SHOCK AND VIBRATION

TECHNOLOGY REVIEW

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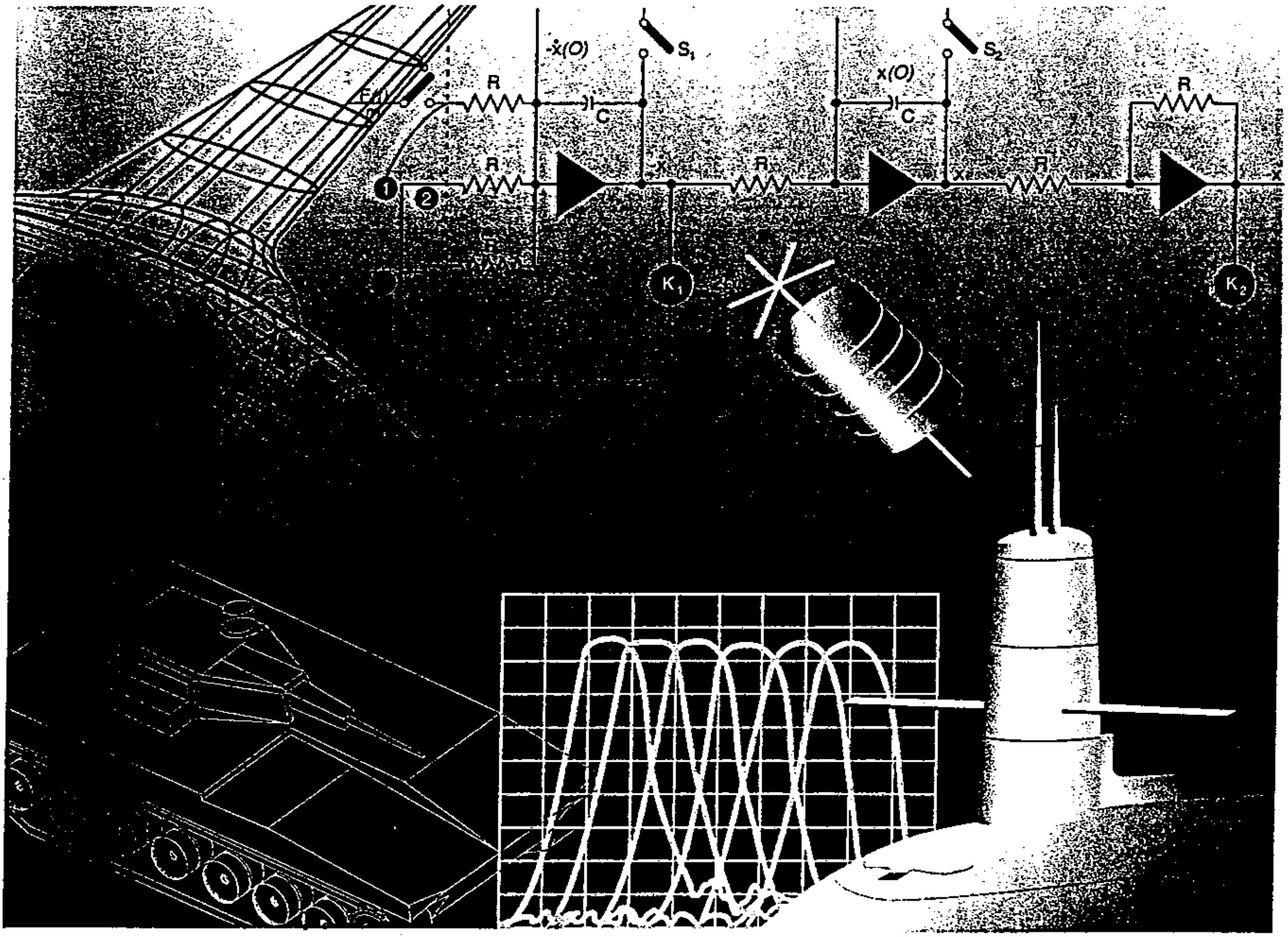

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EDITOR'S DESK

FEATURE ARTICLE

SYMPOSIUM PAPER

BOOK REVIEW

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EDITOR'S DESK

THIS MONTH IN TECHNOLOGY REVIEW

Traditionally, if such a word can be used in this case, our year-end issue is an index of all the articles and abstracts we published throughout the year. With the advent of the new *Journal of Shock and Vibration* and the coming departure of this publication, we decided to include a few articles to make it that much more interesting.

