Copyright © 1996 Elsevier Science Ltd
Paper No. 1854. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SIGNIFICANCE OF ANCHORAGE SLIP ON DYNAMIC INELASTIC RESPONSE OF R/C FRAME STRUCTURES

M. SAATCIOGLU and J. ALSIWAT

Department of Civil Engineering, The University of Ottawa
Ottawa, Ont. CANADA K1N 6N5

ABSTRACT

Significance of anchorage slip in reinforced concrete frame structures was investigated for seismic analysis. A computer software, incorporating hysteretic behavior of deformations due to flexure, shear, and anchorage slip was used to conduct dynamic inelastic analyses of selected frame structures. The results indicate that deformations caused by anchorage slip can significantly alter individual member response. The overall structural response. however, may not be affected as much. The results further indicate that inelastic shear effects tend to be negligibly small in typical frame structures. Hysteretic behavior due to flexure and anchorage slip must be modeled for improved accuracy of seismic analysis of reinforced concrete frame structures.

KEYWORDS

Anchorage slip; bar slip; concrete; ductility; dynamic analysis; earthquake resistant design; hysteretic models; reinforced concrete; seismic design; slip.

INTRODUCTION

Reliability of dynamic inelastic analysis of reinforced concrete structures depends, to a great extent, on hysteretic modeling of structural components. Tests of reinforced concrete elements indicate that the total deformation of a member under lateral load reversals consists of components due to flexure, shear and anchorage slip (Saatcioglu and Ozcebe, 1989). Either one, two or all three of these deformation components may play significant roles on response depending on the geometric and loading conditions of a structure. Consequently, the omission of a deformation component may be a source of significant error in structural analysis.

Most frame structures consist of members with relatively high shear-span-to-depth ratios. Hence, they behave primarily in the flexure mode. Inelastic shear effects in such structures may be negligibly small except for stubby and short members. Anchorage slip, on the other hand, results from flexural behaviour and occurs when the critical section of a member is located near the adjoining member. This situation represents a great majority of structural elements in practice. Anchorage slip becomes significant when the longitudinal reinforcement in tension is strained into strain hardening.

The significance of deformations caused by anchorage slip has been investigated by developing a hysteretic model and conducting dynamic inelastic analyses. The results are presented and discussed in this paper.

DEFORMATIONS CAUSED BY ANCHORAGE SLIP

Reinforced concrete frame structures subjected to seismic excitations develop their critical sections near member ends. If a critical section near the end of a member is strained into the inelastic range of deformations, yielding of longitudinal reinforcement may penetrate into the adjacent member, resulting in extension of reinforcement outside the member in question. The extension of reinforcement within the adjoining member produces cumulative elongation of reinforcement at the interface of two members, often resulting in a wide crack at the interface. The extension of reinforcement becomes quite significant when tensile strains enter into the strain hardening range of reinforcement, which starts at approximately 0.6% to 1% strain. Reinforcement extension is the consequence of inelastic behaviour in flexure and does not necessarily signify inadequate detailing or lack of reinforcement anchorage. Therefore, this type of deformation is quite common in beams and columns, except when the level of axial compression is high.

Progression of yielding into the adjacent member reduces the length of anchorage. When the embedment length of reinforcement is not sufficient, the bar is strained to its end, resulting in slippage of reinforcement. While this may not necessarily prompt an anchorage failure, it does result in slippage of reinforcement which adds to the widening of the crack at the interface. Extension and slippage (if any) of embedded reinforcement produce a rigid-body rotation of the member at the end, which is referred to as anchorage slip. Because these deformations result from actions that take place outside the member, they are not included in flexural computations. Deformations due to anchorage slip have been measured to be as significant as those caused by flexure (Saatcioglu and Ozcebe, 1987). Figure 1 illustrates experimentally recorded displacement components in a test column.

