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SHAKING TABLE TEST OF TWO-STORY STEEL MOMENT FRAME WITH SEISMIC FLOOR SYSTEM

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Abstract

Seismic floor system, which can decrease seismic responses (e.g., story drift, absolute acceleration on the floor, and stress of members) by means of inserting visco-elastic materials (VEMs) between concrete floor slab and beams, has been developed to enhance not only seismic performance but also workability of dismantlement of buildings. The effects of the floor system on the seismic responses have been studied by both dynamic analysis and shaking table tests of single-story simplistic structure model, however the detail of setup of VEMs was not considered. Therefore, this paper describes a shaking table test of two-story steel moment frames with seismic floor system in consideration with real details, and discusses seismic responses of real frames to which the seismic floor system is adopted.

Test specimen is one-third scale of bi-directional steel moment resisting frame, and the long span is 3 meters, the short span is 2 meters, and the height of the story is 1 meters. The frame consists of H-shaped beams and square tube columns. The bending strength of the columns are enough to remain elastic under bi-directional input ground motion. There are two kinds of specification of beam-floor connection, one is full-composite beams which are connected to the concrete floor slab rigidly by headed studs, and another is non-composite beams which are separated from the concrete floor slab. In case of non-composite beam specimen, the tests were conducted when relative displacement of the floor against the beam, that is shear deformation of VEM on beam flange, was unfree (without damping) or free (with damping) respectively.

3D shaking table, whose capacity of the maximum ground acceleration is 1G, was used for the test. The input wave was BCJ L2, which is the art-wave of almost flat pseudo velocity spectrum at over 1 second. The intensity of the input wave increased gradually from 0.25 to 1.5 times of the original level, and the input direction was adopted as 0, 45 and 90 degrees against long span direction. Before each input of BCJ L2, preliminary vibration was conducted by white noise wave of quite small intensity to check the vibration characteristics of specimen.

As a result, it is confirmed that in case of the composite beam specimen without damping the story drift is smaller but the absolute acceleration on the floor is larger than those of the non-composite beam specimen without damping, because the horizontal strength of the composite beam specimen is the largest of all specimens. On the other hand, in case of the non-composite beam specimen with damping, both the story drift and the absolute acceleration on the floor are the smallest of all specimens because of energy dissipation of VEMs. Consequently, it is clarified that utilization of the seismic floor system for real steel structures is valid.

Keywords: Seismic floor system, Steel structure, Visco-elastic material, Shaking table test, Time history analysis

1. Introduction

Reinforced concrete floor slab is often applied to building structures because its structural performance, noise barrier performance, insulation efficiency and application convenience are better than other type floor slabs. However, inertia force under ground motion is mainly caused by the floor slab, since the better part of the weight of the structure acts on the floor slab. Furthermore, steel beams can not be reused after dismantlement since the steel beams suffer some damages by separating the floor slab when the building is deconstructed.

For the purpose of settling these problems about the floor slab, we have developed a new floor system, that is called "seismic floor system," as shown in Fig. 1 [1, 2]. The seismic floor system is made by inserting visco-elastic materials (VEMs) between the concrete floor slab and steel beams. And it may have the advantage that not only seismic response decreases by damping of VEMs but also the workability of dismantlement of buildings becomes better. Past studies about the above problems concerned with the conventional concrete floor slab are focused on only either reduction of seismic response [3] or reuse of steel members [4, 5]. Consequently, the seismic floor system is the only study to try solving all at once these both problems.

In our previous studies about the seismic floor system, the effects of the seismic floor on responses of steel building structures against earthquakes have been researched principally by shaking table test and time history analysis. Major subject was single-story simplistic structure model, and details of installation of VEMs and floor slab was not considered, because it was focused on that the effect of reduction of seismic responses was theoretically revealed and the validity of analysis model was confirmed. Therefore, this paper discusses a shaking table test of two-story steel moment frames with the seismic floor system, for the purpose of verifying reduction effects of seismic responses in consideration with the details of the seismic floor system applied to the real structures.

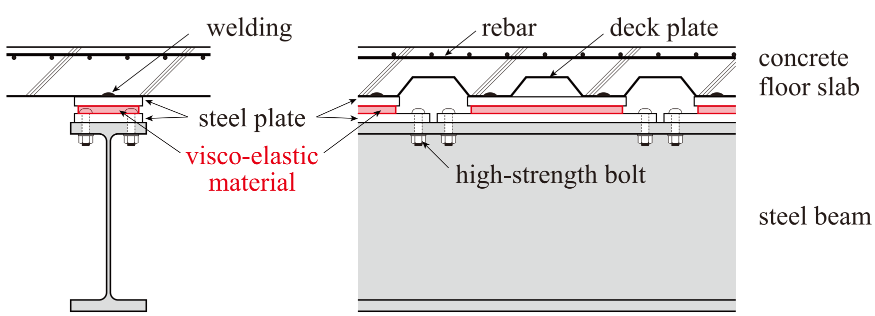

Fig. 1 – Seismic floor system

2. Test Method

2.1 Specimen

Test specimens are bi-directional steel moment resisting frames as shown in Fig. 2. They are a part of two-story frames, whose columns are separated at the midsection of the stories. There are two kinds of test specimens whose specification of the connection between beams and floor slab is different. One has full composite beams, which are connected rigidly to the concrete floor slab by using headed studs (i.e. shear connectors), and that is called "composite beam specimen." Another has non-composite beams, and VEMs are inserted between the concrete floor slab and the beams, at once the floor slab is isolated from the beams. The test of non-composite beam is conducted, either if relative displacement between the floor slab and the beams is restrained by setting the stoppers, or if relative displacement is free by removing the stoppers. The former is called "non-composite beam specimen without damping" and the latter is called "non-composite beam specimen with damping." The same steel moment resisting frame is used for both non-composite beam tests.