In 1992, we invited Jerome Pearson to make a presentation on high-intensity acoustic testing at the opening session of the Shock and Vibration Symposium in Las Cruces, NM. He graciously accepted and gave a very informative talk on high-intensity acoustic testing going on at Wright Laboratory. We are finally able to bring you the written text of that presentation, which has made its way through the stringent clearance procedures of Wright Lab's Public Affairs Office. Far be it from me to make light of our national security interests, but sometimes it wreaks havoc on our printing schedule.

Our Feature article was submitted for presentation at the 64th Symposium in Fort Walton Beach, but events prevented the author, Edward Fischer, from attending. With the abstracts we have included the papers appearing in Volume I of the *Proceedings of the 64th Shock and Vibration Symposium*, this issue might well be considered an addendum to the Proceedings. SAVIAC is pleased to be able to provide a format for this material, no matter where it appears.

William Dunn

FEATURE ARTICLE

DESTRUCTION CAUSED BY THE QUASI-RESONANCE EFFECTS OBSERVED IN THE LOMA PRIETA EARTHQUAKE

ON OCTOBER 17, 1989

by Edward G. Fischer and Thomas P. Fischer
Edward Fischer is a consulting engineer and Thomas Fischer is a senior test engineer for AEA O'Donnell, Inc. in Pittsburgh, PA.

One aspect of the Loma Prieta earthquake that continued to make news in Pittsburgh, PA concerned the damage to some power circuit breakers at the Moss Landing switchyard in California, about halfway down along the Monterey Bay shoreline [1]. Originally, models of the damaged equipment had been exhaustively computer analyzed and then tested at the EERC (Earthquake Engineering Research Center) in Richmond, CA [2]. Subsequently, a careful examination of some published accelerograms [3] immediately aroused attention because of their low frequency vibration content. In particular, one of the strong motion instruments involved was located at the Capitola Fire Station and the record labeled (CHN3-0DEG-0.54g) showed a pronounced, repetitive effect at about 2-4 Hz. Significantly, the Capitola seismic recorder was located only 4.5 miles west of the Loma Prieta earthquake epicenter and also along the Monterey Bay shoreline some 15 miles north of the Moss Landing switchyard.

As expected, the special phenomena at Capitola appeared to be related to news media reports of simultaneous damage in the vicinity as follows: Figure 1 shows the destruction of the subject power

