Effect of Dampers on Seismic Demand of Short Period Structures in Rock Sites

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ABSTRACT

Seismic behavior of short period structures with dampers founded on rock is investigated. A single bay frame with diagonal damper that represents short period structures is evaluated in response to the excitation of a set of earthquake records. The frame system is modeled as a generalized single degree of freedom system, and is subjected to five earthquake records representative of rock site conditions. The relationship between the force modification factor and the global ductility demand for short period structures founded on rock, in the presence of dampers, tends to approach those of long period ones. Compared with seismic demand under general site conditions, short period structures founded on rock show less seismic demand and less sensitivity to earthquake excitations. Similar to seismic demand in general site conditions, dampers with high damping ratios for short period structures in rock sites tend to keep the structural response in the elastic range even for high values of force reductions. Seismic code provisions should be revised to account for short period effect under seismic excitation.

KEYWORDS: Ductility demand, Seismic demand, Short period structures, Rock sites, Dampers.

INTRODUCTION

Earthquake-resistant structures are generally designed with strength much less than their elastic strength demand due to earthquake excitation. According to modern seismic codes, typically well-detailed structures may be designed with a strength capacity as low as 12% of their elastic strength demand (IBC, 2006).

This reduction in strength demand is possible due to many factors such as ductility, energy dissipation and frequency shift. In general, such strength reduction imposes special demand on structures in terms of detailing to achieve specified levels of ductility and energy dissipation which are function of the specified levels of strength reduction. Seismic codes, in general, utilize parameters such as force modification factor, R,

and global ductility demand, μ_d, to implicitly account for strength reductions. Force modification factor is defined as the ratio of elastic strength demand to actual yield force of the structure, whereas global ductility demand is defined as the maximum inelastic displacement under seismic excitation to the actual yield displacement of the structure.

However, the codes do not explicitly address the damping of structures which is an indication of the energy dissipation capacity of the structure. Furthermore, codes do not distinguish between short period and long period structures in their treatment of strength and ductility requirements for design of earthquake-resistant structures.

Many research results on seismic demand indicated that even though ductility demand is feasible for long period structures (tall buildings), high levels of ductility are imposed for short period structures which may not be achievable (Nassar and Krawinkler, 1991).

Furthermore, research results also indicated that ductility demand is very sensitive to strength reduction for short period structures (Armouti, 2003).

Consequently, short period structures should rely on factors other than ductility to achieve strength reduction,

such as energy dissipation. Therefore, this study focuses on examining the effect of explicit damping on ductility demand on one hand and on the feasibility of dampers as an alternative to ductility requirements for short period structures on the other.
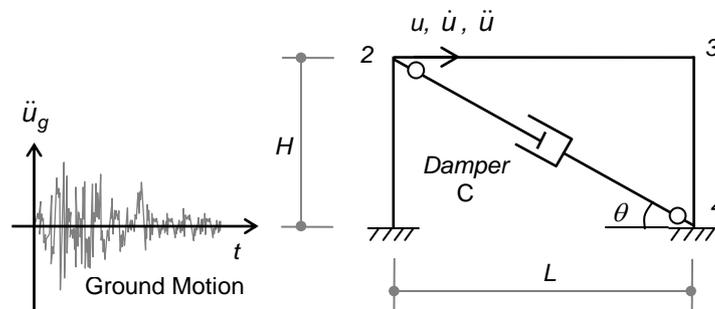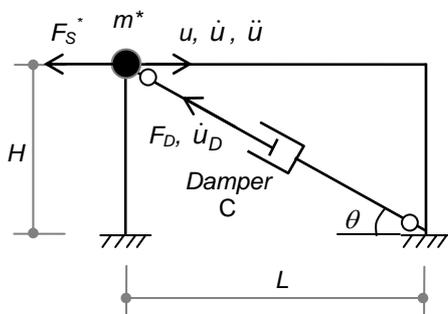

Figure 1: Frame layout

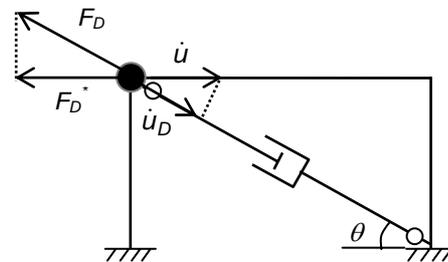**Figure 2: Lumped mass as GSDOF**

Figure 3: Generalized damping due to velocity, $\dot{u}$

Dampers are widely used in structures to alleviate the harmful effect of earthquakes on structures. Dampers are known to be used in new buildings (Nagarajaiah and Narasimhan, 2007), in bridges (Madhekar and Jangid, 2009) and in retrofit of existing structures (Malhotra et al., 2004; Potty and Nambissan, 2008). Dampers have proven to be effective systems for reducing earthquake forces in structures (Chandra et al., 2000; Raju et al., 2005).