One-third scale is chosen as the size of the test specimens according to capacities of the shaking table. As shown in Fig. 2, the specimens have single-span in each direction. The long span between columns is 3 meter, the short span between columns is 2 meter, and the height of story is 1 meter. Square steel tubes are adopted to the columns, and these sectional sizes are selected to prevent themselves from yielding against bi-directional maximum vibrations. The lower ends of the columns are placed on the top plates of base columns and are connected as pin joints illustrated in Fig. 2. And the top plates of the columns are bolted to beams for supporting additional weights which are considered with story shear force acting on upper stories, and the top plates almost behaves as pin joints. The sectional size and the length of the base columns are decided for keeping elastic themselves and adjusting the natural period of the specimen. At the same time, the sectional size of H-shaped beams are selected as the natural periods of both direction are almost equal. On the other hand, the story shear strength differs depending on input direction because the full plastic moment of the beam in Y-direction (called Y-beam) is smaller than that in X-direction (called X-beam). Where, the steel grade of the beams is SS400 and that of the column is STKR400, and these steel grade meet the Japanese Industrial Standard. The yield stress of the beam flange is 289 N/mm^2 and that of the beam web is 352 N/mm^2 based on the coupon tests.

The floor slab is made by pouring fresh concrete after placing corrugated steel deck plate as mold form, whose thickness is 0.8 mm, on the beam upper flange. The thickness of concrete measured from the top of the steel deck is 40mm, and the height of the steel deck is 25 mm. Rebars whose diameter is 10mm are installed into concrete as the distance of each rebar is 90 mm. In case of composite beam specimen, the headed studs whose diameter is 10mm and length is 50 mm are welded to the beam upper flange, and the number of studs on each beam is 14. Compressive strength of the concrete at the time of the test is 28.1 N/mm^2 from the compression test of concrete cylinders.

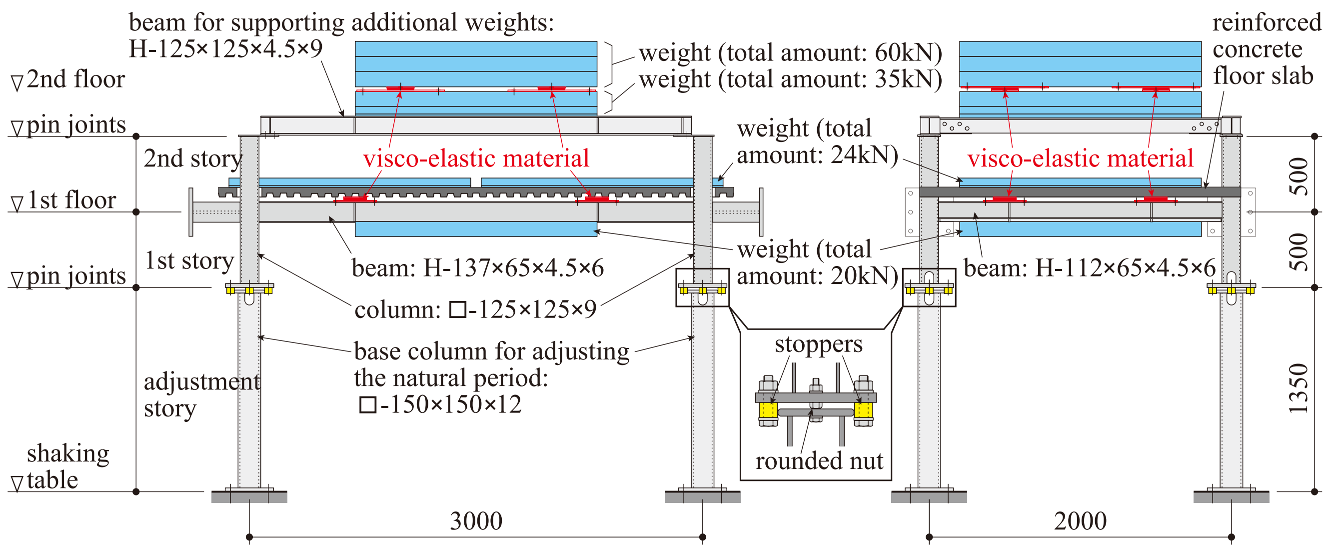

Fig. 2 – Specimen (units: mm)

