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Development of post-installed mass damper for automated warehouse

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Abstract

A vibration control system for an automated warehouse was developed that can be applied to existing warehouses as well as newly built ones. The device used for this system is the "post-installed mass damper" that can be post installed on the cargo storage space in an automated warehouse. This damper has a large mass that causes a sustainable effect of reducing the response across a wide range of natural frequencies of an automated warehouse, which vary depending on the number of stacked cargoes and their weight. The results of the shaking table test demonstrated that the fall of cargoes by the earthquake ground motion could be prevented by using this damper because the accelerations of the rack were reduced to 50%-70%. Moreover, this effect was confirmed by the analysis conducted with the proposed model. The acceleration of the rack top was reduced to 80% and the maximum slip displacement of the cargoes was reduced to 25%.

Keywords: automated warehouse; post install; mass damper; cargoes fall; vibration control; shaking table test; response analysis.

1 Introduction

Fig. 1 shows the overview of an automated warehouse. The warehouse is the steel structure that consists of racks and automated conveying equipment. It can automatically control the storing and shipping of a large number of cargoes within a small floor space. The cargoes are corrugated cartons stacked up on plastic palettes for easy transportation by automated conveying equipment in the automated warehouse (Fig. 2). The palette with the corrugated cartons (cargoes) is stacked on but not fixed to the steel bracket of the rack column. Hence, the cargoes slip by the earthquake ground motion and may fall from the storage space due to the strong motion.

In the 2011 off the Pacific coast of Tohoku Earthquake (The 2011 Tohoku earthquake) and the Hyogoken-nanbu Earthquake, 1995, cargoes in warehouses fell on the floor and it caused significant damage to their content and to the automated conveying equipment. An example of such damage is shown in Fig. 3. These damages required a long time for recovery and resulted in the stoppage of the supplies for human life aid. The importance of the countermeasure against the earthquake for automated warehouses was widely noticed.

Some countermeasures have been proposed, that use damping joint for warehouse columns [1] [2], mass damper [3] [4], or a seismic isolation system [5] [6]. The countermeasures using the damping joint or seismic isolation system were especially developed for newly built automated warehouses, but not for the existing ones. The mass damper was proposed as a countermeasure for the existing automated warehouses [3] [4]. However, with a small mass ratio (mass of the damper/ generalized mass of the rack) as suggested in [3] [4], these dampers are not effective for the wide range of natural frequencies of the automated warehouses that vary depending on the number of cargoes and their weight.

Here, the authors developed a mass damper that

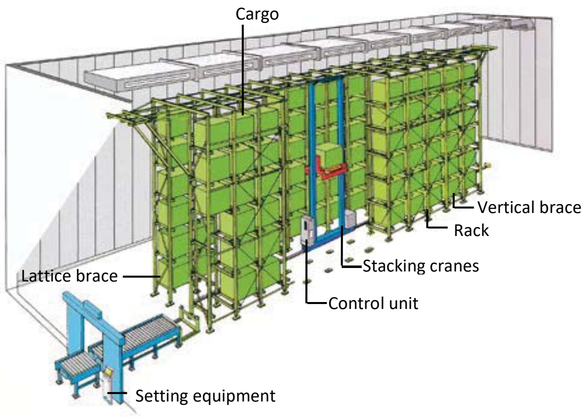


Fig. 1. Overview of automated warehouse

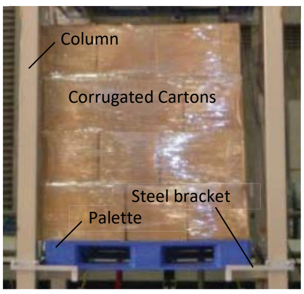


Fig. 2. Aspect of cargo

Fig. 3. Cargoes fall
(Damages in Tohoku earthquake)

is effective for the wide range of natural frequencies of the automated warehouses [7]. Moreover, the damper can be installed at the storage space for cargoes in the automated warehouse using the automated conveying equipment. The details of the damper were contrived for post installation.

