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STUDY ON THE SEISMIC DEVICE AT BUILDING WITH TOGGLE DAMPING BRACE

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Abstract

The object of this study is to develop effective devices to responses of buildings against earthquake motions. The proposed devices in this study named “toggle type seismic structural control amplification mechanism brace” install amplification mechanism and oil-damper at unique earthquake resistance building systems. In the following, “toggle type seismic structural control amplification mechanism brace” is called "toggle damping brace.” The toggle damping brace has two transmitted axial force members and one oil-damper in a frame of the left and right columns and the upper and lower beams, and these structural members constitute the “amplification (lever) mechanism.”

We have come to know that the toggle damping brace has a characteristic structure in that the amplification factors vary according to the deformation of the building caused by an earthquake shake, because the mechanisms have geometric nonlinearity. We show a proposal of the formulation of mathematical model of the toggle damping brace mechanisms and try to present the structural control effectiveness through the seismic response analysis of the building. The responding displacement of the building due to a large earthquake can be minimized by the toggle damping brace, and it can be applied to a large variety of building structure such as steel structure, reinforced concrete structure, and Japanese classic wood structure. Also, an effectiveness of response control is excellent in both cases of new buildings and retrofit of existing reinforced concrete buildings.

This paper reports on seismic retrofit of existing reinforced concrete buildings that our devices had been installed in and was attacked by “the 2011 off the Pacific coast of Tohoku Earthquake,” hereinafter called “311-earthquake.” We tried to analyze effects of the damage by 311-earthquake, using the waveforms of the seismic acceleration recorded by the seismic observation equipment installed in the buildings. The existing structural model for building analysis is a equivalent shear type model of two frame using a multi-degree of freedom system divided into a column-beam frame and an earthquake resisting wall. The hysteresis characteristics are a Takeda model and an origin-oriented model. We used an analysis model combining existing structural model and a toggle damping brace model.

Further, as new buildings fitted with a toggle damping brace, we also report one case in preparation for a major earthquake attack. The new building is a 7th story steel structural building and it was analyzed by eleven seismic acceleration waves. Its target value of the structural performance is 1% of the drift angle of each story, and we have obtained a good position of the toggle damping brace that satisfies the target value by trial and error.

Both the new building and the existing retrofit building were shown to be given a large damping by toggle damping brace. We have proved that it is possible to reduce about 30% displacement of the building due to the earthquake by designing the building with toggle control brace installed compared to building without it. As a result, it can be said that the toggle damping brace, which was able to add a large damping at building, was able to increase the earthquake resistance of the building. Therefore, we have succeeded in developing a response control device, toggle damping device that can be attached to new or existing buildings and perform high resistance to earthquakes.

Keywords: seismic device, structural control, amplification mechanism, damping brace, geometric nonlinear

1. Introduction

The addition of large damping to a building enables the suppression of seismic response displacement of the building. Therefore, we developed a system with large damping by utilizing the principle of the "lever" to amplify the damping force and the displacement of an oil damper for transmission to the frame of the building.

Now, we explain the mechanism and the effect of the toggle seismic control brace (hereafter referred to as "toggle") of the brace type consisting of three members as shown in Fig. 1. That is to say, in the toggle system, the small damping force of an oil damper is amplified to obtain a large damping force by the toggle mechanism. (The details of the toggle mechanism are shown in reference document 1.) The toggle mechanism consists of two axial force transmission members (referred to as toggle arms) and an oil damper as shown in Fig. 1.

Structural members will be described later. The main feature is that the horizontal displacement of the frame (point A) is concentrated and dispersed to the force and the displacement at the middle junction (point B) through the toggle arm. The displacement and the speed of point A is transmitted to the oil damper as amplified displacement and speed at point B. That is to say, the oil damper of the speed-dependent type is a system that returns a large damping force to the frame by utilizing the displacement and the speed amplified at point B.In other words, for the speed and the displacement entered in the oil damper, the speed and the displacement entered in the building are amplified by the toggle.

Therefore, the oil damper works with a large value obtained by amplification even if the building has small displacement and speed.

