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Base isolation response to extreme ground motions

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ABSTRACT: The elastomeric seismic base isolation system employed in the Los Angeles County Fire Command and Control Facility incorporates an "ultimate restraint" system, intended to limit building displacements under extreme levels of ground shaking. Isolator-superstructure response under postulated extreme ground motions, calculated by nonlinear time history analysis, are given. Results indicate that the response is displacement driven and, therefore, the ultimate restraint system does not significantly limit building motions. As expected, overall base shear is increased as the restraint system is engaged. Displacement overcapacity of the isolation system is recommended as the preferred means of providing safety margin above working values.

1 INTRODUCTION

The Los Angeles County Fire Department's Fire Command and Control Facility (FCCF) is an indispensable link in the County's earthquake lifelines. It receives, dispatches and directs county-wide fire and medical emergency relief services in response to 911 calls. This mission is of critical importance during and following major earthquakes in the Los Angeles area. Seismic base isolation was employed by Fluor Daniel in order to provide the highest level of seismic protection for the facility and to assure its continued function.

As an additional design precaution, the isolation system was fitted with a unique ultimate restraint system (URS), meant to limit building motions in the highly unlikely event the ground motions exceed the design displacement capacity of the isolators themselves. In effect, the ultimate restraint system, coupled in series with the reserve displacement capacity of the bearings, exhibits a strain hardening behavior similar to that exhibited by mild steel when deformed beyond its yield plateau. The restraint system was sized to resist a load equal to 125 percent of the design base shear which is transmitted through the isolation system. It should be noted that the decision to use an ultimate restraint system was not to satisfy any code seismic requirement, since at the time detailed engineering for the FCCF was carried out code provisions for seismic isolation had yet to be promulgated.

Analysis, design and construction details of the FCCF seismic isolation system, including the ultimate restraint feature, have been described by Anderson (1990). Dynamic response of this facility as calculated by nonlinear time history analysis for site-specific design ground motions was reported by Bachman, Gomez and Chang (1990). This paper extends those earlier works by reporting on the nonlinear response of the building subjected to ground motions large enough to fully engage the ultimate restraint system.

The primary margin of safety for the isolator system is embodied in the generous 100 percent displacement reserve above that required to satisfy the demand of the 500 year design earthquake. Accordingly, the ultimate restraint feature is highly unlikely to ever be loaded by a real earthquake. Further, the isolation design meets and generally exceeds all extant seismic code requirements that subsequently have been adopted for building base isolation systems (see for example Uniform Building Code (1991)).

The reporting of these special studies is in the general interest of furthering the understanding of design improvements and supporting wider adoption of seismic isolation technology into the mainstream of structural design practice.

2 GROUND INPUT MOTION

Seismic design criteria for the FCCF are described in detail by Bachman, Gomez and Chang (1991). The criteria includes a site-specific ground motion time history designated as SEGM-2, representing a 1000 year event with a peak ground acceleration of 0.50g. This motion has broad band frequency content and is rich in long period components (see Figure 1).

Preliminary analyses showed that the SEGM-2 record required a scaling factor of about two in order to initially engage the ultimate restraint. Additionally, in order to fully exercise the restraint system, an earthquake record was sought with a large velocity pulse and related near-fault characteristics. The James Road record (see Figure 2) from the 1979 Imperial Valley earthquake was selected for this purpose and used in the analyses. It has extremely large long period motion and spectral displacements at least twice as large as the SEGM-2 record.

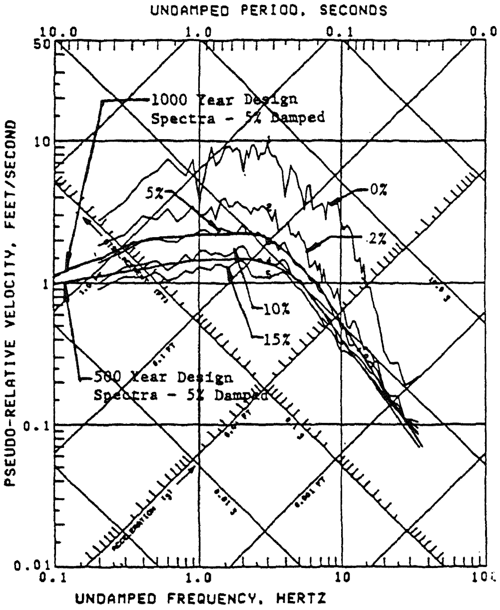

Figure 1. SEGM-2 Response Spectra.

