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Lessons Learned from Damage Events of Passive Dampers During the Tohoku-oki Earthquake

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ABSTRACT

Due to the utilization of high-strength concrete and steel material in building construction, the high-rise buildings are becoming taller and more flexible. In order to suppress the structural vibration induced by the earthquakes or winds, the vibration control techniques are getting more applications currently. However, oil dampers of a steel building had been damaged by the historic great earthquake of East Japan in 2011. This event proved that the dampers have their own limit states, which hasn't been investigated fully and thoroughly. In this paper, several damage events of passively-controlled buildings are reported after the field investigation of Tohoku-oki Earthquake in Japan, including the oil dampers, steel dampers and lead isolators. And the state-of-the-art of current research in the failure process of passively-controlled system and buildings is summarized. The framework of three limit states of passively-controlled buildings is originally proposed to explore the failure mechanism of controlled structures, considering the coupling effect of the passively-controlled system and structural mainframe. The key problems lie in the failure mechanism, the performance evolution and the performance-based design/retrofit philosophy of passively-controlled buildings. In the near future, more efforts needs to be spent in investigating the performance-based theory of controlled high-rise structures and establishing the integrated design and retrofit methodology which incorporates the idea of recoverable and replaceable dampers.

INTRODUCTION

Starting in the 1970s, scientists have been looking for new technologies to control (mainly decrease) structural vibration under earthquakes. Dampers and isolators have been considered as effective and reliable passive energy dissipation devices for reducing the inelastic energy dissipation demand on a structure [1; 2]. These passive devices are getting rapid implementation since the mid-1990s. More than 20,000 buildings equipped with dampers or isolators have been built worldwide in recent 30 years mainly in USA, Japan, China and EU.

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Generally, passive energy dissipation devices are considered to be safe enough during earthquakes and still function after major earthquakes. Until recently, such a belief is beginning to wane due to a series of failure events of passive energy dissipation devices during the historical great earthquake of East Japan in 2011. Cracks of lead dampers for the base-isolated buildings were observed after the 311 earthquake with no report of superstructure damage [3]. The supplement damping system of an 8-story steel building, which is located in Sendai City, Japan, has been seriously damaged by the 311 earthquake [4].

All these damage cases release an urgent warning that the damping devices have their own limit states, which may be damaged or degraded by the major or catastrophic earthquakes. In this paper, several damage events of passively-controlled buildings are reported after the field investigation of the Tohoku-oki Earthquake in Japan, including the oil dampers, steel dampers and lead isolators. Then, the current study on the limit states of dampers and damped building is summarized. For the future research, the framework of three limit states of passively-controlled buildings is originally proposed to explore the failure mechanism of controlled structures.

For the engineers and researchers in seismic community, the lessons should be learned to improve the study and design of the passively-controlled buildings. The knowledge and experience of damper performance obtained in major seismic events would be essential to future development of guidelines and codes for the design of passively-controlled structures.

DAMAGE EVENTS OF PASSIVE DAMPERS

With the innovative damping technology developed, any type of dampers should be tested thoroughly in the lab before they are actually implemented in the structures, in order to evaluate the performance, energy dissipation capability, ultimate states etc. And full-scale building with supplemental damping system has been tested by nature-generated earthquakes [5] or by free and forced vibration [6]; even a full-scale 5-story steel frame building with different types of passive dampers were tested on the E-Defense, the largest three-dimensional shaking table in the world [7; 8].

However, the actual performance of these passive devices has hardly been tested by the major and catastrophic earthquakes. Until the 311 earthquake in 2011, we actually had the chance to observe the realistic performance of these passive dampers during catastrophic earthquakes [4]. The following section will describe several damage events of typical dampers.

