THE EFFECTS OF LARGE DISPLACEMENTS ON THE EARTHQUAKE RESPONSE OF TALL STRUCTURES

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SUMMARY

This paper describes the modification of an inelastic frame analysis to include the effects of large displacements, and then the application to a twelve storey framed structure subjected to a variety of earthquake excitations. Comparisons are then made with results obtained from analyses ignoring these effects. The results are then reviewed in order to determine the nature of the problem, and when these second order effects should be considered,and discusses methods of limiting these displacements.

INTRODUCTION

Most analyses of multistorey frames subjected to earthquake excitation have ignored the secondary effects due to the combination of the gravitational forces and the large lateral displacements, the P-Delta effect. For designs where the lateral displacements are relatively small and the gravitational forces are not great, the neglect of the P-Delta effects is justifiable.

However, as taller structures are now being considered there has been an increasing interest in these P-Delta effects and on methods to control the resultant lateral displacements [1,2].

The problems are (i) at what level of lateral displacement are P-Delta effects considered to be significant and (ii) if they are significant, should control of the deformation be best achieved by increasing the stiffness or the strength of the members.

METHOD OF ANALYSIS

The computer analysis used is a development of the dynamic time-history analysis program for inelastic framed structures originally developed by Sharpe [3]. The program has been adapted to include the effects of large displacements occurring during the analysis so that at every time step the member properties are redefined in terms of the updated coordinates of all the joints in the frame. The disadvantage is a very great increase in the computational effort.

For a rectangular frame such as that occurring in many multi-storey buildings, the reduction in lateral stiffness, due to an increase in the column axial forces on one side, will largely be offset by the increase in lateral stiffness, due to the corresponding decrease in axial forces on the opposite side. Therefore, provided vertical accelerations are negli-

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gible, the total change in the lateral stiffness due to the combination of the interstorey drifts and the column axial forces may be considered as constant.

This initial reduction of lateral stiffness due to the gravitational loads may be carried out at the beginning of the analysis, resulting in a negligible increase in the computational effort when compared to analyses ignoring the P-Delta effects. The results described in this paper used this latter simplification.

THE FRAME EXAMPLE

The elasto-plastic frame used in the analysis was a typical interior reinforced concrete twelve storey two bay frame, designed in accordance with the proposed revisions to the New Zealand concrete design code [4] and loaded to the provisions of the New Zealand Standard 4203 [5] for seismic zone A. This provides for an equivalent static force analysis in order to determine the likely seismic resistance of the frame. The main principal component of the seismic load is determined from the base shear coefficient which is 0.150 g for fundamental periods below 0.45 seconds decreasing linearly with period to 0.075 g for periods above 1.20 seconds. The frame was loaded in its own plane. Further details and discussion of the design are given by Jury [6]. To simulate an equivalent design for seismic zone C the beam and column strengths were reduced by one third.

A Rayleigh damping model, using the initial stiffness, was assumed with 8 per cent of critical damping on modes 1 and 10, so that all modes were subcritically damped.

EARTHQUAKE EXCITATIONS

The earthquakes that were considered were (i) El Centro, May 1940, North-South, since the code level seismic shears and design drift limits are based on the likely response to an El Centro type earthquake, assuming a ductility level of four and the actual likely drifts being 2.4 times those computed using the equivalent static lateral forces; and (ii) Pacoima Dam as it represents the maximum likely intensity earthquake that would be expected to occur in the New Zealand seismic zone A.

RESULTS OF THE ANALYSES

The envelopes of the lateral storey displacements and the inter-storey drifts are shown in Figs. 1 and 2 respectively, while Fig. 3 shows the maximum plastic hinge rotations required at each floor in the girders and at the base of the ground floor columns.

For the El Centro record it will be noted that the P-Delta effect reduces the maximum displacements and in neither case does the inter-storey drift exceed the code recommended limit of 0.01 of the storey height. The plastic hinge rotations at each floor level are reasonably uniform and are well below the limit of 30 x 10^{-3} radians at which stage it becomes impractical to detail for the necessary ductility.

For the Pacoima Dam record, the P-Delta effect leads to a 40% increase in the top storey deflection and correspondingly large increases in the inter-storey drifts in the lower floors. The upper part of the structure appears to be protected by the large degree of yielding in the lower part of the structure.

