A SHEAR MODEL FOR RC STRUCTURES UNDER CYCLIC LATERAL LOADS

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SUMMARY

A shear model for RC members under cyclic lateral loads is presented in this paper. It describes the shear sliding in the critical regions and the shear distortion along the member. Under the action of a significant axial force the proposed shear model is capable of describing the interaction of axial force with the opening and closing of shear cracks. To establish the validity of the proposed model correlation studies of analytical results with experimental evidence of the load-displacement response of shear critical RC members and subassemblies under static load reversals are conducted. The analytical results generally show very good agreement with experimental results.

INTRODUCTION

In many practical situations macroscopic member models of reinforced concrete elements offer sufficient accuracy in the simulation of the seismic response of the structure. These models approximate the physical behavior of RC members and vary in their complexity from phenomenological point hinge models to layer and fiber models.

In the class of phenomenological models a new approach is followed in this study [D'Ambrisi and Filippou 1997, 1999; Filippou et al. 1999]. This approach consists of identifying the basic mechanisms which control the hysteretic behavior of critical regions and, if possible, isolating these mechanisms in individual subelements. Each member is then made up of a number of such subelements. In the following, a shear subelement is presented in detail. It describes the shear sliding in the critical regions and the shear distortion along the member. Under the action of a significant axial force, the model is capable of describing the interaction of axial force with the opening and closing of shear cracks.

The proposed nonlinear model is implemented in a computer program for the nonlinear static and dynamic analysis of RC structures [D'Ambrisi and Filippou 1997, 1999; Filippou et al. 1999] This paper focuses on analytical correlation studies of the nonlinear static response of shear critical RC members and subassemblies to cyclic alternating lateral loads.

REINFORCED CONCRETE FRAME ELEMENT

A reinforced concrete member is decomposed into subelements. Each subelement describes a different deformation mechanism that affects the hysteretic behavior of critical regions in RC elements. This modeling approach permits the simulation of the behavior of RC members subjected to, both, low and high shear stresses. The properties of subelements for the general case of a frame member with axial force are discussed in D'Ambrisi and Filippou [1999]. Girder subelements can be directly derived as a special case by setting the axial force equal to zero. In developing the different subelements, the interaction of axial load, bending moment and shear force with the opening and closing of the cracks is taken into account [D'Ambrisi and Filippou, 1999]. The

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following subelements are used in this study [D'Ambrisi and Filippou, 1999]: (1) an elastic; (2) a spread plastic; (3) an interface bond-slip; and, (4) a shear subelement. Since the presence of axial load affects the hysteretic behavior of frame members with high shear stress differently than that of members with low shear stress, the introduction of two separate subelements to account for the effect of shear and bond slip facilitates the accurate and rational description of the hysteretic behavior of reinforced concrete frame members with axial force. In addition to the effects of shear, flexure, slip of reinforcement and opening and closing of the cracks, the frame element also includes axial deformations and geometric P-Δ effects

SHEAR SUBELEMENT

There is considerable experimental evidence showing that the post elastic response of cyclically loaded members with conventional detailing of reinforcement can be affected by shear deformations in the inelastic zones [Atalay and Penzien 1975; Celebi and Penzien 1973; Mander et al. 1993; Ozcebe and Saatcioglu 1989; Pinto et al. 1995; Spurr and Paulay 1984; Zagajeski et al. 1978]. This is especially the case in members with low shear span to depth ratio a/d. The hysteretic shear force-deformation relation of these members is characterized by a stiffness reduction that depends primarily on the magnitude of inelastic load reversals and the number of post-yield load cycles.

Different models of shear behavior have been proposed in the literature [Atalay and Penzien 1975; Celebi and Penzien 1973; Ozcebe and Saatcioglu 1989; Roufaiel and Meyer 1987; Spurr and Paulay 1984]. It is not economical to model shear behavior in its full complexity in a model that will be used in the dynamic response analysis of large multi-degree-of-freedom structures. Practical limitations are imposed by the scope of the frame element idealization of the present study and by the lack of quantitative information about the response of severely cracked concrete under post-yield load reversals.

