RESUMEN

Un total de 18 diferentes componentes de movimientos sísmicos registrados en América Central fueron seleccionados para hacer una evaluación de su potencial de daño. Se puso énfasis en los sísmos registrados en la reciente actividad sísmica de Costa Rica. Con el propósito de comparación fueron incluidos en el estudio cinco registros obtenidos en diferentes partes del mundo. Como medio para identificar el potencial de daño de los registros, la energía de entrada así como el espectro de energía plástica histerética fueron calculados para diferentes niveles de ductibilidad de los desplazamientos y un coeficiente de amortiguamiento viscoso \( \approx 0.05 \). El efecto de la duración del movimiento sísmico fue estudiado introduciendo el parámetro no-dimensional y y el blanco de ductibilidad \( \mu \) TAR. El parámetro y es una función del máximo desplazamiento y de la demanda de disipación de energía plástica histerética. Los cálculos fueron realizados para sistemas de un grado de libertad con comportamiento elastoplastico histerético. Otras magnitudes de respuesta fueron consideradas fueron la demanda de ductibilidad basada en resistencia constante y la demanda de resistencia basada en la ductibilidad constante. Los resultados son contrastados con las normas de diseño sísmico vigentes en la región tal y como se presentan en los códigos de construcción más recientes.

LIMITED EDITION

INTRODUCTION

For many years, researchers have sought simple ways to characterize the damage potential of earthquake ground motions (EQGMs). Although they have recognized that many of the characteristics of an EQGM (such as intensity, frequency content and duration) are important for estimating its damage potential, the majority of these characteristics have usually been ignored for the sake of simplicity. In this paper, consideration of these factors is attempted. However, it is necessary to point out that damage potential is not an absolute property of an EQGM, and thus, the need arises to establish a frame of reference. Attempts made to establish a frame of reference by neglecting the dynamic characteristics of the structures subjected to the EQGM have lead to unreliable and inconsistent methods for the estimation of damage potential. In this paper, damage potential of an EQGM is measured according to its capacity to produce the failure of ductile reinforced concrete (RC) structures. To allow this, a reference frame is established using fundamental concepts of earthquake-resistant design. RC structures are modelled using single-degree-of-freedom systems (SDOFs) with elastoplastic hysteresis behavior in which damage is estimated according to a damage index for RC members.

SUMMARY

A total of 18 different components of earthquake ground motion recorded in Central America were selected to conduct an evaluation of their damage potential. Emphasis was placed in ground motions recorded during recent seismic activity in Costa Rica. For the purpose of comparison, five records obtained in different parts of the world were included in the study. As a mean of identifying the damage potential of the records, the input energy as well as the plastic hysteretic energy spectra were calculated for different levels of displacement ductility and a viscous damping coefficient \( \approx 0.05 \). The effect of duration of ground motion was studied by introducing the non-dimensional parameter \( y \) and the target ductility \( \mu \) TAR. The parameter \( y \) is a function of the maximum displacement and the plastic hysteretic energy dissipation demands. The calculations were performed for single-degree-of-freedom systems with an elastoplastic hysteretic behavior. Other response quantities considered were the constant strength ductility demands and constant ductility strength demands. The results are contrasted with the current seismic design recommendations for the region as presented in the latest building codes available.
previous statements can be formalized through the following equation, which identifies relevant aspects of the demand-supply approach:

\[
\text{DEMAND} - \text{SUPPLY} \tag{1}
\]

- Stiffness
- Strength
- Stability
- Energy absorption and energy dissipation capacities

All aspects of eq. (1) usually need to be satisfied to achieve adequate EQ-RD [note that the displacement and deformability aspects of eq. (1) complement and are complemented by its stiffness and strength aspects, respectively]. Traditionally, the energy aspect of eq. (1) has been ignored in EQ-RD; nevertheless, the possibility of using an energy demand-supply equation to improve EQ-RD has been suggested (Uang and Bertero 1988).

