Journal of Constructional Steel Research 203 (2023) 107844

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Analysis of behavioral characteristics according to the fixing condition of pallet rack

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ARTICLE INFO

Keywords:
Storage racks
Shaking table test
Seismic performance
Fixing condition
Torsion

ABSTRACT

This study aims to verify the damage and collapse of the pallet rack due to external forces, such as earthquakes, through a shake table test and analyze the behavioral characteristics of the pallet rack column foundation for each fixing condition caused by a continuous external force. A shake table test was conducted on a pallet rack commonly used in warehouses to examine its damage and collapse owing to external forces. In the shake table test, the strength of the load was increased to investigate the collapse of the pallet rack, and the failure of the member connection was regarded as a collapse. The behavioral characteristics were analyzed using the shake table test according to the conditions of the baseplate connections, which are determined by the external forces. The displacements caused by the external force, permanent displacement, cumulative displacement, and damage were analyzed from the data obtained through the experiment. Finally, the possibility of collapse according to the fixing condition was verified.

1. Introduction

Storage racks are typical non-structural components installed for the storage and classification of cargo in the logistics distribution process. Their installations are increasing owing to the increase in logistics. Generally, storage racks are damaged by the vehicle collisions during loading; however, most of the damage that causes collapse occurs because of large external forces, such as earthquakes. Various studies have demonstrated that storage racks are capable of resisting external forces owing to their ductility and energy dissipation [1,2]. Recently, damage and collapse by earthquakes in earthquake-prone areas were investigated [3–6]. However, storage racks were not included in standard building codes because they were considered to be mobile equipment. Nonetheless, some countries have proposed design criteria for storage racks owing to the damage they experience from earthquakes, including structural component testing according to the user requirements [5,7–10].

To facilitate cargo placement and removal, storage racks are generally configured with a moment-resisting frame in the direction of the aisle. Furthermore, to improve the stability and resistance of the columns, they are connected with bracing in the direction orthogonal to the aisle. The lower part of the columns are connected to the floor via baseplates installed on the ground using bolts and other devices. The upper part is often used without fixing. Therefore, predicting the behavior of storage racks is difficult compared to that of general buildings [11]. Extensive research has been conducted using quasi-static and dynamic experiments to predict the behavior of storage racks under external forces [1–4,12–18]. As a representative study of a quasi-static experiment, Gilbert and Rasmussen [19] found that the initial stiffness of the baseplate connection is primarily due to the bending of the upright part and the elastic displacement of the floor, confirming that the baseplate connection significantly affects the lateral response of the storage racks. Kanyilmaz et al. [11] conducted pushover tests on full-scale storage racks to investigate the major factors affecting the response and failure mechanisms of various storage racks. When one bolt was used under various baseplate connection conditions, the plasticity range was very small, and more than 50% of the drift was concentrated on the first level. Pretrone et al. [20] recognized that the direction perpendicular to the aisleway is more prone to overturning than that in the aisle direction, and a collapse problem may occur due to

Abbreviations: RSS, required response spectrum.

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https://doi.org/10.1016/j.jcsr.2023.107844
Received 3 November 2022; Received in revised form 18 January 2023; Accepted 30 January 2023
Available online 13 February 2023

lateral displacement. They studied the seismic performance of the aisle perpendicular to the aisleway of the base connection after fixing one side of the storage rack baseplate to the ground with two bolts. The experiments showed that the inelastic displacement of the baseplate provided a stable hysteresis response through significant ductility and energy dissipation. Gusella et al. evaluated the failure mode and stiffness by performing an experiment on the behavior of the brace–column joint using joint specimens [21]. However, experimental investigations based on the dynamic external forces are required to understand the behavioral characteristics of entire storage racks. Additionally, they are required to improve the design by reflecting the factors for dynamic external forces such as seismic activity. As a representative study of the dynamic experiment, Jacobsen and Tremblay [22] presented the hysteresis response of the column-beam connection and the baseplate through a shake table test and found that the ductility of the storage racks was achieved through the inelastic rotation of the column-beam connection and the baseplate of the column. Firouzianhaij et al. [23] conducted a shake table test using El-Centro ground motion to study the damping of the system. Maguire et al. performed single-axis shaking-table tests to examine the seismic performance in the direction perpendicular to the aisle according to the baseplate, and they studied damage and rollover according to the baseplate connection method [24]. Several studies have confirmed that various factors, such as the stiffness of the brace–column connection, stiffness of the baseplate, and connection stiffness of the bracing and column, have a complex effect on the safety of storage racks [25,26].

This study examines the damage and collapse of storage racks due to external forces through a shake table test and experimentally verifies the behavioral characteristics of storage racks according to the baseplate connection condition, which is selected according to the user's convenience. Among various storage racks, the pallet rack was selected as the target, and the four most popular connection conditions were selected as the baseplate connection conditions. A shake table test was performed to analyze the behavioral characteristics of the pallet rack according to the baseplate connection conditions. The displacement of the pallet rack due to the external force, permanent displacement, cumulative displacement due to the continuous external force, and drift rate was analyzed using the displacement data obtained through the experiment. A stable baseplate connection condition among the four tested was suggested by comparing the damage to the pallet rack through data analysis and experimentation.

2. Damage and collapse of pallet racks due to external force

2.1. Storage racks

Storage racks are typical non-structural components for storing and sorting cargo in the logistics distribution process and include pallet, mezzanine, mobile, and arm racks. Storage racks are of various types, based on their structure and form. In this study, a pallet rack, which is mostly used in large-scale logistics storage places such as logistics centers, was selected. A pallet rack is a type of storage rack that can load standard pallets with cargo and efficiently load cargo using a forklift. It comprises multiple levels to store numerous cargoes in a limited space and is lightweight compared to the load it carries. Pallet racks are classified according to the direction of the aisle, which is the direction in which the cargo is loaded, and the direction perpendicular to the aisle is closed by bracing. The overall height of the pallet rack and that of each level are generally determined as per the user's request, and the width is determined by the size of the pallet to be loaded on the pallet rack. In this study, a general pallet rack consisting of three levels delivered to a distribution center with four spaces was selected, as shown in Fig. 1.

The selected pallet rack determines the width in the aisle direction such that two pallets can be loaded, as shown in Fig. 1. Asian standard pallets with dimensions of 1100 × 1100 × 150 mm were used for those loaded on the pallet rack.

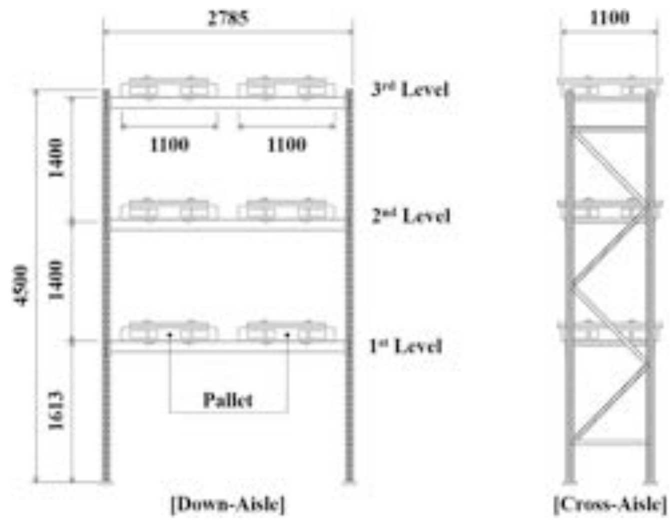


Fig. 1. Construction of pallet rack (unit: mm).

2.2. Pallet rack shake table test

This study analyzed the behavioral characteristics according to the conditions of the baseplate connections, which were determined by external forces. Prior to analyzing the behavioral characteristics for each condition, a shake table test was performed to examine the collapse and damage of the storage racks. The test was conducted by installing the pallet rack shown in Fig. 1 on the shake table, as shown in Fig. 2.

To prevent the separation of columns and beams that may occur during the test process, M8 bolts were used for the column-beam connection. M10 bolts were used to assemble the column-bracing connection in the direction perpendicular to the aisle. The baseplate was fixed to a shake table with four M24 bolts. A loading block of 0.3 tons per unit was used to simulate the cargo loaded on the pallet rack. A load of 1.2 tons, or 80% of the maximum design load (1.5 tons) that does not bend the beam while loading pallets, was applied to each level. This study did not aim to examine the falling of cargo loaded onto pallet racks. Therefore, to prevent the fall damage that may occur during the test, the load block, pallet, and tie beam were fixed with M16 bolts, and the pallet rack beam and tie beam were fixed with M6 bolts, as shown in Fig. 3.

The displacement response of each level was measured in the x- (aisle direction) and y-directions (perpendicular to the aisle direction) of the pallet rack owing to external force through the shake table test. To this end, six displacement sensors were installed on each pallet rack, one for each direction at each level, as shown in Fig. 4. For the displacement sensors, DP 1000E, a wire tension-type displacement transducer of the TML (Tokyo Measuring Instruments Lab), was used.

The test was performed according to the acceptance criteria for seismic certification by shared-table testing of non-structural components proposed by ICC-ES (International Code Council - Evaluation Service), a representative non-structural component test method [27]. It was created to satisfy the ground response spectrum (seismic zone I, normal bedrock), according to the building code [28]. Furthermore, the required response spectrum (RRS) shown in Fig. 5 was used, assuming that the storage racks were installed at the height of the ground ($z/h = 0$). The shake table test was commissioned by the Seismic Research and Test Center of the Korea Construction Engineering Development Collaboratory Management Institute, which is a KOLAS (Korea Laboratory Accreditation Scheme) certification institution. Furthermore, it was carried out while simultaneously driving the shake table in the x- and y-directions using the MTS shake table.

