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Evaluation of the inelastic demand of structures subjected to multiple ground motions

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Summary

In the current seismic design format, the key issue in establishing realistic seismic loads is the behavior factor. It accounts for all the dissipative mechanisms that a structural system may develop under a strong ground motion, however not clearly enough stated yet. It corresponds to the performance level associated to the ultimate limit state (i.e. life safety), related to a 100 years mean return interval of earthquake ground motion with a prescribed peak acceleration of ground.

The paper investigates the effect of repeated Vrancea strong ground motions on the behavior factors and the related parameters that accounts for cyclic structural deterioration due to inelastic response. A large number of integrated analyses, nonlinear response analyses and energy balance-based analyses were carried out and estimates were made on the behavior factors for inelastic SDOF systems controlled by flexure with stiffness degradation. The correlation between behavior factors and damage level are investigated, using the Bozorgnia and Bertero (2001), improved damage index. It is shown that multiple ground motion of Vrancea type for Bucharest, may lead to an important increase of force and drift demand of structures that usually is not taken into account.

KEYWORDS: multiple earthquake ground motions, behavior factor, hysteretic energy, damage index, artificial accelerogram.

1. INTRODUCTION

Romanian territory and neighboring countries are repeatedly exposed to medium to high intensity earthquake ground motions generated from the same source, located in Vrancea region. Bucharest is one of the most exposed cities to damage to buildings and human losses as well.

It is therefore obviously needed to explore the effects of repeated Vrancea strong ground motion and the related implications that may improve the seismic design of new buildings and the evaluation procedures of the existing ones. In the current Romanian seismic design format, based on strength principles, the key issue in establishing realistic seismic loads that account for the actual inelastic response, is the force reduction factor/behavior factor, namely *q*. Basically it accounts for all the dissipative mechanisms that a structural system may develop under a strong ground motion, however not clearly enough stated yet.

It is recognized however that the complexity of inelastic behavior phenomena cannot be reproduced through a single parameter that is intended to fully describe the actual structural response. *q* factor is primarily related to the structural inelastic response (ductility and cumulative effects of repeated cycles of inelastic deformations) and contains some of the ground motions properties.

In most of the seismic design codes and Romanian as well, *q* factor primarily addresses to the selected structural type and includes the effect of inelastic behavior and the over-strength effect. It does not directly account for the influence of strong motion duration nor for the hysteretic behavior of the structural elements. It corresponds to the ultimate limit state performance level (i.e. life safety), related to a 100 years mean return interval of a prescribed peak ground acceleration (*PGA*).

For repeated earthquake ground motions however, there is no clear evidence on how this important factor might be interpreted and used in analyses.

The purpose of the paper is to study the effect of repeated strong ground motions of Vrancea type, on the behavior factors of buildings located in Bucharest; we study the variability of *q* factor and related parameters on structural vibration period and ductility, and on ground motion parameters as well.

2. BEHAVIOR FACTORS FOR SINGLE INPUT GROUND MOTIONS; CYCLING LOADING EFFECT

Currently it is usual to estimate the actual force demand by dividing the base shear force that corresponds to a fully elastic response by the behavior factor.

Early studies revealed the fact that the equal displacement assumption and the equal energy assumption provide a fairly good estimation of the force reduction factors at long and short periods, respectively. These developments accounts for ductility properties only. A study by Newmark and Hall (1973) using 10 ground motions records of 1940 El Centro earthquake, proposed reduction factors that include the effect of both, ground motion and structural properties.

Nassar and Krawinkler (1991), Miranda and Bertero (1994), Watanabe and Kawashima (2002) have been conducted studies on the force reduction factors that give fairly good estimates on *q* factors especially for routine buildings. Ordan *et al.*, 1998 and Arroyo *et al.*, 2003 found that the value of *q* strongly depends on ductility and natural vibration period, and is significantly influenced by the soil type.

