EFFECTS OF FRICTION DAMPERS ON SEISMIC BEHAVIOR OF GYMNASIUM WITH STEEL ROOFS SUPPORTED BY BRIM-SLAB

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Abstract

This paper is intended to investigate the effect of friction dampers on seismic behavior of gymnasium with steel roofs supported by Brim-slab. Reinforced concrete structures with steel roofs are widely used in school gymnasia in Japan, which are assumed to be used as shelters after earthquakes generally. However, many studies have shown that a large numbers of school gymnasia were damaged in recent great earthquakes so that the safety of their use as a shelter had to be rethought. In the past study, a new component named “Brim-slab” applied to gymnasium with steel roof have been investigated. The research results indicate that Brim-slab can take effect to prevent the failure at the anchored connections of steel roof bearings and RC frames. In this paper, considering that since gymnasium with Brim-slab has a plane surface on which steel roof can slide over it, a seismic retrofit method by inserting energy-consuming elements at the roof bearings was proposed to reduce the seismic behavior of the steel roof. The modelings of school gymnasia with steel roofs supported by Brim-slab and roof bearings with friction dampers were carried out by 3-D inelastic response analysis program. The seismic response and the component damage were investigated in relation with earthquake waves and slip friction by changing the friction coefficient of the dampers. By the numerical analysis, the seismic responses of gymnasia under different input motions and slip friction of friction damper were discussed. The motion process of steel roof supported by Brim-slab with friction dampers in earthquake was analyzed and by calculating the displacement of the friction damper, the amount of energy it consumed during the earthquake was calculated.

Keywords: Steel roof gymnasium; Seismic response analysis; Friction damper; Shelter; Roof bearing

1. Introduction

Reinforced concrete structures with steel roofs are widely used in school gymnasia in Japan, which are assumed to be used as the shelters after earthquakes generally. They are usually designed to be stronger to prevent collapse during the earthquakes. However, many studies have shown that a large numbers of school gymnasia were damaged in recent great earthquakes [1].

The observed damage of steel roof gymnasium in the past surveys are shown in Fig. 1. The concrete cracked or flaked-off from columns and the anchor rods deformed or broken during earthquakes. These caused the wall to separate from the roof and the interior materials fell so that the anchored connections of steel roof bearings to RC frame failed. The reason was the excessive out-of-plane response of the cantilevered RC columns and walls supporting roofs [2]. Such damage was observed in not only aged gymnasia but also ones built recently. Therefore, a new type of design that can reduce such damage is required strongly.

Fig. 1 Observed damage of steel roof gymnasium

In the past study, a new designed component named “Brim-slab” applied to the RC frame of gymnasium with steel roof had been investigated [3]. Brim-slab is placed on top story of the substructure and constitutes the entire beams that can be imagined as the headband of the RC frame. The research results indicated that Brim-slab can take effect to raise the stiffness and restoring force of the RC beams in the top story of substructure compared with traditional structures because it increases the cross-sectional area of the components. It can also reduce the shearing force of steel roof as well by disconnecting the roofs and the columns. Therefore, it can reduce the out-of-plane displacement of RC frame significantly for preventing the failure at the anchored connections of steel roof bearings and RC frames. In addition, it is also effective to avoid the collapse and falling of ceiling and interior.

In this study, considering that gymnasia with Brim-slab have a plane surface on which the steel roof can slide, friction dampers were set on it as energy-consuming elements to control the seismic response of the steel roof. A 3-D analysis program SEIN was used in this study. The seismic behavior of gymnasium with steel roofs supported by Brim-slab is investigated that includes the maximum slip, the hysteretic behavior, the residual slip and the energy consumption of damper frictions. The parameters of the analysis are seismic waves and friction coefficients of damper. The placement of Brim-slab and friction dampers is shown in Fig.2.

