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Authors

Zhang, Xianzhao

Zhang, Jiachen

Hutchinson, Tara

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Physical Damage to Rooftop Mechanical Equipment Considering Variations in Attachment Designs

X. Zhang¹, J. Zhang² and T. C. Hutchinson³

ABSTRACT

This paper examines the physical damage observed to lightweight rooftop mechanical equipment installed on a full-scale, ten-story cold-formed steel building tested on a large outdoor shake table. The mechanical equipment units were nominally identical models, but with different attachment designs. The observed damage was analyzed and correlated with measured acceleration and displacement responses of the equipment. Results indicate that screw thread rupture in the fully fixed (direct attached) unit was likely caused by combined shear and tension under worst-case loading conditions, though material uncertainties may also have contributed. In addition, localized deformation in the spring-isolator-supported unit tended to concentrate at anchorages along the predominant vibration direction or at weakened sections of the supporting rack.

Introduction

Earthquake-induced physical damage to both structural systems and nonstructural components has been well documented in post-earthquake reconnaissance archives [1–3]. For structural systems, the widespread availability of acceleration data from strong-motion instrumentation programs, (e.g., see [4]) has enabled the possibility of establishing correlations between observed damage and measured seismic response. For nonstructural components, however, such correlations are difficult, owing to the paucity of recorded data from instrumented nonstructural components in the real built environment [5].

Five lightweight air-conditioning condenser units comprising three slender units and two squat units, were installed on the rooftop of a full-scale, ten-story cold-formed steel (CFS) building (Fig. 1) constructed on the Large High-Performance Outdoor Shake Table (LHPOST6) at the University of California San Diego [6]. A total of 18 sequential earthquake tests were conducted, with the final two scaled to risk-targeted maximum considered earthquake (MCE_R) hazard levels [7]. In the MCE_R tests, only the x- and y-direction motion components were applied. The peak roof accelerations recorded at the calculated center of mass on the roof level occurred in the x-direction, reaching 1.7 g during the first MCE_R test and 2.0 g during the second. These values correspond to acceleration amplification factors of 2.3 and 2.6, respectively, relative to the achieved peak input accelerations at the shake table platen. In addition, the first MCE_R test had relatively balanced excitation in the two principal axes, with a ratio of x- to y-direction peak input acceleration of 1.2, whereas the second was more strongly dominated by the x-direction excitation, with a ratio of 2.3.

¹ PhD Student, Dept. of Structural Engineering, University of California San Diego, La Jolla, CA 92093
(email: xiz217@ucsd.edu)

² PhD Candidate, Dept. of Structural Engineering, University of California San Diego, La Jolla, CA 92093

³ Professor, Dept. of Structural Engineering, University of California San Diego, La Jolla, CA 92093

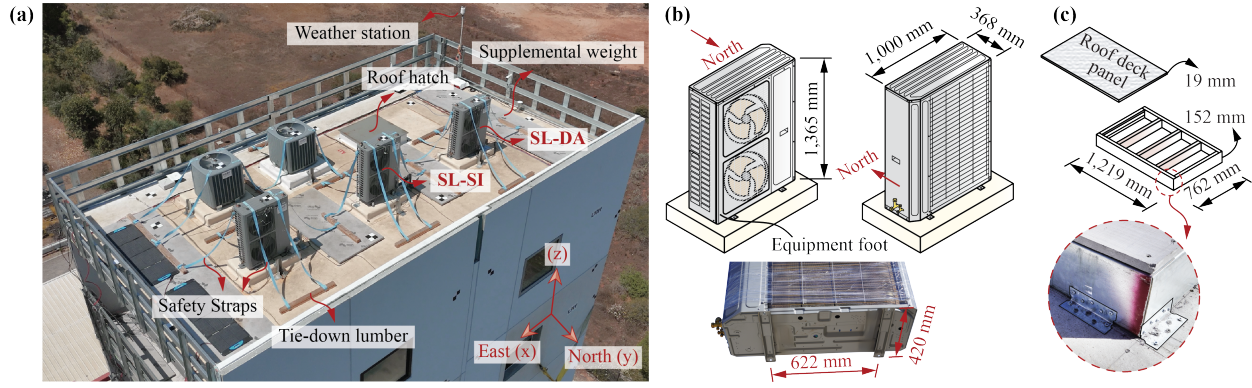


Figure 1. Overview of rooftop mechanical equipment: (a) aerial view of the equipment layout, view from the northeast corner, (b) slender unit geometry, and (c) roof curb design. SL-DA = slender unit with direct attachment, SL-SI = slender unit with spring isolators.