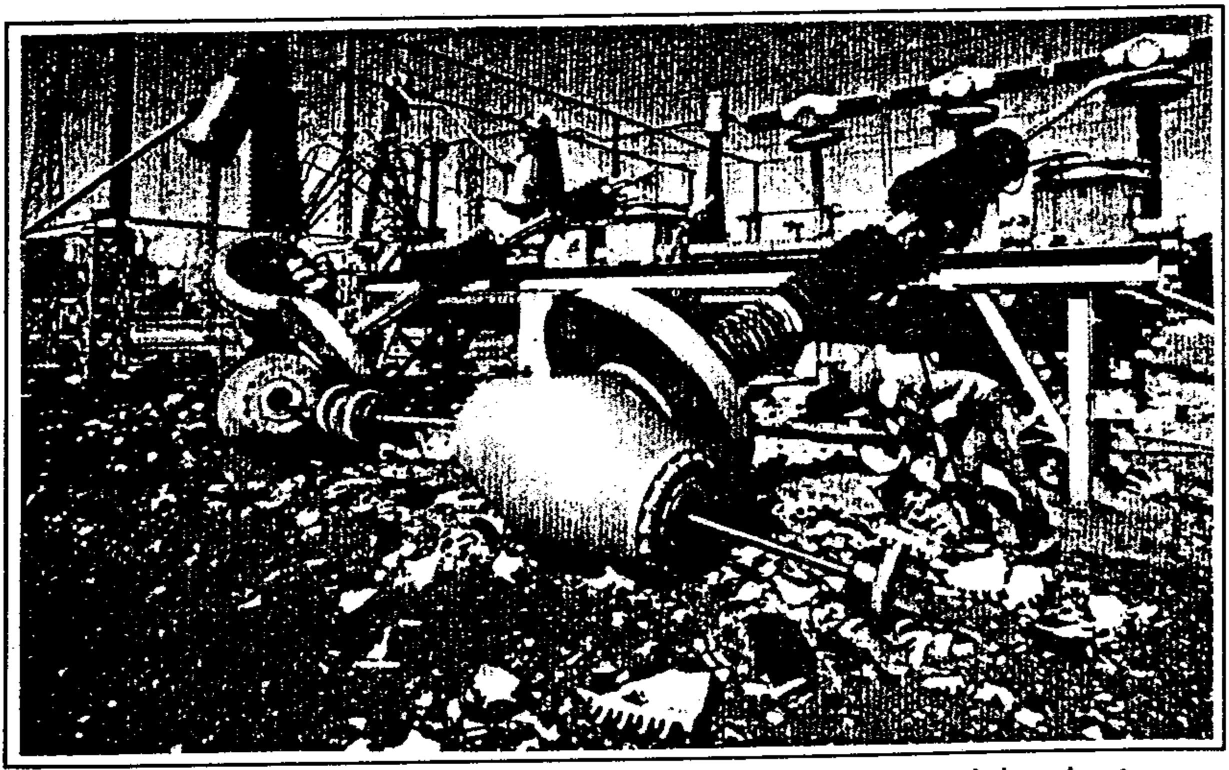

Figure 1 Destruction of circuit breakers at the Moss Landing switchyard by the Loma Prieta earthquake on October 17, 1989

circuit breakers at Moss Landing, CA. An early, tentative explanation of these seismic failures readily followed from an investigation of a similar occurrence during the San Fernando earthquake on February 9, 1971 [4]. Subsequently, the authors eventually became aware of a comprehensive compilation of all the strong-motion records of the Loma Prieta earthquake [5]. (The Capitola ground motion is plotted on Page 25. Also, in the companion volume designated Report No. OSMS91-06, the corresponding "response-spectra data" are shown plotted on quadra-log graph paper on Page 2.) However, these reports make no mention of the underlying time histories that the authors have found to contain important sine-beat phenomena that probably caused the quasi-resonance failures of the circuit breakers.

Seismic Response Plotted as an Acceleration Time History

There is an inherent disadvantage to studying the peak g-levels given by response spectra; namely, the time history is lost and along with it the number of "damaging" motion cycles at each frequency. Such information can be retrieved in a digital computer program [6] by extracting the response time-history plots at each frequency before the maximizing procedure takes place.

This procedure was used for an earlier paper [7] from which Figure 2 has been copied. It shows the time-history response of a few simple oscillators excited by the well-known El Centro 1940 earthquake. By comparison, Figure 3 shows the response spectrum for a 0.5g earthquake *specified* for the design of the circuit breakers located at the Moss Landing, CA switchyard. At 5 percent damping, the peak g-levels shown on the Figure 2 plots can be raised by 1.5 times to agree with the corresponding design spectrum plot at the designated frequencies (see Figure 3). In effect, the El Centro earthquake is being used as a general design criterion. It appears to have been caused by not one, but a series of four or five sequential tremors. The result has been an unusually broadband response spectrum with no pronounced quasi-resonance effects.

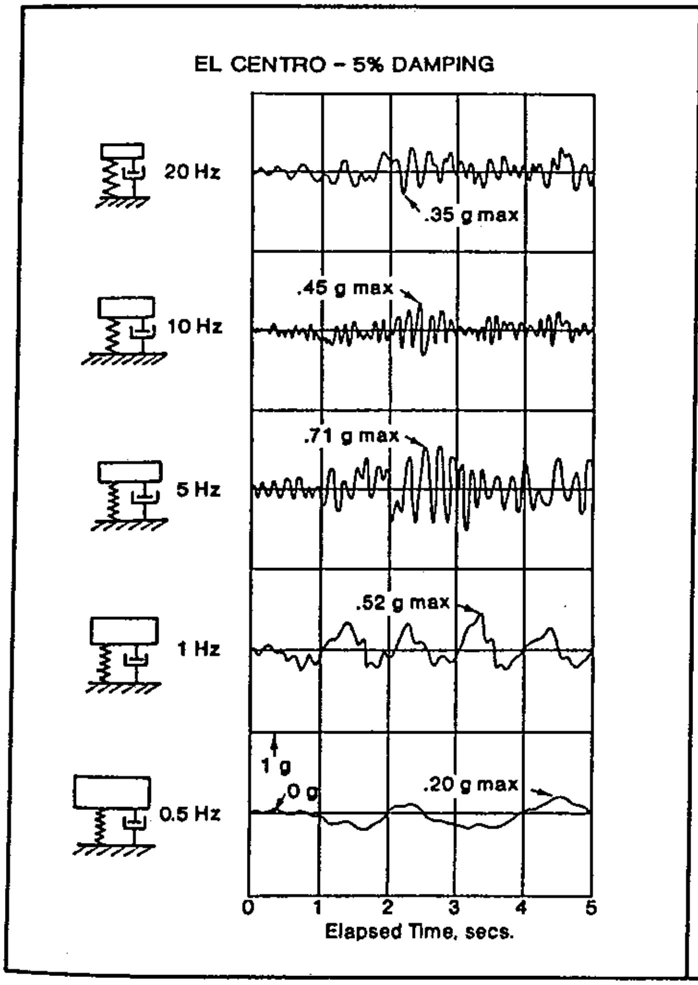

Figure 2 Acceleration (g-level) time histor response to the 1940 El Centro earthquake

