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ASEISMIC DESIGN OF MULTI-STORY SPACE FRAMES

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SUMMARY

The inelastic behavior of a six-story space frame is investigated under the simultaneous action of the two horizontal components of El-Centro-1940 earthquake. The response is compared with elastic and inelastic behavior of constituent plane frames subjected to individual components. The results indicate that inelastic interaction has a significant effect on the response.

1. INTRODUCTION

The inelastic behavior of structures under dynamic loads has received considerable attention during the last two decades. In the design of structures subjected to occasional loads, such as the dynamic loads due to strong motion earthquakes and blasts, it is now generally accepted that the excursion of structural material into inelastic range must be permitted to achieve economical and safe design. This realization has led to extensive research in the inelastic behavior of structures for such loads. Early investigations in this area were based on the considerations of energy input, the elastic energy capacity and the energy dissipated through inelastic deformations, without obtaining a detailed response of the structure [1,2,3]. The availability of high speed digital computers, permitting step-by-step integration of large systems, stimulated detailed studies by several investigators [4,5,6,7,8,9,10]. In these and other similar investigations, the inelastic response of framed structures is obtained under the following simplifying assumptions:

(i) A three-dimensional framed structure is treated as an assemblage of plane frames along each of its principal directions.

(ii) The yield behavior at a section is assumed to depend only on flexure, neglecting the effect of axial and shear forces.

(iii) The response is obtained on the basis of a preassumed moment-rotation (or curvature) relationship of either general yielding [9,10], bilinear [7,8] or elastic-perfectly-plastic type [4].

Since the behavior of a structure during inelastic excursions is nonlinear, the principle of superposition is not applicable, and a response analysis treating a space frame as an assemblage of plane frames subjected to in-plane ground motion is not valid. It is necessary to model a framed structure as a space frame subjected to simultaneous action of ground motion components. A general theory, incorporating the effects of inelastic interactions on the dynamic response of space frames, was developed and applied to a simple space frame in 1967 [11,12]. Since then, several investigators have studied inelastic response of space frames, including the effects of work-hardening [13,14,15,16,17]. The work has also been extended to R/C frames [18].

In this paper, the behavior of a six-story building frame is investigated under the simultaneous action of two horizontal components of El. Centro, 1940 earthquake. The response is compared with the elastic and inelastic behavior of constituent plane frames subjected to individual components investigated by PENZIEN [4]. The results indicate that inelastic interaction has a significant effect on the response.

2. THEORY OF INELASTIC INTERACTION

A framed structure consists of an assemblage of discrete one-dimensional elements interconnected at their ends. Consider a section of such an element and assume that:

(i) Stress-strain relation is elastic-perfectly-plastic.

(ii) The yield behavior at the section is described by an yield surface [11]:

$$\Phi(\bar{Q}) = 1$$

such that
the section is elastic if $\Phi(\bar{Q}) < 1$ (1)

or if $\Phi(\bar{Q}) = 1$ and $\dot{W}^p < 0$ (2)

the section is yielding if $\Phi(\bar{Q}) = 1$ and $\dot{W}^p \geqslant 0$ (3)

where $\bar{Q}$ is the generalised force vector at the section, $\bar{q}$ is the generalised displacement vector at the section, and

$$\dot{W}^p = \langle \bar{Q}, \dot{\bar{q}}^p \rangle \tag{4}$$

representing the rate of plastic work.

Under above assumptions it can be shown that at a regular point on the yield surface [11]

$$\bar{Q} = [K] (\bar{q} - \bar{q}_o) \tag{5}$$

if the section is elastic, and

$$\bar{Q} = [K] \left(\dot{\bar{q}} - \frac{\langle K\dot{\bar{q}}, \frac{\partial \Phi}{\partial \bar{Q}} \rangle}{\langle K \frac{\partial \Phi}{\partial \bar{Q}}, \frac{\partial \Phi}{\partial \bar{Q}} \rangle} \frac{\partial \Phi}{\partial \bar{Q}}\right) \tag{6}$$

if the section is yielding.

$\bar{q}_o$ denotes the current position of equilibrium and K is the stiffness matrix.

