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DISSIPATION OF ENERGY IN STEEL FRAMES UNDER DYNAMIC LOADING

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SUMMARY

Increasing the rotational capacity of partially restrained (PR) connections and thus the energy dissipation capacity of steel frames have become major research topics in post-Northridge investigations. The major sources of energy dissipation, including the energy dissipation at PR connections, are comprehensively addressed in this paper. Traditionally, only dissipation of energy due to viscous damping and due to the hysteretic behavior of the material are emphasized. However, results of this study indicate that the dissipation of energy due to the hysteretic behavior at PR connections may also be significant. The study quantitativaly confirms the general behavior observed during experimental investigations: PR connections reduce the overall stiffness of frames but add a major source of energy dissipation. It is observed that that the dissipation of energy at PR connections is of the same order of magnitude as that of by the viscous damping and by the hysteretic behavior of the material.

INTRODUCTION

Several connections failed in steel frames during the Northridge Earthquake of 1994. In pre-Northridge earthquake investigations, attempts were made to study the changes in the seismic behavior of steel frames due to the presence of partially restrained (PR) connections as opposed to fully restrained (FR) connections [Nader and Astaneh, 1991; Richard, 1993; Leon and Shin, 1995]. It has been established that, even though the presence of PR connections reduce the stiffness of steel frames, it may increase the energy dissipation capacity of the frames. Increasing the rotational capacity of PR connections and thus the energy dissipation capacity of steel frames have become major research topics in post-Northridge earthquake investigations.

The energy imparted to a structure by an earthquake or by any dynamic loading is absorbed and dissipated by the structure through different mechanisms. The absorption mechanism consists of the kinetic energy including the rigid body translation of the structure and the elastic strain energy. The dissipation mechanism, traditionally considered in the seismic and dynamic analysis of steel structures, consists of the hysteretic behavior of the material at locations of plastic hinges and other nonyielding mechanisms usually represented by equivalent viscous damping. However, as qualitatively observed by Nader and Astaneh [1991] and by Leon and Shin [1995], PR connections add another importance source of dissipation of energy.

Many studies were conducted in the area of analysis of frames with PR connections for static analysis [Chen and Liu, 1987; Richard, 1986] and a few studies were carried out for the dynamic case [Haldar and Reyes-Salazar, 1996; El-Salti, 1992]. However, there has not been an explicit analytical evaluation of the energy dissipation capacity of PR connections in steel frames. The main objective of this paper is to investigate the amount of energy that PR connections in steel frames can dissipate when excited by dynamic loadings. The energy balance principle is used to quantify the sources of energy dissipation in steel frames. A nonlinear time-domain finite element algorithm capable of considering nonlinearities due to geometric, material and PR connections is used to quantify the amount of energy dissipation by each source. The algorithm is first verified using available experimental results. The verified algorithm is then used for the parametric study, helping to make some important observations.

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PROPOSED MODEL

The input energy (E_I) into an structure subjected to any dynamic loading for a time interval defined by t_1 and t_2 is absorbed in the form of elastic strain energy (E_S) and kinetic energy (E_K), and dissipated by the hysteretic behavior of the material at the location of plastic hinges (plastic energy, E_P), by viscous damping (E_D), and by the hysteretic behavior of PR connections (E_C) if they are considered. This energy balance for the system can be mathematically represented as:

$$E_I = \Delta E_S + \Delta E_K + E_P + E_D + E_C \tag{1}$$

Each of the energy terms in Eq. (1) is explained below. The input energy for a given $p(t)$ is calculated as:

$$E_I = \int_{u_1}^{u_2} p(t)du = \int_{t_1}^{t_2} p(t)\dot{u}dt \tag{2}$$

where $p(t)$ is the time history of the load acting on the structure and u the corresponding displacement. The variation in the elastic strain energy is given by the following equation:

$$\Delta E_S = \left(\frac{1}{2}\right)_{t_2} - \left(\frac{1}{2}\right)_{t_1} \tag{3}$$