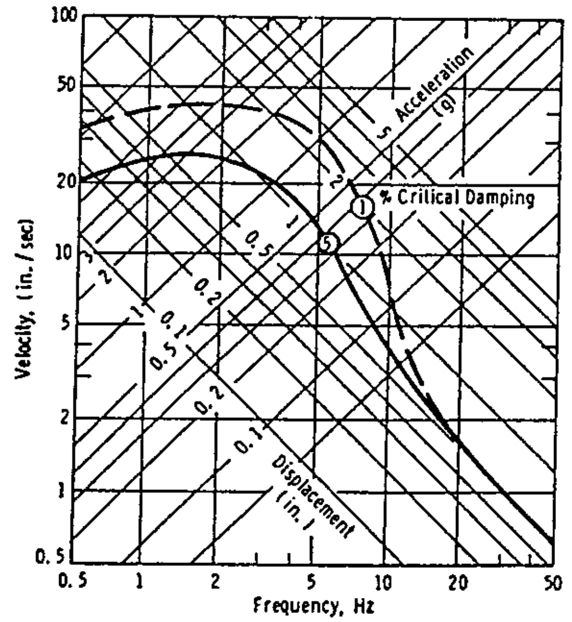

Figure 3 Specified design response spectrum for a 0.5g horizontal ground acceleration

This early precedent has been commented upon by Hudson [8] as follows: "It must always be kept in mind that consideration of long term average conditions may be of small comfort to the engineer whose building (or equipment) was destroyed by an earthquake which happened to depart from the average." Housner [9] has added that the response spectra yield only peak g-levels, which are only "an imprecise specification of *intensity*" (hence, low-cycle fatigue).

Time-History Responses for the Capitola Accelerogram

As mentioned previously, the Capitola record was one of those recognized (before any computer analysis) as being capable of producing unusual quasi-resonance effects. Hence, as the main purpose of this discussion, Figure 4 shows the calculated responses for this recording taken near the San Andreas fault and situated on "alluvium." The time-history response of the 25 Hz simple oscillator corresponds approximately to the original seismic recording for the time interval from 4 to 9 seconds, wherein most of the peak g-levels occur. The maximum response of 2.13g was found at 3.6 Hz and the persistent oscillations were considered to represent damaging low-cycle fatigue in any structure at that natural frequency.

Somewhat arbitrarily, this Capitola record has been assigned to the suspected phenomena at the nearby Moss Landing site, where the circuit breakers were destroyed. Later in this paper, this seismic record will be used to justify the preferred sine-beat testing of the circuit breaker porcelain column on the shaking table at the EERC located in Richmond, CA during November – December 1973 (see Reference 2). In particular, the response at 2.6 Hz with a 1.98g peak for 5 percent damping corresponding to a horizontal ground motion, agrees closely with the quasi-resonance, shaking-table motion performed in anticipation of the actual seismic failure in 1989. As discussed earlier, each peak g-level at its corresponding frequency for the time history plot can be transferred to Figure 5 to obtain the response spectra curve at 5 percent damping.