The force-displacement relations for elastic and yielding behaviors of a one dimensional element can be derived on the basis of equations (5) and (6) [12]. If the effects of inelastic interaction are neglected, Equation (6) reduces to

$$\dot{Q}_i = 0 \quad \text{if} \quad |Q_i| = Q_{yi} \text{ and } \dot{W}_i^p \geqslant 0 \tag{7}$$

where Q_{yi} is the yield level of Q_i.

3. SIX-STORY SPACE FRAME

Consider a six-story space frame shown in Figure 1. The frame is identical in directions 1-1 and 2-2. The floors are assumed to rigid and remain parallel during lateral deformation. The elastic stiffness is such that the fundamental mode of vibration of the plane frames is triangular in shape. The damping is assumed to be viscous and proportional to story stiffness. The entire mass of the structure is concentrated equally at each floor level and the story heights are equal. The yield strength of each plane-frame is specified by a parameter, θ, defined as the ratio of the yield value of the base shear to the total weight of the structure based on idealised elastoplastic behavior shown in Figure 2(b). The yield value of the story shear, $(Q_i)y$, is assumed to be proportional to story stiffness k_i. Table 1 gives the stiffness, damping and yield strength characteristics of the frame.

Under the simplifying assumptions stated above, yielding in a story occurs at the top and bottom sections of the columns simultaneously. The forces acting at these sections are the axial force and bending moments and shear forces in directions 1-1 and 2-2. The yield behavior is governed by the interaction between these forces. If the effect of the axial force and shear forces is neglected, the yield behavior at a section is governed by the interaction between M_{i1} and M_{i2}, the bending moments in the directions 1-1 and 2-2. Since the story shear

$$Q_{ij} = \frac{8M_{ij}}{h_i} \qquad \begin{array}{l} i = 1,2,\ldots 6 \\ j = 1,2 \end{array} \tag{8}$$

the yield behavior of a story is identical to the yield behavior at the end sections and may be expressed in terms of the story shears Q_{i1} and Q_{i2}. Figure 2(a) shows the yield surface in the two dimensional force space. If the effects of interaction are neglected, the yield behavior reduces to idealised elasto-plastic behavior as shown in Figure 2(b).

3.1 Equations of Motion

The equations of motion of the space frame due to base excitation during an earthquake can be written in terms of story shear, Q_{ij}, and lateral displacement, u_{ij}, using Equations (5), (6) and (7). For the ith mass the equations of motion are:

$$m_i \ddot{u}_{1i} + c_i (\dot{u}_{1i} - \dot{u}_{1i-1}) - c_{i+1} (\dot{u}_{1i+1} - \dot{u}_{1i}) + (Q_{1i} - Q_{1i+1}) = m_i \ddot{Z}_1(t)$$

$$m_i \ddot{u}_{2i} + c_i (\dot{u}_{2i} - \dot{u}_{2i-1}) - c_{i+1} (\dot{u}_{2i+1} - \dot{u}_{2i}) + (Q_{2i} - Q_{2i+1}) = m_i \ddot{Z}_2(t) \tag{9}$$

where subscripts 1 and 2 denote directions 1-1 and 2-2 and i denotes the story as shown in Figure 1. Further

- m_i – ith mass;
- c_i – inter floor viscous damping coefficient in the ith story;
- u_{1i}, u_{2i} – the lateral displacements of mass m_i relative to the base;
- Q_{1i}, Q_{2i} – story shears in the ith story;
- $\ddot{Z}_1, \ddot{Z}_2$ – horizontal components of the ground acceleration during an earthquake.