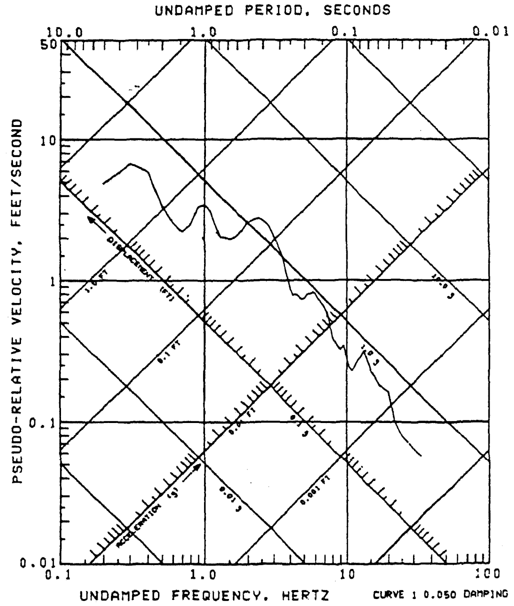

Figure 2. James Road Response Spectra.

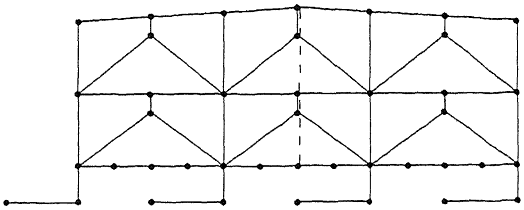

Figure 3. 2-D Transverse Frame Model

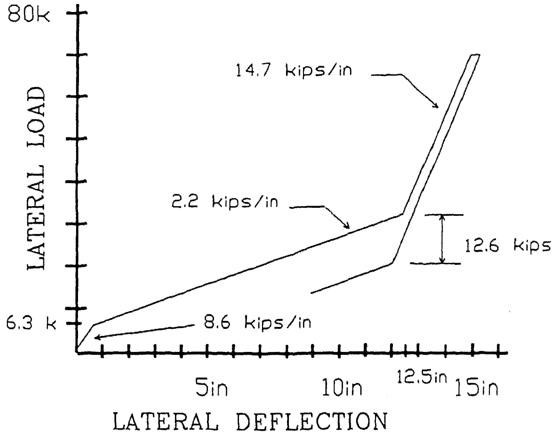

Figure 4. Idealized Base Isolator Force Deflection Properties.

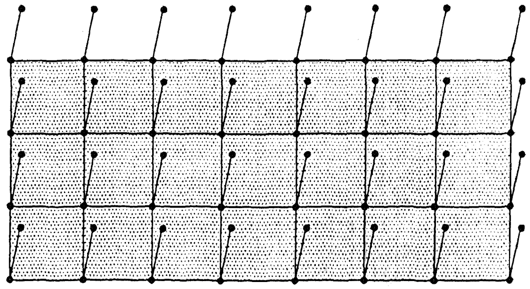

Figure 5. 2-D Base Frame Model.

3 DYNAMIC MODELS

Two primary planar models were developed for the nonlinear time history dynamic analyses. The first model (see Figure 3) was used for transverse frame analyses. It represented a tributary portion of the two-story steel braced frame superstructure using linear elastic elements and a tributary portion of the elastomeric isolator bearings with the ultimate restraint system using idealized tri-linear elements. The force-deflection curve for a single isolator bearing, fitted with the ultimate restraint, is shown in Figure 4.

A second model (see Figure 5) was used for performing torsional (about a vertical axis) analyses. It consisted of a horizontal, elastic planar grid supported on the 32 elastomeric isolator bearings. Only the perimeter isolator units are fitted with the internal ultimate restraint feature. The force-deflection curve shown in Figure 4 represents the behavior for all isolators, except the interior elements do not include the increased stiffness leg shown in this figure for displacements over 12.5 inches; they continue to deflect at the 2.2 kips/in rate for all large displacements. The hysteresis loop represents an equivalent fifteen percent viscous damping for the model at a displacement of about ten inches.

For both of the analysis models, the stiffness behavior of the ultimate restraint component of the models was varied in several ways to assess response sensitivity. The standard system was assumed to respond as previously described (and as generally represented by Figure 4) up to a lateral displacement of 15 inches after which the load-displacement curve was assumed to be perfectly plastic (zero stiffness). This condition is identified in the subsequent tables and figure as non-linear w/URS. A first variation on this standard system was to consider the absence of the ultimate restraint component and assume the isolation system had a simple bilinear load-displacement curve, denoted as non-linear wo/URS in subsequent tables.

