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DEVELOPMENT OF STRUCTURAL CONTROL SYSTEM FOR AUTOMATED WAREHOUSE

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Abstract

An automated warehouse is one that is equipped with automatic transfer machines (stacker cranes) and contains a large number of loads 3-dimensionally. Its rack structure is composed of a steel frame and is configured for stacker cranes to step over aisles. Following the Great East Japan Earthquake 2011, a number of automated warehouse's functions were suspended for a long time because stacker cranes were prevented from operating by loads that had fallen into the aisles. Consequently, demands for effective countermeasures have increased sharply by a business continuity plan (BCP).

The authors developed a structure control system for automated warehouses in 2013 named Attic Damper System (ADS) [1]. The basic idea of ADS is to install oil dampers into the "attic" space to absorb vibration energy by utilizing the bending deformation of the rack structure. ADS shows stable performance and reduces a warehouse's response within permissible values even during large earthquakes. However, although a couple of existing warehouses in Japan have introduced this system, its application is limited to warehouses with enough attic space. One idea to overcome this problem is to introduce a conventional small Tuned Mass Damper (TMD) utilizing the uppermost rack shelves [2]. However this is effective under only limited conditions. When the earthquake level becomes large, the TMD's performance decreases drastically because of the vibration's nonlinearity due to sliding movement of the loads. Furthermore, it is often unacceptable to reduce the warehouse's capacity.

This paper presents a newly developed control system named "Container Damper System (CDS)". If there is not enough space for an ADS, a CDS can be applied by utilizing the loads themselves as weights for the TMD. To realize this system, a device named a "control slider", which makes the loads behave as a TMD, is newly developed. The CDS has several practical advantages in addition to its control capacity.

This paper first outlines the CDS. Then, after examining the effects and target specifications based on numerical analysis, it reports the developement of the control slider. Finally, it presents the results of shaking table experiments using a full-scale rack frame specimen.

Keywords: automated warehouse; structural control; business continuity plan; tuned mass damper; shaking table test

1. Introduction

Following the Great East Japan Earthquake 2011, a number of automated warehouses' functions were suspended for a long time because stacker cranes were prevented from working by loads that had fallen into the aisles. However, if loads had been fixed to the rack frames in order to prevent them from falling, a greater seismic force may have been generated, which may have caused serious damage to the structural frame. Therefore, there is demand for response reduction technology aimed at improving the business continuity plan.

After the Great East Japan Earthquake 2011, a TMD was proposed for reducing seismic responses. This TMD has the advantage that it can be easily applied to existing automated warehouses by simply placing a weight on top of the rack frame. However, this is only effective under limited conditions. In a large earthquake, the TMD's performance decreases drastically because of the vibration's nonlinearity due to sliding movement of the loads. In addition, the weights reduce the warehouse's storage capacity, which is its primary function.

Therefore, in 2013 Yaguchi et al. developed a control system, named "Attic Damper System (ADS)", for an automated warehouse. The basic idea of ADS is to install oil dampers into the "attic" space to absorb vibration energy by utilizing the bending deformation of the rack structure. ADS shows stable performance and reduces the warehouse's response within permissible values even during large earthquakes. This control system has been applied to some existing warehouses in order to prevent reduction of their capacity. However, ADS still has the problem of requiring attic space.

This paper first presents an overview of automated warehouses and existing response reduction techology. Next, it describes a newly developed structure control system to solve these problems. After examining the effects and target specifications based on numerical analysis, the developement of a control slider (described later) is reported. Finally, the results of a shaking table experiment using a full-scale rack frame specimen are presented.

2. Outline of automated warehouse and conventional systems

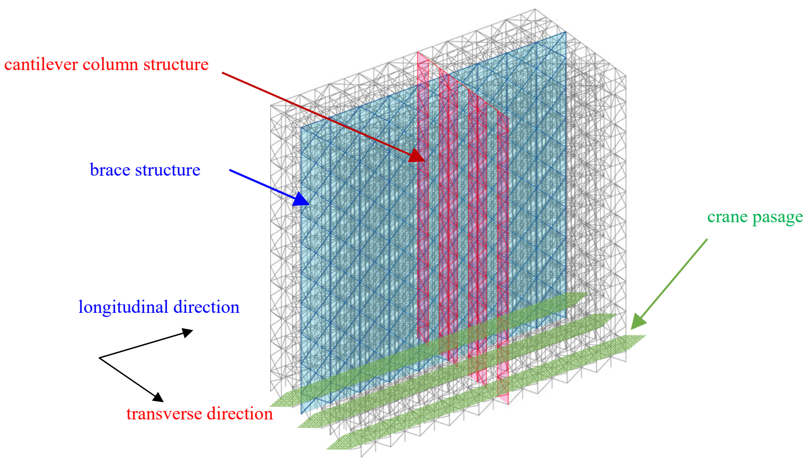


Fig.1 – Image of automated warehouse equipped with automatic transfer machine (stacker crane)

