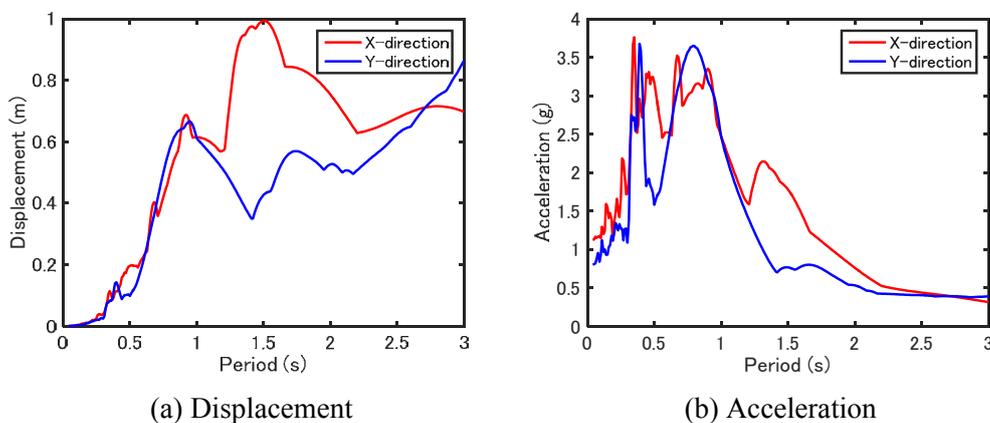

(a) Displacement

(b) Acceleration

Fig. 7 – Response spectra (NF17/18(45°))

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3. Eigenvalue Analysis

Eigenvalue analyses are conducted for the 3-story and 9-story steel moment-frame structures. For reference, the analysis is conducted for the models in which beam element for a girder is placed at the same level to shell elements for floor slab. The 1st, 2nd and 3rd-mode natural periods are given in Table 2. The 1st-mode shape of the 3-story structure is shown in Fig. 8. The 1st-mode shape is translational. The mode shapes of the seismic frame and the gravity frame are also shown. Seismic columns are fixed at the base whereas the gravity column is simply supported, which provides different mode shapes. The 1st and 3rd-mode shapes for the 9-story steel moment-frame structure are shown in Fig. 9. The 1st-mode is translational and the 3rd-mode shape is torsional. Mode shapes of the seismic and gravity frames are different due to the rigid or pin connections between the columns and beams and the rigid or simply-supported conditions at the base.

As shown in Table 2, for the 3-story structure, the 1st natural period is shortened from 1.043 sec to 0.930 sec when shifting beam element for a girder under shell element for floor slab in modeling. This means that the 1st-mode stiffness increases by $(1.043/0.930)^2=1.258$ times due to the composite effect by floor slab, considering both models have the same amount of mass. Similarly, for the 9-story structure, the 1st-mode natural period is shortened from 2.370 sec to 2.100 sec, which means that the 1st-mode stiffness increases by $(2.370/2.100)^2=1.274$ times due to the composite effect by floor slab.

Table 2 – Natural fundamental periods

(a) 3-story structure

	girder placed at same level to slab	girder placed under slab
1st mode	1.043 sec	0.930 sec
2nd mode	1.015 sec	0.877 sec
3rd mode	0.636 sec	0.572 sec

(b) 9-story structure

	girder placed at same level to slab	girder placed under slab
1st mode	2.370 sec	2.100 sec
2nd mode	2.357 sec	2.060 sec
3rd mode	1.455 sec	1.329 sec

(a) Overall   (b) Elevation   (c) Seismic frame   (d) Gravity frame
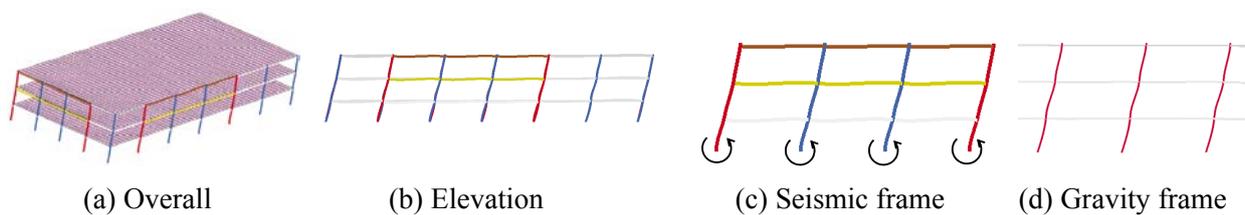
Fig. 8 – Fundamental 1st -mode shapes of 3-story structure