The behavior of short period structures with dampers under the excitation of earthquakes representative of dominant site conditions; namely, rock, deep cohesionless soil, and soft areas is investigated (Armouti, 2010). The investigation has shown that dampers reduce the high ductility demand of short

period structures. Since both short period structures and rock sites vibrate in the high frequency range of the spectrum, this study examines the behavior of short period structures founded on rock.

In order to examine the effect of dampers on the behavior of short period structures founded on rock under seismic excitation, a typical one bay frame with a diagonal viscous damper is considered for this study to examine the effect of viscous dampers on the R-μ_d relationship. A frame with a damper having a coefficient of damping, C, is subjected to a horizontal component of ground motion, $\ddot{u}_g$, as shown in Fig. 1. In order to get a better understanding of the effect of ductility and energy dissipation as outlined above, and to be consistent with previous studies on this subject,

the frame is modeled as a generalized single degree of freedom (SDOF) system, and subjected to five earthquake records generated to be representative of earthquakes in rock sites. Consequently, the force reduction factor, R, and the global ductility demand, μ_d,

are evaluated and compared with previous studies to examine the effect of damping on the ductility demand as an indicator of the behavior of short period structures founded on rock sites.
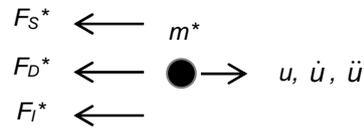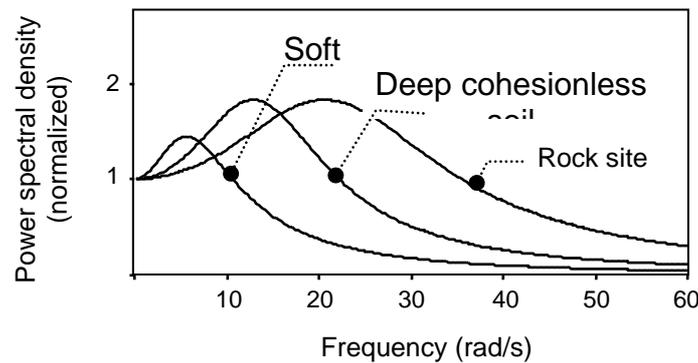

Figure 4: Generalized SDOF

Figure 5: Distribution of power spectral density of earthquakes according to their site conditions

To achieve these objectives, a parametric study using inelastic dynamic analysis is performed by varying the period and the intensity of earthquake excitation. The parameter variation includes five periods, five levels of relative yielding of the hysteresis model and three damping ratios for each of the five earthquake records. This parameter variation results in 375 pairs of R and μ_d values as a result of 125 runs of elastic dynamic analysis and 375 runs of inelastic dynamic analysis which are grouped and evaluated.

For completeness of presentation, a description of the structure, the earthquake records used and the inelastic dynamic analysis procedures including the hysteretic model of the frame are presented.

STRUCTURAL MODEL

As mentioned previously, the structural model is

selected as a frame having four nodes (1 through 4) as shown in Fig. 1. The frame consists of one bay frame fixed at both supports. The frame is provided with explicit diagonal viscous damper with coefficient of damping, C, between nodes 2 and 4. The frame may be modeled as a Generalized Single Degree of Freedom, GSDOF, system by assuming the total mass to be lumped at one node, node 2, as shown in Fig. 2. The generalized degree of freedom in this case is the mass displacement in the direction of, u, at node 2. The generalized resistance of the frame without the damper is obtained due to an induced displacement of the mass in the direction, u, as a generalized spring force, F_S^*, whereas the component of the reactive force of the damper in the direction of displacement, u, is obtained due to induced velocity in the direction of, $\dot{u}$, as the generalized damping force, F_D^*.