2.1 Outline of automated warehouse

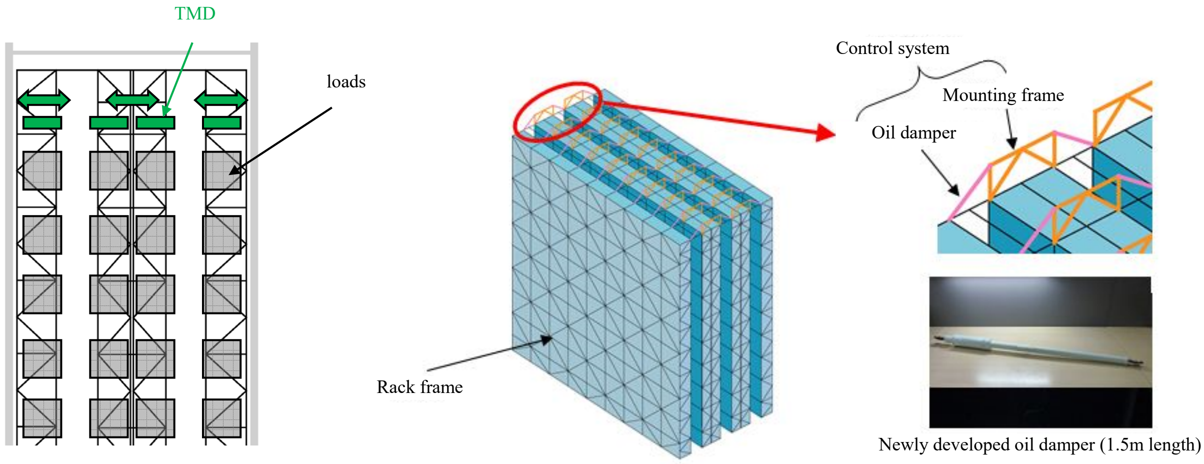
The target is a high-rise automated warehouse (20-30m high) equipped with automatic transfer machines (stacker cranes) and containing a large number of loads placed 3-dimensionally across the crane's passage, as shown in Fig.1. The stacker cranes move vertically and horizontally through the crane passage to carry loads to shelves. In the transverse direction, the structure is a cantilever column structure using the rack itself as assembly equipment, and in the longitudinal direction seismic force is counteracted by vertical braces placed on the back of the rack of shelves. The loads comprise about 70% of the total weight of the rack frame. Based on a previous study [1], loads are less likely to be dropped in the longitudinal direction or to damage structural members, so here we will deal with the response reduction in the short direction at right angles to the crane's passage.

2.2 Outline of conventional systems and problems

Control systems for reducing the responses of automated warehouses have been proposed and put into practical use after the Great East Japan Earthquake 2011. Here, conventional systems and problems are described.

One system involves introducing a small Tuned Mass Damper (TMD) utilizing the uppermost rack shelves, as shown in Fig.2 (A). This system is advantageous in application to existing warehouses with no space to place reinforcing members. A TMD is an effective seismic control device, but it is less effective for automated warehouses where loads slip and the frame period fluctuates. Their effectiveness is reduced during a large earthquake when the loads slide and fall. And this control system reduces automated warehouse capacity.

Yaguchi et al. developed a control system (named "Attic Damper System (ADS)") for reducing responses by installing oil dampers using attic space above the rack frame. With this system, oil dampers are installed together with mounting frame, and it does not reduce the capacity of the automated warehouse. Based on bending deformation in the transverse direction, which is dominant during an earthquake, oil dampers are attached to the upper part of the rack, so that energy can be efficiently absorbed. ADS also exhibits a stable response reduction effect even when the load slips. Since each component of the ADS is small and light, it can be easily installed even in a narrow space. These benefits have been accepted by automated warehouse owners, and ADS have already been adopted in some automated warehouse. However, it still has the problem of requiring attic space.



