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A STUDY ON SEISMIC CAPACITY OF OVERHEAD TRANSPORTATION SYSTEMS IN A HIGH-TECH FAB

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J. C Wang[3], W. J. Lin[4] and C. L. Tsai[5]

ABSTRACT

This study investigates the seismic capacity of the OHS (Overhead System), a transport equipment system in the cleanroom of high-tech factories. By using full-scale static cyclic loading tests, the fracture strength and failure modes at different stages of lateral displacement could be observed. The retrofit program proposed for the OHS not only reduced the problem of the loosened connection points, but also efficiently increased system strength to the designed bracing strength. Structural analysis software SAP2000 was used to build a simulated numerical model, and nonlinear static pushover analysis was performed. We then compared the analysis results to those of the full-scale experiment to understand the internal force distribution. Finally, the computer model analysis quantified system retrofit proposals—effectively enhancing system strength with the least number of members added.

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This study investigates the seismic capacity of the OHS (Overhead System), a transport equipment system in the cleanroom of high-tech factories. By using full-scale static cyclic loading tests, the fracture strength and failure modes at different stages of lateral displacement could be observed. The retrofit program proposed for the OHS not only reduced the problem of the loosened connection points, but also efficiently increased system strength to the designed bracing strength. Structural analysis software SAP2000 was used to build a simulated numerical model, and nonlinear static pushover analysis was performed. We then compared the analysis results to those of the full-scale experiment to understand the internal force distribution. Finally, the computer model analysis quantified system retrofit proposals—effectively enhancing system strength with the least number of members added.

Introduction

In Taiwan, the life-cycle cost evaluation for high-tech factories considers not only the initial purchase price of equipment, but also the potential risk of damage in natural disasters. Among these disasters, earthquakes are one of the most critical threats to equipment.

The design concept for the cleanroom factory is to increase the utilization of space due to difficulties in obtaining land and the high cost of construction. Moreover, because of complex logistical processes and worker circulation, some of the material-transportation cars are suspended on the upper area of the building. The current practice when installing a car-supporting overhead system (OHS) is to fasten suspension systems with clamps and bolts to the building structure instead of welding during construction in an operating cleanroom. The OHS's

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long suspension length, usually above three meters, causes an amplification effect during an earthquake that results in significant displacement.

In this study, an OHS in a high-tech factory in Tainan was tested in the laboratory to understand the behavior of the current suspension system under lateral loads. Comparison of the computer simulation results with the actual behavior, and the method to enhance the performance of the seismic force is discussed below.

Introduction

The photo in Figure 1 is the in-situ condition of an OHS in a high-tech factory. Hanging frames are hung through the ceiling, and some of them are supported by braced frames to resist seismic forces. These frames are connected in parallel by aluminum rails supporting the moving cars, which transport the glasses via cassettes they are loaded upon.

The OHS system includes not only the hanging frames and rail, but also the components through the ceiling above them. As shown in Figure 2, the rails are supported by frames through the ceiling to the higher truss of the actual building structure. Therefore, there are two kinds of suspension rods: the shorter rods are suspended from the ceiling, and the longer rods from the building structure extend through the ceiling to support the frames and rail.

To meet the requirement for horizontal symmetry, and to avoid producing extra torsion, the size of the experimental specimen was chosen to be 7(L)*3.6(W)*4.6(H) meters. In total there are five sets of hanging frames loaded with the maximum weight, among them two sets with bracing frames.

The specimen and its dimensions are presented in Figure 3 and Figure 4.