In case of elastic analysis, the generalized stiffness,

k^*, is simply evaluated by subjecting the frame to a unit displacement in the direction of, u, which can be easily obtained by any structural analysis software. The generalized coefficient of damping, C^*, can be obtained as function of the damper coefficient of damping, C, with reference to Fig. 3 as follows:

Since damper velocity is:

$$\dot{u}_D = \dot{u} \, cos \, \theta$$

The force in the damper is given as:

$$F_D = C. \, \dot{u}_D = C.cos \, \theta \, \dot{u}$$

The generalized force of the damper in the direction of, u, becomes:

$$F_D{}^* = F_D \, cos \, \theta = \dot{u} = C^* \dot{u}$$

Therefore, the generalized damping becomes:
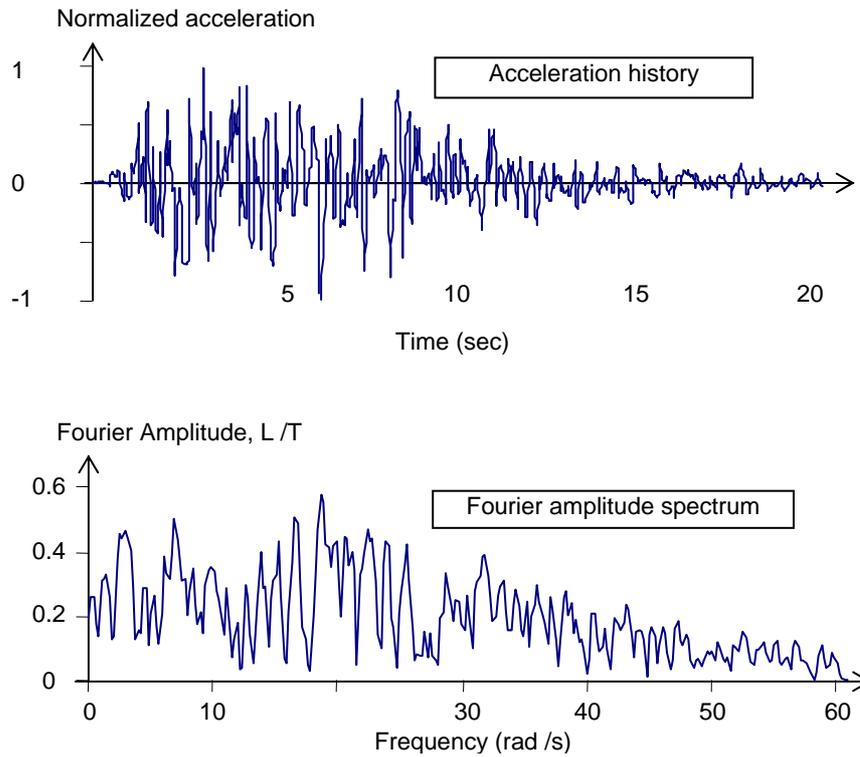
$$C^* = C.cos^2 \, \theta$$

Figure 6: Properties of synthetic record R1.nsa
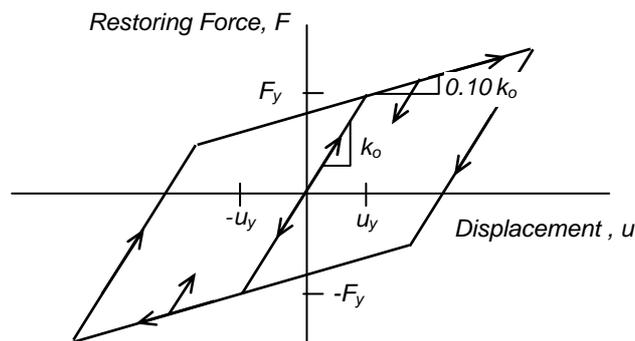

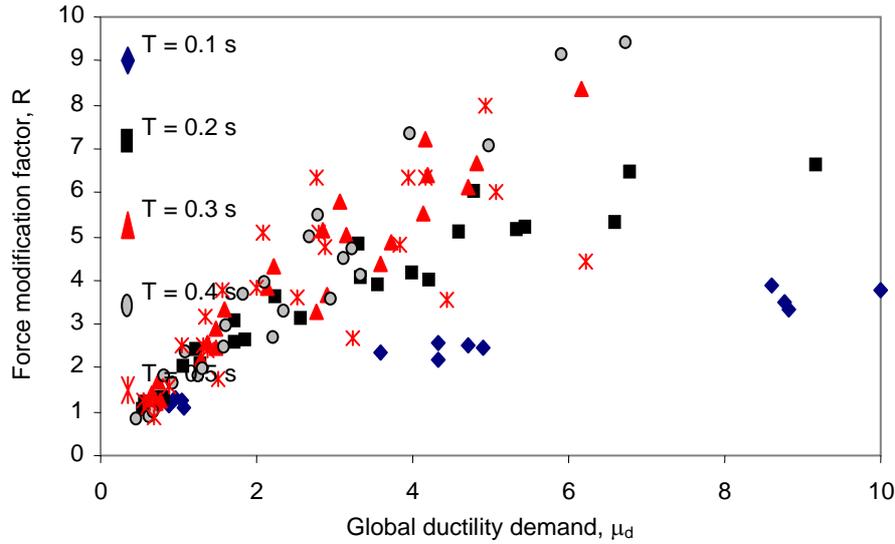**Figure 7: Bilinear hysteresis model**

Figure 8: Relationship between force modification factor and global ductility demand at a damping ratio of 20%

