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SEISMIC BEHAVIOR OF NESTING RACK WITH STACKED CARDBOARDS BASED ON SHAKING TABLE TEST

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Abstract

There are many racks and storage items in logistics warehouses and factories, and there is a risk that the racks may overturn during an earthquake or heavy storage items may collapse and fall. In order to reduce injuries and maintain their functions, it is important to take measures to mitigate indoor damage beforehand. One of fundamental countermeasure is to make the entire building seismically isolated or to fix racks and storage items against a wall or a floor. However, fundamental measures are difficult to carry out because they are too costly and make the efficiency of warehouses and factories go down significantly. There are few studies on the behavior and damage of racks and stored items during an earthquake, so it is necessary to study how effective a trivial measure is.

The aim of this study is to accumulate knowledge that contributes to planning indoor damage mitigation measures in logistics warehouses and factories. In this paper, the behavior of nesting racks and stored items during an earthquake is examined by shaking table tests and simulations. Nesting racks are commonly used in many logistics warehouses and factories because they do not need to be fixed on the floor, and are easy to change the layout, and can be stored compactly when not in use. The shaking table tests have limitations to shaking object size and shaking level, so the shaking tests are conducted for revealing the fundamental vibration characteristics of racks and stored items, and the simulations are used for estimating the behavior during a giant earthquake.

First, shaking table tests are conducted to two stacked nesting racks and three stacked cardboard boxes on pallets in order to reveal the behavior and the vibration characteristics during an earthquake. The horizontal predominant frequency of two stacked nesting racks is about 6 Hz in the empty state, and about 3Hz in the loaded state. The three stacked cardboard boxes on pallets begin to slide in the acceleration level 200 cm/s^2, and collapse in 400 cm/s^2. The horizontal predominant frequency is about 6 Hz and the vertical one is about 11 Hz.

Second, the behavior of the racks and stacked cardboard boxes in the shaking table tests are simulated by DEM. The dynamic parameters of the calculation models such as frictions, spring and damper coefficients are determined from the comparison of the computed behavior with the behavior in the shaking table tests.

Finally, the parametric study is conducted in order to estimate the behavior of nesting racks and stacked cardboard boxes during a giant earthquake. As the result of the parametric study, the overturn threshold of nesting racks and the collapse threshold of stacked cardboard boxes are revealed.

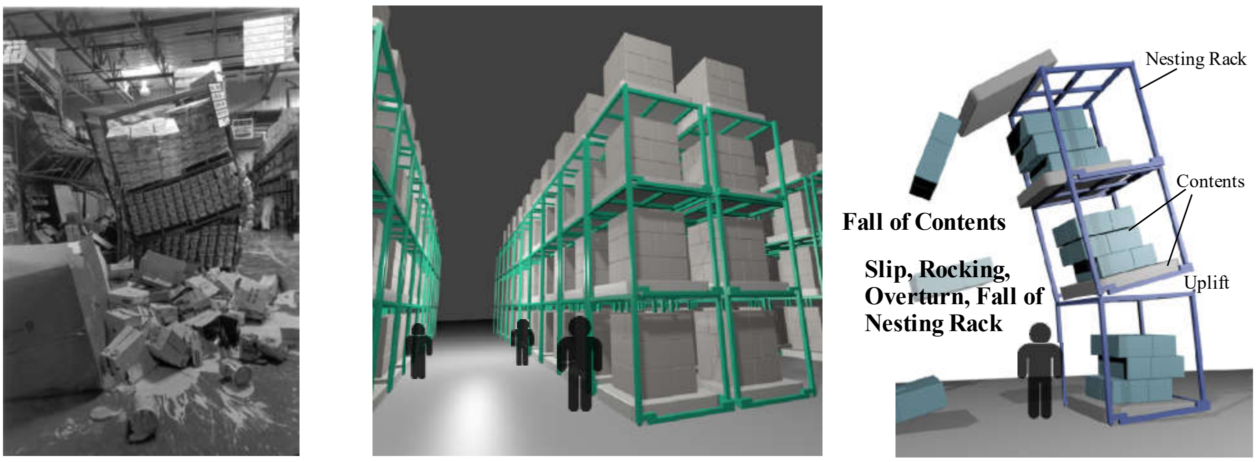
Keywords: nesting rack, stacked cardboard boxes, indoor damage, logistics warehouses, factories

1. Introduction

It is well known that earthquake ground motions can cause storage steel racks to collapse or overturn, or their contents to fall, such as Fig. 1(a) [1]. Fig. 1(b) shows one of the situations that thousands of stacked nesting racks are placed in a logistics warehouse or a factory. Nesting racks are widely used because they do not need to be fixed on the floor, and are easy to change the layout, and can be stored compactly when not in use. However, they have a risk that the racks may overturn, or heavy items may collapse and fall during an earthquake (See Fig. 1(c)). In order to reduce injuries and maintain their functions, it is important to take measures to mitigate such indoor damage beforehand.

The vibration characteristics of stacked cardboard boxes during transportation has been studied by shaking table tests and simulations [2, 3, 4]. Yasukawa et al. has been studied about slip and fall behavior of stacked cardboard boxes in automated warehouse during an earthquake, and about the seismic interaction behavior between floor anchored racks and cardboard boxes [5, 6, 7]. Alternatively, there are few studies on the behavior and damage of not anchored racks and stored items during an earthquake.

One of fundamental countermeasure is to make the entire building seismically isolated or to fix racks and storage items against a wall or a floor. However, fundamental measures are difficult to carry out because they are too costly and make the efficiency of warehouses and factories go down significantly, so it is necessary to study how effective a trivial measure is. In this paper, the behavior of nesting racks and stored items during an earthquake is examined by shaking table tests and simulations for considering countermeasures.