Fig. 2. Shake table test for pallet rack collapse and damage.

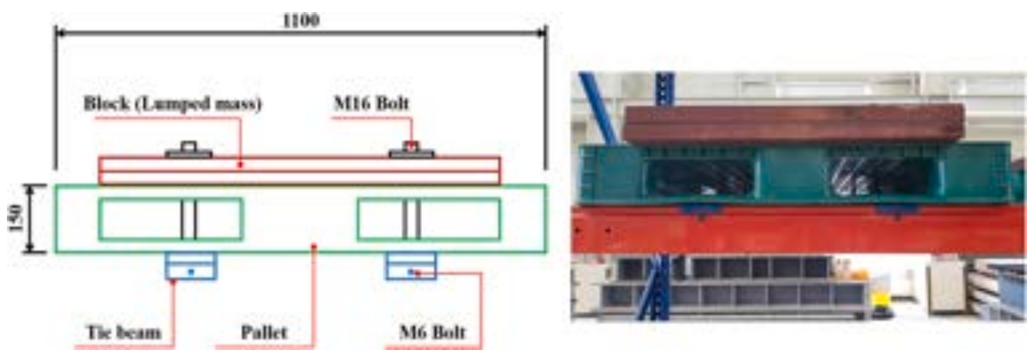


Fig. 3. Pallet with lumped mass.

2.3. Damage and collapse of the pallet rack

To check the damage and collapse of the pallet rack caused by the external force, the shake table test was conducted using the seismic wave illustrated in Fig. 5, increasing the external force in intervals of 50% from 50% to 300%. Fig. 6 shows a pallet rack with damage close to collapse, as a result of testing with an external force of 300%.

As shown in Fig. 6, the pallet rack incurred significant damage owing to torsion. The damage occurred asymmetrically and was concentrated at the first and second levels. The cross-section of the lower part of the column was severely damaged, and the columns below the second level and near the bracing connection were damaged. In this damage, the bolt connecting the column and bracing was cut (or loosened) owing to an external force; furthermore, the bracing fell from the bonding position, resulting in torsional loss. Fig. 7 shows a graph comparing the test results with the smallest exciting force and the results of the 300% exciting force that collapsed it. The test data are the data for the right pallet rack shown in Fig. 6. The response was smaller than the case where the displacement was large because the displacement sensor was installed on the opposite side of where considerable damage occurred.

As shown in Fig. 7 (a) and (c), when an excitation with 50% force was applied, the maximum displacement of the storage racks in the x- and y-directions were − 29.05 and 23.28 mm, respectively. In the x-direction, the response in the displacement state lied between 20 and 23 s in the second and third levels, respectively; however, it was restored after 23 s. When excitation was applied with a 300% exciting force shown in Fig. 7 (b) and (d), displacement started to occur in the x-direction after 10 s. The displacement direction changed after 20 s and increased significantly after 30 s. In the y-direction, displacement started to occur after 15 s, which increased significantly after 30 s. Fig. 8 shows the displacement and inter-level displacement from 30 s to the end of the test.

Fig. 8(a) shows the displacement response at each level. As shown in the figure, owing to the 300% excitation, permanent displacements at the top level were − 123.5 (2.79%) and 100.60 2.28% mm in the x- and y- directions, respectively, which correspond to the collapse at the damage level of Ghobarah [29]. Fig. 8(b) shows the inter-level displacement, where the displacements along the x- and y- directions were the largest at the first and second levels, respectively. The smallest inter-level displacement occurred at the top level. This is because the damage to the pallet rack was concentrated at the first and second levels.

3. Behavioral characteristics analysis experiment according to the baseplate connection condition of the pallet rack

The safety of key components, such as columns, beams, and bracing composing pallet racks, were verified through structural calculations at the time of designing. However, the baseplate connection condition of the pallet rack is determined as per the convenience of the user. Various studies have shown that the baseplate has a significant effect on the response of storage racks orthogonal to the aisle [19,30]. In Section 2, the damage and collapse due to the torsion of the pallet rack caused by the external force were confirmed. Based on these results, when an external force was applied, the behavioral characteristics were

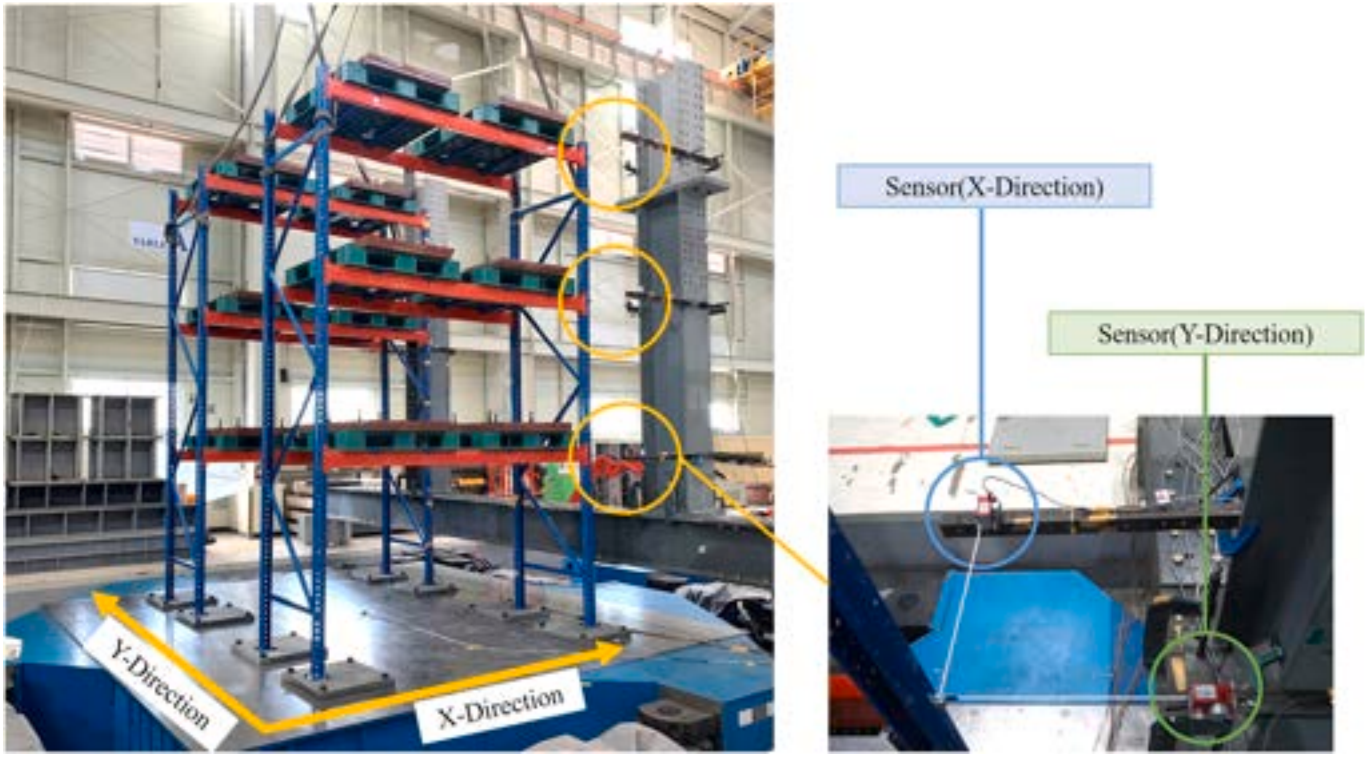


Fig. 4. Sensor installation to measure responses.

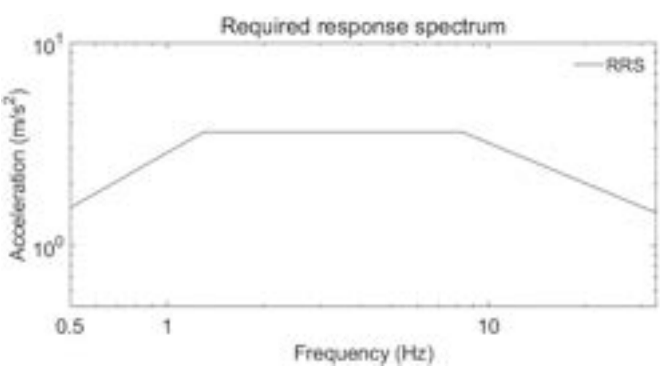


Fig. 5. Signals for operating the shake table.

experimentally analyzed according to the difference in the baseplate connection condition of the pallet rack. In particular, depending on the baseplate, an attempt was made to examine the difference in the torsion of the pallet rack confirmed in Section 2. A pallet rack of the same type as that used for the shake table test was used to examine the collapse and damage. As shown in Fig. 9, four baseplate connections were generally selected when installing a pallet rack.

