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Performance Study of an Eight-story Steel Building Equipped with Oil Dampers Damaged During the 2011 Great East Japan Earthquake
Part 1: Structural Identification and Damage Reasoning

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Abstract

Oil dampers installed on the first floor of an eight-story steel building were completely destroyed during the 2011 Great East Japan Earthquake. It is believed to be the first time in the world that real oil dampers in service failed due to earthquakes. Before this failure event, the actual performance of buildings that use oil dampers during catastrophic earthquakes has never been verified. Investigating the cause of the damage of the oil dampers is thus necessary and urgent. In this paper, a comprehensive identification was conducted to rebuild the numerical model of this damped structure equipped with/without damaged oil dampers using the measurement data of the installed monitoring system. Furthermore, the damage process of the oil dampers was postulated based on the identification and simulation results. The limit states of the oil dampers were studied. Based on the damages of the dampers and connection, the oil dampers experienced the displacement limit state when the allowable displacement limit was surpassed and the central cylinder pushed against the abutment. The insufficient stroke limit is the main cause of the collision between the damper and the abutment on the floor, which finally led to the failure of the oil dampers.

Keywords: oil damper; simulation; steel building; damage; the 2011 Great East Japan Earthquake

1. Introduction

Since the mid-1990s, passive energy dissipation devices have been used more widely to enhance the energy dissipation capability of a structure and reduce the damage to the structural frame in which they are installed. Dampers and isolators, such as viscous fluid dampers, viscoelastic dampers, metallic dampers, and rubber bearings, are considered effective and reliable devices to mitigate seismic hazards as well as rehabilitate deteriorating or deficient structures (Symans *et al.*, 2008, Soong and Spencer Jr., 2002). According to the Japan Society of Seismic Isolation (Kasai *et al.*, 2013), more than 7,000 buildings in Japan are equipped with seismic isolation systems or supplemental damping systems.

Researchers have been experimenting with passively controlled structures to examine and evaluate the real performance of passive devices after deployment. A full-scale building with a supplemental damping system was tested during nature-generated earthquakes (Chang and Lin, 2004) or using free and forced vibration (Lai *et al.*, 1995); some small-scale passively controlled buildings were tested in shaking tables (Chang *et al.*, 1995, Chang *et al.*, 2001). However, the actual performance of these passive devices during major and catastrophic earthquakes has never been tested. In 2007, Japan tested a full-scale five-story steel frame building with different types of passive dampers on the E-Defense, which is the largest three-dimensional shaking table in the world, to validate the performance of these passive dampers under extreme circumstances (Ji *et al.*, 2013, Kasai *et al.*, 2010). The yielding of the frame member cases and ultimate state of dampers were never investigated experimentally because the frame members remained mostly elastic during the shaking table tests.

The 3/11 Japan earthquake, which hit Sendai City, is an unprecedented case that provides an opportunity to observe the actual performance of an eight-story passively controlled steel building during a catastrophic earthquake (Cao *et al.*, 2012). All eight sets of oil dampers on the first floor were completely destroyed with abutment breakage. This event is believed to be the first reported case in which real oil dampers in service were damaged during earthquakes.

Generally speaking, passive energy dissipation devices are considered sufficiently safe during major earthquakes. As suggested in current guidelines, passive devices have a displacement/velocity capacity with a certain safety margin under the maximum considered earthquake level. However, this failure event may cast doubt on the safety of these passive devices. Therefore, investigating the cause of the damage as well as the limit state of the oil dampers in this event is important.

This paper investigates the damage event of this passively controlled building during the 2011 Great East Japan Earthquake and studies the cause of the damage of the oil dampers during the earthquake. The damage process of the oil dampers is postulated through identification and simulation. The limit states of the dampers are discussed according to the damage description of the connection and dampers.

2. Building Description and Damage Event
2.1 Overview of the Building
The eight-story Administration Building on the main campus of the Tohoku Institute of Technology (in Sendai, Japan) was constructed in 2003 and has a length of 48 m, a width of 9.6 m, and a height of 34.2 m, as shown in Fig.1. The superstructure is a steel-frame structure with precast concrete slabs, and the one-story basement is reinforced concrete. This steel building was designed to satisfy the Japanese Earthquake Resistance Code for School Buildings without any control equipment. To verify the effectiveness of the newly developed oil damper at the Tohoku Institute of Technology and improve the structural earthquake resistance capability, 56 sets of dampers were installed, as shown in Fig.2. Each floor has eight sets of oil dampers, which are connected with the use of V-type braces between the adjacent floors, as illustrated in Fig.3. The first floor and the second floor were merged to form a large space with a height of 8 m.