The model presented in this study is a simple phenomenological description of the shear distortion behavior of reinforced concrete members under severe cyclic loading. It is primarily directed at representing the aggregate interlock and the interaction of shear and axial forces with the opening and closing of the cracks. The model consists of a concentrated translational spring of zero dimension located at each member end. The two springs are connected by an infinitely rigid bar to form the subelement (Fig. 1a). The basis for the derivation of the flexibility matrix of this element is the section shear force-deformation relation. Equibrium yields the relation between shear force and end moments. The contragradient law of matrix analysis yields the relation between end rotations and shear deformation. It is thus possible to establish a relation between end moments and corresponding rotations which takes the form

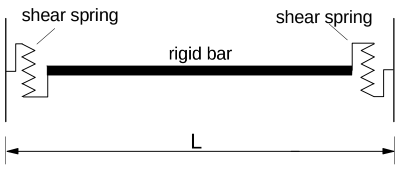
$$\boldsymbol{\theta}_{shr} = \mathbf{f}_{shr}\,\mathbf{M} \tag{1}$$

where the flexibility matrix of the shear subelement $\mathbf{f}_{shr}$ takes the form

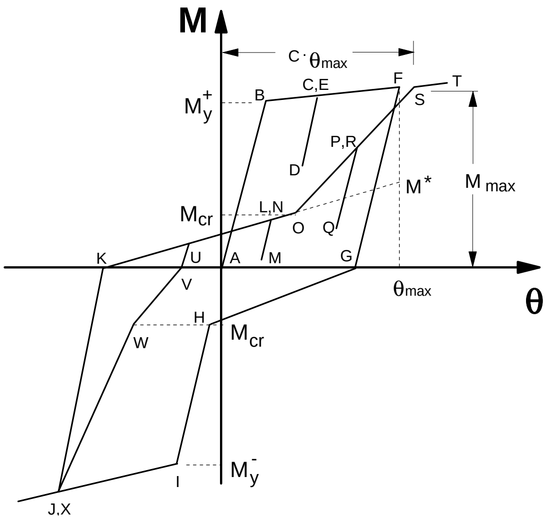
$$\mathbf{f}_{shr} = \frac{f_s}{L^2}\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \tag{2}$$

f_s is the flexibility (inverse of the tangent stiffness) of the section shear force-deformation relation and depends on the monotonic envelope and the hysteretic model. The flexibility matrix of the shear subelement is not invertible on its own, as is well known from structural analysis. It becomes invertible only after the addition of the flexural contribution. The monotonic envelope of the section shear force-deformation relation is derived with the modified compression field theory [Vecchio and Collins 1986]. The hysteretic shear force-deformation relation is reported in Fig. 1b and is described in detail in D'Ambrisi and Filippou [1999].

The effect of axial load on the shear behavior of the element is included as follows: (a) The axial load increases the yield moment capacity of the column section and, thus, delays the opening of flexural cracks due to yielding of flexural reinforcement. This, in turn, delays the propagation of flexural-shear cracks and results in a reduction of shear sliding. The axial load effect is taken into account in the derivation of the primary curve of the shear force deformation relation with the modified compression field theory. (b) The axial load reduces the pinching effect due to sliding. The pinching parameters of the column shear subelement result in a larger amount of pinching with decreasing axial compression.



(a)



(b)

Figure 1: Shear Subelement: (a) Shear Distortion Distribution; (b) Shear Subelement Deformation

CORRELATION WITH EXPERIMENTAL RESULTS

The proposed member model is implemented in a computer program for the nonlinear static and dynamic analysis of reinforced concrete structures [D'Ambrisi and Filippou 1997, 1999; Filippou et al. 1999]. To validate the shear subelement and its interaction with the other subelements, the program is used to simulate the hysteretic response of shear critical reinforced concrete members and subassemblies under cyclic lateral loads. The selected specimens have a small span to depth ratio, so that the effect of high shear plays an important role in the hysteretic response. The first specimen was designed and tested by Celebi and Penzien [1973] to simulate reinforced concrete beams under the combined action of bending moment and shear. The second specimen was designed and tested by Atalay and Penzien [1975] to simulate reinforced concrete columns under the combined action of bending moment, shear, and axial load. The third specimen in the correlation studies was a 1/2.5 scale model of a RC bridge pier and was tested at the European Laboratory for Structural Assessment in Ispra by Pinto et al. [1995].