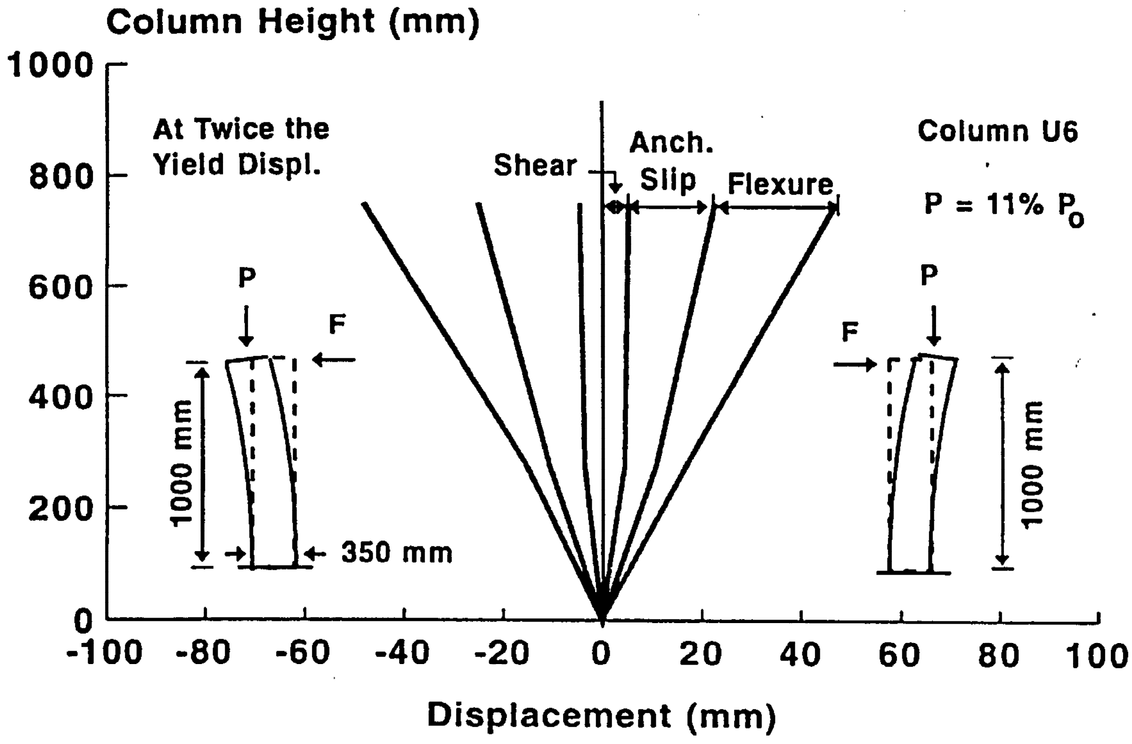


Fig. 1 Components of displacement in a typical test column (Saatcioglu and Ozcebe, 1989)

Computation of anchorage slip under monotonic loading

Anchorage slip has two potential components caused either by slip and/or extension of reinforcement. The extension of reinforcement can be computed by integrating steel strains within the embedment length. The reinforcement in this region may consist of elastic and inelastic segments. Alsiwat and Saatcioglu (1992) developed a simple analytical procedure to establish the strain distribution within the embedment length of reinforcement. Figure 2 illustrates the distribution of strains within various segments of reinforcement in concrete. The length of each segment is computed with due considerations given to bond stress between concrete and steel.

The bond stress used for the elastic segment is referred to as elastic bond, and is assumed to be uniform within the segment. The bond stress within the inelastic segment, including yield plateau and strain hardening regions, is taken to be equal to frictional bond. The length of each region is then computed from equilibrium of bar segments, using Eq. 1.

$$L = \frac{\Delta f_s d_b}{4u} \tag{1}$$

where, L is the length of each segment, Δf_s is the incremental steel stress between the beginning and end of a segment, d_b is the bar diameter, and u is the bond stress within a segment. The integration of the strain diagram (area under the curve), shown in Fig. 2, gives the cumulative extension of reinforcement (δ_{ext}) at the interface.