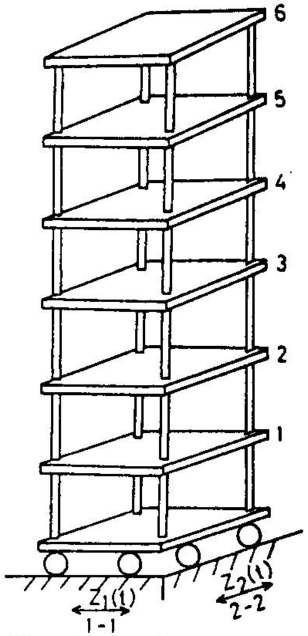

Fig. 1 Space Frame

Story	$\frac{K_i}{K_1}$	$\frac{C_i}{C_1}$	$\frac{(Q_i)_y}{(Q_1)_y}$
6	6/21	6/21	6/21
5	11/21	11/21	11/21
4	15/21	15/21	15/21
3	18/21	18/21	18/21
2	20/21	20/21	20/21
1	1	1	1

$M = \sum_{i=1}^{6} m_i$

$K_1 = \frac{14\pi^2 M}{T^2}$

$C_1 = \frac{14\pi M \zeta}{T}$

$(Q_1)_y = \theta M g$

Table. 1 Structural Properties of Space Frame

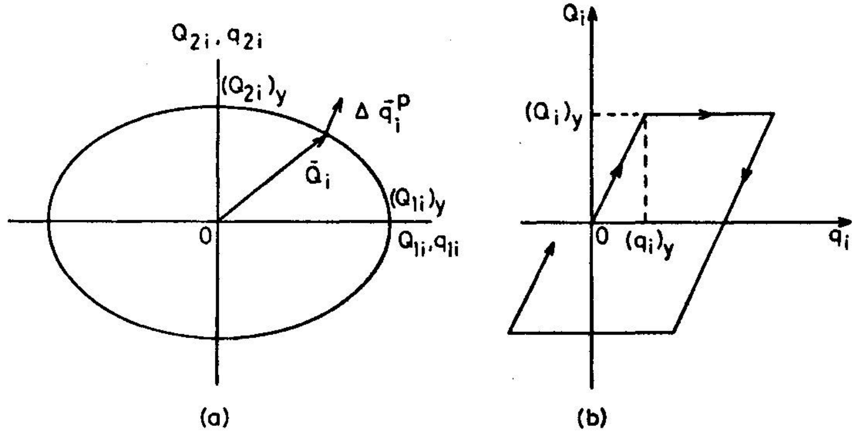

Fig. 2 Yield Surface for i th Story (a) With Interaction (b) Without Interaction

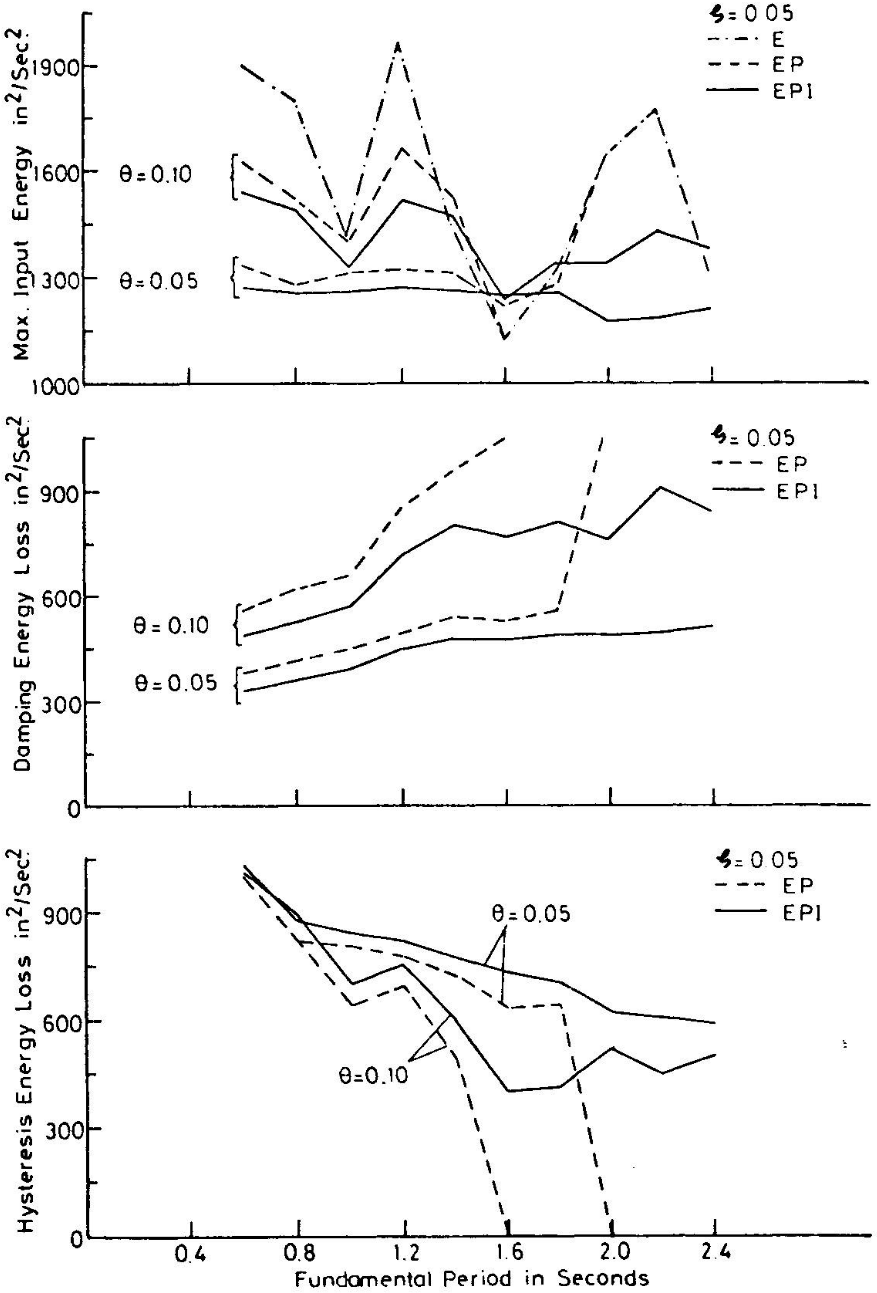

Fig. 3 Energy Input and Dissipation.

The relationship between story shears and story displacements depends upon whether the story is elastic or yielding. Further during yielding it depends upon whether the effects of inelastic interaction are included or ignored. For each of these three cases, the story shear-displacement relations can be derived using Equations (5), (6) and (7) as under:

Elastic Behavior (E)

$$\begin{aligned} Q_{1i} &= k_i\, q_{1i} \\ Q_{2i} &= k_i\, q_{2i} \end{aligned} \qquad (10)$$

where

$$\begin{aligned} q_{1i} &= (u_{1i} - u_{1i-1}) \\ q_{2i} &= (u_{2i} - u_{2i-1}) \end{aligned}$$

Elasto-Plastic Behaviour Without Interaction (EP)

$$Q_{1i} = k_i\,[q_{1i} - (q_{1i})_o] \quad \text{if } |Q_{1i}| < (Q_{1i})_y$$

$$\text{or if } |Q_{1i}| = (Q_{1i})_y \text{ and } \dot{W}^p_{1i} < 0$$

$$|Q_{1i}| = (Q_{1i})_y \quad \text{if } \dot{W}^p_{1i} \geq 0$$

$$Q_{2i} = k_i\,[q_{2i} - (q_{2i})_o] \quad \text{if } |Q_{2i}| < (Q_{2i})_y$$

$$\text{or if } |Q_{2i}| = (Q_{2i})_y \text{ and } \dot{W}^p_{2i} < 0$$

$$|Q_{2i}| = (Q_{2i})_y \quad \text{if } \dot{W}^p_{2i} \geq 0 \qquad (11)$$

Elasto-Plastic Behavior with Interaction (EPI)

$$\begin{aligned} Q_{1i} &= k_i\,[q_{1i} - (q_{1i})_o] \\ Q_{2i} &= k_i\,[q_{2i} - (q_{2i})_o] \end{aligned}$$

$$\text{if} \quad \Phi(Q_{1i}, Q_{2i}) < 1; \quad \text{or if } \Phi(Q_{1i}, Q_{2i}) = 1$$