The frame system, therefore, can be represented by a system with a generalized single dynamic degree of freedom consisting of a lumped mass subjected to generalized forces and displacements as shown in Fig. 4. The equation of motion in this case takes the form:

$$F_I^* + F_D^* + F_S^* = -m^* \ddot{u}_g$$

In case of elastic analysis:
$$m^* \ddot{u} + C^* \dot{u} + k^* u = -m^* \ddot{u}_g$$

$$\ddot{u} + 2\zeta\omega\dot{u} + \omega^2 u = -\ddot{u}_g$$

where;
u = generalized displacement.
$\dot{u}$ = generalized velocity.
$\ddot{u}$ = generalized acceleration.
$\ddot{u}_g$ = ground acceleration (earthquake).
m^* = generalized mass.
F_I^* = generalized inertial force.
C^* = generalized coefficient of damping.
F_D^* = generalized damping force.
k^* = generalized stiffness.
F_S^* = generalized spring force.

ω = frequency of the generalized system.
ζ = damping of the generalized system.

Since the parametric study uses predefined values of period and damping ratios, the exact values of these parameters, in this study, become immaterial. Therefore, the values of mass, stiffness, damping and level of ground motion are adjusted to produce the intended parameter values of the study.

Consequently, the force reduction factor, R, is defined as the ratio of the elastic strength demand of the structure, F_e, to the actual yield strength, F_y, whereas global ductility demand, μ_d, is defined as the ratio of the maximum displacement reached during the excitation history, u_{max}, to the actual yield displacement of the structure, u_y. These ratios are given in mathematical form as follows:

$$R = \frac{F_e}{F_y} \ , \qquad \mu_d = \frac{u_{max}}{u_y}$$

RECORDS OF EARTHQUAKES

In view of earthquake characteristics, earthquake records are selected to be representative of the rock site conditions found in reality. In order to be comparative,

three synthetic records used in this analysis were adopted from previous studies (Armouti, 2003; Armouti, 2010). Additional two records are generated with the same pewer spectral density curve for rock sites. The records are based on the PSD distribution for rock sties given in Fig. 5.

Using this PSD distribution, five synthetic records are generated. If the letter (R) indicates rock site for future reference, these records are designated as R1.nsa, R2.nsa, R3.nsa, R4.nsa and R5.nsa. Sample of these records, R1.nsa, with its associated Fourier Amplitude Spectrum are shown in Fig. 6.

INELASTIC DYNAMIC ANALYSIS

The purpose of this study is to examine the effect of viscous dampers on the relationship between R and μ_d for short period structures founded on rock. Since the relationship between R and μ_d can be only evaluated in a statistical sense due to the extreme randomness and uncertainty of earthquake characteristics, inelastic dynamic analysis (Clough and Penzien, 1993) is needed to generate a data base for this purpose. In addition to the selected nine earthquake records, the parameter variation includes five periods, five ductility ratios and three damping ratio resulting in 5x5x5x3=375 data points.

The inelastic dynamic analysis can be performed using SAP 2000 software (CSI, 2008) under Time History Function. The GSDOF frame may be modeled in SAP 2000 as direct elasto-plastic link, whereas the damper is modeled as damper link. The parameters of the link and the damper are selected in view of the intended parameter variation values in conjunction with the equation of motion which is given before as:

$$m^* \ddot{u} + C^* \dot{u} + k^* u = -m^* \ddot{u}_g$$

In case of inelastic dynamic analysis, the stiffness will not be constant, and the frame resistance is taken as a reactive generalized restoring force, F_S^*, hence the equation of motion takes its final form as:

$$m^* \ddot{u} + C^* \dot{u} + F_S^* = -m^* \ddot{u}_g$$

where

u = generalized displacement of the mass in the direction of the single degree of freedom.
$\dot{u}$ = generalized mass velocity.
$\ddot{u}$ = generalized mass acceleration.
$\ddot{u}_g$ = horizontal ground acceleration.
m^* = generalized total mass.
C^* = generalized coefficient of viscous damping.
F_S^* = generalized restoring force (hysteresis model).