A second variation (denoted as mod 1) was to assume the ultimate restraint system exhibited unchanged stiffness as it displaced beyond 15 inches, rather than go from elastic to perfectly plastic at this point. For the third variation, the ultimate restraint system stiffness was increased by a factor of about three, and denoted as mod 2 in the tables and figures.

4 DYNAMIC ANALYSES

The computer code DRAIN-2D (Kanaan (1974)) was used to conduct all of the nonlinear time history analyses. The program was modified to include an equivalent "chain element" to represent the ultimate restraint system. Transverse and torsional analysis models were subjected to a variety of SEGM-2 time histories, scaled from 0.05 to 4 times the normal record, as well as the unscaled James Road record. Scaling of the SEGM-2 record was undertaken in order to study response variations as the intensity of input motion was increased to gradually, then fully engage the ultimate restraint system.

5 ANALYSIS RESULTS

5.1 *Displacements*

Peak response relative displacements using the transverse model are summarized in Table 1. Note, the ultimate restraint system begins to engage at a lateral displacement of 12.5 in.

An examination of displacements in Table 1 indicates that response is clearly displacement driven. That is, the ultimate restraint system does not provide a significant reduction in maximum displacement. The URS is engaged at an input level of about two and one-half times the SEGM-2 input motion. Hence, differences in response arising from the URS would be seen in comparing responses for 4.0 * SEGM-2 and the James Road inputs. For the 4.0 * SEGM-2 input the URS essentially has no influence on displacement. In fact, the response is seen to increase slightly with the URS, e.g., first floor displacement increases from 29.63 in., without the URS, to 31.57 in., with the URS. The nonlinear increase in response due to a doubling in input motion (2.0 to 4.0 * SEGM-2) is a result of engaging the URS (leads to reduced displacement) and a reduction in equivalent viscous damping (leads to increased displacement) as displacements are increased. It appears that for this particular input, the latter effect outweighs the former.

Table 1
Calculated Horizontal Peak Relative
Displacement at Center of Floor

Analysis Model	Input Motion	Displacement (in) 1st Floor	2nd Floor	Roof
Non-Linear wo/URS	0.10 * SEGM-2	0.83	0.88	0.90
	0.15 * SEGM-2	0.95	0.99	1.00
	0.25 * SEGM-2	1.23	1.27	1.30
	1.0 * SEGM-2	4.08	4.15	4.21
	2.0 * SEGM-2	10.89	11.06	11.15
	4.0 * SEGM-2	29.63	30.07	30.29
	JAMES ROAD	20.33	20.63	20.66
Non-Linear w/URS	0.10 * SEGM-2	0.83	0.88	0.89
	1.0 * SEGM-2	4.08	4.15	4.21
	2.0 * SEGM-2	10.89	11.06	11.15
	4.0 * SEGM-2	31.57	32.07	32.34
	JAMES ROAD	17.62	17.99	18.03
	JAMES ROAD (mod 1)	17.25	17.76	17.80
	JAMES ROAD (mod 2)	17.41	18.28	18.34

Table 2
Equivalent Period, Viscous Damping and Corresponding
Spectral Displacement at Maximum 1st Floor Displacement

Analysis Model	Input Motion	T (sec)	ζ (% critical)	$S_d(T,\zeta)$ (in.)
Non-Linear wo/URS	0.10*SEGM-2	1.31	5.4	0.50
	0.15*SEGM-2	1.37	10.1	0.52
	0.25*SEGM-2	1.50	16.4	0.71
	1.0 *SEGM-2	2.01	17.9	3.8
	2.0 *SEGM-2	2.27	9.7	11.6
	4.0 *SEGM-2	2.39	4.2	36.3
	JAMES ROAD	2.35	5.8	22.3
Non-Linear w/URS	0.10*SEGM-2	1.31	5.4	0.50
	1.0 *SEGM-2	2.01	17.9	3.8
	2.0 *SEGM-2	2.27	9.7	11.6
	4.0 *SEGM-2	2.40	3.9	38.2
	JAMES ROAD	2.34	6.6	18.7
	JAMES ROAD (mod 1)	2.33	6.7	18.7
	JAMES ROAD (mod 2)	2.34	6.7	18.7

For the James Road input, the displacement response is seen to reduce with the URS in place, but the level of reduction, 15 percent, is quite small. The URS does not appear to significantly limit displacements for the two input motions considered.