In this paper, the specifications of the proposed damper are introduced, and the method for the post installation of the damper is presented. Experimental results of the shaking table test for a part of an automated warehouse are shown, and the effect of the damper is verified. Additionally, the analysis model of the cargoes based on the experimental results is proposed, and the results of the response analysis for an actual warehouse with the proposed model are presented.

2 Features of the mass damper

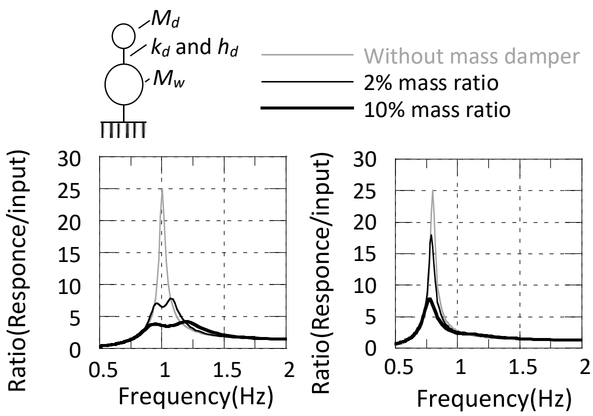
2.1 Mass ratio and damping

The natural frequency of the automated warehouse changes depending on the load conditions, e.g. the amount of stored cargoes, the variation in the weight of the cargoes, slip characteristics of cargoes between the steel bracket and the palette. For example, consider the case of a warehouse with a height of 30 m and the cargo weight of 540 kg. The natural frequency of the warehouse on being fully loaded is 0.91 Hz, while it is 1.67 Hz when the warehouse is empty. This means that the mass damper should enhance the effects of consistent vibration control against varying natural frequencies of the warehouse. The mass ratio for the proposed damper is set at approximately 10%, because the damper can have a consistent effect with a large mass ratio. The frequency response functions of the warehouse with and without the mass damper are compared with each other to examine the effect of the mass ratio. The mass ratio of the damper is either 2% or 10%. Each mass ratio is set as the optimal damping ratio that is described in section 5.1. As illustrated in Fig. 4, the analysis model used in the study is the two masses model. One mass, M_w, is the mass of the warehouse, and the other mass, M_d, is the mass of the mass damper. The two masses are connected to each other by the spring and dashpot of a viscous damper (k_d and h_d). The frequency response functions are shown in Fig. 4. Fig. 4(a) shows the case where the natural frequency of the damper, f_d, is tuned with the natural frequency of the warehouse, f_w. Both the natural frequencies have the same magnitude of 1.0 Hz. Fig. 4(b) shows the case where the natural frequency of the damper (f_d = 1.0 Hz) is not tuned for natural frequency of the warehouse (f_w = 0.8 Hz).

As shown in Fig. 4, it can be confirmed that a large mass is more effective than a small mass for reducing the response acceleration across the wide range of natural frequencies that vary depending on the number of cargoes and the weight of cargoes.

2.2 Post installation method

Fig. 5 shows the outline of the proposed mass damper. Fig. 5(a) shows the picture and Fig. 5(b) is the configuration diagram of the damper. Springs and an oil damper connect the moving mass and a base. These springs are tuned to the natural



(a) f_w = 1.0 Hz, f_d = 1.0Hz (b) f_w = 0.8 Hz, f_d =1.0 Hz

Fig. 4. Response function with/without damper

frequency of the warehouse or to a frequency that is a little less than the natural frequency. The base is fixed on the column of the rack with a fix appliance.