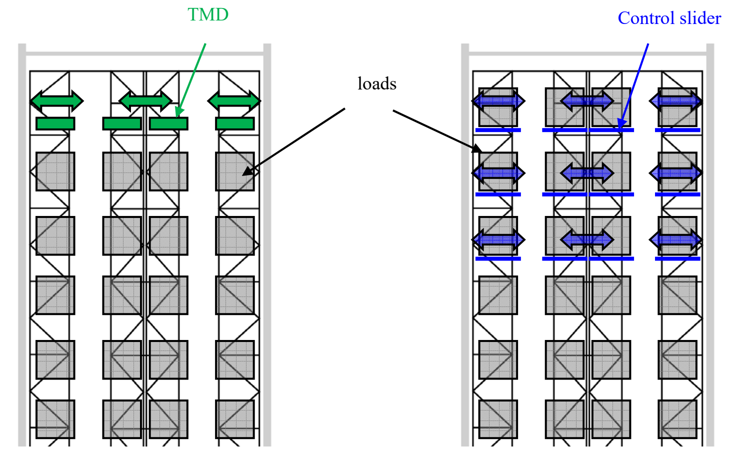
(A) Conventional small TMD (B) Attic Damper System (ADS)

Fig. 2 – Image of conventional systems

Therefore, we have developed a control system that solves both problems with the TMD concept using rack shelves while maintaining the advantage of ADS that it does not affect the the automated warehouse's capacity. We also aimed at a system that can be easily introduced into existing automated warehouses.

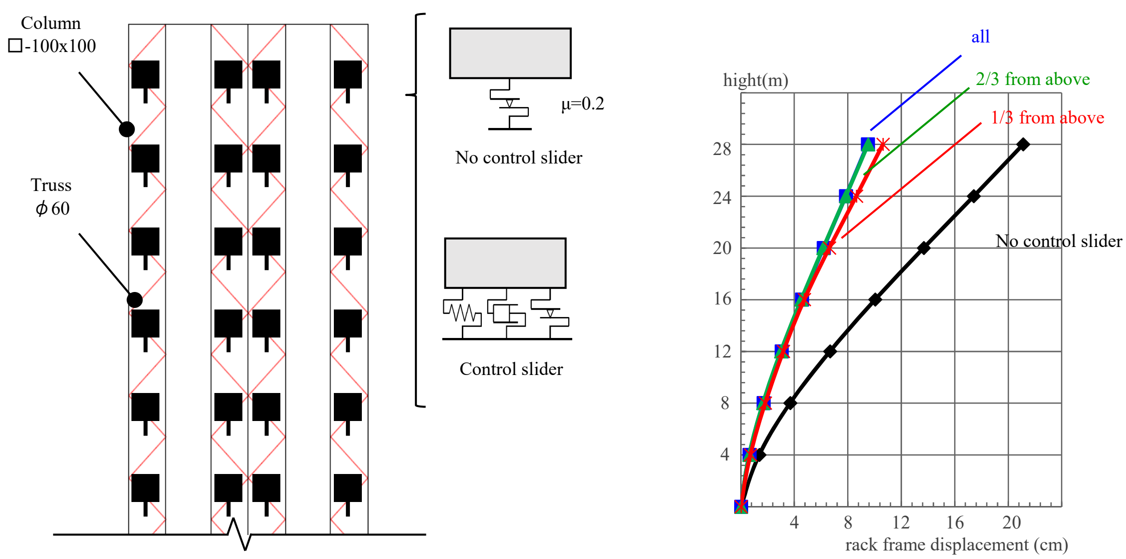
3. Features and outline of "Container Damper System (CDS)"

Our newly developed control system, named "Container Damper System (CDS)", utilizes the loads stored in the automated warehouse as the TMD weight. As a result, it utilize a large weight ratio without affecting the load capacity and can cope with a large earthquake. Fig.3 (B) shows the concept of this control system. By placing a smoothly sliding control slider comprising springs and dashpots between the load pallet and the rack member, the loads behave as a TMD during an earthquake. Fig.4 (A) shows an example of an analysis conducted to set the target specifications and the range necessary to install the control slider. Fig.4 (B) shows results that verified the response reduction effect during an earthquake by changing the range of the control slider using an analysis model. Since the rack frame has a structure with dominant the loads, a control slider was installed in the upper 1/3 of the load to ensure a weight ratio of over 50%, enabling strokes of a few centimeters to be achieved during an earthquake. The feature of this control system is that it has high robustness against variation in the load weight and rack frame characteristics, and this enables a standardized specification of the control slider [3].