Fig. 9 (a) shows the most commonly used baseplate connection conditions in South Korean distribution centers, that is, the method of connecting the baseplate and the floor with bolts through a hole in the open direction (inside the pallet rack) in the cross-section of the column. Fig. 9 (b) shows the baseplate connection condition used in the warehouse-type marts and others, where the baseplate has a wider cross-section than that in Fig. 9 (a). This method involves connecting the baseplate and floor using only two diagonal directions out of the four holes, which was determined to be convenient for user installation. Fig. 9 (c) uses the baseplate under the same conditions as Fig. 9 (b);

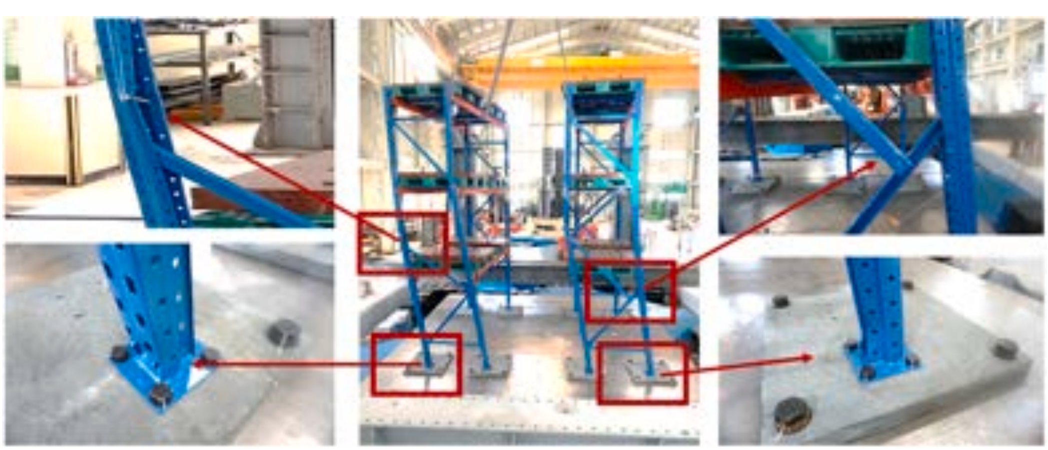
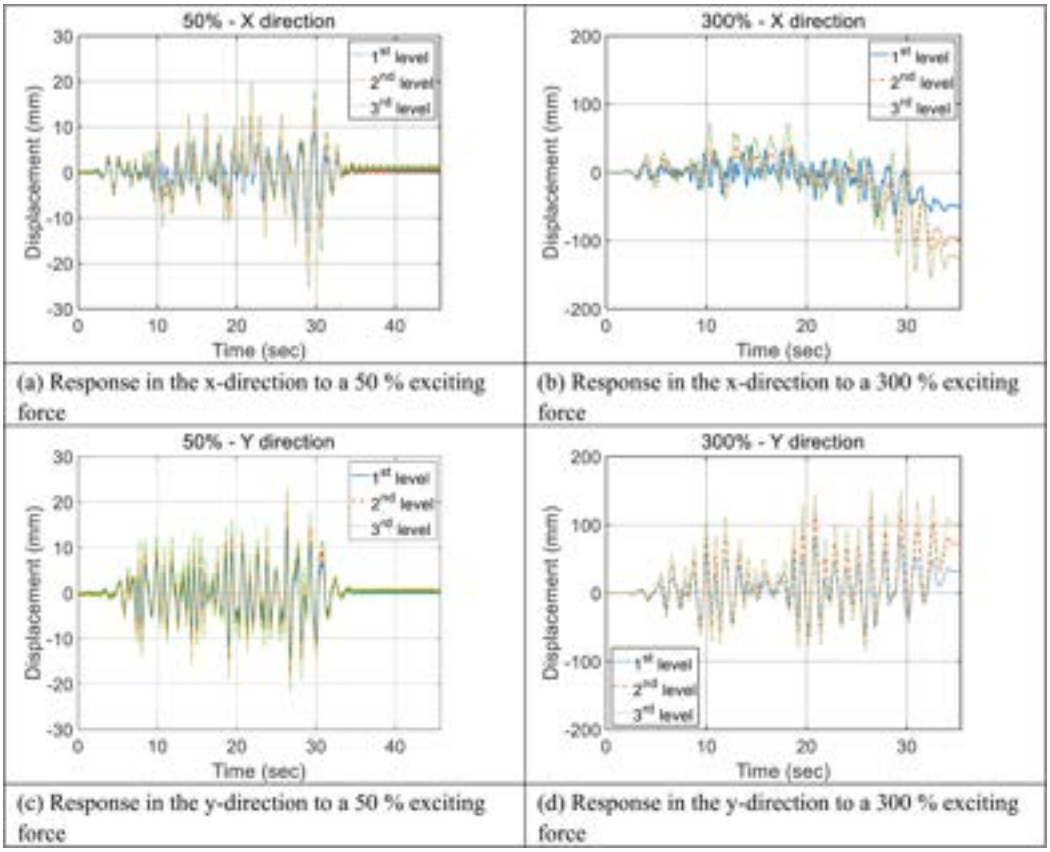
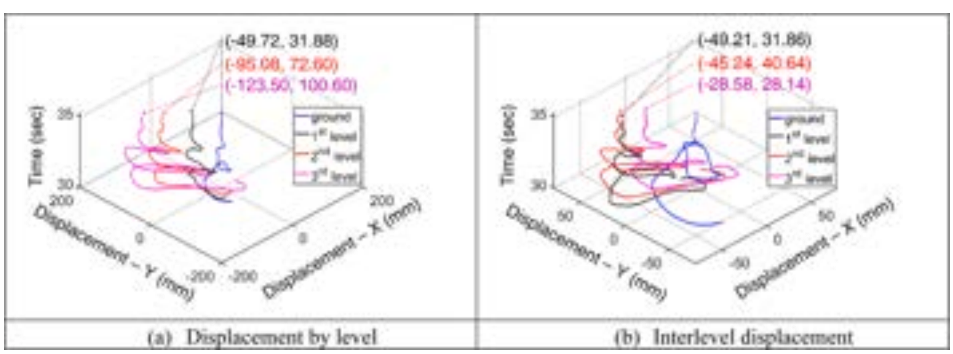


Fig. 6. Damage of pallet rack due to external force.



(a) Response in the x-direction to a 50 % exciting force
(b) Response in the x-direction to a 300 % exciting force
(c) Response in the y-direction to a 50 % exciting force
(d) Response in the y-direction to a 300 % exciting force

Fig. 7. Displacement responses of pallet racks due to external force.



(a) Displacement by level
(b) Interlevel displacement

Fig. 8. Permanent displacement of pallet racks due to external force.

however, all four holes were used to connect to the floor. The method illustrated in Fig. 9 (d) is generally not used. However, it was selected for comparison with 4 bolts by thickening the baseplate in Fig. 9 (c) to increase the bending resistance of the baseplate by an external force so that it could be connected to the floor as closely as possible.

Several researchers have analyzed behavioral characteristics using analytical methods. However, the pallet rack has difficulties in model configuration, such as the column-beam connection gap, member connection method using bolts, and the gap between the bolts and holes. Therefore, it is challenging to confirm the exact behavioral characteristics of storage racks through analytical studies. In this study, an experimental investigation was conducted to target full-scale storage racks used in the actual field. To analyze the behavioral characteristics of the pallet rack according to the baseplate connection conditions, shake table tests were performed under the identical conditions described in Section 2.2. As shown in Fig. 10, the experiment was performed by combining two of the four pallet racks that reflected each of the four conditions in Fig. 9 as one set. Fig. 10 (a) shows that the baseplate was connected to the shake table and attached to the jig plate with 4 and 2 bolts. In Fig. 10 (b), 1 and 4 bolts were connected to the jig plate, and the condition using 4 bolts used a thicker 20 mm baseplate compared to the other conditions. For the remaining conditions, a 4.5 mm baseplate was used.

4. Behavioral characteristics by fixing condition of storage racks due to external force

Section 2 presented the details of the test conducted using a seismic wave that meets the Korean Building Code. In this experiment, to examine the difference depending on the baseplate condition, the El-centro seismic wave, which has been commonly used in experiments worldwide and caused the largest drift rate with similar peak ground

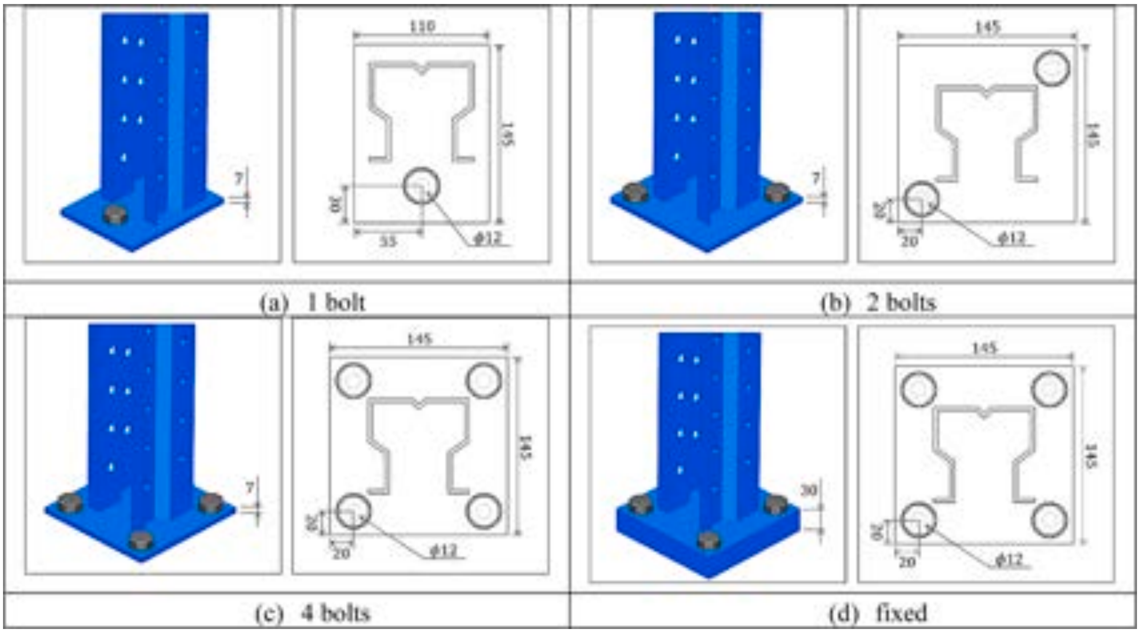


Fig. 9. Different baseplate connections (unit: mm).