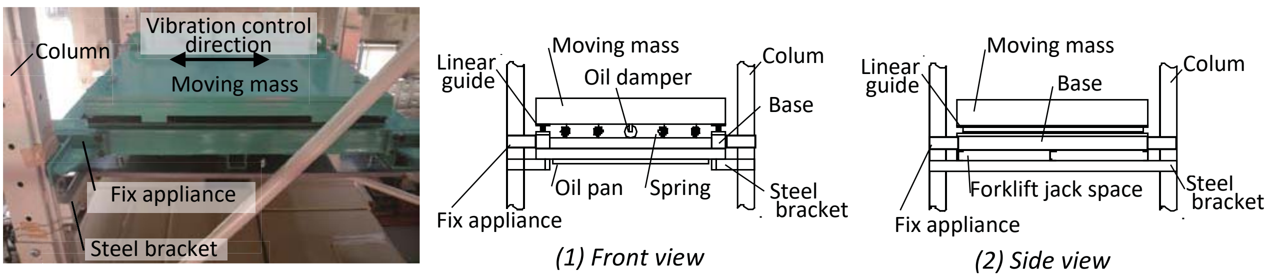
The warehouse operation should not be stopped even while installing the damper. The dampers were contrived for transportation by the automated conveyer system for the same reason. The outer dimension of the mass damper is 1100 mm × 1100 mm, and the height of the damper is reduced to 305 mm. The weight of the damper is below the maximum capacity load of the cargo. Moreover, the bottom surface of the damper is flat for easy transportation. This flat bottom is the pan that avoids oil leakage from the oil damper.

3 Shaking table test

To demonstrate the effectiveness of the mass damper, the shaking table test for a test rack with the damper was conducted. In this section, the outline and results of the experiment are presented.

3.1 Outline of experiment

Fig. 6 illustrates the outline of the test rack and the measurement points. The basement of the test rack is a steel trestle that is supported by linear guides and springs. The weights are installed on the trestle for tuning the natural frequency of test rack to that of the whole warehouse. The test rack is the model of the three upper layers of the actual warehouse. The proposed mass damper is installed on the top layer, and the cargoes are stacked in the other layers. The cargoes are configured by four layers of corrugated cartons, where each layer has eight corrugated cartons. A band fastens the top layer



(1) *Front view* (2) *Side view*

(a) Photo of damper *(b) Configuration diagram*

Fig. 5. Outline of mass damper

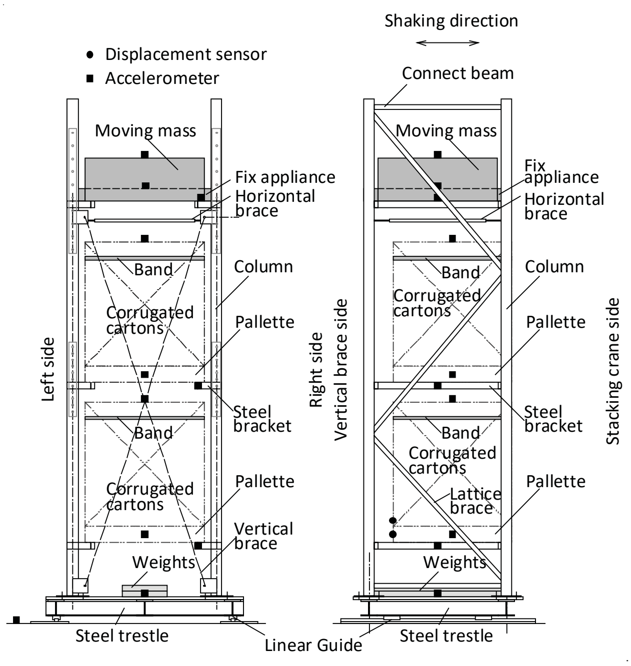
of the corrugated cartons. The natural frequency of the test rack is 1.0 Hz, which corresponds to that of the warehouse that is 25 m high. The natural frequency of the damper is tuned to 1.0 Hz, and the damping ratio is 24%.

Accelerometers are placed on the steel bracket, palette, top of corrugated cartons, fix appliance of the damper, and moving mass. Displacement sensors are installed on the palette and on the corrugated cartons for measuring their slips (Fig. 6).