Seismic frame   Gravity frame

(a) 1st-mode (Translational)   (b) 3rd-mode (Torsional)
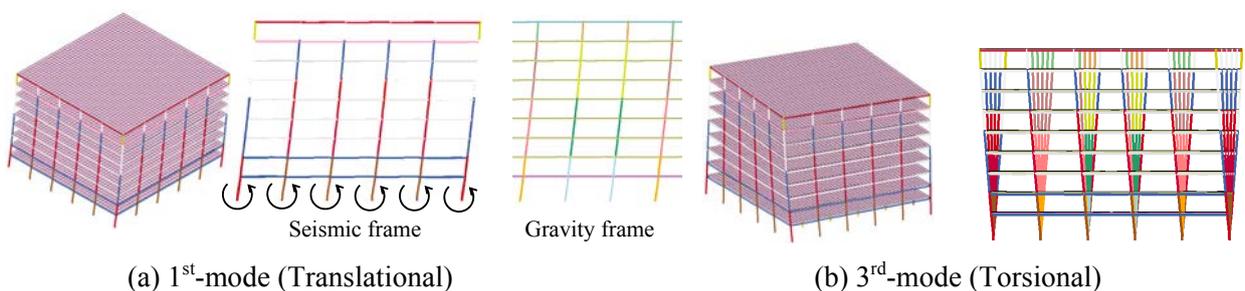
Fig. 9– Fundamental mode shapes of 9-story structure

4. Seismic Response

Seismic analyses are conducted for the U.S.-type 3-story and 9-story steel moment-frame structures. The ground motion input is the NF17/18(45°).

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4.1 3-story Structure

The time-history of the story drift angles (SDA) of the 3-story structure in the X- and Y-directions are shown in Fig. 10. Here, the SDAs are computed based on the averaged values of the displacements at four corners on each floor. The maximum SDAs are 5.75% in X-direction and 4.01% in Y-direction. Both maximum SDAs occur at the 1st-story. The deformation at the maximum SDA in X- and Y-directions is shown in Fig. 11.

Bending moments of the seismic frames at the occurrence of the maximum 1st-SDA in X-direction (*t*=8.94 sec) and in Y-direction (*t*=8.82 sec) are plotted in Fig. 12. Yield moment of the 1st-story seismic beam (W33×118) is 1459 kN·m. Yielding occurs at many beam ends in the seismic frames.

Bending moments of the gravity frames at *t*=8.94 sec are plotted in Fig. 13. Yield moments of the 1st-story gravity column (W14×68) are 582 kN·m in a strong axis and 137 kN·m in a weak axis. The gravity columns yield around the beam-column joints in both strong and weak axes.

The time-history of axial force of the interior and corner gravity columns (W14×68) in the 1st-story is plotted in Fig. 14. The yield axial force, N_y, is 4452 kN. Initially, inner gravity column is subjected to axial force of 1436 kN in compression, which corresponds to the axial force ratio of 0.323, due to dead and live loads. During the ground shaking, the column has the maximum axial force of 1831 kN, which corresponds to the axial force ratio of 0.411. Also, the corner gravity column is subjected to the axial force in tension during the ground shaking.

If gravity columns remain elastic, the continuous column effects, in which the drift concentration in particular stories is mitigated by the flexural stiffness of the continuous columns, can be expected [3, 4]. However, if gravity columns yield due to bending moment and axial force, such continuous column effects may not be expected.
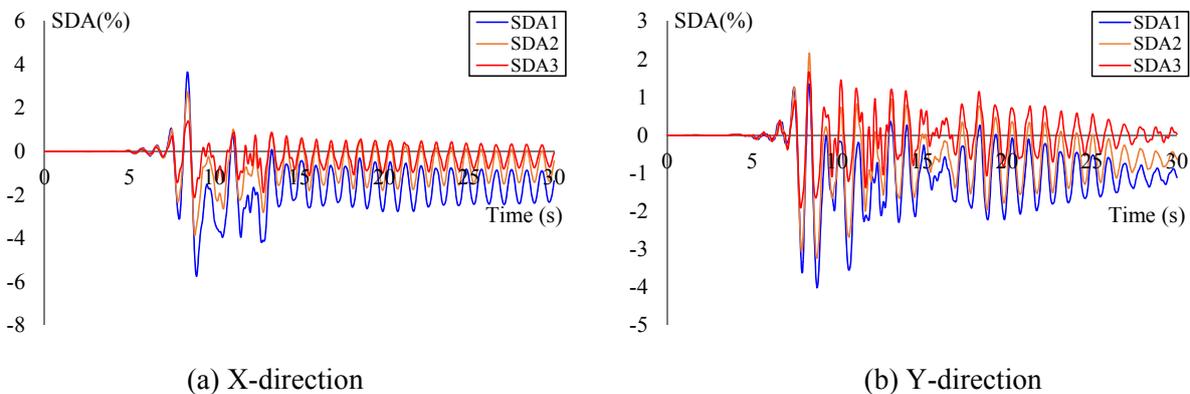

