SEISMIC SIMULATION OF JAPANESE AND U.S. TYPE STEEL MOMENT-RESISTING FRAME STRUCTURES: MACRO-MODELING WITH BEAM AND SHELL ELEMENTS

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Introduction

Typical steel moment-resisting frame structures in Japan are designed so that almost all frames resist vertical and horizontal loading simultaneously, connecting all columns to beams with rigid connections as shown in Figure 1(a). Since columns are subjected to biaxial bending, hollow-square section members are often used for columns. In contrast, typical steel moment-resisting frame structures in the United States and many other countries in seismic regions consist of seismic and gravity frames as shown in Figure 1(b). 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 connections in practical designs.

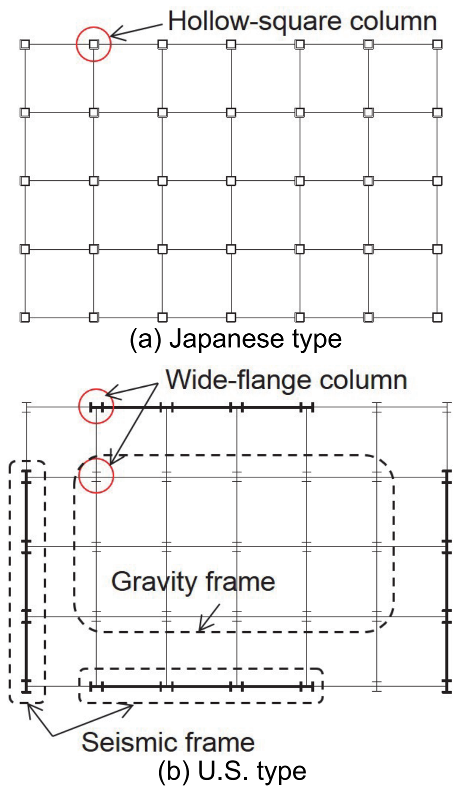


Fig. 1: Steel moment-resisting frame structures (plan)

MacRae and Mattheis [1], and MacRae and Tagawa [2] conducted 3D frame analysis for U.S. and Japanese type steel frame structures. These studies suggested that the different framing systems may exhibit different collapse mechanisms. Particularly, Japanese type steel structures may exhibit soft-story mechanisms due to biaxial yielding of columns when subjected to a severe earthquake [2]. Hasegawa et al. [3] and Kimura [4] conducted 2D frame analysis for Japanese and U.S. type steel frame structures. However, in these previous analyses, floor slabs were not modeled. Moreover, conventional structural analysis programs that account for geometric nonlinearity, often referred to as P-Δ effect in structural engineering, assuming small deformation were used, thereby signifying that complete collapse behavior was not simulated. In this study, seismic simulation was conducted for Japanese and U.S. type moment-resisting frame structures using a general-purpose finite element analysis program. In this paper, a macro-modeling approach using beam elements for columns and girders and shell elements for floor slabs is described; an eigenvalue analysis was conducted to verify the modeling approach.

Modeling Approach using Beam and Shell Elements

Analysis models for Japanese and U.S. type steel moment-resisting frame structures are shown in Figure 2. These are set on the same plane, referred to as the virtual shaking table in this study, and subjected to the same level of ground motion in seismic simulations. A list of member sizes is given in Table 1. In the Japanese type simulation, hollow-square section columns were used. The elastic modulus of steel used was 205 kN/mm^2 and that of concrete used was 11.25 kN/mm^2. The density of steel used was 7.85 ton/m^3 and that of concrete used was 2.4 ton/m^3. The thickness of floor slab was 150 mm. Member and section sizes were derived from the three-story steel moment-resisting frame structure designed in the SAC steel project [5] for the U.S. type and the three-story steel frame structure designed according to Japanese standards by Hasegawa et al. [3] for the Japanese type.

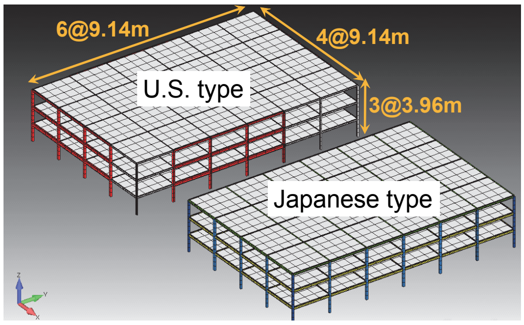


Fig. 2: Analysis models on virtual shaking table

Table 1: List of member sizes

(a) Japanese type

	Column	Beam
3/roof	□-450x16	H-550x200x9x19
2/3	□-450x19	
1/2	□-450x22	H-550x200x12x22