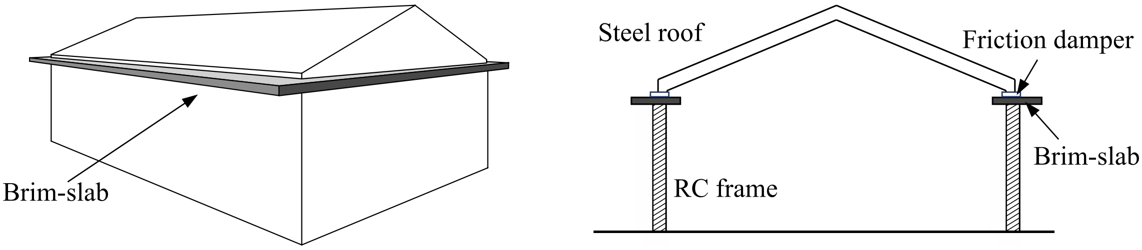
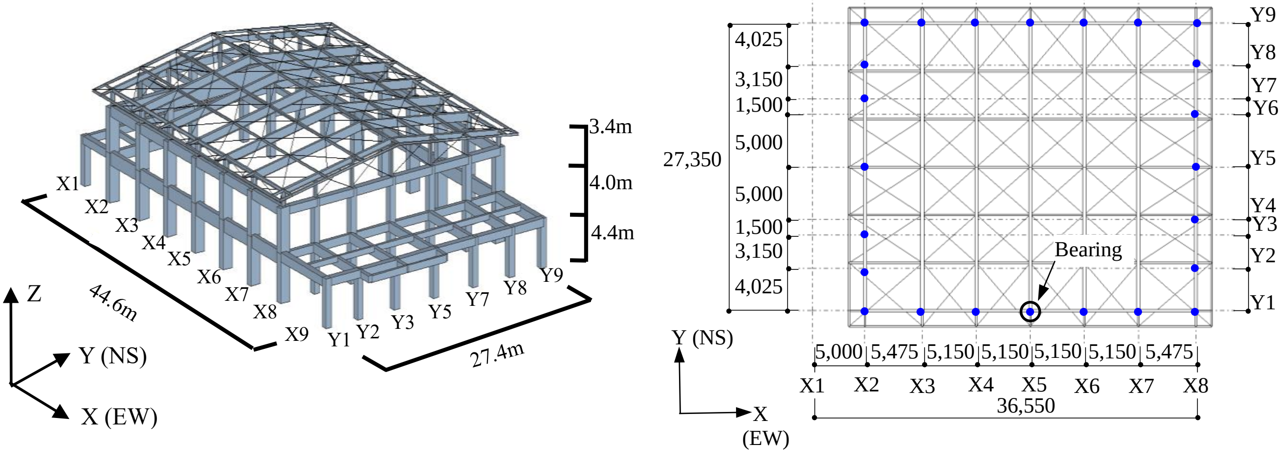


Fig. 2 Setting of Brim-slab and friction damper

2. Analytical model

The analytical models were the same as in reference [3], which were based on a real gymnasium which suffered the 2016 Kumamoto earthquake in Japan. The models were built by RC frame substructure and steel roof supported by Brim-slab at the bearings and the friction dampers were set on it. Fig.3 shows the main structure of the building models. Span and longitudinal directions are EW (X) and NS (Y) directions respectively. The bending stiffness of the beams of the top story of the RC frame around the weak axis was set to 50 times of the original building's considering that Brim-slab can raise the stiffness of beams.



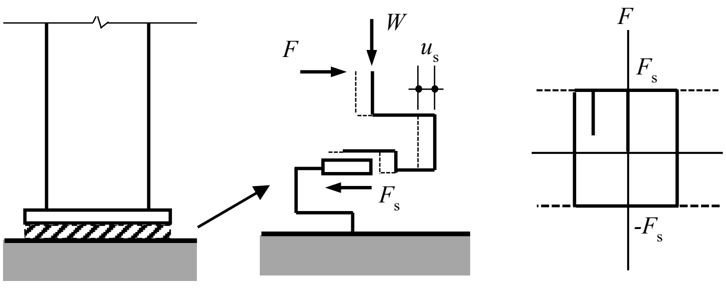
(a) Main structure of building model (b) Roof plan and bearing position