$$\text{and } \dot{W}^p_i < 0 \qquad (12)$$

and

$$\dot{Q}_{1i} = \frac{k_i\left[\left(\frac{\partial\Phi}{\partial Q_{2i}}\right)^2 \dot{q}_{1i} - \frac{\partial\Phi}{\partial Q_{1i}}\frac{\partial\Phi}{\partial Q_{2i}}\dot{q}_{2i}\right]}{\left[\left(\frac{\partial\Phi}{\partial Q_{1i}}\right)^2 + \left(\frac{\partial\Phi}{\partial Q_{2i}}\right)^2\right]}$$

$$\dot{Q}_{2i} = \frac{k_i\left[-\frac{\partial\Phi}{\partial Q_{1i}}\frac{\partial\Phi}{\partial Q_{2i}}\dot{q}_{1i} + \left(\frac{\partial\Phi}{\partial Q_{1i}}\right)^2 \dot{q}_{2i}\right]}{\left[\left(\frac{\partial\Phi}{\partial Q_{1i}}\right)^2 + \left(\frac{\partial\Phi}{\partial Q_{2i}}\right)^2\right]}$$

if $\phi(Q_{1i}, Q_{2i}) = 1$ and $\dot{W}_i^p \geq 0$ (13)

It may be noted that for elastic (E) and elasto-plastic behavior (EP), the equations of motion are uncoupled in the directions 1-1 and 2-2 and can be integrated independently. For elasto-plastic behavior with interaction (EPI), the equations of motion are coupled.

3.2 Response Computation

The equations of motion of the space frame for elastic, elasto-plastic and elasto-plastic behavior with interaction are integrated using the fourth order Runge-Kutta method of step-by-step integration. First 30 seconds of the E-W and N-S components of El-Centro-1940 earthquake record are used as ground acceleration $\ddot{Z}_1$ and $\ddot{Z}_2$ respectively. The interval of integration $\Delta t = T/50$, where T is the fundamental natural period of the frame. The response is computed for yield strength parameter $\theta = 0.05$, 0.1, 0.2; damping ratio $\zeta = 0.05$ and fundamental period T varying from 0.6 to 2.4 secs. For elasto-plastic behavior with interaction, the yield surface is expressed by

$$\left[\frac{Q_{1i}}{(Q_i)_y}\right]^2 + \left[\frac{Q_{2i}}{(Q_i)_y}\right]^2 = 1 \qquad (14)$$

The response parameters computed are the energy input and energy dissipated due to damping and hysteresis during yielding; absolute displacements and ductility ratios; permanent set and number of inelastic excursions and plastic energy ratio for each story.

4. RESULTS AND DISCUSSION

Figure 3 shows the maximum energy input per unit mass to the space frame during the earthquake and the energy loss due to damping and hysteresis during yielding for elastic, and elasto-plastic behavior with and without interaction. The curves show that, in general, inelastic deformations reduce the energy input and interaction reduces it further, the reduction depending significantly on the yield strength parameter θ. The inelastic deformations reduce the energy dissipation due to damping and interaction reduces it further. This fact is significant in modern high-rise buildings with low damping as it implies less dependence on damping to limit the response. It is further seen that if the interaction is ignored, elasto-plastic analysis would indicate that the space frame remains elastic for ($T > 1.6$, $\theta = 0.1$) and ($T > 2.0$; $\theta = 0.05$), whereas, the frame will actually yield due to interaction.

Figure 4 shows the absolute displacements of the space frame in the two directions for the fundamental periods T = 0.6 and 1.2. It is seen from the curves that for T = 0.6, interaction causes a large increase in displacement over elastic and elasto-plastic behavior in both directions. For T = 1.2, there is a large increase in the direction 1-1 due to interaction, but the dis-