Fig.1. Administration Building of the Tohoku Institute of Technology

The main frame of the superstructure was completed in June 2002, but the partition walls and building devices were not yet installed. Forced vibration tests were conducted to identify the natural frequencies of the structure with/without the oil dampers. Before the installation of oil dampers, the building was vibrated by using an excitation machine that was mounted on the roof, and the first natural frequencies of the building without dampers were obtained. The frequencies were 1.050 Hz for the short side (nearly the NS direction) and 1.025 Hz for the long side (nearly the EW direction). After the installation of the dampers, the first natural frequencies of the building with dampers were 1.125 Hz for the short side and 1.100 Hz for the long side. The natural frequencies in both directions increased because oil dampers increase the stiffness of the building.
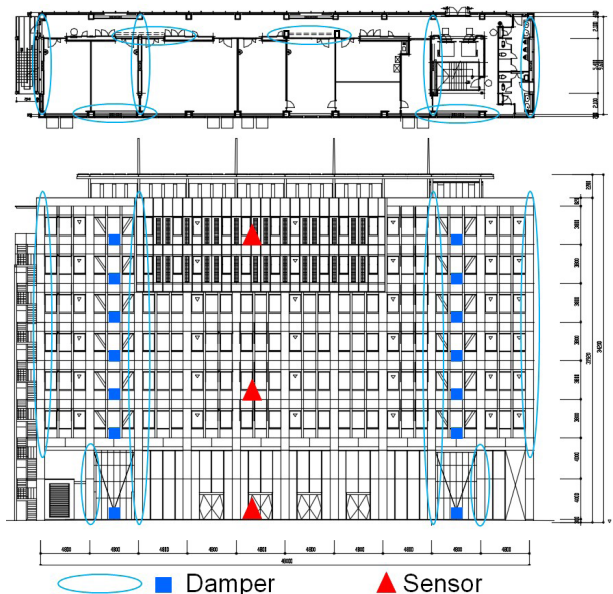

■ Damper   ▲ Sensor

Fig.2. Allocation of Oil Dampers

Fig.3. Brace of the Oil Damper

2.2 Oil Dampers
Kawamata *et al.* (Funaki *et al.*, 2001, Kawamata *et al.*, 2000) proposed a new type of oil damper that is composed of a cylinder and a pair of pistons. The gaps between the cylinder (oil container) and pistons are sealed with viscoelastic polymer, as illustrated in Figs.4. and 5. The sealing scheme relaxes the manufacturing

precision of matching the cylinders and pistons, and makes the damper compact and cheap. The contained oil flows through the narrow orifice and creates strong fluid turbulence to dissipate energy when the piston moves reciprocally. Furthermore, the sealing polymer is subjected to dynamic shearing deformation, which results in additional viscoelastic resisting force. On the basis of the harmonic excitation tests, the resisting force provided by oil flow acts nonlinearly with the piston velocity and appears to be stronger under a large amplitude and high excitation frequency, while the viscoelastic resisting force of the sealing polymer increases almost linearly with the piston velocity.

Two types of oil dampers are installed in the Administration Building to investigate the performance of the oil dampers in real application. An oil damper is 424 mm wide and 328 mm high with different piston diameters and orifice specifications for the 1F floor and 3–8F floors. These two types of dampers also have different stroke limits (the displacement extent of piston in one direction), which are 16 mm for 1F dampers and 8 mm for 3–8F dampers, respectively. The pistons are fixed with the U-type abutment on the floor and the central cylinder is attached to the V-type brace. The moving direction of pistons is horizontal. Therefore, the damper displacement is the same as the interstory drift, without considering the deformation of the rigid V-type braces. The central cylinder moves back and forth along the axis of the pistons within the stroke limit when the interstory drift occurs because of ground motion. An extra cushion limit is prepared (8 mm for 1F dampers, 5 mm for 3–8F dampers) to protect the central cylinder from colliding with the abutment.
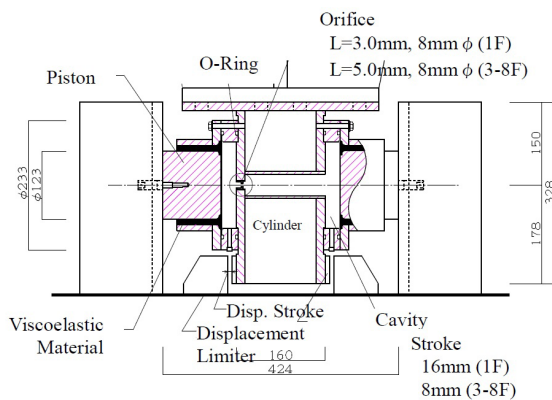

Fig.4. Intact Oil Damper

Fig.5. Dimension of the Oil Damper

2.3 Monitoring System

A monitoring system is installed in this building. Two-direction accelerometers were located on the first, fourth, and eighth floors to record the dynamic responses of the structure; the location of accelerometers is shown in Fig.2. To examine the performance of oil dampers in real application, load cells with a strain meter and displacement transducers were installed on the dampers on the first and eighth floors in both directions to obtain the restoring force and displacement of the dampers during earthquakes.