**Absolute Energy Equation.** Before establishing the relevance of energy demands in EQ-RD, it is necessary to obtain an energy equation capable of establishing the demand-supply balance of energy in an earthquake-resistant structure. For this purpose, consider the equation of motion of a viscously damped SDOFS subjected to horizontal EQGM:

\[
m\ddot{v} + c\dot{v} + f_s = 0 \tag{2}
\]

where \( m \) is the mass of the SDOFS, \( c \) its damping coefficient, \( f_s \) its restoring force, \( \dot{v} \) the displacement of the mass relative to the ground, \( v_g \) the ground displacement, and \( \dot{v}_t = \dot{v} + v_g \) is the absolute displacement of the mass. By integrating eq. (2) with respect to \( v(t) \) from \( t=0 \), the following is obtained:

\[
\frac{1}{2}m\dot{v}^2 + \int c\dot{v}dv + \int f_sdv = Jmv, \tag{3}
\]

Equation (3) can be expressed as:

\[
E_k + E_m + E_a = E_i \tag{4}
\]

where \( E_k \) is the absolute kinetic energy, \( E_H \) is the viscous damping energy, \( E_a \) the absorbed energy, and \( E_i \) the absolute input energy. Note that \( E_a \) can be expressed as the sum of the plastic hysteretic energy (\( E_{H\mu} \)) dissipated by the SDOFS plus the recoverable elastic strain energy (EEs) stored in the same system. Thus, eq. (4) can be rewritten as:

\[
E_k + E_{EEs} + E_m + E_{H\mu} = E_i \tag{5}
\]

A physically meaningful interpretation of \( E_i \) can be found by considering that \( E_i \) represents the work done by the total base shear at the foundation along the foundation's displacement (Uang and Bertero 1988). Uang and Bertero (1988) note that the energy equation can be expressed using an alternative formulation (relative energy equation); nevertheless they note that for the period range of practical interest (\( T = 0.3 \) to 5 sec) the maximum value of \( E_i \) obtained using both formulations are very similar.

Equation (5) can be expressed as a demand-supply equation of energy by considering that \( E_i \) represents the energy demanded from the SDOFS while the sum of \( E_k \), \( E_{EEs} \), \( E_m \), and \( E_{H\mu} \) represents the energy supplied to that SDOFS. Note that the sum of \( E_k \) and \( E_{EEs} \) is the energy stored in the SDOFS while the sum of \( E_m \) and \( E_{H\mu} \) is the energy dissipated by the SDOFS. For rational EQ-RD, it is necessary to provide the structure with adequate supplies of \( E_{H\mu} \) and \( E_{EEs} \). Although \( E_i \) has become relevant in EQ-RD in recent years (given that some real structures are being provided with special energy dissipating devices such as viscoelastic dampers), this paper concentrates on the dissipation of \( E_{H\mu} \). Note that \( E_{H\mu} \) dissipation and damage are closely related in RC members and structures, i.e., \( E_{H\mu} \) dissipation implies nonlinear behavior which in turn implies damage in them.
sound and rational EQ-RD procedure should provide means to estimate the strength and deformability capacity to be supplied to a structure so that it will not undergo excessive deterioration of its mechanical properties (or even failure) due to low-cycle fatigue. Some researchers have tried to relate low-cycle fatigue damage in RC members to the $E_H/\mu$ demand imposed to those members. For this purpose, analytical relationships (damage indexes) that either implicitly or explicitly relate $E_H/\mu$ to damage have been developed. A summary of several damage indexes can be found elsewhere (Chung et al. 1987).

Because of its simplicity, the Park and Ang damage index (Park et al. 1985), $D_MIPA$ to estimate damage in RC beams and columns is used in this paper. In some cases, evaluating $D_MIPA$ for SDOFs can provide valuable information to assess damage in RC buildings. Such is the case when the contribution of upper modes is not relevant to the response of the building and damage is distributed uniformly among all the building’s ductile members (i.e., beams for ductile RC frames). $D_MIPA$ is defined as:

$$D_MIPA = \frac{\mu \delta_y}{\mu_u \delta_u} - \frac{\beta E_H/\mu}{F_y/\mu_y \delta_y}$$

In eq.(6), $\delta$ is the maximum displacement demand; $\delta_u$ is the maximum displacement the member can undergo when subjected to monotonically increasing deformation; $F_y$ is the yield strength; and $\beta$ is a parameter determined experimentally and ranging from -0.3 to 1.2. From experimental calibration, a value of $D_MIPA$ less than or equal to 0.4 can be interpreted as repairable damage, from 0.4 to less than 1.0 as damage beyond repair, and larger than or equal to 1.0 as failure.