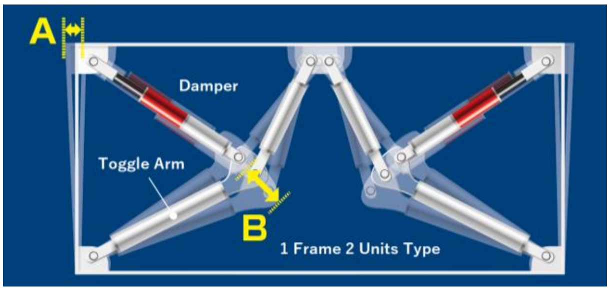

Fig. 1 Mechanism of toggle seismic control brace

2. Structural members of toggle

The toggle is a basic member in which an oil damper and two toggle arms constitute the toggle mechanism (lever mechanism) in the frame surrounded by columns and beams of the building as shown in Fig. 2. Other than these, rotation supports, pin shafts, gusset plates depending on installation situation, and peripheral steel frames shall be included. Main members constituting the toggle will be explained now.

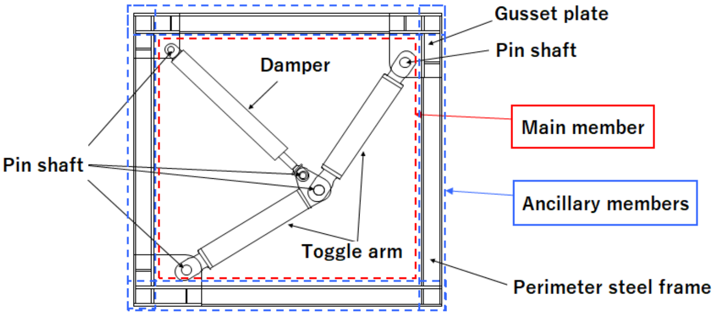

Fig. 2 Structural members of toggle

1) Oil damper

The oil damper is a mechanism having the effect of converting the vibration energy of an earthquake to thermal energy to reduce tremors. See reference document 5. Fig. 3 shows the schematic diagram of the oil damper.The resistance of the oil damper is generated by the motion where a piston head slides in a steel tube filled with oil, and it increases in proportion to the piston speed.

This resistance is the damping force. In Fig. 3, the sliding motion of the cylinder in the right direction compresses oil to generate the resistance. The main methods of testing for guaranteeing the performance of the oil damper are verified by conducting the performance limit tests in which the speed is increased until the downturn of the damping force and the endurance tests by applying the repetition of several tens of thousands of times. In addition, we recognized the basic performance, such as the durability of 60 years or more, by also conducting the thermal degradation tests considering aging degradation. Fig. 4 shows the relationship between the damping force and the displacement of the oil damper of the type in which the damping force is relieved at 250 kN.

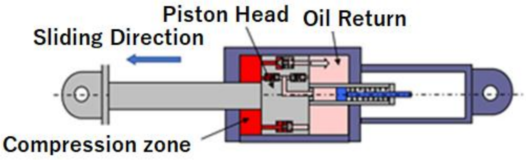

Fig. 3 Schematic diagram of oil damper

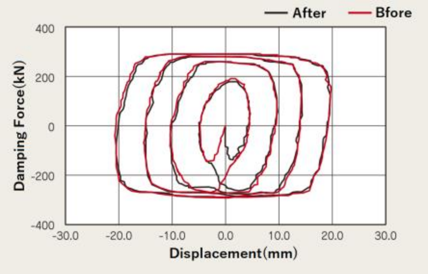

Fig. 4 Performance curve of oil damper

2) Toggle arm

Two toggle arms transmit the relative horizontal displacement and the horizontal force between the upper and lower parts of the layer of the building installed with the toggle to the oil damper play the role of an energy absorbing device. Therefore, a steel tube of STK or STKM material is used for the toggle arm, the outer diameter of the steel tube is determined in the range of 216.3 mm to 270.3 mm, and the wall thickness is in the range of 25 mm to 50 mm considering the required performance because we think that the rigidity (axial rigidity) of the toggle arm members is more important than the yield strength of the members. The rotation supports are mounted to both ends of the toggle arm by welding. There are two types of toggle arm. That is to say, one type of toggle arm has rotation supports for connecting to other toggle arms at both ends as shown in the lower part of Fig. 5, and another type has the same rotation support as the above at one end and a rotation support for connecting to the other toggle arm and an oil damper at the other end as shown in the upper part of Fig. 5. This enables the installation of a single oil damper, and only the oil damper can be independently replaced if a contingency requires replacement just in case.

