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ENERGY DESIGN APPROACH FOR BRACED FRAMES WITH DISSIPATIVE DEVICES

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ABSTRACT

Several meaningful results of an extensive parametric analysis of the seismic response of braced steel frames equipped with dissipative devices are presented. The energy and kinematic parameters of the dynamic response of the systems examined are correlated with the input energy, which makes it possible to derive design suitable criteria for a large class of structures. The analysis is carried out by a simplified modeling of the behavior of one-story braced frames to which multistory braced frames can be reduced by a reliable criterion of equivalence. The values of lateral stiffness and strength, which in the paper are suggested to optimize the performance of the examined systems, have to be understood as global values for actual multistory systems equipped with dissipative devices, whose cyclic behavior can be modeled as done here.

KEYWORDS

Dissipative devices, seismic response, nonlinear dynamic analysis, braced frames, energy efficiency, energy spectra, displacement spectra.

INTRODUCTION

In the steel frame seismic design field, the use of bracing systems equipped with devices able to dissipate large amounts of energy by hysteretic behavior makes it possible to get round the slight dissipative capacity of ordinary cross-bracing systems. The devices are inserted to interrupt the continuity of the braces or the brace-to-frame joints, in order to prevent tensile brace yielding and consequent pinching of the hysteresis cycles (Aiken and Kelly, 1990).

Design criteria suitable for moment-resistant frames stiffened by dissipative bracing systems have to be able: a) to provide the optimal values of lateral stiffness and strength by which the frame and the bracing systems have to be affected, starting from global values of these quantities to be determined in relation to the seismic input considered (Filiatrault and Cherry, 1988a, 1989, 1990; Colajanni and Papia, 1995; 1996, Vulcano 1995); b) to suggest the distribution of stiffness and strength along the height of the structure, so that the highest performance of the whole structural system can be achieved (Filiatrault and Cherry, 1998b; Colajanni e Papia, 1993; Ciampi et al. 1995).

With reference to item a), the most suitable approach, which is adopted in a lot of studies concerning the problem considered here, consists in defining equivalent SDOF systems, to which a large class of multistory structures can be reduced, and in deriving design spectra of practical use from step-by-step analysis of its nonlinear dynamic response.

This approach requires: a) the assumption of a force-displacement cyclic law for the SDOF system, able to represent a large class of moment-resistant braced frames equipped with different dissipative devices; b) the definition of a procedure making it possible to reduce an actual multistory system to an equivalent one-story system; c) careful modeling of the seismic excitation so that the results can be assumed to have general validity; d) the choice of structural and response parameters allowing simple and meaningful interpretation of the results obtained. The steps above also concern studies addressed to deriving design criteria for seismic-resistant steel frames of conventional type. But the analysis of the seismic behavior of these structures, when dissipative devices are used, must be specialized in relation to the different meaning which the structural and response parameters take on (structural ductility, behavior factor, hardening factor, and so on).

In the present paper, after the basic assumptions by which items a)-d) are treated are summarized, the most meaningful results of an extensive parametric numerical analysis of the seismic response of the equivalent SDOF system are discussed. The input characterization and the response parameters chosen make it possible to understand the results themselves from an energy point of view. This approach supplies design suggestions about the range of values of the structural parameters optimizing the seismic behavior of the braced steel frames equipped by dissipative devices.

MODELS AND PARAMETERS FOR RESPONSE EVALUATION

Analysis Model

The structural scheme modeling the behavior of the equivalent SDOF system is defined considering the following assumptions: i) the force-displacement law of a large class of bracing dissipative systems can be modeled considering the cyclic behavior of an elastic-plastic oscillator with hardening, affected by the same strength and average lateral stiffness as the actual system (this modeling can be made by substituting the horizontal branch of the actual cycle, due to operation of the dissipative device, with an ideal plastic phase of the equivalent oscillator, as done in Colajanni and Papia (1995)); ii) the bracing system and the surrounding steel frame are dimensioned so that the frame behaves elastically during the whole period of motion consequent to seismic excitation (Filiatrault and Cherry, 1990).