where $\mathbf{K}_t$ is the tangent stiffness matrix of the structure and $\mathbf{U}$ is the displacement vector. The variation in the kinetic energy is obtained as:

$$\Delta E_K = \left(\frac{1}{2}\right)_{t_2} - \left(\frac{1}{2}\right)_{t_1} \tag{4}$$

where **m** is the mass matrix and $\dot{\mathrm{U}}$ 5 is the velocity vector. The plastic energy dissipation at plastic hinges is the work done by the resultant stresses through the corresponding plastic deformations. For plane frames it can be expressed as (Haldar and Nee, 1989):

$$E_P = \sum_{i=1}^{n} M_P \, \Theta_P + \sum_{i=1}^{n} P_P \, H_P \tag{5}$$

where M_P and P_P are the moment and axial force, respectively, acting on a plastic hinge when it is formed in an element, Θ_P and H_P are the corresponding plastic rotation and plastic elongation, and n is the total number of plastic hinges developed in the frame. The energy dissipated by viscous damping is given by:

$$E_D = \int_{\dot{u}_1}^{\dot{u}_2} \mathrm{C}\,\dot{\mathrm{U}}\,\mathrm{du} = \int_{\mathrm{t}_1}^{\mathrm{t}_2} \dot{\mathrm{U}}^{\mathrm{t}}\,\mathrm{C}\,\dot{\mathrm{U}}\,\mathrm{dt} \tag{6}$$

where **C** is the the damping matrix of the structure and all the other terms were defined earlier. Finally the dissipation of energy at PR connections can be calculated as:

$$E_C = \sum_{j=1}^{k}\left(\int_{\theta_1}^{\theta_2} M \; d\theta \right) = \sum_{j=1}^{k}\left(\int_{t_1}^{t_2} M \; \dot{\theta} dt \right) \quad \textbf{(7)}$$

where M is the connection moment, θ is the relative rotation of the connection, and k is the total number of PR connections in the frame.

MODELING CONNECTIONS-THE RICHARD MODEL

Connections are structural elements through which resultant stresses are transmited between beams and columns. In general these resultant stresses may consists of axial force, shear force, torsion and bending moments. For two dimensional structures, the torsion effect is negligible. The effect of shear and axial forces is also expected to be small and can be neglected. Thus, the bending moment at the connections and the corresponding relative rotations need to be considered to quantify the amount of energy dissipation in them. Generally, the behavior of a PR connection is represented by a moment-relative rotation (M-θ) curve. Several analytical expressions have been proposed to represent this curve. The Richard's Model is adopted in this study to represent the behavior of the PR connections. This model is used because of its applicability to wide variety of connections and it is developed using experimental data. It is not possible to give here the details of the model due to lack of space, but they can be found in the literature [Richard, 1993; Reyes-Salazar, 1997].

MATHEMATICAL FORMULATION

To meet the objectives of this study, the nonlinear dynamic response of steel frames is obtained by using an efficient finite element-based time-domain algorithm, already developed for the authors and their associates [Gao and Haldar, 1995; Reyes-Salazar, 1997]. The algorithm estimates nonlinear seismic responses of steel frames with PR connections considering all major sources of energy dissipation. Material and geometric nonlinearities are considered.

Most of the currently available finite-element based nonlinear analysis techniques for frames are based on an assumed displacement field. In order to capture the effect of change in axial length of an element due to large deformation, several elements are needed to model each member. The necessity for a large number of elements coupled with the use of a numerical integration scheme to obtain the tangent stiffness matrix for each element several times during the analysis, makes this approach uneconomical.

Considering its efficiency, particularly for steel frame structures, the assumed stress-based finite element method [Kondoh and Atluri, 1987; Haldar and Nee, 1989; Shi and Atluri, 1988] is used in this study. Using this approach an explicit form of the tangent stiffness matrix is derived without any numerical integration. Fewer elements can be used in describing a large deformation configuration without sacrificing any accuracy. Furthermore, information on material nonlinearity and connection flexibility can be incorporated in the algorithm without losing its basic simplicity. It gives very accurate results and is very efficient compared to the displacement-based approach. The procedure has been studied and extensively verified with existing theoretical and experimental results. Details of the algorithm are not given here due lack of space.