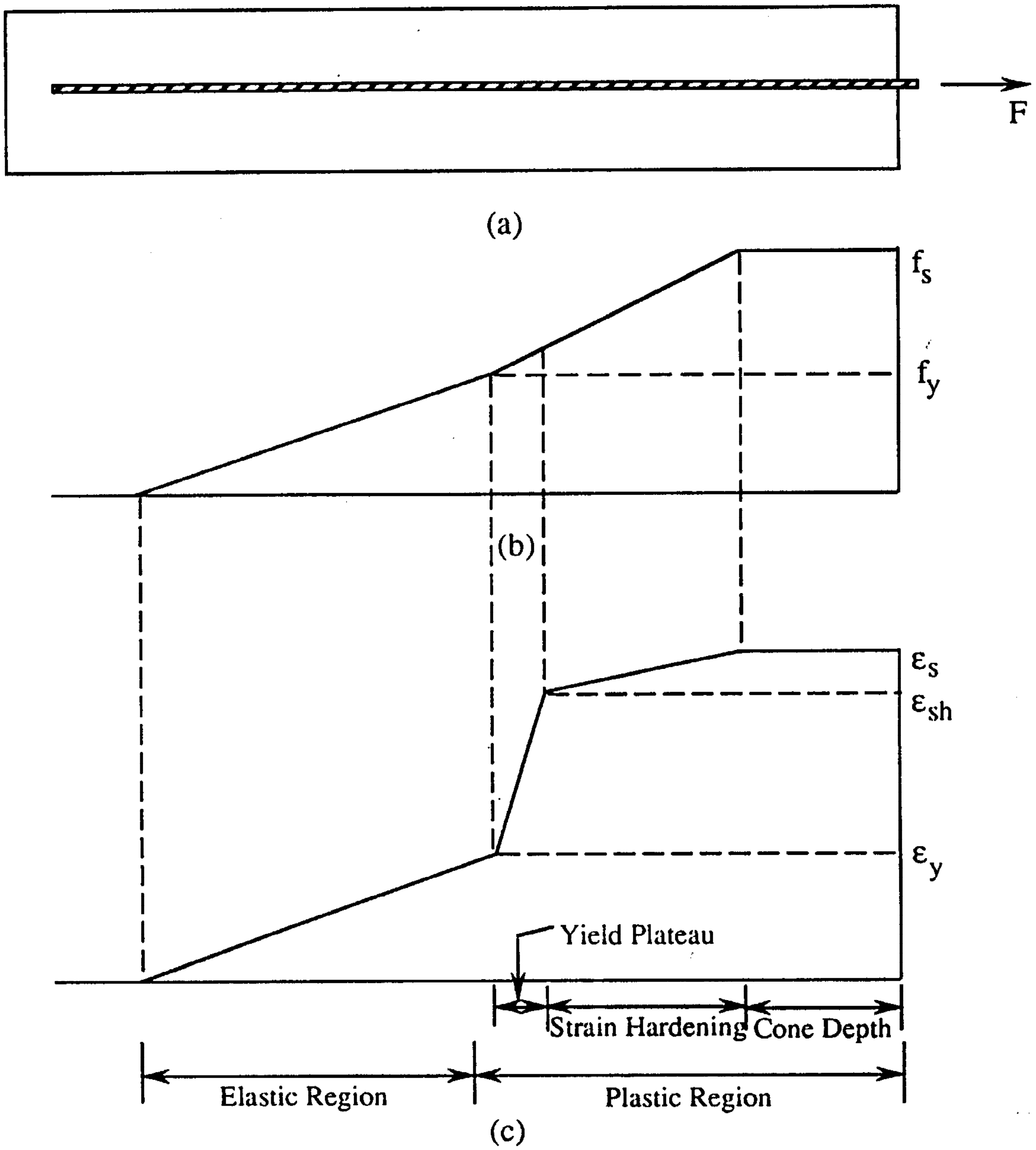


Fig. 2 Steel stress and strain distributions within the embedment length

Slip deformations develop when a bar is stressed throughout its entire embedment length. This usually occurs when the embedment length is small, and results in increased bond stresses within the elastic segment of the bar.

If the strain profile established by applying Eq. 1 indicates that the bar is strained until the far end, the bond stress increases within the elastic region to maintain equilibrium with reduced elastic length. The available elastic length can then be used in Eq. 1, in place of L, to solve for increased elastic bond stress. The slip increases with increased bond stress, following bond-slip relationship. The increase in slip continues until the ultimate bond stress is attained. Bar slip usually forms only a small fraction of total deformation due to anchorage slip.

Once the cumulative extension of reinforcement with or without the bar slip is computed at the end of a member, this value can then be used to compute member end rotation and displacement. This can be done by dividing the anchorage slip at the interface by a section depth about which the member is considered to be rotating. This depth may be taken to be equal to the distance between the reinforcement and neutral axis, as indicated in Eq. 2.

$$\Theta_{as} = \frac{\delta_{as}}{d-c} \tag{2}$$

Hysteretic Behavior of Anchorage Slip

The procedure described above can be used to establish the primary force-deformation relationship under monotonically increasing loading. This relationship can be employed to establish the hysteretic behavior of a member under reversed cyclic loading. A hysteretic model for anchorage slip was developed and extensively verified against experimental data by Saatcioglu, Alsiwat and Ozcebe (1992). Figure 3 illustrates the basic features of the model. The model consists of a bi-linear primary curve and incorporates the effects of asymmetric cross-sections and axial loads. Unloading branch is determined by computing the area of the plastic portion of strain diagram as unrecoverable deformation. The hysteretic rules for unloading and reloading branches were obtained from experimental observations.