The structural response is represented by a bilinear hysteresis model with post yielding stiffness equal to 10% of its initial stiffness as shown in Fig. 7. The properties of the hysteresis model are included in SAP 2000 through the elasto-plastic link nonlinear properties. A yield force of 10 kN and yield displacement of 0.01 m are used for this purpose. Since the model properties are required arbitrarily to obtain a predefined period, the elastic stiffness, k_o, of the model is selected as 1000 kN/m, whereas the mass is calibrated for each case to obtain the desired period, since the period is given as:

$$T = 2\pi \sqrt{\frac{m^*}{k^*}} .$$

The generalized damping coefficient is calculated in view of the desired damping ratio and the selected mass and stiffness as follows.

The critical damping, C^*_{CR}, is calculated as:

$$C^*_{CR} = 2 \sqrt{k^* m^*}$$

The damping coefficient, C^*, is then calculated as function of damping ratio, ζ, and critical damping, C^*_{CR}, as:

$$C^* = \zeta \, C^*_{CR}$$

The five periods of the model are chosen by adjusting the mass to produce the desired period. Since the R$-\mu_d$ relationship is targeted in this study for short period structures, the five periods used in this study are 0.1, 0.2, 0.3 and 0.4s in addition to a fifth period of 0.5s included in the study as it marks the border line between short and long period values of structures under typical earthquake excitation.
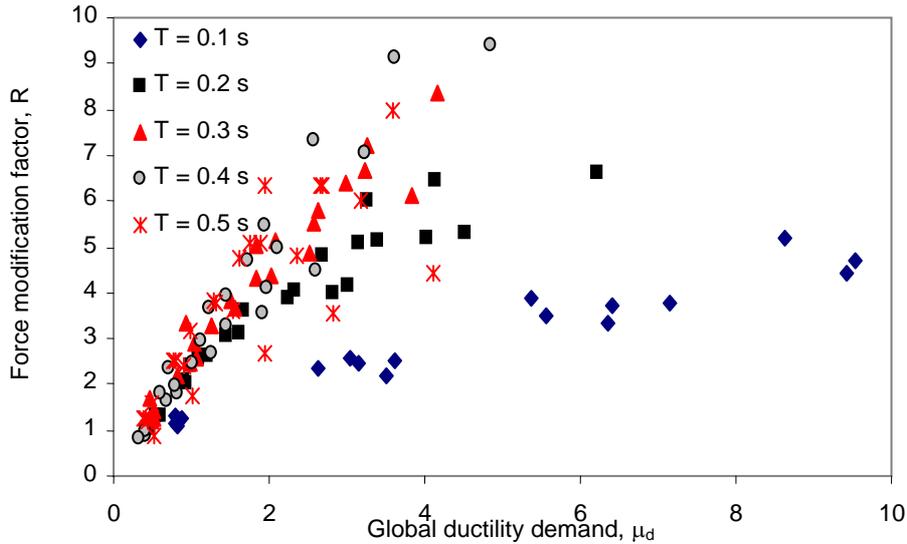
**Figure 9: Relationship between force modification factor and
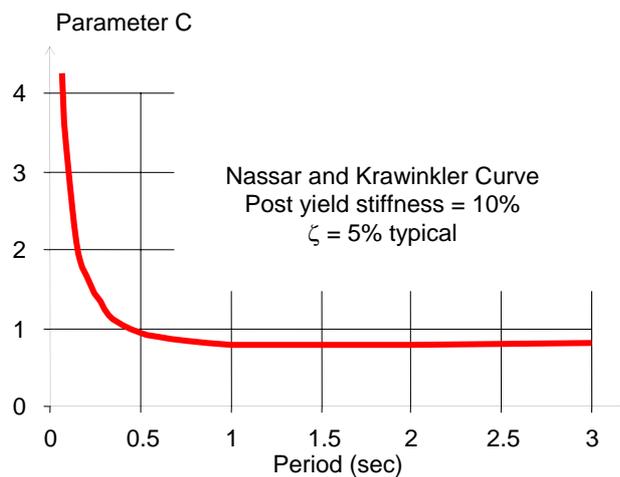global ductility demand at a damping ratio of 40%**