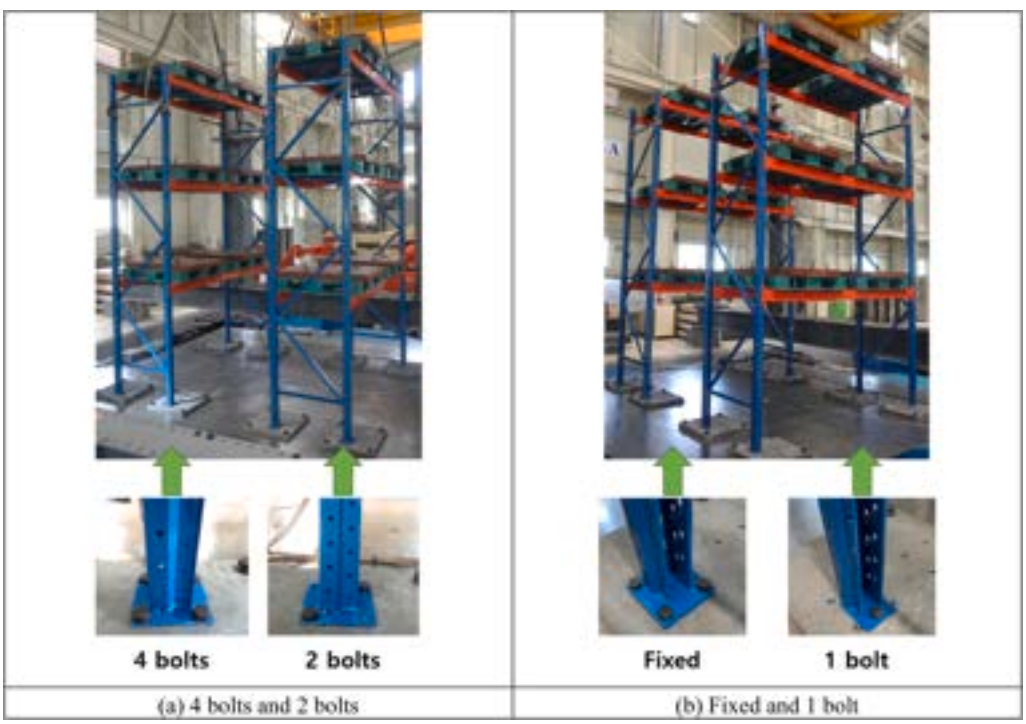


Fig. 10. Shake table test by fixing condition.

acceleration to earthquakes that occurred in Korea in 2016 and 2017, was used [31]. The behavioral characteristic analysis of the pallet rack was conducted according to the baseplate connection condition by increasing the external force at intervals of 50% from 50% to 200% using the El-Centro seismic waves. The displacement data obtained from the displacement sensors installed at each level were compared. The maximum displacement during the experiment, permanent displacement due to external forces, and torsion of the storage racks were analyzed.

4.1. Displacement response and permanent displacement

The displacement of the storage racks due to external forces can cause the cargo to fall. Therefore, in this study, the displacement response owing to the external forces was analyzed for each baseplate connection. Fig. 11 shows the displacement response in the pallet rack aisle direction (x-direction) obtained from the shake-table test. In Fig. 11, the row represents the baseplate connection condition and the column represents the exciting force condition.

In the 1 bolt condition, a small permanent displacement was generated toward the top level at a 50% exciting force. At 100%

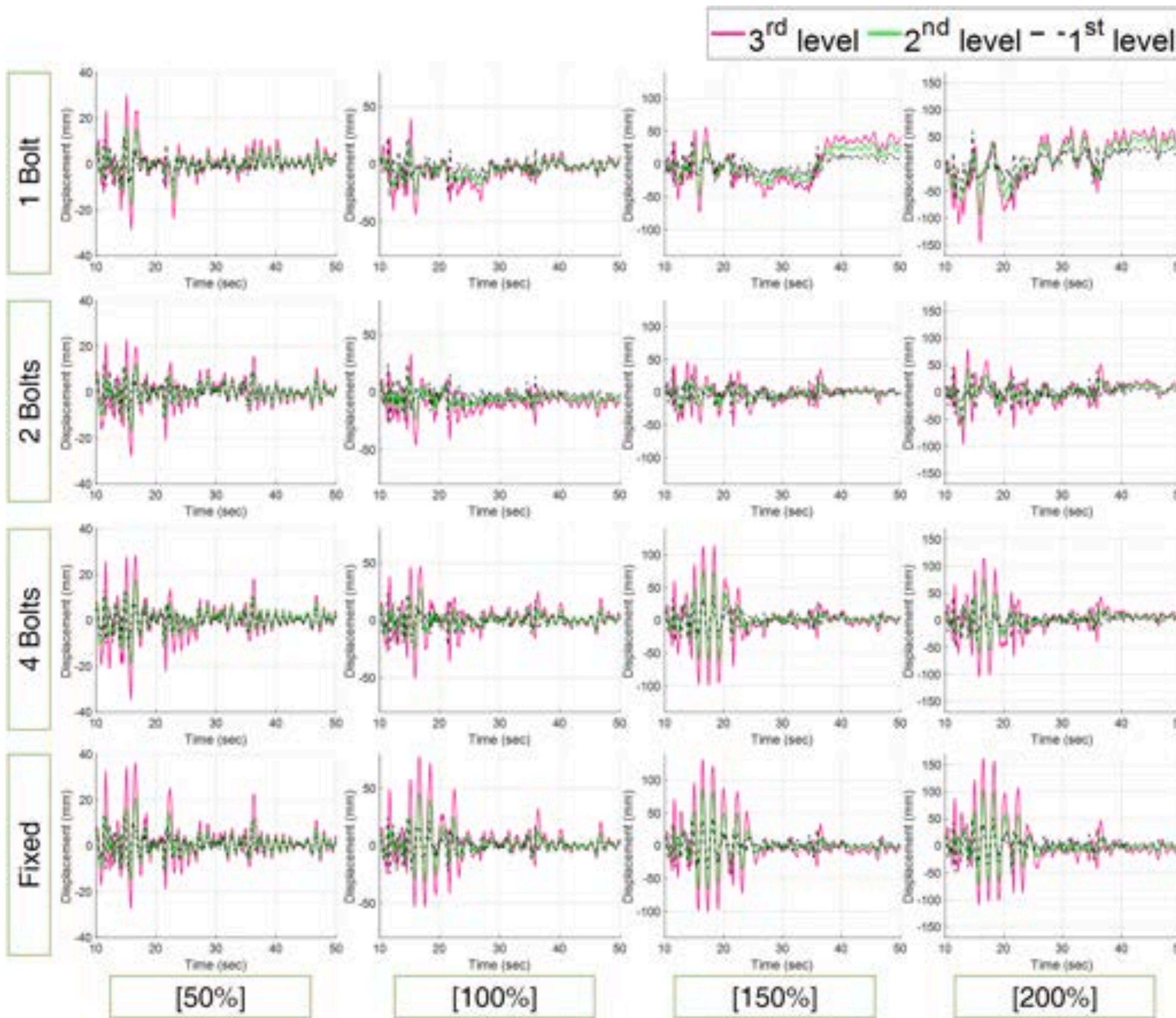


Fig. 11. x-direction displacement response.

excitation force, displacement occurred after 16 s during the experiment, which recovered 37 s after showing a response in the state in which the displacement occurred. At 150% excitation force, the displacement started to increase after 22 s; furthermore, the direction of the displacement changed after 37 s, and a large permanent displacement of 40 mm or more occurred. At an exciting force of 200%, a relatively small ground displacement started to occur at the beginning of the experiment; and the displacement direction changed after 25 s, which was followed by a large permanent displacement. In the 2 bolts condition, no displacement occurred at a 50% excitation force, a small displacement occurred after 22 s at a 100% excitation force in the first level, and displacement occurred after 11 s in the second and third levels. At a 150% excitation force, no displacement occurred in the first level, and after 37 s, 50% of the displacement in the second and third levels was recovered, as the displacement occurred in the reverse direction of the displacement generated by the 100% exciting force.

Furthermore, at an excitation force of 200%, the displacement at every level occurred in the direction of the displacement generated at an excitation force of 150%, and a displacement of approximately 17 mm was confirmed at the top level. In the 4 bolts condition, a small displacement of less than 2 mm occurred at 50% excitation force; however, no displacement occurred at 100% excitation force. Even with an exciting force of 150%, a displacement of less than approximately 2.5 mm was observed. Moreover, a maximum displacement of less than 8 mm occurred at an excitation force of 200%. Similar micro-displacements occurred in the fixed condition.

As a result of comparing the displacement of each baseplate connection under the four conditions, the responses of the 1 and 2 bolts conditions in the second and third levels were smaller in the 4 bolts and fixed conditions, respectively. Under the 1 and 2 bolts conditions, the baseplate was not fully bonded to the shake table. Hence, the baseplate moved upwards and downwards. Because the force transmitted along the column was dissipated, the displacement response was considered to be smaller than the 4 bolts and fixed conditions. In the 4 bolts and fixed conditions, the displacement increased significantly toward the upper level. It is speculated that this is because the baseplate was joined to the shake table, and the external force of the shake table was transmitted along the column to the top. It is considered that the large response of the 1 bolt condition at a 200% exciting force is because the response includes a large displacement. Tables 1 and 2 compare the maximum

Table 1
Displacement comparison of the 150% testing results in the x-direction.