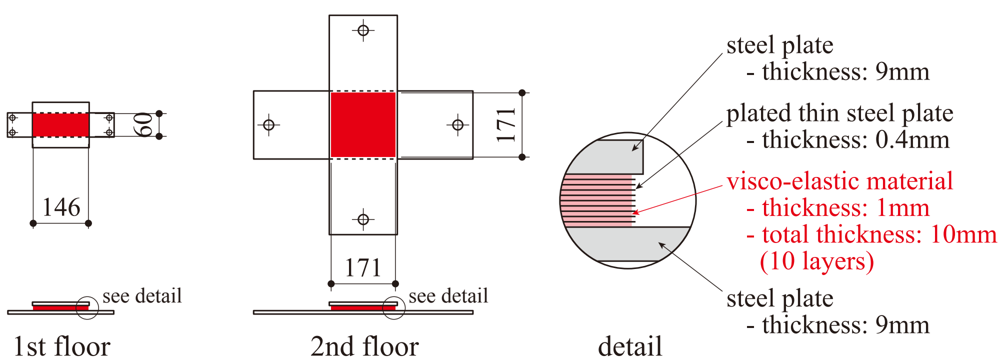

Fig. 3 – Detail of damping device by laminated visco-elastic material

In case of non-composite beam specimen, laminated acrylic visco-elastic materials (VEMs) which are a kind of the damping devices based on an original idea by the authors are adopted. 8 pieces of VEMs are inserted between floor slab and beam upper flange on the 1st floor, and 4 pieces of VEMs are inserted between additional weights on the 2nd floor, as shown in Fig. 2. The damping device is made by pasting visco-elastic material sheets and plated thin steel plates alternately, in order to increase the compressive stiffness and to be less likely to deform after setting the floor slab on the VEMs directly. In case of non-composite beam specimen without damping, the shear deformation of the VEMs is restricted by stoppers. On the other hand, in case of non-composite beam specimen with damping, the restrictions are removed. Furthermore, coolite, whose thickness is 20 mm, is installed around the columns as the clearances, not to bump the floor slab into the column depending on the shear deformation of the VEMs. Here, the material properties of VEM are obtained from another dynamic cyclic shear loading test result, and the method of identification is the same as the previous research [1].

Additional weights, which are made of steel blocks, are installed as shown in Fig. 2 because of the lack of mass according to the dynamic similarity of the specimen. The weight of specimen which consists with the frame own weight and the additional weight at each floor is shown in Table 1. In the test results as shown later, the inertia force acting on each part is obtained by multiplying the mass by the absolute acceleration on the additional weight. In case of the specimen, the ratio of the weight of floor, which is except for the frame weight, to the total weight is about 0.6, and it is assumed the average value of common building steel structures.

2.2 Shaking table and input wave

3D shaking table, which has been administrated in Disaster Prevention Research Institute of Kyoto university, was utilized for the test. It is able to support 150kN as the total weight and exert 1G as the maximum ground acceleration in any direction. Fig. 4 shows the overview of set-up of the test specimen in case of non-composite beam specimen with damping.

Table 1 – Weight of the test specimen (units: kN)

Floor	Position	One's own weight	Additional weight	Sub-total weight	Total weight
2nd floor	Floor	0	60	60	99
	Frame	4	35	39	
1st floor	Floor	12	24	36	59
	Frame	3	20	23	

Fig. 4 – Overview of set-up of specimen

White Noise and BCJ L2 are chosen as the input waves. Based on the dynamic similarity of the specimen, the time increment of the input waves is reduced to 0.577 times of the original waves, and the input durations of White Noise and BCJ L2 are 40.96 s and 34.64 s respectively. Intensity of BCJ L2, which is the art-wave of almost flat pseudo velocity spectrum at over 1.0 sec., is increased step by step in order to confirm seismic responses against each input level. There are four levels as the intensity of BCJ L2, which are 25%, 50%, 100% and 150% of the original level. Where, the maximum acceleration of the original level of BCJ L2 is 3.56m/s^2. Furthermore, input directions, which are 0, 45, 90 degrees with respect to X-axis, are added as the test parameters. Before each excitation of BCJ L2, the test specimen is slightly vibrated by White Noise, whose maximum ground acceleration is 0.98m/s^2, in order to check the variation in structural characteristics of specimens.

3. Test Results

3.1 Identification of structural characteristics of specimen

Structural characteristics of the test specimen which consists of the moment resisting frame must be identified, in order to simulate the test results by means of the numerical analysis. In this section, identification of the natural period and the damping coefficient of the frame are described, based on the test results of non-composite beam specimen with damping, as an example with 90 degrees input of White Noise before 25% of BCJ L2 input.

The natural period of the frame is identified, based on transfer function obtained from dividing the Fourier transformed absolute acceleration on the first floor by that on the shaking table. Fig. 5 shows the transfer function smoothed by the Parzen's filter of 0.1 Hz window width. In this case, the first natural period T^F can be identified with 0.413 sec., based on the peak of the spired solid line in Fig. 5.