Fig. 4 shows the percentage increase of maximum inter-storey drift due to the P-Delta effect versus the maximum inter-storey drift for analyses ignoring P-Delta. It is seen that if the maximum inter-storey drift without P-delta is less than about 0.015 of the storey height, then, for this building, the inclusion of P-Delta reduces the maximum response. This is most likely due to the fact that P-Delta increases the natural period from 1.880 seconds to 1.905 seconds. If the non-P-Delta drift was greater than about 0.02 of the storey height then the increase of the drift appears to be greater than 50% and tends to exceed the limit of practical detailing for the required plastic hinge rotation.

The Parkfield and Bucharest records were also run to represent the effects of a nearby moderate and a distant large earthquake respectively.

In an endeavour to determine the most practical way of controlling the increase of drifts due to P-Delta two further runs using the Pacoima Dam record were carried out. The first, increasing the stiffness by 25% but maintaining the original strength had an increase of maximum drift of 49% compared with that of the original frame with 62%, and the second analysis increasing the strength by 25% but maintaining the original stiffness reduced the increase of maximum inter-storey drift to 21%.

CONCLUSIONS

It has been found that provided the maximum inter-storey drifts due to the design earthquakes are not significantly greater than 0.01 of the storey height, then P-Delta may be justifiably ignored, but for greater inter-storey drifts the gravitational load leads to a rapidly increasing augmentation of the inter-storey drifts and quickly exceeds the ability of the structure to provide the necessary ductility. It also appears, that for inelastic frames, increasing the strength, rather than the stiffness offers the most effective means of controlling these increases in displacements.

REFERENCES

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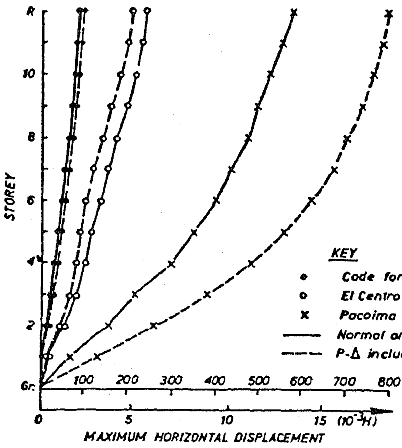

FIGURE 1

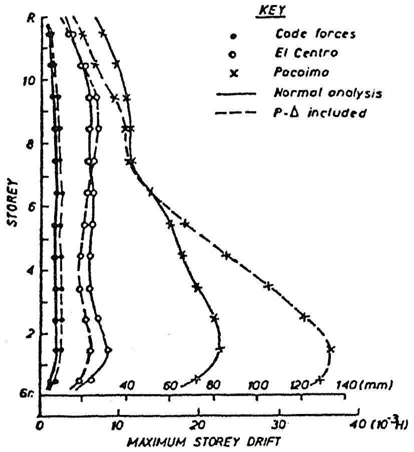

FIGURE 2

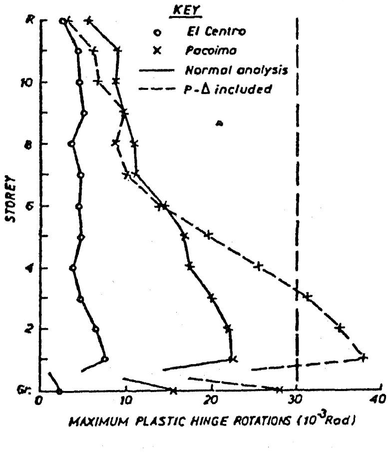

FIGURE 3

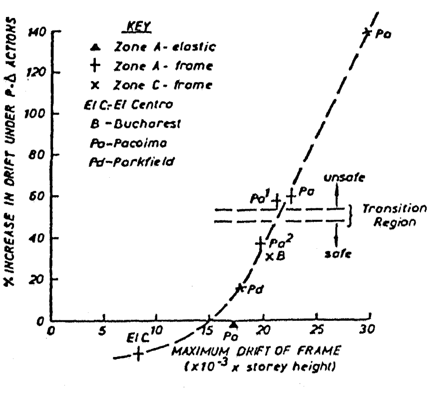

FIGURE 4