(a) Collapsed storage racks and falled contents during an earthquake (FEMA, 2005)   (b) One of the situations in a logistics warehouse or a factory   (c) Risk of nesting racks and contents

Fig. 1 – Risk of nesting racks and contents during an earthquake

2. Shaking Table Tests

2.1 Overview of shaking table tests

The aim of shaking table tests is to reveal fundamental characteristics of the behavior of nesting racks and stored items. Fig. 2 shows the photos and the specifications of a nesting rack, a cardboard box, and a pallet used for shaking table tests. The nesting rack is placed on the floor, not anchored. The “Plug” and “Socket” in the figure are fit when the racks are stacked. The upper rack is also only placed on the lower rack, so the upper rack comes off easily. The cardboard box filled with lots of A4 papers and tied up with two bands. The friction coefficients are also shown in Fig. 2. The friction coefficient between the RC plate floor and the nesting rack is measured by a shaking table test, and the others are measured by a static tension test.

Fig. 3 shows the condition of shaking objects. "CB" has 3 stacked cardboard boxes (12 cardboard boxes) on a pallet. The total mass of CB is about 285kg. Non-slip sheet is spread between the floor and the pallet. "R2" is empty two stacked nesting racks. The total height of R2 is about 2.5m. The lower rack is fixed when "R2FIX" is shaken in order to reveal the uplift threshold between the upper and lower rack. "R2+CB" contains CB on the top of lower rack. "R2+2CBW" contains two stacked cardboard boxes (8 cardboard boxes) with pallet on the top of the lower rack and 3 stacked cardboard boxes with pallet on the top of the upper rack. All cardboard boxes are wrapped with a wrap. The total height of R2+2CBW is about 3.4m and the total mass is about 575kg. The acceleration at the top of each shaking objects is measured with acceleration sensor, and the whole motion of shaking objects is measured with motion capture. The positions of an acceleration sensor and motion capture markers are shown in Fig. 3.

The cases of shaking table tests are shown in Table. 1. Shaking table test is conducted twice. First shaking test is conducted by the shaking table owned by ITOKI CORPORATION on July 30-31, 2019. Shaking object CB, R2, and R2+CB are shaken, and the floor of this test is a ceramic tile with a smooth surface. Second shaking test is conducted by the shaking table in The University of Tokyo, Kashiwa Campus on November 21-22, 2019. R2, R2FIX, and R2+2CBW are shaken, and the floor of this test is a RC plate.

The shaking direction is one horizontal component or horizontal + vertical two components. The cases of a sweep wave input are conducted in order to find out the resonance period of each shaking objects. Fig. 4 shows the normalized acceleration time histories and the response spectrums of observed input waves used for shaking table test. The detail of four observed input waves, "311Haga", "Mashiki", "Takatori", and "311Tsukidate", is described in Table. 1. These waves have different characteristics, such as duration or predominant period. For example, 311Tsukidate has about 130sec long duration, and predominant period at about 0.25sec. On the contrary, Takatori has about 20sec short duration and predominant period at about 1.1sec.

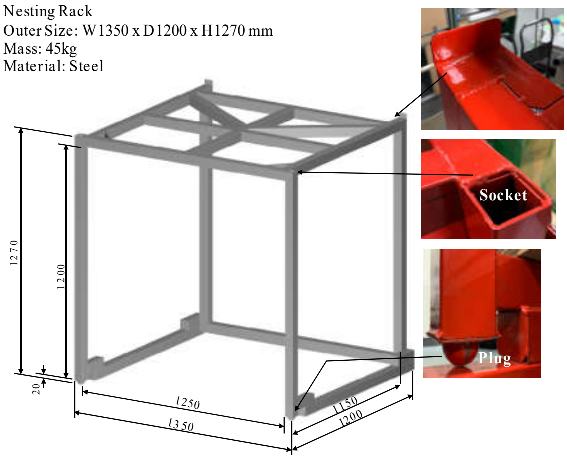
2.2 Result of shaking table tests

Fig. 5 shows the transfer function of shaking objects obtained by sweep wave input shaking cases. The transfer functions are obtained by dividing a fourier amplitude spectrum of measured displacement time histories at upper position (circle symbol in the figure) by one at lower position (triangle symbol in the figure). The horizontal resonance frequency of empty two stacked nesting racks (R2) is about 6Hz. The resonance frequency of 284.4kg loaded racks (R2+CB) and 484kg loaded racks (R2+2CBW) is about 3.1Hz and 2.5Hz, respectively. The vertical resonance frequency of R2 is not obtained by shaking test, but it may be over 15Hz. The vertical resonance frequency of R2+CB is about 9Hz. The horizontal resonance frequency of three stacked cardboard boxes without wrap is about 6Hz and the vertical resonance frequency is about 11Hz. The horizontal resonance frequency of two stacked cardboard boxes is over 10Hz.

The summary of shaking table tests is also shown in Table. 1. As the results of the shaking case I04, I05, and I06, CB begins to slide in the acceleration level 200 cm/s^2, and collapse in over 400 cm/s^2 due to a 1Hz sine input wave. The snapshot of the shaking case I06 is shown in Fig. 6 (a). The boundaries between lower and middle cardboard boxes slides mainly. The slide directions of cardboard boxes are asymmetry due to the bands which ties cardboard boxes up. On the other hand, CB is not collapsed in the shaking case I09 due to 311Haga input wave that has acceleration level 490cm/s^2. This is because the displacement level of I09 is about 1/4 of I06.

Fig. 6 (b) shows the snapshot of the shaking case T03. The upper rack continues to rock and uplift on the lower rack and fall off in the end. As the result of the shaking case T05 and T06, the uplifting acceleration threshold of the upper rack is in between 647cm/s^2 and 1070cm/s^2.

Fig. 6 (c) shows the snapshot of the shaking case T23. The racks overturn and the cardboard boxes and pallets are fall in this case. All objects are mainly rocking in 1st mode. The slide of objects is little.