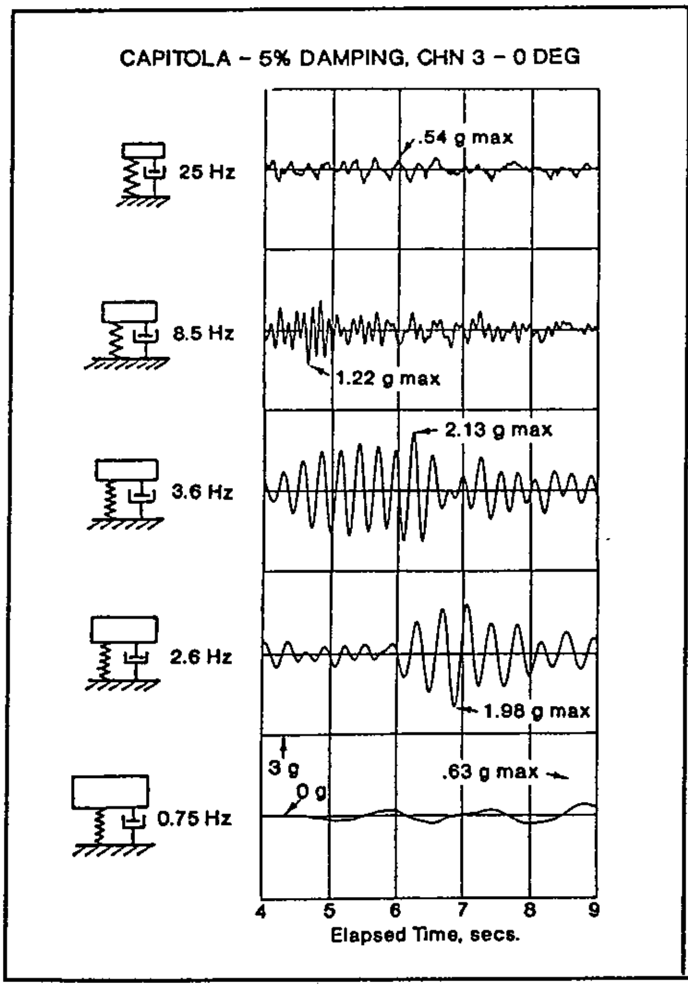

Figure 4 Acceleration (g-level) time history response at Capitola Station to the 1989 Loma Prieta earthquake

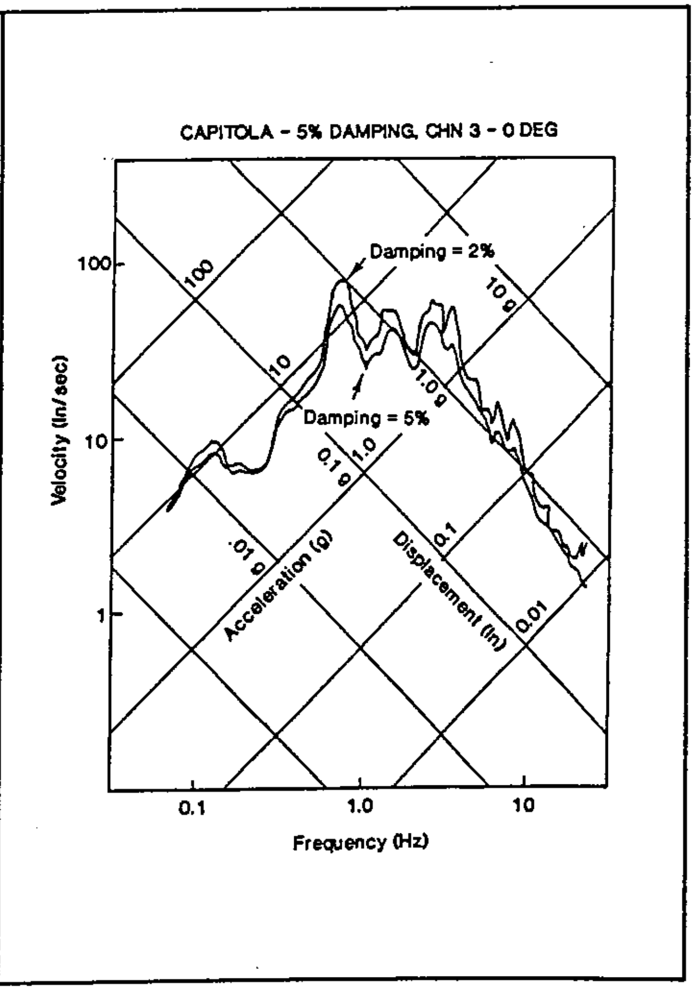

Figure 5 Quadra-log plot of the response spectra at the Capitola Station for the 1989 Loma Prieta earthquake

Shaking-Table Qualification Tests at the EERC in November-December 1973

Figure 6 shows a single column of a QR (quake-resistant) type circuit breaker subassembly mounted on the EERC (Earthquake Engineering Research Center) shaking table, where it was subjected to three-direction accelerations. Quoting from [2] as follows: "The available 20- by 20-foot test table area could conveniently accommodate only one column of the 500 kV gas circuit breaker (shown undamaged in the right-hand background of Figure 1). A 3,800-pound current interrupter was supported on top of a 180-inch tall porcelain insulating column, which was anchored to a flexible, steel base plate." (see Reference [2]).

Figure 7 refers to an earlier computer-aided analysis of the entire 3-column circuit-breaker assembly on its elevated steel platform, wherein the 1-column measured test response should be raised by a factor of 1.3 times for the worst case of cross-coupling effects found by the computer analysis of the assembly. Hence, the 3-column assembly as installed at the Moss Landing switchyard was accepted as "quake-resistant" in terms of the original specifications [10]. Finally, this would mean that the specification anticipated a peak response acceleration of about 1.63g (= 0.5x2.5x1.3) and no damage. (Compared to transient loads caused by lightning or short-circuit events, such seismic loads are not considered important.)