**Figure 10: Relationship between parameter C and period
(Nassar and Krawinkler, 1991)**

In order to obtain various levels of R values, the yield level of the frame is kept constant while changing the intensity of the earthquakes, i.e. the peak ground acceleration of the earthquakes. Accordingly, the parameter variation is generated by taking a different level of peak ground acceleration for each period and each earthquake record. The elastic strength demand, i.e. the maximum elastic force, F_e, and the maximum elastic displacement, u_e, are then obtained using elastic dynamic analysis, i.e. Time History Analysis with infinite yielding. For each value of, F_e, an R-value is calculated as follows:

$$R = \frac{F_e}{F_y}$$

For each value of R obtained above and for each

level of damping of the damper, inelastic dynamic analysis, i.e. Time History Analysis with yielding force, at 10kN, is performed to evaluate the maximum displacement demand during the time of excitation, u_{max}. Knowing u_{max} and u_y, μ_d is calculated as follows:

$$\mu_d = \frac{u_{max}}{u_y}$$

A total number of 900 pairs of R and μ_d from the above procedures is obtained. Samples of such results are shown in Fig. 8 for a 20% damping ratio and in Fig. 9 for a 40% damping ratio. It can be noticed that the data points still exhibit the level of randomness associated with such analysis.
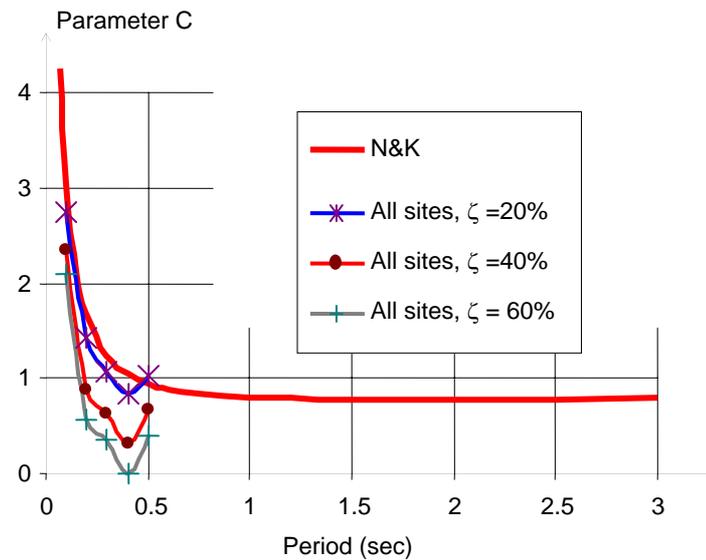

**Figure 11: Values of parameter C
for different periods from reference models of
(N&K, 1991) and study of (Armouti, 2010)**

NASSAR AND KRAWINKLER MODEL

Based on an extensive study which resulted in a large data base of seismic demand characteristics using fifteen actual earthquake records, Nassar and Krawinkler, N&K, (Nassar and Krawinkler, 1991) have proposed the following expression for the relationship between R and μ_d factors:

$$R = [C.(\mu_d - 1) + 1]^{1/C}$$

where C is given as

$$C(T) = \frac{T^a}{1 + T^a} + \frac{b}{T}$$

For a bilinear model with 10% post yielding stiffness and typical damping ratio of 5%, N&K have

used nonlinear regression analysis to produce values of (a = 0.8) and (b = 0.29). Using these values, a plot of the parameter C *versus* the period T is shown in Fig. 10. This Figure will be used in this study as the reference relationship between R and μ_d for a bilinear hysterisis model under the excitation of earthquake records. It is worthwhile to mention that when the value of the parameter C = 1, the R-μ_d relationship tends to the well known equal displacement criterion ($R = \mu_d$); and when the value of the parameter C = 2, the R-μ_d relationship tends to the well known equal energy criterion ($R = \sqrt{2\mu - 1}$).

It is worthwhile also to point out that, in the statistical sense, the C-T relationship shown in Fig. 10 seems to become steady in the long period region