Measured Friction Coefficient

Lower	vs	Upper	Static Friction Coef.	Dynamic Friction Coef.
Cardboard	vs	Cardboard	0.20	0.18
Pallet	vs	Cardboard	0.26	0.25
Nesting Rack	vs	Pallet	0.25	0.25
Ceramic Tile Floor	vs	Nesting Rack	0.25	0.24
RC Plate Floor	vs	Nesting Rack	0.40	0.40

Fig. 2 – Photos and specification of a nesting rack, a cardboard, and a pallet

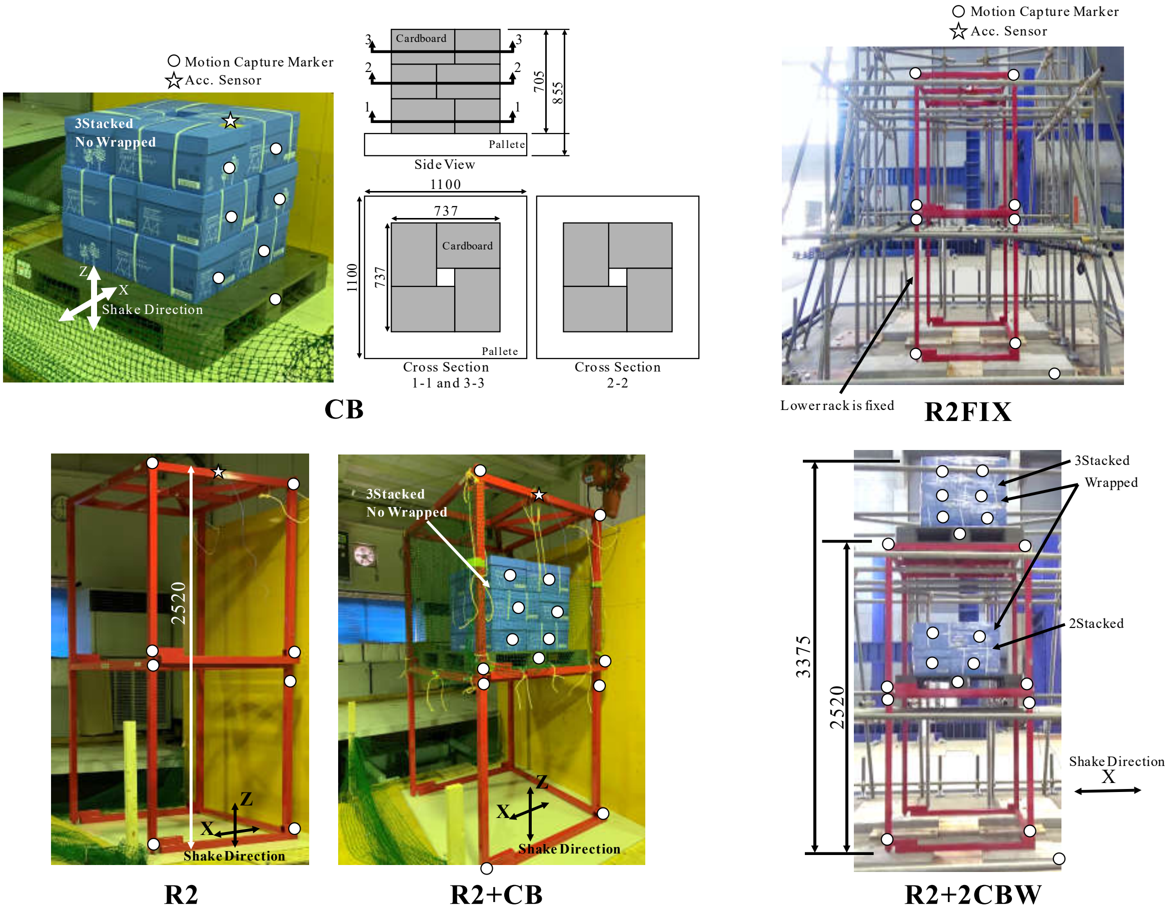


Fig. 3 – Condition of shaking objects

Table. 1 – The cases and the results of shaking table tests

Test Date: 2019/7/30-31 Shaking Table: ITOKI CORPORATION

Case Id	Shaking Object	Input Wave			Floor Measured Max Input				Nesting Rack				Stored Items		
					X		Z			MaxUpliftZ(cm)		Max Top DispX (cm)		MaxDispX(cm)	
		Wave		Shake Direction	Acc (cm/s^2)	Disp (cm)	Acc (cm/s^2)	Disp (cm)	Behavior	Lower Rack Bottom	Upper Rack Bottom		Behavior	Card-board	Pallet
I01	CB	Sweep	50gal 15-0.3Hz	X	60	0.3	-	-	-	-	-	-	Vibration	0.1	0.1
I02		Sweep	50gal 15-0.3Hz	Z	-	-	64	0.2	-	-	-	-	Vibration	0.0	0.0
I03		sine	100gal 1Hz	X	100	2.2	-	-	-	-	-	-	Vibration	0.1	0.1
I04		sine	200gal 1Hz	X	200	4.0	-	-	-	-	-	-	Vibration	0.2	0.1
I05		sine	300gal 1Hz	X	336	6.2	-	-	-	-	-	-	Slide	4.1	0.2
I06		sine	400gal 1Hz	X	-*3	8.2	-	-	-	-	-	-	Collapse	89.9	5.5
I07		311Haga*1	MaxAccX 400gal*2	X	390	3.5	-	-	-	-	-	-	Slide	4.2	0.1
I08		311Haga	MaxAccX 400gal	XZ	395	3.5	318	1.8	-	-	-	-	Slide	4.9	0.1
I09		311Haga	MaxAccX 500gal	XZ	490	4.4	370	2.2	-	-	-	-	Slide	9.3	0.3
I10	R2	Sweep	50gal 15 - 0.3Hz	X	56	0.3	-	-	Vibration	0.1	0.1	0.3	-	-	-
I11		Sweep	50gal 15 - 0.3Hz	Z	-	-	73	0.2	Vibration	0.0	0.0	0.0	-	-	-
I12	R2 + CB	Sweep	50gal 15 - 0.3Hz	X	56	0.3	-	-	Vibration	0.1	0.1	0.4	-	-	-
I13		Sweep	50gal 15 - 0.3Hz	Z	-	-	64	0.2	Vibration	0.2	0.1	0.0	-	-	-
I14		311Haga	MaxAccX 300gal	X	299	2.6	-	-	Vibration	0.3	0.1	0.9	Slide	4.5	0.8
I15		311Haga	MaxAccX 300gal	XZ	288	2.6	282	1.3	Vibration	0.3	0.1	0.9	Slide	5.7	0.6
I16		311Haga	MaxAccX 400gal	X	398	3.5	-	-	Vibration	0.5	0.1	1.8	Slide	1.8	6.7
I17		311Haga	MaxAccX 500gal	X	526	4.4	-	-	Vibration	0.3	0.2	1.3	Slide	1.3	1.0

*1 "311Haga": Observed at KiK-net TCGH16(Haga) NS during The 2011 off the Pacific coast of Tohoku Earthquake

*2 "MaxAccX ***gal" means that the maximum acceleration of an observed wave is adjusted to *** gal.