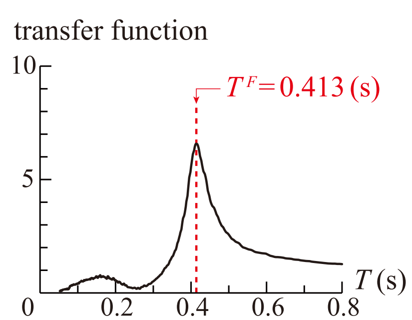

Fig. 5 – Identification of the natural period

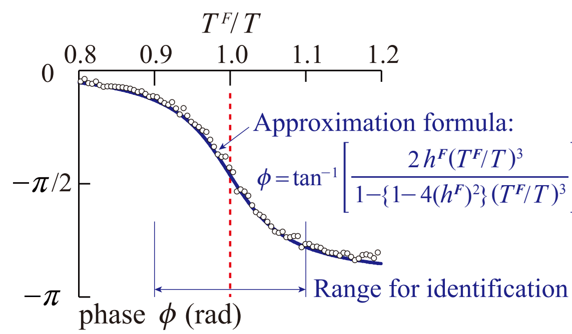

Fig. 6 – Identification of the damping coefficient

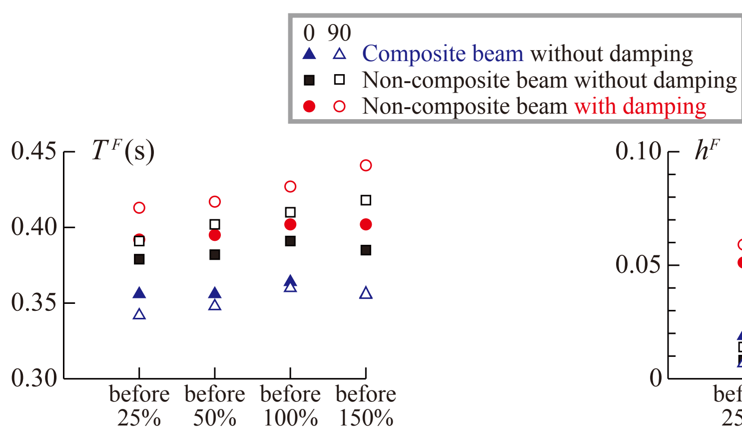

Fig. 7 – Change in the natural period

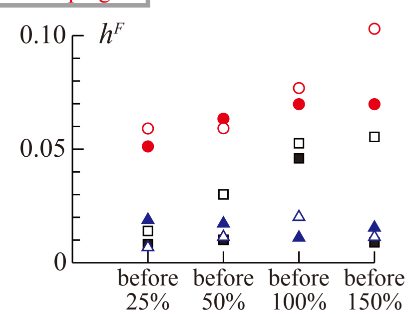

Fig. 8 – Change in the damping coefficient

On the other hand, the damping coefficient of the frame is identified, based on phase of transfer function. In Fig. 6, the circle marks mean the test results and solid line means the approximation formula, and vertical axis is the phase of transfer function. The damping coefficient is determined by minimizing the errors between the test results and calculating results by the approximation formula. From Fig. 6, damping coefficient h^F of the first mode can be identified with 0.0591.

Fig. 7 and 8 show the identified results of the natural period and the damping coefficient of all tests respectively. From Fig. 7, it is confirmed that the natural period of the composite beam specimen is the shortest of all specimens because the stiffness of the beam increases due to the composite effect by the reinforced concrete floor slab. As compared with the input direction, the natural period of 0 degrees input is slightly longer than that of 90 degrees input in case of the composite beam specimen, on the contrary, the natural period of 0 degrees input is slightly shorter than that of 90 degrees input in case of the non-composite beam specimen.

From Fig. 8, it is seen that the specimen with damping has three or four times the damping coefficient of the other specimens before 25% input. Both the natural period and the damping coefficient become larger as the input intensity increases, in particular, the rates of increase of these properties are larger in case of 90 degrees input. The main reason is that the floor slab is damaged by flexural cracks and slippage between headed studs and concrete.

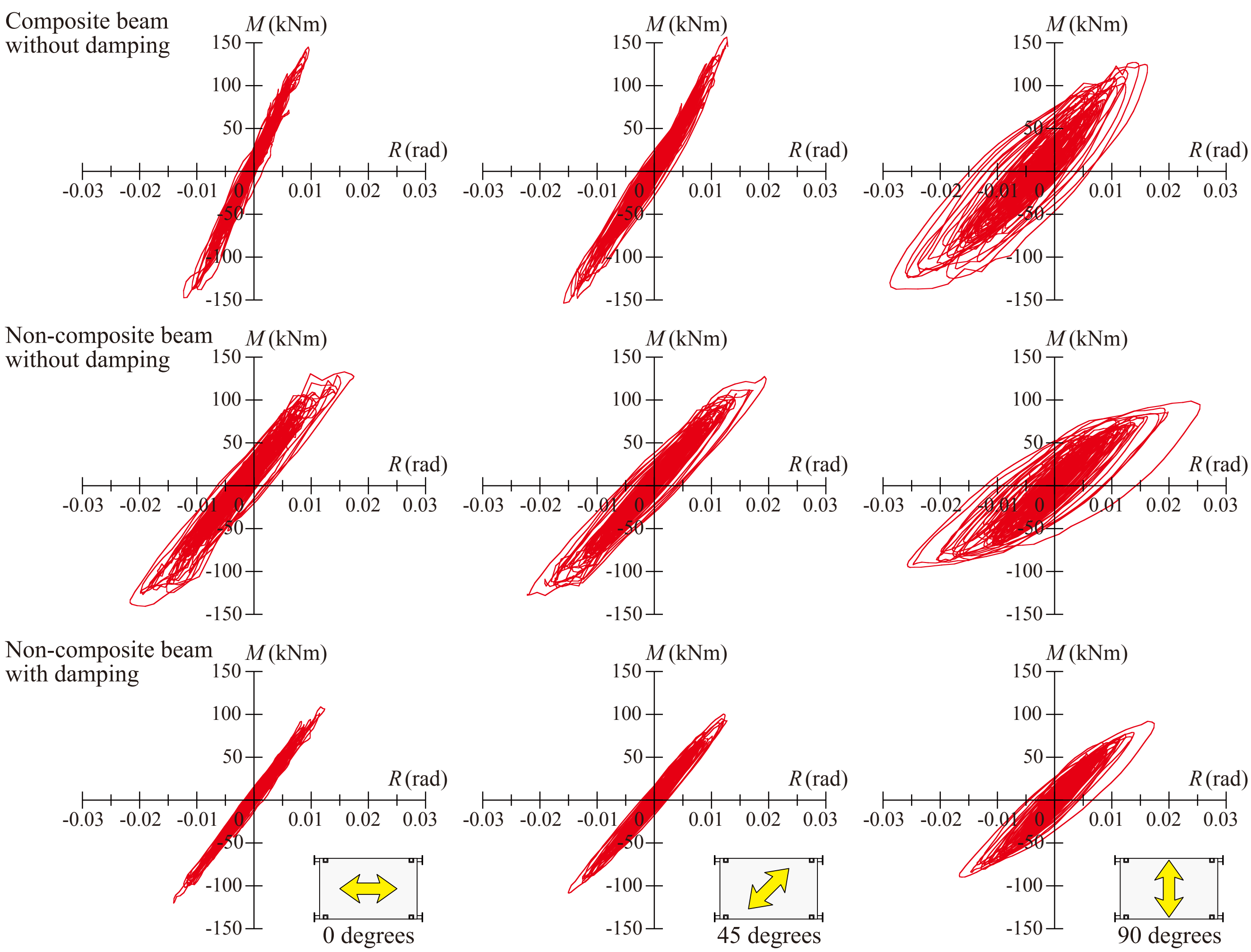

Fig. 9 – Hysteresis loops of the frame (Input level: 150%)