Consequently, the analysis model is reduced to that shown in Fig. 1a. It consists of an infinitely elastic one-story steel frame, made of axially unextensible members and affected by lateral stiffness K_f, stiffened by a stubby diagonal brace of lateral stiffness K_d and strength $F_{u,d}$, the latter corresponding to the horizontal load, acting on the brace, at which the dissipative device begins to be in operation (Fig. 1b.). The force-displacement bilinear resultant cycle, which is shown in Fig. 1c, is characterized by the slope of the two linear branches $\overline{OA}$ and $\overline{AB}$, and by the "yielding" strength F_u. For such a system, denoting as δ the current value of horizontal story displacement and as δ_u the value bringing into operation the dissipative device, the response parameter

$$\mu = \frac{\delta}{\delta_u} \tag{1}$$

can be defined as an "equivalent ductility" demand. The dimensionless equation of motion can be written as a function of the quantities μ, T, ζ, γ and q (Colajanni e Papia, 1995), where T is the period of vibration corresponding to the initial global lateral stiffness of the system ($K=K_f+K_d$), ζ is the damping ratio,

$$\gamma = \frac{K_d}{K_f} \tag{2}$$

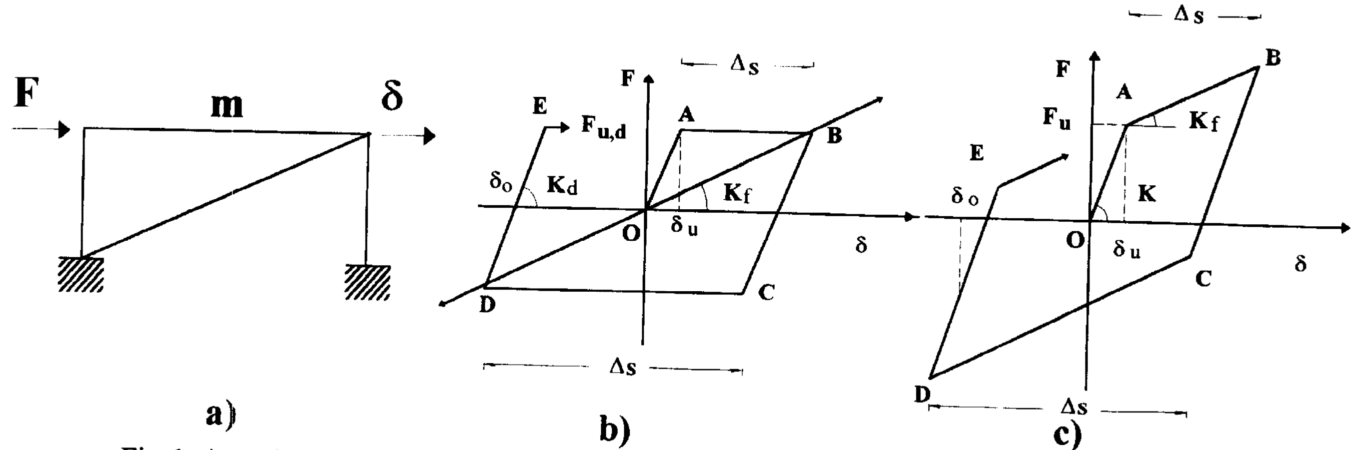

Fig. 1 a) analysi model; b) bracing system and frame F-δ laws; c) braced frame F-δ law.

is the ratio between the lateral stiffness offered by the bracing system and that of the frame, and

$$q = \frac{F_{el}(T,\zeta)}{F_u} \tag{3}$$

is the behavior factor, defined as the ratio between the horizontal force obtained by the response spectrum technique for the SDOF system in Fig. 1 affected by an infinitely elastic behavior, and the strength F_u defined above (see Fig. 1c.).