*3 The acceleration data of a floor is not obtained due to emergency stop

Test Date: 2019/11/21-22 Shaking Table: The University of Tokyo, Kashiwa Campus

Case Id	Shaking Object	Input Wave			Floor Measured Max Input				Nesting Rack				Stored Items		
					X		Z			MaxUpliftZ(cm)		Max Top DispX (cm)		MaxDispX(cm)	
		Wave		Shake Direction	Acc (cm/s^2)	Disp (cm)	Acc (cm/s^2)	Disp (cm)	Behavior	Lower Rack Bottom	Upper Rack Bottom		Behavior	Card-board	Pallet
T01	R2	Mashiki*1	MaxAccX 400gal	X	425	7.4	-	-	Vibration	0.6	0.0	1.7	-	-	-
T02		311Tsukidate*2	MaxAccX 1500gal	X	1932	2.0	-	-	Vibration	0.8	0.5	2.4	-	-	-
T03		sine	1000gal 1.5Hz	X	1188	13.7	-	-	Fall*4	18.3	14.3	66.9	-	-	-
T04	R2FIX	sine	300gal 1.5Hz	X	360	3.2	-	-	Vibration	0.1	0.0	0.2	-	-	-
T05		sine	600gal 1.5Hz	X	647	6.7	-	-	Vibration	0.2	0.4	1.1	-	-	-
T06		sine	800gal 1.5Hz	X	1070	8.7	-	-	Fall*4	0.9	10.2	22.7	-	-	-
T07	R2 + 2CBW	Sweep	50gal 0.25 - 2Hz	X	102	5.2	-	-	Vibration	0.0	0.0	0.3	Vibration	0.1	0.0
T08		Sweep	50gal 2 - 10Hz	X	70	0.3	-	-	Vibration	0.1	0.0	0.8	Vibration	1.7	0.0
T09		311Tsukidate	MaxAccX 200gal	X	180	0.4	-	-	Vibration	0.0	0.0	0.3	Vibration	0.2	0.0
T10		311Tsukidate	MaxAccX 300gal	X	284	0.6	-	-	Vibration	0.0	0.0	0.3	Vibration	0.4	0.0
T11		311Tsukidate	MaxAccX 400gal	X	402	0.8	-	-	Vibration	0.0	0.0	0.4	Vibration	0.5	0.0
T12		311Tsukidate	MaxAccX 500gal	X	460	1.0	-	-	Vibration	0.0	0.0	0.4	Vibration	0.5	0.0
T13		311Tsukidate	MaxAccX 600gal	X	535	1.0	-	-	Vibration	0.0	0.0	0.5	Vibration	0.7	0.0
T14		311Tsukidate	MaxAccX 700gal	X	694	1.3	-	-	Vibration	0.1	0.0	0.5	Vibration	0.9	0.1
T15		311Tsukidate	MaxAccX 800gal	X	811	1.4	-	-	Vibration	0.1	0.1	0.6	Slide in Wrap	1.5	0.4
T16		311Tsukidate	MaxAccX 1000gal	X	938	1.8	-	-	Vibration	0.1	0.0	0.7	Slide in Wrap	1.9	0.4
T17		Mashiki	MaxAccX 300gal	X	334	5.9	-	-	Vibration	0.6	0.0	2.0	Slide in Wrap	4.0	0.6
T18		Mashiki	MaxAccX 400gal	X	419	7.5	-	-	Vibration	1.9	0.0	4.7	Slide in Wrap	9.5	9.4
T19		Mashiki	MaxAccX 500gal	X	689	11.5	-	-	Rocking	8.7	0.2	21.1	Slide, Wrap Tear	19.8	1.4
T20		Mashiki	MaxAccX 600gal	X	689	11.4	-	-	Rocking	7.8	0.7	18.1	Slide, Wrap Tear	17.8	21.7
T21		Takatori*3	MaxAccX 200gal	X	229	7.9	-	-	Vibration	0.3	0.0	1.4	Slide in Wrap	1.2	0.1
T22		Takatori	MaxAccX 300gal	X	321	11.8	-	-	Rocking	4.0	0.0	9.7	Slide in Wrap	7.3	2.7
T23		Takatori	MaxAccX 400gal	X	393	15.6	-	-	Overturn	31.2	0.8	73.9	Fall	69.3	47.1

*1 "Mashiki": Observed at KiK-net KMMH16(Mashiki) EW during the main shock of The 2016 Kumamoto Earthquake occurred at 2016/4/16 1:25 (JST, GMT+9)

*2 "311Tsukidate": Observed at K-NET MYG004(Tsukidate) NS during The 2011 off the Pacific coast of Tohoku Earthquake

*3 "Takatori": Observed at JR Takatori Station EW during The 1995 Hyogo-ken Nanbu Earthquake

*4 Uplift and Fall off of Upper Rack

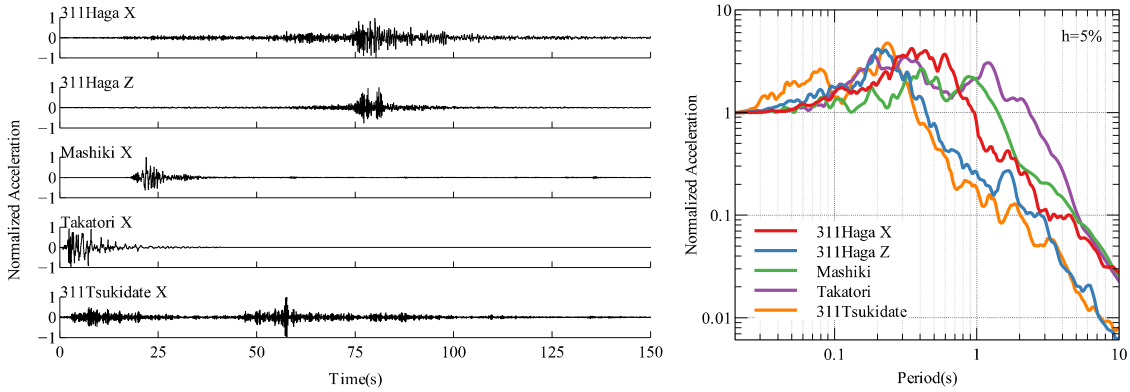


Fig. 4 – Normalized acceleration time histories and response spectrums used for shaking table test