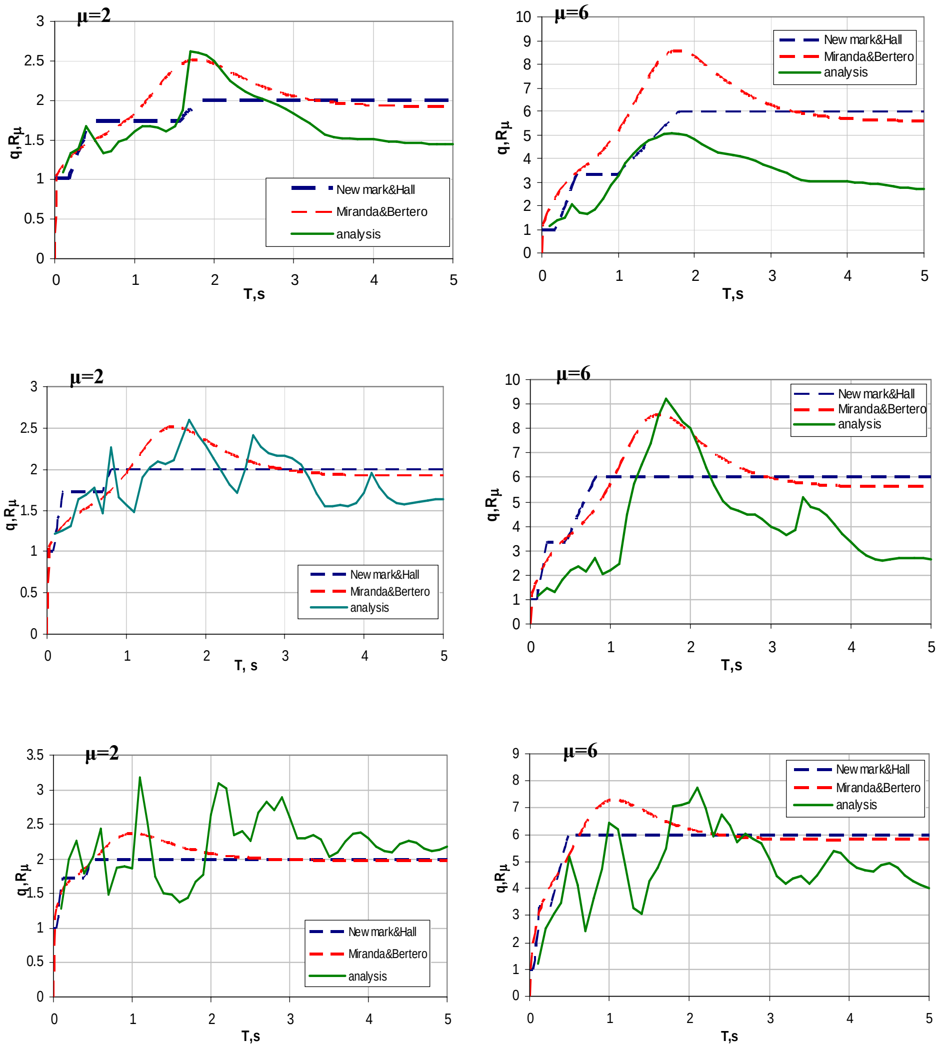

Figure 1. *q* factors for VN77NS, VN86NS, VN90NS records (INCERC Bucharest station)

Inelastic behavior depends on many parameters, associated to the excitation and the structural system. In order to uniformly grasp the effect of multiple earthquake ground motions, and for the sake of clarity we used spectral representations of SDOF systems response, having 5% damping ratio, and bilinear restoring force characteristics, with stiffness degradation and 10% post-yielding stiffness ratio; all systems have equal displacement ductility.

For flexible structures however, SDOF models are expected to reproduce with some degree of inaccuracy the actual response. For routine buildings we expect however realistic estimates.

By definition, the behavior factor is given by

$$q = \frac{F_{el}(\xi_{el}, T)}{F_y(\mu, \xi_{nl}, T)} \qquad (1)$$

where F_{el} and F_y are the maximum linear and nonlinear base shear force respectively, μ is the displacement ductility factor, ξ_{el} and ξ_{nl} are the damping ratios in the linear and nonlinear behavior range respectively, and T is the vibration period of the model. By simplicity, usually ξ_{nl} is taken same as ξ_{el}.

We first compared the formulations of Newmark and Hall (1973) and Miranda and Bertero (1994), with q factors obtained from analysis for low and high displacement ductility systems, using the NS component accelerograms recorded during 1977, 1986 and 1990 at the INCERC Bucharest station (fig.1).