For input ground motions, two observed ground records are selected: (a) The 1952 Kern County earthquake recorded at the Taft station (Taft wave), (b) The 2011 Tohoku earthquake recorded at the K-NET KNG009. The synthetic acceleration time history is also used, which is generated in random phases for fitting into the design response spectrum defined in the Japanese building code (Japanese building code wave). Fig. 7 shows the normalized time histories of the input waves. In the experiment, these waves are scaled to have the maximum acceleration as listed in Table 1.

3.2 Result of experiment

The results of the experiment are listed in Table 1. Fig. 8 shows the final states of the quantities listed as No. 7 and No. 8 in Table 1. These photos are selected because it is easy to compare the effect of the proposed mass damper. In the case where



(a) Vertical brace side elevation *(b) Right side elevation*

Fig. 6. Outline of test rack and measurement points

Table 1. Result of experiment

No.	Input earthquake motion	Maximum acceleration (cm/sec^2)	With or Without Mass Damper	Result: Distance between corrgated cartons	Cargoes Slip	Cargoes fall dawn
1	Japanese building code wave	200	With	No	No	No
2			Without	Yes	No	No
3		320	With	Yes	No	No
4			Without	Yes	Yes	No
5	Taft wave	290	With	No	No	No
6			Without	Yes	Yes	No
7		590	With	Yes	Yes	No
8			Without	Yes	Yes	Yes
9	The 2011 Tohoku earthquake	130	With	Yes	Yes	No
10			Without	Yes	Yes	Yes

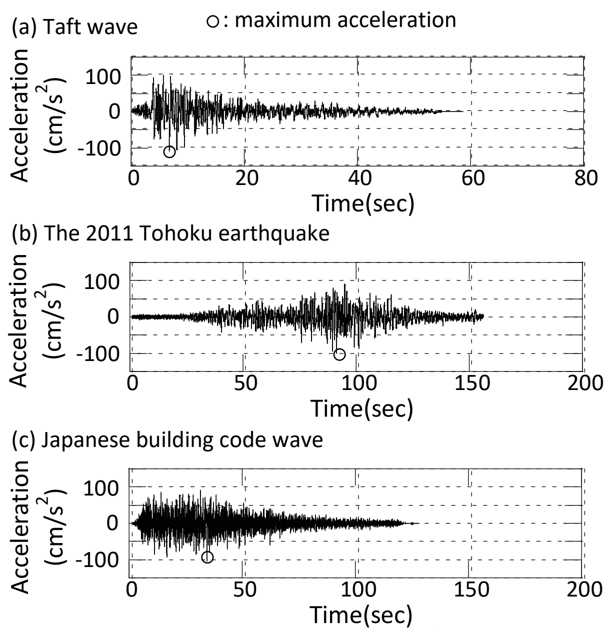


Fig. 7. Normalized time histories of input wave

(a) No. 7 *(b) No. 8*

Fig. 8. Final states

no damper was used (No. 8), the cargoes fell. On the contrary, when the damper was used (No. 7), the cargoes did not fall, while a short slip between the palette and corrugated cartons was observed.

The maximum acceleration distributions in cases of quantities listed as No. 5, No. 6, No. 7, and No. 8 are shown in Fig. 9. As shown in Fig. 9(a), the accelerations of the rack in cases where the damper is used (No. 5 and No. 7) are reduced to 50%-70% of those in the cases where no damper is used (No. 6 and No. 8). In the case No. 7, the acceleration of the steel bracket in the third layer is smaller than that in second layer.

In case of No. 8, the corrugated cartons of the first and second layers and the palette of the second layer collided with the vertical brace. Moreover, the corrugated cartons were in contact with each other. Therefore, as shown in Fig. 9(b), the accelerations at the top of the corrugated cartons and at the palette of second layer show large values. On the other hand, in case of No. 5, No. 6, and No. 7, which are not affected by the collision, the acceleration of the palette is smaller than that of the steel bracket, because the cargoes may slip. The acceleration of the corrugated cartons was larger than that of the palette owing to the vibration of the cargoes. The acceleration of the corrugated cartons in the case where the damper is used was reduced to 20%-70% of the acceleration when no damper was used. Obviously, reducing the acceleration is effective for reducing the slip displacement. As a typical example, Fig. 10 shows the time histories of the cargoes' slip displacement for the cases where the damper was used (No. 7) as well as where the damper was not used (No. 8). In the case where no mass damper was used (No. 8), the cargo slipped above 400 mm in 7 sec to 12 sec, and the cargo fell at the 12 sec mark. In the case where the mass damper was used (No. 7), the cargo slipped about 150 mm, but did not fall.