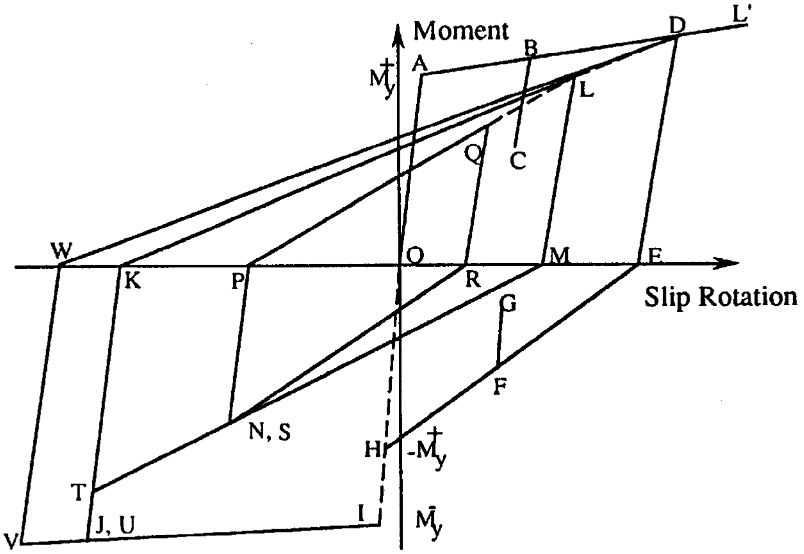


Fig. 3 Hysteretic model for anchorage slip (Saatcioglu Alsiwat and Ozcebe, 1992)

DYNAMIC INELASTIC ANALYSIS

Computer program DRAIN-2D (1973) was used to conduct dynamic inelastic response history analyses of selected structures. The program was modified substantially to incorporate two new hysteretic models to account for inelastic shear and anchorage slip effects, in addition to the existing flexural model that was developed by Takeda et al. (1970). The new models consisted of those developed by Ozcebe and Saatcioglu (1989) for shear, and Saatcioglu Alsiwat and Ozcebe (1992) for anchorage slip. Each hysteretic model was assigned to a separate spring in the mechanical member model, as illustrated in Fig. 4.