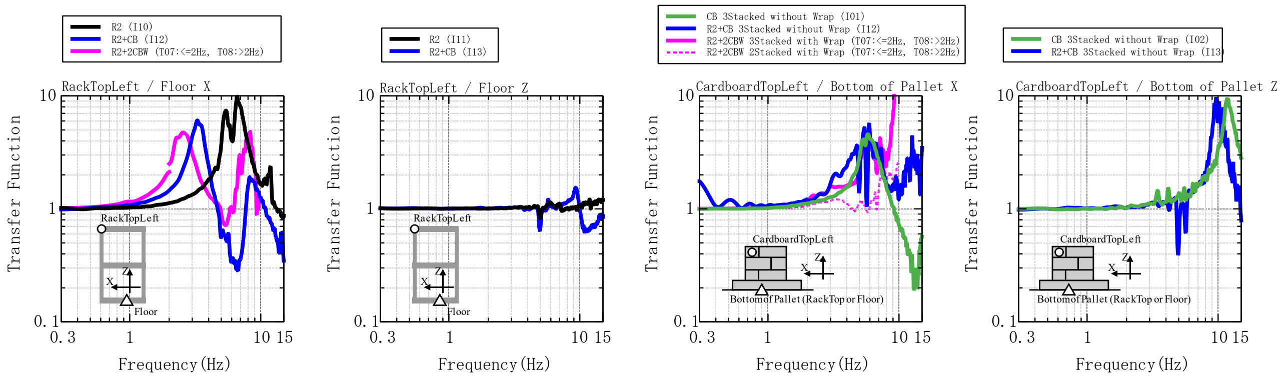
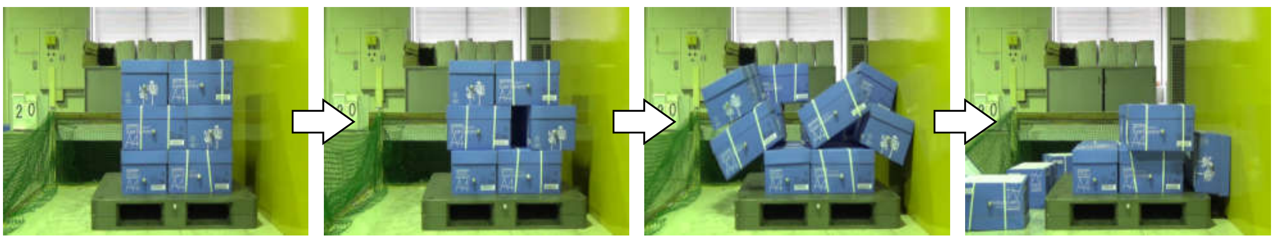
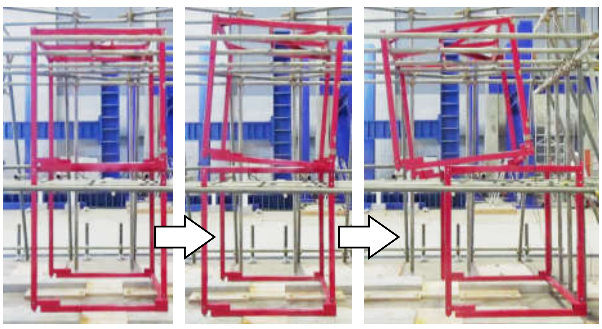


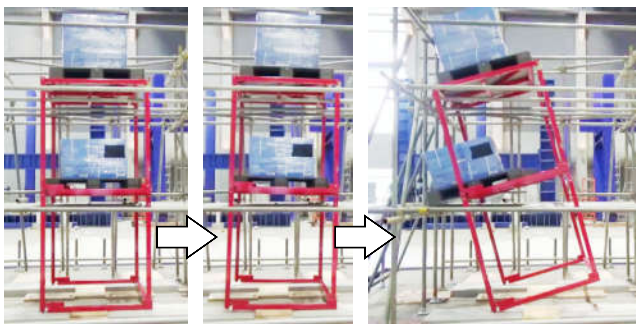
Fig. 5 – Transfer function of shaking objects



(a) CB: I06 Sine 400gal 1Hz



(b) R2: T03 Sine 1000gal 1.5Hz



(c) R2+2CBW: T23 Takatori Max AccX 400gal

Fig. 6 – Snapshots of shaking table tests

3. Simulation of Shaking Table Tests

3.1 Overview of simulation method and model

The behavior of the rack and the stored items in the shaking table tests is simulated by a rigid body simulation program called Springhead [8]. In Springhead, contact forces are computed by DEM. A contact area is divided into several triangle elements, and springs and dampers are set at the triangle element (See Fig. 7). The contact force computed from the triangle elements is used in the simulation. The GJK algorithm [9] is used for the contact detection of arbitrary convex objects in Springhead. Dynamic parameters of the shaking objects used in the simulation such as friction, spring and damper coefficients are determined from the comparison of the computed behavior with the behavior in the shaking table tests.

Fig. 7 shows the schematic figures of simulation 2D model. The model of a nesting rack is constructed from four rigid bodies and four hinge joints. The deformation of a nesting rack is simulated by the hinge joints. A linear rotational spring and a damper is set to a hinge joint. The shape of plug, socket, and stopper between an upper and a lower rack (See Fig. 2) is modelized in order to simulate the uplift and coming off behavior of upper rack. A pallet and cardboard boxes are modelized to one rectangular rigid body even without wrapping. The behavior of stacked cardboard boxes is too complex to simulate because the cardboard boxes are tied up with bands, and the influence against the behavior of cardboard boxes may be large. The contact parameters, such as spring and damper, is adjusted in order to simulate the resonance phenomenon of a pallet and cardboard boxes obtained by shaking table tests.