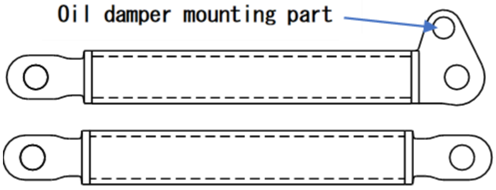

Fig. 5 Toggle arm

3) Rotation support made of forged material (see reference document 4))

Since the rotation support (clevis) shown in Fig. 6 turns slightly around the pin shaft while subjected to a high axial force generated in the toggle arm, hardness resistant to wear is required, although high strength is essential. Weldability is also required because the clevis is joined to the toggle arm by welding. Although hardness and weldability are contradictive properties, material satisfying both properties is required. However, if material satisfying these properties among the specified building materials stipulated in the Building Standards Law is used, the clevis becomes too large and that means it is not practical. Therefore, we first performed the development of materials that satisfy these performance requirements and acquired certification of the specified building materials stipulated in Article 37 of the Building Standards Law.

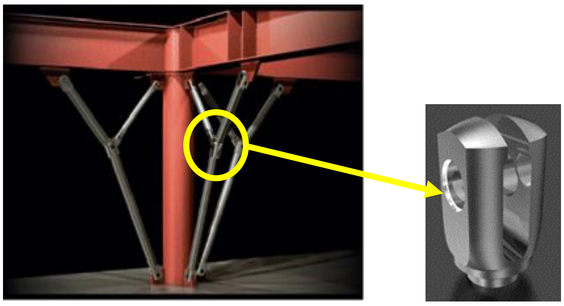

Fig. 6 Rotation support made of forged steel

3. Basic performance

1) Basic principle of toggle

We explain the basic principle of the toggle as a lever using the single degree of freedom system model shown in Fig. 7. In the diagram, *m*, *c*, and *k* represent the mass of the main frame, the viscous damping coefficient, and the rigidity, respectively, and those symbols with suffix *d* mean the auxiliary mass attached to the amplifier, the damping system (viscous damping coefficient) and the spring (rigidity), respectively.

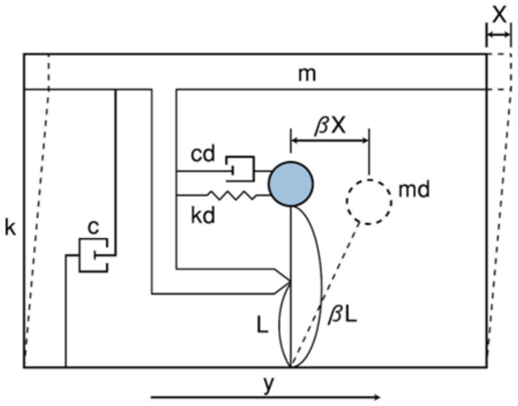

Fig. 7 Basic model of “lever” in frame

Here the displacement magnification factor shall be called β. Since β is the value for the lever, it is always $|\beta| > 1$. Although we omit a part of the expansion at the time of formulation, this single degree of freedom system model can be expressed as a vibration equation shown in Eq. 1, and the arrangement of Eq. 1 using Eq. 3 will return to Eq. 2 with the form of a generally used vibration equation. However, since γ_c is multiplied to the term in the right side, and the term in the right side always has the relationship of $\gamma_c \cdot y < 1$ as shown by Eq. 3, the effect of input reduction can be expected.

$$(m + m_d\beta^2)\ddot{x} + (c + c_d\beta^2)\dot{x} + (k + k_d\beta^2)x = -(m + m_d\beta)\ddot{y} \quad (1)$$

$$\ddot{x} + 2h_c\omega_c\dot{x} + \omega_c^2 x = -r_c\ddot{y} \quad (2)$$

$$\gamma_c = \frac{1 + (m_d/m)\beta}{1 + (m_d/m)\beta^2} \quad (3)$$

2) Magnification of toggle

Although it was found that the mechanism of the lever can be expressed by a vibration equation, in the case of the mechanism in which the fulcrum, the point of application, and the point of action are aligned on a straight line as shown in Fig. 7, the generation of bending, shearing, and axial stresses in each member of the lever requires an increase in the size of the members. Therefore, the bending and shearing stresses of the toggle are reduced as much as possible by providing pins to the clevises of the toggles as shown in the above Fig. 2, and the mechanism that transmits the stress only axially to obtain the amplification factor is adopted.