3.2 Hysteresis loop

In order to confirm the differences of progress of plasticity in case of 150% input, relationships between floor moment and story drift angle are shown in Fig. 9. Where, the floor moment is obtained by summing the bending moment at the all nodes of beam-to-column connections on the 1st floor, and the story drift angle is average value of both the 1st story and the 2nd story. For calculating the bending moment at the nodes, it is assumed that the bending moment at pin joints of column ends is zero and the story shear force is equal to the inertia force obtained from multiplying the mass by the absolute acceleration. Both the floor moment and the story drift angle in these figures are the value projected onto the input direction.

It is confirmed that the plastic deformation dominantly occurs at the non-composite beam specimen without damping, and the other specimens are almost kept elastic except for 90 degrees input. The elastic stiffness and the strength of the composite beam specimen are the largest because of the composite effect mentioned in Section 3.1. As compared about the input directions, the story drift angles of all specimens in 90 degrees input are the largest because the story shear strength is the smallest in all directions. In particular, in case of the composite beam specimen, it is seen that both stiffness and strength decrease until as large as the non-composite beam specimen, and the story drift angle moves toward negative direction because the composite effect is vanished after crushing concrete at the face of the columns.

Fig. 10 shows hysteresis loops of VEMs in case of 150% input. The vertical axis means the total shear force of all VEMs in the 1st floor, which is obtained by multiplying the mass of the 1st floor (see Table 1) by the acceleration of the 1st floor. And the lateral axis means the average shear deformations of VEMs, which are divided into two groups (i.e. X-beams or Y-beams). The shear deformation is the average value of four VEMs set on the beams in each group.

From Fig. 10, in case of 0 degrees input, the shear deformation of VEMs on both X-beams and Y-beams are almost same, however in case 45 degrees and 90 degrees, those of VEMs on X-beams are smaller than those on Y-beams. The most rational reason for the differences of the shear deformations is that X-beams are bent around minor axis under the inertia force in Y-direction. In case of this test specimen, the additional weights are installed into the horizontal plane because of the lack of the mass due to the dynamic similarity of the specimen. In-plane stiffness of the horizontal plane of the seismic floor is quite smaller than that of the conventional floor slab because the concrete floor slab is separated from the beams. Consequently, the shear deformation of VEMs decreases due to the deflection about minor axis of the beams if the horizontal inertia force acts on mid-span of the beams. It is recommended that out-of-plane deformation of the beam is restrained by lateral stiffeners if any weights, for examples equipments, non-structural members, and so on, are supported at mid-span of the beam.

Fig. 11 is the horizontal orbit of story drift angle and shear deformation of VEMs of the non-composite beam specimen with damping in case of 150% input. There are little phase differences of deformations of the frame and the VEMs because the natural periods in both X- and Y-direction are close as shown in Fig. 7. However, deformation in Y-direction is larger than in X-direction due to the difference of the story shear strength. And it is confirmed that the shear deformation of VEMs is less than the clearance between the column and the floor slab in all tests.

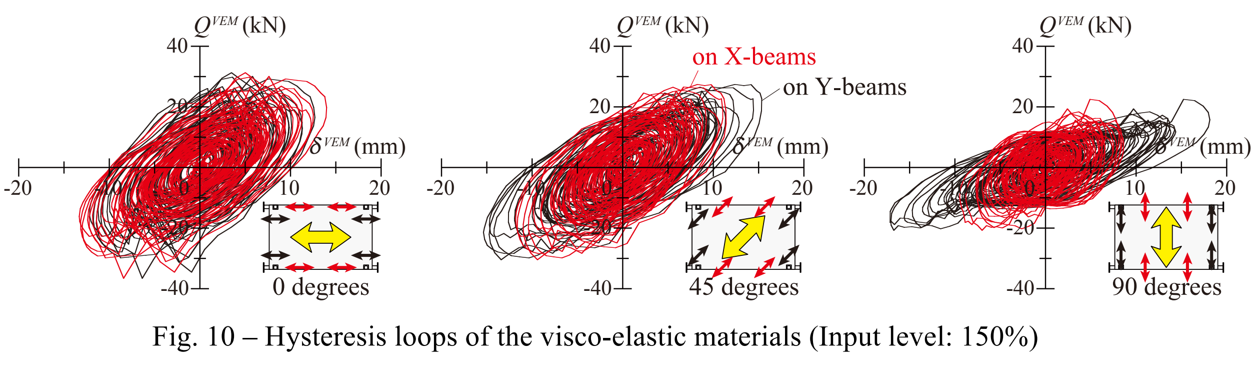

Fig. 10 – Hysteresis loops of the visco-elastic materials (Input level: 150%)