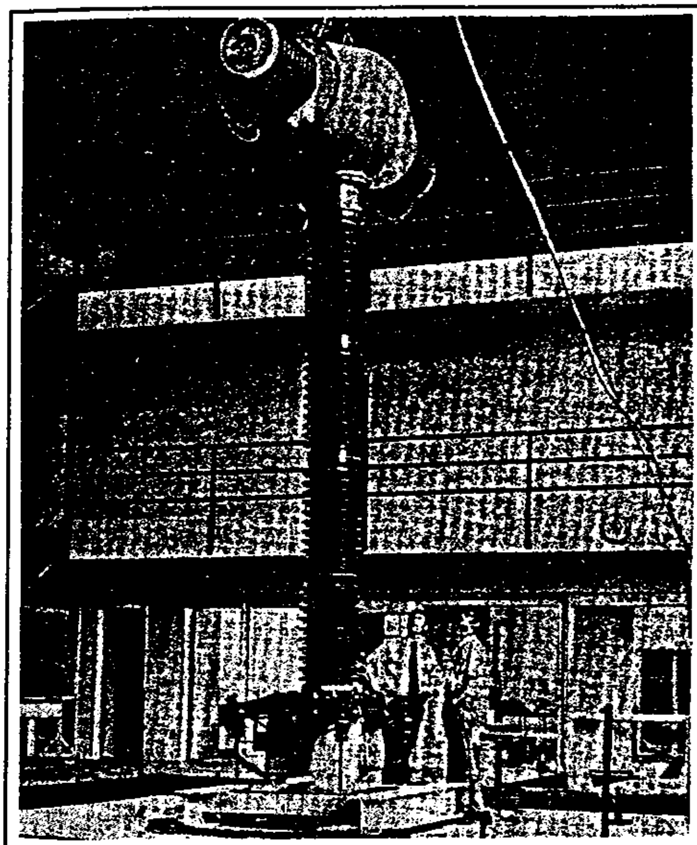

Figure 6 1-column circuit breaker subassembly seismic tested on shaking table at EERC at Richmond, CA Field Station of University of California

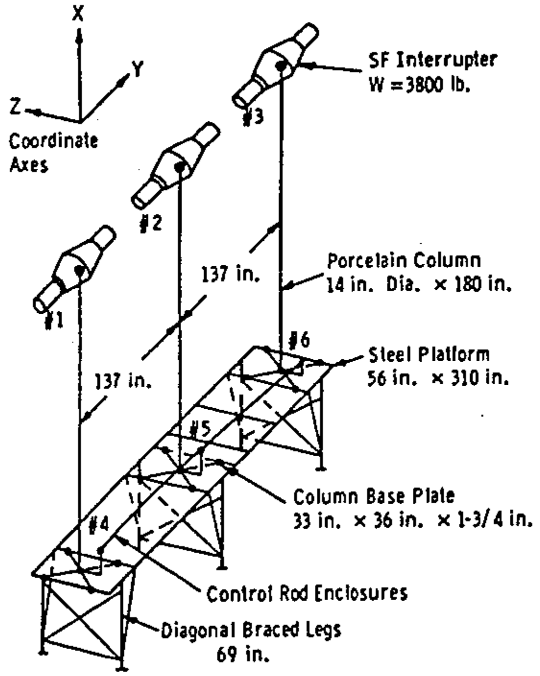

Figure 7 Structural model of 3-column assembly used with NASTRAN computer program

During the *specified* shaking-table test, the measured acceleration at the top of the interrupter for an excitation of 1.5 times El Centro 1940 (the required 0.5g earthquake) amounted to a magnification of about 2.5 times, or about 1.2g, for either longitudinal or lateral excitation (both horizontal). Judging by the circumferential stress measured at the base of the column due to bending, the porcelain was in no danger of surface "cracking." (The vertical hydraulic driver for the shaking table was inoperative, but of no consequence since the vertical response of the column was negligible.)