Celebi and Penzien [1973] tested a series of beams with different span to depth ratios. The selected specimen carried the designation of #12 and had a span to depth ratio of 2.3. Atalay and Penzien [1975] tested a series of columns with different span to depth ratios and constant axial force. The selected specimen carried the designation of #3 and was subjected to a an axial force of 267 kN. The design of both specimens satisfied the general requirements of Appendix A of the 1971 ACI Code, Special Provisions for Seismic Design. The test setup for both specimens was the same, except for the application of the axial force in the series by Atalay and Penzien [1975]. A single concentrated lateral load was applied at midspan of both specimens. The load history of the specimens was similar, as shown in Fig. 2 and 3 except for the magnitude of the imposed lateral displacement. The load history of the ISPRA specimen consisted of lateral displacement cycles with increasing amplitude (1, 2, 4, 6, 8 and 10 mm), followed by three cycles at a displacement ductility of 1.5 (18 mm), three cycles at a displacement ductility of 3 (36 mm) and, finally, three cycles at a displacement ductility of 6 (72 mm).

The analytical model for the simulation of the hysteretic behavior of these specimens consists of frame elements made up of an elastic, a spread plastic, an interface bond-slip, and a shear subelement with the exception of the ISPRA specimen, where a concentrated plastic subelement was used for flexure and the interface bond-slip subelement was not activated as reinforcing bar pull-out was not significant in the squat bridge pier. The parameters of the constituent subelements are derived from the material and geometric properties of the specimens. With the measured stress strain relations of concrete and reinforcing steel, the section geometry, and the reinforcement layout the monotonic moment-curvature relation of a typical member section can be established with well known principles of reinforced concrete analysis. The parameters for the elastic and spread plastic subelement are determined from the moment-curvature envelope of the member end section. The parameters of the interface bond-slip subelement are determined from the monotonic moment-fixed end rotation envelope. This envelope can be established from a simplified analysis of pull-out deformations under the assumption of a uniform bond stress distribution in the anchorage zone of the reinforcing bars and with due account of the bond damage in the cover of the member into which the bars are anchored. These calculations are presented in Appendix A of EERC Report 92-08 [Filippou et al. 1992]. The parameters of the shear force deformation relation are established with the modified compression field theory [Vecchio and Collins 1986]. The resulting shear force-distortion relation of the ISPRA specimen is shown in Figure 4. The parameters of the different subelements for these specimens are listed in Tables 1, 2 and 3.

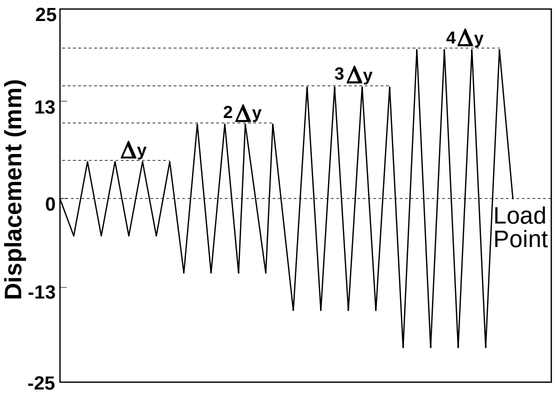


Figure 2: Load History of Specimen #12 by Celebi and Penzien (1973)

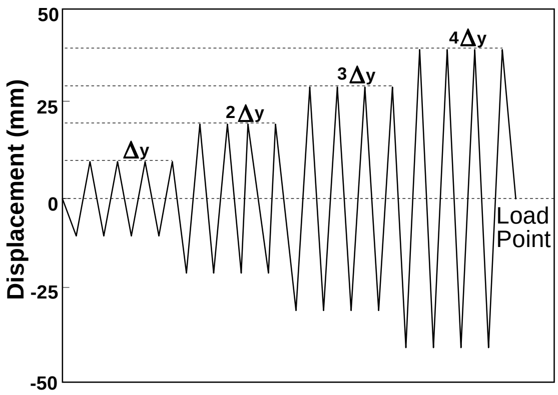


Figure 3: Load History of Specimen #3 of Atalay and Penzien (1975)