Level	Maximum displacement (mm)				Permanent displacement (mm)			
	1 bolt	2 bolts	4 bolts	Fixed	1 bolt	2 bolts	4 bolts	Fixed
1	37.28	37.96	39	42.98	12.20	−0.68	2.54	0.26
2	46.8	33.26	76.48	86.44	27.16	1.20	1.20	−2.16
3	73.32	51.04	114	131.6	40.60	3.34	−0.03	−6.70

Table 2
Displacement comparison of the 200% testing results in the x-direction.

Level	Maximum displacement (mm)				Permanent displacement (mm)			
	1 bolt	2 bolts	4 bolts	Fixed	1 bolt	2 bolts	4 bolts	Fixed
1	68.26	57.56	44.08	51.64	27.18	6.66	3.74	1.58
2	94.32	67.42	76.96	102.6	43.54	12.92	6.14	−2.02
3	144.9	96.4	114.9	161.5	53.82	17.52	8.1	−7.12

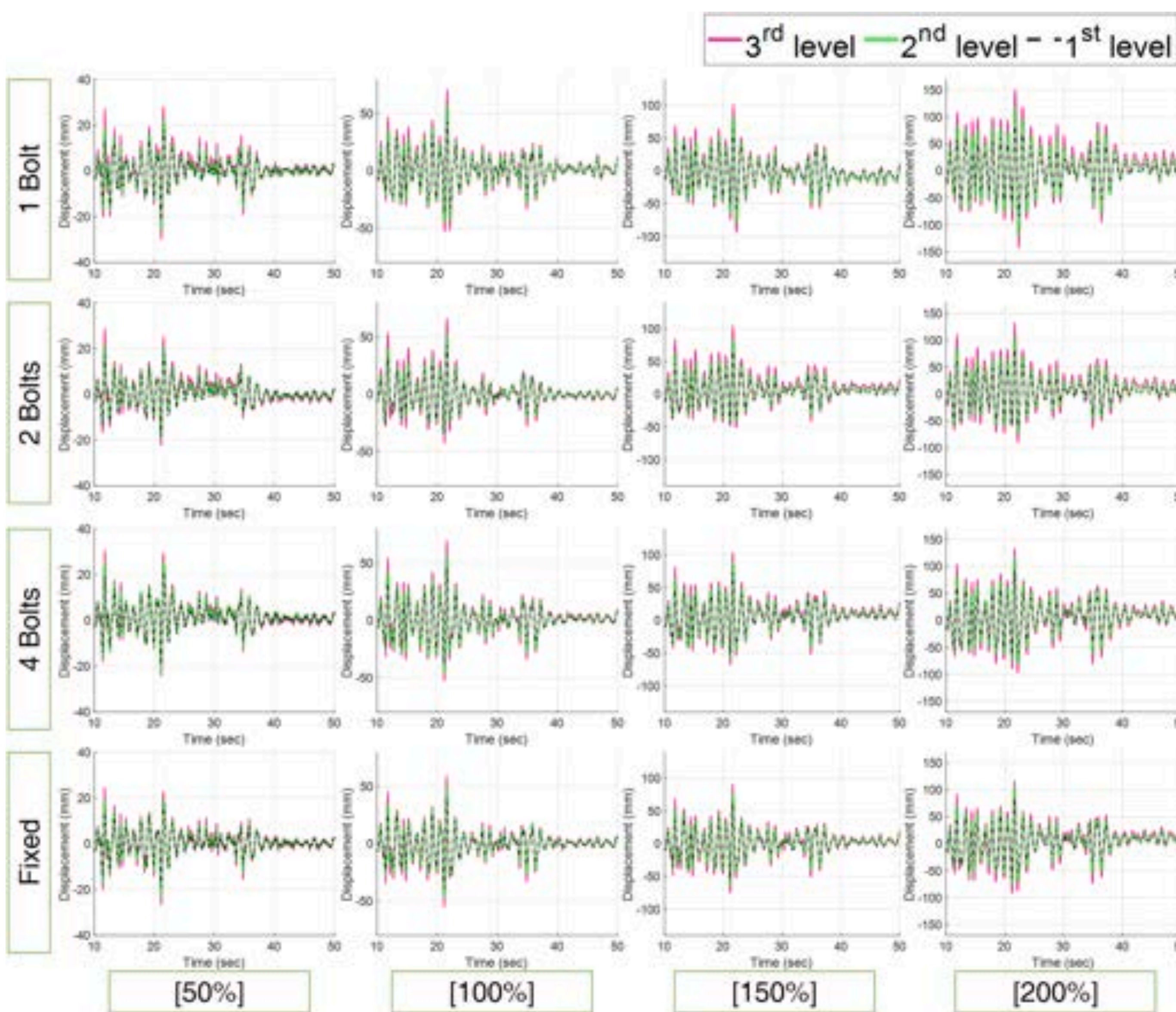


Fig. 12. y-direction displacement response.

displacement (absolute value) and permanent displacement for each baseplate connection under 150% and 200% exciting-force conditions, respectively.

As shown in Table 1, the maximum displacement at 150% excitation occurred in the fixed baseplate connection condition, whereas the maximum permanent displacement occurred in the 1 bolt condition. In the case of 4 bolts, the permanent displacement decreased toward the upper level. However, because the displacement was small, this was not considered to be an abnormal phenomenon (less than 1.5 mm); furthermore, the displacement increased toward the upper level when 200% excitation was applied (Table 2). Fig. 12 shows the displacement response in the direction perpendicular to the pallet rack aisle (y-direction) obtained through the shake table test.

As shown in Fig. 12, the displacement response in the direction perpendicular to the pallet rack aisle (y-direction) due to the external force did not exhibit a significant difference in the baseplate connection conditions. In the 50% and 100% exciting force experiments, the difference in the displacement response for each condition over time was not large, and the permanent displacement was found to be less than 3 mm. In the 150% exciting force experiment, displacement occurred in the entire layer after 39 s under all the conditions, and displacement in the opposite direction occurred in 1 bolt compared to the other conditions. In the 200% exciting force test, 1 bolt had a larger displacement compared to that of the other conditions, and the displacement occurred in the opposite direction to the direction of that occurring at the 150% exciting force. For the remaining conditions, the displacement increased in the same direction as that of the 150% displacement. The baseplate on the side where the bolt was not installed moved, a large displacement occurred, and the displacement direction changed because, as the exciting force increased owing to the external force in the y-direction, the baseplate was fixed with 1 bolt inside the cross-section of the column. Tables 3 and 4 compare the maximum displacement (absolute value) and permanent displacement for each baseplate connection under 150% and 200% exciting force conditions, respectively. As shown in Table 4, the maximum permanent displacement occurred in the third level of the fixed condition; however, it is 0.04 mm different from the third level under the 4 bolts condition. Because larger permanent displacement occurred in the first and second levels under the 4 bolts condition compared with other conditions, the 4 bolts condition was judged to be more vulnerable to permanent displacement than the fixed condition. In the 1 bolt condition, the displacement in the direction opposite to the displacement direction of the 150% exciting force experiment occurred in the 200% exciting force experiment. At 150%, the largest displacement occurred in the third level of the 2 bolts, whereas at 200%, the largest displacement occurred at 1 bolt in the third level. In the case of 1 bolt, as the excitation force increased, the surface of the baseplate, which was not connected to the shake table with bolts, moved up and down, damaging the baseplate. Furthermore, among the four conditions, the smallest displacement occurred in the fixed baseplate connection condition.

4.2. Cumulative displacement

In this study, the excitation force was increased to analyze the behavioral characteristics of the pallet rack according to the baseplate connection condition. Fig. 13 shows a graph comparing the cumulative displacement for each baseplate connection condition to verify the displacement accumulated by the continuous excitation force.

The graph in Fig. 13 shows the cumulative displacement of the pallet rack for each excitation force under the baseplate connection condition. To represent the data in a graph, the values of the 65 to 70 s section of the obtained displacement data were averaged, and a cumulative displacement of less than 5 mm was not analyzed because it was small. As shown in Fig. 13, the cumulative displacements in the x- and y- directions were the largest in the 1 and 4 bolts conditions. In the 2 bolts condition, the cumulative displacement increased significantly from the 100% exciting force; however, in other conditions, the cumulative displacement increased significantly from the 150% exciting force. Under the 1 bolt condition shown in Fig. 13 (a), the displacement direction changed counterclockwise and the displacement increased as the exciting force increased. The displacement in the x-direction was larger than that in the y-direction, and the accumulated displacement in the y-direction after 200% of the experiment occurred at approximately 10 mm in the first and third levels in the opposite directions. In the 2 bolts condition shown in Fig. 13 (b), the cumulative displacement on the graph changed clockwise as the exciting force increased. The 150% cumulative displacement in the x-direction was smaller than the 100% cumulative displacement because the direction of the x-direction displacement changed from 150%. In the 4 bolts condition of Fig. 13 (C), the cumulative displacement of the second and third levels occurred in the direction opposite to that of the first level in the 150% experiment. In the fixing condition of Fig. 13 (D), the cumulative displacement of the second and third levels occurred in the direction opposite to that of the first level in both the 150% and 200% experiments. In the 4 bolts and fixed conditions, the direction of the cumulative displacement in the first level did not change in the 200% experiment compared to that in the 150% experiment. Fig. 14 shows the cumulative displacement for each baseplate connection condition after the experiment was completed using four exciting forces.