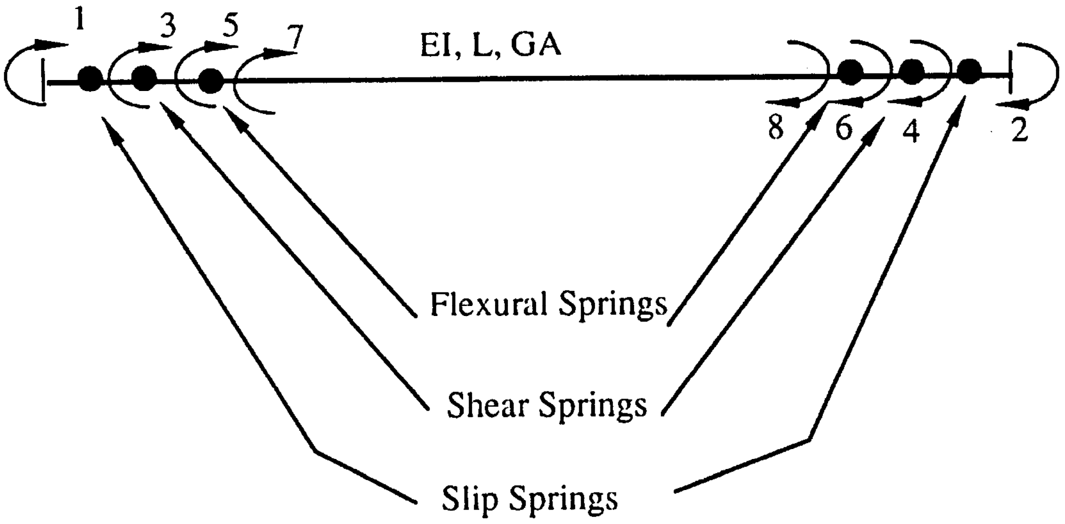
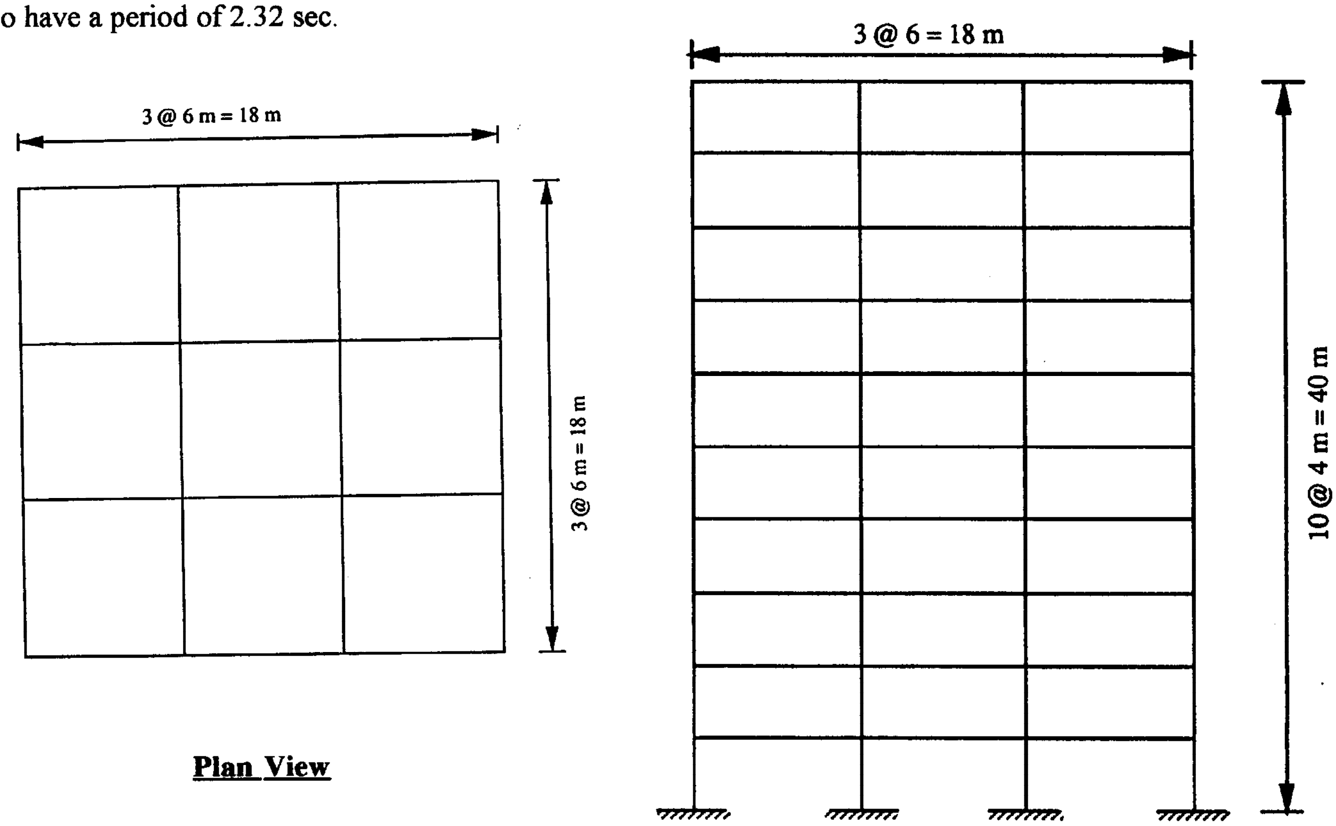


Fig. 4 Modified one-component model

A ten-story reinforced concrete frame structure was selected for analysis. The structure selected was an office building with a three-bay square plan. Geometric properties of the floor plan and elevation are given in Fig. 5. The structure was designed on the basis of the National Building Code of Canada (1990). Design parameters and structural properties are summarized in Table 1. The fundamental period of the selected structure was 3.21 sec. It was analysed using the E-W component of El Centro 1940 earthquake record, with accelerations normalized to have 0.5g as the peak acceleration. Because of the close interaction between the frequency of the structure and the frequency content of the exciting force, another structure with a different fundamental period was also selected. The second structures was obtained by changing the stiffness and mass of the original 10-story building to have a period of 2.32 sec.