Defining the displacement ductility ratio, $\mu$, and the ultimate displacement ductility ratio under monotonically increasing deformation, $\mu_u$, as normalized by the yield displacement, $0_y$, respectively (i.e., $\mu = 0/0_y$ and $\mu_u = \alpha 0/0_y$), and the normalized plastic hysteretic energy, $E_{H/\mu}$, as $E_H/\mu$ normalized by $F_y/\mu_y$ (i.e., $E_{H/\mu} = E_H/\mu_y$), eq.(6) can be rewritten as follows:

$$D_MIPA = \frac{\mu \delta_y}{\mu_u \delta_u} - \frac{\beta E_H/\mu}{F_y/\mu_y \delta_y}$$

and $D_MIPA = 1 \Rightarrow \mu_{u} = \mu + \beta E_{H/\mu}$

Note that $\mu$ and $E_{H/\mu}$ are normalized measures of the $0$ and $E_{H/\mu}$ demands on the SDOFS, respectively. Equation 7b is depicted graphically in Fig.1 (denoted as $D_MIPA = 1$) within a $\mu$ vs. $E_{H/\mu}$ Cartesian axis system. As shown, the $D_MIPA = 1$ line delimits the no failure and failure zones. Note that $\mu < 1$ (linear behavior) implies that $E_{H/\mu} = 0$ (i.e., the response of a SDOFS cannot fall in the shaded area 1 of Fig.1). Given that for monotonically increasing deformation $E_{H/\mu} = \mu - 1$, the value of $E_{H/\mu}$ cannot be smaller than $\mu - 1$ (i.e., the response of a SDOFS cannot fall in the shaded area 2 of Fig.1).

Sorne characteristics of $D_MIPA$ are worth noting. First, a value of $\beta$ less than 0 does not have any physical meaning and is difficult to interpret. Second, the expression estimates damage as a linear combination of $0$ and $E_{H/\mu}$ (or $\mu$ and $E_{H/\mu}$). When $0$ and $E_{H/\mu}$ are highly correlated (as in the case when the structure is loaded monotonically), the estimate of damage obtained using $D_MIPA$ is difficult to
interpret. To illustrate this, note that a SDOFS subjected to monotonically increasing deformation will move along line \( NE_{\mu} = \mu - 1 \) (see Fig.1). Using DMIpA as a failure criteria in this case, the ultimate ductility that the SDOFS can develop is \( \mu_{pA} \) which as shown in Fig.1, is less than \( \mu_u \). Nevertheless, undermonotonic loading the SDOFS would not fail until \( \mu \) reaches a value equal to \( \mu_u \). It can be concluded that DMIpA overestimates damage in SDOFS whose response falls close to line \( NE_{\mu} = \mu - 1 \). In spite of the above, DMIpA can be used in several cases to characterize damage on RC members and structures. One important advantage of using DMIpA is that there is no need to know the way in which \( E_{H\mu} \) has been dissipated to estimate damage (although in some cases, this can lead to incorrect estimation of damage).

The use of damage indexes and energy demands in EQ-RD. The \( E_{\mu} \) dissipating capacity of a RC member or structure is not constant, as can be concluded by following the failure line DMIpA = 1 in Fig.1. As shown, the larger the \( \mu \) demand in the structure the smaller the \( E_{\mu} \) that it can dissipate up to failure (i.e. as \( \mu \) increases \( NE_{\mu} \) decreases and vice-versa). The above fact has important implications in EQ-RD given that if a RC structure has to dissipate a significant amount of \( E_{\mu} \) through several cycles of inelastic deformation, the maximum \( \mu \) demand that this structure can develop should be considerably smaller than its \( \mu_u \). The following question arises: What is the maximum \( \mu \) demand that can be allowed in a RC structure that will have to dissipate a significant amount of \( E_{\mu} \) during an EQGM? For a rational EQ-RD it is necessary to introduce the concept of target ductility (\( \mu_{TAR} \)) which is the maximum value of \( \mu \) that a RC structure can develop given that its \( E_{\mu} \) dissipating capacity meets its corresponding demand. Fajfar et al. (1992) have introduced a factor to allow for a simple method to evaluate \( \mu_{TAR} \):

\[
y = \sqrt{\frac{E_{H\mu}}{m \omega \delta}} = \sqrt{\frac{E_{\mu}}{8 \mu^2}} \frac{\frac{E_{1w}}{F}}{\mu} \quad (8)
\]

It has been observed that the \( y \) factor tends to increase for EQGMs with longer duration, but it is a very stable quantity for a given EQGM, i.e., it is fairly independent of the value of \( \mu \) (or strength) that the SDOFS develops and its viscous damping coefficient, \( S_\delta \) (Fajfar et al. 1992). From eq. (8) it can be concluded that \( NE_{\mu} = \gamma y \). This parabola is depicted in Fig.1, where a graphical interpretation of \( \mu_{TAR} \) given. It should be noted that \( \gamma \) is fairly insensitive to the value of \( \mu \) only for moderate and high values of \( \mu \) (i.e., \( \mu \lesssim 2 \)), given that if the \( \mu \) demand in a SDOFS tends to 1, the value of \( \gamma \) tends to 0. In Fig.1, this is schematically shown by plotting in continuous line the \( NE_{\mu} = \gamma y \) curve in the region of \( \mu \) where \( \gamma \) is stable with respect to \( \mu \), and in discontinuous line where it is not.

