Seismic response of single-story steel moment frame with isolated floor system

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SUMMARY
We have developed a new floor system, that is called isolated floor system, to enhance seismic performance of a building structure. The floor system is built up by installing visco-elastic materials (VEM) between floor slab and beam upper flange. This paper deals with numerical analysis and shaking table test in order to verify seismic response in the elastic range of single-story steel moment frame equipped with the proposed floor system. From analytical and experimental studies, it was clarified that the maximum story drift angle and the maximum story shear force decrease while the maximum shear deformation of VEM increases if ratio of shear area to thickness of VEM S/d become small. As a result of detailed investigation, it was revealed that seismic response in elastic range of single-story frame with the isolated floor system can decrease about thirty to fifty percent compared with that of ordinary frame without the system if S/d is chosen appropriately.

Keywords: steel structure, floor slab, visco-elastic material, time-history analysis, shaking table test

1. INTRODUCTION

In a building structure, floor slab is usually made from reinforced concrete (RC) to enhance the performance of fire resisting, insulation of sound, reduction of vertical deformation or vibration and so on. In case of the building with RC floor slab, amount of the dead load of the floor and the live load on the floor is about fifty to seventy percent of total weight of the building. Consequently, by means of either reducing weight (including dead load and live load) of the floor or acceleration of the floor during earthquake, seismic force acting on the building structure can decrease.

On the other hand, under construction of a building structure, steel deck plates, which are welded to beam upper flanges, are used for concrete molds. Therefore, it is hard to separate the concrete floor slab from beams on demolition of the building. Furthermore, if beams are reused to another building, it is expected that an easily demountable floor slab is developed [Nishimura, et al. (2006) and Kosaka, et al. (2007)].

In this research, a new floor system, into which visco-elastic materials (VEM) are installed between floor slab and beam upper flange, is proposed in order to reduce seismic response of a steel moment frame. The thin VEM is adhered to two steel plates, then the lower plate is bolted to beam upper flange

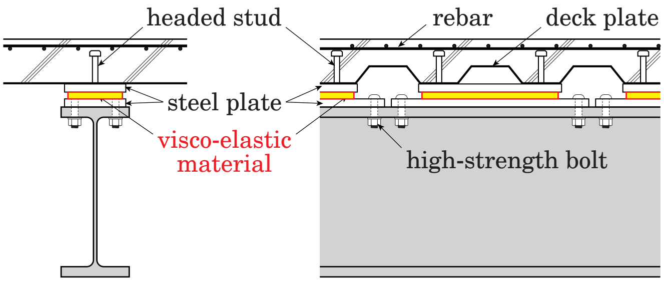


Figure 1. An new floor system to enhance the seismic performance

and deck plate is welded to the upper plate. Thereby floor slab can be detached easily from a beam by removing high-strength bolts under demolition work, and the beam can be reused for construction of another building.

As the initial investigation for practical application of the proposed floor system, this paper represents seismic response of single-story steel moment frame equipped with the floor system. Firstly, analysis model of the single-story frame is built up with the use of a reasonable and high-precision hysteresis model of visco-elastic material. Next, qualitative detection of seismic response in the elastic range is verified by numerical analysis, and furthermore the reason of reduction of seismic response would be revealed. And finally, quantitative investigation of seismic response of the frame with the isolated floor system is conducted by means of comparison between shaking table test and numerical analysis.

2. ANALYSIS MODEL

In order to develop an analysis model to obtain seismic response of a single-story steel moment frame with the isolated floor system, it is divided into a floor and a frame as shown in Fig. 2 (b). Assuming that the floor and the frame vibrate respectively in the horizontal direction, and they are connected by visco-elastic material (VEM). When shear deformation of VEM δ^{VEM} (see in Fig. 3) is given as stationary vibration whose natural frequency is ω, hysteresis behavior of VEM can be presented by using Voigt model. Therefore shear force of VEM (Q^{VEM}) is obtained from Eqn. (1).

$$Q^{VEM} = K^{VEM}\,\delta^{VEM} + C^{VEM}\,\dot{\delta}^{VEM} = G'\frac{S}{d}\,\delta^{VEM} + \frac{G'\eta}{\omega}\cdot\frac{S}{d}\,\dot{\delta}^{VEM} \tag{1}$$

Here, S/d is ratio of shear area to thickness of VEM (see in Fig. 3 (a)), G' is storage modulus and η is loss factor (see in Fig. 3 (b)). In case of acrylic visco-elastic material, both G' and η can be estimated properly by next equations [Kasai, et al. (1993) and Kasai, et al. (2001)].

$$G' = G\,\frac{1+ab\omega^{2\alpha}+(a+b)\omega^{\alpha}\cos(\alpha\pi/2)}{1+a^2\omega^{2\alpha}+2a\omega^{\alpha}\cos(\alpha\pi/2)} \tag{2}$$

$$\eta = \frac{(-a+b)\omega^{\alpha}\sin(\alpha\pi/2)}{1+ab\omega^{2\alpha}+(a+b)\omega^{\alpha}\cos(\alpha\pi/2)} \tag{3}$$