Plan View

Fig. 5 Geometric properties of the 10-story frame structure used in dynamic analysis

Table 1 Properties of the frame structure considered in dynamic analysis

Fundamental Period	3.21 sec	Beam Yield Moments:	
Building Height	40 m	Floor Beams:	
Beam Stiffness Parameters:		$(M_y)_{positive}$	178 kN.m
Floor Beams:		$(M_y)_{negative}$	329 kN.m
EI	39,735 kN.m^2	Roof Beams:	
GA	1,441,662 kN	$(M_y)_{positive}$	137 kN.m
EA	4,676,537 kN	$(M_y)_{negative}$	220 kN.m
Roof Beams:			
EI	30,312 kN.m^2	Column Yield Moments:	
GA	1,463,313 kN	Exterior Columns	387 kN.m
EA	4,676,537 kN	Interior Columns	676 kN.m
Column Stiffness Parameters:			
Exterior Columns:		Ground Motion	
EI	22,690 kN.m^2	(1940 El Centro E-W)	
GA	1,552,756 kN	Intensity	0.5g
EA	5,261,104 kN	Duration	10 sec
Interior Columns:			
EI	42,214 kN.m^2	Mass:	
GA	2,388,000 kN	Floors	60,461 tons
EA	7,859,181 kN	Roofs	44,469 tons

The two 10-story frame structures with two different periods of vibration were subjected to 10 sec. of ground excitation using the computer software described above. Each building was analysed three times. In the first set of analyses inelasticity of flexural springs were considered while the springs simulating inelastic shear and anchorage slip were suppressed. The second and third sets of analyses included inelastic shear and inelastic anchorage slip springs, respectively, while also considering inelasticity in flexure. The results are presented in Figs. 6 and 7. The figures depict the overall behavior as represented by roof displacement time history and displacement envelope along the building height. The envelops of maximum flexural ductility ratios for beams are also presented along the height of the structure. The ductility ratios plotted in Fig. 7 are those reflecting flexural deformation demands, computed as the ratio of maximum flexural chord rotation to chord rotation at first flexural yielding. In the one-component model used for analysis, the chord rotations referred to are those that occur at the end of each member over a cantilever length of one half the member length. Hence, they may also be viewed as displacement ductility ratios at member ends.

The results clearly indicate that inelastic shear effects are negligible as expected. Typical frame members of reinforced concrete building structures have high shear span-to-depth ratios and hence do not develop significant shear deformations. The behavior of such structures is dominated by flexure. The effect of anchorage slip appears to be small on overall structural response, as indicated by roof displacement histories and horizontal displacement envelops. This can be explained by the fact that flexure and anchorage slip both contribute to softening of members within the inelastic range, and in the absence of one, the other action assumes the burden alone, producing similar rigidity while experiencing excessive degree of inelasticity. Therefore, when inelastic deformations due to anchorage slip are suppressed, inelastic deformations due to flexure increase excessively to absorb the seismic induced energy alone. This becomes evident in maximum flexural ductility ratios (flexural ductility demands), and has significant implications on structural design. Figs. 6 and 7 indicate that, depending on the interaction between the natural period of vibration of the structure and the frequency characteristics of the exciting force, the flexural ductility demand is increased between 15% and 42% when the anchorage slip is ignored. Since seismic resistant concrete frame elements are designed and detailed to improve flexural deformations, analysis results without the effects of anchorage slip would call for more stringent design and detailing than what is indicated by actual structural response. Therefore, the effect of anchorage slip on individual member response can be very significant, and the omission of this deformation component in seismic analysis may result in erroneous results.

SUMMARY AND CONCLUSIONS

The effect of anchorage slip was investigated on seismic response of reinforced concrete frame structures. Two frame structures with two different frequencies were considered for analysis. Each structure was analysed three times with various combinations of inelastic effects due to flexure, shear, and anchorage slip. The results indicate that inelastic shear effects can be ignored in dynamic inelastic analysis of typical frame structures without significantly affecting the results. However, deformations due to anchorage slip may play an important role on the flexural ductility demand, which is used to design and detail seismic resistant structures. While the effect of anchorage slip can be quite substantial on individual member behavior, the effect on overall response, as indicated by lateral deflections, may not be significant.