(b) U.S. type

[Seismic frame]

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

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

Each beam element for columns and girders was divided in four, and each edge of floor slab was divided in four, according to the division of the adjacent girders. The number of nodes for the U.S. type was 2300, and the number of elements was 1116 for beam elements and 1152 for shell elements. In the actual building, the axis line of a girder is located under the center line of the floor slab. Therefore, a beam element for a girder was placed under the shell element for the floor slab and the multiple-point constraint (MPC) condition was applied to connect the nodes of the girder and slab as shown in Figure 3. This MPC condition kept the distance between two nodes constant, assuming that the plane remained intact following deformation. This modeling approach was expected to account for composite effects of the floor slab, such as increased stiffness and strength explicitly. The modeling was conducted using FEMAP [6].

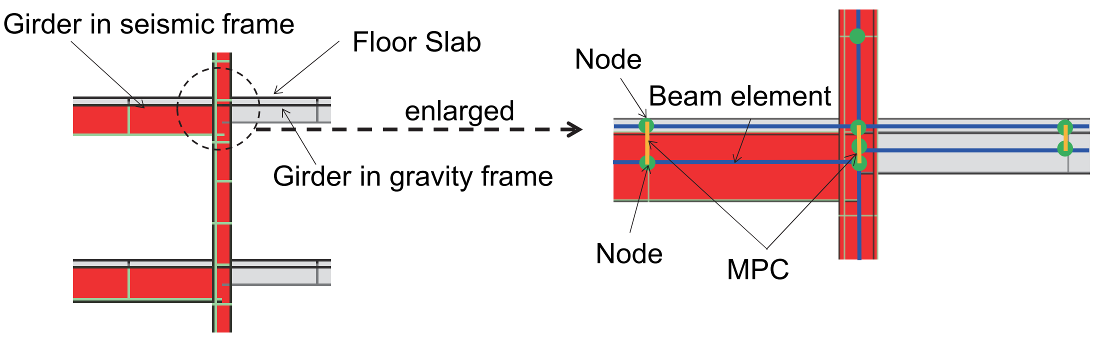


Fig. 3: Multiple-point constraint (MPC) condition between nodes of the slab and girder

Eigenvalue Analysis

Eigenvalue analysis was also conducted for Japanese and U.S. type steel moment-resisting frame structures using NX-Nastran [6]. For reference, the analysis was conducted for the models in which the beam element of a girder was placed at the same level as the shell elements of the floor slab as shown in Figure 4. The 1st, 2nd, and 3rd natural periods are shown in Table 2. The 1st mode shape for the U.S. type is shown in Figure 5. This is a translational mode. The 3rd mode shape is shown in Figure 6. This is a torsional mode.

As shown in Table 2, for the U.S. type structure, the 1st natural period was shortened from 0.769 s to 0.678 s when shifting the beam element of a girder under the shell element of the floor slab in the modeling. This means that the 1st mode stiffness increased by $(0.769/0.678)^2 = 1.286$ times because of the composite effect of the floor slab, considering both models have the same amount of mass. Moreover, the 1st and 2nd natural periods (which correspond to the translational mode) of the U.S. type were larger than those of Japanese type. This is likely because of the smaller number of seismic frames in the U.S. type structure. However, the 3rd natural period, which corresponds to the torsional mode, was smaller than that of the Japanese type. This is likely because of the location of stiff seismic frames at the perimeters of the structure, which is most effective for torsion.

Table 2: Natural fundamental periods

(a) Japanese type

	girder placed at same level to slab	girder placed under slab
1st mode	0.621s	0.524s
2nd mode	0.608s	0.516s
3rd mode	0.533s	0.457s

(b) U.S. type

	girder placed at same level to slab	girder placed under slab
1st mode	0.769s	0.678s
2nd mode	0.748s	0.654s
3rd mode	0.496s	0.443s