(T>0.5 sec). For long period regions, where parameter C is low (C<1), ductility demand is usually low and steady, whereas, for short period regions where parameter C is high (C>>1), the seismic demand becomes sensitive and high. This type of behavior is known to be a characteristic behavior of structures in response to earthquake excitation. It should also be pointed out that when the value of C is greater than one, the ductility demand becomes more than the force reduction value, and when the value of C is smaller than one, the ductility demand becomes less than the force reduction value.
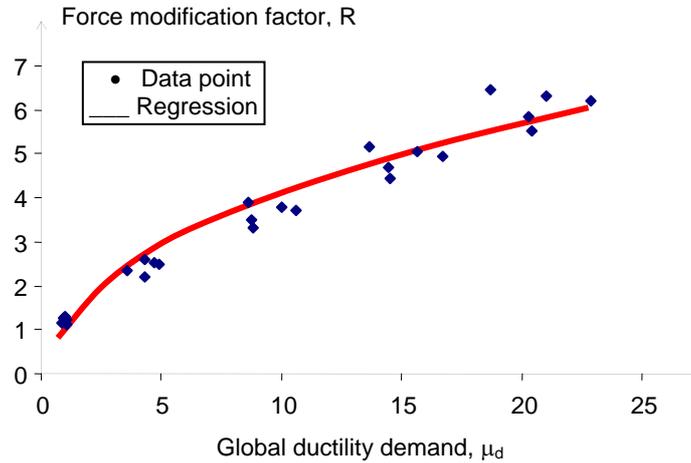
Figure 12: Sample nonlinear regression curve for C value at a period of 0.1 sec and a damping ratio of 20%
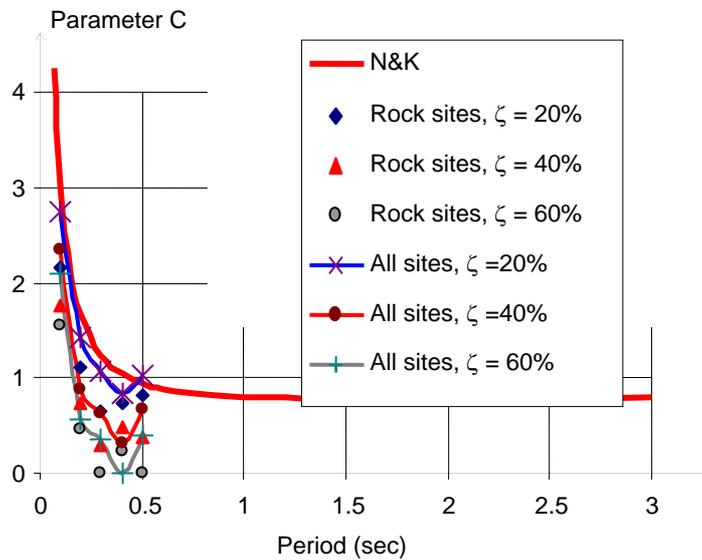
Figure 13: Values of parameter C for different periods from this study against reference models of (N&K, 1991) and (Armouti, 2010)

ARMOUTI REFERENCE RESULTS FOR GENERAL SITE CONDITIONS

Response of short period structures with dampers under general site conditions was investigated by Armouti (Armouti, 2010). His study considered nine earthquakes representative of the three dominant site conditions; namely, rock conditions, deep cohesionless conditions and soft soil conditions, where three earthquakes of each type were included in the analysis.

A comparison with N&K model was presented as shown in Fig. 11, where the study showed that using dampers has smoothened the seismic demand in the presence of dampers for short period structures.

Table 1 shows values of the parameter C obtained by Armouti study, which are also plotted in Fig. 11 for reference comparison with this study which includes the effect of dampers on short period structures founded on rock sites.
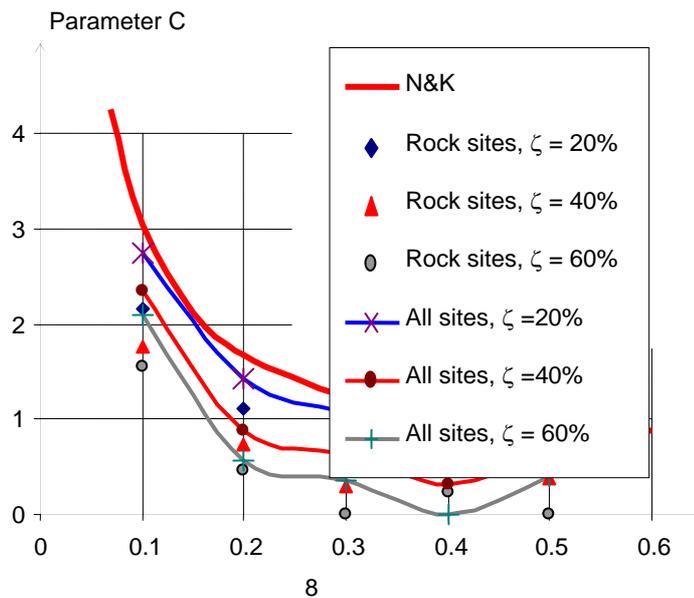
Figure 14: Values of parameter C for different periods from this study against reference model of (N&K 1991) and (Armouti, 2010)

ANALYSIS OF NUMERICAL RESULTS

Evaluation of the numerical results obtained as outlined previously is accomplished through a comparison with N&K model and Armouti results, established by finding the parameter C at the selected periods of the system under the excitation of the selected earthquake records at each damping ratio. The resulting values of the parameter C will then be compared with C-T plot results from N&K model and Armouti results.

Fig. 12 shows one sample of nonlinear regression curve used to find the parameter C for a period of 0.1 sec at a damping ratio of 20%, from which a value of C = 2.15 is obtained. Similar nonlinear regression analysis is conducted to produce the rest of the C-values for the selected periods as given in Table 2.