Furthermore, modifications to the URS stiffness (designated as mod 1 and mod 2 in Table 1) has essentially no influence on total system response. This result further supports the observation that the response is strongly displacement driven.

The foregoing observations on nonlinear response are also supported by the response factors shown in Table 2. Equivalent period and corresponding equivalent viscous damping as calculated at the point of maximum relative first floor displacement are given for each input time history shown in Table 1. In addition, Table 2 shows the spectral displacement S_d corresponding to the calculated equivalent period and damping values. It can be seen that because of the nonlinearity of stiffness (or period) and damping, the corresponding spectral relative displacement does not increase in a linear fashion with a corresponding increase in input ground motion, or acceleration. Also, the resulting spectral displacements in Table 2 compare reasonably well with the first floor displacements from which one would conclude that a single degree of freedom approximation is reasonable.

Table 3
Calculated Peak Horizontal Response Accelerations
Non Linear Response wo/URS

Location	Acceleration (g) SEGM-2 Time History				Accel. (g) James Road Time History
Scaling Factor	0.10	1.0	2.0	4.0	1.0
Roof End Frame	0.054	0.22	0.42	0.87	0.39
2nd Floor End Frame	0.051	0.13	0.25	0.66	0.37
1st Floor End Frame	0.048	0.15	0.28	0.58	0.37
Peak Ground Accel.	0.05	0.50	1.0	2.0	0.37

Table 4
Calculated Peak Horizontal Response Accelerations
Non Linear Response w/URS

Location	Acceleration (g) SEGM-2 Time History				Accel (g) James Road Time History		
Scaling Factor	0.10	1.0	2.0	4.0	1.0	mod 1	mod 2
Roof End Frame	0.05	0.22	0.42	1.22	0.60	0.56	1.13
2nd Floor End Frame	0.05	0.13	0.25	0.87	0.52	0.58	0.94
1st Floor End Frame	0.05	0.15	0.28	1.06	0.54	0.56	1.09

5.2 *Accelerations*

Use of the URS involves the trade off between displacement and acceleration as always exists in the field of structural dynamics. Any displacement-reduction benefit will result in increased response accelerations. Calculated response accelerations are summarized in Tables 3 and 4.

The effect of the URS on the acceleration response is best illustrated by comparing Tables 3 and 4 for the 4.0 * SEGM-2 records. Addition of the URS is seen to result in an 80 percent increase in response acceleration as measured at the first floor end frame for the 4.0 * SEGM-2 input, viz., 0.58g to 1.06g. The increase is smaller for the James Road ground motion, increasing somewhat less than 50 percent, except for mod 2 in which the URS stiffness is increased. For mod 2, the result is a factor of three increase in acceleration. Clearly, this is a large potential penalty to pay for an insignificant reduction in response displacement. It could be concluded from this result that additional safety margin might better be achieved with additional isolator displacement capacity reserve (and corresponding additional rattle space surrounding the building) rather than considering displacement control in this fashion.

It can also be noted from Table 3 that significant nonlinearity occurs between 0.1 and 1.0*SEGM-2 input motion. Reduction of ground motion experienced by the building, i.e., isolation, begins at input motion just above 0.1*SEGM-2.

5.3 *Torsional response*

An evaluation of torsional response, using the planar grid model for generally the same pattern of ground motion inputs, revealed similar response behavior noted above. That is, response is displacement driven and is little influenced by the URS.

It was also observed during the course of the investigation that a conservative preliminary estimate (within 20 percent) of the maximum displacement of the isolated building system, with or without an URS, could be simply taken as the spectral displacement of a single DOF system at an equivalent viscous damping ratio corresponding to the nominal design displacement. This evaluation would allow one to size the rattle space gap at an early stage in design development for later confirmation by nonlinear time history studies.

6 CONCLUSIONS

The results of the analyses performed indicate that the FCCF will not only meet its original design criteria, but also will safely respond to input motions approaching four times the site-specific ground motions.

Ultimate restraint systems may be quite effective in resisting uplift arising from overturning in more slender structures. However, incorporation of an ultimate restraint system to control building displacements as ground motion input levels increase appears to have limited usefulness. Providing additional isolator displacement capacity and free rattle space seems to be the more realistic approach to achieving increased safety margin. It is believed that this latter conclusion has important implications for the design of all seismic isolation systems.

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