Fig. 14 shows that, compared to the other three conditions, the cumulative displacement in the x-direction was greater in the 1 bolt condition, and the cumulative displacement in the y-direction was the highest in the 4 bolts condition. The cumulative displacements in the y-direction of the 2 bolts and fixed conditions were similar. However, the cumulative displacement in the x-direction was reversed in the second and third levels. The cumulative displacement in the x-direction of the 1 and 2 bolts conditions increased toward the upper level. However, in the 4 bolts and fixed conditions, the cumulative displacement of the second and third levels occurred in the direction opposite to the first level. In the case of the 1 bolt condition, because the shake table and baseplate were fixed with 1 bolt installed inside the column cross-section, both sides of the unfixed aisle direction of the baseplate moved up and down, causing the baseplate to bend. Moreover, the change in the displacement direction and the large displacements that occurred in the x-direction during the experiment were considered to be accumulated while rotating around the bolt. In the case of the 4 bolts and fixed conditions, the displacement of the baseplate was prevented by the strong bonding between the baseplate and shake table. Thus, the displacement in the x-direction of the first level was insignificant. However, it is considered that the displacement direction of the second and third levels changes as the column-beam connection is damaged by the exciting forces transmitted along the column. In the y-direction, the displacement direction of the first level only in the 1 bolt condition was different from that of the second and third levels. This is attributed small damage that occurred in

Table 3
Displacement comparison of the 150% testing results in the y-direction.

level	Maximum displacement (mm)				Permanent displacement (mm)			
	1 bolt	2 bolts	4 bolts	Fixed	1 bolt	2 bolts	4 bolts	Fixed
1	61.24	65.5	72.38	62.78	−6.14	4.6	7.48	2.52
2	83.72	84.32	90.22	78.96	−8.56	8.24	11.78	4.98
3	100.5	104.8	102.8	90.56	−7.98	11.6	15.88	6.64

Table 4
Displacement comparison of the 200% testing results in the y-direction.

level	Maximum displacement (mm)				Permanent displacement (mm)			
	1 bolt	2 bolts	4 bolts	Fixed	1 bolt	2 bolts	4 bolts	Fixed
1	84.18	83	92.06	84.9	1.88	5.76	9.06	8.08
2	122.8	107.5	118.3	106.1	6.96	10.60	13.66	12.46
3	151.1	132.3	133.9	116.5	13.48	14.70	17.04	17.08

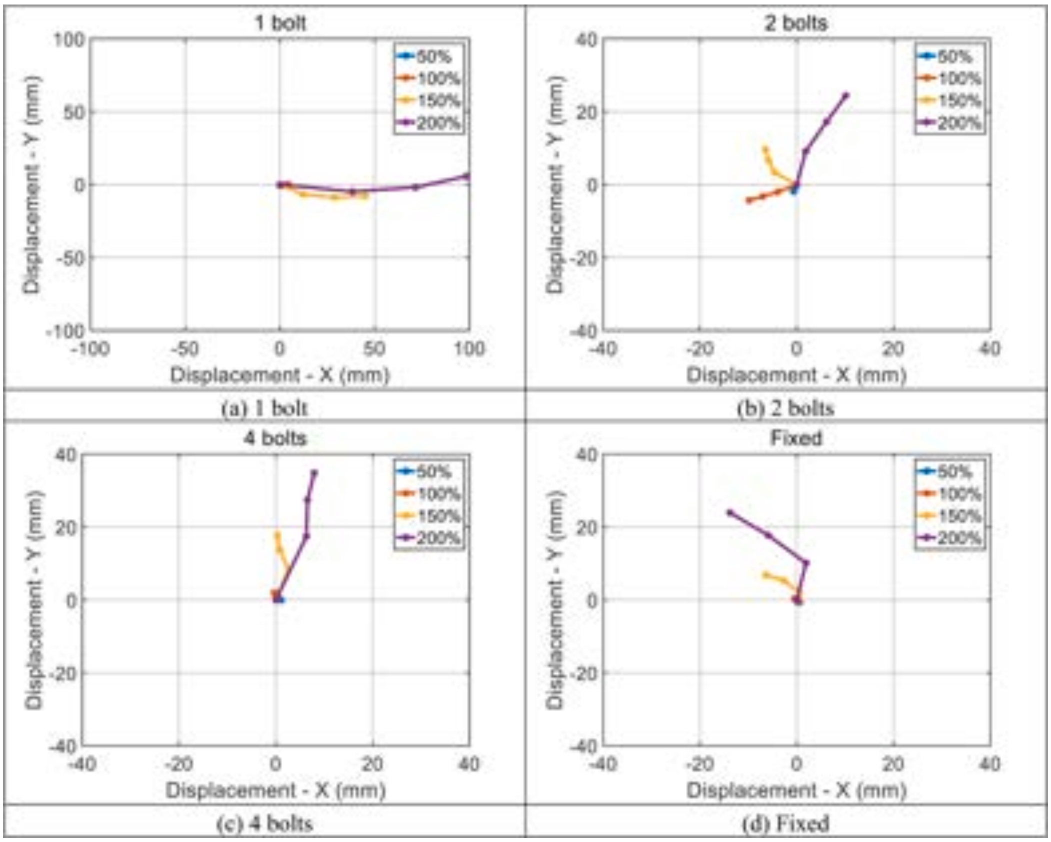


Fig. 13. Cumulative displacement by baseplate connection condition.

the column between the first and second levels in the y-direction because of the large displacement in the x-direction. Unlike the 4 bolts and fixed conditions, the 2 bolts did not join the shake table or the entire area. Hence, some of the exciting forces transmitted to the upper level dissipated. The damage accumulated in both the x- and y-directions was insignificant because the rotation and displacement of the baseplate under the 1 bolt condition did not occur because of the diagonal bolt connection. Table 5 lists the permanent drift rates obtained by dividing the cumulative displacement shown in Fig. 14 by the height at which the sensor was installed to check the degree of damage.

In the x-direction, a permanent drift rate of approximately 2.4% was confirmed under 1 the bolt condition, and a permanent drift rate of less than 0.5% was confirmed under the other conditions. In the y-direction, a permanent drift rate of approximately 0.8% or more was confirmed in the 4 bolts condition, a maximum of 0.3% for 1 bolt, approximately 0.56% for 2 bolts, and approximately 0.58% for the fixed condition. Table 6 shows the damage level of Ghobarah according to the permanent drift rate shown in Table 5 [29].

The pallet rack softly resists the moment generated by an external force. Therefore, compared to the damage levels of the ductile moment-resisting frames, the 1 bolt condition caused severe damage owing to the external forces. Moreover, the 2 bolts and fixed conditions were considered to have caused repairable damage, whereas the 4 bolts condition caused irreparable damage.

4.3. Interlevel cumulative displacement and damage

For the 1 bolt condition, the displacement direction in the y-direction changed. For the 4 bolts and fixed conditions, the displacement direction changed in the x-direction, as shown in Fig. 14. In the experiment described in Section 2, the difference in the interlevel displacement was confirmed in the collapse of the pallet rack owing to the external forces. Therefore, the inter-level cumulative displacement for each baseplate connection condition was checked. Fig. 15 and Table 7 show the inter-level cumulative displacement graph and figures after the 200% exciting force experiment, respectively, and Fig. 16 shows the damage to the pallet rack.

As shown in Fig. 15 and Table 7, the largest inter-level cumulative displacement in the x-direction occurred under the 1 bolt condition, wherein the inter-level cumulative displacement decreased from that of the first level. In the 2 bolts condition, the displacement decreased from that of the second level. In the case of the 4 bolts and fixed conditions, the interlevel cumulative displacement decreased from that of the first floor, and the displacement direction changed. In the y-direction, the largest inter-level cumulative displacement occurred in the 4 bolts condition, and the displacement decreased from that of the first level in

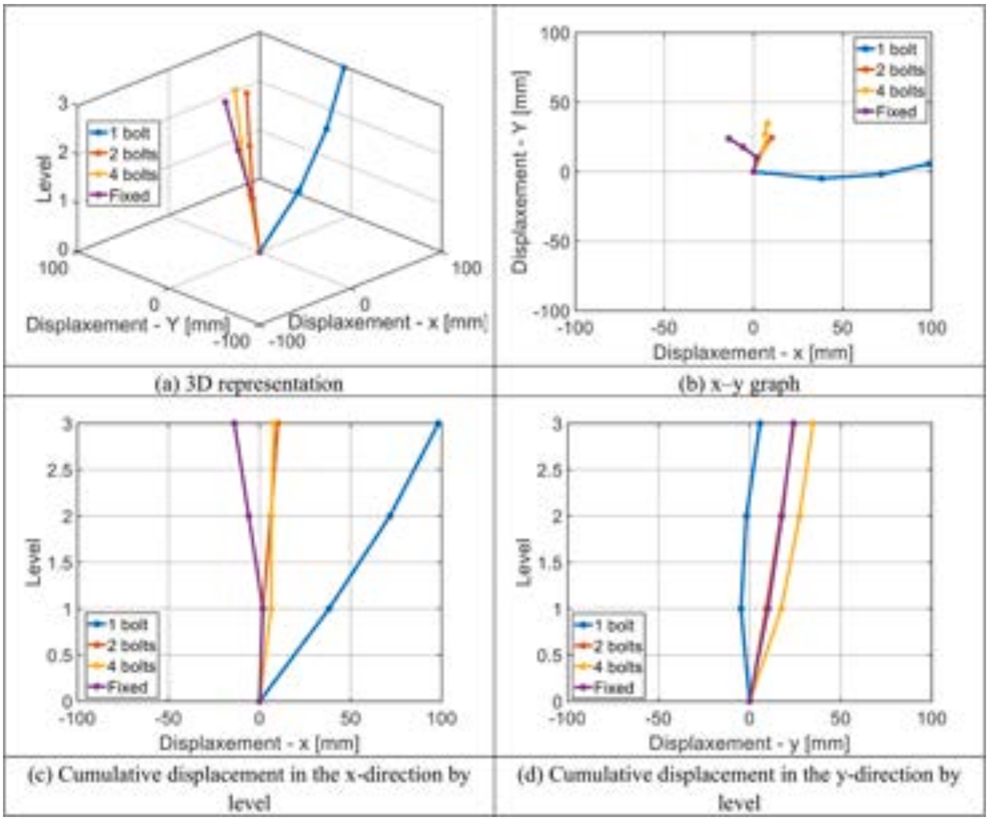


Fig. 14. Cumulative displacement of the 200% excitation condition.