Fig. 13 and Fig. 14 show a comparison between the obtained C-values from this study and the references (N&K model and Armouti results). It can be seen that the results from this study lie below the reference curves. It can also be noted that the C-values for the

period of 0.1 sec remain above the value of one which means that, for this period even with high values of damping, the ductility demand remains higher than the force reduction. However, high damping brings the level of demand closer to a value of two which is the

equal energy criterion. Furthermore, it is indicated that the behavior of short period structures founded on rock area requires less seismic demand than those founded in general site conditions. It can be noted that damping ratios of 40% and higher lie below the value of 2.

Table 1: Nonlinear regression results for parameter C
under general site conditions (Armouti, 2010)

Period (second)	Damping ratio			
	20%	40%	60%	80%
0.1	2.75	2.35	2.09	1.88
0.2	1.42	0.89	0.56	0.31
0.3	1.08	0.63	0.35	0.18
0.4	0.84	0.31	***	***
0.5	1.03	0.67	0.39	0.17

Table 2: Nonlinear regression results for parameter C
under rock site conditions

Period (second)	Damping ratio		
	20%	40%	60%
0.1	2.15	1.76	1.55
0.2	1.10	0.73	0.47
0.3	0.65	0.28	***
0.4	0.73	0.49	0.23
0.5	0.82	0.38	***

Fig. 13 and Fig. 14 also indicate that, except for a period of 0.1 sec, damping ratios of 20% and higher bring the ductility demand of short period structures to comparable values of long period structures, and even with lesser values.

Referring to Fig. 8 and Fig. 9, the scatter of data can be observed which is reflected by the extreme randomness of earthquakes and their random effect on the response of structures. Careful examination of these two figures shows that the data points of Fig. 9 (40% damping) seem to shift to the left of the data points of Fig. 8 (20% damping), indicating less ductility demand with increased damping. Furthermore, it should be noticed that many responses of the structure remain

elastic at reduced force values which are marked by values of ($R > 1$) and values of ($\mu_d < 1$). This general trend is also observed in the case of response of short period structures under general site conditions in previous research (Armouti, 2010).

Comparison between Fig. 8 and Fig. 9 indicates also that the points that remain elastic at reduced force are much more for the case of 40% damping than for the case of 20% damping. It can be noticed also that the structure with 40% damping remains elastic at higher values of R (R goes up to 3) than the structure with 20% damping (R goes up to 2). In other words, the reduction of elastic strength demand is simply shared between the system ductility and the damper.

CONCLUSIONS

Responses of structures to earthquake records are known to impose high ductility demand for short period structures much higher than those of long period structures. Such high demand for short period structures may not be even feasible to achieve. Seismic codes, in general, overlook this issue and do not distinguish between long and short period structures for this matter.

Armouti (2010) has evaluated the effect of explicit dampers as a mean of alleviating the high ductility demand for short period structures through a parametric study using one bay frame with diagonal damper under the excitation of nine earthquakes representative of dominant site conditions. His work examined this issue through the relationship between the force modification factor and the global ductility demand under seismic excitation as defined by most modern seismic codes (IBC, 2006). This relationship constitutes the basic relationship for defining seismic design forces and the associated required ductility capacities.

In view of the extreme randomness of earthquake characteristics and the reflection of this randomness on the response of structures, and since both short period structures and earthquakes in rock sites vibrate in the high frequency range, this study focuses on the response of structures founded on rock sites. The obtained results in this paper indicate, in statistical sense, that the response of short period structures founded on rock to earthquakes after yielding is in fact less sensitive and less demanding than the case of response to earthquakes under general site conditions. In addition, they indicate that the dampers with damping ratios up to 20% of critical damping tend to reduce the ductility demand consistently with the period values. However, dampers with higher critical damping (more than 20%) seem to bring the behavior of short period structures to levels of the behavior of long period ones. Even more, they show that higher damping improves the behavior of short period structures to levels that are feasibly achievable in practice. It has also been found that the higher the damping presence in the structure, the higher will be the presence of elastic behavior of the structure at even higher values of force reduction.

It can be concluded that, even though, response of short period structures founded on rock sites is less demanding than that of short period structures founded in general site conditions. Structures with short periods should still be carefully designed taking into consideration additional measures other than ductility to include some acceptable levels of safety. Furthermore, as this issue is overlooked in seismic codes, the codes ought to revisit the concept of force reduction and distinguish between long period structures and short period structures. Short period structures may need additional provisions to provide them with enough safety measures.

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