Fig. 8 shows an example of an amplification factor curve. The assumed frame shall be 4,500 mm wide and 3,000 mm high and shall be a toggle of a one-frame one-unit type with an initial magnification factor of 2.25. If the toggle is assumed to move by 30 mm in horizontal displacement, the fluctuation of the magnification factor due to geometrical nonlinearity is from 2.0 to 2.6 times, and the fluctuation of oil damper displacement is from -63 mm to +73 mm.

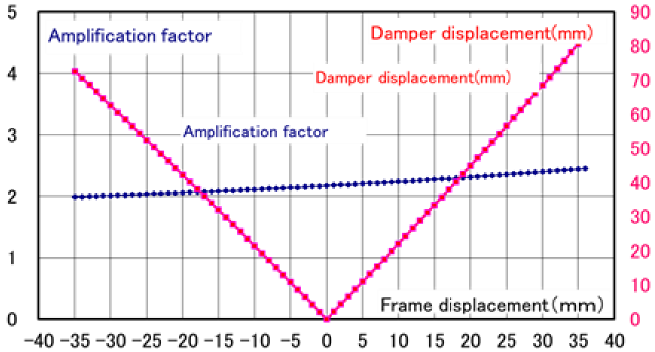

Fig. 8 Example of magnification factor curve

4. Design of toggle and application range

We obtained a technical evaluation of the toggle design and manufacturing by the optional rating in 2012 (updated in 2018) in the Japan Association for Building Research Promotion as shown in reference 6.

1) Feature and type

The toggle is a seismic control brace that enables higher efficiency for seismic energy absorption by amplifying the small interlayer displacement generated in a building and the speed for application to an oil damper. The definitions of the magnification factor of amplification and the horizontal damping force generated as a toggle are shown by the following formulae (1) and (2), respectively:

Magnification factor of amplification = Oil damper displacement/Interlayer displacement (1)

Brace damping force = Magnification factor of amplification × Oil damper damping force (2)

There are concave and convex types of toggles when viewing the shapes of the toggle arm in a column-beam frame, and there are two cases of the arrangements, namely the first is one unit arrangement in one frame and the second is two units arrangement in one frame when the span of the frame is large as shown in Fig. 9.

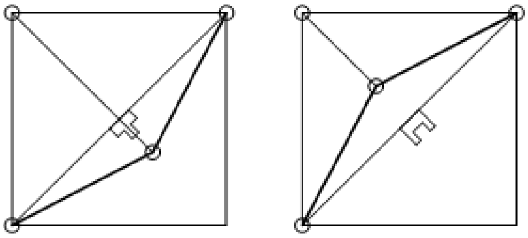

Fig. 9 Type of toggle

2) Model for analysis

The outline of an analysis model of a toggle is shown in Fig. 10. Each member shown in the right diagram of the toggle shape is individually converted to a wire rod as a line diagram shown on the left, depending on each shape, the rigidities of the toggle arm and the clevis are evaluated as serial springs, and the damping characteristic of an oil damper is calculated by substituting a Maxwell model.

3) Maximum allowable value

The oil damper has two types regarding a standard damping force, namely 500 kN and 850 kN types, and the maximum speed is assumed to be 600 mm/s for both types. The stroke is ±110 mm (p-p 220 mm).

The expected horizontal damping force is 1,000 kN to 2,125 kN because the damping force of an oil damper is multiplied by the recommended factor (2.0 to 2.5 times) as shown by [Damping force of oil damper] × [Magnification factor]. Since the stress of the toggle arm is resolved into an axial component at the central intersection point of the toggle (Point B in Fig. 10) and transmitted, and the maximum axial force of the toggle arm is required to be several times the damping force, the axial yielding strength must be obtained based on the shape of the toggle.