Table 5
Permanent-drift-rate comparison of the shake-table testing results.

level	Permanent drift rate x (%)				Permanent drift rate y (%)			
	1 bolt	2 bolts	4 bolts	Fixed	1 bolt	2 bolts	4 bolts	Fixed
1	2.36	0.11	0.39	0.12	0.30	0.56	1.08	0.63
2	2.37	0.20	0.22	0.20	0.06	0.57	0.91	0.58
3	2.23	0.23	0.18	0.31	0.13	0.55	0.79	0.54

Table 6
Maximum permanent drift rate and damage levels.

Condition	Max. Permanent drift rate (%)	damage levels
1 bolt	2.37	Severe damage
2 bolts	0.57	Repairable damage
4 bolts	1.08	Irreparable damage
Fixed	0.63	Repairable damage

every condition. In particular, for the 1 bolt condition, the displacement direction changed with a reduction in the interlevel cumulative displacement. As shown in Fig. 16 (a), a large displacement occurred in the 1 bolt condition owing to the rotation of the baseplate and lack of resistance at the corners of the baseplate in the x- and y-directions. Moreover, a significant displacement in the y-direction lead to various damages, such as bending damage to the corners of the baseplate in the x- and y-directions, and damage to the column at the top of the first-level column-bracing connection. As shown in Fig. 16 (b)–(d), damage to the column on the baseplate was observed in the remaining conditions, except for the 1 bolt condition. In the 2 bolts condition, the damage to the lower part of the column was smaller than that in the 4 bolts and fixed conditions. It is considered that a small displacement occurred because the non-fixed edge of the baseplate moved up and down and consumed energy, resulting in minimal damage. The greatest damage to the lower part of the column occurred in the 4 bolts condition. A large displacement occurred because the exciting force was transferred to the upper level, owing to the connection of the four corners of the baseplate to the shake table with bolts. Furthermore, it is considered that damage occurred in the lower part of the column close to the bolts, whereas the baseplate at the center moved up and down because of the large displacement.

5. Conclusions

This study examined the damage and collapse of a pallet rack caused by an external force through shake table tests and experimentally analyzed the behavioral characteristics of the pallet rack according to the baseplate connection condition. To obtain and analyze the displacement response due to external forces, four shake table tests were conducted with commonly used pallet racks for each baseplate connection condition. The conclusions of this study are as follows:

(1) As a result of the shake table test conducted to check the damage and collapse of a pallet rack due to the external force, the pallet rack exhibited torsion from the asymmetry caused by the arrangement of the bracing in the direction perpendicular to the aisle. When the bolt connecting the column and the bracing due to torsion was cut, the resistance in the direction perpendicular to the aisle was lost. The lower part of the column was observed to be damaged and collapsed.
(2) To analyze the behavioral characteristics of the pallet rack for each baseplate connection condition, a shake table test was conducted for each of the four baseplate connection conditions. As a result, in the x-direction, a large displacement occurred in the 4 bolts and fixed conditions. The reason for this is speculated to be the fact that the baseplate was more strongly bonded to the

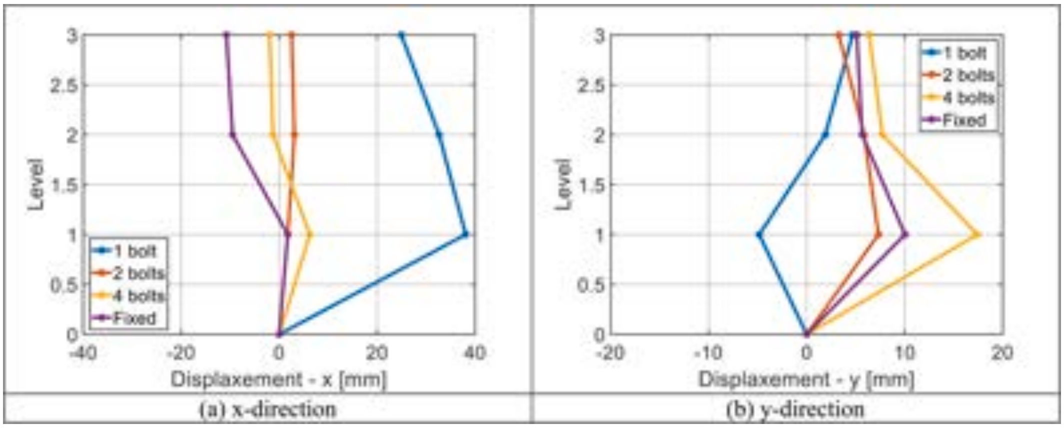


Fig. 15. Interlevel cumulative displacement.

Table 7
Permanent displacement comparison of the shake table testing results.

level	Permanent displacement x (mm)				Permanent displacement y (mm)			
	1 bolt	2 bolts	4 bolts	Fixed	1 bolt	2 bolts	4 bolts	Fixed
1	38.06	1.745	6.234	1.754	−4.843	7.332	17.42	10.03
2	32.64	3.1	−1.28	−9.52	1.9	5.86	7.72	5.66
3	24.92	2.52	−1.96	−10.78	4.68	3.28	6.38	5.12

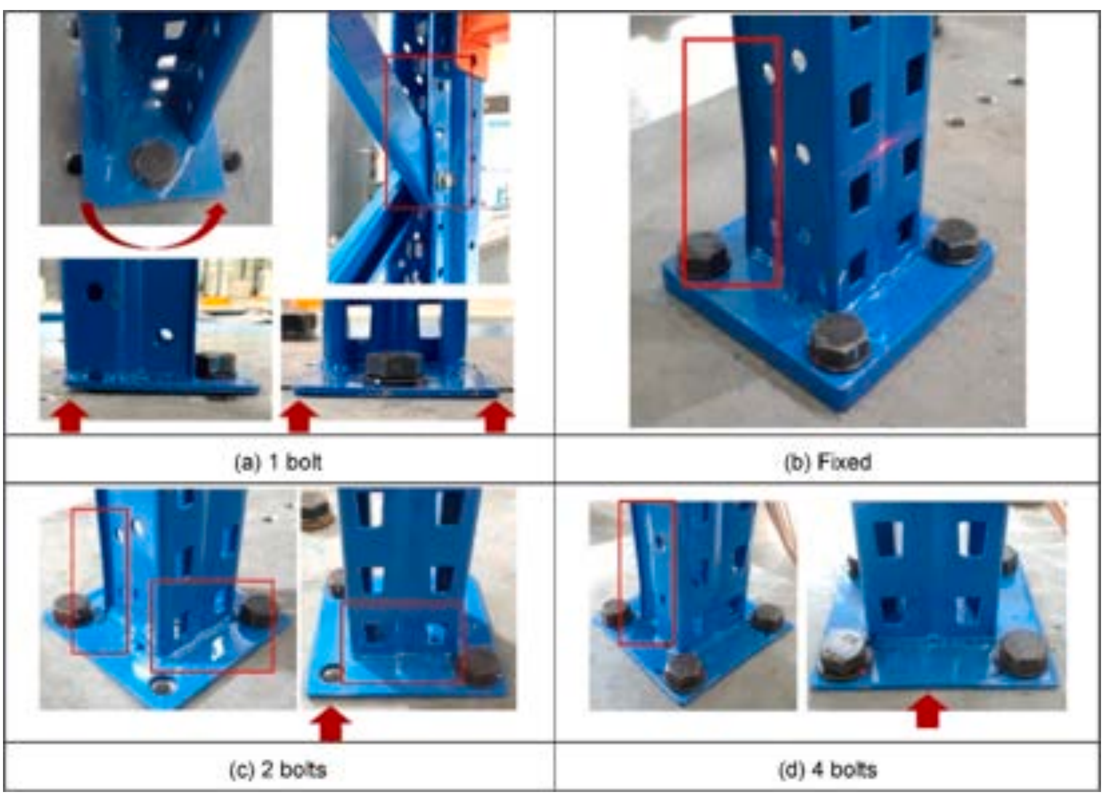


Fig. 16. Damage by baseplate connection condition.

shake table than that in the 1 and 2 bolts conditions, and the exciting force was transferred to the upper level without dissipation of energy. In the x-direction, similar displacements occurred under conditions other than the 1 bolt condition. In the 1 bolt condition, a large displacement occurred because of the decrease in the resistance caused by the damage accumulated while moving up and down on one side of the baseplate.