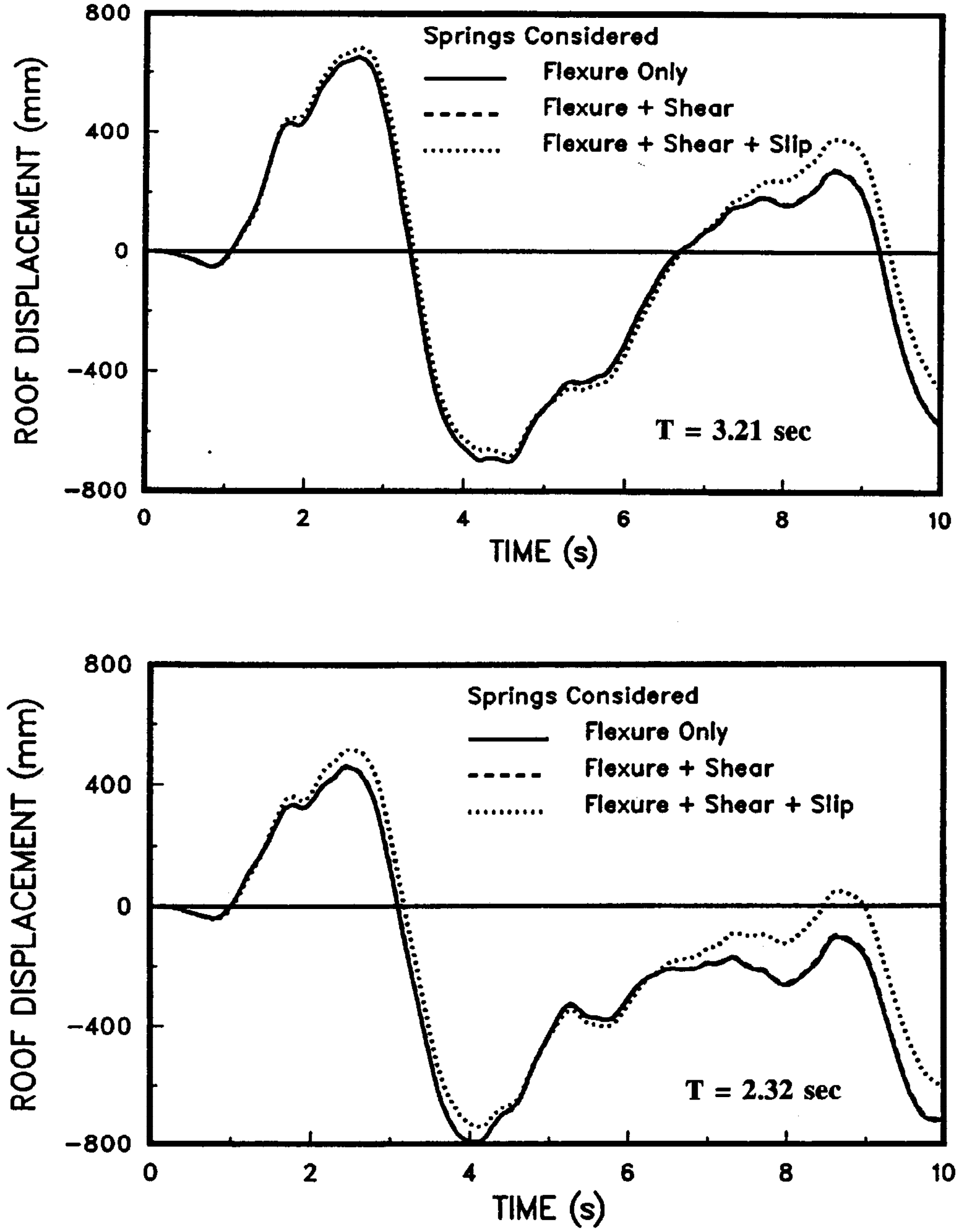


Fig. 6 Roof displacement history

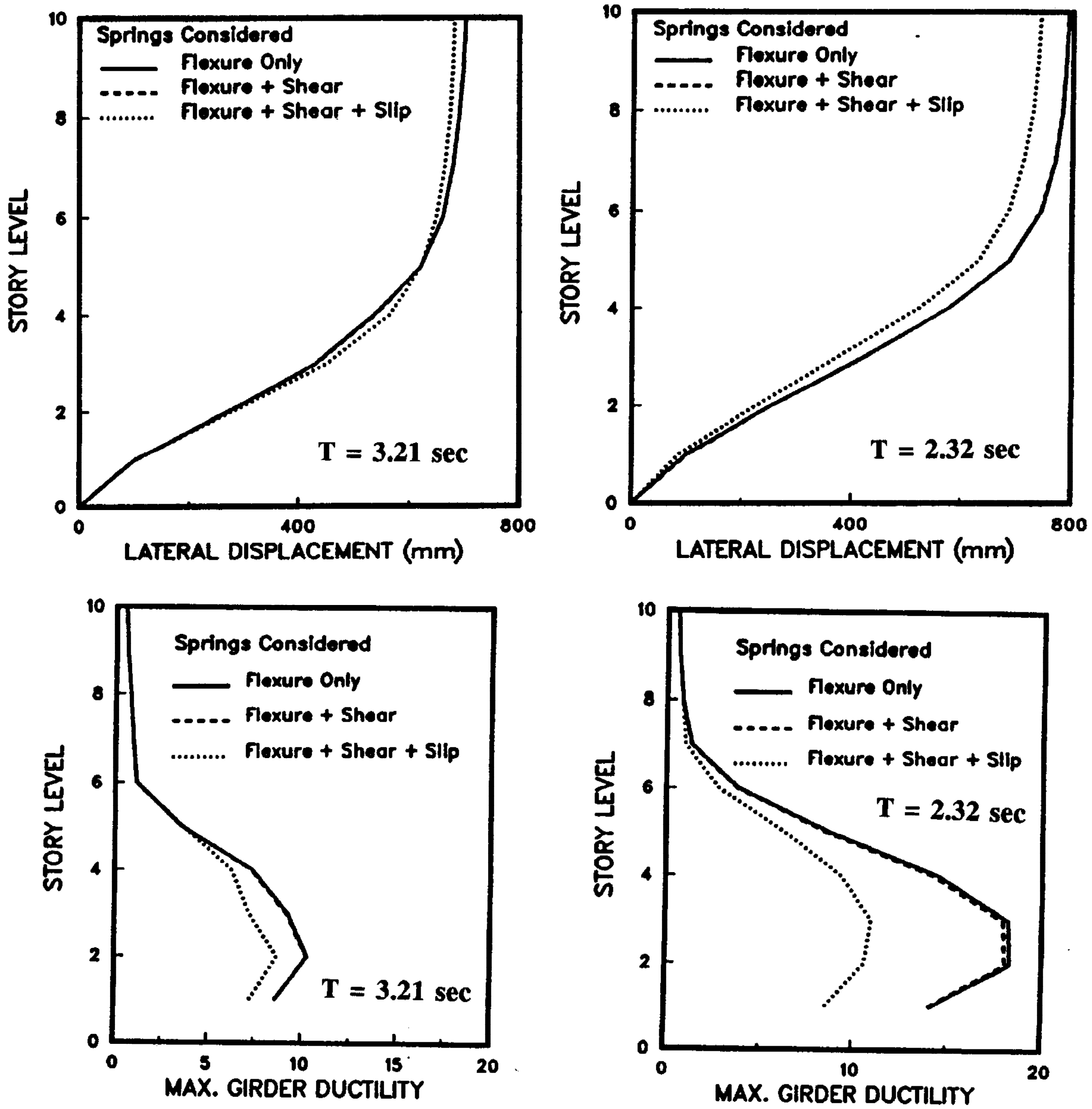


Fig. 7 Displacement and flexural ductility envelops

REFERENCES

Alsiwat, J., and Saatcioglu, M. (1992). Reinforcement anchorage slip under monotonic loading. *ASCE Journal of Structural Engineering*, 118. 2421-2438.

Kanaan, A.E. and Powell, G.H. (1973). Drain-2D User's Manual. Earthquake Engineering Research Center Report No. EERC 73-22, The University of California, Berkeley.

NBCC-National Building Code of Canada (1990). National Research Council of Canada, Ottawa, Ont. Canada.

Ozcebe, G. and Saatcioglu, M. (1989). Hysteretic shear model for reinforced concrete members. *ASCE Journal of Structural Division*, 115,. 132-148.

Saatcioglu, M., Alsiwat, J., and Ozcebe, G. (1992). Hysteretic behavior of anchorage slip in R/C members. *ASCE Journal of Structural Engineering*, 118. 2439-2458.

Saatcioglu, M. and Ozcebe, G. (1989). Response of reinforced concrete columns to simulated seismic loading. *ACI Structural Journal*, 86. 3-12.

Saatcioglu, M., and Ozcebe, G. (1987). Effect of bar slip on hysteretic behavior of concrete columns. Proceedings of the 5th Canadian Conf. on Earthquake Engineering, Ottawa, Ont., Canada. 833-839.

Takeda, T., Sozen, M.A., and Nielsen, N.N. (1970). Reinforced concrete response to simulated earthquakes. *ASCE Journal of the Structural Division*, 96. 2557-2573.