Velocity-dependent Dampers

An 8-story Administration Building in the main campus of Tohoku Institute of Technology (located in Sendai City, Japan) had been constructed in 2003, as shown in Fig.1a, with 48-meter length, 9.6-meter width and 34.2-meter height. The superstructure is a steel frame structure with precast concrete slab, and the one-story basement is reinforced concrete. In terms of earthquake resistance capability, the building itself (without dampers) satisfies the Japanese Building Code for School. But for the purpose to improve the seismic capability and verify the effectiveness of the oil damper developed by this university. 56 sets of these oil dampers with 8 sets on each floor have been installed as shown in Fig.1b, there is no dampers installed on the 2nd floor because the 1st floor and the 2nd floor have been merged as one floor to form large space with the height of 8 meters. The oil dampers are connected by V-type braces between adjacent floors as illustrated in Fig. 1c. The dimension of an oil damper is 424-mm wide and 328-mm high with different piston diameters and orifice diameters for 1st floor and 3rd~8th floors as illustrated in Fig. 1d. A monitoring system has been deployed in this building; 2-direction accelerometers are installed on the 1st, 4th and 8th floor to record the dynamic responses of the structure (location of accelerometers is shown in Fig.1b).

The customized damper employed viscoelastic polymer to seal the gap between the cylinder and piston for relaxing the demand of manufacturing precision of matching these two parts and consequently reducing the fabrication expense [9],[10], as illustrated in Fig. 2. The sealing scheme relaxes the manufacturing precision of matching the cylinders and pistons, and makes the damper compact and cheap. When the piston moves reciprocally, the contained oil flows through the narrow orifice and creates strong fluid turbulence to dissipate energy, and the sealing polymer is subjected to dynamic shearing deformation which gives rise to additional viscoelastic resisting force. Based on harmonic excitation tests, the resisting force provided by oil flow acts nonlinearly with the piston velocity and appears to be stronger under larger amplitude and at higher excitation frequency, while the viscoelastic resisting force of the sealing polymer increases almost linearly with the piston velocity.

