ELECTRONIC DATA PROCESSING EQUIPMENT BRACED
TO RESIST SEISMIC LOADING

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ABSTRACT

Described is a new and economical method to restrain electronic data processing equipment situated on raised floors of buildings located in all earthquake zones. A bracing technique is developed that employs a prestressed cable-like anchorage that clamps computer cabinets and raised floor systems securely to the building structure while allowing for some cushioning motion to occur prior to achieving full restraint. Nonlinear static and dynamic analyses incorporating finite element techniques are used together with a series of simulated-earthquake vibration tests to verify system performance.

INTRODUCTION

Different analytical approaches have been used to determine the response of a secondary structure mounted on a primary support structure. Exact methods have been employed[1] that take into account the time history of an earthquake excitation, as well as approximate methods[2,3] that make use of either direct amplification of the site-response spectra or random-vibration techniques. This paper presents both a static and a dynamic analysis of a computer-cabinet/raised-floor bracing scheme. The new scheme has been modeled as shown in Figure 1 and analyzed by means of the matrix displacement method, which is based on finite element idealization. The dynamic-response solution employs a model analysis and a response-spectra approach. Static and dynamic tests were run on full-scale assemblies and the results were used to establish performance data and verify the analyses.

THE TOGGLE BAR: A PRE-ENGINEERED BRACING SCHEME

The bracing scheme described employs a 1/2-inch-diameter threaded rod (the toggle bar) that attaches at the base of a computer cabinet, extends downward through the raised floor, and is anchored at the lower end in the structural concrete floor. Each toggle bar is preloaded in tension so as to clamp the cabinet and raised-floor system securely to the concrete floor below. Under earthquake conditions, the toggle bar acts solely as would a cable. Initially, the toggle bar offers little resistance to horizontal forces, but when friction between the cabinet and the raised-floor surface is overcome, the bar becomes increasingly angled and its tensile loading increases, ultimately reaching a level sufficient to completely restrain the cabinet from further motion. The toggle bar resists vertical motion (and, hence, overturning) at all times, thus preventing the cabinet from hammering against the raised floor.

STATIC-DYNAMIC ANALYSES

Formulation of the Problem. The computer-cabinet/raised-floor bracing system is modeled as an assembly of 135 discrete structural elements. The cabinet and the raised floor are treated as three-dimensional frames. Attention is focused on the cabinet's base pads, on the contact points between the base pads and the raised-floor surface, and on the toggle bar.

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The base pads consist of a nonlinear elastic material (rubber), the stiffness of which increases as compression increases. Each base pad is modeled as a system of four vertical springs in parallel. (Spring constants $K_1>0$, K_2, K_3, $K_4<0$.) The kinematic hardening is achieved by introducing a limiting force for each negative stiffness. As the compression on each base pad reaches successive limiting forces, the corresponding stiffnesses are removed, one by one, resulting in an increasing equivalent stiffness.

When horizontal friction forces are exceeded, sliding occurs. This introduces a singularity to the analysis. This is handled by introducing an interface element, representing two plane surfaces that may maintain or break physical contact and may slide relative to each other. This is expressed as

$$X_H = 0 \text{ when } F_H<\mu|F_N| \quad \text{(a)} \qquad\qquad X_H \neq 0 \text{ when } F_H \geq \mu|F_N| \quad \text{(b)}$$

where X_H is the horizontal displacement of the cabinet's base pads relative to the raised-floor surface, F_H is the applied horizontal load, F_N is the normal load at point of contact, and μ is the coefficient of friction. (0.42 static and 0.32 sliding on vinyl asbestos floor tile.)

The toggle bar is modeled as a cable element. Its load change depends on the displacements of the system. The governing equation for the induced tension T in the bar due to a net horizontal displacement X between the cabinet base and the concrete floor is derived from Taylor's series as

$$T = (Ka-c) + \frac{K}{2a} X^2$$

where K is the initial bar stiffness, a is its initial length minus any accumulated vertical displacement of the system, and c is the initial tension.

Methods of Solution. The matrix displacement method, which is based on finite-element idealization, is used throughout the analysis, in conjunction with the ANSYS[4] computer package. Small- and large-deflection procedures are used to analyze the model in Figure 1 statically and dynamically.

In the static analysis, the governing force-displacement equation for large displacements with stress stiffening is

$$([K_{up}] + [K^s_{up}]) \{x\} = \{F^n\} + \{F^{ld}\} + [K^s_{up}] \{x_0\}$$

where, $[K^s_{up}]$ is the stress stiffness, $[K_{up}]$ is the stiffness based on updated geometry, $\{x\}$ is the displacement, $\{F^n\}$ is the applied nodal-point force, $\{F^{ld}\}$ is the large-displacement force (a fictitious load generated on the basis of kinematic corrections), and $\{x_0\}$ is the previous displacement.

In the dynamic analysis, the model is analyzed to determine the natural frequencies of the system, and a system spectrum response is used to compute velocities and accelerations. A base acceleration excitation is used for the spectrum analysis. The participation factors γ_i for a given excitation direction are computed by means of

$$\gamma_i = \{\Psi\}^T_i \; [M] \; \{D\}$$

where $\{D\}$ is the unit vector describing the excitation direction. The reduced displacement vector $\{x\}_i$ is computed from the normalized eigenvector $\{\Psi\}_i$ and the input spectral acceleration excitation S_{ai} at frequency ω_i, and it is given by

$$\{\hat{x}\}_i = \frac{S_{ai}\,\gamma_i}{\omega_i^2}\,\{\Psi\}_i$$

The acceleration response spectra used as input load for the spectrum analysis constitute an upper bound determined in an analytical study of earthquake-induced in-building motions[5].