As a result, it can be observed that the proposed mass damper is effective for decreasing not only the response acceleration but also the slip displacement, and prevents the cargoes from falling.

4 Model of the cargo behavior

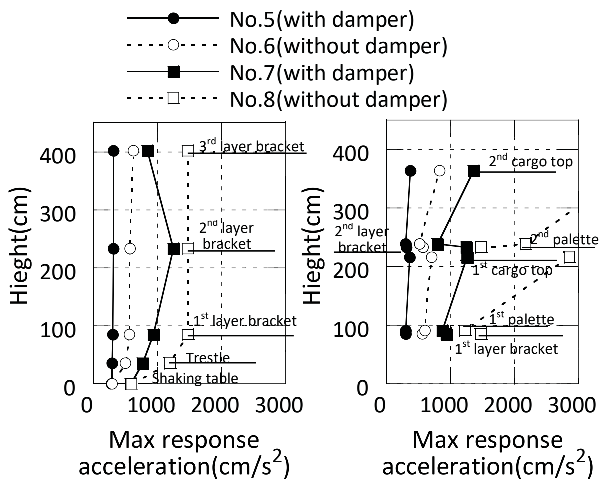
In this section, the analysis model of the cargoes' slip is proposed based on the experimental results of the test rack. This model will be used for the response analysis of the actual warehouse in the next section.

4.1 Aspect of the cargoes

As mentioned above, cartons are stacked on plastic palettes in layers that are about 1.0-1.5 times the height of the palette width. After the Hyogoken-nanbu Earthquake, 1995, it has been encouraged that the cargoes should be wound by using a shrink or a band. From Fig. 8, it seems that the corrugated cartons collapsed. However, they slipped together until they fell. Hence, the corrugated cartons can be assumed as one elastic body.

4.2 Analysis model

Fig. 11 shows the analysis model, which is the two masses model. One mass, M_1, is the mass of the



(a) Rack *(b) Cargoes and palette*

Fig. 9. Maximum acceleration distributions

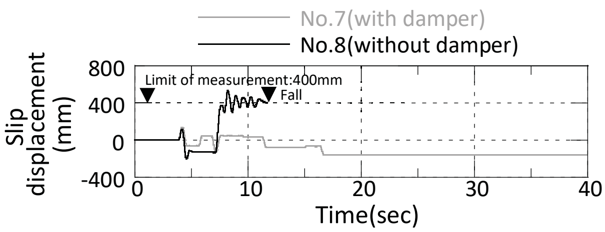


Fig. 10. Time histories of cargoes' slip displacement

corrugated cartons, and the other mass, M_2, is the mass of the palette. The linear spring, k_1, and the dashpot represent the vibration of the cargo. The frequency of the cargo is 4.62 Hz. The non-linear spring, k_2, represents the cargo slip. The damping ratio of the dashpot, h_1, is 16.7%. The hysteresis model of k_2 is shown in Fig. 12. Static friction and dynamic friction are incorporated in the model. The coefficient of static friction, μ_s, is 0.46 and the coefficient of dynamic friction, μ_d, is 0.17. These constants are decided based on the previous test results [8].

The analysis results as well as the experimental results for case No. 3 are shown in Fig. 13. It can be concluded that the analysis can substantially reproduce the experimental results both for accelerations and for slip displacements.