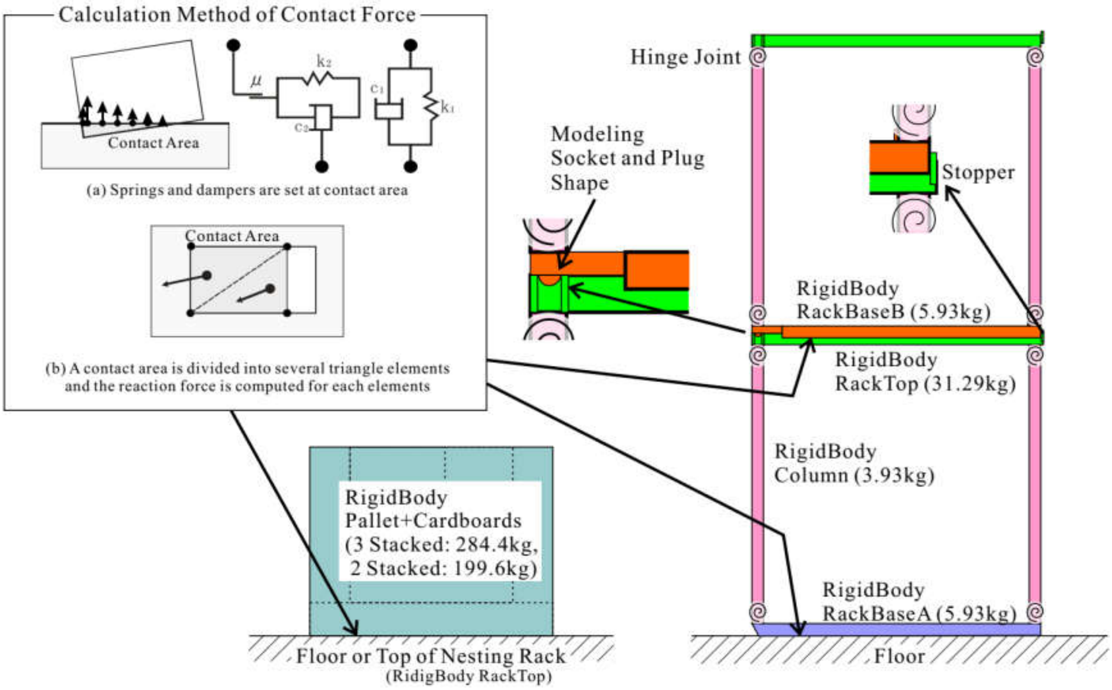
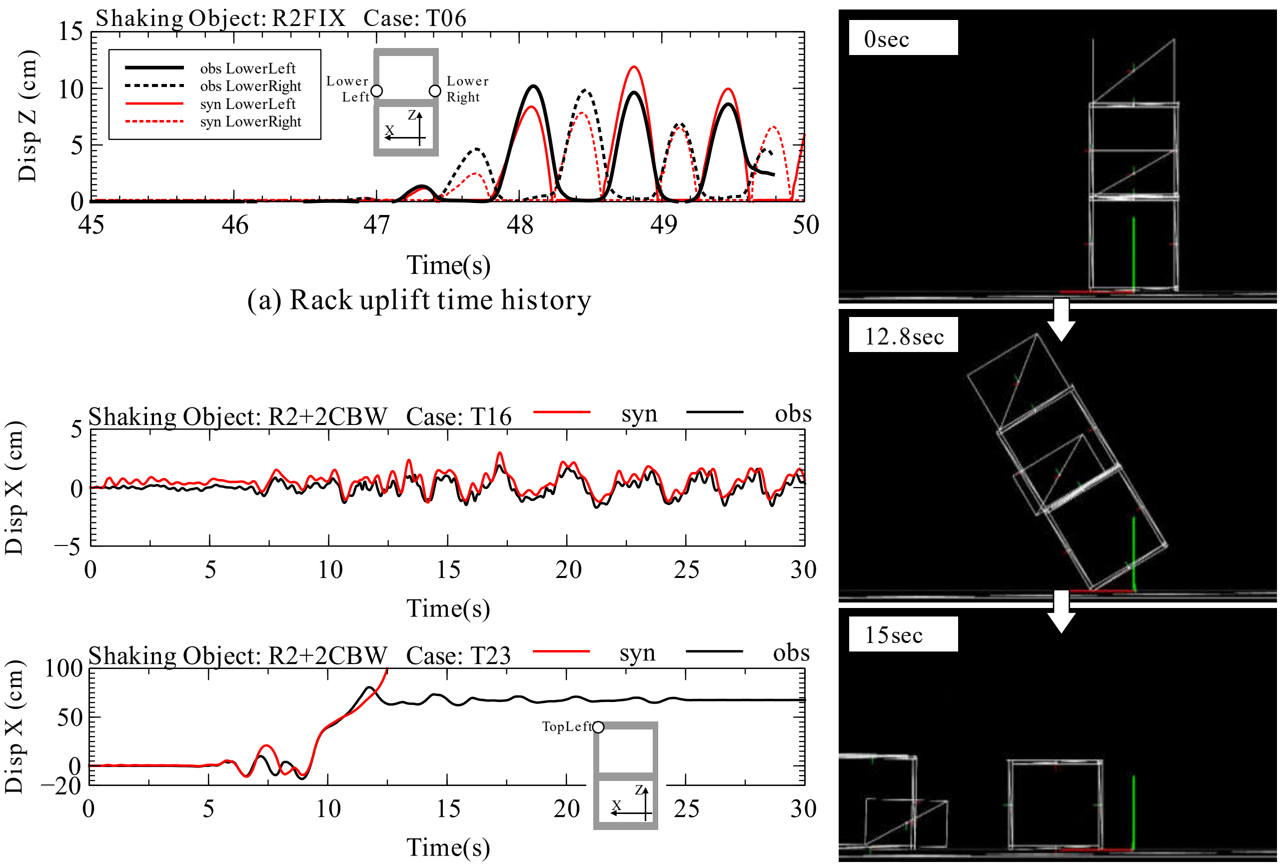


Fig. 7 – Schematic figures of simulation model

3.2 Simulation result of shaking table tests

The simulation results of shaking table test are shown in Fig. 8. Fig. 8 (a) shows the comparison between observed and simulated uplift (vertical displacement) time history at the lower left and right of the rack during shaking case T06. The uplift amplitude and timing are relatively close to observations. Fig. 8 (b) shows the comparison between observed and simulated horizontal displacement time history at the top left of the rack during shaking case T16 and T23. The rack vibrates only during the shaking case T16. On the contrary, the rack overturned during the shaking case T23 at time about 10 sec. The shape and amplitude of the simulated time history are close to observed one. Fig. 8 (c) is the snapshot of simulated behavior during the shaking case T23. All objects are mainly rocking in 1st mode, and sliding is little. This simulated behavior is same as observed one.