(A) Conventional small TMD (B) Developed control system Container Damper System (CDS)

Fig. 3 — Image of "Container Damper System (CDS)"



(A) CDS modeling overview (B) Analysis result

Fig. 4 — Examination of installation range of control slider using analytical model

4. Configuration and performance verification of Control Slider

4.1 Configuration of control slider

The Vibration Control Unit is composed of two control sliders installed so as to cover the arm lumber so that there is no hindrance to the stacker crane. The control slider is a simple mechanism in which bent steel plates are stacked one above the other with a sliding piece sandwiched between them and are connected by a coil spring and oil damper. The lower steel plate is fixed to the arm lumber with bolts (fixed side), and the upper steel plate with anti-slip on the surface in contact with the loads moves with the loads during the earthquake (movable side). The target rack is 20-30m long (period when loads are fixed: about 0.7-1.0s), and the weight per load is about 250-700kg. The simulation results obtained in advance are based on the above, and the target specifications of the control slider were set as shown in Table 1.

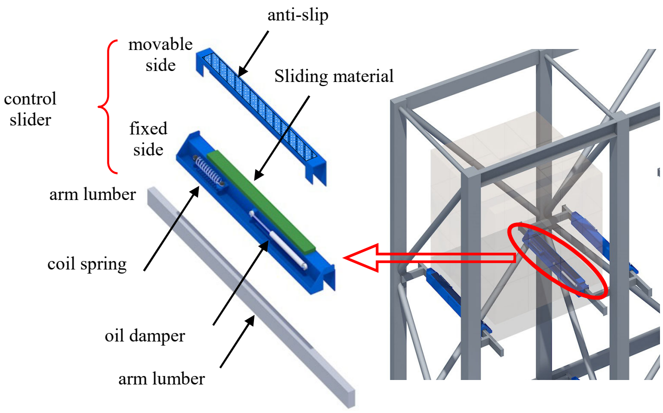


Fig. 5 – Installation of control slider

Table 1 – Target specification of control slider

stiffness of coil spring	3.5 kN/m
Damping coefficient of damper	1.35 kNs/m
Static friction coefficient	0.05
stroke	±50mm

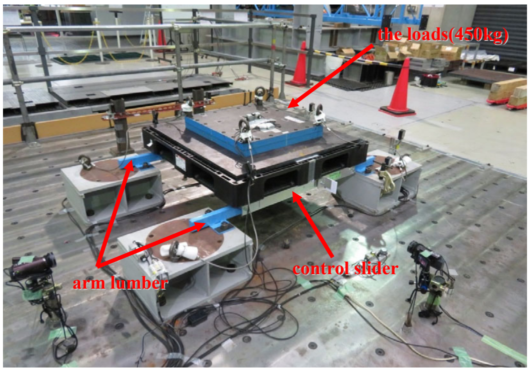


Fig. 6 – Experiment to confirm perfomance of control slider

4.2 Performance verification test and simulation analysis

Fig.6 shows the performance confirmation test of the control slider. The control slider was attached to a square pipe instead of the arm lumber of the rack frame, and the loads was simulated by stacking steel plates on a pallet. Excitation was performed using a three-dimensional shaking table. Sinusoidal and seismic response waves at the upper arm lumber position evaluated by the analytical model of the high-rise rack frame were used as input waves. Fig.7 shows the time history of the control slider's force when excited using the response wave to the seismic motion in the Japanese Code. Simulation results using the analytical model of the control slider (Fig.8) are also shown in the figure. In the analytical model, a spring element representing a coil spring, a dashpot representing an oil damper and a friction element representing friction of the oil damper and a sliding component are arranged in parallel. It was confirmed that the control slider behaved as expected during an earthquake. The excitation was not only in one direction but also in the