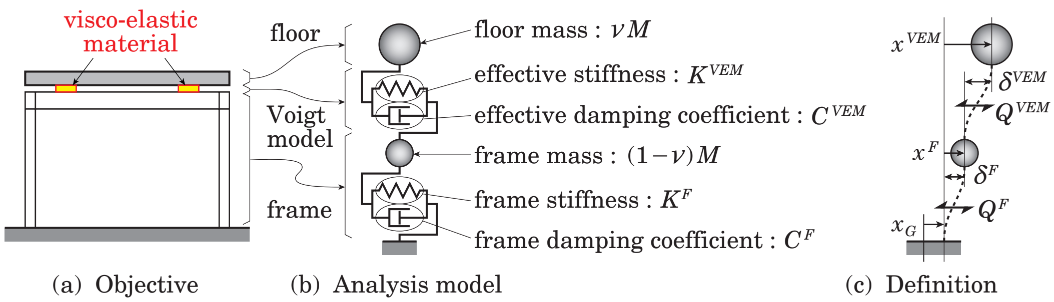


Figure 2. Objective and analysis model

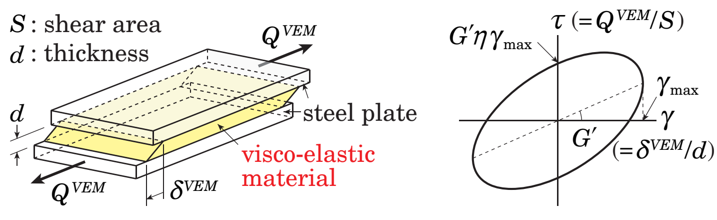


Figure 3. Model of visco-elastic material

In Eqn. (2) and (3), a and b represent the temperature dependency of VEM and they are given by Eqn. (4) based on the material properties.

$$a = 5.6 \times 10^{-5} \lambda^{\alpha}, \quad b = 2.10 \lambda^{\alpha} \tag{4}$$

$$\lambda = \exp\left[\frac{-14.06(\theta - \theta_{ref})}{97.32 + \theta - \theta_{ref}}\right] \tag{5}$$

Here, θ is temperature of VEM, and θ_{ref} is the reference temperature (20℃). In Eqn. (2), (3) and (4), G and α are defined by material properties.

The modeling of VEM mentioned above is concerned with behavior under stationary vibration. On the other hand, the frequency ω including Eqn. (1), (2) and (3) are varied every second under nonstationary vibration. In this paper, the next equation [Huang, et al. (1999)] is applied to the frequency of nonstationary vibration.

$$\omega_t = \sqrt{\frac{\sum_{j=1}^{n}\left|(\dot{\delta}_t^{VEM})^2 - (\dot{\delta}_{t-j\Delta t}^{VEM})^2\right|}{\sum_{j=1}^{n}\left|(\delta_t^{VEM})^2 - (\delta_{t-j\Delta t}^{VEM})^2\right|}} \tag{6}$$

Here, n in Eqn. (6) is natural number which is defined as $n\Delta t$ is the closest to one fourth of natural period of frame T. Referring to symbols of the analysis model in Fig. 2, the equation of motion is represented by Eqn. (7).

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{1\}\ddot{x}_G \tag{7}$$

Where,

$$[M] = \begin{bmatrix} (1-\nu)M & 0 \\ 0 & \nu M \end{bmatrix} \tag{8}$$

$$[C] = \begin{bmatrix} C^F + C^{VEM} & -C^{VEM} \\ -C^{VEM} & C^{VEM} \end{bmatrix} \tag{9}$$

$$[K] = \begin{bmatrix} K^F + K^{VEM} & -K^{VEM} \\ -K^{VEM} & K^{VEM} \end{bmatrix} \tag{10}$$

$$\{x\} = \{x^F \quad x^{VEM}\}^{\mathrm{T}} \tag{11}$$

and $\ddot{x}_G$ is acceleration of ground motion.

3. TIME HISTORY ANALYSIS

3.1. Analysis Parameters

Time history analysis using the analysis model in Fig. 2 was conducted in order to reveal seismic responses of steel moment frames with the isolated floor. As shown in Table 1, analysis parameters are ratio of shear area to thickness of VEM S/d, ratio of weight of floor to total weight of frame ν, and natural period of frame T. The total weight of the frame W_T is 10000 kN and the frame stiffness K^F is calculated from T and W_T. Damping factor is 2% and temperature of VEM is 20℃ , and these values are constant during vibration.