Table 1: Model Parameters for Specimen #12 by Celebi and Penzien (1973)

Moments [kN-m]		MOMENT-CURVATURE RELATION		INTERFACE MOMENT-ROTATION RELATION		SHEAR FORCE DISTORTION RELATION	
Mcr	28	INITIAL STIFFNESS	STRAIN HARDENING	INITIAL STIFFNESS	STRAIN HARDENING	INITIAL STIFFNESS	STRAIN HARDENING
M+	88	7.8	0.017	28	0.04	94	0.035
M-	85	7.8	0.017	28	0.04	94	0.035

Table 2: Model Parameters for Specimen #3 by Atalay and Penzien (1975)

Moments [kN-m]		MOMENT-CURVATURE RELATION		INTERFACE MOMENT-ROTATION RELATION		SHEAR FORCE DISTORTION RELATION	
Mcr	34	INITIAL STIFFNESS	STRAIN HARDENING	INITIAL STIFFNESS	STRAIN HARDENING	INITIAL STIFFNESS	STRAIN HARDENING
M+	103	11.4	0.02	17	0.04	71	0.025
M-	101	11.4	0.02	17	0.04	71	0.025

Table 3: Model Parameters for Squat Bridge Pier Specimen by A.V. Pinto et al. (1995)

Moments [kN-m]		MOMENT-ROTATION RELATION		INTERFACE MOMENT-ROTATION RELATION	SHEAR FORCE DISTORTION RELATION	
Mcr	---	INITIAL STIFFNESS	STRAIN HARDENING	NOT INCLUDED	INITIAL STIFFNESS	STRAIN HARDENING
M+	3640	1380	0.03		360	0.012
M-	3640	1380	0.03		360	0.012

Figure 5 shows the experimental and analytical lateral load-displacement relation of specimen #12 by Celebi and Penzien [1973]. Figure 6 shows the correlation of the lateral load-displacement relation for the specimen #3 by Atalay and Penzien [1975]. Finally, Figures 7 and 8 show the lateral load-displacement relation and the local shear force-distortion relation of the ISPRA specimen by A.V. Pinto et al. [1995], respectively.

A careful study of the results leads to the following conclusions: (a) Excellent agreement between analytical and experimental results is generally observed. (b) The shear subelement can accurately model the shear effects in the post yield range of response of reinforced concrete girders. (c) The pinching of the hysteretic behavior of the girder caused by the interaction of shear forces with the opening and closing of the cracks is simulated well by the analytical model. This effect is important in short span members, as clearly exhibited by the local shear force-distortion relation of the ISPRA specimen, and must be taken into account in order to accurately predict the energy dissipation of the member. (d) The strength degradation is not very significant in the first two specimens, but is a bit more pronounced in the ISPRA specimen with a shear span ratio of 1.75 in the post-yield cycles; in any case it is captured well by the proposed shear subelement (e) The pre-yield stiffness of the specimen is underestimated in the early stages of loading, because the model does not take into account the stiffness change between the uncracked and cracked state. The model uses instead a secant pre-yield stiffness, since emphasis is placed on predicting the response of RC members under large cyclic deformation reversals. A change to an appropriately defined trilinear envelope curve should be included in future versions of the model.