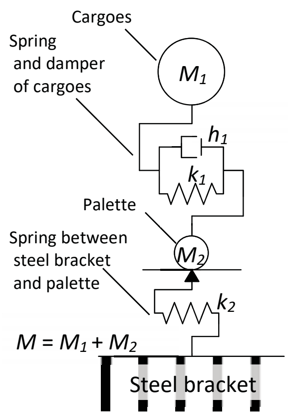


Fig. 11. Slip model of cargo

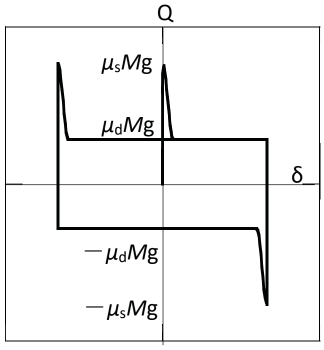
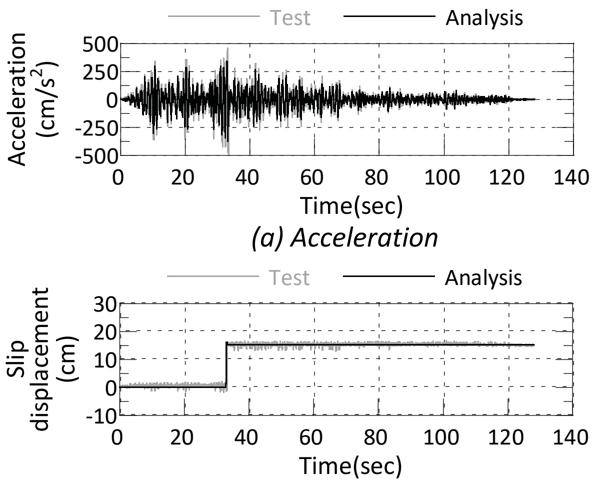


Fig. 12. Hysteresis model of k_2



(a) Acceleration

(b) Slip displacement

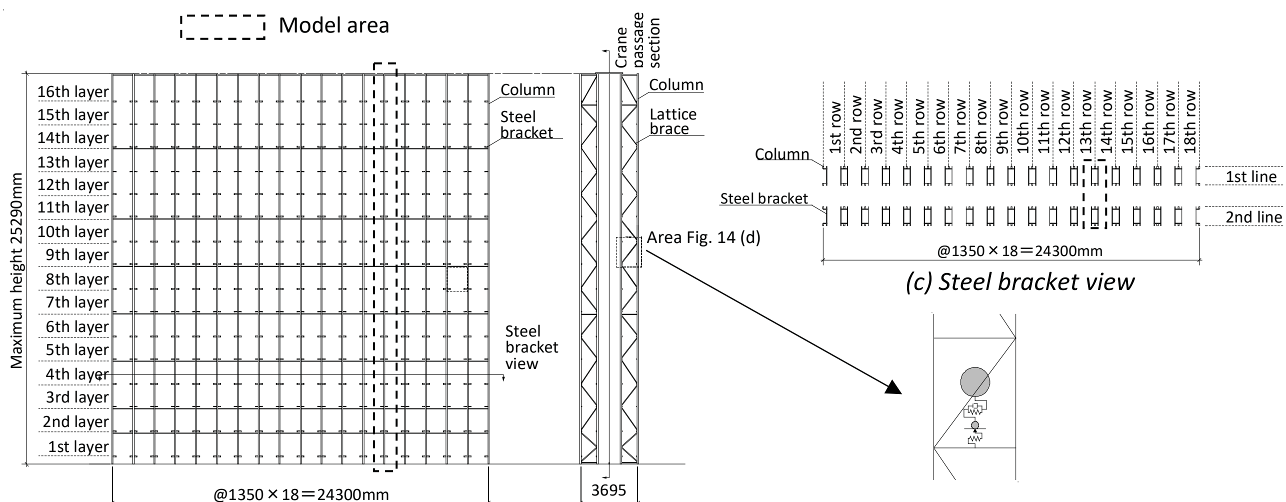
Fig. 13. Time histories of cargo

5 Analysis of full scale model

In this section, the effect of the proposed mass damper is discussed with the results of the response analysis of the actual rack using the analysis model of the cargo.