DESCRIPTION OF TESTS

A DEC computer cabinet was used, supported on a stringer supported raised-floor system utilizing steel panels. Two schemes of bracing the cabinet and the raised floor were used. The first used two toggle bars, one located at the front and one at the back of the base flange of the cabinet The second used one toggle bar located at the center of the cabinet base, attached to a supplementary steel cross beam.

In the static tests, a hydraulic cylinder applied a horizontal load gradually, 50-pound steps from 0 to 1000 pounds, at the center of gravity and at the base of the cabinet. Figure 2 clearly shows the bi-modal nature of the resulting displacements for the two conditions of toggle-bar restraint. Similarly, Figure 3 illustrates the resulting tensions in the toggle bars caused by the static loadings and shows the generally favorable comparison of these with the analytically determined results.

Dynamic tests were run by placing a full-scale segment of a computer-cabinet/raised-floor installation upon a reinforced-concrete slab that in turn was shaken by a programmable hydraulic machine. The slab was forced to follow a range of synthesized earthquake motions [5] that were developed to match horizontal floor motions in multistory buildings situated in differing seismic regions[6], as well as the floor response spectra used in the analysis. Figure 4 shows the dynamic displacement time response motions and toggle bar tension-time histories for a typical test condition.

RESULTS

Table I presents pertinent results of the testing program and shows the favorable comparison of these with corresponding analytic predictions. Under the maximum earthquake conditions expected in the USA, it is seen that the computer cabinet will slide less than 2 inches horizontally relative to the structural concrete slab, and the peak accelerations in the cabinet will range from about 2 g's at the bottom to 6 g's at the top of the cabinet.

REFERENCES

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TABLE I

STATIC* RESULTS

Max Displacement**	Test	Analysis	% Error
Raised Floor	475 (mils)	431 (mils)	9.26
Cabinet	1810 (mils)	1600 (mils)	11.6

DYNAMIC RESULTS

Max Displacement**	Test	Analysis	% Error
Raised Floor	429 (mils)	432 (mils)	1
Cabinet	1870 (mils)	1602 (mils)	14.3

FUNDAMENTAL FREQUENCIES (HZ)

	Test	Analysis
Raised Floor	12-16	13.45
Raised Floor & Cabinet & Bracing	3.5-5.1	4.9

MAXIMUM ACCELERATIONS (g's)

100% Earthquake Intensity (Zone 4 upper floor)

Positions	2 Threaded Rods	1 Threaded Rod+Beam
Cabinet Top	5.77	4.49
Cabinet Middle	3.66	2.20
Cabinet Bottom	3.66	3.26
Floor Top	1.94	3.33

*1000 lbs. load applied at the center of gravity of the cabinet

**Horizontal displacement relative to concrete floor.

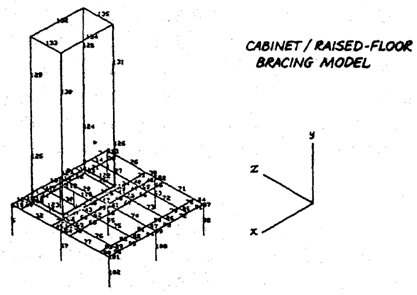

FIGURE 1

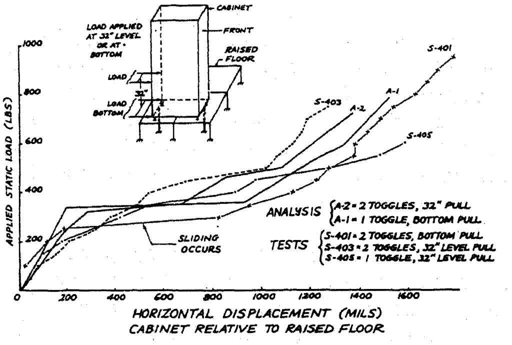

FIGURE 2

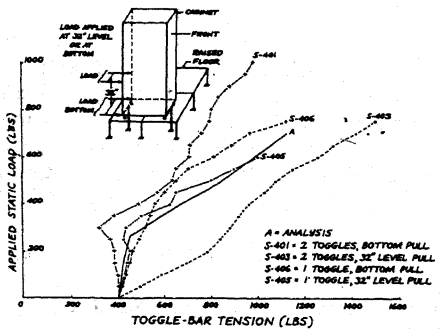

FIGURE 3

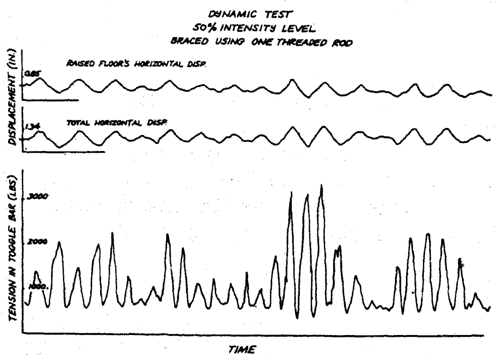

FIGURE 4