Table 1. Analysis parameters

Analysis parameters	Objectives
Ratio of shear area to thickness of VEM S/d	1 - 200
Ratio of weight of floor to total weight of frame ν	0.5, 0.7, 0.9
natural period T (s)	0.5, 1.0, 2.0

Table 2. Input earthquakes

Earthquake	Max. acc. (m/s^2)	Duration (s)
El Centro NS, 1940	5.11	53.7
Taft EW, 1952	4.97	54.3
Hachinohe NS, 1968	3.33	51.0
Kobe NS, 1995	8.18	40.0
BCJ L2 (art wave)	3.56	120.0

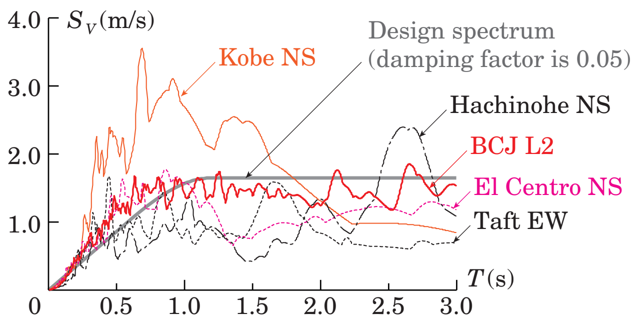


Figure 4. Pseudo-velocity response spectrum of input earthquake (in case of damping factor is 0.02)

Table 2 shows input earthquakes. Maximum acceleration of ground motion of El Centro NS, Taft EW and Hachinohe NS are increased to 0.5 m/s of the maximum velocity of ground motion, and others are the same as original waves. BCJ L2 is an art wave and its response spectrum is almost identified with that of level 2 in Japanese seismic code, as shown in Fig. 4.

3.2. Analysis Results

Fig. 5 shows the maximum base shear coefficient of frame ($C_{B\max}$), which is obtained from dividing the total weight of the frame (W_T) by the maximum shear force of the frame ($Q^F_{\max}$). And Fig. 6 shows

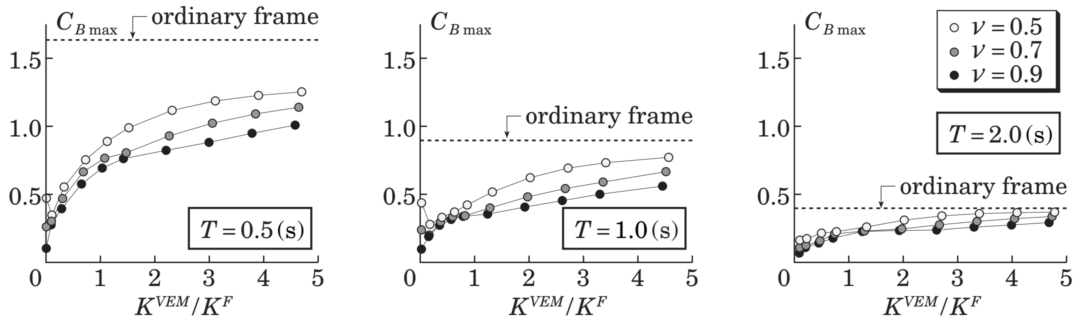


Figure 5. Maximum base shear coefficient of frame $C_{B\max}$

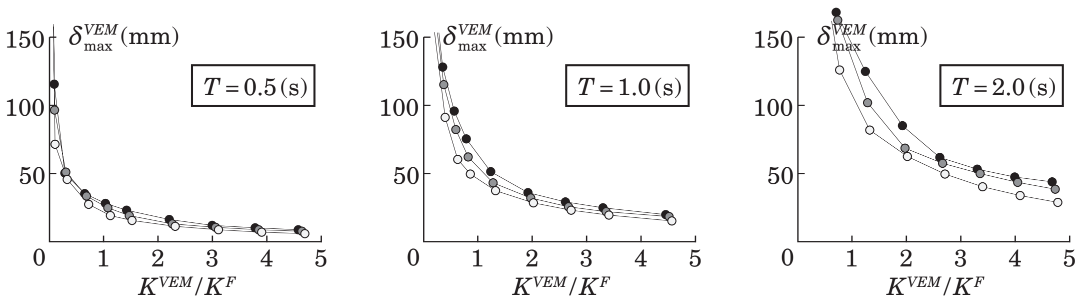


Figure 6. Maximum shear deformation of VEM $\delta^{VEM}_{\max}$

the maximum shear deformation of VEM ($\delta_{\max}^{VEM}$) in case the input earthquake is BCJ L2. Lateral axis of each figure means the normalized stiffness, which is obtained from dividing the frame stiffness (K^F) by the effective stiffness of VEM (K^{VEM}). The dash line in Fig. 5 means the maximum base shear coefficient of the ordinary frame without the isolated floor. According to these analysis results, the following three findings are obtained.

- As the normalized stiffness K^{VEM}/K^F becomes small, that is ratio of shear area to thickness of VEM S/d becomes small, the maximum base shear coefficient decreases, on the other hand, the maximum shear deformation of VEM increases.
- As ratio of weight of floor to total weight of frame ν become large, the maximum base shear coefficient decreases.
- As natural period of frame T become long, the maximum shear deformation of VEM increases, and at the same time, the maximum base shear coefficient is almost even or increases.