Innovative Sine-Beat, Quasi-Resonance Testing at EERC

Additional, innovative tests were performed to build up to the resonant-type circuit breaker failures originally caused by the 1971 San Fernando earthquake [4]. Figure 8 shows the horizontal shaking-table excitation to consist of a sine-beat of 5 cycles/beat with a 0.25g peak and at 2.6 Hz, the measured natural frequency of the single column. (This input happens to represent the peculiar feature originally noticed in the published accelerogram [3] recorded at the Capitola Fire Station and labeled

CHN 3 - 0 DEG - 0.54g). As previously mentioned with regard to Figure 4, the corresponding 1-column response motion is quite similar to the Capitola (computed) response of 1.98g at 2.6 Hz, except that the peak test response is only 1.3g. Also, because of rotational cross coupling, the 1-column response shows a delayed lateral response with a peak value of 0.5g. The similarity of the response motions at 2.6 Hz in both Figures 4 and 8 offers a highly probable cause for the circuit breaker destruction at Moss Landing during the Loma Prieta earthquake.

By comparison, the single peak g-level produced by the random type of excitation (1.5 times El Centro 1940) was only slightly smaller than in the sine-beat test. However, the low-cycle fatigue stress measured at the base of the porcelain column (as introduced by the quasi-resonance response to the sine-beat input) meant that catastrophic damage was imminent. For safety reasons, the quasi-resonance testing had to be concluded. Since engineers are always on the lookout for resonant-type structural failures, the time-history response plots become of more value than the usual peak g-levels in the response spectrum.

Figure 9 shows the response of a simple oscillator to sine-beat excitation in terms of a Q-factor (magnification number) for different values of the "cycles/beat" and for "percent of critical damping." In the earlier discussion of Figure 6 it should have been mentioned that three (3) vertically-acting oil dashpots were attached between "ground" and three (3) horizontal, radially-disposed (120° apart) steel cantilevers attached to the base of the porcelain column. During the sine-beat tests, they supplied about 5 percent damping, which explains the Q-factor of about 5 times (= 1.3g/0.25g) given by the 5 cycle/beat curve.

Also, in the earlier discussion of Figure 1, it could have been explained that the damping devices appeared *not* to have been installed, in which case the column damping of only about 1 percent would mean a possible Q-factor of at least 8 times for a sine-beat ground motion. The 500 kV circuit-breaker porcelain columns that originally failed in the 1971 San Fernando earthquake [11] had since then been much strengthened for short-circuit loading, but were still not adequate to withstand suspected quasi-resonance effects, which were found in the 1989 Loma Prieta earthquake.

In retrospect, the generally accepted specification of a 0.5g earthquake did not anticipate the "resonance" effects that caused the circuit breaker failures in both March 1971 and October 1989.

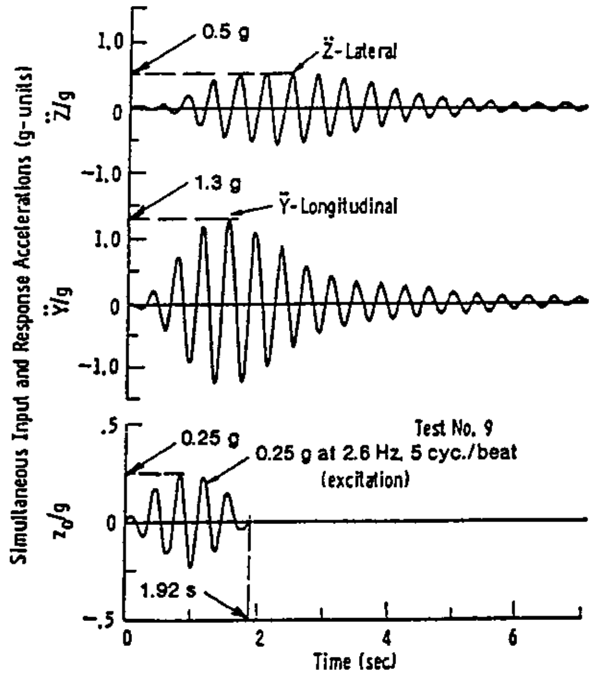

Figure 8 Longitudinal and lateral column response to sine-beat input in Y-direction