From the above plots can be observed that q tends to one as T approaches zero. Proposed relationships fairly estimate the analysis results, especially for short-medium vibration period and for low-medium displacement ductility; for flexible structures with high ductility, the results are grossly overestimated, especially in the case of 1977 strong ground motion. On the other hand, a large variability of q in terms of T and μ can be observed. The variability of spectral response was more detailed investigated, using a number of 15 accelerograms of 1986 Vrancea earthquake, recorded in Bucharest (fig.2).

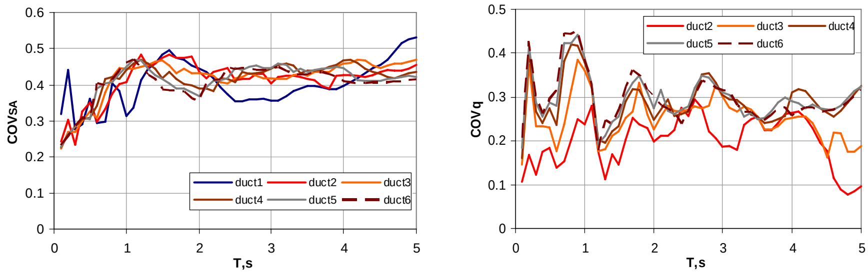

Figure 2. COV of *SA* and *q* factors for 1986 EQGM (15 records, Bucharest)

The results are showing a larger variability corresponding to high ductility in small vibration period region. As for the *q* factor, the scattering is much more pronounced; the variability is lower for low ductility structures.

From the definition, one of the major disadvantage of *q* factor is that does not account for the effect of hysteretic demand, as a powerful damage indicator (Uang *et al.,* 1990; Iancovici, 2005). The mass normalized hysteretic energy is given by

$$EH(t) = (1-\beta_k)\omega^2 \int_0^t z(\tau)\dot{x}(\tau)d\tau \qquad (2)$$

where, β_k is the ratio of pre- and post-yielding stiffness, ω is the natural circular frequency and *z(t)* is the nonlinear (hysteretic) displacement. For the sake of investigating the patterns of *q* factors and hysteretic energies, we plotted their mean plus one standard deviation values on the same graph (fig.3).

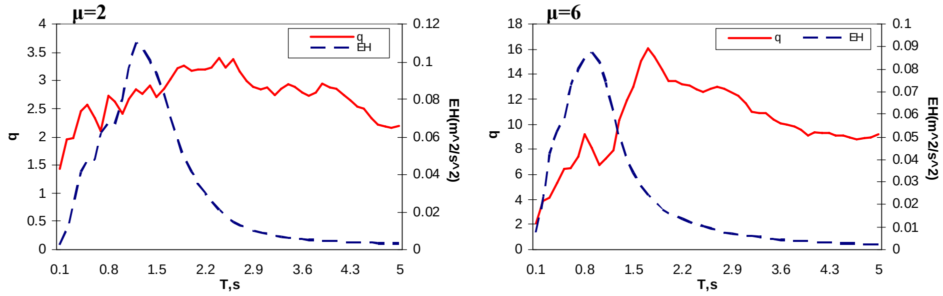

Figure 3. *q* factor and hysteretic energy spectral representations (15 records, Bucharest)

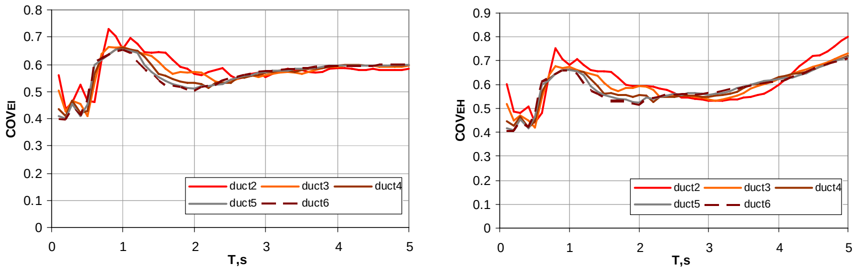

Figure 4. COV of input and hysteretic energies 1986 EQGM (15 records, Bucharest)

As suggested, the variation pattern differs considerable; generally *q* factor could not correctly reproduce the hysteretic energy distribution over the whole vibration periods range. The coefficients of variation for the input energy that the structure will receive and the hysteretic energy that the structure will absorb are plotted in fig. 4.