(a) X-direction (b) Y-direction

Fig. 10 – SDA response of 3-story structure for NF17/18(45°)

(a) Deformation in X-direction (*t*=8.94 sec) (b) Deformation in Y-direction (*t*=8.82 sec)

Fig. 11 – Deformation at maximum SDAs

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Slabs and gravity beams are removed for clarity.

(t=8.94 sec) (t=8.82 sec)

(Unit: kNm)

(a) Overall structure   (b) Seismic frame (X-direction)   (c) Seismic frame (Y-direction)

Fig. 12 – Bending moments in seismic frames for NF17/18(45°)

Gravity frames
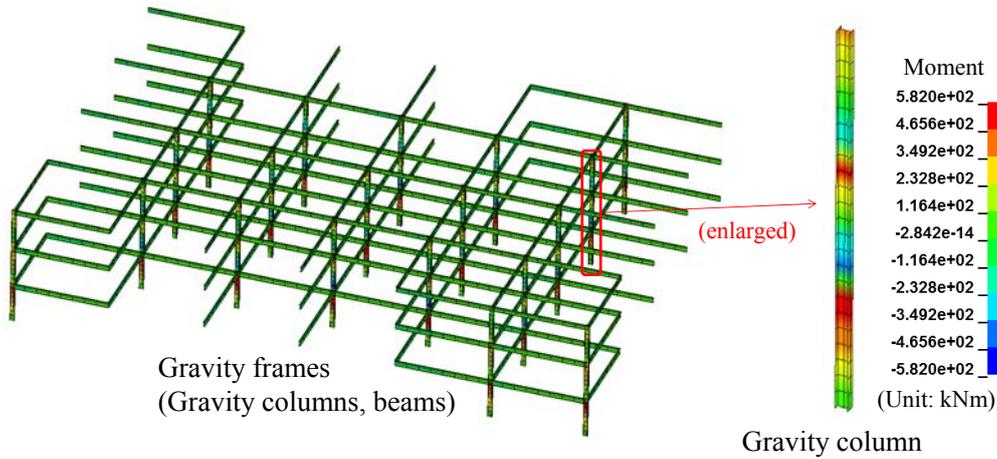(Gravity columns, beams)

(enlarged)

(Unit: kNm)
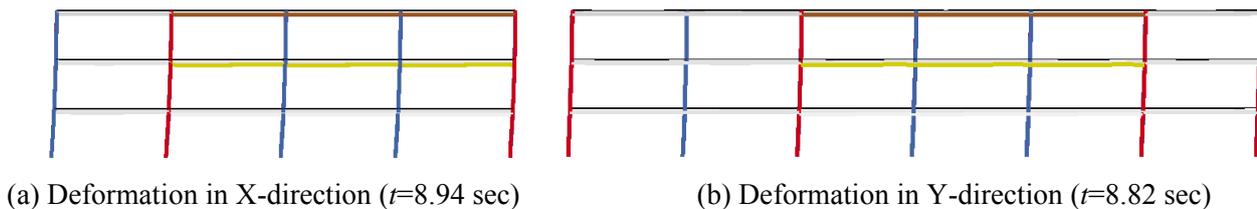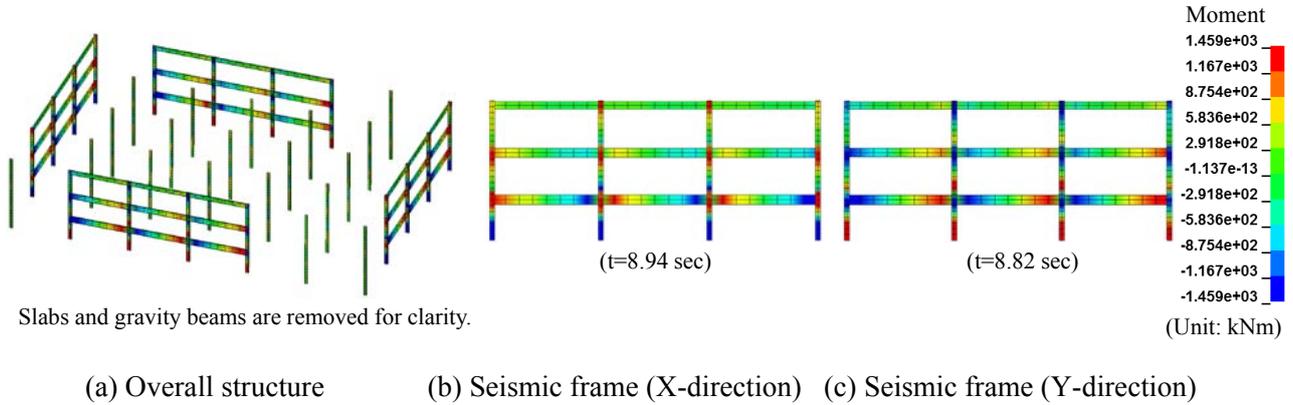
Gravity column