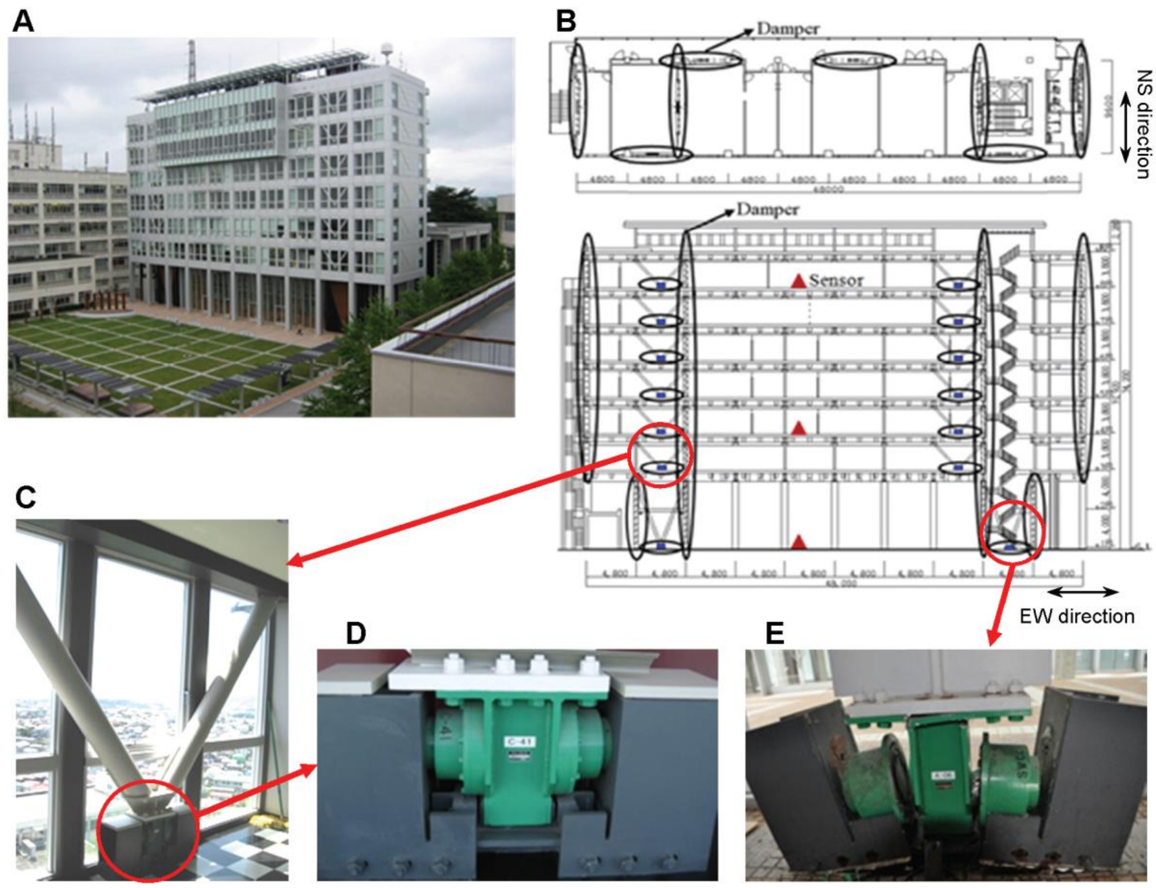

Fig. 1. 8-story Administration Building of Tohoku Institute of Technology in Sendai City, Japan. (A) The exterior appearance of the building. (B) The allocation of oil dampers and accelerometers: blue rectangles represent oil dampers, red triangles are accelerometers. (C) The brace of oil dampers on the 3rd floor. (D)

During the 311 earthquake, all of the 8 set dampers on the 1st floor had been destroyed, as shown in Fig. 1e. The damper pistons on both sides were torn apart from the central cylinder, and the U-type abutments fixed on the slab of the 1st floor were opened wider as the pistons ran out of the stroke limit and collided with the abutments. 16 sets of oil dampers on the 3rd and 4th floors had severe oil leakage, because the viscoelastic polymer for sealing the oil between a cylinder (oil container) and pistons was worn out. Due to power failure occurred during the extremely intensive earthquake hitting the building on 11th March, 2011, the acquisition devices failed to record the responses of the building. But fortunately, there is an observation station of ground motion about 50 meters away from this building, which successfully captured the ground motion of the 311 earthquake, the recorded PGA (peak ground acceleration) is 354 gal in EW direction and 280 gal in NS direction. After the earthquake, the field observation was immediately carried out, there was no other structural damage found except the damaged oil dampers and oil leakage. After the quick safety evaluation, this building was put into use without any retrofit.

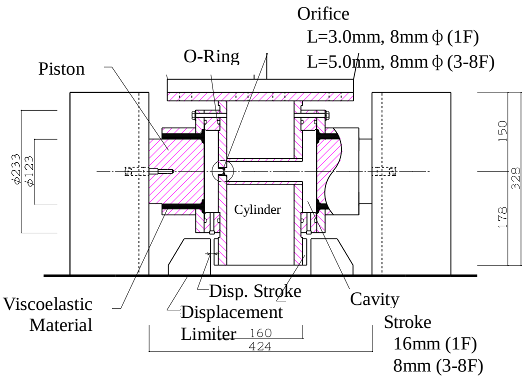

Fig. 2. Dimension of the oil damper

Isolators

According to the Japan Society of Seismic Isolation (JSSI), in Japan there are over 6000 buildings having seismic isolation and over 950 buildings equipped with supplemental damping systems [11]. After the Tohoku-oki earthquake in 2011, JSSI investigated the performance of passively-controlled buildings, including 327 base-isolated buildings and 130 supplementally damped buildings. These response-control technology were well demonstrated their advantage and effectiveness, none structural failure were ever found. However, some significant failures of lead dampers associated with isolation system were reported by JSSI.

About 60% of these investigated isolated buildings are located in Kanto area (Tokyo), 25% of them are close to Miyagi area (Sendai). In Miyagi area, the largest displacement of isolators was 41.5 cm, and the mean value was about 20cm. However, about 15% of investigated building have found problems with the isolation system. Among them, the most significant damage was the found cracks of the lead dampers of five buildings after field investigation.