5.1 Outline of the analysis

Fig. 14 illustrates plan and view of the actual warehouse, which has 2 lines, 18 rows, and 16 layers. In this study, the analysis model of warehouse is the one row and two lines model, which is a part of the actual warehouse, as illustrated in Fig. 14(b).



(a) Crane passage view *(b) Frontage view* *(c) Steel bracket view* *(d) Part of analysis model*

Fig. 14.Plan and view of automated warehouse

Fig. 14(d) illustrates a part of the analysis model of the cargo. Steel elements of the rack are modelled as the beam elements of the frame model. In the analysis model, the cargoes are arranged such that all the storage space in the racks is occupied. The mass of one cargo, which is the sum of the mass of the corrugated cartons and the mass of the palette, is approximately 500 kg, and the cargoes are stacked up to 80% of the stacked ratio (the number of stacked cargoes/capacity). Therefore, the weight of the cargo is set as 400 kg. The natural frequency of warehouse is 0.66 Hz.

The mass damper is installed on the top of the rack, and the mass ratio of the damper is 2% or 10%. A generalized mass is determined at the layer where the mass damper is installed. The optimal natural frequency of the damper, $(f_{TMD})_{opt}$, and the optimal damping ratio of the damper, $(h_{TMD})_{opt}$, are calculated by *eq.* (1) and (2), respectively. Here, μ is the mass ratio of the damper and f_w is the natural frequency of the warehouse.

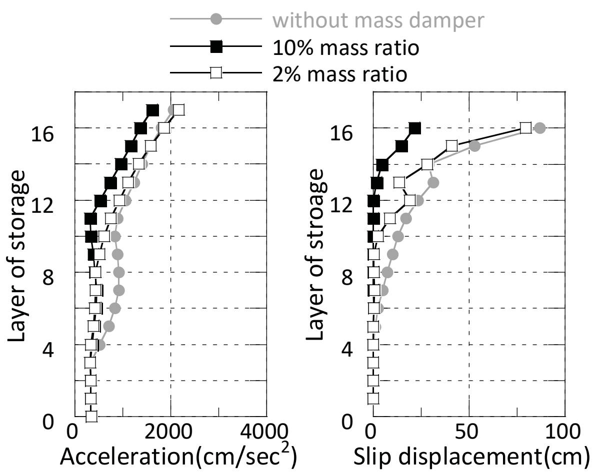
$$(f_{TMD})_{opt} = \frac{f_w}{1+\mu} \quad (1)$$

$$(h_{TMD})_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}} \quad (2)$$

5.2 Result of analysis

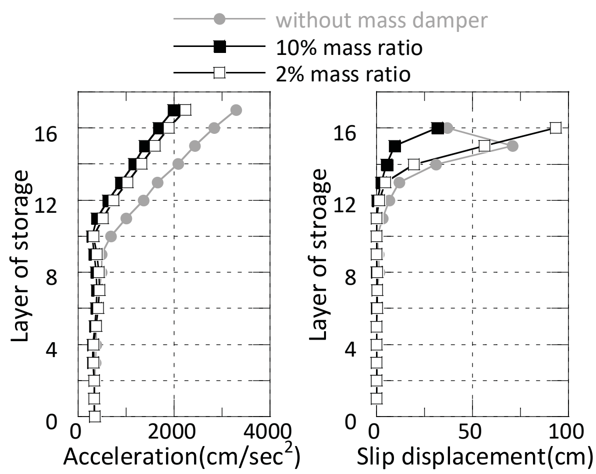
Fig. 15 shows the maximum response distributions, for cases without the damper, with the 2% mass ratio damper or with the 10% mass ratio damper. The accelerations and slip displacements increase as the layers reach the upper part of rack. It can be confirmed that the accelerations are reduced in cases where the damper is used. The acceleration at the top of rack in the case of 10% mass ratio is reduced to 80% of the acceleration in the case where no damper is used. The slip displacement at the top of the layers is reduced in the case of 10% mass ratio to 25% of the slip displacement in the case when no damper is used. On the other hand, in the case of 2% mass ratio, even though the accelerations from the third to the fourteenth layers are reduced, the acceleration at the top of rack is greater than the one in the case where no damper is used. Moreover, the slip displacement at the top of the layer is reduced to only 92% of that in the case when no damper is used.