Meaning of Structural and Response Parameters for MDOF Systems

The SDOF system in Fig. 1. can be assumed to be equivalent to corresponding actual MDOF systems if the structural and response parameters defined above are adequately understood. For an actual multistory braced frame the following assumption must be made: - δ is the current value of horizontal displacement of the top story; - δ_u is the horizontal displacement of the top story when any of the dissipative devices inserted at the various stories begins to operate, measured by performing static analysis with increasing seismic forces distributed along the height of the frame proportionally to the deformed shape of the first mode of vibration; - T is the fundamental period of vibration of braced frames; - the parameter γ, by an extensive reading of (2), defines the ratio between the period T and the fundamental period of vibration T_f of the unbraced frame, by the relationship

$$\frac{T}{T_f} = \frac{1}{(1+\gamma)^{1/2}} \tag{4}$$

Finally, the strength F_u, which appear in (3), must be assumed to be the global seismic force producing the displacement δ_u. It can be evaluated in the same simplified way (static analysis) as that adopted for the displacement δ_u itself.

Input Characterization

The analysis is carried out considering fifty accelerograms artificially generated in such a way as to be compatible with the normalized elastic response spectrum type B provided by EUROCODE 8. This generation is made by using the power density function $S_\omega(\omega)$ shown in Fig. 2., which was calibrated as done in Di Paola and La Mendola (1992). Excluding the initial phase, where an envelope function is adopted (Preumont, 1994), each input accelerogram is modeled as a sample of a stationary process. Therefore, the average results recorded during a meaningful time range are considered valid for any phase of motion.

The design criteria for multistory braced frames equipped with dissipative devices are derived examining the dynamic response (step-by-step analysis) of the SDOF system in Fig. 1., on the basis of the equivalence criterion derived above. The results, which will be shown later on, are mean values of the quantities recorded for each of the fifty accelerograms utilized.

The range of values of the structural parameters considered are: 0.25 sec.$\leq$ T$\leq$ 1.5 sec; $0.5\leq\gamma\leq5$; $q\leq15$. They include a large class of actual multistory braced frames, both in the field of new structures (high values of γ) and in the field of seismic retrofitting of unbraced moment-resistant existing frames (small values of γ). The upper limit assigned to the behavior factor depends on the need for the structure to behave adequately in the serviceable condition. The effectiveness of the performance of the braced frames is evaluated considering as response parameters quantities chosen according to the most important functions that have to be performed by the bracing dissipative systems:- to dissipate the seismic energy; - to limit the maximum displacements and stresses in the frame.

Therefore, a first series of results shows the values of the seismic input energy E_i transmitted to the system with variation in the structural parameters defined above, and the energy efficiency of the bracing system, i.e. the ratio between the energy E_h absorbed by the dissipative devices and E_i. Both these quantities are referred to unit time, taking into account that the response process was assumed to be stationary. A successive series of results shows the different values of the maximum horizontal displacement δ_{max} obtained with variation in the structural parameters. In both cases the results are normalized considering an ideal SDOF reference system with infinitely elastic behavior ($\mu_{max}\leq1$), affected by the same period of vibration T as the actual system in the initial condition. Therefore, the quantities E_i and δ_{max} are made dimensionless by the ratios with the corresponding quantities E_{el} and δ_{el} referring to this ideal elastic system.

Energy Response Spectra

The input energy is equal to the work done by the global shear acting at the base of the structure (restoring plus damping force) during the seismic motion. Therefore, the following expression can be derived:

$$\frac{E_i}{m\,A_{max}^2} = -\frac{\beta(T)}{q\,(t_2-t_1)}\int_{t_1}^{t_2}\left(\frac{2\zeta}{\omega}\dot{\mu}+\mu-\frac{\gamma}{\gamma+1}\mu_p\right)d\dot{s}_g \tag{5}$$