A high coefficient of variation can be observed for both parameters. For short natural periods range the variation is higher for low ductility; for flexible systems, the ductility effect on COV nearly vanishes.

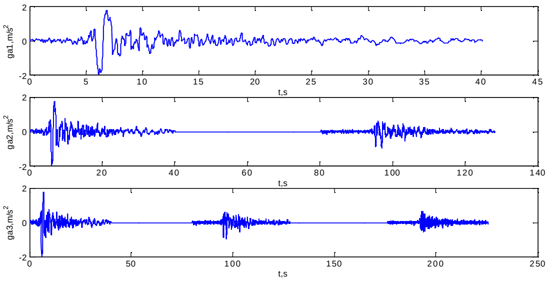

Figure 5. Multiple input motions of 1977, 1986 and 1990 EQGM, NS components (INCERC Bucharest station)

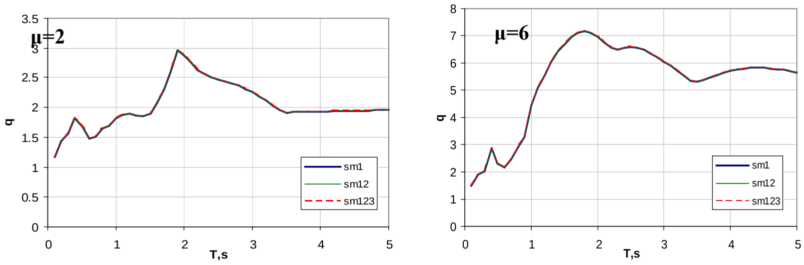

Figure 6. q factors for 1977, 1986 and 1990 EQGM, NS components (INCERC Bucharest station)

3. MULTIPLE GROUND MOTIONS EFFECT ON STRUCTURAL RESPONSE

The multiple input ground motion effect was introduced by a set of two and three accelerograms respectively. The effect of longer duration motions was removed from analyses by considering 40 seconds relaxation time intervals between excitations. We chose for our purpose again the NS component accelerograms recorded at the same site, INCERC Bucharest station during 1977, 1986 and 1990 earthquakes and the generated pulses are shown below.

The spectral representation corresponding to low and high displacement ductility show that there is no sensitivity on *q* factors for the considered multiple input motions.

Taking the VN77NS record as reference and representing the ratios of the corresponding hysteretic energies (fig. 7), it can be observed that the variation is pronounced for *SM12* and has almost doubled values for *SM123*, especially in the case of low-medium vibration periods. This fact is not reproduced by the behavior factors ratios.

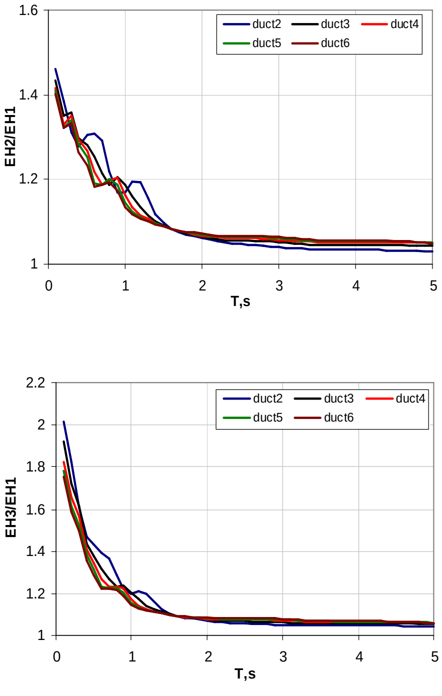

Figure 7. Hysteretic energy ratios for 1977, 1986 and 1990 EQGM, NS components (INCERC Bucharest station)

It is therefore desirable to relate the behavior factors with damage. Earthquake structural damage may be expressed as a contribution of excessive inelastic deformation and cyclic reversal loading effect. For the purpose of studying the correlation that might exist between behavior factors and damage, we used an improved damage model developed by Bozorgnia and Bertero, 2001. This addresses to inelastic SDOF systems and tends to eliminate the disadvantages of the well known Park and Ang damage index (Williams *et al.,* 1995; Mehanny *et al.,* 2000).