In order to consider the major reason that the response of frame decreases due to the isolated floor system, input energy by ground motion (E_T) is illustrated in Fig. 7 and dissipation energy of VEM (E_D^{VEM}) is illustrated in Fig. 8. As shown in Fig. 7, input energy by ground motion (E_T) is affected by only natural period of frame T except for a case the normalized stiffness K^{VEM}/K^F is quite small, E_T are almost constant if either ratio of shear area to thickness of VEM S/d or ratio of weight of floor to total weight of frame ν is varied. On the other hand, it is revealed that reduction of seismic response of the frame with the isolated floor system is caused by dissipation energy of VEM because input energy almost dissipates by damping of VEM, as shown in Fig. 8, as well as the seismic response decreases when the normalized stiffness K^{VEM}/K^F becomes small.

Above-mentioned findings are observed also from analysis results against other earthquakes. As a result, it is revealed that S/d is the parameter to have the most effect on seismic response of the frame, and as S/d become small, the maximum base shear coefficient (i.e. the maximum story drift angle and the maximum story shear force) decrease because of dissipation energy of VEM, at the same time the maximum shear deformation of VEM increases. Here, it needs to take notice that clearance between the floor slab and columns / walls is as large as not to crash each other when the proposed floor system is applied to a steel frame. From this viewpoint, the clearance around the floor slab must be larger than the maximum shear deformation of VEM ($\delta_{\max}^{VEM}$), referring to Fig. 6.

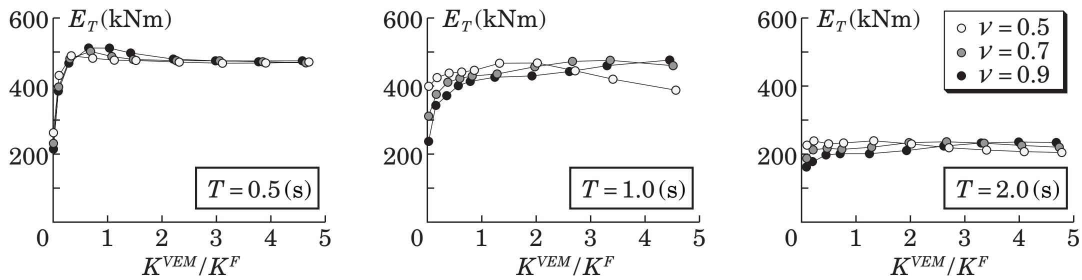


Figure 7. Input energy by ground motion

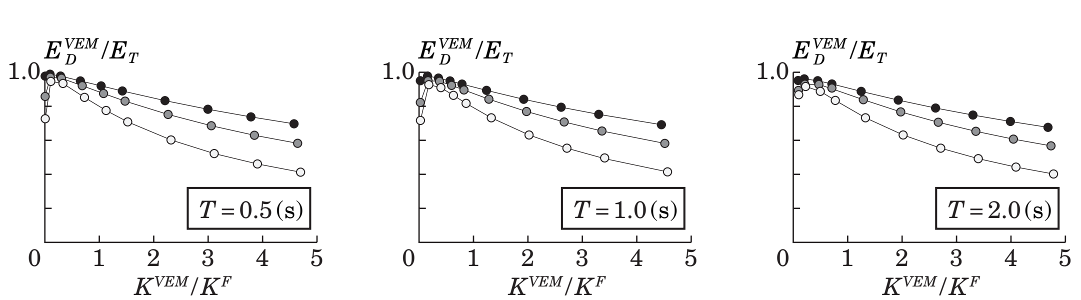


Figure 8. Dissipation energy of VEM

4. SHAKING TABLE TEST

4.1. Test Specimen and Test Parameter

Shaking table test (see in Fig. 9) of single-story steel frame of about twenty percent of full-scale model was conducted to confirm validity of analysis model and analysis results. Test specimen consists of three plane-frames, a floor slab, and sets of visco-elastic material (VEM), as shown in Fig. 10.
The components of each plane-frame are a beam, a foundation beam, two link members, and spring plates. Link members, which are connected by pins at both ends, are supported the weight of the beam and the floor slab, however do not resist against lateral force. Spring plates (thickness is 10 mm and width is 100 mm), whose material is high-strength aluminum alloy (A7075), are applied for the lateral resisting element, and they are bolted to the beam and the foundation beam by using double-angles. To avoid eccentricity of the specimen, weight of frame, lateral stiffness, and shear area of VEM at the exterior frame are identical with each other, and they are half of those at the interior frame. And these plane-frames are connected by lateral braces rigidly, so it can be considered that the story drift of all plane-frames are identical.