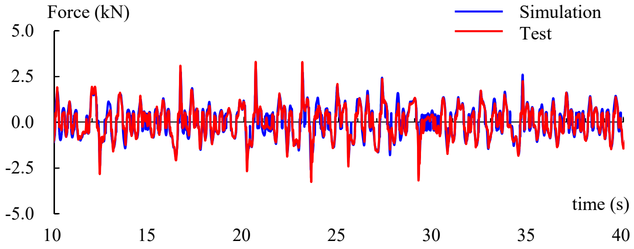


Fig. 7 – Force time history of control slider

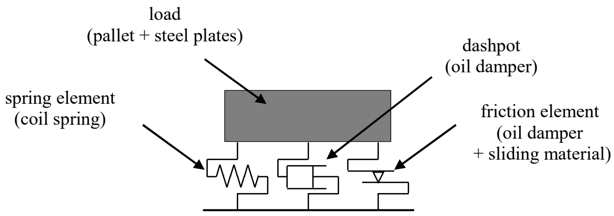


Fig. 8 – Analysis model diagram of control slider

orthogonal direction and the vertical direction in combination, and it was confirmed that the vibration was smooth. It was also confirmed that the behavior of the control slider can be tracked accurately using this analysis model.

5. Full-scale shaking table test

5.1 Outline of specimen

In order to verify the effect of the newly developed control system, a shaking table test was conducted using a full-scale rack frame. However, the entire rack frame with a height of 20m to 30m could not be simulated on the shaking table due to size and weight limitations. Therefore, three layers of a full-scale automated rack frame on a frame made of laminated rubber bearings and a steel frame (adjustment frame) was used, as shown in Figs.9 and 10. The adjustment frame was designed to reproduce the behavior of the 25m class rack frame, including not only the primary natural period but also the effective mass of the entire system and the secondary natural period. The loads were reproduced by stacking steel plates on the pallet. The following four cases were assumed as the load states during excitation.

(1) Without load

(2) With load

(3) With load and fixed to arm lumber

(4) With load and control slider

In case (4), the effective mass for the specimen was about 40% of the full load.

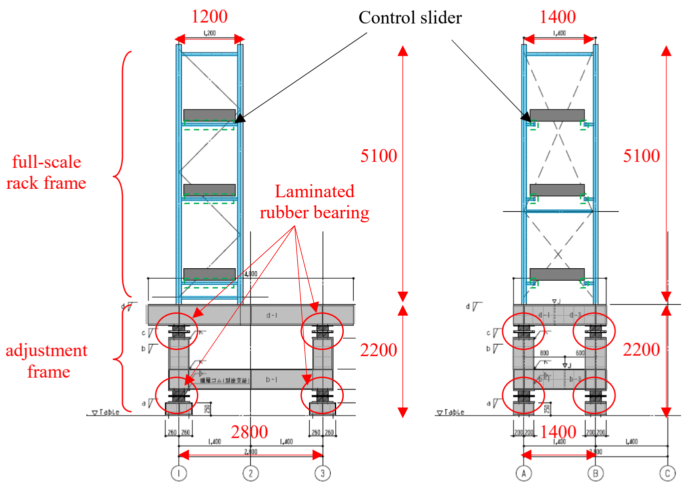
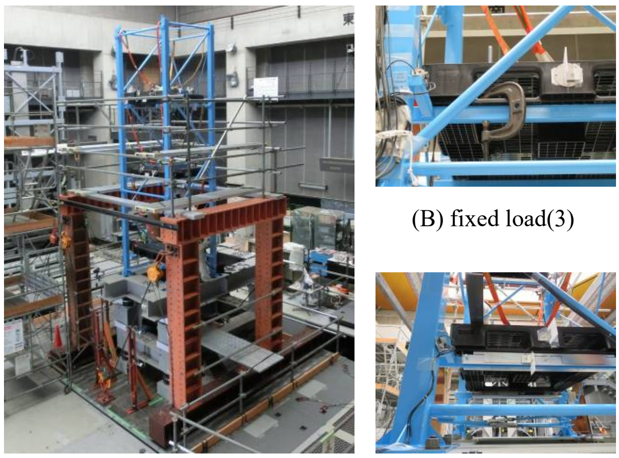


Fig. 9 – Outline of full-scale test specimen



(A) whole view
(B) fixed load(3)
(C) control slider(4)

Fig. 10 – External view of full-scale test specimen

5.2 Measurement and excitation plan

In the experiment, the acceleration of each level of the shaking table and the adjustment frame and rack frame, the inter-layer deformation of the adjustment frame, the relative deformation of the control slider and the loads (load displacement), and the stroke of the control slider were measured. Table 2 lists the vibration cases. A free vibration test and a sinusoidal one were performed to confirm basic characteristic. For seismic wave excitation, in addition to the Japanese code excitation, the records of the Ibaraki Prefecture (K-NET Edosaki) excitation where the Japanese code equivalent was observed during the Great East Japan Earthquake 2011 will be adopted. In this area automated warehouses were heavily damaged during the Great East Japan Earthquake 2011. Fig.11 shows the velocity response spectrum of K-NET Edosaki. In the seismic excitation, not only the moving direction of the control slider but also the orthogonal and vertical directions were applied.