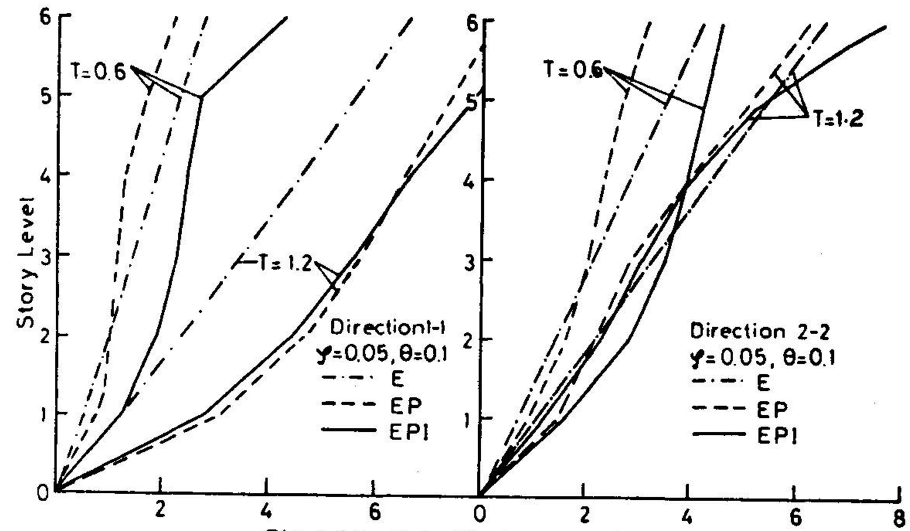

Fig. 4 Absolute Displacement in Inches

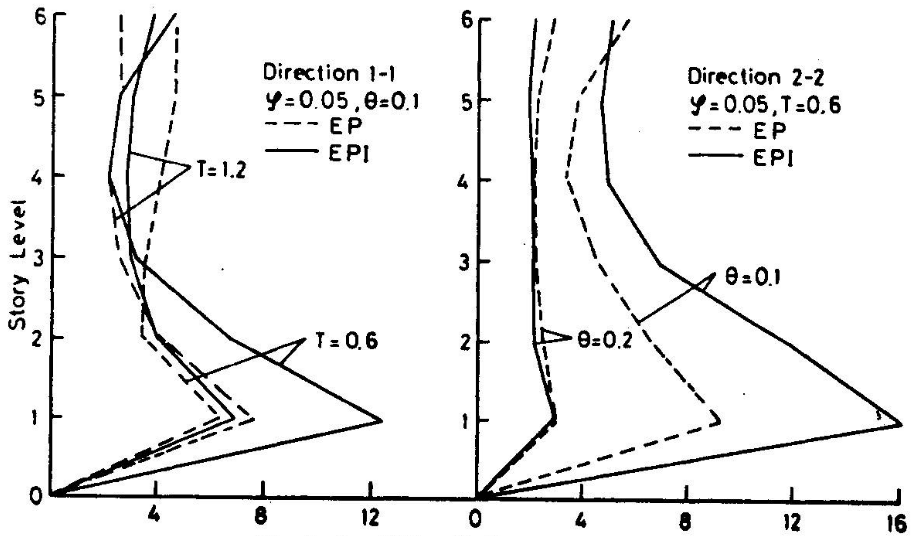

Fig. 5 Ductility Ratio.