Fig. 13 – Bending moments in gravity frames for NF17/18(45°)
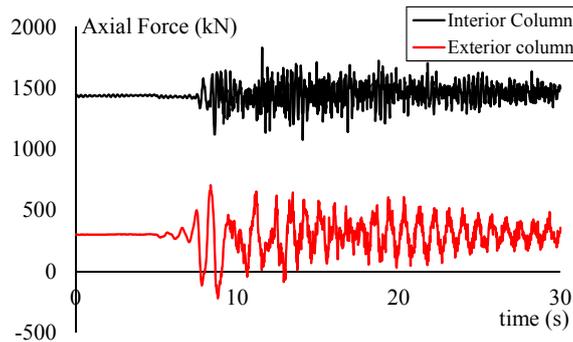
Fig. 14 – Axial force response of gravity interior and exterior columns for NF17/18(45°)

4.2 9-story Structure

The time-history of the SDAs of the 9-story structure in the X- and Y-directions are shown in Fig. 15. The maximum SDAs are 3.60% in X-direction and 4.18% in Y-direction. The maximum SDA in the X-direction occur at the 7th-story and the maximum SDA in the Y-direction occur at the 1st-story. The deformation at the maximum SDAs in X- and Y-directions is shown in Fig. 16.

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Bending moments of the seismic frames at the occurrence of the maximum 1st-SDA in X-direction (t=9.15 sec) and in Y-direction (t=8.75 sec) are plotted in Fig. 17. Yield moment of the 1st-story seismic beam (W36×160) is 2203 kN·m. It is found that yielding occurs at many beam ends in the seismic frames.

Bending moments of the gravity frames at t=8.75 sec are plotted in Fig. 18. Yield moments of the 1st-story gravity column (W14×211) are 1911 kN·m in a strong axis and 735 kN·m in a weak axis. The gravity columns yield around the beam-column joints in a weak axis.

The time-history of axial forces in the 1st-story gravity column under the penthouse (W14×211) is plotted in Fig. 19. The yield axial force, N_y, is 13800 kN. Initially, inner gravity column is subjected to axial force of 4388 kN in compression, which corresponds to the axial force ratio of 0.318, due to the dead and live loads. During the ground shaking, the column has the maximum axial force of 5461 kN, which corresponds to the axial force ratio of 0.396.
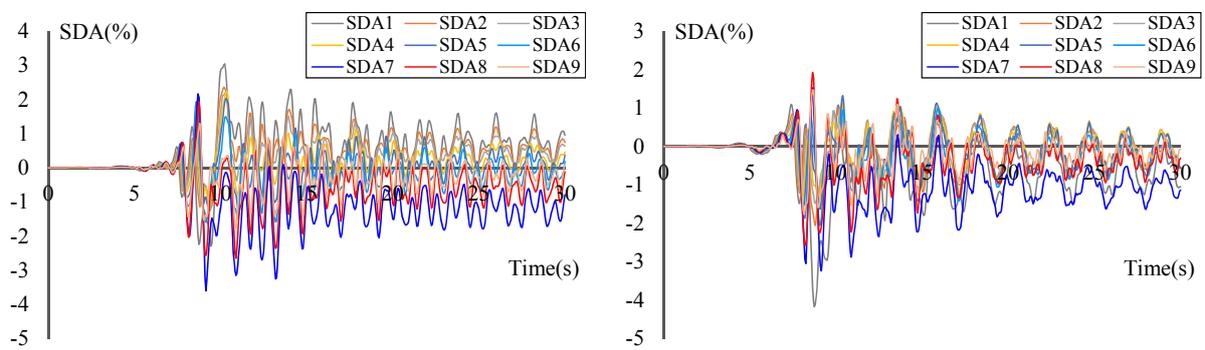
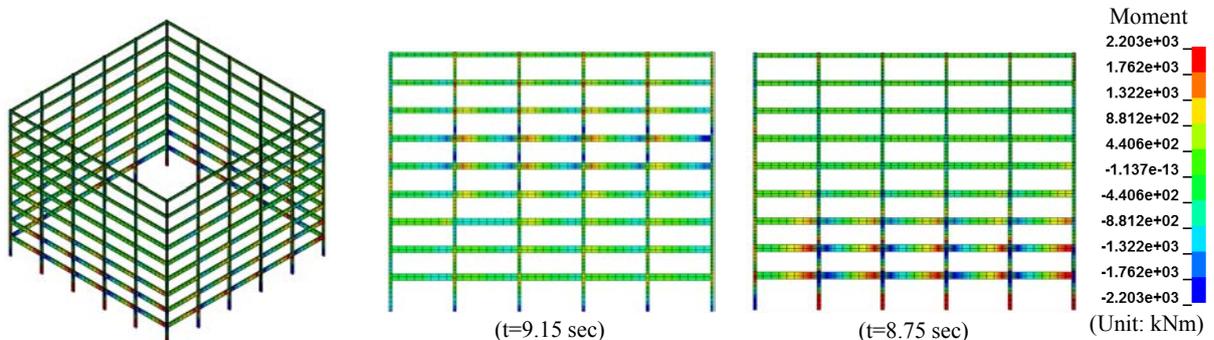