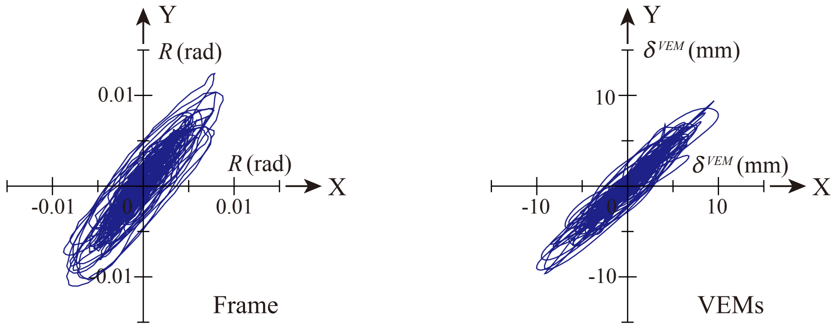

Fig. 11 – Horizontal orbit (45 degrees input)

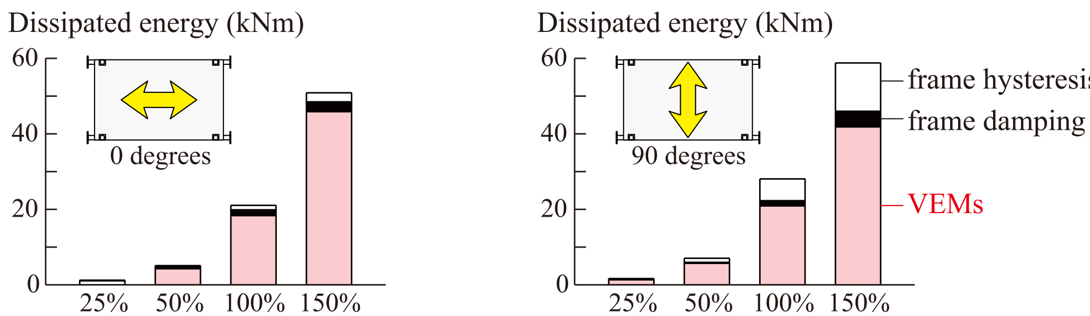

Fig. 12 – Dissipated energy of non-composite beam specimen with damping

3.3 Energy dissipation

Fig. 12 shows rate of the dissipated energy at each part of the non-composite beam specimen with damping. In case of 0 degrees, majority of input energy is absorbed by VEMs because the frame is almost kept elastic as shown in Fig. 9. On the other hand, in case of 90 degrees of 100% and 150% input, the hysteresis energy of the frame increases due to the occurrence of the plasticity of the beams, however the most energy is still dissipated by VEMs. From these discussions, it is revealed again that the reduction of the seismic response by the seismic floor is mainly caused by the damping of the VEMs as mentioned in Ref. [2].

3.4 Maximum response

In order to compare the maximum responses among the specimens, the maximum story drift angles are shown in Fig. 13 and the maximum absolute accelerations on the 1st floor are shown in Fig. 14. From Fig. 13, it is revealed that the maximum story drift angle of the non-composite beam specimen without damping is the largest of all specimens and that of the composite beam specimen is almost equal or smaller than that of the non-composite beam specimen with damping. However, in case of only 150% input, the maximum story drift angle of the composite beam specimen increases severely, compared with the tendency of other input levels. The main reason is the reduction of the composite effect of the beams due to the crush of concrete involved by plasticity of the beams as mentioned in Section 3.2. Furthermore from Fig. 14, the maximum absolute acceleration on the floor of the composite beam specimen is the largest of all specimens because its story shear strength is the largest. From the point of view of both the story drift angle and the maximum absolute acceleration, the structure with the seismic floor has the structural advantage with the conventional floor whether the plasticity occurs.