Fig. 3 Building model

Behavior of friction dampers is based on Coulomb's friction law which is expressed by Eq. (1). The friction damper model is shown in Fig. 4. It can be seen from Fig. 4 (c) that the initial stiffness of the friction damper has infinity value, which should be set to extremely large (10^6kN/mm). At the beginning, the force of slip friction increases without the damper sliding. When the force of friction damper reached maximum, it remains constant and the damper begins to slide.

$$F_s = \mu \cdot W \tag{1}$$

where F_s: force of slip friction, μ: the coefficient of slip friction, W: the contact pressure of the friction element. It is assumed that the pressure on the friction elements keep constant and the plane on which the friction dampers are located is always horizontal.



(a) Bearing (b) Friction damper (c) F-u_s relation

Fig. 4 Friction damper model

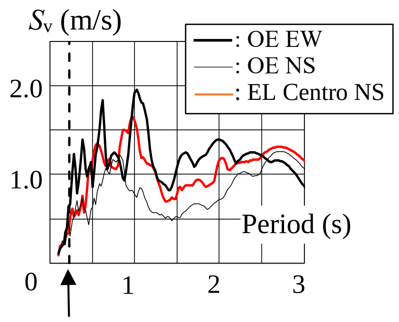


Fig. 5 Velocity response spectra

The seismic response analysis of the models has been calculated by using 3-D inelastic response analysis program (SEIN La DANS). Newmark-β method ($\beta = 1/4$) is used as the numberical integration scheme for a time history response analysis. The time interval of the analysis is 0.002s. The Rayleigh Damping is chosen as the viscous damping of models. The damping factors of the first mode (h1) and the second mode (h2) are assumed to be 0.03. OE wave which is the full scaled ground motion of the 2016 Kumamoto earthquake is used as the input ground motion, as well as the El Centro wave. The duration of the dynamic analysis was 20 s and 30 s respectively. The velocity response spectra of input ground motions are shown in Fig. 5. The details of the earthquakes' information are shown in Table 1.

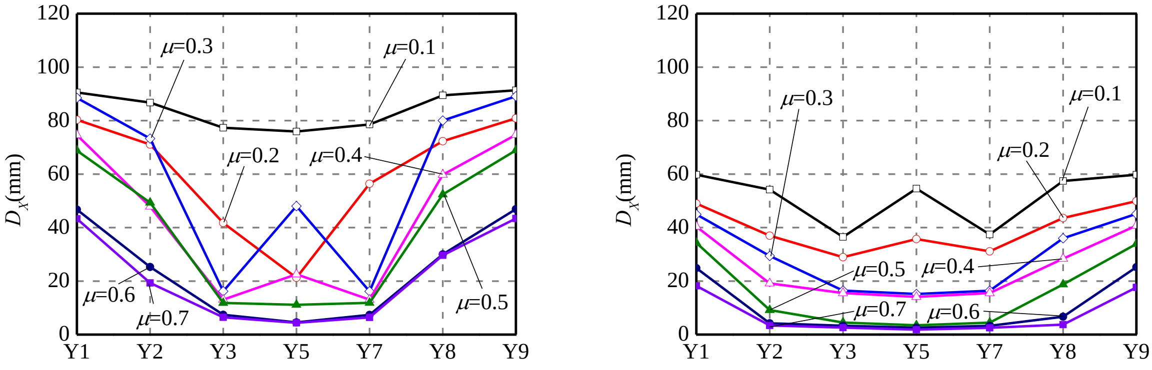
Table 1 – Earthquake records

Earthquake records	Peak of acceleration (m/s^2)	Duration (s)
EL (NS)	7.65	30.0
OE (NS)	6.27	20.0
OE (EW)	4.78	20.0