2.4 Damage Event

During the 2011 Great East Japan Earthquake (also known as the 3/11 Earthquake), all eight sets of dampers on the first floor were destroyed, as shown in Fig.6. The damper pistons on both sides were torn from the central cylinder (oil container). The U-type abutments fixed on the first floor were opened wider as the pistons ran out of the stroke limit and cushion limit, and pushed against the abutments. Sixteen sets of dampers on the third and fourth floor had severe oil leakages, because the sealing viscoelastic polymer had worn out. However, the mechanical parts of the oil dampers remained undeformed.

The acquisition devices failed to record the dynamic responses of the building because of the power failure that occurred when the extremely intensive earthquake struck the building on March 11, 2011. Fortunately, an observation station of ground motion about 50 m from the building successfully captured the ground motion of the 3/11 Earthquake and recorded the peak ground acceleration (PGA) of 354 gal in the EW direction and 280 gal in the NS direction. After the earthquake, a field observation was immediately conducted and no cracks were found on the surface of the beam-column joints. No other structural damage was found except the damaged oil dampers and oil leakage. This building was put into use without any retrofitting after a quick safety evaluation because it was designed to satisfy the Japanese Earthquake Resistance Code for School Buildings even without oil dampers.

Fig.6. Damaged Oil Damper and Abutment

3. Simulation Model of the Building
3.1 Numerical Model

For the nonlinear dynamic analysis, the numerical model of this steel building was established by using finite element analysis software SAP2000, as shown in Fig.7. The superstructure was modeled and fixed on the

ground without considering the basement and the soil-structure interaction. All structural members, including the steel columns, beams, and braces of the dampers, were modeled according to the described dimensions in the design book. Moreover, the material parameters were set based on the Japanese Steel Design Code. The bilinear plastic-elastic model was used for the steel material. The joints between columns and beams were rigidly fixed. The concrete slabs were modeled using shell elements in plane stress. The partition walls, equipment, and furniture on the floors were regarded as lumped mass that was attached to the floor. Therefore, the mass density of the slab material is referred to as a changeable variable, because the lumped weight is considered.

The actual restoring force of an oil damper consists of the resisting force generated by oil flows and the viscoelastic shear force from the sealing polymer. In experiments, the restoring force is both amplitude and frequency dependent. However, in a numerical simulation, an oil damper model is simplified, which is represented by link elements with the type of damper in SAP2000. The mathematical model for describing the behavior of oil dampers is given through the following nonlinear force-velocity relation:

$$F(t) = C|\dot{u}(t)|^{\alpha} \, \mathrm{sgn}[\dot{u}(t)] \qquad (1)$$

where $F(t)$ is the restoring force developed by the damper; $u(t)$ is the relative displacement between the oil piston and the abutment; $\dot{u}(t)$ is relative velocity between the oil piston and the abutment; C is the damping coefficient; α is the exponent whose value is determined using the piston head orifice design; and sgn[·] is the signum function.
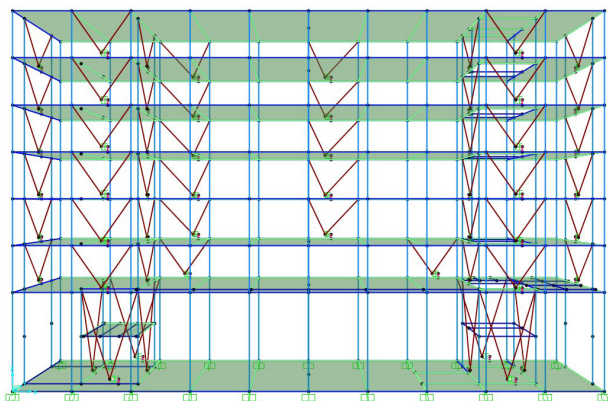

Fig.7. FEM Model of Building with Dampers

3.2 Identification Results

For the established numerical model, some parameters remain undetermined. Based on the measured response data of the building, two steps are needed to identify the unknown parameters. The first step is to build the mathematical model of the oil dampers. The monitoring system collects the relative

displacement and the restoring force of the oil dampers. The parameters of the damper model are determined by minimizing the difference between the captured data and the simulated response, which is used in the next identification step.