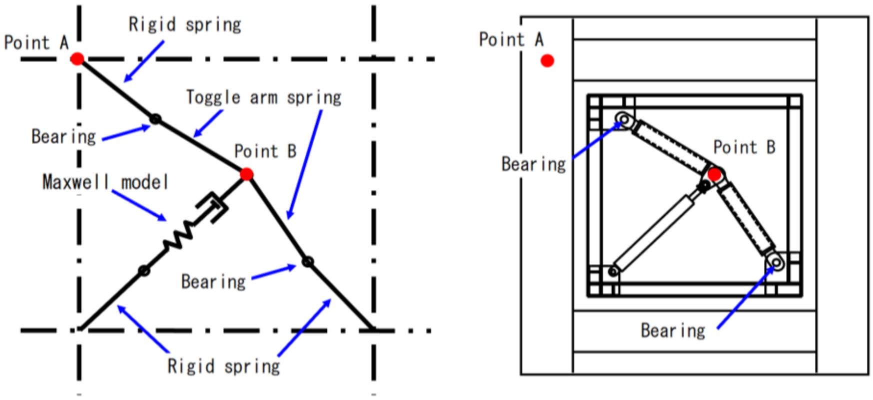

Fig. 10 Conceptual diagram of analysis model

4) Load for design

Concerning the structural performance required for a building, the degree of force necessary for suppressing the tremors of the building against the magnitude of an external force (seismic force) determines the number of required toggles, namely the magnitude of the maximum attenuation. It is important that each member constituting the toggle, such as the toggle arm is designed within the short-term allowable stress intensity so that the toggle demonstrates the expected damping capacity in the design stress obtained by this assumed maximum damping force and the magnification factor. It is necessary to set the design load by considering the fluctuation in the magnification factor due to the installation error of the toggle and the geometrical nonlinearity as explained in Fig. 8 of the previous section. In addition, it is also necessary to examine the design load acting on an outer surface by considering the outer surface acceleration that is generated when the weight of the toggle arm and the oil damper are vibrated at the outer surface.

5. Effect of toggle on structural performance

5-1 Sendai municipal office

1) Overview

In 2008, we performed the aseismic retrofit (vibration control reinforcement) of the main government building of the Sendai municipal office, and simultaneously installed seismometers on the first and roof floors to start seismic observations. We will now explain by mainly quoting reference document 3. The office was subjected to strong tremors in the Great East Japan Earthquake on March 11, 2011, as shown by the observation of an earthquake measuring upper 6 in the vicinity of the municipal office. According to the record of acceleration waveform in this earthquake, the acceleration observed on the first floor was 283.7 cm/s^2 in the direction of the crossbeams and 412.9 cm/s^2 in the span direction. We verified the effect of the toggle vibration control reinforcement by assuming the earthquake observation record obtained by this building as input earthquake motion. The appearance of this government building is shown in Photo 1.

Photo 1 Main government building of the Sendai municipal office

2) Design target

We assumed the target of the seismic performance of this building to be the level that the collapse in which a *building presents hazards to human life does not occur at the very least against large-scale earthquake vibration that rarely occurs during the life of the building* as stipulated in the new aseismic designing method.

We assumed the index of design criteria to be the displacement quantity of each floor of the building in order to perform seismic control reinforcement and assumed the interlayer deformation angle to be 1/150 or less. In addition, we provided the rigidity so as to prevent the partial fragile destruction that exposes the building to danger, examined the balance of the entire building, implemented the reinforcement by extending extension walls, reinforced structural slits and columns, and assumed the axial force ratio of columns at the time of an earthquake to be 0.5 or less. Furthermore, the damping force of an oil damper was assumed to be within 490 kN (potential of damping force of oil damper at 600 kN was used). The number of toggles installed was 94 in the direction of the crossbeams (X) and 88 in the span direction (Y).

3) Verification of building modeling

We obtained the load-deformation curve of the building model by an incremental analysis in the X- and Y-directions, and separated the Rahman frame and the earthquake resisting wall from its skeleton curve. We assumed the Rahman frame to be a modified tri-linear Takeda-type model and the earthquake resisting wall to be a tri-linear origin directional model to assume the building model by connecting two multi-degrees of freedom system models in parallel. In addition, we adjusted the rigidity of each member of the Rahman frame and the earthquake resisting wall of the building considering the damage (crack situation, etc.) due to an earthquake this time. The predominant period of the waveform (shown in reference document 2) of 0.96 seconds in the X-direction and 0.90 seconds in the Y-direction generated by the response of the observed earthquake obtained on the roof floor was assumed to be the first natural period in each of the X- and Y-directions of the analysis model. Structural damping was assumed to be 3% of the first natural period in both the X- and Y-directions. We adopted the two multi-degrees of freedom system models in which the building is divided into the Rahman frame and the wall frame. We arranged the frame of the toggle in the number of stories and units where the toggles are installed, arranged it in parallel with the two multi-degrees of freedom system models, and decided to use the model that behaves in the same displacement on each layer (hereafter referred to as toggle reinforcement model) as shown in the conceptual diagram of Fig. 11.