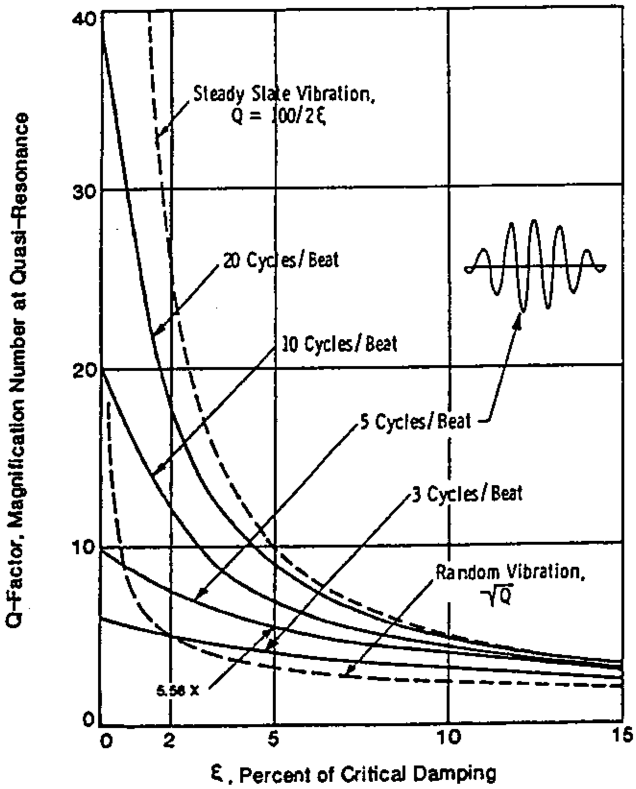

Figure 9 Theoretical vibration magnification in simple system by sine-beat input

However, the additional sine-beat testing in November 1973 for quasi-resonance served to anticipate a "worst-case" scenario.

The Need for Investigation of Local Seismic Damage Potential

The authors cannot directly relate the peculiarities found in the Capitola accelerogram to the ground conditions at the Moss Landing switchyard, some 15 miles away along the Monterey Bay shoreline. However, an earlier quote [2,12] is worth repeating, as follows: "The prime reason why a low value of ground acceleration caused such surprising damage to modern reinforced concrete structures is concluded to be the resonance phenomenon arising from the natural period of the structures coinciding with the predominant period of the soil." In addition, Rice [13] and Plunkett [14] have shown that random motion during transmission can respond as a "narrow-band, quasi-sinusoidal waveform with a slowly varying amplitude." This would amount to the low-frequency, amplitude fluctuations first noticed in the Capitola recording.

As engineers depending upon local newspaper accounts, the 1989 Loma Prieta quake was invariably discussed in terms of isolated damage in San Francisco, CA, with no explanation of how the epicenter and widespread damage were concentrated some 60 miles to the south. Understandably, emphasis was placed upon the ill-fated Oakland freeway (Interstate 880), designed some 40 years ago, without factoring in possible long-distant seismic effects in terms of local landfill considerations. However, there were also the failures of two new motels built on landfill near the main airport. It would seem that present-day analysis of building structures will not guarantee safety when the seismic specifications do not recognize possible "resonance."

In the December 1989 Minutes of the Congressional Hearing [15] in San Francisco, the pertinent discussion of the forementioned peculiarities appeared as an afterthought with the inclusion of [4,11] by Fischer. Subsequently, in some correspondence with Congressman Doug Walgren, D-PA, it was agreed that two important issues had been suggested during the Hearing, namely: the need for more micronization studies to indicate local damage potential, and the need for adequate insurance based on local seismic risk.

Conclusions

A resonant-type vibration buildup has caused the destruction of similar 500 Kv electrical circuit breakers during both the 1971 San Fernando quake at Sylmar, CA and the 1989 Loma Prieta quake at Moss Landing, CA. The *specified* 0.2g and 0.5g seismic design spectra, respectively, failed to anticipate the quasi-resonance response of the equipment with its damaging low-cycle fatigue effects. A novel examination of the time-history response of a Loma Prieta accelerogram obtained near the epicenter at the Capitola Fire Station, showed low-frequency, sine-beat ground motions that could excite resonance in the circuit breakers under reexamination. Also, it is well known that specified random type ground motion during transmission over large distances can develop into a "narrow-band, quasi-sinusoidal waveform with a slowly varying amplitude."

Hence, when such quasi-resonance type of structural response can be anticipated (based upon local seismic risk evaluations using vibration equipment) a conservative design approach should require structural natural frequencies above the seismic range of excitation or the introduction of adequate damping in the system. Regarding equipment design, shaking tables should be used with sine-beat excitation to both anticipate and protect against a "worst-case" scenario.

Acknowledgments

The authors wish to express their appreciation to Congressman Doug Walgren, D-PA, for including an adversary letter and published papers in the minutes of his "Loma Prieta" Hearing; to William P. Welch of Santa Cruz, CA, for his timely reporting of 1989-90 earthquake publications to Pittsburgh, PA; to K.K. Wong of NIS-EE (National Information Service - Earthquake Engineering) for Loma Prieta and CALTECH digitized program diskettes; and finally to Suzan C. Bissert-Fischer for her knowledgeable use of diskette information and digital computer programming and ultimately for the PC composing and typing of this paper.

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