RESPONSE SPECTRA OF SDOFS SUBJECTED TO SELECTED EQGMs

Selected Earthquake Ground Motions. In recent years, three relevant seismic events have occurred in Costa Rica: 1990 Cóbano EQ, 1990 Alajuela EQ and 1991 Limón EQ. The authors evaluated the damage potential of several EQGMs recorded during these three events, selected the EQGM with the highest damage potential for each event, and compared their damage potential against that of other well-known recorded EQGMs. Table 1 summarizes the EQGMs selected to carry out this comparison plus relevant information about them.

Constant Ductility. Figure 2 shows the response spectra of EPP SDOFS in which \( \mu = 1 \) and \( \delta = 0.05 \). The following demands were considered:

- Strength, \( (S_{a/g} \text{ or } c_\mu) \). With the exception of C1 and short period (T), the elastic \( S_{a/g} \) demand of the Costa Rica EQGMs is considerably smaller than that of the world’s EQGMs (Fig.2a). CH and Nr have very high elastic \( S_{a/g} \) demand for short T; while that of Mx is the largest for longer periods (although Mx has very small demands for short T). The elastic \( S_{a/g} \) demands of Nr are also significant for long T. As shown Jp and
| EQGM       | Felt ground acceleration | Effective duration "**sec**" | Damage Potential | Soil Condition | [**P**]**(sec)** | Magnitude | Epicentral distance (km) |
|------------|--------------------------|------------------------------|------------------|---------------|----------------|------------|--------------------------|
| Secretaria de Comunicaciones y Transporte E-W/MX | 0.11g                      | 0.04g                        | 122.8            | Sunday        | 39             | 8.5        | 150                      |
| Miyagi-Kinchi N-S (Jp) | 0.24g                      | 0.118                        | 12.9             | Seismic event | 14             | 1.6        | 100                      |
| Leduc NIOE (CH) | 0.61g                      | 0.51g                        | 22.1             | sandstone & volcanic rock | 36             | 1.8        | 5                        |
| Sylmar N-S (C2) | 0.91g                      | 0.87g                        | 36.8             | alluvium      | 5              | 6.7        | 15                      |
| Emeryville 260 (LP) | 0.26g                      | NA                           | 9                | bay mud       | 9              | 6.9        | 97                      |
| Alajuela E-W (CI) | 0.45g                      | NA                           | 4.4              | firm soil, volcanic deposits | 10             | 6.1        | 20                      |
| Cartago N-S (C2) | 0.26g                      | 0.35g                        | 3                | soft recent | 28             | 7.4        | 93                      |
| Puntarenas B-W (C3) | 0.268                      | 0.21g                        | 3.9              | soft, coastal | 17             | 6.8        | 49                      |

(1) according to ATC 3-06 (1978)
(2) according to Araya and Saragoni (1984), units: cm x sec
(3) strong motion duration according to Trifunac and Brady (1975)

LP have significant elastic Sa/g demand for T around 1 and 1.5 sec, respectively. Similar tendencies as those discussed above can be observed for µ = 4 in Fig.2c; nevertheless, it is interesting to note that for longer T (T ~ 1.8 sec), Mx and Nr have similar S/g demands.

Absolute input energy, El As shown in Fig.2b, the elastic El demands of the Costa Rica EQGMs are considerably smaller than those of the world's EQGMs. In spite of large S/lg demands, the elastic El demands for Nr are considerably smaller than those of CH in the short T range and are considerably smaller than those of Mx for longer T. Of all EQGMs, Mx has the largest value of maximum elastic El. The elastic El demands of LP and LP are important for T ~ 1 and 1.5 sec, respectively. Similar tendencies can be seen for µ ~ 4 in Fig.2d, although as shown,
the maximum value of $E_t$ for CH and Mx are similar.