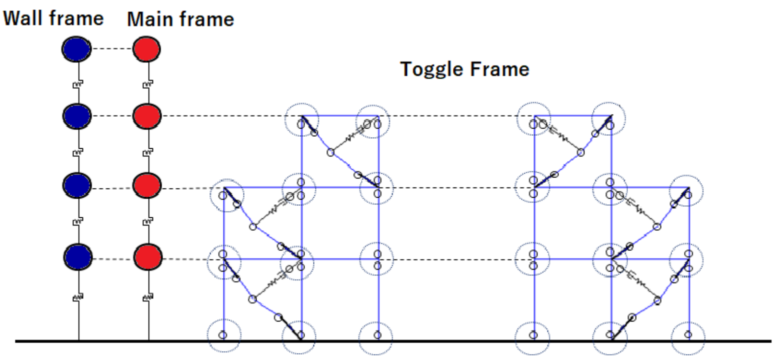

Fig. 11 Lumped mass system building model and toggle frame model

Fig. 12 shows the overlapped waveforms given by performing response analyses under the assumption that the acceleration of the observation record obtained on the first floor is the input earthquake vibration, performing the analysis of response displacement waveform on the roof floor, and converting the acceleration waveform obtained at the time of the earthquake on the roof floor to displacement. In the diagram, the red curve and the blue curve show the analysis result and the observed waveform, respectively. Since good matching was obtained in both the X- and Y-directions, it can be said that the reasonability of the analysis results of the building model assumed this time was verified. We decided to consider that the response result of each layer also has mostly reproduced the physical properties of the building from the analysis condition in this model used for comparing the roof floor and to hereafter proceed with the examination.

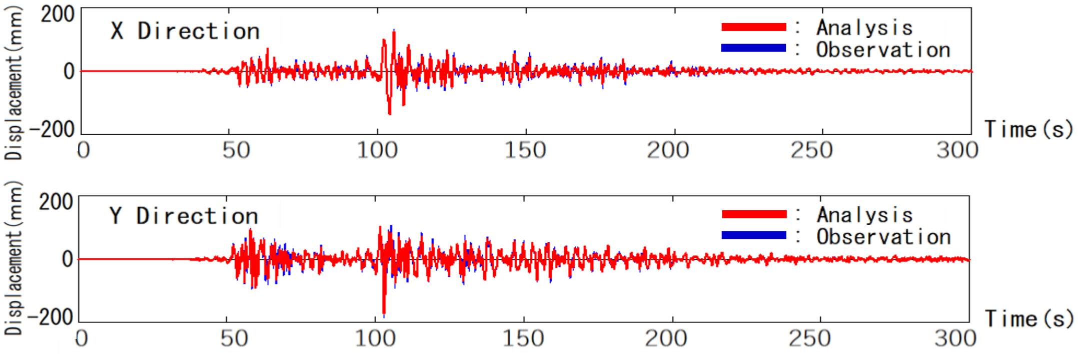

Fig. 12 Comparison of observed and analyzed waveforms

4) Comparison of presence and absence of toggle reinforcement

Since we can consider that the afore-mentioned analysis model of the multi-degrees of freedom system can mostly reproduce the main government building reinforced by the installation of toggles (toggle reinforcement model), we decides to evaluate the building model in the case of the absence of toggle reinforcement (referred to as present building model) by removing the toggles from the toggle reinforcement model.