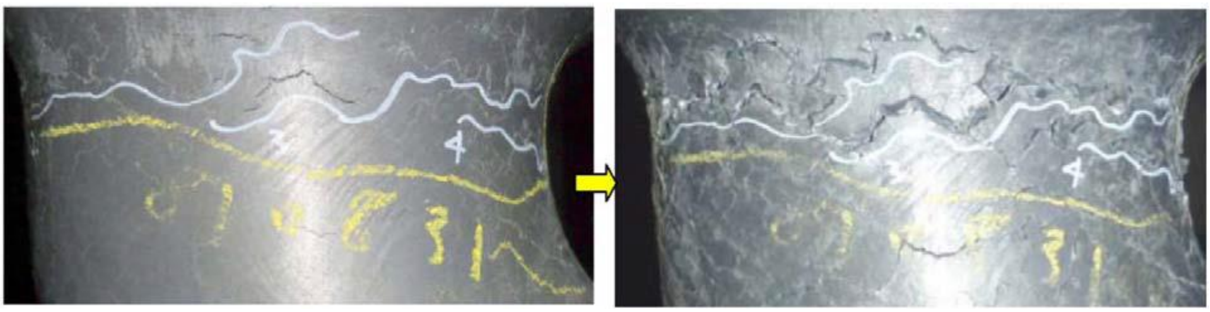

Fig. 3. Damage cases of lead dampers in Tohoku-oki earthquake: (crack depth changed from 8 mm pre-earthquake to 32 mm post-earthquake) [3]

Some minor damage has happened to the lead dampers after the earthquake, the depth of the cracks extended several millimeters. Fig. 3 shows one of the severe damage case of lead dampers, the depth of cracks extended from 8 mm up to 32 mm due to the Tohoku-oki earthquake.

Displacement-dependent Dampers

In the investigation by JSSI, bolt loosening was observed in steel dampers connecting the foundation, some residual deformation was also found in the steel dampers. But no crack was reported in these yielding components.

A school building G3 located in Tokyo Institute of Technology adopted an innovative energy dissipating system of rocking walls. The steel dampers were utilized for connecting the rocking walls and the main frame, viscous dampers were implemented as well. In total, 336 steel dampers and 284 viscous dampers were deployed in this building. Some of the steel dampers yielded during the Tohoku-oki earthquake, while the inter-story drift ratio was about 1/1900. And micro cracks were found in the nonstructural walls.

The steel dampers are designed to dissipate seismic energy purposely by material yielding. After major earthquake, the yielded steel components might lose the capability of energy dissipation, and need to be replaced. Therefore, the dampers should be examined and evaluated after earthquakes, and the decision should be made whether or not to replace the yielded dampers. However, the evaluation of the dampers and the procedure of replacement after earthquakes still remained unsolved for the owners and engineers.

LIMITE STATES OF PASSIVELY-CONTROLLY BUILDINGS

Limit State of Dampers

Miyamoto et al. [12] conducted the pioneering work of investigating limit states of a viscous damper experimentally. Several limit states were examined, such as force limit state and displacement limit state. Force limit state could have occurred when the damper was subjected to a large-velocity (force) pulse as blast or explosion, and the one of the mechanical parts of the dampers reached its strength limit. And displacement limit state could have happened when the stroke limit in extension and retraction was reached. In this study, the oil dampers of the steel building experienced the displacement limit state according to the damage scenario.

During the 311 Earthquake, the dampers on 1st floor of 8-story Administration Building in the main campus of Tohoku Institute of Technology were damaged severely and the abutments were wrecked. On the basis of the damage description, both the stroke limit and cushion limit of the pistons seemed to be 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 some cases of high-rise building, viscous dampers are installed to suppress the vibration induced by wind. The deformation requirement is usually very small (several millimeters), but the output damping force is relatively high. Under the frequently reverse wind loading, the viscous dampers might have fatigue issues [13], which need to be investigated thoroughly in the future. The lead damper of the isolation system might have the same problem, for the stiffness of the isolation layer is usually not as stiff as the superstructure.

As the new technologies and new types of dampers continuously emerging, the limit states of dampers and their effect on the collapse mode of buildings should be well studied before their practical implementation.