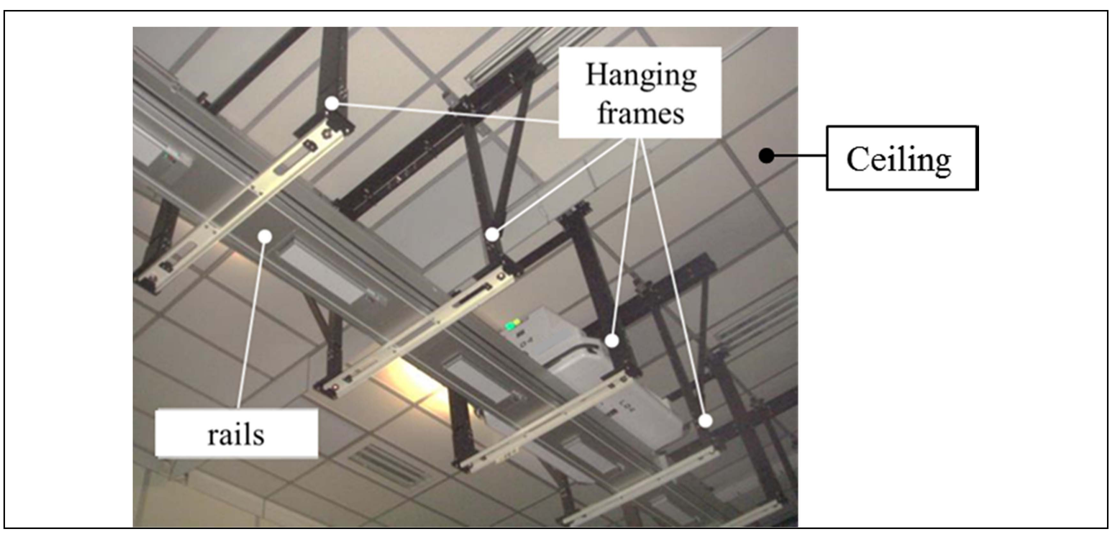

Figure 1. OHS photos in a factory

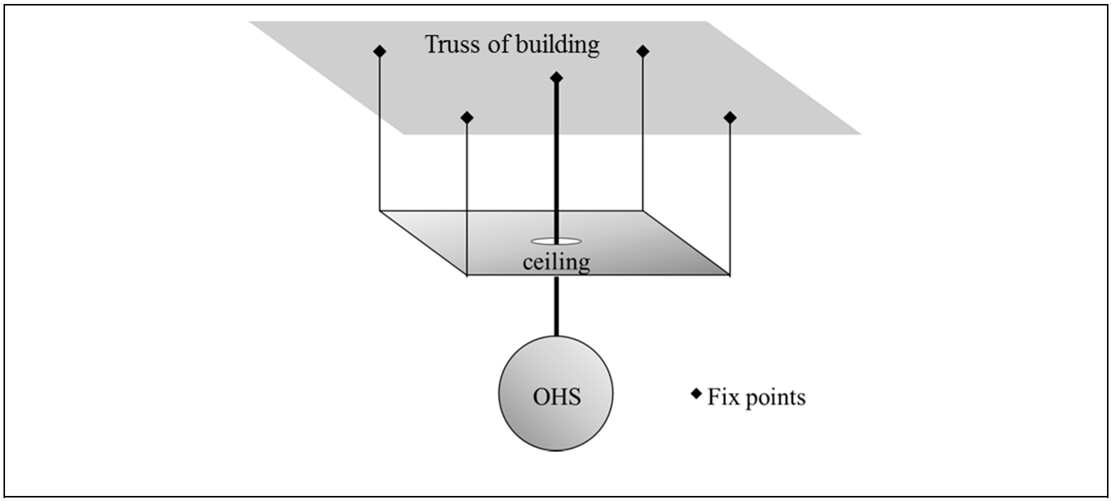

Figure 2. Schematic OHS Supporting Systems

Figure 3. Specimen of OHS

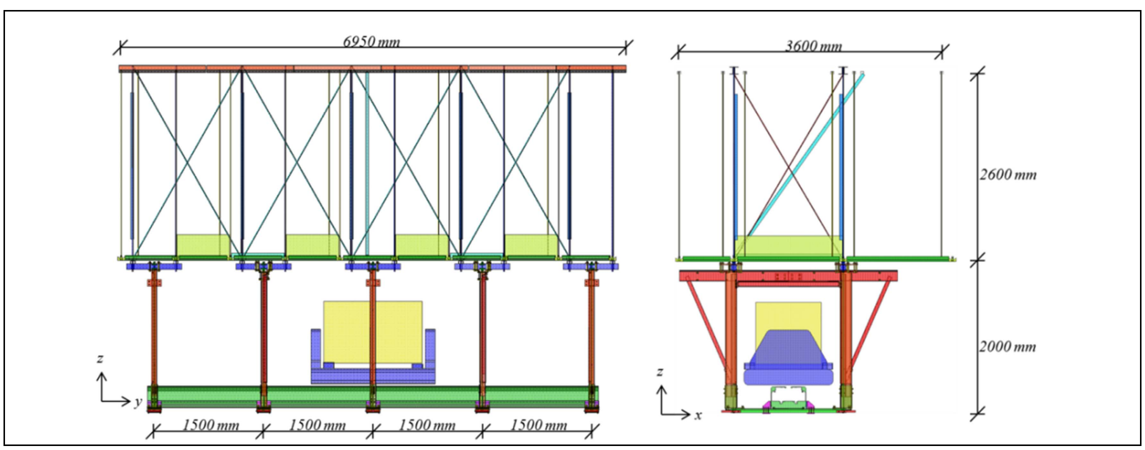

Figure 4. Dimension of OHS Testing Specimen

Methodology

A suspension system in a building, such as the OHS, under earthquake motion can be simplified as a SODF system under support excitation. The excitation frequency, Ω, can be idealized as a single value representing the fundamental frequency of the building structure as shown in Fig.5 (a). This model can be transformed into equivalent force acting on the system as shown in Fig.5 (b). Therefore by applying a static force and measuring the system displacement, we will be able to identify the system stiffness.

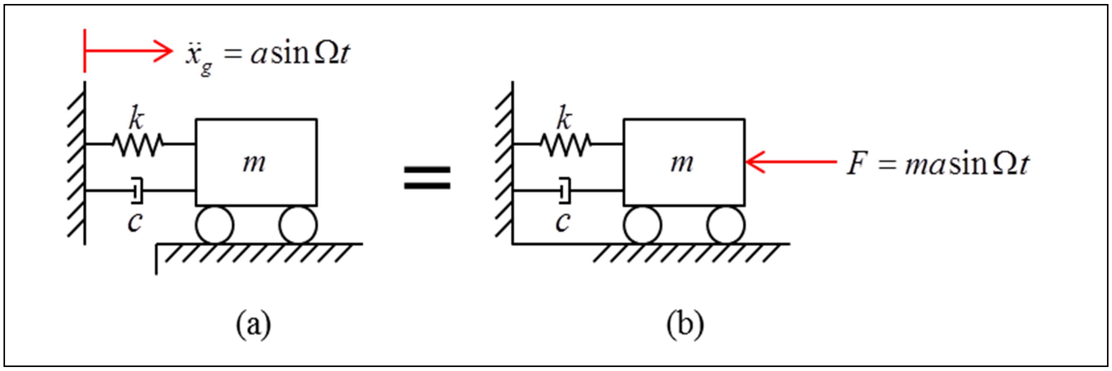

Figure 5. Model of Conversion of SDOF Object in Structural Dynamic Theory.

The theoretical description of the dynamic equation of a structure model is shown as follows. Consider a SDOF system excited by base acceleration:

$$\ddot{x}_g = a\sin\Omega t \tag{1}$$

and the relative displacement of the specimen is

$$x^* = \frac{a}{\omega^2}\beta\sin(\Omega t + \phi) \tag{2}$$

Where
β : dynamic magnification factor
ω :natural frequency of OHS
Ω :excitation frequency

Therefore, a relationship between deformation and base acceleration can be established. On the basis of this theory, we performed full scale experiments to acquire the system deformation. The experimental specimens were cyclically loaded according to FEMA 461(Quasi-Static Cyclic Testing)[1], shown in Figure 6.There are ten stages to the tests in total, increasing the displacement by 40% each time. The first phase tests with six loops, and the rest of the stages with two loops each.

