EXPERIMENTAL PERFORMANCE OF FLOOR MOUNTED NONSTRUCTURAL COMPONENTS UNDER SEISMIC LOADING

T. Feinstein¹ and S. Mahin²

ABSTRACT

Research attention to nonstructural damage has been awakened in recent years, as performance based earthquake engineering has advanced and loss estimations have shown that more than fifty percent of the damage following an earthquake is due to nonstructural components. Nonstructural components response importance was first considered over life safety concerns. The possibility of nonstructural components, including but not limited to floor mounted equipment, to shift or topple over during a seismic event has led the addition of specific code provisions for the anchorage of nonstructural components. Available methodologies for seismic design of nonstructural components anchorage are based on very simplistic equations. Using constant values for generalized sub-groups of components, together with a basic dynamic approach of spectral acceleration distribution throughout the structure height. Current design equations and variables are considered to lead to very conservative results, due to the simplicity and over-strength incorporated in anchorage design. Previous testing of nonstructural component anchorage has been performed without considering the contribution of the structural system of the component itself. In order to deepen the understanding of the seismic loading of nonstructural components, shake table tests were conducted with floor mounted components anchored to concrete and steel, using instrumented anchors. The shake table was subjected to input motions from several ground motions based on real recordings and broadband spectrum matching. The ground motion includes different excitation directions allowing the comparison of 1 vs 2 and 3 components of motion. This paper focuses on the component responses and anchor loads, comparing results to predictions using design equations and first principles and presents implications for design practice of floor mounted nonstructural components.

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T. Feinstein\(^1\) and S. Mahin\(^2\)

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Research attention to nonstructural damage has been awakened in recent years, as performance based earthquake engineering has advanced and loss estimations have shown that more than fifty percent of the damage following an earthquake is due to nonstructural components. Nonstructural components response importance was first considered over life safety concerns. The possibility of nonstructural components, including but not limited to floor mounted equipment, to shift or topple over during a seismic event has led the addition of specific code provisions for the anchorage of nonstructural components. Available methodologies for seismic design of nonstructural components anchorage are based on very simplistic equations. Using constant values for generalized sub-groups of components, together with a basic dynamic approach of spectral acceleration distribution throughout the structure height. Current design equations and variables are considered to lead to very conservative results, due to the simplicity and over-strength incorporated in anchorage design. Previous testing of nonstructural component anchorage has been performed without considering the contribution of the structural system of the component itself. In order to deepen the understanding of the seismic loading of nonstructural components, shake table tests were conducted with floor mounted components anchored to concrete and steel, using instrumented anchors. The shake table was subjected to input motions from several ground motions based on real recordings and broadband spectrum matching. The ground motion includes different excitation directions allowing the comparison of 1 vs 2 and 3 components of motion. This paper focuses on the component responses and anchor loads, comparing results to predictions using design equations and first principles and presents implications for design practice of floor mounted nonstructural components.

**Introduction**

Nonstructural components response importance was first considered over life safety concerns. The possibility of nonstructural components, including but not limited to floor mounted equipment, to shift or topple over during a seismic event has led to the addition of a specific provision for the anchorage of nonstructural components. Anchorage design for nonstructural components is generally based on seismic force equations from these provisions, such as in ASCE 7-10 [1].

From an early stage, the seismic force design equation has considered a few influences that are believed to be most crucial for determining the force transferred to the nonstructural

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component. Those key performance parameters include component ductility, component period, location within the structure, hazard risk and importance of post-earthquake operation. The anchorage of the component was not considered directly in the force equation for simplicity, and was encouraged to have a ductile behavior with a non-ductile penalty factor [2].

Since the first component force demand equation formulated, there haven’t been major changes in the concepts, but rather small modification of the factors themselves. The efforts in developing the design considerations are built on limited knowledge from laboratory tests, simplified structural analyses and field observations and, as such, are hampered by the lack of an ability to carry out research that addresses gaps in the behavior of anchored equipment during seismic events, or validates the adequacy of current and proposed design equations. Development in recent years focused on floor acceleration demands [3,4] and the properties of the components to determine the ductility and flexibility of different components. In most previous tests, the nonstructural component has been idealized as a simplified SDOF system consisting of a steel mass connected to a column.

Research attention to nonstructural damage has been growing in recent years, as performance based earthquake engineering has advanced and loss estimations have shown that more than 50% of the damage following an earthquake is due to the performance of nonstructural components [5]. Performance evaluations from recent earthquakes have pointed to many failures of nonstructural anchorage or bracing systems and have also shown the need for improvements of seismic demands for anchored components [6]. Moreover, code provisions concentrate on life safety and don’t provide any guidelines for component protection. Some equipment may hold extremely valuable content that will be vulnerable under a design level earthquake or even in lower levels of ground motion, for example a medical research freezer containing hazardous materials or research samples collected over a decade.