3. Results of analyses

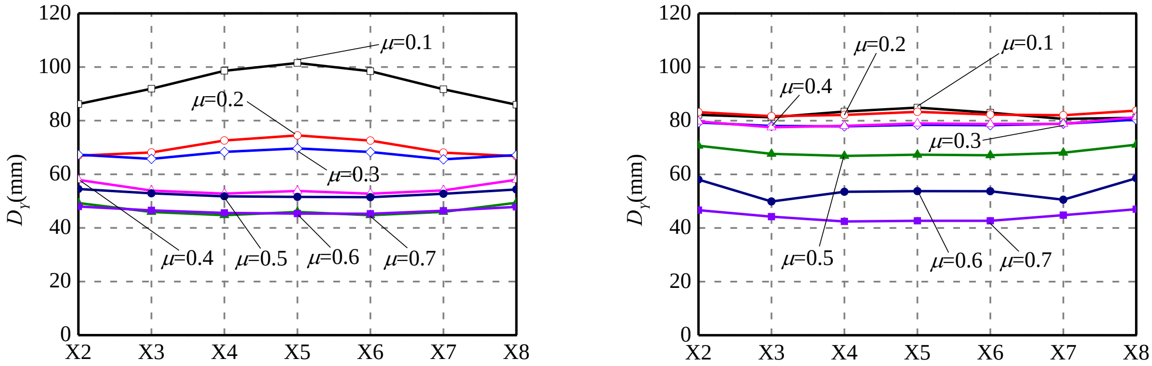
3.1 Maximum slip of friction dampers

Fig. 6 shows the relationship between the slip coefficient μ and the maximum slip D of the friction dampers. The horizontal axis shows the bearing number in Fig. 3 and the slip means the deformation between steel roof and RC frame. According to Fig. 6 (a) and (b), it can be found that the maximum slips in X direction decrease as the slip coefficient increases except for the damper located at Y5. The slip of friction dampers at Y1 and Y9 bearings are larger than the others under any slip coefficients. The reason is that there is a lower RC frame at the second floor from Y3 to Y7 line between X1 and X2 line of the model, which causes the slip of steel roof in this section to decrease.



(a) X direction (EL NS)

(b) X direction (OE NS, EW)



(c) Y direction (EL NS)

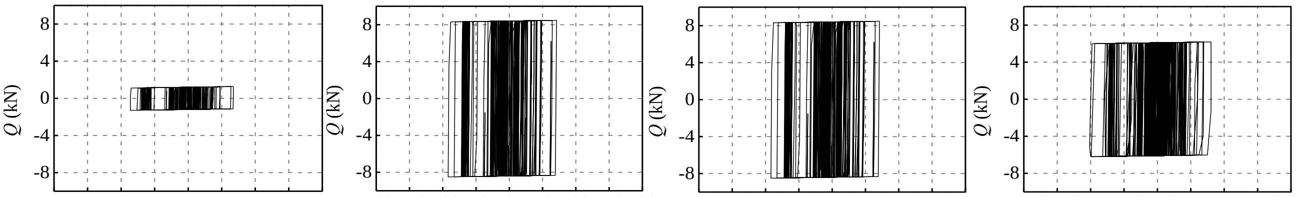
(d) Y direction (OE NS, EW)

Fig. 6 Maximum slip of friction damper

Meanwhile, the maximum slips in Y direction also decreases when the slip coefficient increases, as shown in Fig. 6 (c) and (d). The slips between the friction dampers in same line are almost constant. This is because the roof is composed of a steel crossing purlins frame so that it can move together. Compared with installing friction damper on the bearing directly, it can be found that the gymnasium with Brim-slab can solve the problem that the center friction damper has a large slip and energy consumption, but the ones of side are not obvious.