Slender Unit with Direct Attachment (SL-DA)

As a benchmark attachment design, a slender unit was directly secured at its four manufacturer-provided feet to the CFS studs of the roof curb using self-drilling screws, each with a thread length of 76.2 mm and a nominal shank major diameter of 6.2 mm. A fender washer measuring 6.4 mm in inner diameter, 25.4 mm in outer diameter, and 1.6 mm in thickness was placed between the screw head and the equipment feet to ensure proper tightening [8]. As shown in Fig. 2(a), attachment failure occurred during the first MCE_R test, leaving a 19 mm protrusion of the screw at the northwest attachment point. The screw ruptured near the intersection with the CFS stud, leaving approximately two-thirds of its threaded length embedded in the stud. The three remaining attachment points maintained their integrity. Before the second MCE_R test, to retrofit the damaged anchorage, a CFS support clip was installed near the original equipment foot and secured with six self-drilling screws, three on each leg (Fig. 2(b)). As shown in Fig. 3(a), a maximum uplift of 21.8 mm was recorded by a linear potentiometer installed 101.6 mm from the attachment failure point, occurring 8.3 sec after the initiation of ground motion from the shake table. This maximum uplift lagged by approximately 2 sec behind the peak acceleration response of the equipment (Fig. 3(b)).

As a conservative estimate, screw tensile demands were obtained using the measured peak component accelerations (PCAs) of 2.0 g (x-direction) and 3.4 g (y-direction) to calculate the maximum horizontal seismic force, taken as PCA multiplied by the equipment mass, 146.25 kg. The maximum resultant shear demand, corresponding to 3.9 g, was determined as the square root of sum of the squares of the x- and y-direction PCAs. Fig. 3(c) compares the calculated fastener demands with allowable strengths defined using a safety factor of 3.0. The code-based demand-to-capacity ratio was derived using ASCE/SEI 7-22 [9] Eq. (13.3-1), which defines the horizontal seismic force. Based on measured PCAs, the utilization of allowable strength was 32.9% in shear and 44.4% in tension. When considering the combined effects of shear and tension in screws using AISI S100-16 [10] Eq. (J4.5.3-1a), the summation of demand-to-capacity ratios for shear and tension is 0.77, which exceeds the limit of $1.3/\Omega \approx 0.43$. This indicates that screw thread rupture was likely caused by the combined action of shear and tension. However, material uncertainties may also have contributed to the attachment failure, since the above calculations were based on acceleration measured at the top of the equipment, which are expected to be higher than PCAs associated with the center of mass.

Slender Unit with Spring Isolators (SL-SI)

To modify base boundary condition of SL-DA, each equipment foot was supported by a spring isolator (Fig. 4(a)). The localized deformation of the SL-SI attachment observed after the first and the second MCE_R tests is summarized in Fig. 4(b–f). Fig. 5(a) shows the acceleration response of the SL-SI under the first MCE_R test. The PCAs were 3.5 g (x-direction) and 2.0 g (y-direction). The occurrence frequency of component acceleration responses was relatively evenly distributed across all directions, mostly within the range of 6% to 10%.

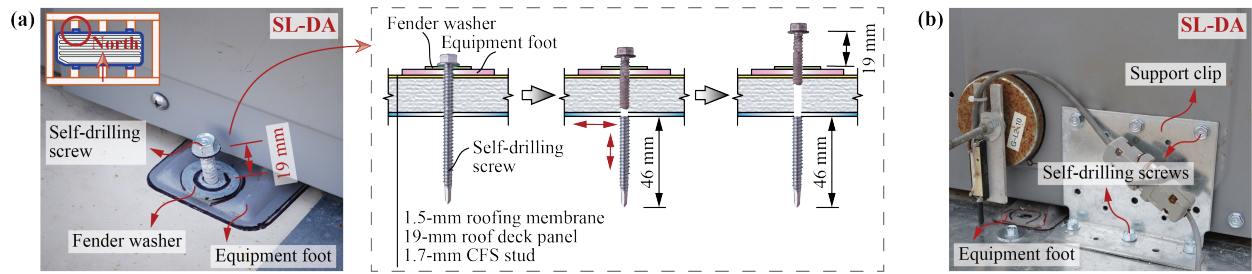


Figure 2. Physical damage to the SL-DA anchorage connection: (a) combined shear and tension failure (MID 17) and (b) anchorage retrofit (before MID 18). MID = Motion identification number.