- Plastic hysteretic energy, $E_{h\mu}$. As shown in Fig. 2e, the $E_{h\mu}$ demands for $\mu = 4$ of the Costa Rica EQGMs are considerably smaller than those of the world's EQGMs. Similar tendencies than those described for $E_l$ and $\mu = 4$ (Fig. 2d) can be observed in Fig. 2e for $E_{h\mu}$ and $\mu = 4$; nevertheless, it can be observed that the maximum demand of $E_{h\mu}$ for Mx becomes about twice that of CH.

The study of the above demands suggests that the damage potential of the recorded Costa Rica EQGMs is considerably lower than that of the world's EQGMs. Within the world's EQGMs, three seem to have very large damage potential (although with very different characteristics): Mx has large $S_{tg}$ and energy demands for large $T$; Nr
has very large Sijg demands over the whole T range under study (especially for short T) but has small energy demands; CH has large Sijg and significant energy demands for short T.

**Constant Strength.** Figure 3 shows the response spectra of EPP SDOFS with \( c_y = 0.1 \) and \( c_y = 0.2 \) and \( \gamma = 0.05 \). The following response quantities were considered:

- Ductility, \( \mu \). As shown in Figs. 3a and 3b, Nr has in general the largest \( \mu \) demands, except for longer T, in which Mx has comparable and in some cases larger \( \mu \) demands. In general the Costa Rica EQGMs have smaller \( \mu \) demands throughout the whole T range under study.

- Input energy, \( E_h \) and plastic hysteretic energy, \( E_{pl} \). As shown in Figs. 3c, 3d, 3e and 3f,
the maximum $E_l$ and $E_H$ demands of the Costa Rica EQGMs are considerably lower than that of the world's EQGMs. As shown in both figures, $M_x$ demands very large $E_l$ and $E_H$ for SDOFS with large $T$; while $CH$ does something similar for SDOFS with short $T$. $Nr$ demands fairly large $E_l$ and $E_H$ for $T$ ranging from 0 to 3 sec.

Similar conclusions than those discussed in the previous section can be made regarding the damage potential of the EQGMs recorded in Costa Rica.

**DAMAGE POTENTIAL OF SELECTED EARTHQUAKE GROUND MOTIONS**

In this section, the damage potential of the selected EQGMs is measured according to their capacity to cause failure in ductile RC structures. For this purpose, $DM_{I_pA}=1$ for EPP SDOFS is established as a frame of reference. To estimate $DM_{I_pA}$, $P$ is assumed equal to 0.15 given that it has been shown that the use of $DM_{I_pA}$ with this value of $P$ yields similar results to those obtained using other well known damage criteria (Cosenza et al. 1990); and $\mu$ is assumed equal to 6, given that this value has been considered to represent the deformability capacity of special moment-resisting RC frames (ductile frames) designed according to current U.S. code specifications such as UBC and ACI-318.

**Constant ductility.** FigA summarizes the response of EPP SDOFS to the selected EQGMs in $\mu$ vs $NE_H$ Cartesian axes (in which the $DM_{I_pA}=1$ line is shown in discontinuous line) corresponding to different $T$. This figure summarizes the response of SDOFS with $=0.05$ and developing a $\mu$ of 2, 3, and 4. Note that the strength demand varies from EQGM to EQGM for a given value of $\mu$. The following can be observed:

- Alajuela E-W, C1. $NE_{I_p}$ demands are relevant for short $T$ (0.35 and 0.5 sec) in which the response of SDOFS with $\mu=4$ falls in the failure zone. $NE_{I_p}$ becomes relevant again for a $T$ of 2 sec.
- Cartago N-S, C2. $NE_{I_p}$ demands are relevant for intermediate and long $T$ (0.75, 1 and 2 sec). For these $T$ (specially for a $T=2$ sec), the response of SDOFS with $\mu=4$ falls in the failure zone.
- Puntarenas E-W, C3. $NE_{I_p}$ demands are only relevant for large $T$ (2 and 3 sec) in which the response of SDOFS with $\mu=4$ falls in the failure zone.
- Sylmar N-S, Nr. For all $T$, the response of SDOFS to $Nr$ falls in the no failure zone. $NE_{I_p}$ demands are small for short $T$ (0.35, 0.5 and 0.75 sec) and tend to increase for larger $T$ (1.5 and 2 sec). SDOFS would survive this EQGM (according to $DM_{I_pA}$) if they develop a $\mu=4$.
- SCT E-W, Mx. With the exception of short $T$, $M_x$ demands very large $NE_{I_p}$ (1, 1.5, 2 and 3 sec). This is especially true for $T=2$ sec where it can be seen that the response of SDOFS that develops a $\mu=3$ falls in the failure zone due to high $NE_{I_p}$ demands.
- Llolleo, CH. $NE_{I_p}$ demands are not significant for long $T$ but are relevant for SDOFS with short and intermediate $T$ (0.5, 0.75, 1 and 1.5 sec) in which the response of SDOFS with $\mu=4$ falls in the failure zone.
- Miyagi-ken-Oki, Jp. $NE_{I_p}$ demands are significant for a wide range of $T$ (0.5, 0.75, 1 and 2 sec) in which the response of SDOFS with $\mu=4$ falls in the failure zone.
- Emeryville, LP. $NE_{I_p}$ demands are relevant for intermediate and large $T$ (0.75, 1, 1.5, 2 and 3 sec) in which the response of SDOFS with $\mu=4$ falls in the failure zone. Note that for $T=1.5$ sec, the response of a SDOFS that develops a $\mu=3$ falls on top of $DM_{I_pA}=1$.