The second step is to find suitable values for the mass density of the slab, which are set as variables for the additional weight consideration. The optimization target is to minimize the differences of the resonant frequencies and the maximum acceleration responses between the measured and simulated responses by adjusting the variables using the optimization technique. During optimization, more weights are assigned to the lower resonant frequencies because lower modal information is reliable and more important.

## 4. Data Analysis and Damage Reasoning
4.1 Earthquake Records

The structural responses induced by earthquakes before and after the 3/11 Earthquake were collected by using the monitoring system; the collected data provide valuable information about the state of the building. The dataset can be divided into two categories; one is the building equipped with dampers and the other without dampers. The foreshock record of March 11, 2011 and the aftershock record of April 7, 2011, which represents each category, respectively, are used for identification and analysis. No measurement was recorded during the 3/11 Earthquake. Thus, the ground motion captured by an observation station is used as the ground excitation for the simulation of the main shock on March 11, 2011.

4.2 Foreshock on March 9, 2011

The building equipped with dampers experienced an earthquake two days before the main shock. The ground motion of March 9, 2011 had a PGA of 32 gal in the EW direction and a PGA of 26 gal in the NS direction. The two-step identification procedure was performed to build the numerical model for nonlinear dynamic analysis. Fig.8.(a) shows the acceleration responses on the fourth floor of observation and the simulation in both directions. Fig.8.(b) demonstrates the transfer functions between the fourth and the first floors in the frequency domain. Fig.8.(c) compares the maximum acceleration on each floor of observation and simulation. The acceptable agreement between the measured and simulated responses verified the identified numerical model.

### 4.3 Aftershock on April 7, 2011

After the 2011 Great East Japan Earthquake, a large aftershock struck the building in the middle of the night on April 7, 2011, which was almost one month after the main shock. The seismic intensity of this aftershock was the same as that of the main shock in Sendai City. This aftershock damaged some buildings in Sendai City, which were safe during the main shock. Fortunately, this aftershock caused no further damage
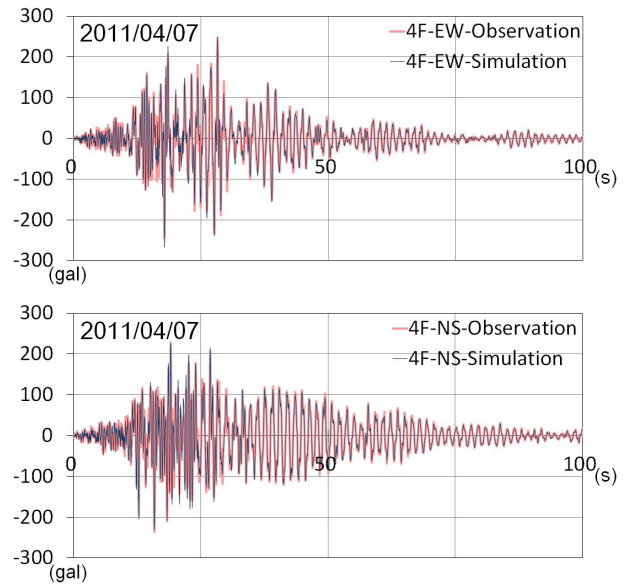
(a) Time History of Acceleration