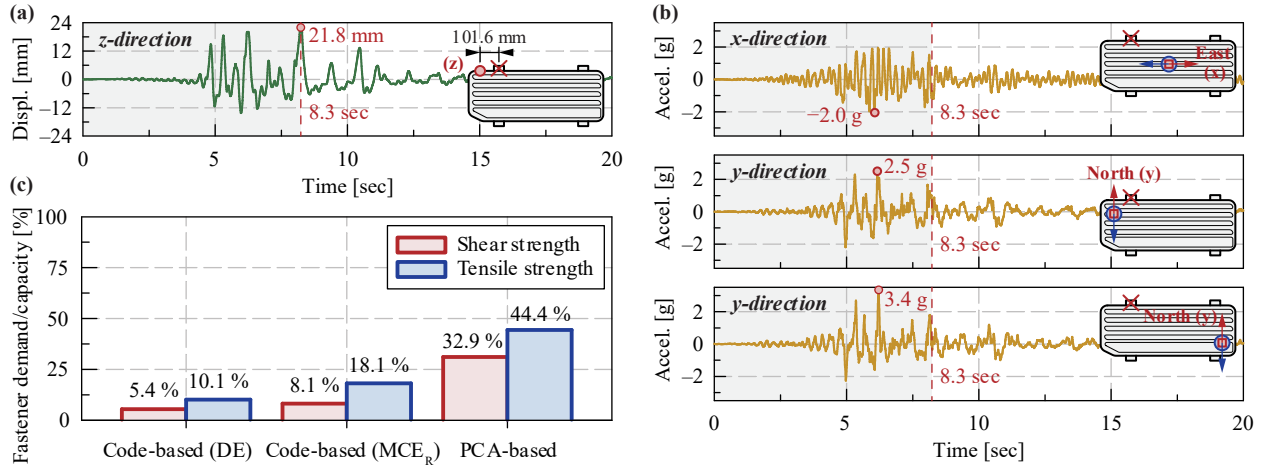


Figure 3. Inference of anchorage failure from measured response of the SL-DA: (a) vertical displacement time history measured near the failure location, (b) translational acceleration time history, and (c) fastener demand-to-capacity ratio.

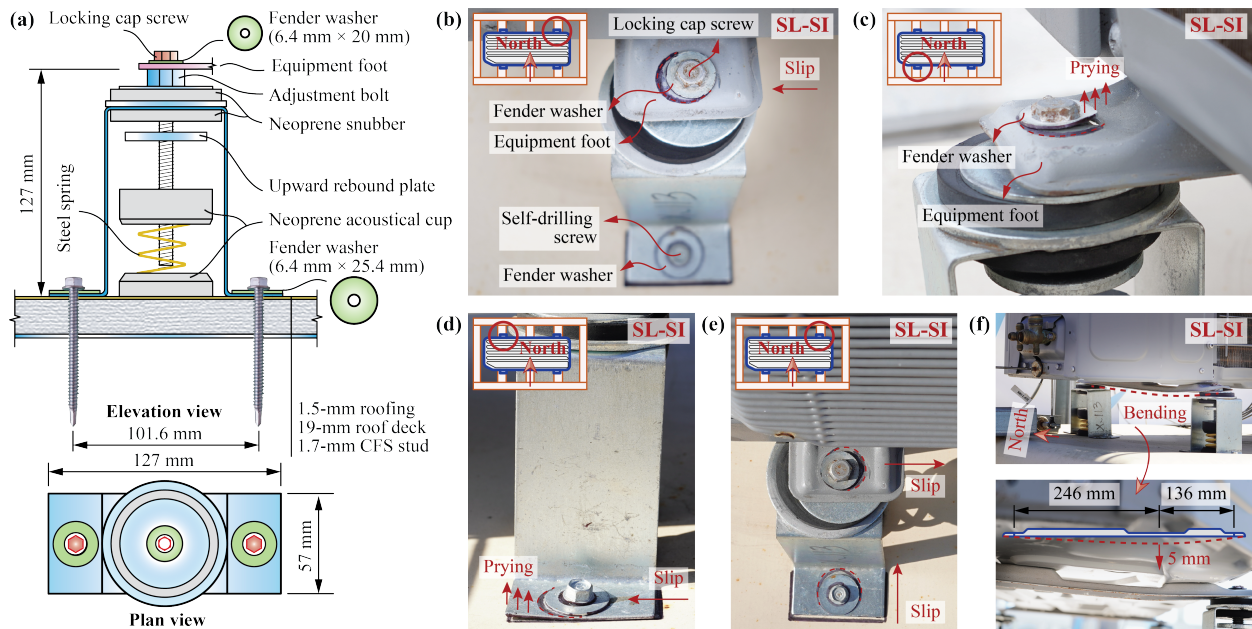


Figure 4. Physical damage to the SL-SI anchorage connection: (a) SL-SI anchorage design, (b) anchorage slip (MID 17), (c) washer prying (MID 17), (d) combined anchorage slip and washer prying (MID 18), (e) anchorage slip (MID 18), and (f) supporting rack bending (MID 18).