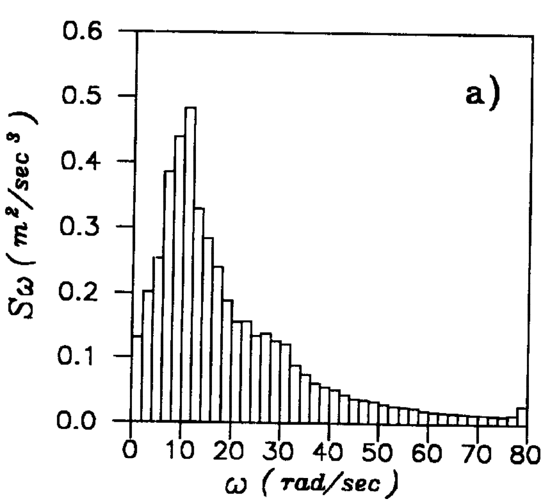

Fig. 2 Power spectral density of the input

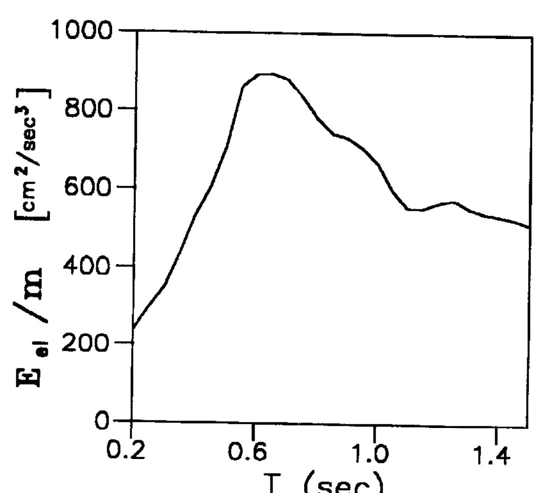

Fig. 4 Input energy for elastic systems

where Δs is the excursion occurring during the operation of the device (Fig. 1.), and $\mu_p=\Delta s/\delta_u$ its normalized value; A_{max} is the maximum ground acceleration, and $\ddot{s}_g$ the instantaneous value of ground acceleration, normalized with respect to A_{max}; $\beta(T)$ is the ordinate of the normalized elastic response spectrum utilized; m is the mass of the system. Considering that for the energy dissipated by the dissipative devices one can write the relationship

$$\frac{E_h}{m\,A_{max}^2} = \frac{1}{(t_2 - t_1)}\left(\frac{\beta(T)}{q\,\omega}\right)^2 \frac{\gamma}{\gamma + 1} \int_{t_1}^{t_2} d\mu_p \tag{6}$$

one deduces that the ratio E_i/E_{el} and the efficiency E_h/E_i depend on the parameters utilized to integrate the equation of motion and are independent of A_{max}.

Fig. 3. shows the energy E_{el} referred to unit mass and to unit time versus the period T, for $A_{max}=1$. The shape of the curve in Fig. 3, is closely related to that of the PSD of the seismic excitation (Fig. 2.). This is because E_{el} depends on the ground displacement(independent of the structure) and on the dynamic response of the system, which, the system being an elastic oscillator, becomes maximum for period values around $T_g=0.6$ sec. making the ordinate of the histogram in Fig. 2 maximum. (for $T_g=0.6$ sec. $\omega_g=10.47$ rad/sec.).

Fig. 4. shows the normalized input energy and the energy efficiency curves versus the behavior factor q, for different values of the period T, with variation in the stiffness ratio γ. The curves E_i/E_{el}-q reveal a different behavior between "short period" systems ($T<T_g$), to which Figs. 3a1-3a3 refer, and "medium or long period" systems ($T \geq T_g$), for which the curves in Figs. 3b1-3b3 have to considered (these figures again show results obtained for T=0.5 sec in order to emphasize the different responses of the two structural classes). When the dissipative devices begin to operate, the dynamic behavior of the system (transfer function) lies between those corresponding to systems affected by the initial frequency value $\omega_0=2\pi/T$ (q=1) and the frequency $\omega_1=\omega_0/(1+\gamma)^{1/2}$ ($q=\infty$), and the higher q is the more it tends to the latter. Consequently, the input energy increases, because the corresponding values of the input PSD are greater than the one corresponding to the initial frequency ω_0. By contrast, since the initial frequency ω_0 of the "medium or long period" system is equal to or lower than that of the maximum energy of the seismic input, the further reduction, due to operation of the dissipative devices, produces a decrease in the energy E_i. Fig. 4. also shows that the higher the stiffness ratio γ is the more the normalized input energy differs from the unit value. This is because the range $[\omega_0-\omega_1]$ increases with γ. A similar effect on the ratio E_i/E_{el} is detected when the ratio $S_\omega(\omega_1)/\ S_\omega(\omega_0)$ leaves the unit value.