Collapse State of Buildings with Dampers

After the determination of limit states of dampers, Miyamoto et al. established a detailed mathematical model of a viscous damper considering limit states, and evaluated the near collapse state of passively-controlled structures [14]. They pointed out that the simple damper model without limit states will overestimate the energy dissipated by the dampers, resulting in underestimating the demand of structural frame for intensive earthquakes beyond the maximum considered level.

Although various types of dampers are increasingly used in Japan since the Kobe earthquake, the damping system have never been verified under the catastrophic events before the Tohoku-oki earthquake. In order to validate the realistic performance of damped structures, Japan launched a project of conducting a series of full-scale shake table tests of damped structures in 2009 [8]. A full-scale 5-story steel frame building with different types of passive dampers were tested on the E-Defense, the largest three-dimensional shaking table in the world. But the research was concentrated on the seismic performance and dynamic characteristics of passively-controlled building with proper functioning of dampers. So far, there is no shaking table experiments ever conducted considering the limit states of the dampers, let alone the consecutive collapse mode of damped buildings.

Above all, the limit states of dampers are the vital step for further understanding the force acting on the main frame developed by the damper and the failure mechanism and collapse mode of passively-controlled buildings.

DAMPER AS STRUCTURAL FUSE

Typically, a ductile seismic design allows the structure to undergo inelastic deformations during major earthquakes, while maintains the structural stability without losing the load capacity significantly. Most of the seismic energy is dissipated through hysteretic behaviour of structural members. But the residual deformations will cause tremendous cost to repair the structural main frame.

Thus, the “damage control” strategy for seismic design concept has developed to dissipating most of the seismic energy by additional damping devices, instead of the ductile structural members [15], in order to reduce the inelastic deformation of the moment-resisting frames. The concept is to concentrate the damage on the replaceable components.

For achieving even more stringent seismic performance, the “damage control” concept has evolved into the structural fuse concept. The structural fuse is well-defined plastic yielding dampers for energy dissipation before the frame yields, whereas the main structural frame is design to remain elastic or only minor inelastic deformation is tolerable [16]. After devastating earthquakes, only the yielding elements need to be replace. This concept will make the repair work easily and speedy, making the structure resilient. The researchers have implemented several types of dampers as structural fuses, such as friction brace devices [17], steel coupling beam [18], buckling restrained braces [19], etc.

Not like the metallic dampers dissipating energy by yielding, the oil dampers or viscous dampers consume the seismic energy by heating of the turbulent flow through orifices. The fuse concept should be altered slightly for oil and viscous dampers. They can be sacrificed and disposable when subjected to the earthquakes beyond the maximum considered level, while function well at design level.