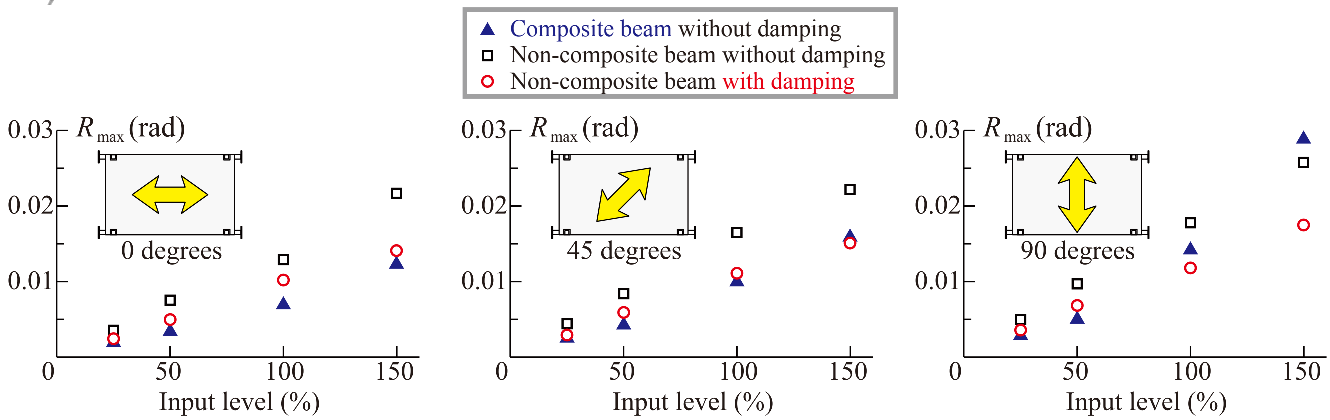

Fig. 13 – Maximum story drift angle

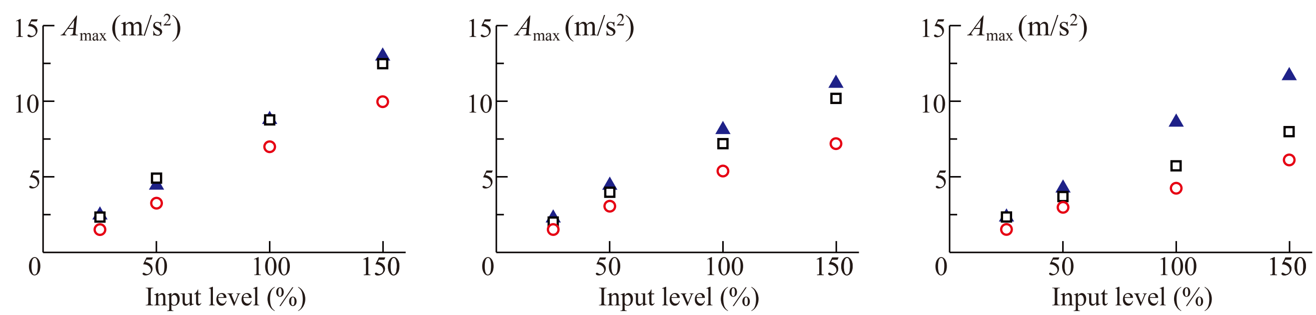

Fig. 14 – Maximum absolute acceleration on the 1st floor

4. Analysis

4.1 Analysis method

In order to confirm the correspondence between a simplified analysis and the shaking table test, the time history analysis is conducted by using the analysis model shown in Fig. 15. The analysis model consists of the frame and the floor, which are identified with the test specimens. Fishbone model which is proposed in Ref. [6, 7] is applied to the frame, and voigt model is applied to the VEMs. The masses are separated from the frame and the floor on each floor level, and the values in the row of "Sub-total weight" shown in Table 1 are provided to the weight of the corresponding masses.

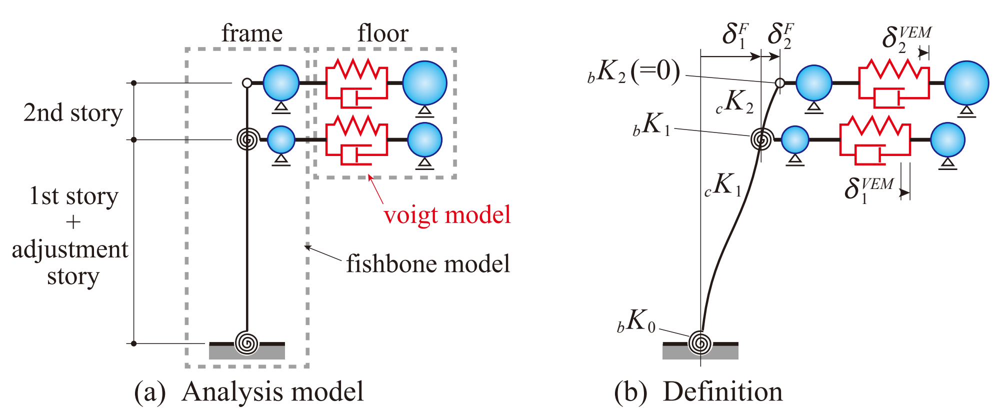

Fig. 15 – Analysis model

The elastic stiffnesses of columns and rotational springs of the fishbone model are obtained by the following procedure. Firstly, the stiffness of rotational spring at the 2nd floor is assumed as zero because the beams for supporting additional weights are connected as pin joints. The stiffness of the rotational spring at the base is obtained by refering as the exposed column base. The flexural stiffnesses of the members are calculated, and the sum of stiffness of the beams in each direction at the 1st floor is adopted to the stiffness of the rotational spring at the 1st floor, on the other hand, the sum of stiffness of the columns in each story is adopted to the column stiffness. Where, ${}_cK_1$ is obtained by averaging the stiffnesses of both the 1st story and the adjustment story in consideration for the equivalence of the total deformation, and the pin joints at the boundary of the both stories are ignored in this analysis model. Next, the eigenvalue analysis is conducted by using the initial model with the stiffnesses obtained above. Finally, the stiffnesses are proportionally modified based on ratio between the first natural period of the eigenvalue result to that of the test result.

For calculating the strength of columns and rotational springs, it is assumed that the columns and the base rotational spring keep elastic. And elasto-plastic behavior of the rotational spring in the 1st floor can be occurred because the beams in the 1st floor only yield in the shaking table test. The rotational spring in the 1st floor is modeled as tri-linear hysteresis loop of kinematic hardening rule. The first brunch strength is assumed as a half of the full-plastic moment, and the second brunch strength is assumed as the full-plastic moment. And the tangent stiffness after reaching the first brunch is 0.25 times of the elastic stiffness, and that after reaching the second brunch is 0.05 times.

The damping coefficient of the non-composite specimen without damping which is identified from the shaking table test is applied to the fishbone model. The hysteresis characteristics of acrylic VEM, which are the same as Ref. [1, 2], are adopted to the voigt model based on the mechanical properties from the dynamic cyclic shear loading test. The detail of constitutive law of acrylic VEM is discussed by Kasai et al. (see Ref. [8, 9]).

The acceleration records on the shaking table which are measured in the test are used as the input waves. Here, the responses in 45 degrees input are obtained by combining the responses under uni-directional input which is each acceleration records in either X-direction or Y-direction, because the analysis model in Fig. 15 can be utilized only against uni-directional input.

4.2 Comparison of analysis results and test results

Fig. 16 shows time history responses in case of 0 degrees of 150% input. The dashed lines mean the test results and the solid lines mean the analysis results. Sum of horizontal displacements of both the 1st story and the adjustment story, except for the displacement due to the rocking of the frame, is represented as story drift in Fig. 16(a). And the shear deformation of VEMs of the test result is the average value of all VEMs on the 1st floor, and is not classified as setting on X-beams or on Y-beams.