The curves in Fig. 4., referring to the energy efficiency, have the same pattern for both the first and the second classes of systems. Moreover, they prove to be almost independent of the period T. The ratio E_h/E_i increases greatly when q increases from 1 to 3; then it increases slightly until the maximum value is achieved (in the range $4 \leq q \leq 6$); finally, it decreases with a very small slope for higher values of q. The energy efficiency is influenced greatly by the ratio γ, as also shown by (6). When γ increases from 0.5 to 2, the maximum value of E_h/E_i, which can be obtained by adopting a suitable value of q, increases meaningfully from 0.45 to 0.62. Further increases in γ do not produce appreciable increases in energy efficiency.

Displacement response spectra

With reference to the maximum horizontal displacement δ_{max}, by evaluating δ_{el} by the response spectrum technique, one obtains

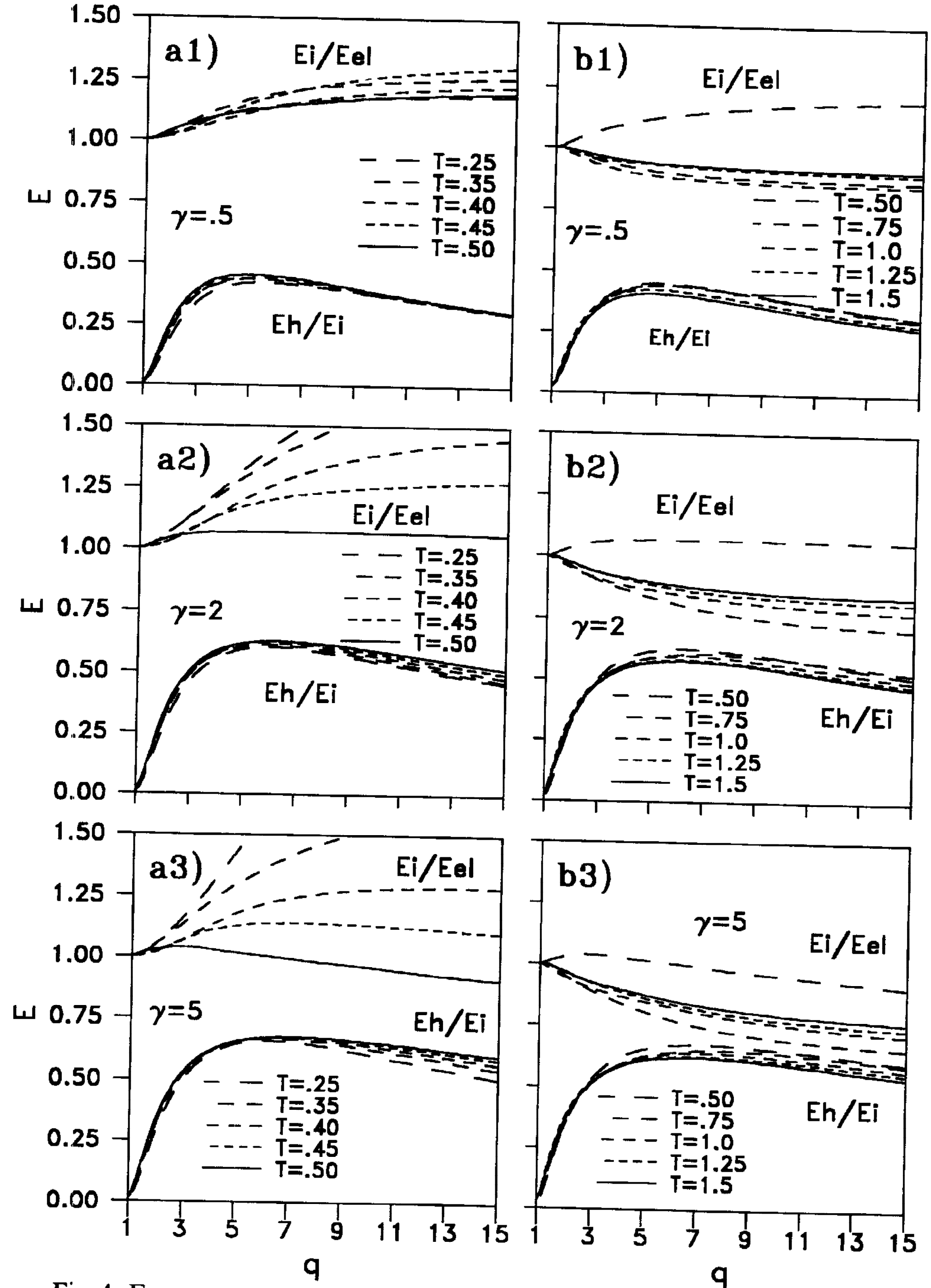

Fig.4. Energy response spectra: a1)-a3) "short period structures"; b1)-b3) "medium or long period structures"

$$\frac{\delta_{max}}{\delta_{el}} = \mu_{max}\, \delta_u \frac{K}{m\, A_{max}\, \beta(T)} = \frac{\mu_{max}}{q} \tag{7}$$

As previously observed for the ratios E_i/E_{el} and E_h/E_i, equation (7) shows that the normalized maximum displacement too is independent of the maximum ground acceleration A_{max}.

The curves δ_{max}/δ_{el} versus q, for the same values of the period T and ratio γ as for the energy spectra, are shown in Fig. 5. They reveal that the use of dissipative devices allows meaningful reduction in the actual maximum displacement with respect to that corresponding to an infinitely elastic response. This possible reduction depends not only on the dissipative capacity of the system, but also on the variation in the input energy with respect to that corresponding to the initial frequency, as stressed above. Therefore, the different behavior between "short period" and "medium or long period" systems can also be