As the results of this study, it is found that the seismic real behavior of a nesting rack, a pallet, and, wrapped cardboard boxes are well reproducible by this simulation method and model. The reproduce of the seismic behavior of not wrapped cardboard boxes is a future subject.



(a) Rack uplift time history
(b) Displacmenet time history at the top of rack
(c) Simulation snapshot of case T23

Fig. 8 – Simulation results of shaking table tests

4. Estimation of the Seismic Behavior of Nesting Racks

4.1 Estimation method

Shaking table test has the limitation of shaking level, so the parametric study is conducted in order to estimate the seismic behavior of nesting racks and stacked cardboard boxes due to various shaking waves including a giant earthquake. In this study, the behavior of R2 and R2+2CBW is simulated due to sine waves and earthquake waves using the simulation models constructed in Chapter 3. The frequency range of the sine waves is 0.25 - 15Hz, and the acceleration range is 100 – 1200 cm/s^2. The four horizontal earthquake waves shown in Fig. 4 are used in this study, and the acceleration is adjusted in the range of 100 – 1200 cm/s^2. Shaking direction is one horizontal direction, and regarding the case of earthquake wave input, the case where the phase of the wave is inverted is also examined.

4.2 Estimation result

Fig. 9 shows the estimation result of the seismic behavior of R2 and R2+2CBW. The horizontal axis is the frequency of input waves and the vertical axis is the acceleration level. The behavior type of each input wave is shown in the figure. The behavior is classified to following four types: "Slightly Damage", "Rack Uplift > 2cm", "Contents Fall", and "Rack Overturn". "Slightly Damage" means that the racks only vibrate and the stored items only slide on the rack. "Rack Uplift > 2cm" means that the rocking of the racks is large and the uplift at the bottom of the rack is over 2cm. 2cm is the height of plug in Fig. 2. There is a possibility of falling the upper rack if the uplift is over 2cm. "Contents Fall" means that the stored items fall and the racks is not overturn. The black markers show the results of sine waves and the magenta markers show the results of earthquake waves. The frequency of earthquake waves is equivalent frequency F_e [10]. F_e of 311Haga, Mashiki, Takatori, and 311Tsukidate are 1.79Hz, 1.46Hz, 0.84 Hz, and 3.69 Hz, respectively. Black line shows the overturn threshold calculated by the simple evaluation formula [11]. The overturn threshold of the formula is evaluated under the assumption that an object is one rectangular rigid body, and the parameter values of the formula, b and h, are shown in Fig. 10. b is smaller than the half of rack outer width due to the offset at the plug in Fig. 10. b/h of R2 and R2+2CBW are 0.36 and 0.25, respectively.

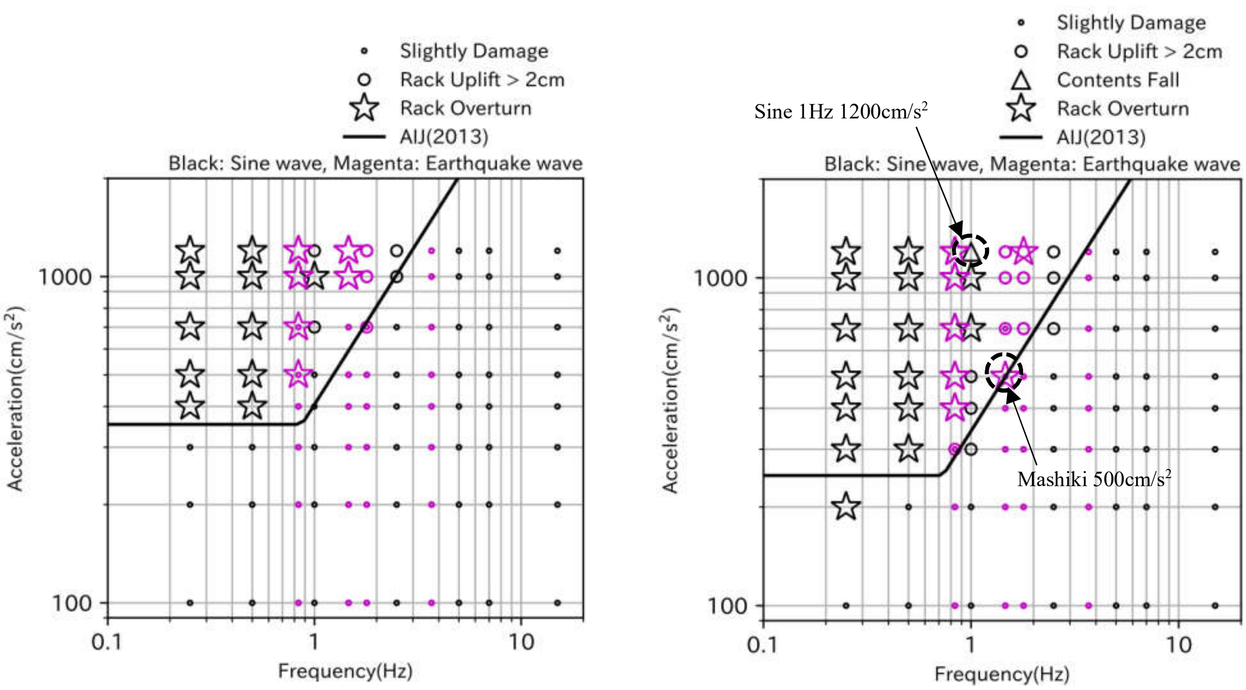
Focusing on the result of R2 in Fig. 9, the overturn threshold is between 300cm/s^2 and 400cm/s^2 in the frequency range of lower 0.6Hz. And in the range of 0.6Hz - 1Hz, the threshold is between 400cm/s^2 and 500cm/s^2, and in the range of 1Hz - 2Hz, the threshold is between 900cm/s^2 and 1000cm/s^2, and in the range of over 2Hz, the threshold is over 1200cm/s^2. The behavior type "Rack Uplift > 2cm" occurs only in the frequency range of 1Hz or over. The overturn threshold of the simple evaluation formula is relatively close to the threshold of the simulation in the frequency range of lower 0.6Hz. On the contrary, in the frequency range of upper 0.6Hz, the overturn threshold of the simple evaluation formula is smaller than the threshold of the simulation. This difference seems to have occurred due to the influence of the uplift and collision against upper and lower rack. Focusing on the result of R2+2CBW, the overturn begins to occur in the acceleration level 200cm/s^2, 300cm/s^2, 400cm/s^2, 700cm/s^2, and 1200cm/s^2 in the frequency of 0.25Hz, 0.5Hz, 0.84Hz, 1Hz, and 1.79Hz, respectively. In the case of "Mashiki 500cm/s^2" shown in the figure, the overturn threshold is lower compared to the threshold in the nearby frequency range. An overturn occurs only in the case where the phase of the wave is not inverted. This implies that the phase of the input wave might have coincidentally synchronized with the rocking phase of R2+2CBW. The behavior type "Contents Fall" occurs only one case "Sine 1Hz 1200cm/s^2" shown in the figure. The simulation snapshot of this case is shown in Fig. 11. The lower and upper racks continue rocking and uplifting severely after 2.3sec. The stored item on the top of lower rack slides largely at 3.2sec, and falls at 4.3sec. The upper rack comes off at 12 sec, but the racks does not fall or overturn to the end. The overturn threshold of the simple evaluation formula is larger than the threshold of the simulation in the frequency range of 0.25Hz. On the contrary, in the frequency range of over 0.6Hz except 1.46Hz, the threshold of the formula is smaller than the threshold of the simulation. This difference seems to have occurred due to the influence of the uplift and collision against upper and lower rack, and the friction between racks and stored items.