To confirm the effect of the reducing response across the wide range of natural frequencies of the warehouse, Fig. 16 shows the maximum response distributions in case of 100% stacked ratio. The weight of cargo is set as 500 kg, where the natural frequency of the warehouse shifts to 0.59Hz. The dampers for each mass ratio are the same as the case shown in Fig. 15. As shown in Fig. 16, in the case when no damper is used, the slip displacement of the sixteenth layer is smaller than that of the fifteenth layer, because the cargoes move complicatedly owing to their elasto-plasticity hysteresis. In spite of this result, the



(a) Rack acceleration *(b) Cargoes slip displacement*

Fig. 15. Maximum response distributions in case of 80% stacked ratio



(a) Rack acceleration *(b) Cargoes slip displacement*

Fig. 16. Maximum response distributions in case of 100% stacked ratio

accelerations and slip displacements in the case of 10% mass ratio are still reduced. On the other hand, those in the case of 2% mass ratio are larger than the ones in the case of 10% mass ratio. Particularly, the slip displacement at the top of the layer is larger than that at the top of the layer in the case when no damper is used.

Consequently, it is clear that a large mass is more effective than a small mass for the reduction of the response acceleration and the slip displacement of cargoes, even if the natural frequency of the warehouse is changed.

6 Conclusions

A vibration control system for an automated warehouse was proposed in this paper, and its effect was discussed with the following experimental results and analysis:

1) The effect of reducing the response acceleration was confirmed for the wide range of natural frequencies that vary, and it depends on the number and the weight of the cargoes.
2) The effect of the proposed mass damper was confirmed by the shaking table test.
3) The model of cargoes slip was proposed. It was confirmed that the behavior of the cargoes could be predicted with the proposed analysis model of the cargoes.
4) The effect of the proposed mass damper for reducing the response was also verified by the response analysis.

7 References

[1] TANIGAWA M., YAMADA S., and WADA A. Proposal of truss column with ductile joint. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*. 2000; **C-1**: 539-540.

[2] TANIGAWA M., et al. Proposal of truss column with ductile joint. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*. 2001; **C-1**: 991-996.

[3] KIHARA K., LIOU M., TERADA T., SARUTA M., and KANEKO M. Earthquake Response Reduction Method using Tuned Mass Dampers for Existing Automated Storage and Retrieval Systems. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*. 2012; 943-946.

[4] MATSUNO Y., TAKEUCHI T., MATSUI R., and NISHI O. Seismic Response Control of Rack Warehouse taking Slipping and Falling of Live Load into Account. *Journal of structural engineering. B.* 2 014; **60B:**317-326

[5] AONO S., NAGASIMA I., TAKAKI M., HIBINO H., IZUMO Y., and FUJII H. Analytical Study on Isolated Racks in Automatic Warehouse. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*. 2014; 581-582.

[6] TAKEUCHI T., YOSHIDA M., UCHIDA M., NISHI O., and MATSUI R. Application of Seismic Isolation Bearings for Rack Warehouse to Prevent Goods Falling. *Transactions of AIJ. Journal of structural and construction engineering.* 2016;Vol.81:629-637.

[7] TAKAKI M., NAGASHIMA I., HIBINO H., AONO S., IZUMO Y, and MASEKI R. Study on Vibration Control of Rack in Automatic Warehouse. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*. 2012; 873-876.

[8] YASUKAWA M., TAKAKI M., KITAMURA H., SATO D., SATO T. A Study on Slip and Fall of Stacked Cargoes in Automated Warehouse. *Transactions of AIJ. Journal of structural and construction engineering.* 2017;Vol.82:183-192.