Multiple shake table tests of anchored components were performed to assess the adequacy of the design forces developed using code equations. The behavior of non-idealized components was evaluated and key design parameters on anchor forces and overall performance were assessed. This paper describes the test design and key results related to different connection design, contribution of multidirectional input motion and force flow in the component.

### Seismic Design Requirements

The seismic design force for nonstructural components as appears in chapter 13 of ASCE 7 [1] is defined in Eq. 1.

$$F_p = \frac{0.4 \cdot a_p S_{DS} W_p}{I_p} \left(1 + 2 \cdot \left(\frac{z}{h}\right)\right)$$

where $a_p, R_p, W_p, I_p$ are component properties, $S_{DS}$ is the peak ground motion for the imposed hazard level, and $1 + 2 \cdot \left(\frac{z}{h}\right)$ is to account for the position of the component in the structure. $W_p$ is the component weight. $I_p$ is the component importance factor, that accounts for the functionality expected post-earthquake. $a_p$ accounts for component flexibility which can produce a magnification of the floor acceleration throughout the component, $a_p$ is taken as 1 for a rigid component, or 2.5 for a flexible one. $R_p$ accounts for the ductility and inelastic behavior of the structure, and is taken as a value between 1 to 6. The component factors $a_p, R_p$ are given in
tables according to component type.

Demand forces are calculated using LRFD with an additional multiplier for the component force $F_p$. That multiplier is the over strength factor $\Omega_0$, which is used when the anchor failure is assumed to be non-ductile. Recently the $\Omega_0$ factor has been better quantified through research [7], but other component parameters are not based on quantified data. Once the demand force $F_p$ is obtained the designer decides on the force flow between the component and the anchors. Due to lack of information, the component is usually considered symmetrical and the only factors affecting the calculation are the location of the component’s center of gravity, the number of anchors used and the distance between the anchors.

**Experiment Setup**

The test program leveraged efforts by a manufacturer to qualify a heavy battery cabinet. In the preliminary tests, the manufacturer, as is common industry practice, anchored their cabinet to a steel plate mounted on the UC Berkeley 6DOF shaking table. The cabinet was to be qualified for an on-ground location using the IEEE standard, with an SDS value of 2.5, thus certifying it for every location within the state of California. For these tests, instrumented machine bolts were used to attach the brackets at the base of the cabinet to the steel mounting plate.

The preliminary tests provided information about the response of the equipment and helped evaluate the ability of instrumentation to measure parameters of importance. However, the cabinets were not anchored to a concrete slab using conventional expansion anchors. Thus, a second set of tests was performed with the equipment anchored to a reinforced uncracked concrete slab. For these tests, two types of components were considered, a battery cabinet and a medical freezer commonly found in hospitals and medical research facilities.

**Specimen design**

A total of two components were tested, consisting of battery cabinets with the same design, but with varying mass and centers of mass, as one cabinet had one battery missing on the top rack. For consistency of notation the heavier cabinet will be referred to as the heavy battery cabinet (HBC), and the lighter cabinet as the light battery cabinet (LBC). The HBC weight was measured as 4334 lb, with a center of mass located 41 in above the slab surface. Both cabinet dimensions are H 84.2 in x W 32.4 in x D 50 in. The LBC had a weight of 4213 lb, with its center of mass located 40 in above slab surface.

Attachment of the cabinets to the shake table during the test were done using two designs, for the preliminary tests the HBC was mounted to a steel plate using 25mm instrumented bolts, as usually done in qualifying tests. In the second set of tests all the components were anchored to a 124 in x 88 in x 12 in, concrete slab that was attached to the shake table, concrete strength at time of testing was measured to be 4.7ksi. Specimen configurations are presented in Fig 1. Attachment of the components to the slab was done via instrumented Hilti HSL-3-G M12 and M16 post expansion anchors, the HSL-3-G design allows the replacement of the original threaded rod with an instrumented threaded rod, which allows measurements of individual anchor tension force throughout the test.

In addition, numerous accelerometers and displacement transducers were installed to measure input accelerations and acceleration responses at various positions on the cabinet, and lateral displacements of the cabinet at its top relative to its base. In this fashion, the axial forces
in the anchor bolts, inertial forces and deformations in the cabinet could be recorded during testing and compared to values predicted using code equations.

Figure 1. Specimen configuration during the tests. (a) Steel mounted HBC, (b) Concrete anchored HBC (right cabinet) and LBC. (c) Component axis

**Input motion**

The test plan involved numerous dynamic test performed on the UC Berkeley 6DOF shaking table. Various input motions were used to evaluate effects of floor height throughout the structure, differences between recorded ground motion and broadband manufactured motion and effects of multidirectional input motion. A combination of horizontal and vertical input motions were used to better understand the effects of realistic 3D excitations on anchorage. Input motions were applied in the two principal directions of the cabinet. In the test program undertaken in this research, the horizontal components were applied in the standard one-degree motion, in both horizontal directions separately, but also in a multidirectional input in both horizontal directions simultaneously, and with an additional vertical input acceleration.