(a) X-direction

(b) Y-direction

Fig. 15 – SDA response of 9-story structure for NF17/18(45°)
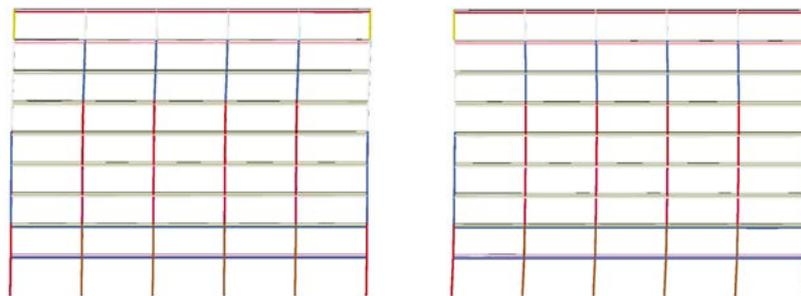
(a) Deformation in X-direction (t=9.15 sec)

(b) Deformation in Y-direction (t=8.75 sec)

Fig. 16 – Deformation at maximum SDA

Slabs and gravity frames are removed for clarity.

(a) Overall structure   (b) Seismic frame (X-direction)   (c) Seismic frame (Y-direction)

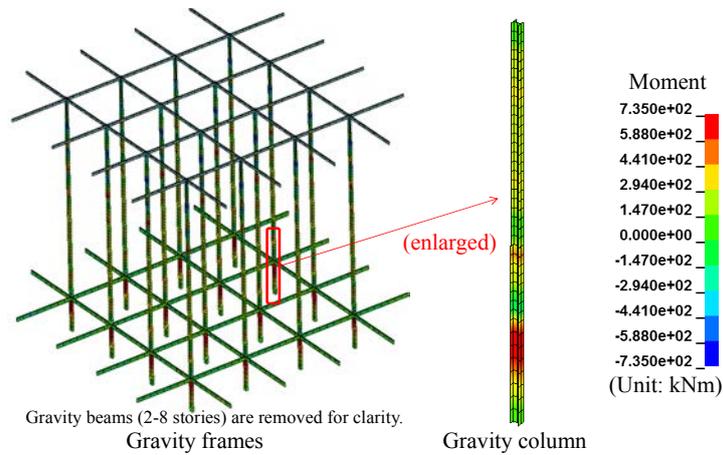Fig. 17 – Bending moments in seismic frames for NF17/18(45°)

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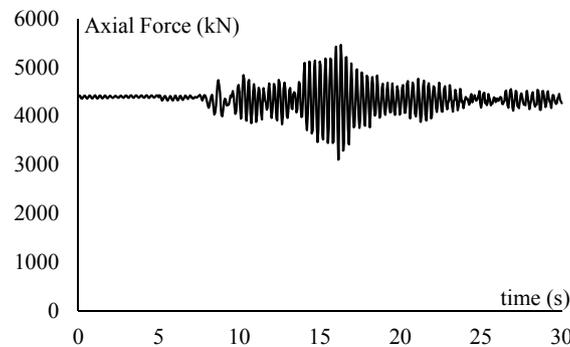Fig. 18 – Bending moment in gravity frames for NF17/18(45°)

Fig. 19 – Axial force response of gravity column under penthouse for NF17/18(45°)

5. Collapse Mechanism

The intensity of input ground motions is gradually increased to identify the collapse mechanism. Scaled NF17/18(45°) are used for the dynamic time-history analyses of the U.S.-type 3-story and 9-story structures.