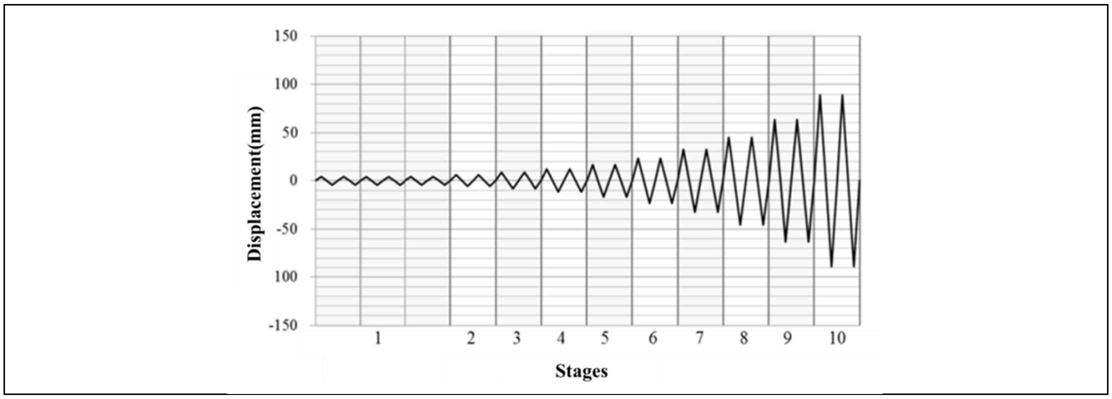

Figure 6. Waveform of Displacement

Suspended equipment relies on bracing to resist lateral forces during earthquakes. If the lateral displacements exceed the bracing's capacity, the whole system will become unrestricted and exhibit large displacement. However, we observed from the first test that the lateral vibration capacity of the OHS was degraded quickly at the beginning of the test with many minute installation imperfections. This is caused by loosening of many parts that were bolted or clamped on the existing building structure. Therefore, premature loosening took place before bracing could provide strength. To fully utilize the bracing strength, we have to identify the "loosening parts" in the existing system first and reinforce them to provide a higher strength so that the bracing system can function normally to resist earthquake forces.

Laboratory experiment program

There are two experiments with laterally applied forces on two OHS specimens in sequence and they are named as experiment (a) and (b).

Experiment (a): Current state Experiment

This specimen behavior shows the failure modes of in-situ OHS under the lateral static loading.

Experiment (b): Repaired OHS Experiment

After reinforcing the loosening parts of the specimen (a), we apply the same external test upon improved OHS under the same condition.

After testing specimen B, we acquired adequate stiffness data on the OHS and could build a reliable computer model upon them. Structural analysis software, SAP2000, was used to generate computer models. We performed a retrofitting scheme analysis to develop an economical strengthening strategy for the OHS.

Experiment Result

Experiment (a)

The existing construction practice for the bracing rod connector isn't strong enough for bracing to provide its full strength, because the connection clamps easily loosen and failed prematurely. The descending slope in Figure 7(a) exhibits degrading stiffness in cyclic loadings caused by the loosening of clamps.

The OHS system has a natural frequency of 2.53 Hz from the ambient vibration test. We also understand that the building's fundamental frequency is close to 1.22 Hz. The decay of stiffness represents OHS's natural frequency diminishing gradually and getting closer to the building' s natural frequency. The concern for resonance cannot be ignored, which means in a real earthquake condition, even a little vibration may lead to large displacement by resonance and cause fatal destruction.

Experiment (b)

After improving the clamps loosening problems[2], experiment (b) was conducted. The comparison of two experiments' force-displacement diagrams is shown in Fig.7(b). The stiffness decay problem was improved after reinforcement of local attachments. Comparing the two experiments at the same stage of force-displacement, as in Fig. 8, the residual displacement at stage 5, when the force is returned to zero, is reduced. The same phenomenon was observed in every stage of the loading waveform as shown in Fig. 9. Experiment (b) was finally terminated with many suspension rods buckled and exhibiting great lateral displacement.