Compared with the analysis results and the test results, it is seen that the vibration period of the analysis results corresponds to the test results. On the contrary, the amplitude of the analysis result is smaller than the test result, in particular, the shear deformation of VEMs of the analysis result is only about 0.6 times value of the test result. These tendencies are confirmed regardless of the input directions and the input levels. Consequently, the analysis model and the hysteresis characteristics must be revised for achieving the purpose of further improvement of the accuracy of the analysis results.

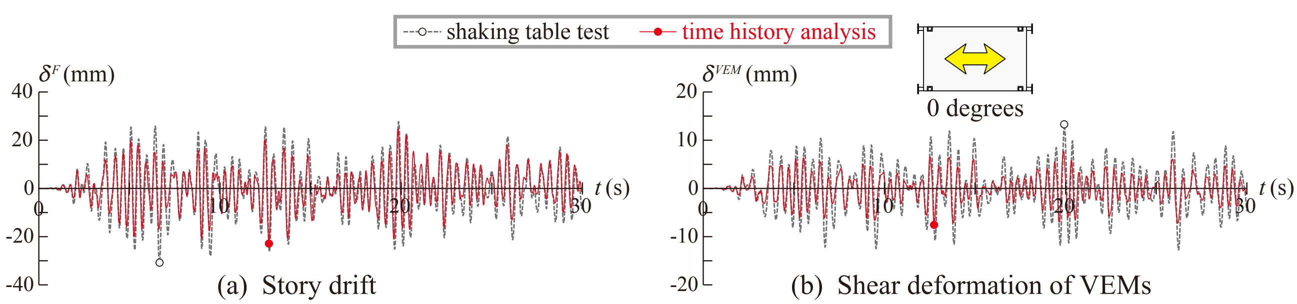

Fig. 16 – Comparison of time history response

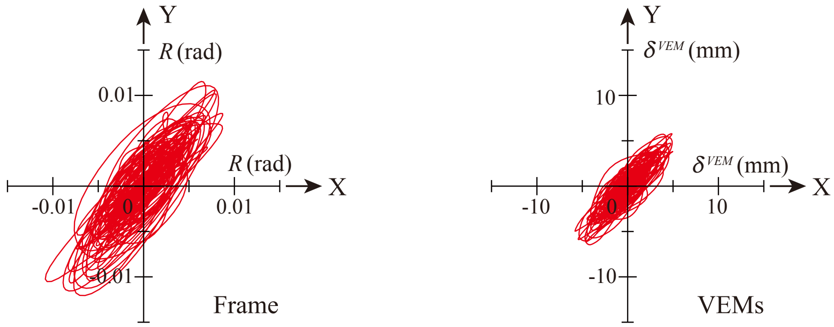

Fig. 17 – Analysis result of horizontal orbit (45 degrees input)

Fig. 17 shows the analysis results in case of 45 degrees input about the horizontal orbit of story drift angle and shear deformation of VEMs as well as Fig. 11. These orbits are illustrated by combining the analysis results of both 0 degrees input and 90 degrees input, which are severally conducted by using the plane frame models. As mentioned above, the analysis results is smaller than the test result (see in Fig. 11), however, the lineament of the orbit is almost similar. It is notable that responses under bi-directional input can be obtained from combining responses calculated separately in the orthogonal directions if columns keep elastic as well as this shaking table test.

5. Conclusions

This paper presented the results of both shaking table test and time history analysis about two-story steel moment resisting frame with seismic floor system in consideration with the real details. The major findings obtained from this study are as follows:

1) From identified results of the structural properties, the first natural period of the composite beam specimen is the shortest of all specimens. And the natural period becomes slightly longer because concrete floor slab suffers damage, if the intensity of the input ground motion increases step by step.

2) From the shaking table test results, in elastic range, the story drift angle of the composite beam specimen without damping, which has the conventional floor slab, is the smallest of all specimens. However, the story drift angle of the composite beam specimen increases severely as well as the non-composite beam specimen without damping, according to progress of the plasticity of the beams. In particular, in case of 150% of BCJ L2 input, the story drift angle of the non-composite beam specimen with damping, which has the seismic floor slab, is the smallest regardless of the input directions.

3) The absolute acceleration of the frame with seismic floor is the smallest at any conditions in the test. The main reasons are that the story shear strength and elastic stiffness of the composite beam specimen are larger those of the other specimens due to the composite effect of floor slab, and also the damping coefficient of the non-composite beam specimen with seismic floor is larger.

4) Associated with 2) and 3), the additional damping coefficient of the test specimen by the seismic floor is about 3-4 percent, and the input energy is mainly dissipated by visco-elastic materials in case of the non-composite beam specimen with seismic floor.

5) The laminated visco-elastic materials, which are proposed for enhancement of the compressive stiffness, behave stably under bi-directional ground motion as well as uni-directional ground motion. And the clearance around the columns, which is decided by the maximum shear deformation of visco-elastic materials obtained from analysis, is enough not to bump the floor slab to the columns. However, the visco-elastic materials do not work appropriately if a beam is bent about weak axis by out-of-plane inertia forces due to additional weights. Consequently, it is recommended that out-of-plane deformation of the beam is restrained by lateral stiffeners at mid-span of the beam which additional weights act on.

6) From the analysis results by means of the simplified model, lineament of time history responses and horizontal orbits is similar between the analysis and the test. However, the amplitude obtained by the analysis is smaller than test results, and therefore the analysis model must be improved to evaluate the test results properly.

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