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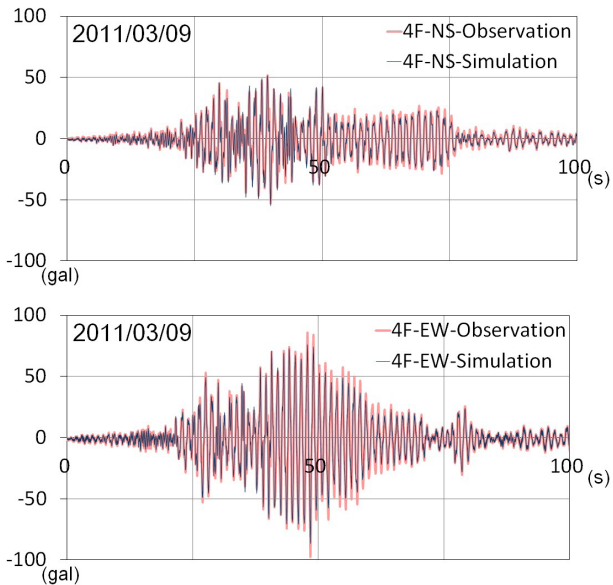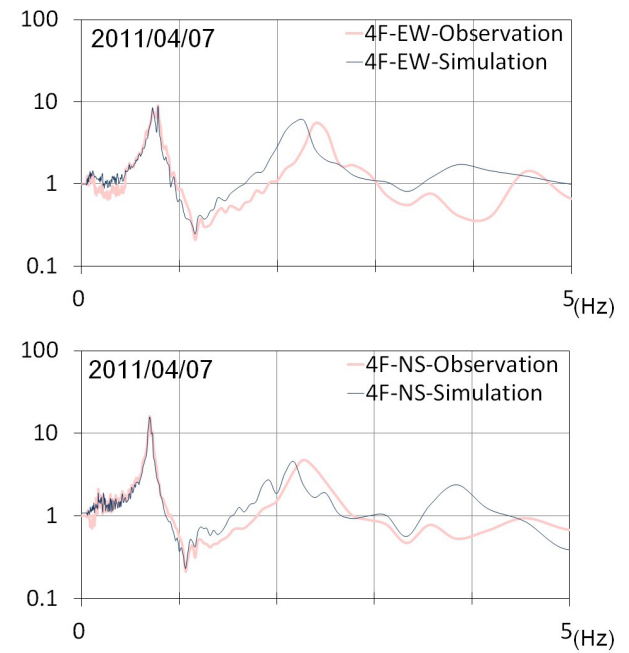
(b) Transfer Function
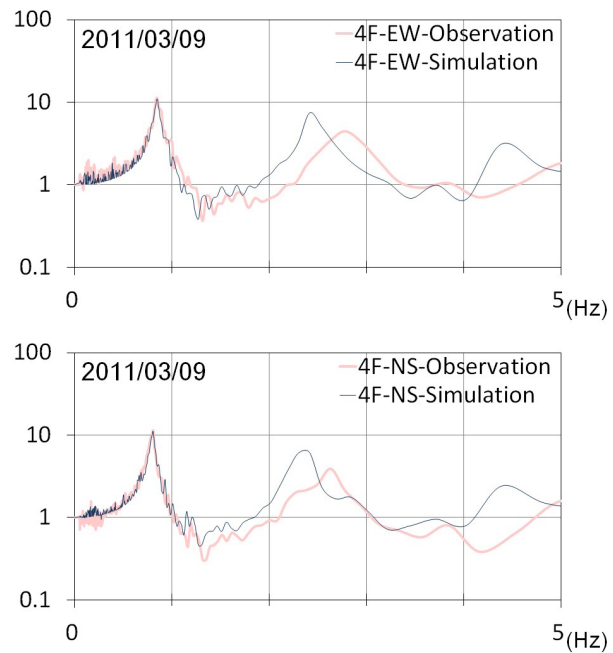
(b) Transfer Function

(c) Maximum Acceleration on Each Floor
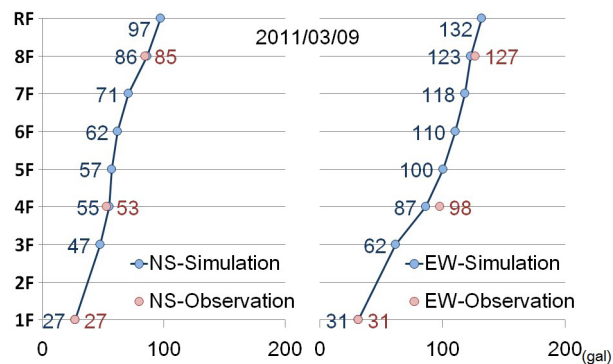
(c) Maximum Acceleration on Each Floor

Fig.8. Comparison of the Observation and Simulation (March 9, 2011)
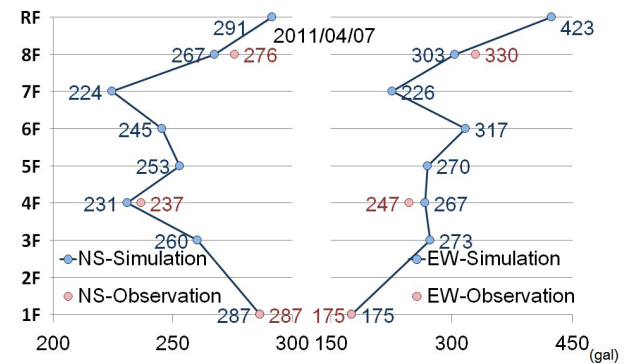
Fig.9. Comparison of the Observation and Simulation (April 7, 2011)

to the administration building. The ground motion of April 7, 2011 had a PGA of 176 gal in the EW direction and a PGA of 289 gal in the NS direction.

The main shock on March 11, 2011 devastated the dampers on the first floor and disabled the dampers on the third and fourth floors because of oil leakage, whereas the main frame of the building had no structural damage. No retrofitting measurement was conducted before April 7, 2011. The numerical model is altered to consider the change of damper configuration. The oil dampers of the first, third, and fourth floors were removed from the model in both directions. The mass distribution of this building in the vertical direction was also changed because most of the bookshelves that fell over during the 3/11 Earthquake remained on the floor on April 7. The identification was conducted to rebuild the numerical model for the case of April 7, 2011.