At the same time, the floor slab, which is made of single steel plate, is connected to beams with both linear sliders and sets of VEM. The floor slab is prevented from movement in a direction perpendicular to plane-frame and is also supported vertically by linear sliders. The weight of floor slab is 9.64 kN

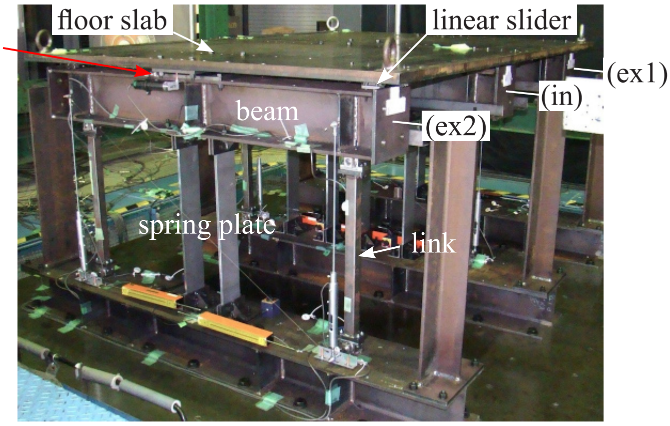


Figure 9. Test setup

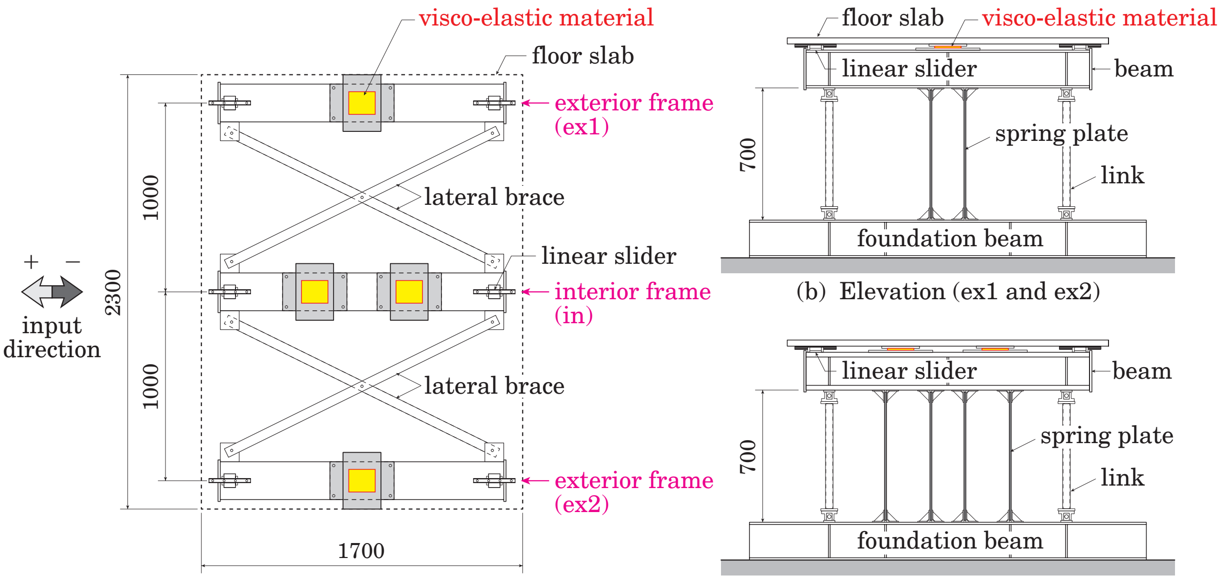


Figure 10. Test specimen

and total weight of frame is 15.23 kN, consequently ratio of weight of floor slab to total weight of frame ν is 0.63.

As test parameter, ratio of shear area to thickness of VEM S/d is adopted because it is the most important parameter to investigate seismic response of the frame with the isolated floor system from analysis results. Shear area of VEM, which is acrylic visco-elastic material, is selected as large as ratio of shear area to thickness of VEM S/d is 1 m, 5 m and 20 m. And additionally, the shaking table test without the floor system, that is to say the relative deformation between the floor slab and the beams is fixed, was conducted in order to obtain the results in case of the ordinary floor slab and identify the structural parameters as mentioned in section 4.3.

4.2. Test Method

For the shaking table test, strong earthquake response simulator, which has been operated by Disaster Prevention Research Institute of Kyoto University in Japan, was utilized. Tri-directional shaking table test, whose maximum acceleration limitation is 1G in all direction, can be carried out by using the testing equipment.

In the test, input direction is one way, that is parallel to the plane-frames, and two basic input waves, whose acceleration histories are shown in Fig. 11, are adopted. White noise has a constant spectrum at selected frequencies from 0 to 30 Hz. The maximum acceleration of ground motion are decided according to linear limitations of spring plates and VEM. Thus, the maximum acceleration of ground motion and the input duration in case of BCJ L2 are different from those values as shown in Table 2.