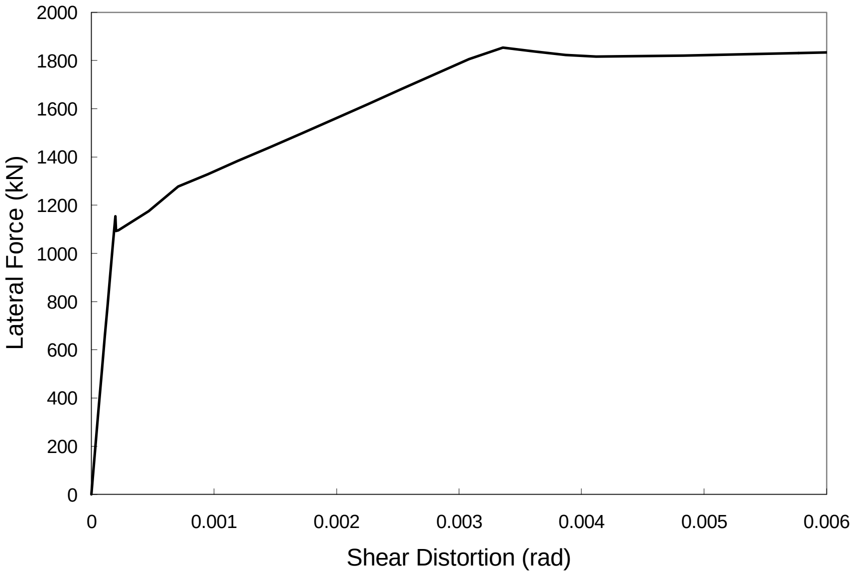


Figure 4: Shear Force-Deformation Relation by Modified Compression Field Theory of Squat Bridge Pier Specimen by A.V. Pinto et al. (1995)

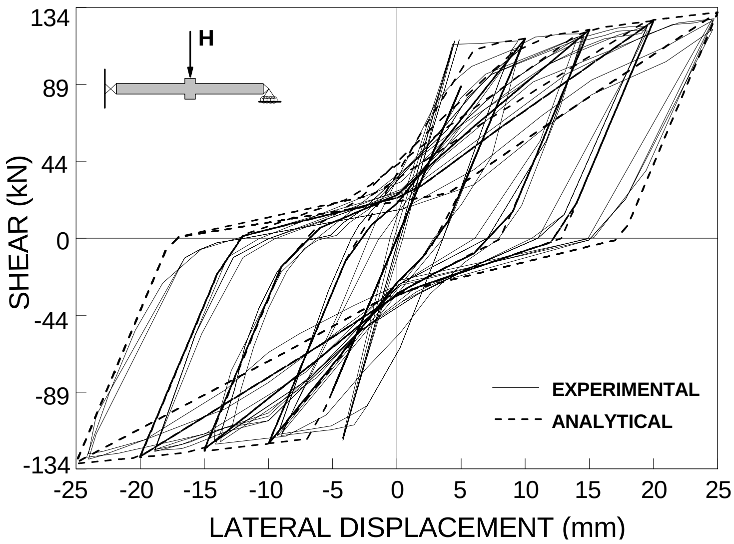


Figure 5: Lateral Load-Displacement Relation of Specimen #12 of Celebi and Penzien (1973)

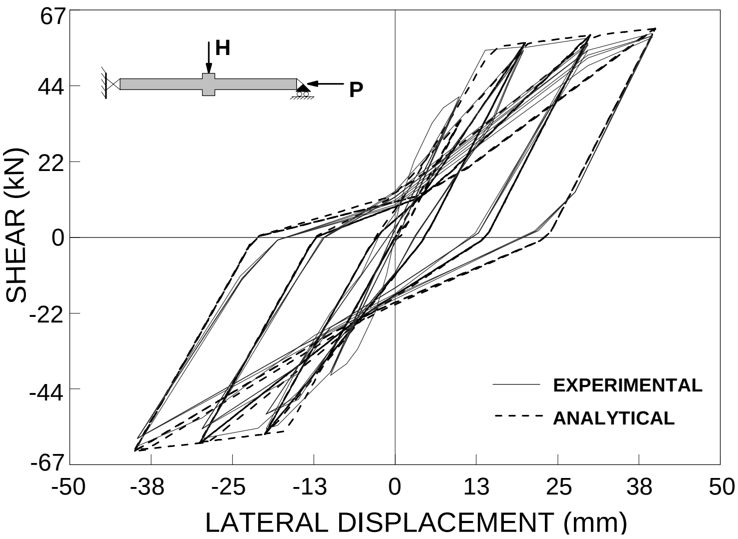


Figure 6: Lateral Load-Displacement Relation of Specimen #3 by Atalay and Penzien (1975)