Fig.9. shows the acceleration responses that were recorded and simulated in the time domain of the fourth floor as well as the transfer functions in the frequency domain and the maximum acceleration of each floor.

4.4 Simulation of Main Shock

The acquisition system did not work during the 3/11 Earthquake because of the power blackout. Thus, the numerical model of the steel building could not be built through direct identification by using response measurement. However, the numerical model for the main shock can be established by combining the identification results of the foreshock and aftershock.

The mass distribution of the building during the main shock is the same as that of the undamaged building before the main shock. It is assumed that the dampers on the first, third, and fourth floors were not in operation from the beginning on March 11. The identified mathematical models of the oil dampers in the case of aftershock are used to simulate the velocity-force behavior of dampers during the 3/11 Earthquake. In the simulation of the main shock, the ground motion captured by an observation station was used as the ground excitation. This step aimed to simulate the dynamic responses of the building and predict the maximum displacement of the dampers during the main shock.

The acceleration responses on the fourth floor simulated for the main shock are plotted in Fig.10.(a). The transfer functions between the fourth floor and the ground excitation are plotted in Fig.10.(b).

The transfer functions from the first floor to the eighth floor in the NS direction are shown in Fig.11. for a comparison between the dynamic properties of the foreshock, the main shock, and the aftershock. The first period of aftershock is larger than that of foreshock because of the absence of the dampers on the first, third, and fourth floors. The maximum magnification factor in the first period of the aftershock is higher than in the other two cases. These facts reveal the effectiveness of the dampers in adding damping as well as suppressing building vibration.
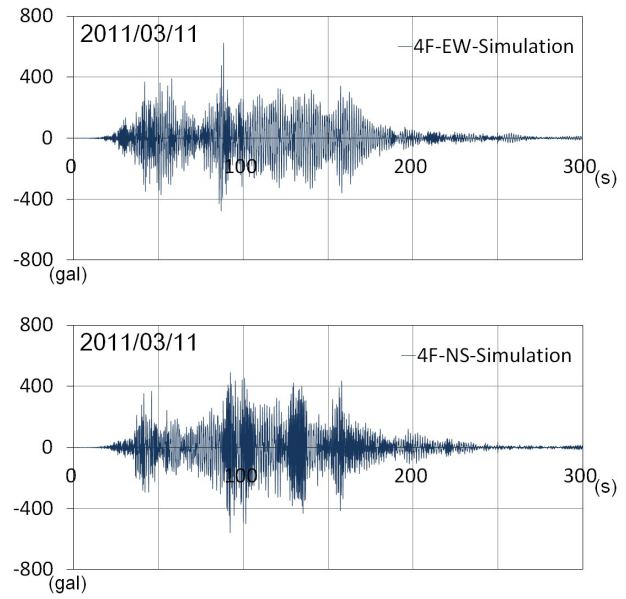
(a) Time History of Acceleration
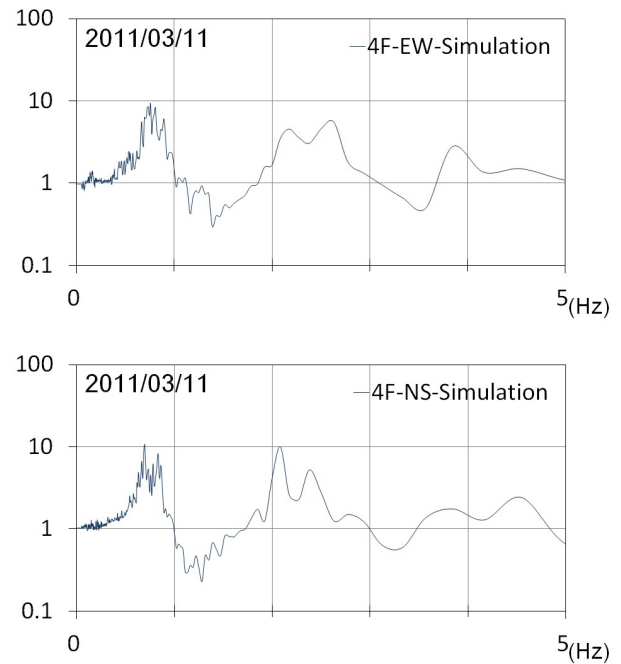
(b) Transfer Function