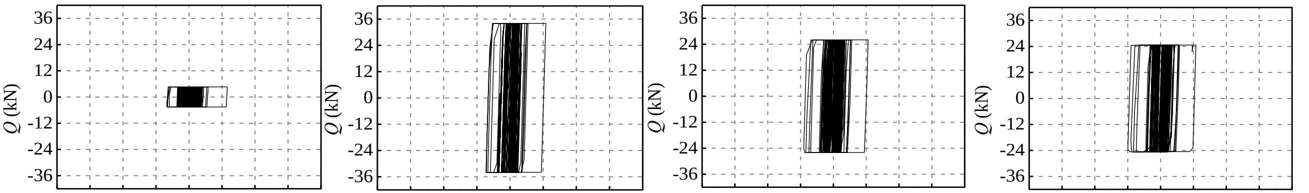
3.2 Hysteretic behavior of damper

Fig. 7 shows the hysteretic behavior of the dampers with slip coefficients μ=0.1 and 0.4 for the bearings of Y1 line from X2 to X5. The input ground motion is El Centro NS. It can be found that the hysteretic behavior of all friction dampers is consistent with the relationship curve shown in Fig. 4 (c). The dampers at all positions in the same line have apparent slip deformations during earthquake, indicating that they can consume the energy generated by earthquake. The energy consumption performance of friction damper placed on Brim-slab is mainly related to its maximum friction force. In addition, comparing the hysteretic behavior at friction coefficients of 0.1 and 0.4, it can be found that as the coefficient increases, the slip deformation of same friction damper decrease.



(1) X2 bearing (2) X3 bearing (3) X4 bearing (4) X5 bearing

(a) Slip coefficient *u*=0.1



(1) X2 bearing (2) X3 bearing (3) X4 bearing (4) X5 bearing

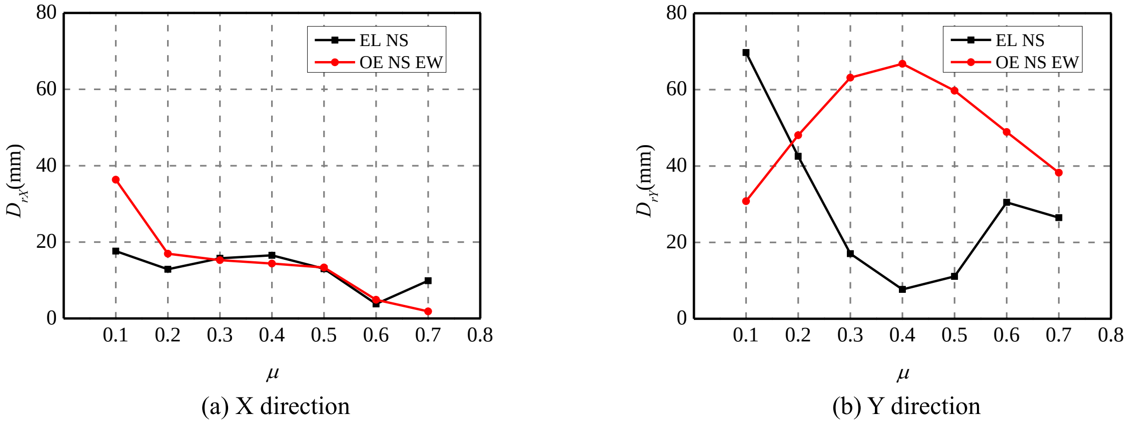
(b) Slip coefficient *u*=0.4

Fig. 7 Hysteretic curves of friction dampers

3.3 Residual slip of friction dampers

Residual slip after earthquakes is one of the important indicators for restoring a building to its original state. In other words, if the amount of residual slip becomes excessive, there is a problem that it takes a lot of time and effort to repair.

Fig. 8 shows the relationship between the slip coefficient μ and the maximum slip *Dr* of the friction dampers. Looking at the maximum residual slip in the X direction in Fig. 8 (a), it is generally 40mm or less. There is a tendency for the maximum residual slip in the X direction that it decreases as the slip coefficient increases. The maximum residual slip in the Y direction in Fig. 8 (b) varies with the ground motions. In El Centro NS, the maximum residual slip in the Y direction decreases with the increasing of slip coefficient, and increases when the slip coefficient reaches 0.4. It reaches a minimum residual deformation of 7.7 mm when the friction coefficient is 0.4. On the other hand, in the OE NS EW, conversely, the residual slip increases as the slip coefficient increases, and decreases when the slip coefficient reaches 0.4. It reaches a maximum residual deformation of 68.2 mm when the friction coefficient is 0.4. For the residual slip in the Y direction, its relationship with the friction coefficient of damper is not obvious, the change of it cannot be predicted by changing the friction coefficient.