4.3. Identifications of Specimen Characteristics

Characteristics of the frame and VEM must be identified in order to simulate the test results by the numerical analysis. Firstly, natural period of the frame is identified, based on the test results in case the relative deformation between the floor slab and the beams is fixed. Fig. 12 shows Fourier spectrum of story drift. From this figure, natural period of the frame is identified with 0.493 (s).

Next, in order to identify the damping factor of the frame, Fourier phase spectrum is obtained from the transfer function of acceleration response of the frame (beam) to that of the foundation beam. Round plots in Fig. 13 mean the Fourier phase spectrum and solid line means approximation of Fourier phase spectrum by Eqn. (12). The damping factor of the frame h^F is decided to minimize the error which is

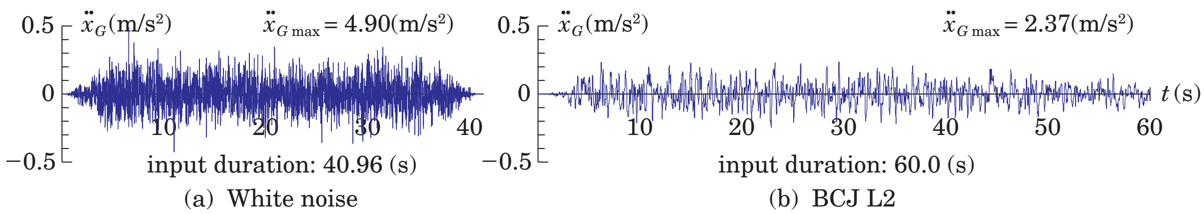


Figure 11. Input waves

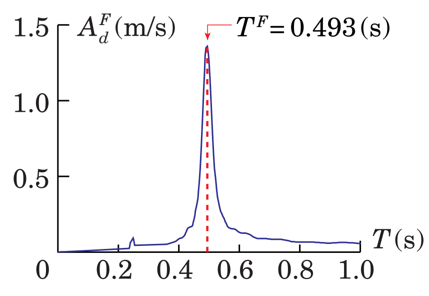


Figure 12. Natural period

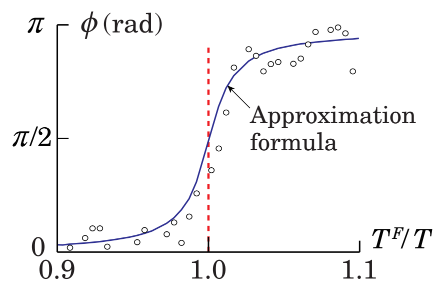


Figure 13. Damping factor

the sum of square of deferences of Fourier phase spectrum between test results and calculated results by Eqn. (12). The range of 10 % of natural period is chosen for identification of the damping factor of the frame.

$$\phi = \tan^{-1}\left[\frac{2h^F(T^F/T)^3}{1-\{1-4(h^F)^2\}(T^F/T)^2}\right] \tag{12}$$

Fig. 14 shows the comparison of time history response of story drift between the test result and time history analysis result, which is obtained by using the identified natural period and damping factor. The time history analysis result almost corresponds with the test result, so that identifications of the natural period and the damping factor are considered proper.

On the other hand, material properties of acrylic VEM are identified from dynamic cyclic loading test results. G and α in Eqn. (2), (3) and (4) is decided to minimize the error which is the sum of square of deferences of shear stress between test results and calculated results. Finally, as a result, material properties of VEM ($G = 0.560$ and $\alpha = 0.0364\,\mathrm{N/mm^2}$) are obtained. Shear stress of VEM vs shear strain relationship is shown in Fig. 15, compared with test result and identified result. From Fig. 15, it is clarified that both test results and calculated results quite agree.

4.4. Test Results

Fig. 16 shows time history responses of story drift and Fig. 17 shows those of shear deformation of VEM. Both figures are seismic responses with the isolated floor system against BCJ L2 whose maximum acceleration of ground motion is $1.78\,\mathrm{m/s^2}$. Ranges of lateral axis of these figures are decided by including the time of the maximum response. Dash lines in these figures mean the shaking table test results and solid lines mean the time history analysis results. It can be seen that test results and analysis results in Fig. 16 and Fig. 17 are almost equal regardless of ratio of shear area to thickness of VEM S/d.