5.1 3-story Structure

The time-history of the SDAs of the 3-story structure in the X- and Y-directions for the 1.4 times scaled NF17/18(45°) are shown in Fig. 20. The maximum SDAs are 7.01% in X-direction and 5.98% in Y-direction. The deformation at the occurrence of the maximum 1st-SDA in X-direction (t=10.52 sec) and at t=30.0 sec is shown in Fig. 21. It is shown that two gravity columns in the 1st-story deform locally like buckling.
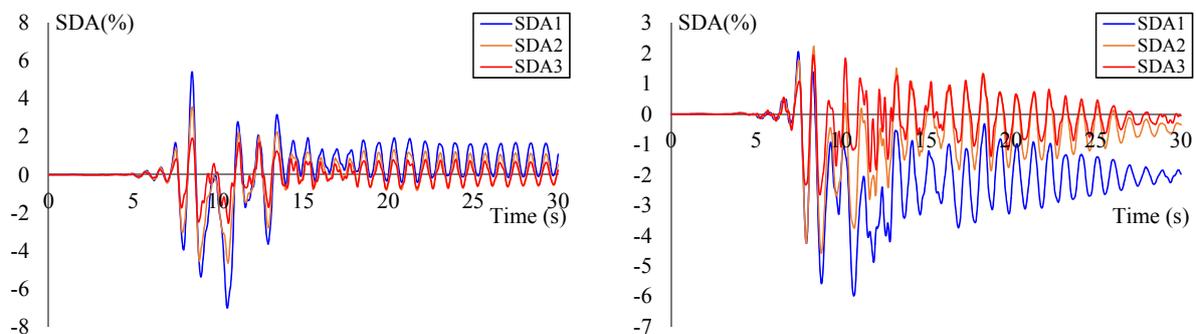
(a) X-direction

(b) Y-direction

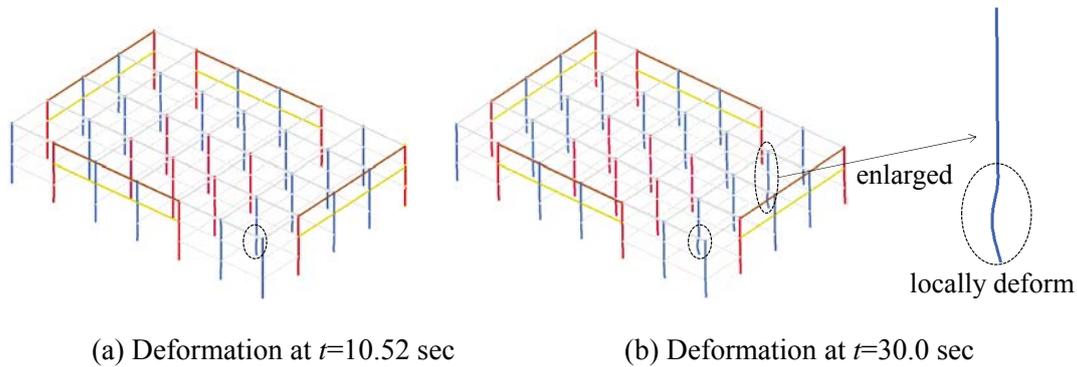Fig. 20 – SDA response of 3-story structure for 1.4 times scaled NF17/18(45°)

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(a) Deformation at *t*=10.52 sec   (b) Deformation at *t*=30.0 sec

Fig. 21 – Failure of gravity columns for 1.4 times scaled NF17/18(45°)