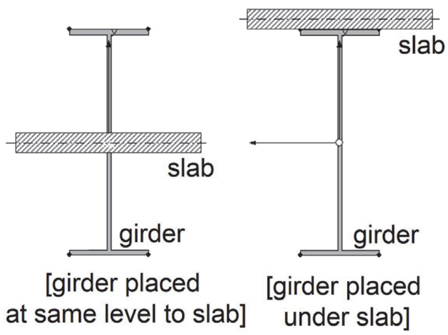
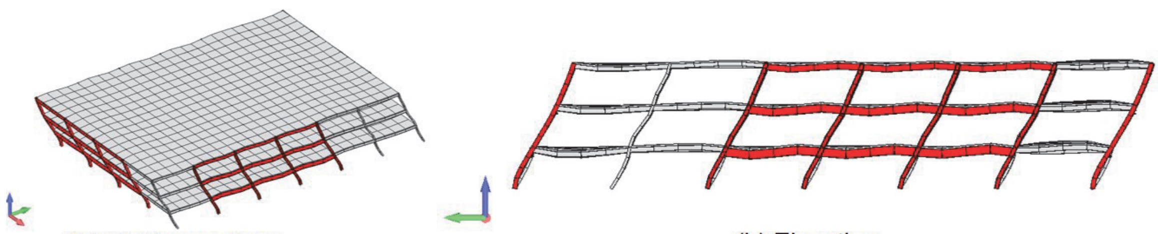
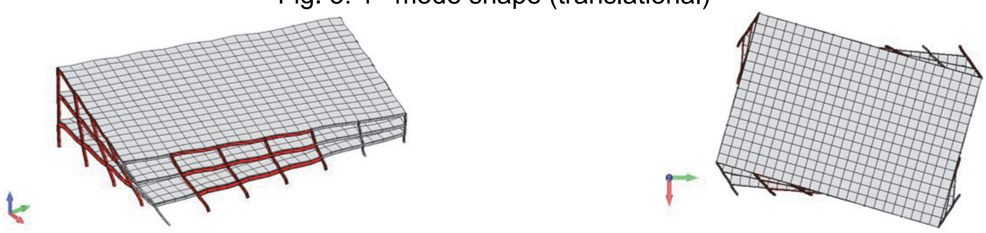


Fig. 4: Location of slab and girder in modeling



(a) Bird's eye view (b) Elevation

Fig. 5: 1st mode shape (translational)



(a) Bird's eye view (b) Plan

Fig. 6: 3rd mode shape (torsional)

Architecture Studio in Mukogawa Women's University

In this study, a framing system consisting of a 3D moment-resisting frame was considered to be the "Japanese type," and one consisting of separate seismic and gravity frames was referred to as the "U.S. type." This is not always true. For example, Architecture Studio at Mukogawa Women's University consists of seismic and gravity elements as shown in Figure 7. Walls decorated with border tiles are of seismic nature, and exposed-concrete wall pillars contain gravity elements as shown in Figure 8.

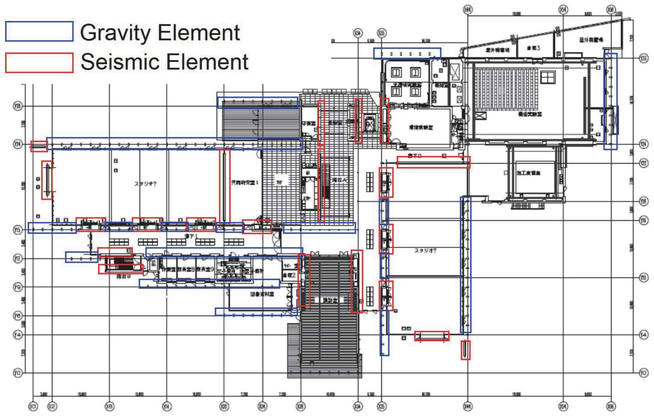


Fig. 7: Architecture Studio in Mukogawa Women's University

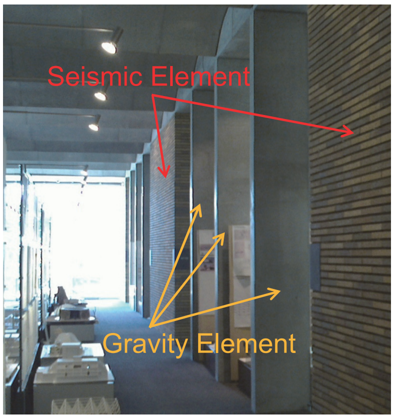


Fig. 8: Seismic and gravity elements

Conclusions

A macro-modeling approach using beam and shell elements is explained. To consider the composite effects of floor slabs, beam elements representing girders were placed under shell elements representing floor slab and MPC conditions were applied to connect the nodes of these elements. Eigenvalue analysis was conducted for Japanese and U.S. type three-story steel frame structures. The 1st natural period of the U.S. type steel structure was shortened from 0.769 s to 0.678 s when shifting the girder under the floor slab due to the composite effects of the floor slab. The macro model proved to be a successful tool for use in seismic simulations of Japanese and U.S. type steel frame structures.

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