Fig. 18 shows the maximum story drift (see Fig. 18(a)) and the maximum shear deformation of VEM (see Fig. 18(b)). From Fig. 18(a), the maximum story drift is smaller than the value of horizontal line, which means the maximum response without the proposed floor system. Consequently, seismic

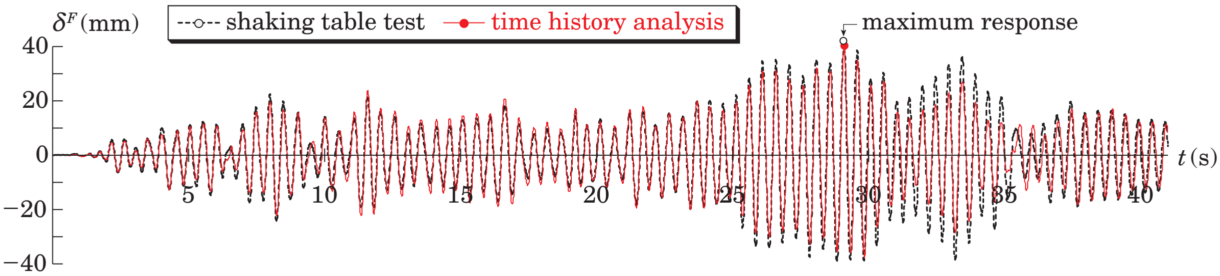


Figure 14. Comparison of story drift (white noise; $\ddot{x}_G = 4.90\,\mathrm{m/s^2}$)

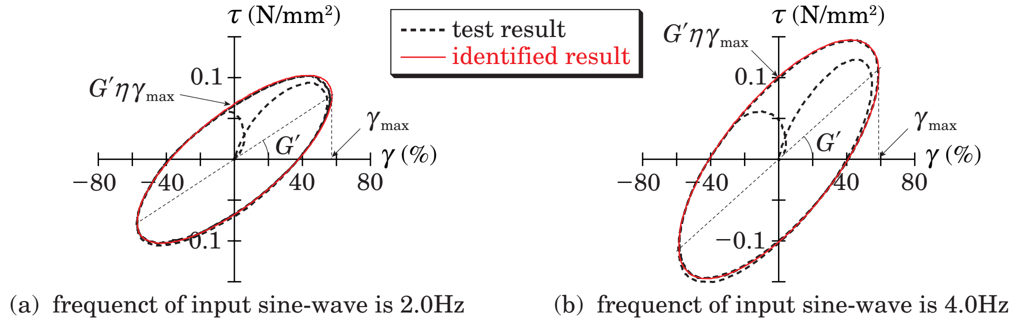


Figure 15. Comparison of hysteresis of VEM

response of the frame can be reduced by equipment of the isolated floor system as mentioned in the previous chapter. Furthermore as compared the difference in the maximum responses between test results and analysis results, although it is observed that the maximum story drift of the analysis result in case of S/d = 20 m is slightly smaller than that of test result and the maximum shear deformation of the analysis result in case of S/d =1 m is slightly smaller than that of test result, analysis results almost agree with the test results in a macroscopic sense.

Fig. 19 shows hysteresis loop of VEM in case of S/d = 5 m and Fig. 20 shows time history of temperature of VEM. In this paper, hysteresis behavior of VEM is simulated by assuming the temperature of VEM is constant under vibration, as mentioned above. From Fig. 19, it is clarified that the analysis result about equals to the test result, because the temperature of VEM hardly increase during the tests. Based on this remark, it is suggested that the hysteresis behavior of VEM can be estimated by the simple model introduced in this paper if the increment of the temperature of VEM is less large.