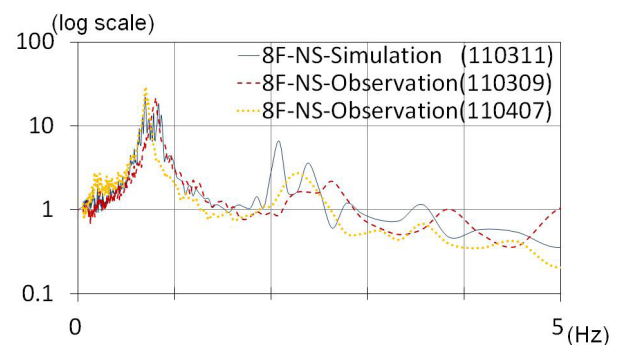Fig.10. Simulated Results of Earthquake (March 11, 2011)

Fig.11. Comparison of the Transfer Function

4.5 Limit State of Oil Dampers

Buildings equipped with fluid oil dampers have not been subjected to intensive earthquakes. In addition, no data or failure events of oil dampers during catastrophic events were available until the oil dampers of this steel building were devastated during the 3/11 Earthquake. Even in experiments, the limit states of the dampers were seldom tested. To evaluate the near collapse state of passively controlled structures, Miyamoto *et al.* (Miyamoto *et al.*, 2010) conducted a comprehensive experimental investigation to determine the limit states of a viscous damper and established a detailed mathematical model of a viscous damper that considers the limit states of dampers. Miyamoto examined several limited states in the laboratory. The two most common types are the force limit state and the displacement limit state. The force limit state can occur when a damper is subjected to a large-velocity (force) pulse within the stroke limit and when one of the mechanical parts of the dampers reaches the corresponding material limit. The displacement limit state can occur when the stroke limit in extension and retraction is reached.

During the 3/11 Earthquake, the dampers on the first floor were damaged severely and the abutments were wrecked. The damage description indicates that both the stroke and cushion limits of the pistons seemed to have been reached, and the central cylinders were pounded against the abutment repeatedly until the abutment connection and oil dampers were broken. Therefore, the displacement limit state is assumed to be the damage scenario of the oil dampers. In this study, the damage process of oil dampers was replayed based on identification and simulation.

According to the design book, the designed stroke limit displacement of the damper for the first floor is 16 mm (pink line in Fig.13.) and 8 mm for the third to eighth floors. In addition to damper protection, a cushion limit was also designed with 8 mm (red line) for the first floor and 5 mm for the third to eighth floors. The damper reaches the displacement limit state and the cylinder pushes against the abutment when the stroke and cushion limits run out. If the cylinder does not retract and continues to push against the abutment, the relative piston-cylinder velocity drops to zero. Thus, the restoring force of oil dampers becomes zero, and the V-type steel brace and the abutment on the floor carry the resistant force caused by restraining the interstory drift beyond the stroke and cushion limits. Once the dampers reach the destructive limit displacement, as depicted in Fig.12., the accumulated deformation energy is abruptly released to break the abutment connection and oil dampers. However, the difficulty lies in determining the destructive limit displacement of the abutment.

Considering the situation of dampers on the fourth floor, the oil container, piston, and abutment were not damaged. However, the sealing material had worn
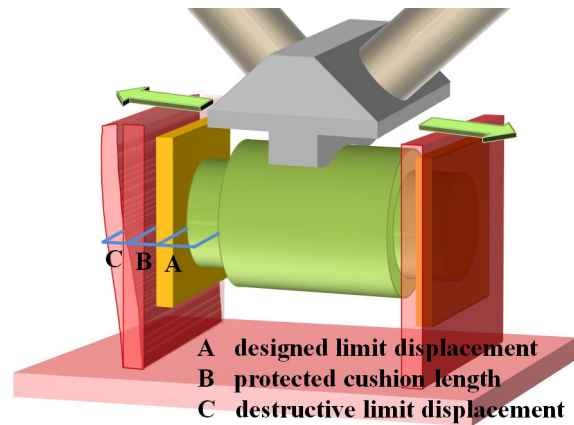

A designed limit displacement
B protected cushion length
C destructive limit displacement