FUTURE RESEARCH

Three Limit States of Passively-controlled Buildings

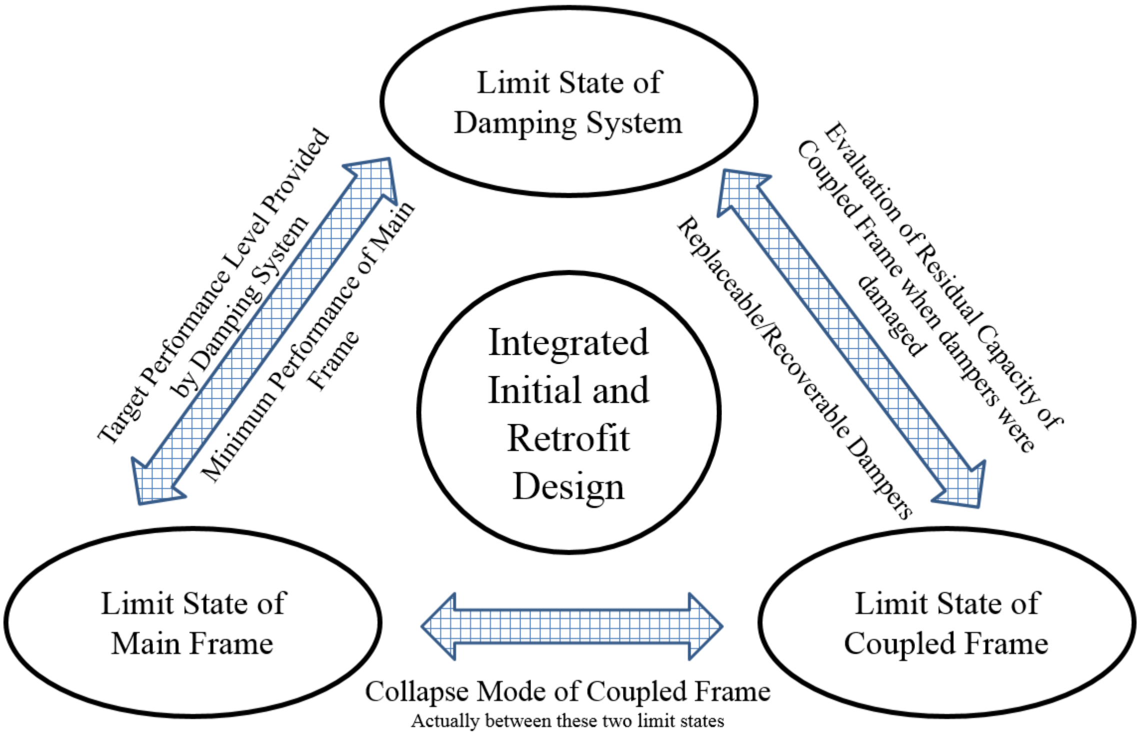

Fig. 4. Three limit states of passively-controlled buildings

Passively-controlled buildings consist of two subsystems, the main frame (without dampers) and the damping system. The target performance level of coupled frame can be achieved through proper design of the damping system and the main frame. The balanced portion of seismic energy dissipated by the damping system will reduce the inter-story drift effectively, in some cases only cause minor plastic damage of the main frame. As before-mentioned “Structural Fuse Concept” describes, the reliability of damping system might be lower than that of the structural frame, thus the catastrophic earthquakes could damage dampers, and the structural frame will be protected by sacrificing the passive dampers. The idea of replaceable and recoverable dampers will make the building resilient, which means the rapid repairing after earthquakes.

In order to study the effect of failure states of dampers on the consecutive collapse modes of coupled frame, the idea of three limit states of passively-controlled buildings is proposed originally in this paper. They are the limit state of coupled frame (with the damping system), the limit state of damping system and the limit state of the main frame (when the damping system fails), respectively, as depicted in Fig. 4.

Under extreme circumstance, if the damping system fails completely (hardly happened, usually partially failed), the main frame of the structure should fulfil the basic performance level of collapse prevention for major earthquakes. But in real world, the most possible damage scenario of damped buildings is between the limit states of the main frame itself and the coupled frame. And after the earthquake, both the damping system and the structural frame should be evaluated, the residual performance of coupled frame is essential information for the decision of damper replacement or retrofit work.