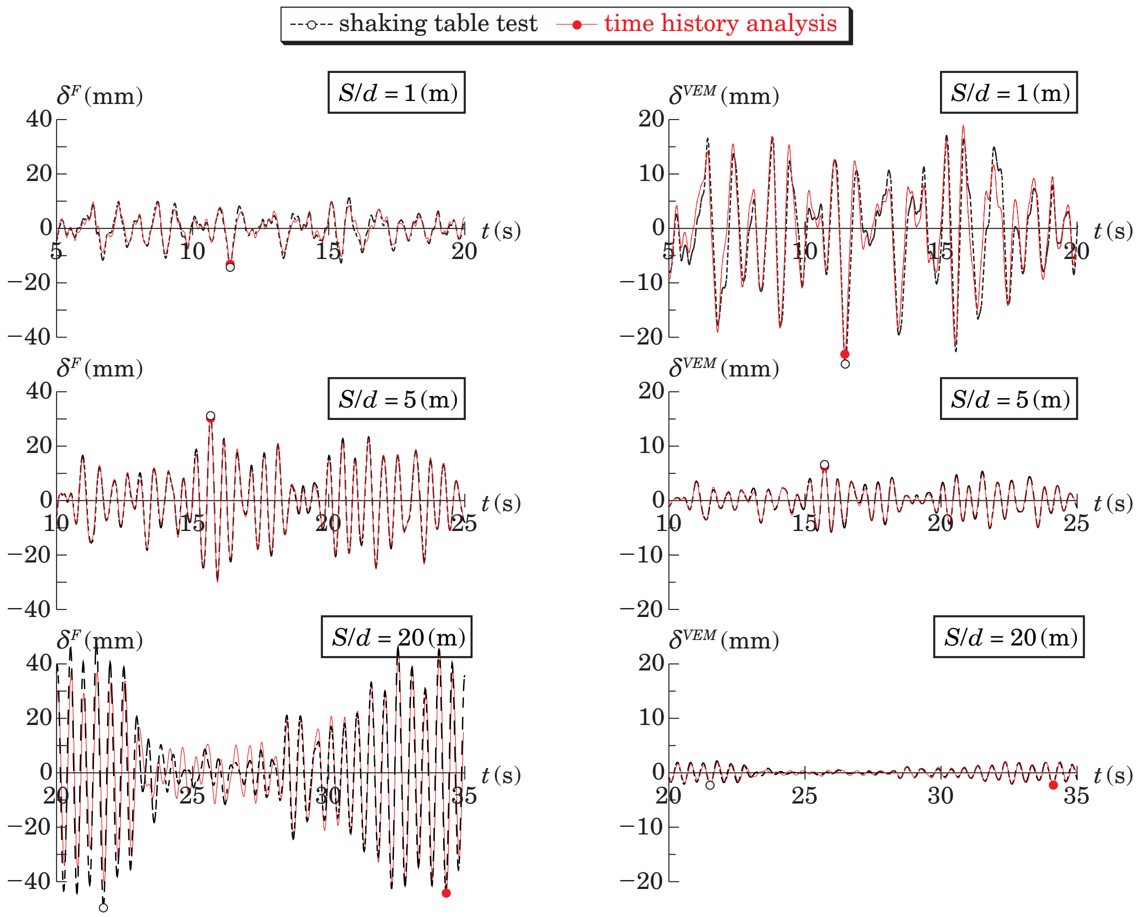
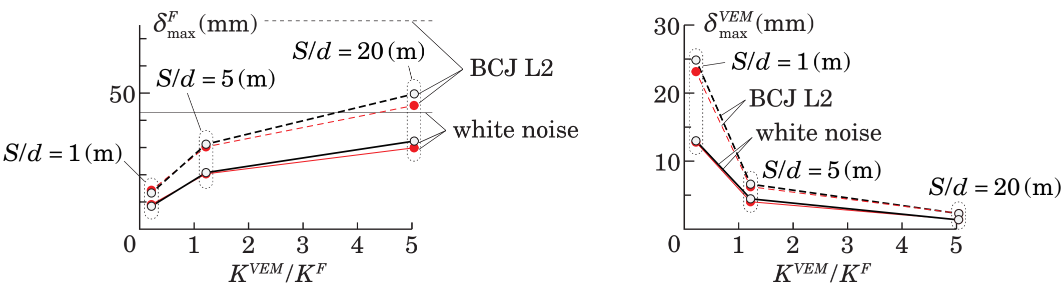


Figure 16. Comparison of story drift

Figure 17. Comparison of shear deformation



(a) maximum story drift

(b) maximum shear deformation of VEM

Figure 18. Maximum response

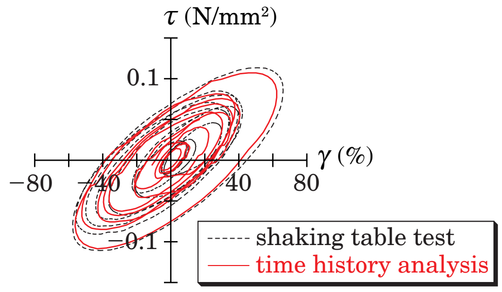


Figure 19. Comparison of hysteresis loop of VEM (in case of $S/d = 5\,(\mathrm{m})$)

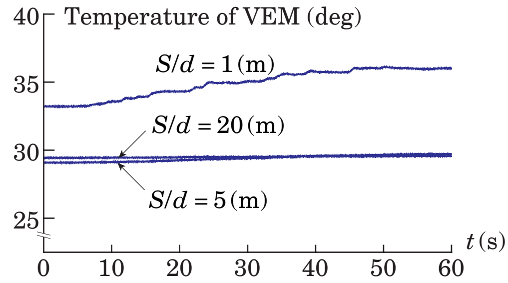


Figure 20. Time history of temperature of VEM

5. CONCLUSIONS

In this paper, seismic response of single-story steel moment frame in the elastic range equipped with the isolated floor system was confirmed by numerical analysis and shaking table test. Major findings obtained from these investigations are as follows.

1. Seismic response of the frame (i.e. the maximum story drift angle and the maximum story shear force) decreases if ratio of shear area to thickness of VEM S/d, which is the most important parameter, becomes small. At the same time, the maximum shear deformation of VEM increases as S/d becomes small, so that it must be paid attention that the clearance around the floor slab is as large as not to crash columns or walls.
2. As ratio of weight of floor to total weight of frame becomes large, seismic response of the frame with the floor system decreases. On the other hand, influence of natural period of frame on seismic response of the frame is less.
3. It can be considered that the proposed analysis model for single-story frame in the elastic range is valid because analysis results almost agree with the shaking test results in a macroscopic sense.
4. Seismic response in elastic range of the frame with the isolated floor system can decrease about thirty to fifty percent compared with that of ordinary frame without the system if ratio of area to thickness of VEM S/d is chosen appropriately.

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