By definition, the Bozorgnia and Bertero damage index is given by

$$DI = (1-\alpha_1)\frac{\mu-\mu_e}{\mu_{mon}-1}+\alpha_1\frac{EH}{EH_{mon}} \tag{3}$$

where μ is the displacement ductility, μ_e is the ratio of maximum elastic portion of deformation to yield displacement, μ_{mon} is the monotonic displacement ductility capacity, EH_{mon} is the hysteretic energy capacity under monotonic load and $0<\alpha_1<1.0$ is a constant. The associated damage index ratios are represented in fig. 8.

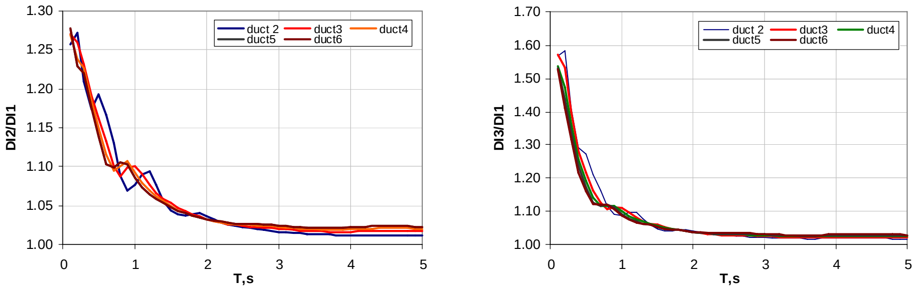

Figure 8. Damage index ratios for 1977, 1986 and 1990 EQGM, NS components (INCERC Bucharest station)

The spectral distribution of damage shows attenuation with the vibration period, with small influence of ductility. However the increase in damage ratio is up to 25% for *SM12* and up to 60% for *SM123*.

There are a very limited number of records that can serve to our purpose, able to drive the structure up to the desired performance level.
We chose then to simulate a large number of artificial strong ground motion accelerograms which realistically aim to reproduce a prescribed structural response and have similar amplitude, frequency content and duration as the real ones, recorded in Bucharest on soft soil conditions (fig. 9).

Artificial ground motions were simulated using the procedure described by Gasparini *et al.* 1976), who's response spectra match the elastic acceleration response spectra, given in the Romanian seismic design code P100-2006.

Sokolov and Bonjer (2006) proposed a procedure to estimate the ground motion parameters based on site-dependant Fourier spectra, obtained by attenuation relationships. Based on this procedure, estimates of peak ground accelerations, for 1940 event in Bucharest, were made as 0.24g. Comparisons with recorded accelerograms during 1977, 1986 and 1990 events were proven the availability of the proposed technique.

Based on these estimates, we generated three sets of 20 accelerograms compatible with the elastic response acceleration spectra for Bucharest, having peak ground accelerations of 0.24g (first and last) and 0.20g (middle).

Since the problem of generating artificial ground motions has many issues, our simulation intends to reproduce the possible succession of events that occurred and may occur in the future, primarily focusing on the structural response and ground motion characteristics from engineering point of view (fig. 9)

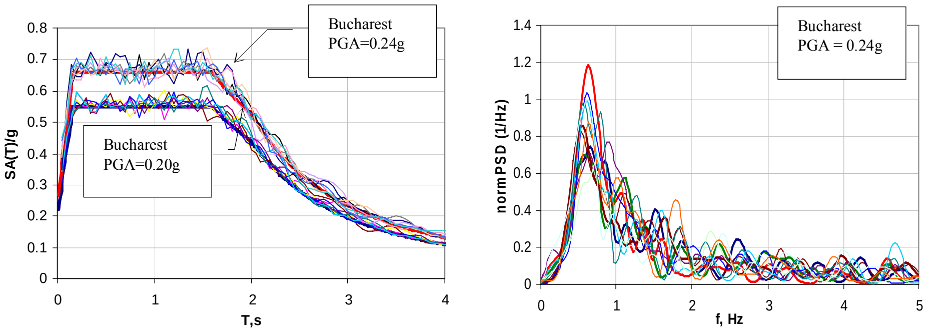

Figure 9. Code spectra compatible accelerograms and corresponding normalized PSD functions

Typical simulated accelerograms are presented below (fig.10).