From the above results it can be concluded that for practically all the EQGMs under study (with the exception of $Nr$), $NE_{I_p}$ demands become relevant for the failure of SDOFS that develop a $\mu=4$ (although the $T$ region in which this happens varies from EQGM to EQGM). From this point of view, $Nr$ shows small damage potential while $M_x$ and LP (in which even the response of SDOFS developing a $\mu=3$ falls in the failure zone) have large damage potential. Different Costa Rica EQGMs show large damage potential in different $T$ range; nevertheless, it is interesting to note that all 3 have significant $NE_{I_p}$ demands for $T$ of 2 sec.
Fig. 4 Constant ductility response of EPP SDOFS subjected to selected EQGMs.
Constant strength. In the previous section, the response of SDOFS with very different strengths was compared. In this section, the response of SDOFS with the same strength and $\sim = 0.05$ is compared. The results are presented in Fig.5 and are discussed period by period rather than EQGM by EQGM to facilitate their analysis:

- **T = 0.35 sec** The $\mu$ and/or $\text{NE}_{\mu}$ demands for a SDOFS with cy of 0.30 are so large for CH and Nr that its response to these EQGMs does not fit in the graph. For cy of 0.30, Jp and C3 demand a $\mu$ around 4 with small $\text{NE}_{\mu}$, while C1 has relevant $\mu$ and $\text{NE}_{\mu}$ demands, and LP, Mx and C2 have small demands. For a SDOFS with cy of 0.60, Jp and C3 fall well within the failure zone (although $\text{NE}_{\mu}$ is relevant for Jp, it is not for C3), LP and C2 have significant $\mu$ demands (around 5) but low $\text{NE}_{\mu}$ demands, C1 stays in the no failure zone (although with significant $\text{NE}_{\mu}$ demand) and the response to Mx is very small. For a SDOFS with cy of 0.40, the response for practically all the EQGMs fall well within the no failure zone with the exception of CH and Nr: CH falls in the $\text{DMI}_{\mu} = 1$ line while Nr falls well within the failure zone (note that both exhibit large $\mu$ demand and small $\text{NE}_{\mu}$ demand) and that as shown in Fig.1, $\text{DMI}_{\mu}$ overestimates damage in this zone, i.e., the response falls close to the line $\text{NE}_{\mu} = \mu - 1$.

- **T = 0.5 sec** The $\mu$ and/or $\text{NE}_{\mu}$ demands for a SDOFS with cy of 0.20 are so large for CH and Nr that its response to these EQGMs does not fit in the graph. For cy of 0.20, Jp and C3 fall well within the failure zone (although NE$_{\mu}$ is relevant for Jp, it is not for C3), LP and C2 have significant $\mu$ demands (around 5) but low $\text{NE}_{\mu}$ demands, C1 stays in the no failure zone (although with significant $\text{NE}_{\mu}$ demand) and the response to Mx is very small. For a SDOFS with cy of 0.40, the response for practically all the EQGMs fall well within the no failure zone with the exception of CH and Nr: CH falls well within the failure zone with considerable $\text{NE}_{\mu}$ demand while Nr has a small $\text{NE}_{\mu}$ demand and $\mu$ around 5.

- **T = 0.75 sec** The response of a SDOFS with cy of 0.20 to CH and Nr falls well within the failure zone ($\text{NE}_{\mu}$ is more relevant for CH than Nr), that of Jp falls in the failure zone but is close to $\text{DMI}_{\mu} = 1$ and shows a large $\text{NE}_{\mu}$ demand, that of C3 has a $\mu$ demand around 4.5 and small $\text{NE}_{\mu}$ demand, while that of the other EQGMs falls well within the no failure zone.