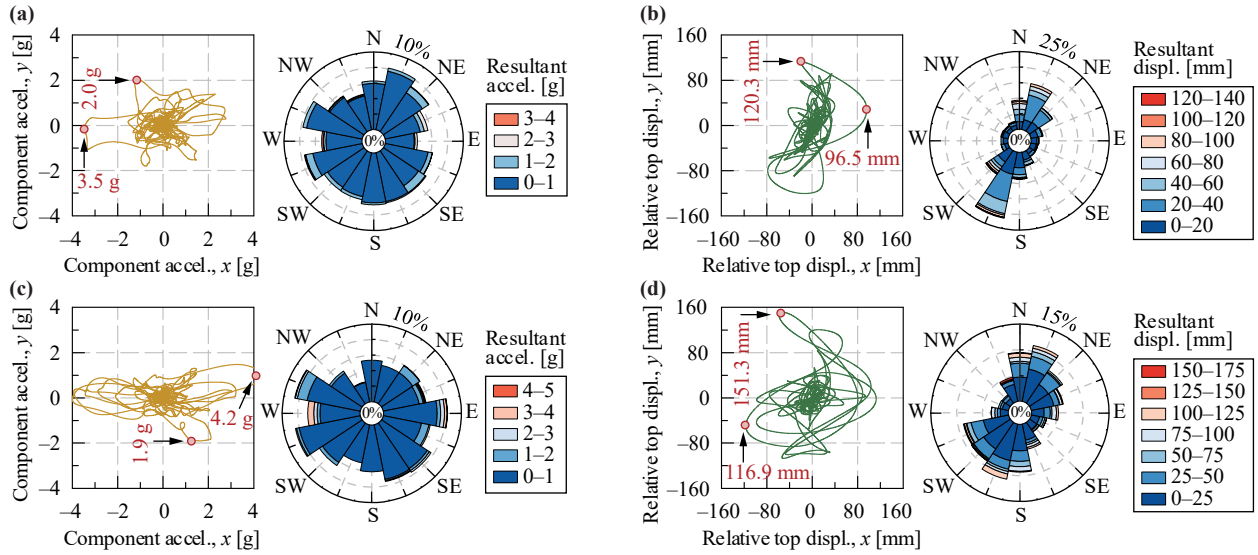


Figure 5. Measured response of the SL-SI: (a) acceleration and (b) displacement under MID17, and (c) acceleration and (d) displacement under MID18. Note that the y-direction acceleration was taken as the average of the measurements from the two top corners of the unit.

However, the plots of displacement response (Fig. 5(b)) indicate that the unit vibrated predominantly along the north–northeast (NNE) and south–southwest (SSW) directions. This behavior is attributed to the unit’s high slenderness ratio of 3.7 in the north–south direction (y-direction), which corresponds to its weak axis and makes it more prone to rocking. In addition, the mass of the slender unit was offset toward the west side opposite the fan, resulting in an uneven distribution of seismic weight. Consequently, the anchorages at the northeast and southwest points, as shown in Figs. 4(b–c), experienced sustained and repeated displacement demands. As shown in Fig. 5(c), a PCA of 4.2 g in the x-direction was recorded for the SL-SI during the second MCE_R test, representing the highest PCA for this unit across all earthquake tests. Localized deformation was observed in the lower portion of the anchorage, including prying (Fig. 4(d)) and slip of the metal housing (Fig. 4(e)). As shown in Fig. 4(f), a supporting rack beneath the location of the compressor, which carries much of the equipment’s weight, exhibited residual downward bending of approximately 5 mm. This damage is attributed to the uneven cross-section of the manufacturer-supplied rack where the weakened section became the most vulnerable zone and experienced the largest deformation.

Conclusions

Observed physical damage to nonstructural components often provides an indication of the severity of earthquake effects when measured response data are unavailable. To enhance understanding of their seismic performance, this paper described and analyzed the physical damage of two identical slender mechanical equipment units with different attachment designs, using measured response quantities from shake table tests. For the unit directly attached to the CFS studs, screw thread rupture was observed. This unexpected attachment failure is likely attributed to the combined effects of shear and tension in the screws. For the unit supported by spring isolators, minor localized deformation was observed, which tended to concentrate at anchorage along the predominant vibration direction or at weakened sections of the supporting rack.

Acknowledgments

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