The deformation for the 1.5 times and 1.6 times scaled NF17/18(45°) is shown in Fig. 22. It is shown that as the intensity of the ground motions increases, the number of gravity columns which deforms locally like buckling increases.
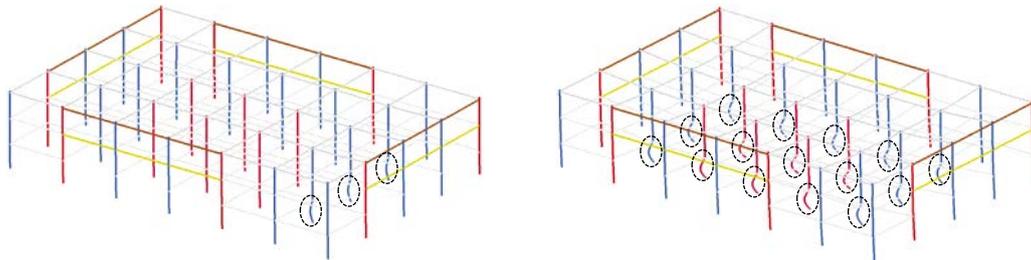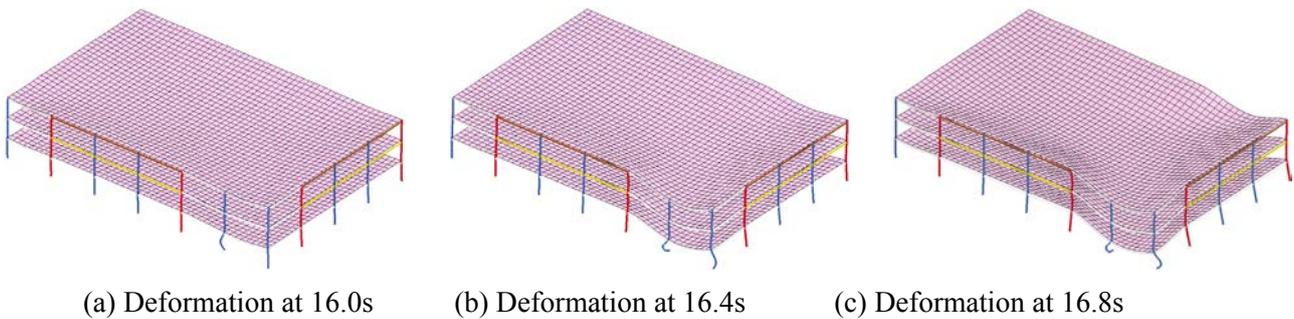

(a) Deformation for 1.5 times scaled NF17/18(45°)   (b) Deformation for 1.6 times scaled NF17/18(45°)

Fig. 22 – Failure of gravity columns scaled NF17/18(45°)

Finally, overall structure collapses for the 1.7 times scaled NF17/18(45°) as shown in Fig. 23. It is shown that overall structural collapse initiates at the gravity frames although the seismic frames do not collapse.

(a) Deformation at 16.0s   (b) Deformation at 16.4s   (c) Deformation at 16.8s

Fig. 23 – Structural collapse for 1.7 times scaled NF17/18(45°)

5.2 9-story Structure

The 9-story structure does not collapse for the 1.4 times scaled NF17/18(45°). However, the maximum SDAs are significantly large, 4.56% in the X-direction and 8.13% in the Y-direction. Both maximum SDAs occur at the 1st-story. Seismic columns in the 1st-story yield at the top and bottom. Also, pin-supported gravity columns in the 1st-story yield at the top. Therefore, a soft-story mechanism forms in the 1st-story.

The 9-story structure collapses for the 1.5 times scaled NF17/18(45°). The deformation during the structural collapse is shown in Fig. 24. The above illustrates the deformation including the slabs and the below removes the slabs to show the deformation of columns and beams clearly. The deformation of the seismic and gravity frames during the structural collapse is shown in Fig. 25. Here, the seismic frames and gravity frames collapse in the 1st-story almost simultaneously and in a similar manner.
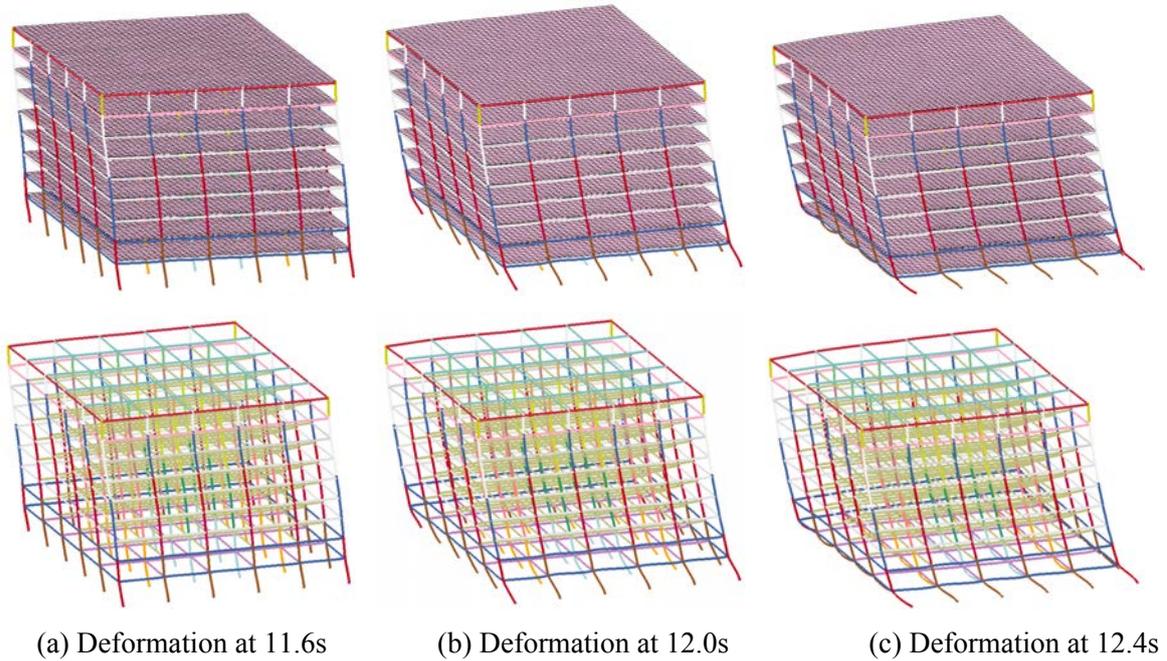
10