The study results are only the results for the study conditions assumed in this parametric study. Therefore, it is necessary to consider various conditions in the future.

5. Conclusions

In this paper, the seismic behavior of nesting racks and stacked cardboard boxes on a pallet is studied by shaking table tests and simulations. First, the shaking table tests are conducted to two stacked nesting racks and stacked cardboard boxes on pallets in order to reveal the seismic behavior and the vibration characteristics. Second, the behavior of the racks and stacked cardboard boxes in the shaking table tests are simulated by DEM. As the results of this study, it is found that the seismic real behavior of a nesting rack, a pallet, and, wrapped cardboard boxes are well reproducible by the simulation. Finally, the parametric study is conducted in order to estimate the seismic behavior of nesting racks and stacked cardboard boxes due to various shaking waves including a giant earthquake. As the results of parametric study, the relations between a shaking level and the behavior type are revealed.

The study results are only the results for the study conditions assumed in this paper. Therefore, it is necessary to consider various conditions in the future.



(a) R2 (b) R2+2CBW

Fig. 9 – The estimation result of the seismic behavior of R2 and R2+2CBW

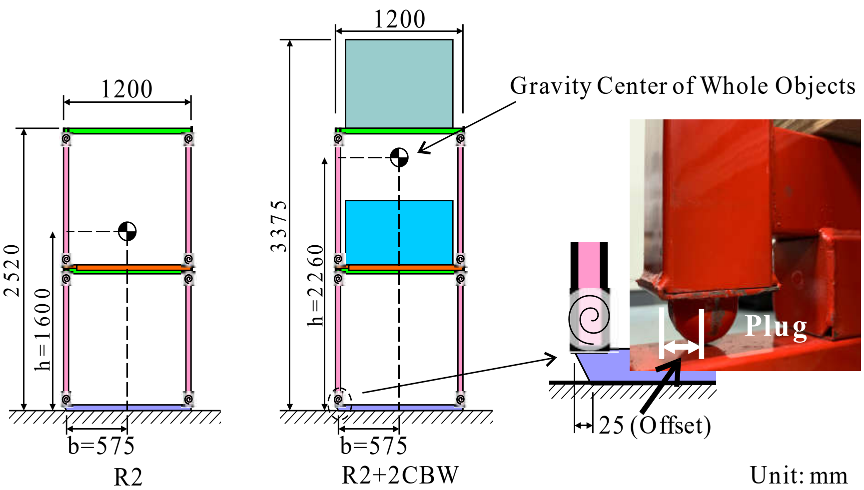


Fig. 10 – The parameter values of the simple overturn evaluation formula

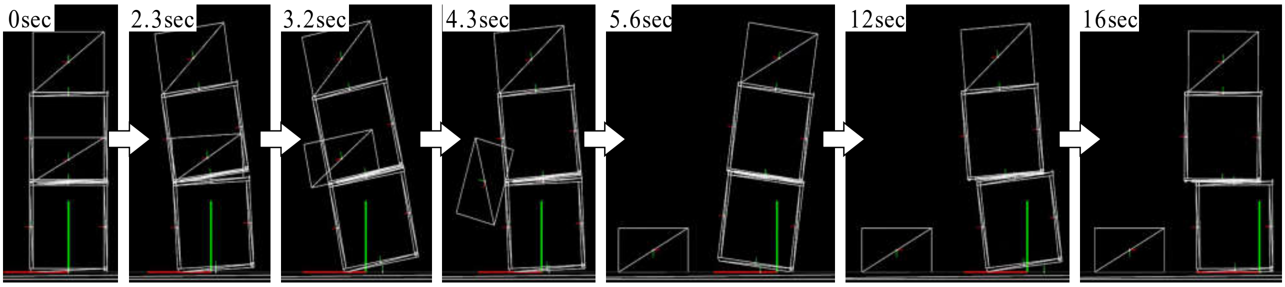


Fig. 11 – The simulation snapshot in the case of 1Hz 1200cm/s^2 sine wave input

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