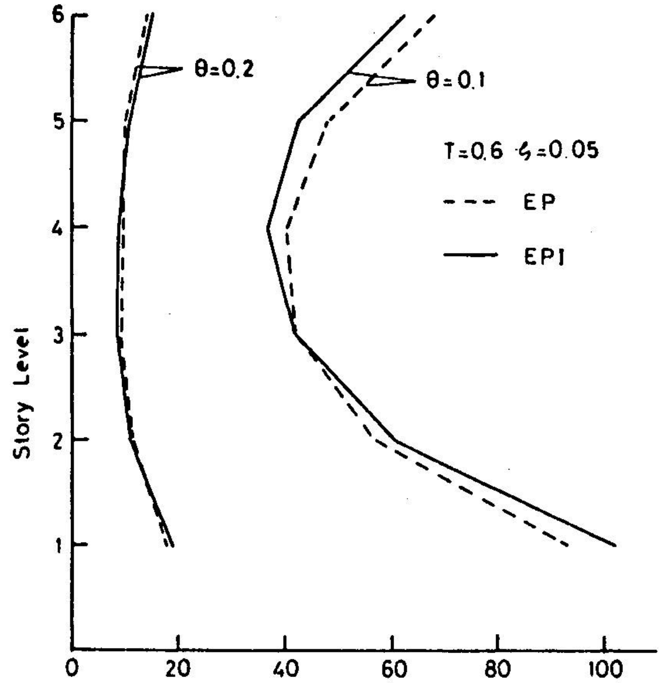

Fig. 6 Story Plastic Energy Ratio

Story	Permanent Set (ins)		No. of inelastic excursión	
	E - P 1 - 1	E P I	E P 1-1	E P I
1	0.036	0.656	30	55
2	0.03	0.280	29	50
3	0.0033	0.0403	27	48
4	-0.0426	-0.0198	29	47
5	0.00248	-0.112	34	50
6	0.099	-0.329	39	59

Table 2: Permanent Set and Number of Inelastic Excursions. θ = 0.1, T = 0.6.

placements are nearly same in the direction 2-2. Large interfloor displacements occur in the top and bottom storys due to inelastic behavior and interaction causes further increase suggesting the need to strengthen these storys. If the interaction effects are ignored, as in conventional plane frame elasto-plastic analysis, displacements may be grossly under estimated.

Figure 5 shows the ductility ratio in each story for $T = 0.6$, 1.2 and $\theta = 0.1$ in direction 1-1 and $T = 0.6$ and $\theta = 0.1$ and 0.2 in direction 2-2. It is seen that for $T = 0.6$ and $\theta = 0.1$, the ductility requirement is large in the top and bottom storys. For $T = 0.6$ and $\theta = 0.2$, the ductility requirement is significantly reduced and interaction effects are insignificant. Comparison of curves for $\theta = 0.1$ and 0.2 also indicates, what may happen to a structure designed for $\theta = 0.1$, if it is subjected to an earthquake of twice the intensity of the design earthquake. For $T=1.2$ sec and $\theta = 0.1$, the ductility requirement is low and interaction effects are significant only in the top story. On the basis of idealised elasto-plastic analysis of plane frames, PENZIEN [4] recommended optimum values of $\theta = 0.3$, 0.2 and 0.1 for $T = 0.3$, 0.6, 0.9 and more, respectively. Due to large computer time required, it has not been possible to study the response for several values of θ. However, on the basis of limited results and the fact that the general nature of response for elasto-plastic behavior, with and without interaction, is same, it appears that the above recommendations shall also apply to space frames. The large ductility requirements in top and bottom storys suggest strengthening of these storys to remain within acceptable limits for safe aseismic design.

Plastic energy ratio has been suggested as a criterion for inelastic design [11,12]. Figure 5 shows the plastic energy ratio in each story for $T = 0.6$ and $\theta = 0.1$ and 0.2. It is seen that unlike ductility ratio the effect of interaction on plastic energy ratio is small. Increase in θ from 0.1 to 0.2 decreases the ductility requirement significantly and makes it nearly uniform over the entire frame.

Table 2 gives the number of excursions in the inelastic range and the permanent set at the end of the earthquake in the direction 1-1. The behavior in direction 2-2 is similar. It is seen that elasto-plastic analysis without interaction grossly under estimates the number of excursions. This result is important because strength degradation during repeated yielding increases with the number of excursions in the inelastic range. The interaction significantly increases the permanent set in the top and bottom storys, which may determine the serviceability of the structure after an earthquake.

The inelastic behavior of the space frame has been analysed in terms of parameters governing inelastic design, such as, energy input and energy dissipated, lateral displacement, ductility ratio, plastic energy ratio, number of excursions into the inelastic range and permanent set. The overall behavior is consistent with the general findings of the earlier investigations based on simple space frames [11,13]. The results clearly show that the conventional elasto-plastic analysis, treating a space frame as an assemblage of plane frames, may significantly underestimate the ductility requirements in the low period range for small values of yield strength. The inelastic behavior is sensitive to the yield strength parameter, θ, which must be chosen carefully. Several codes specify stiffness distribution to give a triangular first mode. The results indicate the need to strengthen the top and bottom storys of such frames. The investigation did not take into account the P-Δ effect and the effect of work-hardening which may alter some of the conclusions.

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