STRUCTURAL MODEL

To evaluate the different sources of energy dissipation in steel frames, a steel frame used by other researchers in experimental investigations [Leon and Shin, 1995], is considered in this study. It is a two-story two-bay frame. The span of each bay is 4.06 m and the story height is 1.88 m. W6x25 wide flange section is used for the interior columns and W6x20 for the exterior columns. All beams are made of W8x18. All beams and columns are made of A36 steel. The connections consist of top and seat angles (L6 x 3 1/2 x 5/16) and web angles (2L3 1/2 x 2 1/2 x 1/4) and are made of A36 steel. More details of the frame are discussed elsewhere [Leon and Shin, 1995].

The Richard Model and the Masing rule [Reyes-Salazar and Haldar, 1999] are used to represent the behavior of PR connections during the loading, unloading and reloading process. To define the stiffness of the connections, a parameter called the T ratio is introduced. It is the ratio of the moment the connection would have to carry [Disque, 1964] and the fixed end moment of the beam. Using the Richard Model, the T ratio for the above connection is estimated to be 0.3, representing a very flexible connection.

RESULTS AND OBSERVATIONS

To evaluate the energy dissipation by different sources, the frame is excited laterally by a sinusoidal load of the form $p(t) = P_o \sin \omega t$, applied at the top, where P_o *and* ω are the amplitude and the frequency of the excitation, respectively. The energy dissipated at PR connections (E_C), by viscous damping (E_D) and at plastic hinges (E_P) are estimated for the frame. The response of the frame, in terms of the top lateral displacement for a P_o of 22,500 N, ω of 6 rad/sec, ζ (viscous damping expressed in terms of critical damping) of 1% and a T ratio of 0.3, is shown in Fig. 1. It can be observed that the lateral displacement approaches the steady state response after a few cycles. The dissipation of energy per cycle for each source is calculated for the steady state phase of the response.

To make the observation meaningful, different combinations of P_o, ω, ζ and the T parameter are selected for the parametric study. For each combination, all terms in Eq. (1) are calculated. The maximum lateral displacement d_{max}, E_C, E_D and E_P (if plastic hinges are formed) are presented in this paper.

The results for P_o of 8100 N, ω of 3, 6 and 9 rad/sec, ζ of 1, 2, 5 and 10%, and a T ratio of 0.3 are presented in Table 1. The fundamental frequency of the frame, ω_1, with a T ratio of 0.3, is found to be 10.6 rad/sec. The frame did not develop any plastic hinge, and thus E_P is not shown in Table 1. To study the importance of dissipation of energy at PR connections, relative to that due to the viscous damping, a parameter R_1 is introduced. It is defined as $R_1 = (E_C / E_D) \times 100\%$ and is shown in Table 1. It is observed from this table that for a given ω, d_{max} and E_C decrease and E_D increases with an increase in the damping values, as expected. Also, as ω decreases, indicating moving away from the resonance condition, the d_{max} values decrease. The most important observation that can be made is that, for low damping values (ζ = 1 and 2 %) expected in a typical steel frame, the R_1 values are large, indicating that the dissipation of energy at PR connections may be comparable to that dissipated by viscous damping. Also, if d_{max} and the rotation of PR connections remain large, either due to low damping or as the frame approaches the resonance condition, the energy dissipation at PR connections becomes significant. Thus, large deformation of the frame is essential to have significant energy dissipation at PR connections.

The effect of the stiffness of PR connections is studied next. The same frame is considered again with a connection represented by a T ratio of 0.6 and 0.9. The fundamental frequencies of the frame with these connections are 12.8 and 13.9 rad/sec, respectively. The frame is excited by the same sinusoidal load considered when the T ratio was 0.3. The frame did not develop any plastic hinge. The results for the T ratio of 0.6 are shown in Table 2. It is observed that the E_C and R_1 values significantly decrease with the increase in the connection stiffness. The results for the frame with a T ratio of 0.9 are not shown here due to lack of space. However, E_C and R_1 are practically zero.