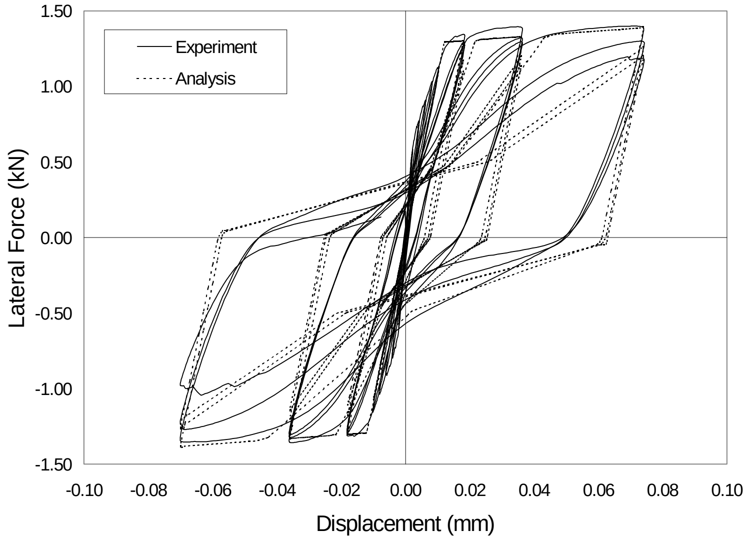


Figure 7: Lateral Force-Displacement Relation of Squat Bridge Pier Specimen by A.V. Pinto et al. (1995)

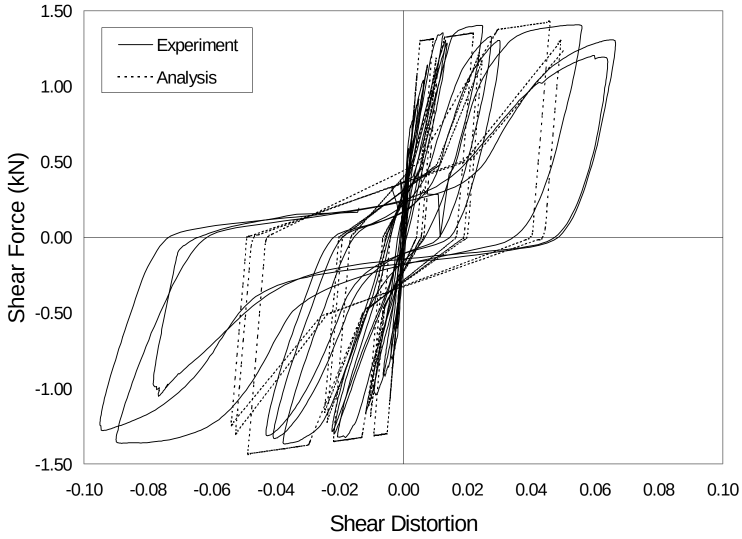


Figure 8: Shear Force-Distortion Relation of Squat Bridge Pier Specimen by A.V. Pinto et al. (1995)

It is particularly encouraging that the model can correctly identify the contributions of the individual deformation mechanisms, as is evident in Fig. 8 which shows the correlation between the shear force-distortion relation for the squat bridge pier specimen of ISPRA. The discrepancy in the negative direction of loading in Fig. 8 raises doubts about the accuracy of the experimental data, as the lack of symmetry in the measured shear distortions is puzzling, particularly, in the early post-yield cycles.

CONCLUSIONS

A shear model for RC members under cyclic lateral loads has been presented in this paper. It describes the shear sliding in the critical regions and the shear distortion along the member. Under the action of a significant axial force, the model is capable of describing the interaction of axial force with the opening and closing of shear cracks.

The proposed model has been used to simulate the nonlinear static response of shear critical RC members and beam-column subassemblages to cyclic lateral loads. Very good agreement between analytical and experimental results has been generally observed. It is particularly encouraging that good agreement has been also obtained in the local shear force-distortion correlation, which confirms that the model can identify correctly the contribution of the different deformation mechanisms. Future extensions of the model need to account for the uncracked and cracked stiffness of reinforced concrete members by permitting a trilinear monotonic envelope for the flexure and shear force-deformation relation and for the eventual softening of flexural and shear strength due to cyclic damage. This can be accomplished with a more sophisticated hysteretic model.

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