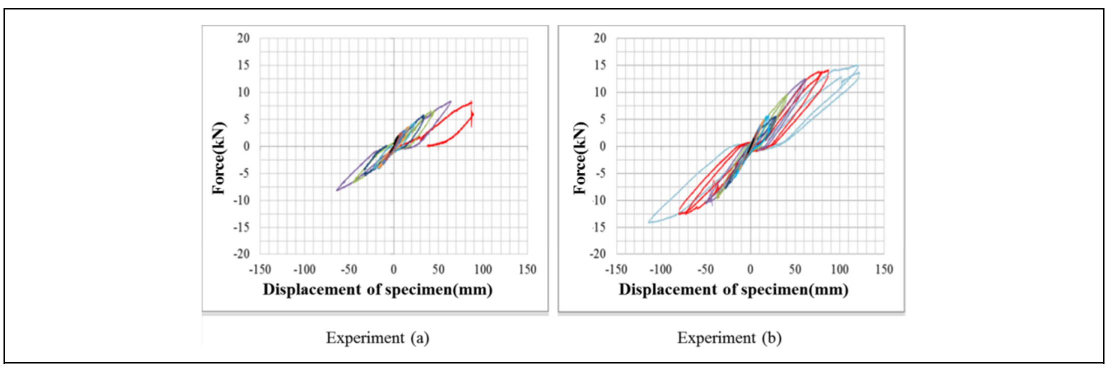

Figure 7. Displacement of Force, Experiment(a) and (b)

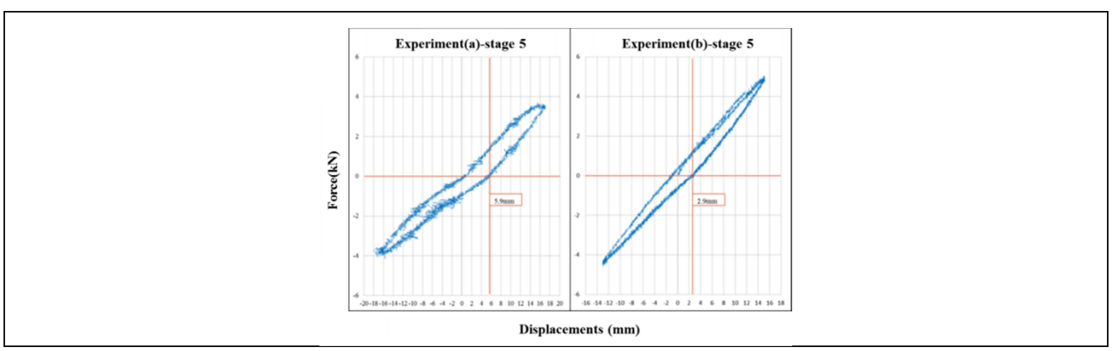

Figure 8. Residual Disp. Comparison of Experiment (a) and (b)---Stage Five

Stage	Exp.A (mm)	Exp.B (mm)
5	5.9	2.9
6	9.1	4.7
7	13.0	7.4
8	18.2	9.7
9	23.0	14.9
10	23.0	22.5

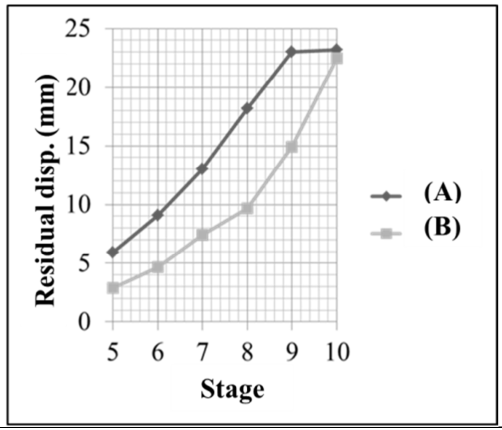

Figure 9. The Comparison of Residual Displacement

Computer Simulation of the models

In this study, a full-scale numerical model is created by software SAP2000, shown in Figure 10, and we explored different retrofit schemes by assuming the connecting components of the specimen have been improved as in experiment (b). The validity of the computer model is proven by exhibiting the same stiffness in the elastic range as that in experiment (b). We then compare the nonlinear pushover analysis envelope curve to capacity curves from experiment (b) in Fig. 11, to find that the envelop curve matches the experiment curve very well.