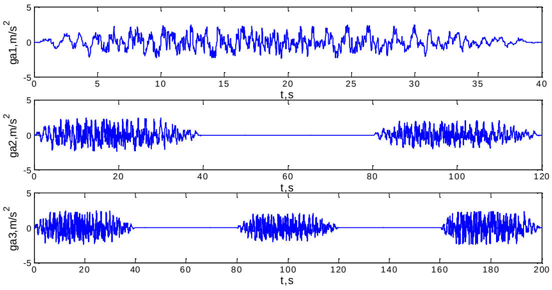

Figure 10. Typical code spectra compatible simulated accelerograms

By analyses, means plus one standard deviation values of *q* factors were obtained and are represented in fig.11.

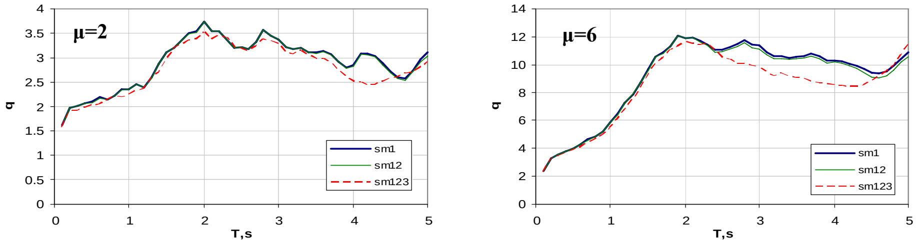

Figure 11. *q* factors (means plus one standard deviation), artificial accelerograms

The results are showing a general decreasing trend of the *q* factor; a slight decrease of *q* factor corresponding to *SM12* and a more pronounced decrease in the case of *SM123*, especially in the case of flexible structures.

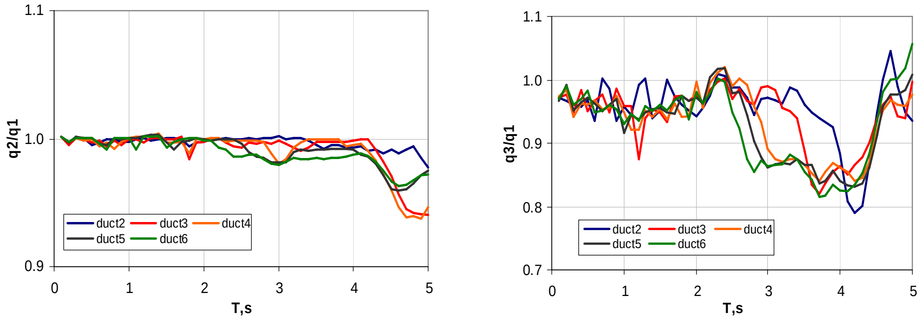

Figure 12. *q* factors ratios

Similarly, we computed the ratios of means plus a standard deviation of the behavior factors, corresponding to *SM12* and *SM123*, taking as reference those corresponding to *SM1* (fig.12).

One can be observed that generally, in the case of two input motions, the decrease of behavior factor goes up to 6% and up to 21%, in the case of three input motions, for flexible structures having low ductility. In the range of low-rise buildings, the variation is rather uniform and goes up to 2-3% for two input motions and up to 12% for three input motions.

Consequently, the decrease of *q* will generate an increase in the force and drift demands, that the structure should be able to supply. Slight increases of *q* can be observed in the case of high-rise buildings with low ductility.

4. CONCLUSIONS

The behavior factors cannot reproduce the effect of hysteretic energy demand. We have shown that for a typical multiple strong motions recorded at the same site, INCERC Bucharest station during 1977, 1986 and 1990 Vrancea earthquakes, there is no variation on behaviour factors. However, in the same time, the hysteretic energy demand goes up to 40% and 80% respectively. Same tendency was observed in the case of associated damage indices.

For a large number of artificially generated accelerograms, the effect of repeated ground motions on q factor might be considerable, especially in the case of three input motions, for the flexible structures having low ductility. Consequently, the base shear demand would increase considerably. This could be the case of some reinforced concrete buildings in Bucharest, designed in the pre-code or low code era, with low inelastic deformation capacity and low hysteretic energy performance.

These are however estimates that might be reliable for routine buildings. For flexible buildings however changes are expected due to the higher modes effect and the effect of over-strength.

Amadio *et al.,* 2002 suggested that the reduction on q factor is even larger than for SDOF systems, in the case of steel moment resisting frames. A seismic design procedure that does not take into account the cumulative inelastic deformation demand that a structure will likely undergo during severe ground motion could lead to unreliable performance.

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