The response of SDOFS with cy of 0.04 fall well within the no failure zone for all EQGMs.

- **T = 1 sec** The response of a SDOFS with cy of 0.10 to the selected EQGMs is as follows: the response to Mx and Nr is well within the failure zone and is so high that it does not fit in the graph ($\text{NE}_{\mu}$ is very large for Mx while $\mu$ is very large for Nr), the response to CH and Jp is well within the failure zone with high $\text{NE}_{\mu}$ demand and a $\mu$ demand larger than 6, the response to LP and C3 is in the failure zone but is smaller than that produced by CH and Jp (LP exhibits large $\text{NE}_{\mu}$ demand and C3 large $\mu$ demand), while C1 with a $\mu$ around 4.5 and C2 with a $\mu$ around 2 stay well within the no failure zone. For a SDOFS with cy of 0.20, Nr seems to have the largest damage potential by demanding a $\mu$ of 5; while the response to all other EQGMs fall well within the no failure zone (Jp and CH demand a relevant $\text{NE}_{\mu}$ while C3 a relevant $\mu$).

- **T = 1.5 sec** The response of a SDOFS with cy of 0.10 to the selected EQGMs is as follows: the response to Mx and Nr is well within the failure zone ($\text{NE}_{\mu}$ is very large for Mx while $\mu$ is large for Nr), the response to Jp is close to the failure zone, while the response to the rest of the EQGMs falls well within the no failure zone (C3 demands a $\mu$ slightly larger than 3). For a SDOFS with cy of 0.20, the response to all EQGMs fall well within the no failure zone (Mx and Nr produce the most relevant $\text{NE}_{\mu}$ and $\mu$ demands).

- **T = 2 sec** The response of a SDOFS with cy of 0.10 to the selected EQGMs is as follows: the response to Mx is well within the failure zone with a large demand of $\text{NE}_{\mu}$, the response to Nr is close to failure zone with a $\mu$ demand of 4, while the response to the rest of the EQGMs falls well within the no failure zone. For cy of 0.20, Mx is the only EQGM that produces significant inelastic demands.

The above results confirm the low damage potential of the EQGMs recorded in Costa Rica when compared to that of the world’s EQGMs. Also, it has been confirmed that Mx has a very large damage
Fig. 5 Constant strength response of EPP SDOFS subjected to selected EQGMs.

Potential for SDOFS with large T in which it demands very high values of $E_H\mu_r$; $N_r$ has very large damage potential over the whole T range under study (especially for short T) but demands small values of $E_H\mu_r$ and that $CH$ has large damage potential for short T and exhibits large $E_H\mu_r$ demands in this T range. Of the Costa Rica EQGMs, $C_3$ exhibits the largest damage potential although its $E_H\mu_r$ demands are not relevant.

Strength according to Costa Rica EQ-RD provisions. In this section, an attempt to estimate the damage potential of the Costa Rica EQGMs to ductile RC structures designed in Costa Rica is assessed. This attempt can only be qualitative given the lack of information regarding the typical mechanical properties and overstrength of ductile RC structures designed and built in Costa Rica. Because ACI-318 is currently enforced for the EQ-RD of ductile RC structures in Costa Rica, it is assumed that $\mu = 0.15$ and $\mu_u = 6$. EPP SDOFS with $T = 0.5, 1$, and $2$ sec are designed to have a strength according to the specifications given by the current Costa Rica Seismic Code (Gutiérrez et al. 1987) for ductile frames (Type 1). For each EQGM, the EPP SDOFS were designed according to the soil condition and seismic coefficient ($S_{1g}$) corresponding to the location at
which the EQGM was recorded. C1 was recorded on firm soil while C2 and C3 were recorded on soft soil. The final strength of the SDOFS was obtained by assuming an overstrength (OVS) of 200% for $T = 0.5$ sec and 100% for $T = 1$ and 2 sec. Fig. 6 summarizes the results obtained. As shown, the NE demands for all EQGMs are very small. C1 demands $\mu'' = 1.8$ for $T = 0.5$ sec and $\mu'' = 2.6$ for $T = 1$ sec. C3 demands $\mu'' = 2.7$ for $T = 1$ sec and $\mu'' = 1.7$ for $T = 2.0$ sec, while all the SDOFS's subjected to C2 remain elastic. Note that the response of all SDOFSs fall in the no failure zone, and that the recorded EQGMs seem to have larger damage potential for SDOFS with $T = 1$ sec.