(a) X direction (b) Y direction

Fig. 8 Residual slip of friction dampers

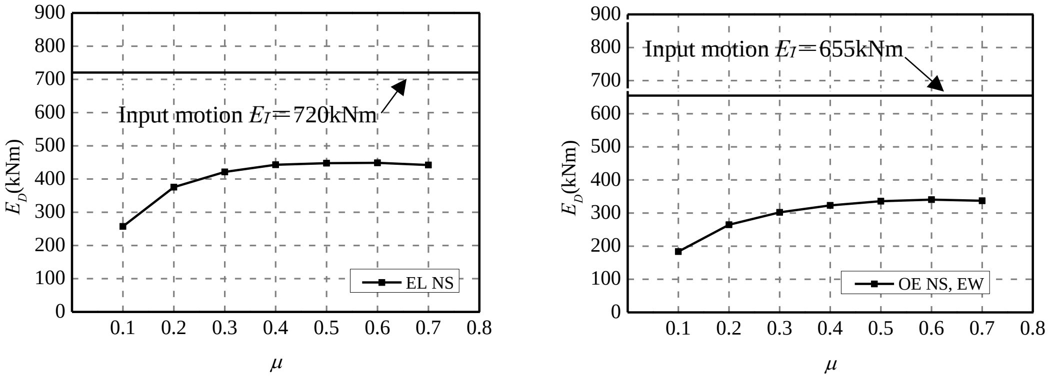
4. Energy consumption

The performance of the friction dampers is evaluated by calculating the energy consumed by them during earthquakes. The calculation method is to calculate the area of the hysteretic loop of the friction dampers as shown in Fig. 7. The calculation formula is expressed as Eq. (2).

$$E = \int Fds \tag{2}$$

where E: the energy consumed by friction damper, F: the friction force of damper, s: the displacement of friction damper.

Fig. 9 shows the relationship between the slip coefficient μ and the total energy consumption E_D. In the Figure, the input energy E_I of each ground motion is shown by a solid line for comparison. According to the Fig. 9, when the slip coefficient is between 0.1 and 0.6, the energy consumption of friction dampers increases monotonically with it. When the slip coefficient reaches 0.6, the energy consumption attains the maximum, which is 448.7kNm and 340.5kNm respectively. The maximum energy consumption is approximately 1.75 times of it when slip coefficient is 0.1. Thereafter, energy consumption decreases with the increasing of slip coefficient. The change in energy consumption is obvious when the slip coefficient is increased from 0.1 to 0.2. In El Centro NS, when the slip coefficient is between 0.4 and 0.7, the energy consumption remains almost the same which is about 440kNm. The relationship between the energy and the slip coefficient in OE EW NS



(a) EL Centro NS (b) OE NS, EW

Fig. 9 Energy consumption

shows a similar tendency. When the slip coefficient is between 0.4 and 0.7, the energy consumption is almost the same about 335kNm. From the consumed energy ratio (E_D/E_I), the maximum energy consumed by the friction damper accounts for 62.9% and 50.4% of the input energy respectively. This means more than half of the input ground motion can be consumed by friction dampers.

5. Conclusions

In this study, we modeled gymnasia with steel roof supported by Brim-slab, in which friction dampers were added on the Brim-slab. The following conclusions were drawn from this study:

1. The maximum slips in the X and Y directions tends to decrease when the slip coefficient of the friction damper increases. The maximum slip in the X direction fluctuates greatly with the positions of the damper, and it in the Y direction shows a nearly constant value.

2. The maximum residual slip differs depending on the response direction of models and the change of seismic motions. The amount of residual slip in the X direction decreases with an increase in the slip coefficient. However, the one in the Y direction fluctuates and is difficult to predict. In this study, it was 69.7mm.

3. The amount of energy consumed by the friction dampers changes depending on the slip coefficient. It can be ensured that damage of the frame can be avoided by properly adjusting the slip coefficient, which was 0.6 in this study.

However, these results are under limited conditions. The seismic behavior of gymnasium is affected by the input ground motion and the scale of model deeply. In the future, the relations between them needs to be addressed.

Acknowledgements

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