Performance Evolution of Passively-controlled Buildings

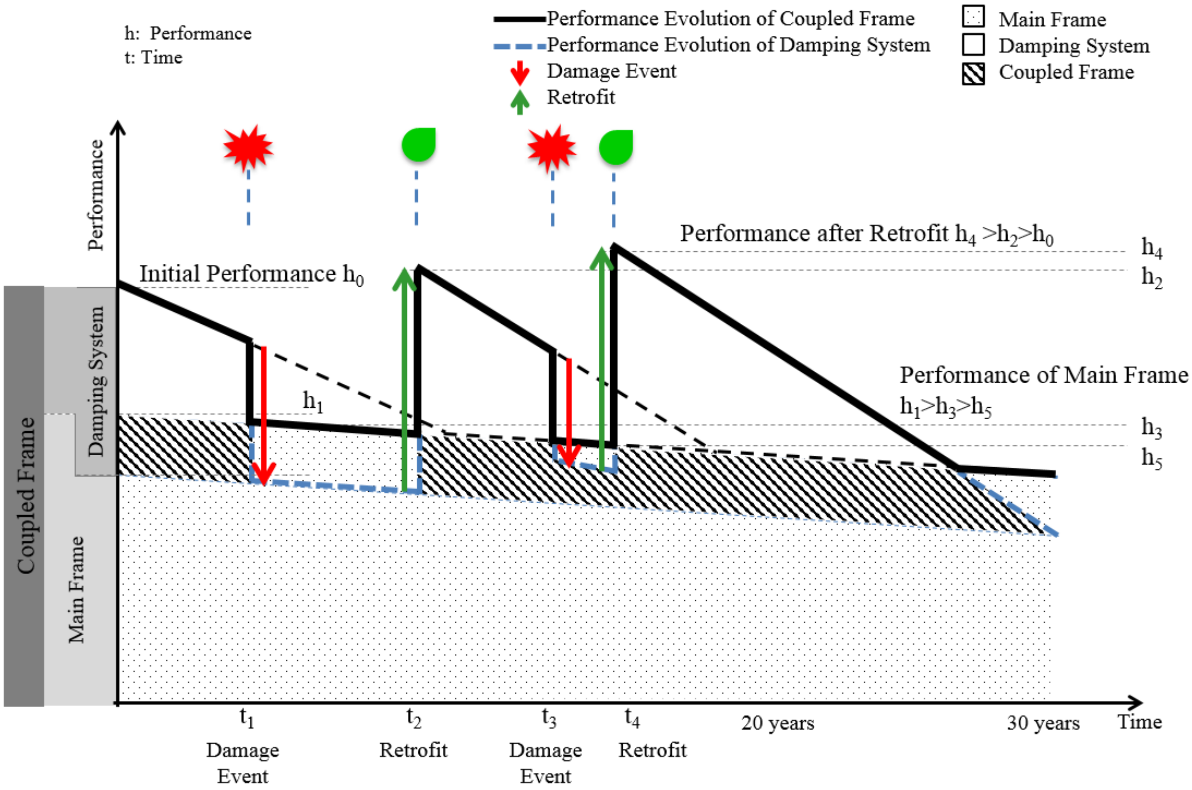

Fig. 5. Performance evolution of passively-controlled buildings under extreme loading condition

Another important issue is the performance of the passively-controlled buildings during the life cycle, as illustrated in Fig. 5. The overall performance of controlled buildings (black solid line in Fig. 5) is contributed by the damping system and the main frame itself, and is changing with time (simplified as a linear process). The overlap area marked by the diagonal stripes denotes the nonlinear coupling mechanism of the damping system and the main frame.

During its life span, the regular degradation and unexpected disasters will deteriorate the performance of the damping system and the structural components, consequently affect the overall performance of coupled frame. As depicted in Fig. 5, the initial performance h_0 is the combination performance of main frame h_1 and the damping system. The unexpected disasters will significantly reduce the overall performance of damped buildings by damaging the dampers. After these damage events, rehabilitation work should be taken to recover the capability of the damping system and the coupled structure.

The performance of the deteriorating structures is playing an important role in setting the initial performance level of coupled frame and damping system, making the decision of rehabilitation, setting the retrofitted performance level after catastrophic events. The engineers should bear in mind that the dampers have their own limit states and might be degraded gradually or damaged suddenly. Therefore, integrated method should be formulated to design the damped buildings considering the limit states of dampers, the replacement procedure of dampers and the rehabilitation work of the coupled frame from the beginning.

CONCLUSION

In this paper, several damage events of typical types of passive dampers were presented after the field investigation of Tohoku-oki Earthquake in Japan, including the oil dampers, steel dampers and lead isolators. These events have warned us that dampers and its connection with the structural frame can be damaged by catastrophic earthquakes beyond the considered level. Then the state-of-the-art of current research in the failure process of passively-controlled system and buildings is summarized. The original idea of three limit states of passively-controlled buildings is proposed to investigate the failure mechanism of damped structures. The future vision of energy dissipation devices is that they are acting like a fuse for protecting the structure which is consumable, replaceable, or even recoverable. It is an important paradigm shift from the once-deployed-work-for-ever damper devices to fuse-type damper devices. In the near future, more efforts needs to be spent in investigating the performance-based theory of controlled high-rise structures and establishing the integrated design and retrofit methodology which incorporates the idea of recoverable and replaceable dampers.

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