Input motions included commonly used on-ground location IEEE standard, with an SDS value of 2.5, as part of the test leveraged from ongoing qualification tests. In addition, another set of input motions were based on a medical research facility, the Health Sciences Instruction and Research (HSIR) complex, located in the Parnassus campus of the University of California San Francisco. The present research focused on one of the HSIR’s two laboratory buildings, 16 stories tall, designed as a steel moment frame structure made of large built-up sections. A realistic numerical model was developed using the Open System for Earthquake Engineering Simulation (OpenSees) [8], floor accelerations were recorded from the simulation for a design level event at ground level, mid-height and roof level. Floor spectra was later spectrally matched in a similar way to the procedure used for equipment qualification in AC156 [9]. Both spectrally matched broadband motion and the original floor spectra considered five percent damping in the component, as required in AC156. Floor spectra at mid-height from the HSIR simulation were used as the shake table input motion and are presented in Fig 2.
Design process

Design of the lateral design force, $F_p$, for the battery cabinets was done in accordance with ASCE 7-10 Chapter 13 [1], using the parameters $a_p = 1$, $I_p = 1$, $R_p = 2.5$. Other parameters regarding the input motion were controlled by the chosen floor motion for each specific test, multidirectional ground motion was not considered for this calculation as the $F_p$ equation does not take it into account. As the anchor design includes installing post expansion anchors, a ductile response is not expected, thus a factor $\Omega_0 = 2.5$ is added to account for a brittle concrete failure. Finally, the anchor forces are calculated by assuming the moment caused by the design force $F_p \cdot \Omega_0$ acting in the center of mass is divided equally between the two anchors.

Results

The goal of the testing sequence was to evaluate the behavior of non-idealized anchored nonstructural components. The evaluation focused on component acceleration amplification, force flow through the anchors and the effects of multidirectional input motion. Table 1 shows the conducted tests that are the basis for the presented results, each with the calculated anchor design force and the maximum measured anchor force from the test, for the LBC component.

Anchor forces

Anchor forces were measured using instrumented anchors in the interest of comparing these to the design forces and understanding the force flow in the component. Recorded forces were verified through simple equilibrium equations in all tests performed as part of the research.

Discrepancy between the design and test anchor forces are apparent from the last column of Table 1, for most cases the recorded force was larger than the design force. Also notable is the major difference between the broadband input motion and the recorded motion, comparing between test 1 and 5 reveals an almost 8 times larger force for the broadband test in the Y direction. Broadband input motion is used for qualification tests as a worst-case scenario, as the component can be installed in a variety of structures with unknown properties. It is important to note that the chosen structure’s natural periods did not resonate with the component, but in other
structures this might occur for higher modes and could produce a more significant response than the broadband.

Table 1. Tests description including anchor design and maximum measured forces

<table>
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<tr>
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</table>

*Mounted to a steel plate.

Force flow in the component was majorly influenced by the component’s structural system and was highly asymmetric. The component structural system is “C” shaped and not box-shaped as the door cannot transfer any shear forces. Thus, torsional effects are observed when the component is excited in the X direction, axes are shown in Fig 1. Furthermore, for the same excitation there is large force concentration in the back anchors. An example from test number 8 is shown in Fig 3, the tension forces in the front anchors are almost zero and all the force is concentrated in the back of the cabinet.

Figure 3. Anchor tension forces for LBC during test number 8.
Acceleration amplification

Component acceleration amplification can be divided into two separate contributions, as illustrated in Fig 4 (a), the first is the floor amplification from peak ground acceleration (PGA) to peak floor acceleration (PFA) throughout the height of the structure. The second contribution is the amplification of the component relative to the floor. Performing shake table tests with real equipment provide quantitative data for the component contribution. Peak component acceleration (PCA) was measured at the component center of gravity and PFA has been recorded from the table, the ratio between PCA and PFA for all the tests is shown in Fig 4 (b). Values of the ratio are always larger than one and are capped at 2.7 for the given tests.

Amplification of component acceleration relative to the floor is also considered in the current design equation by taking the ratio between the component parameters $a_p/R_p$. $R_p$ represents the ductility in the component and as such is always larger than one. Thus, the assumption of a rigid component cannot hold as the cabinet acts as a flexible component, with an amplification of the floor accelerations in all cases. The results from test number 8 suggest that the $a_p$ parameter should be larger than 2.5, which is the maximum according to the code.