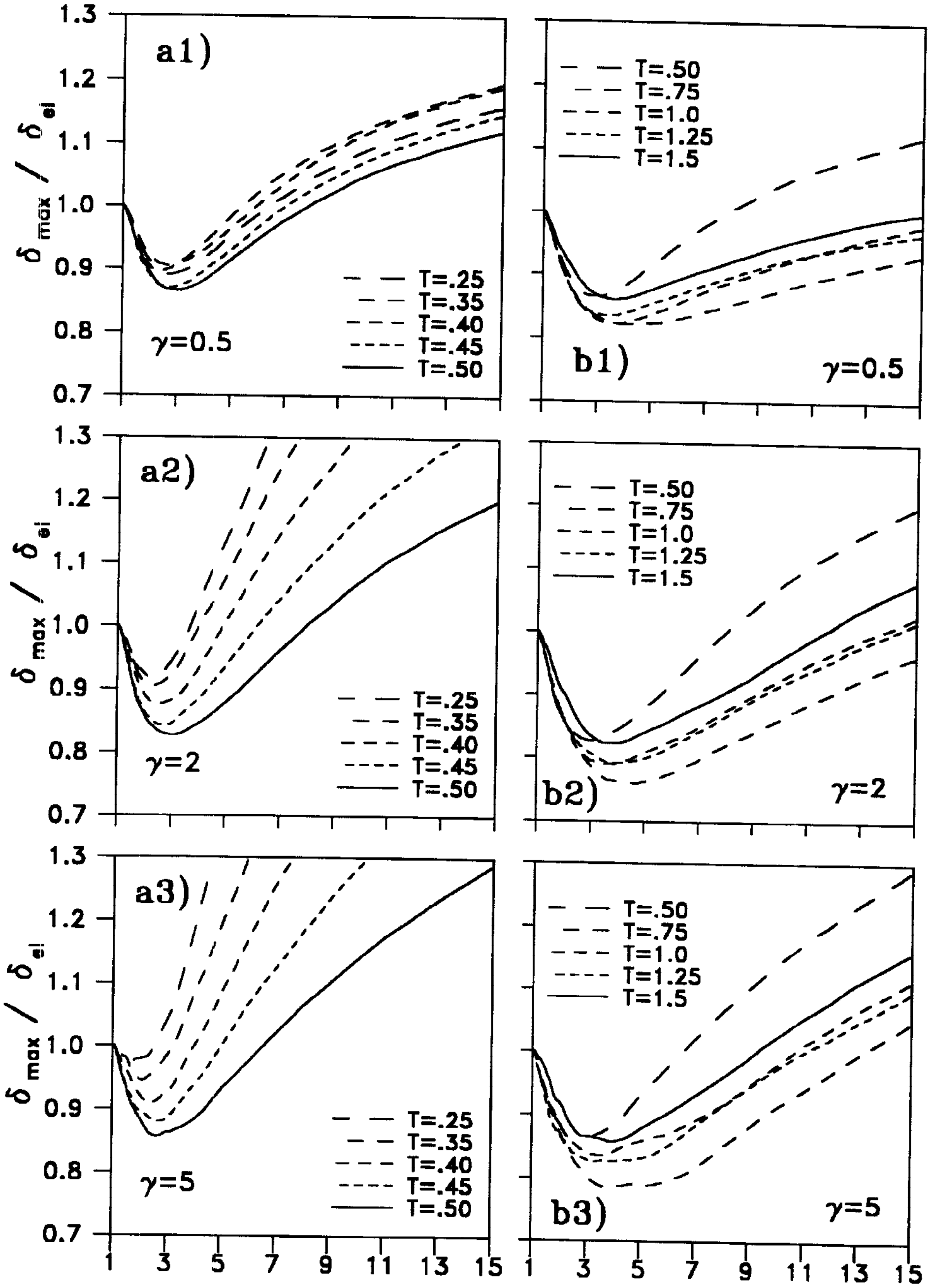

Fig. 5. Displacement response spectra: a1)-a3) "short period structures"; b1)-b3)"medium or long period" structures

observed in terms of maximum displacements. For the first class of systems ($T<T_g$), the maximum reduction in δ_{max} with respect to δ_{el}, occurring for values of q close to 3, is not very high in any case. When values of q higher than 3 are considered, δ_{max} increases fast, and this effect is more evident when the lateral stiffness ratio γ is high. Moreover, for "short period" structures (Figs. 5a1-5a3) the normalized maximum displacement depends meaningfully on T, which implies the different values for the ratio $S_\omega(\omega_1)/ S_\omega(\omega_0)$ and, consequently, for the input energy. For "medium or long period" structures ($T\geq T_g$), the maximum reduction of the maximum horizontal displacement with respect to the ideal elastic system occurs for values of q close to 5. The more the ratio $S_\omega(\omega_1)/ S_\omega(\omega_0)$ differs from the unit value (the maximum difference occurs for T=0.75 sec.) the more the ratio δ_{max}/δ_{el} decreases. Moreover, the curves in Figs. 5b1-5b3. show that increasing values of q do not imply meaningful increases in δ_{max}, since in any case is $\delta_{max}/\delta_{el}<1$ in the range $q\leq 10$.

DESIGN GUIDELINES AND CONCLUSION

The results described above and others which are not shown for brevity's sake, suggest the following considerations:

-in the case of "short period" systems ($T<T_g$) the use of dissipative devices allows absorption of seismic energy, but also implies that the frequency of the structure shifts towards the range of values where the input exhibits its maximum power. Therefore, only a slight reduction in the maximum horizontal displacement with respect to that corresponding to an infinitely elastic response can be achieved. The optimal performance of the system, to which the minimum displacement and the maximum energy efficiency correspond, can be obtained by calibrating the dissipative device so that the behavior factor q proves to be close to 3; higher values of q imply a fast increase in the input energy and in the normalized maximum displacement. This effect is greatly influenced by the lateral stiffness ratio γ between the bracing system and the surrounding frame. The results of the numerical analysis show that values of γ close to 1 can ensure good performance of the system. In any case values of $\gamma>2$ must be avoided.

-in the case of "medium or long period" structures ($T\geq T_g$) the absorption of energy is accompanied by a reduction in input energy. Therefore, considerable reduction in the response with respect to the elastic one can be obtained even for high values of the behavior factor. The minimum value of the horizontal displacement and the maximum energy efficiency (optimal performance) for assigned values of γ correspond to a value of q of about 5; nevertheless, higher values of q do not imply a meaningful reduction in the performance of the system. The energy efficiency of the system increases with the lateral stiffness ratio γ, while the maximum reduction in horizontal displacement occurs for $\gamma=3$. Higher values of γ in any case involve values of δ_{max} compatible with an acceptable risk condition.

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