The effect of the connection stiffness on the dissipation of energy at PR connections can be observed by comparing Figs. 2 and 3. The moment and the corresponding rotation at the PR connection located at the top left hand joint of the second floor for P_o of 22,500 N, ω of 6 rad/sec, ζ of 1% and T ratios of 0.3 (Fig. 2) and 0.6 (Fig. 3) are plotted in these figures for a few cycles of vibration. It is clearly observed that the dissipated energy (area under the M-θ curve) is much larger for the frame with more flexible connections.

As stated earlier, large deformation of the frame is essential to have significant dissipation of energy at PR connections. To study the effect of large deformation of the frame (lateral displacement and rotation at PR connections), the same frame is considered with three different connection stiffness given by T ratios of 0.3, 0.6 and 0.9, respectively. In this case the amplitude of the sinusoidal excitation is adjusted in such a way that the frame undergoes significant deformation in all cases. The results are not shown here due to lack of space. However, they demostrate that if the frame undergoes significant deformation, the dissipation of energy is comparable and may be even larger than that dissipated by viscous damping.

In all cases discussed earlier, plastic hinges did not develop in the frame. To study the importance of the dissipation of energy at plastic hinges with respect to dissipation of energy by viscous damping and at PR connections, the same frame with a T ratio of 0.9 is considered. The magnitudes of the load are adjusted so that the frame develops two or three plastic hinges and the energy dissipated in them (E_P) is calculated. The results are summurized in Table 3.

For the ease of discussion, two additional parameters, R_2 and R_3 are introduced. R_2 represents the ratio of the energy dissipated at PR connections to that dissipated at plastic hinges or $R_2 = (E_C / E_P) \times 100\%$, indicating their relative importance. R_3 represents the ratio of the energy dissipated at plastic hinges to that dissipated by viscous damping or $R_3 = (E_P / E_D) \times 100\%$.

Results in Table 3 validate all the observations made on R_1 in the previous cases. It is observed that E_P decrease as damping increases, as expected. It is important to note that, since the E_P values shown are close to the lower limit, R_2 and R_3 are close to the upper and lower bounds, respectively. The E_P values will increase as the frame develops more plastic hinges on its way to failure. E_C becomes less significant relative to E_P if more plastic hinges develop. For low damping values, the dissipation of energy at plastic hinges is comparable and sometimes larger than that dissipated by viscous damping.

CONCLUSIONS

After the failure of connections of steel frames during the Northridge Earthquake of 1994, increasing the rotational capacity of partially restrained (PR) connections, and thus the energy dissipation capacity in steel frames, has become a major research topic in post-Northridge investigations. The major sources of energy dissipation, including the energy dissipated at PR connections, are comprehensively addressed in this paper. Traditionally, only dissipation of energy due to viscous damping (E_C) and due to the hysteretic behavior of the material (E_P) are considered. However, the dissipation of energy at PR connections (E_C) may be also significant. The dissipation of energy at each source is evaluated by using a sophisticated algorithm developed and implemented in a computer program by the authors. The frame is subjected to a sinusoidal dynamic load applied at the top. This analytical study confirms the behavior observed in experimental investigations: PR connections reduce the the overall stiffness of frames but add a major source of energy dissipation. This is particularly significant if the connection is very flexible. Therefore, for flexible frames PR connections may be one of the most important sources of energy dissipation in steel structures. However, a frame with flexible connections must satisfy the lateral deformation requirements. For low damping values, expected in typical steel frames, the dissipation of energy at PR connections is comparable and may be even larger than that dissipated by viscous damping. As the connections becomes stiffer, the contribution of PR connections to energy dissipation becomes less significant. Also for low damping values the dissipation of energy at plastic hinges is comparable to that due to viscous damping and increases as the frame approaches to failure.

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