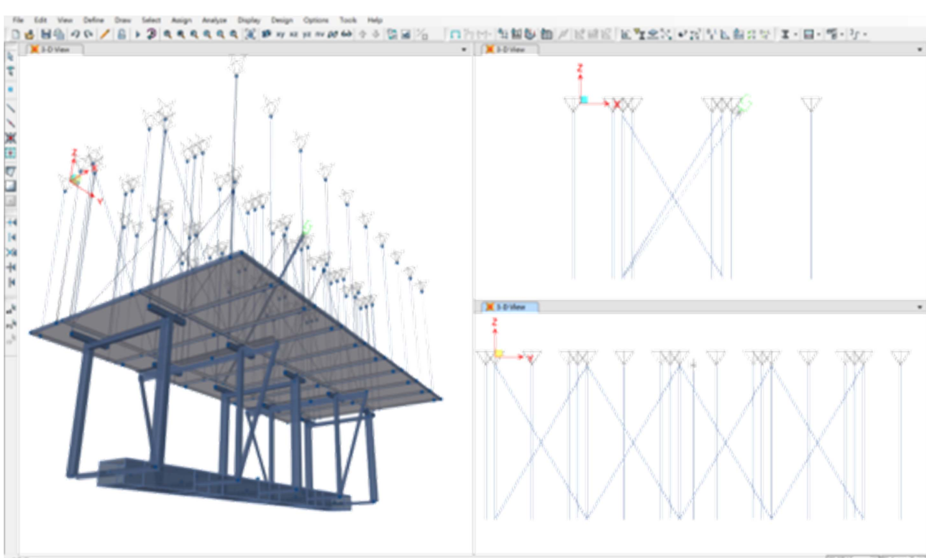

Figure 10. OHS Computer Model

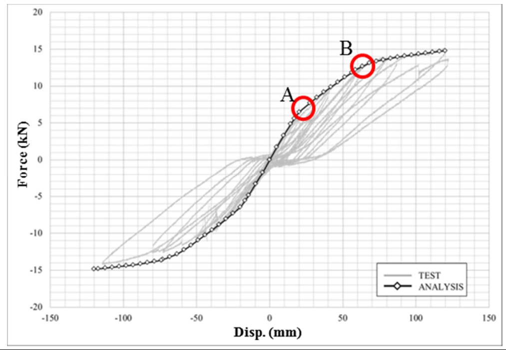

Figure 11. Capacity Curves of SAP and Physical Model

We also noticed that there were two critical points, A and B, where the stiffness of the envelope curve undergoes a major reduction from Fig. 11. To understand the behavior at the critical points, we analyzed the internal forces of members. In Fig. 12, it shows the left end row of the suspending frames above the ceiling was in compression when subjected to a horizontal force to the left at the car position. Among these frames, the rod (ϕ 5/8"* 2600mm) with reinforced C channel (50 * 50 * 2 * 2000mm) attracted the largest compression force as shown in Fig. 13. The critical points on the envelope curve represents the compression members in Fig. 12 reaching the buckling load and caused stiffness reduction. This phenomenon is also observed in experiments as shown in Fig. 14.