(3) As a result of analyzing the displacement related to the collapse of the pallet rack, an anomaly occurred in the 1 bolt condition, wherein the direction of the displacement changed during the experiment. Moreover, as the exciting force increased, the

accumulated permanent displacement increased significantly compared to the other conditions. As a result of evaluating the degree of damage by calculating the permanent drift rate for each baseplate connection condition, the 1 bolt condition caused severe damage, 2 bolts condition and fixing condition caused repairable damage, and the 4 bolts condition was irreparable because of the cumulative displacement caused by the continuous external force.

(4) As a result of analyzing the interlevel cumulative displacement related to the torsion of the pallet rack, the largest displacement in the x-direction was determined to occur in the 1 bolt condition and the largest displacement in the y-direction in the 4 bolts condition. In the case of the 1 bolt condition, the displacement direction was opposite to that of the other conditions in the y-direction. The causes of this displacement for the 1 bolt condition were considered to be the rotation of the baseplate, bending damage to the corner of the baseplate, and the damage to the bracing connection column. For the 4 bolts condition, the cause was considered to be that the baseplate cannot resist the displacement caused by the exciting force transmitted to the upper part, resulting in the bending damage of the baseplate and damage to the lower section of the column.

Finally, the behavioral characteristics of each baseplate connection condition of the pallet rack were analyzed. The results showed that the pallet rack that softly resists external force can resist displacement if it is strongly attached to the ground. However, problems such as the falling of cargo occur because of the large displacement at the top. If it is fixed to the ground with 1 bolt for the convenience of installation, collapse may occur owing to the displacement caused by a large external force resulting from insufficient resistance of the baseplate. If there is no threat of a strong earthquake, no problems occur under any condition. However, in an earthquake-prone area, it is better to first consider the 2 bolts condition among the four conditions for the convenience of installation and safety of the pallet rack.

Funding

This research was supported by National Research Foundation of Korea through funding from the Ministry of Education [grant number NRF-2018R1A6A1A03025542]. The funding agency had no role in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

CRediT authorship contribution statement

Gwanghee Heo: Resources, Project administration, Supervision. **Byeongchan Ko:** Investigation, Visualization. **Youngdeuk Seo:** Methodology, Writing – review & editing. **Chunggil Kim:** Conceptualization, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Much appreciation and acknowledgement goes to the National Research Foundation who made this research possible. We would also like to thank Editage (www.editage.co.kr) for English language editing.

References

[1] H. Krawinkler, N.G. Cofie, M.A. Astiz, C.A. Kircher, Experimental Study on the Seismic Behavior of Industrial Storage Racks, Report No. 41, The John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA, 1979.
[2] A. Filiatrault, A. Wanitkorkul, Shake-Table Testing of Frazier Industrial Storage Racks, Report No. CSEE-SEESL-2005-02, Structural Engineering and Earthquake Simulation Laboratory, Departmental of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York, 2004.
[3] A. Filiatrault, Shake Table Tests of Storage Racks and Contents, Presentation Material at the April 12, 2001 Seismic Safety Commission Hearing on Industrial Storage Racks, San Francisco, CA, 2001.
[4] C. Bernuzzi, C.A. Castiglioni, Experimental analysis on the cyclic behavior of beam-to-column joints in steel storage pallet racks, Thin-Walled Struct. 39 (2001) 841–859, https://doi.org/10.1016/S0263-8231(01)00034-9.
[5] European Commission (SEISRACKS2), Seismic Behaviour of Steel Storage Pallet Racking Systems, Directorate-General for Research and Innovation, Brussels, 2014, https://doi.org/10.13140/RG.2.1.2325.5929.
[6] I. Connor, Performance of steel storage racks in the Darfield earthquake, Bull. N. Z. Soc. Earthq. Eng. 45 (2) (2012) 61–70, https://doi.org/10.5459/bnzsee.45.2.61-70.
[7] FEMA 460, Seismic Considerations for Steel Storage Racks Located in Areas Accessible to Public, National Institute of Building Sciences, USA, 2005.
[8] CEN, EN 15512, Steel Static Storage Systems - Adjustable Pallet Racking Systems - Principles for Structural Design, CEN European Committee for Standardization, 2009.
[9] RMI MH 16.1, Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks, Racks Manufacturers Institute, 2012.
[10] AS 4084–2012, Steel Storage Racking, Standards Australia, Sydney, Australia, 2012.
[11] A. Kanyilmaz, C.A. Castiglioni, G. Brambilla, G.P. Chiarelli, Experimental assessment of the seismic behavior of unbraced steel storage pallet racks, Thin-Walled Struct. 108 (2016) 391–405.
[12] J.A. Blume and Associates, Seismic Investigation of Steel Industrial Storage Racks, Report Prepared for the Rack Manufacturer's Institute, San Francisco, CA, 1973.
[13] C.K. Chen, R.E. Scholl, J.A. Blume, Earthquake simulation tests of industrial steel storage racks, in: Proceedings of the Seventh World Conference on Earthquake Engineering, Istanbul, Turkey, 1980, pp. 379–386.
[14] C.A. Castiglioni, N. Panzeri, J. Brescianini, P. Carydis, Shaking table tests of steel pallet racks, in: Proceedings of the Conference on Behaviour of Steel Structures in Seismic Areas-Stessa 2003, Naples, Italy, 2003, pp. 775–781.
[15] B. Tagliafierro, R. Montuori, I. Vayas, S. Antonodimitraki, M. Titirla, M. Simoncelli, X. Lignos, Experimental testing campaign and numerical modelling of an innovative baseplate connection for pallet racking systems, in: COMPDYN 2021, Athens, Greece, 2021, https://doi.org/10.7712/120121.8687.19514.
[16] S. Avgerinou, X. Lignos, D. Tsarpalis, I. Vayas, Full-scale tests on used steel storage racks, Steel Constr. 12 (3) (2021) 231–242, https://doi.org/10.1002/stco.201900009.
[17] J.R. Maguire, L.H. Teh, G.C. Clifton, J.B.P. Lim, Residual capacity of cold-formed steel rack uprights following stomping during rocking, J. Constr. Steel Res. 159 (2019) 189–197, https://doi.org/10.1016/j.jcsr.2019.04.039.
[18] M.S.A. Shaheen, K.J.R. Rasmussen, Seismic tests of drive-in steel storage racks in cross-aisle direction, J. Constr. Steel Res. 162 (3) (2019), 105701, https://doi.org/10.1016/j.jcsr.2019.105701.
[19] B.P. Gilbert, K.J. Rasmussen, Determination of the base plate stiffness and strength of steel storage racks, J. Constr. Steel Res. 6 (67) (2011) 1031–1041, https://doi.org/10.1016/j.jcsr.2011.01.006.
[20] F. Petrone, P.S. Higgins, N.P. Bissonnette, A.M. Kanvinde, The cross-aisle seismic performance of storage rack base connections, J. Constr. Steel Res. 122 (2016) 520–531, https://doi.org/10.1016/j.jcsr.2016.04.014.
[21] F. Gusella, M. Orlando, K. Peterman, Stiffness and resistance of brace-to-upright joints with lipped channel braces assembled flange-to-flange, J. Constr. Steel Res. 193 (2) (2022), 107258, https://doi.org/10.1016/j.jcsr.2022.107258.
[22] E. Jacobsen, R. Tremblay, Shake table testing and numerical modelling of inelastic seismic response of semi-rigid cold-formed rack moment frames, Thin-Walled Struct. 119 (2017) 190–210, https://doi.org/10.1016/j.tws.2017.05.024.
[23] A. Firouzianhaij, N. Usefi, B. Samali, P. Mehrabi, Shake table testing of ttandard cold-formed steel storage rack, Appl. Sci. 11 (2021) 1821, https://doi.org/10.3390/app11041821.
[24] J.R. Maguire, L.H. Teh, G.C. Clifton, Z.H. Tang, J.B.P. Lim, Cross-aisle seismic performance of selective storage racks, J. Constr. Steel Res. 168 (2020), 105999, https://doi.org/10.1016/j.jcsr.2020.105999.
[25] Z. Huang, Y. Wang, X. Zhao, K.S. Sivakumaran, Determination of the flexural behavior of steel storage rack baseplate upright connections with eccentric anchor bolts, Thin-Walled Struct. 160 (2021), 107375, https://doi.org/10.1016/j.tws.2020.107375.
[26] A. Firouzianhaij, M.G. Azandariani, N. Usefi, B. Samali, Performance of baseplate connections in CFS storage rack systems: an experimental, numerical and theoretical study, J. Constr. Steel Res. 196 (2022), 107421, https://doi.org/10.1016/j.jcsr.2022.107421.
[27] International Code Council Evaluation Service, Acceptance Criteria for Seismic Certification by Shake-Table Testing of Nonstructural Components, AC156–2010, 2015.

[28] KBC, Korean Building Code-Structural, Architectural Institute of Korea, Seoul, Korea, 2016.

[29] A. Ghobarah, On drift limits associated with different damage levels, in: International Workshop on Performance-Based Seismic Design Concepts and Implementation, Dept. of Civil Engineering, McMaster University, 2004.

[30] N. Baldassino, C. Bernuzzi, Analysis and behaviour of steel storage pallet racks, Thin-Walled Struct. 37 (4) (2000) 277–304, https://doi.org/10.1016/S0263-8231(00)00021-5.

[31] J.-S. Jong, H. Choi, Y. Seo, C. Kim, G. Heo, Seismic performance of steel industrial storage racks subjected to Korea earthquakes, journal of the earthquake engineering Society of Korea, J. Earthq. Eng. Soc. Korea. 22 (3) (2018) 149–160.