We performed the earthquake response analyses of the building tremors using the same input earthquake vibration in the case of the presence and absence of the toggle, performed the comparison, and showed the results of the interlayer deformation angle of each layer in the X- and Y-directions in Figs. 13-1 and 13-2, respectively. In the X-direction of Fig. 13-1, the interlayer deformation angles of the present building model (not reinforced) on the third to seventh floors exceeded the target value of 1/150 of the interlayer deformation angle stipulated in the design criteria, and the maximum angle was 1/61. In the Y-direction of Fig. 13-2, the angles exceeded the target value of 1/150 on the first, seventh, and roof floors, and the maximum angle is 1/58. On the other hand, the angles of the toggle reinforcement model (reinforced) satisfied the interlayer deformation angle to be 1/150 of target value on all the floors in both the X- and Y-directions, and they were mostly about 1/200, resulting in angles far lower than the value of the design criteria. These facts indicate that there was a high possibility that this government building was heavily damaged if it were subjected to the earthquake on March 11, 2011, in the condition without reinforcement of the building.

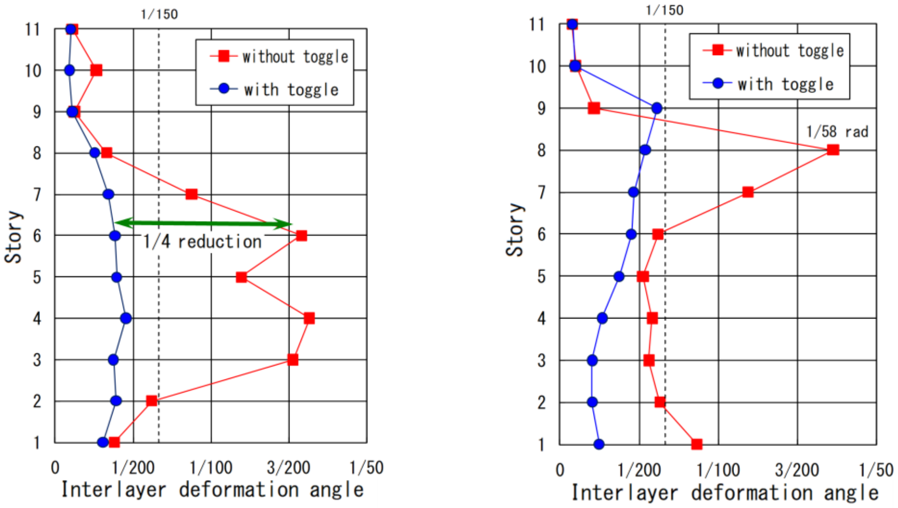

Fig. 13-1 X-direction

Fig. 13-2 Y-direction

Fig. 13 Comparison of response results

As Photo 2 shows the situation of the inside of the first floor after two days from the disaster (on March 13, 2011), the overturning of shelves and furniture and the damage to structural members of the columns, beams, and walls of the building and to non-structural members of the walls is not recognized, and any falling of the ceilings is not found, which enabled the evacuation starting from the same day of the earthquake. Therefore, we consider the seismic control reinforcement to have functioned effectively. In addition, since almost no damage was found in this government building, the building could continuously maintain the functions just after the occurrence of the earthquake, enabling achievement of municipal office tasks, we consider it an approach to a resilient building.

Photo 2 Situation of the first floor after the earthquake (March 13)

5-2 Serecon Square

1) Background

Serecon Square shown in Photo 3 is a seven-story office building of steel structure constructed in Shinkawa Chuo-ku, Tokyo, in 2013. Since the old building was subjected to large tremors from the Great East Japan Earthquake, the owner examined the construction of the building with high aseismic performance. Since the site is close to neighboring buildings in the metropolitan area and the site allowance is small in the case of the adoption of an seismic isolation structure, he considered the seismic control structure to have satisfied the required condition, and selected the toggle installation for the purpose of the improvement of structural performance.

Photo 3 Serecon Square Building

2) Overview of design

We designed a building incorporated with toggles so as to enable the satisfaction of the Building Standards Law after designing a basic building with the general allowable stress design method. In order to calculate the number of reinforcement toggles, we first calculated the interlayer speed of each floor using the modal analysis to obtain a displacement response spectrum. Then, we converted the displacement response spectrum into a speed response spectrum, calculated the damping force of the toggle, and incorporated its resistance as a reaction force into the design of the peripheral column-beam frames. To evaluate the performance of the building, we performed earthquake response analyses in the condition of three-dimensional members and planned the building so as to make interlayer deformation angles due to tremors 1/100 or less in both the short and long side directions.