| (a) Deformation at 11.6s | (b) Deformation at 12.0s | (c) Deformation at 12.4s |

Fig. 24 – Collapse for 1.5 times scaled NF17/18(45°)

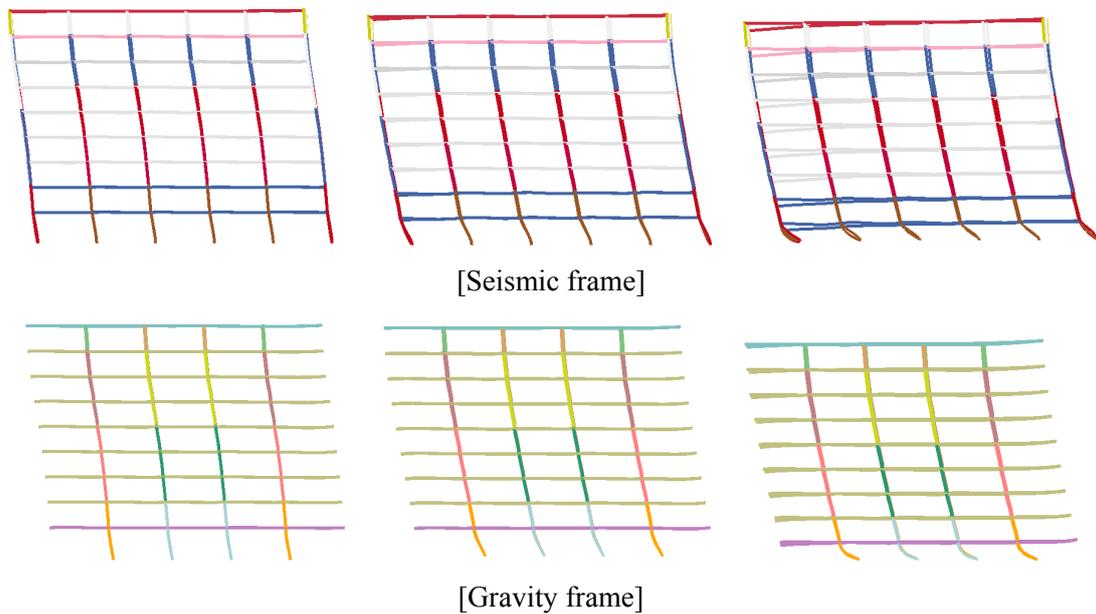[Seismic frame]

[Gravity frame]

Fig. 25– Collapse for 1.5 times scaled NF17/18(45°)

6. Conclusions

The U.S.-type 3-story and 9-story steel moment-frame structures are analyzed using practical macro modeling using beam and shell elements to consider composite effect of floor slab. The intensity of the input ground motions is increased to identify the collapse mechanism of the structures. The 3-story structure collapses with the initiation of the collapse of gravity frames for the 1.7 times scaled NF17/18(45°). The 9-story structure collapses in the 1st-story with almost simultaneous collapse of seismic frames and gravity frames forming a soft-story mechanism for the 1.5 times scaled NF17/18(45°).

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