Fig. 6. Response of EPP SDOFS with strength according to Costa Rica EQ-RD Code.

Target ductility for Costa Rica EQGMs. In this section, the effect of duration of motion for the Costa Rica EQGMs is discussed by analyzing their values of $\mu_{TAR}$. As shown in Fig. 1, $\mu_{TAR}$ obtained using $DMI_{PA} = 1$ as a failure criteria, and as shown $DMI_{PA}$ tends to underestimate $\mu$ for systems subjected to monotonically increasing deformation (compare $\mu_{PA}$ and $\mu$ in Fig. 1). For the values of $\mu$ assumed in this paper, $\mu_{PA} = 5.4$, which means that according to $DMI_{PA}$ the maximum ductility a system can undergo under monotonic deformation is 5.4. Fig. 7 shows $\mu_{TAR}$ spectra for C1, C2 and C3, and a horizontal line for which $\mu_{TAR} = 5.4$. For all EQGMs, $\mu_{TAR}$ tends to 5.4 (monotonic deformation) as $T$ tends to 0, and $\mu_{TAR}$ tends to increase monotonically as $T$ increases. For some $T$, $\mu_{TAR}$ corresponding to C1 and C2 is less than 4 (recall $\mu = 6$), which outlines the relevance of $E_{dw}$ dissipation for the design of RC structures for theseEQGMs.

OBSERVATIONS AND CONCLUSIONS

In this paper an attempt has been carried out to evaluate the damage potential of EQGMs recorded during recent seismic events in Costa Rica, and compare this damage potential to that of well-known EQGMs recorded around the world. For this purpose, the authors have established a reference frame using fundamental concepts of EQ-RD. A few relevant observations follow:

Damage Indexes. Relevant parameters to estimate $DMI_{PA}$ have been assumed ($I^3 = 0.15$ and $\mu = 6$) for all SDOFS. It should be mentioned that considerable analytical and experimental research needs to be carried out not only to determine the applicability of damage indexes to RC frames and buildings, but also to evaluate the parameters ($I^3$ and $\mu$) involved in these damage indexes, identifying the depen-
dency that these parameters have on the structural properties of real RC buildings (i.e., detailing, period, structural system, etc.)

Overstrength. Considerable effort needs to be made to estimate the overstrength of real buildings according to their structural properties (period, structural system, structural material, design method, etc.).

SDOFS model. In some cases a SDOFS can provide valuable information to assess the behavior of a multi-story building. If upper modes of a regular building are not significant in its total response, an equivalent SDOFS can give a reasonable estimate of the global displacement and energy demands of a multi-story building (Qi and Moehle 1991, Zhu et al. 1992).

The damage potential of EQGMs recorded in Costa Rica is considerably smaller than that of other well-known EQGMs. Of the analyzed EQGMs, Mx, Nr and CH seem to have the highest damage potential, although the way and the period range in which they produce significant damage varies considerably. The EQGMs recorded during recent seismic events in Costa Rica (1990 Cóbano EQ, 1990 Alajuela EQ and 1991 Limón EQ) did not produce relevant seismic demands in EPP SDOFS representing ductile RC structures (Type 1) designed and built in compliance with the current Costa Rica Seismic Code. Studies to assess the seismic vulnerability of ductile RC structures located in different cities and towns in Costa Rica need to consider that, in general, the recorded EQGMs have not been a good test to the soundness of the behavior of Costa Rica’s ductile RC structures. Also, the adequacy of current EQ-RD provisions for the design of ductile RC structures can only be assessed by comparing the magnitude and epicenter location of the recent seismic events in Costa Rica with the magnitude and epicenter location of the seismic events that have been considered for the formulation of such provisions.

It is interesting to note that in spite of the very different characteristics of C1, C2 and C3, they exhibit important $NE_{\mu}$ demands for $T = 2$ sec and constant ductility demand (see Fig. 4). Although not discussed before in this paper, the previous observation seems to be true for several other EQGMs recorded during the Costa Rica seismic events, in which relevant $NE_{\mu}$ demands (for constant ductility) were observed for long $T$ (around 2 sec). Although this can be explained for some of these EQGMs given that they were recorded at sites with soft soil, it is not as easy to explain for other EQGMs that were recorded in firm soil (C1). This issue deserves further research.

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