We adopted a total of 11 waves consisting of generally used three observation waves, five notified waves, a site wave, a long-period ground motion wave, and a wave observed in the Great East Japan Earthquake as the waves of the input earthquake vibration assumed to apply to the design, and assumed an input acceleration of about 500 cm/s^2. In addition, the number of the toggles was determined by arranging them so as to satisfy the design target value without arranging them on all the floors of the building considering economic efficiency.

3) Results of response analysis

Here we show the reported random number phase wave of which the response result was the maximum among 11 waves of the input earthquake vibration in the short side direction. The input acceleration was 444 cm/s^2 on the ground surface, and this is the acceleration of a strong earthquake wave corresponding to the seismic intensity of upper 6 when converting to the seismic intensity scale of the Meteorological Agency. Fig. 14-1 shows the comparison of interlayer deformation angles.

Although the interlayer deformation angle on the fourth floor is as large as about 1/70 before the installation of toggles, the target interlayer deformation angle of 1/100 is satisfied by all the layers after the installation of toggles. Fig. 14-2 represents the relative displacement of each layer from the ground, and the displacement at the top of the building was reduced by about 30% when comparing that before the installation of toggles, meaning that the structural performance of the building was improved because the tremors of the building were suppressed by the toggles.

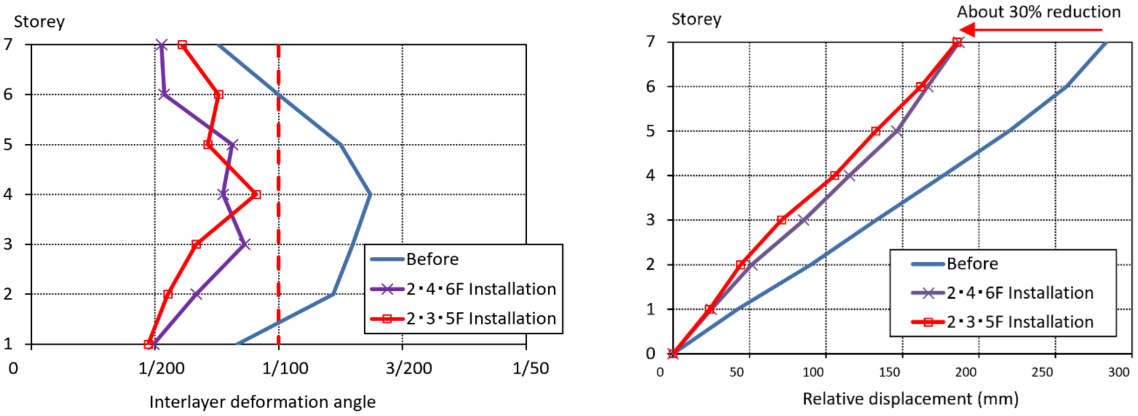

Fig. 14-1 Interlayer deformation angle

Fig. 14-2 Relative displacement

Fig. 14 Results of short side direction

6. Quality control of toggle

Although the toggle can work an oil damper efficiently using an amplification mechanism, the amplification mechanism sometimes amplifies the dimension and installation errors of the members. Therefore, there is a possibility that the mechanism could greatly influence the fluctuations of the magnification factor. Since the manufacturing of toggle members requires accuracy greater than that of general steel members, the toggle arms and clevises are manufactured with machining accuracy, and pinholes are machined with an accuracy of 0.1 mm. Therefore, quality control is important, and we perform highly accurate quality control on many items, such as length, torsion, bending, and misalignment, based on our unique manufacturing instructions.

7. Example of toggle installation achievement

Finally, Photo 4 shows the aseismic retrofit (seismic control retrofit) of Tokyo University as the achievement of the toggles, Photo 5 the new building of Nihon University constructed for the improvement of performance, and Photo 6 an example of the application of an aseismic retrofit of a large-scale wooden building.

Photo 4 University of Tokyo (retrofit)

Photo 5 Nihon University (newly constructed)

Photo 6 Large-scale wooden building (retrofit)

8. Acknowledgements

We appriciate by we got the cooperation of the staff of Sendai City Hall and using the records of the seismometer installed at Sendai City Hall. Also we supported by the owner of the Serecon Square building.

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