Fig.12. Diagrammatic View of the Damper's Limits

-·- Destructive limit displacement
─── Protected limit displacement
       (including the cushion limit)
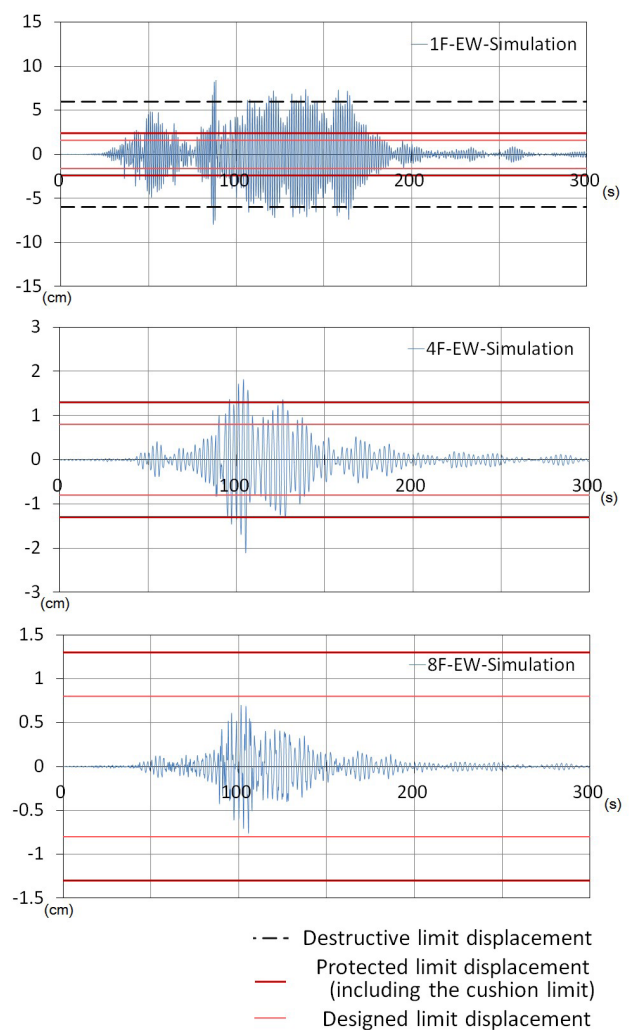─── Designed limit displacement

Fig.13. Displacement of Dampers During the 3/11 Earthquake

out and the oil leaked during the 3/11 Earthquake. A reasonable assumption is that the oil dampers on the fourth floor were in critical condition and were about to reach the destructive limit displacement. Based on the simulation results of the fourth floor oil dampers, the ratio of the maximum interstory drift to the sum of stroke and cushion limits can be calculated and used as a normalized index to determine the deformation

limit of other floors (2.6 for the fourth floor). With this normalized index applied to the first floor, the destructive limit displacement was determined to be 59.8 mm, which is shown as black dashed lines in Fig.13. The simulated interstory drift of the damper on the first floor in the EW direction on March 11, 2011 is plotted in Fig.13. The dampers of the first floor were most likely destroyed in about 90 seconds during the 3/11 Earthquake.

Of course, there are some flaws in this damage simulation. Continuous impacts of the central cylinder against the abutment caused the U-type abutment to open. The number of collisions between the central cylinder and the abutment before the breakage of the abutment and oil dampers cannot be determined. In this study, the breakage is assumed to be caused by the impact of maximum displacement. Furthermore, the mathematic model of the oil damper does not incorporate the limit state of dampers. Thus, the maximum interstory drift in the simulation is not the same as in the real case.

5. Conclusion and Discussion

This paper reports the first failure event of oil dampers during the 2011 Great East Japan Earthquake. Rebuilding the numerical model of oil dampers and the steel structure is possible through a monitoring system and two-step identification. Based on the identification and simulation, the damage process of the oil dampers was investigated.

The main cause of the damper failure was the insufficient stroke range of pistons. The total allowable moving range of oil dampers was 24 mm for the dampers on the first floor in one direction (the sum of the 16 mm stroke limit and 8 mm cushion limit). Thus, the interstory drift angle of the first floor was 0.3% when the damper reached the displacement limit. Furthermore, the elastic limit of the interstory drift angle in the Japan Steel Building Code is 0.5% for minor earthquakes. The authors can infer that the original design of this administration building intended to use oil dampers to control structural responses to minor earthquakes while the structure responds elastically. However, the unprecedentedly intense earthquake caused large interstory drift, which the oil dampers could not withstand and consequently broke the dampers.

The limit states of oil dampers were studied based on the damage scenario. The oil dampers experienced the displacement limit state when the allowable limit was surpassed and the central cylinder pushed against the abutment. In the future, more experiments should be conducted to determine all the possible limit states of oil dampers, and a numerical model that incorporates the limit states can be established to test the collapse state under intensive earthquakes.

Passive energy dissipation devices are deployed to reduce the inelastic energy dissipation demand induced on a structure, especially requested by a major earthquake. The passive devices shall have a displacement/velocity capacity under the considered earthquake level. Improper design of dampers should be avoided. Dampers are not made to survive catastrophic earthquakes. The limit states of dampers should be considered during design, especially when earthquakes beyond the considered level are likely to shake the passively controlled structure.

The failure event has prompted researchers and engineers to review the design philosophy of passively controlled buildings. Considering the limit state of the dampers during the design is necessary at this point because future catastrophic events may damage the dampers. This study will benefit the earthquake engineering community.

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