Component dynamic response from broadband input motion was studied from the comparison between tests 1 and 2 vs 5 and 6 respectively. The response was consistently more severe for the broadband input motion. Two factors contribute to this observation, firstly - was a higher recorded PFA, secondly was a larger component amplification factor, as observed in Fig 4. Contrary to belief, the component amplification factor was lower in Y direction for the broadband matched motion, the more severe response recorded in the test resulted only from the much higher PFA in test number 5, 0.42 g vs 1.05 g in the broadband input motion.

Multidirectional input motion

Effects of multidirectional excitations on anchored equipment were observed through a series of shake table tests repeating the same excitation in different combinations. Including bidirectional horizontal and vertical components of excitation, listed as tests number one to four in Table 1.
Often codes simplify lateral force calculation by separating excitations into two principle directions. Consequently, the design forces calculated for the multidirectional tests were simply taken as the larger out of the two principle directions. Recorded forces shown in Table 1 suggest that anchor forces are larger when subjected to more than one direction of excitation, forces were amplified by almost 30 percent for the bi-directional excitation. An additional eight percent increase in the maximum force was recorded when vertical excitation was included.

Unlike the increased anchor forces, component properties and overall behavior remained similar under multidirectional excitation. Comparison between the component’s center of gravity accelerations under the different input motions, as shown in Fig 5, demonstrates that the 2D and 3D excitations track the accelerations recorded in the one-dimensional excitation test. Component’s natural period remained unchanged, but there was an amplification of the values at the maximum response that contributed to the increase in the anchor forces.

![Figure 5. Acceleration of LBC center of gravity under multidirectional excitation, (a) Acceleration in Y direction, (b) Acceleration in X direction.](image)

**Attachment Effects**

Attachment design has a noteworthy influence on the component dynamic response resulting in modified component demands that are transferred from the floor through the anchors. Two designs were tested for the attachment of the battery cabinet, using bracket connection as shown in Fig 6. The first design, used in test number 8, is the commonly used connection in qualifying tests, a quarter inch bracket was connected to a steel plate with 25mm instrumented machine bolts with an additional quarter inch washer. The second design consisted of an HSL-3-G post expansion anchor in a one foot deep concrete slab, making it a much more flexible connection.

The most notable change between the two designs was the amplified response in the component attached to the steel plate. Accelerations at HBC measured a 38 percent increase in the stiffer steel connection. Maximum anchor force in the concrete connection was significantly lower. Two major differences between the designs are worth noting, firstly the brackets in the concrete connection did not have an additional washer which allowed the formation of a plastic hinge at the base of the angle. Significant uplift was observed, as shown in Fig 7, which eventually resulted in a fatigue failure of the cabinet in a later test. Secondly, the anchor capacity
of the machine bolt is substantially higher than that of the post expansion anchor, though the forces in the test were not limited by this, as none of the anchors reached its capacity.

![Image of machine bolt and post expansion anchor](image1.jpg)

Figure 6. Attachment design for different floor types (a) concrete, (b) Steel plate.

Modifications in the component’s overall stiffness were observed through a major change in the natural period of the HBC. The natural period in the X axis of the component shifted from 0.1 seconds in the stiff steel connection to 0.2 seconds when connected to concrete. Previous research supports that these changes seen in the dynamic response of components depends on the anchor characteristics [7].

![Image of component attached to concrete](image2.jpg)

Figure 7. Uplift of the component attached to concrete.

### Conclusions

A dynamic shake table test program with anchored components was performed to assess the adequacy of the design forces developed using code equations. The performance of the component was evaluated under multidirectional input motion, applying recorded ground motion and broadband spectrum compatible motion, and testing different anchorage designs. Notable observations and conclusions are as follows.

a. Code lateral force equations are commonly believed to give conservative results. However, test results show that even with consideration of the overstrength factor $\Omega_0$, the code equation gave unconservative values relative to measured anchor tension forces. Test results clearly show that component factors $\alpha_p$ and $R_p$ do not predict
actual component amplification. Additionally, the component internal structural system controls the force flow in the anchors, which results in a highly asymmetrical force distribution that is not usually considered in the anchor design process.

b. Component dynamic response to broadband input motion was more severe, compared to the design level recorded floor motion. Interestingly, the ratio of PCA to PFA wasn’t consistently higher for the broadband motion, which suggests that broadband input motion does not always produce the largest amplification of responses.

c. Currently multidirectional input motion effects are not considered in code design. However, the results show an increase in the component dynamic response with higher recorded accelerations and anchor forces. Component dynamic properties remained unchanged, though it is important to note that these effects are limited to heavy components, with distributed mass and full contact with the floor.

d. Attachment design has considerable influence on the component dynamic response. Flexible attachments elongate the component’s natural period and could potentially create a plastic hinge that could act as a fuse to control the maximum demand that can be transferred to the component and the anchors.

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