Table 2 – List of vibration cases

vibration cases		(1) Without load	(2) With load	(3) Fixed load	(4) Control slider
free vibration		○	–	○	–
sinousoidal excitation		○	–	○	○
Earthquake	Japanese code	○	○	–	○
	K-NET Edosaki (observed earthquake)	○	○	–	○

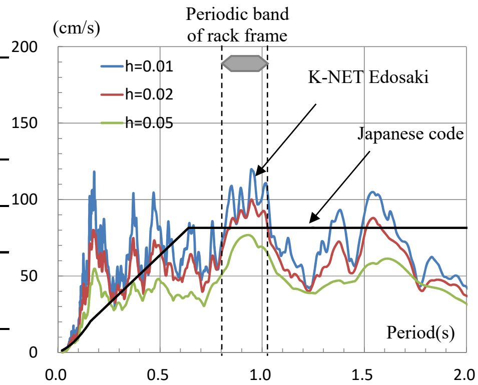


Fig 11 – Velocity response spectrum

5.3 Sinusoidal excitation result

Fig.12 shows the resonance curve obtained for sinusoidal excitation with varying frequency. The acceleration response magnification of the rack frame top with respect to the input when the input acceleration was 50 cm/s^2 is shown. The results for three cases ((1) without load, (3) fixed load, and (4) control slider) with different load states are shown. When the vibration characteristics in cases (1) and (3) were estimated from the free vibration test conducted in advance, the natural periods were 0.73 seconds for case (1) and 0.88 seconds for case (3), and the damping ratio was about 4%. From the resonance curve shown in Fig.12, it can be confirmed that the natural period corresponds to the result based on the free vibration test when the natural period was estimated from the resonance frequency and the damping ratio was estimated from the response magnification considering the stimulation coefficient. Although the rack

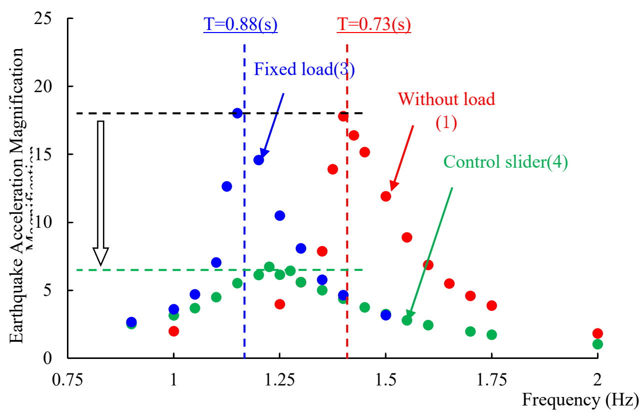


Fig. 12 – Experimental results (sinousoidal excitation)

frame's damping is slightly larger, this is mainly due to the hysteresis damping of the adjustment frame portion of the laminated rubber bearing. On the other hand, in case (4), it can be seen that the response magnification is greatly reduced compared to case (1) and case (3), and a large damping constant exceeding 10% was obtained.

5.4 Seismic excitation result

Fig.13 shows the time history of displacement in the upper part of the adjustment frame for the results of seismic excitation using the observation record (K-NET Edosaki) as the input wave, comparing case (2) (with load) and case (4) (control slider). Case (2) shows the sliding amount of the load, and case (4) shows the control slider's stroke. In case (2), assuming a normal rack automated warehouse, the loads fall off the shelves in the first half of the vibration. On the other hand, in case (4), the loads did not fall during the excitation, and it behaved stably. The response of the rack frame was also smaller than that for case (2), and the response reduction effect of the newly developed control system could be confirmed. It can also be confirmed that the stroke of the control slider is about 35mm at maximum and satisfies the specification range.