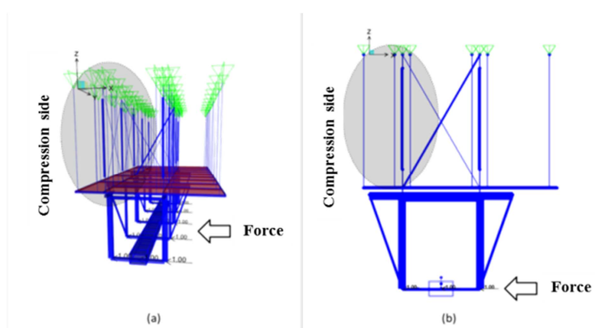

Figure 12. Diagram of Side-Compression

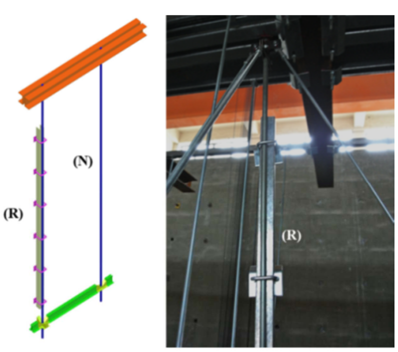

Figure 13. Reinforcement Rod

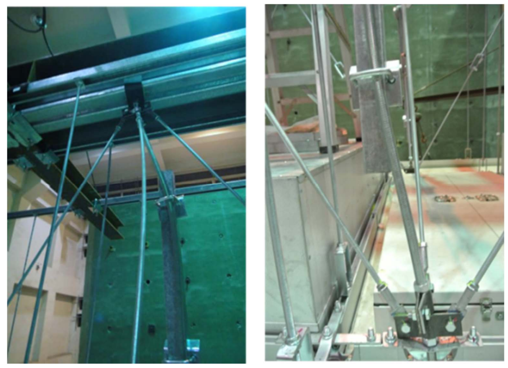

Figure 14. Side Rod Buckling in Experiment (b)

On the left-hand side of Fig. 15, the buckling axial capacity of the reinforced rod are shown on the drawing, while the corresponding system stiffness reduction is shown on the right-hand side. Based on this buckling-controlled system behavior, we developed a system retrofit scheme as shown in Fig. 16. We added four new bracings on both end rows of the suspension frames at the reinforced rod. These four bracing bars increase the stiffness of the system, and disperse the axial stress of compression caused by tensile bracing when lateral force is applied to the car. The increased seismic capacity curve is shown in 17.

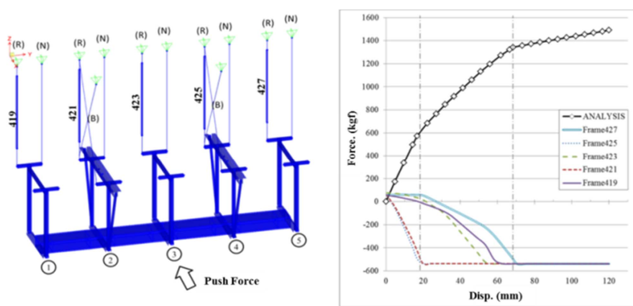

Figure 15. Diagram of Curve of Compression Capacity

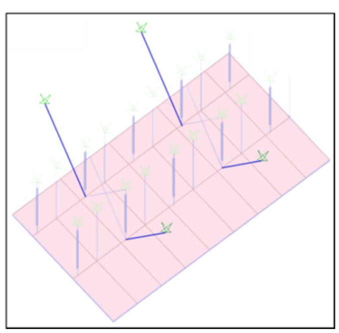

Figure 16. Additional Bracing Components

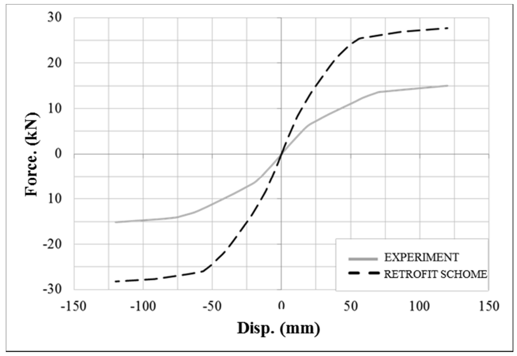

Figure 17. Result of Systemic Reinforcement

Conclusions

1. The in-situ capacity of OHS was tested in the laboratory with horizontal force applied at the car level. Many loosening parts at the connection points of the bracing reduced the system stiffness and may result in resonance amplification with the building structure. A series of reinforcing methods that were developed to prevent the premature loosening of parts proved effective in experiment (b).

2. A computer model was developed based on experiment (b) data and can explain the buckling behavior of the suspension rods. This computer model was then used to further develop an efficient retrofit method by adding bracing at the right location.

Acknowledgments

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