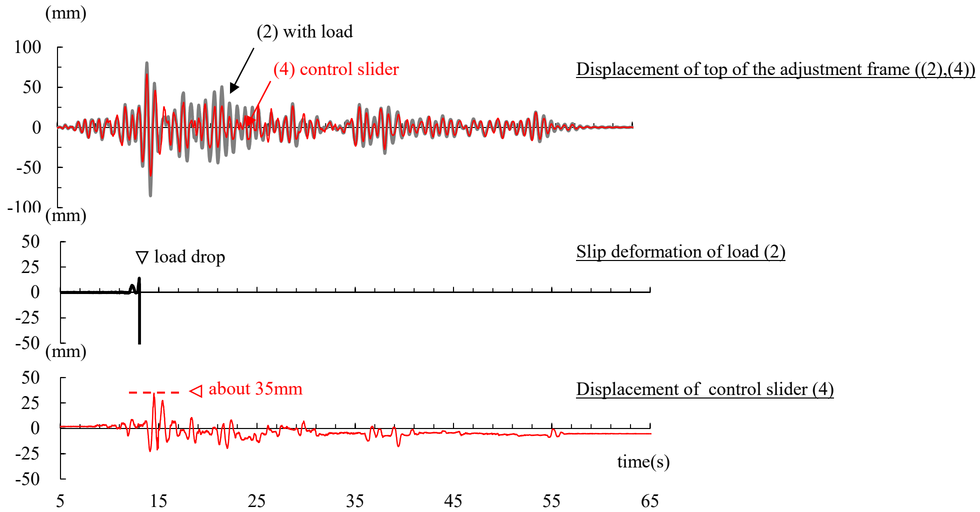


Fig. 13 – Experimental results (eathquake excitation)

6. Simulation analysis

Here we confirm that the experiment can be accurately simulated by analysis. Fig.14 outlines the analytical model used for the simulation. The adjustment frame is modeled by two masses, and the laminated rubbers are modeled by a linear spring. The upper rack frame is modeled by a beam element and a truss element, and the load is made into a mass and connected to the rack frame via the control slider analytical model shown in Fig.8. Fig.15 shows the simulation results for the seismic excitation for case (4). The input wave is K-NET Edosaki. The experiment and analysis results of the displacement time history at the top of the adjustment frame are compared, and it was confirmed that the seismic behavior of the automated rack with the proposed control system can be accurately simulated by this simple analytical model.

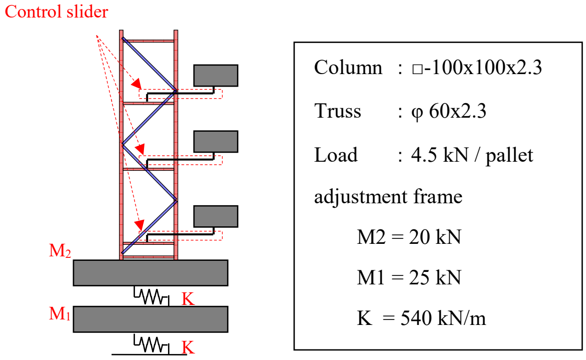


Fig. 14 – Outline of analysis model

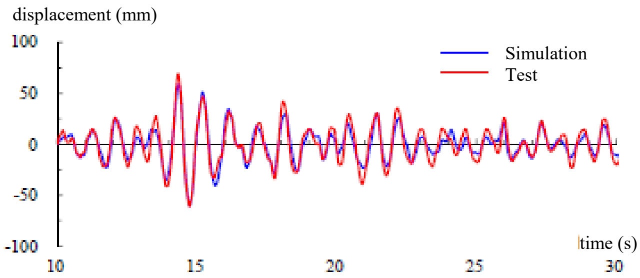


Fig. 15 – Displacement time history (top of the adjustment frame)

7. Conclusions

The concept of the newly developed control system using the load weight as the TMD weight as a vibration control method for an automated warehouse and the development of a control slider were presented. Also, the effect was verified by a shaking table test using a full-scale test specimen, and it was confirmed that the expected response reduction effect was exhibited. This response reduction control system can be easily installed not only in new construction but also in existing automated warehouses, and is expected to greatly contribute to improving the business continuity of companies with automated warehouses after an earthquake.

8. Acknowledgements

In the production of the control slider, we received the cooperation of Senqcia Co., Ltd. As the input wave of the full-scale shaking table experiment, we used the observation record of K-NET, the strong motion observation network of the Disaster Prevention Research Institute of Science and Technology.

9. References

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