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Important issues in the seismic shear response of reinforced concrete

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ABSTRACT

This paper highlights some important issues which, when combined with a model for monotonic shear response of reinforced concrete, can capture the seemingly complex behaviour of reinforced concrete membrane elements subject to reverse-cyclic shear. A rational model is proposed for the "pinched" hysteretic behaviour during shear strain reversal. In the model, the biaxial strain state during unloading and reloading of a membrane element subjected to reverse-cyclic shear is defined by the elastic and plastic strains in the two reinforcement directions, and the normal strain in the direction of the closing diagonal cracks. The normal strains in the direction of the opening cracks is assumed to be a consequence of the biaxial strain state. Both diagonal crack directions are assumed fixed. Similar to the results from recent membrane element tests, which are examined in detail in this paper, the model predicts that there is significant deviation in the direction of principal compression stress and the direction of minimum principal strain at low levels of shear stress.

INTRODUCTION

The performance of concrete structures during the recent Loma Prieta, Northridge and Kobe earthquakes has clearly demonstrated that our understanding of the fundamental mechanisms involved in the seismic shear response of reinforced concrete is inadequate.

The approach taken in the design of new structures is to use a conservative shear strength model to design the transverse reinforcement and limit the maximum shear stress. This approach seems reasonable for structures where shear response can be effectively suppressed such as in a tall concrete wall. For shear dominated structures, such as short walls, the situation is more complicated. Even the design of structures that are not shear dominated will often have complex seismic shear design issues. For example, analysis of a tall building will often indicate very large shear reversals in the basement walls if they are included in the analysis, due to the rigid interconnection with floor slabs. The magnitude of the shear calculated for these walls is very sensitive to the assumed shear stiffness. Designers are then faced with questions such as to what extent will diagonal cracking reduce the shear stiffness, and does yielding of the transverse reinforcement constitute failure or simply a further softening of the wall.

In the seismic assessment of existing structures, the issues are further complicated by the fact that engineers must deal with the existing arrangement of reinforcement. A simple conservative shear strength model is not appropriate for making decisions on the need for a costly retrofit.

A long-term research project is being conducted at The University of British Columbia to develop rational methods for the design and assessment of reinforced concrete subjected to reverse-cyclic shear. The first phase of this work (Adebar et al., 1995) involved the testing of numerous beam and column elements to study the interaction of axial load, flexural ductility and degradation of seismic shear response. The present phase of the work is aimed at developing a fundamental understanding of the mechanisms involved in the seismic shear response of reinforced concrete.

Collins (1979) developed the concept of studying membrane elements subjected to uniform biaxial stress and strain in order to investigate fundamental issues of reinforced concrete subjected to shear. Stevens et al. (1991) conducted three large-scale tests on well instrumented membrane elements subjected to reverse-cyclic shear. A comprehensive analysis of that experimental data was undertaken, and this paper presents some important issues that were identified.

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MEMBRANE ELEMENT SUBJECTED TO SEISMIC SHEAR

Stevens et al. (1991) tested three 1600 mm square by 285 mm thick membrane elements that had different reinforcement and were subjected to different loading. This paper focusses on one particular specimen which was reinforced with 10M reinforcing bars spaced at 72 mm in the *y*-direction ($\rho_y = 1\%$) and 20M reinforcing bars spaced at 72 mm in the *x*-direction ($\rho_x = 3\%$). The yield strength of the *y*-direction reinforcement was 479 MPa, while the yield strength of the *x*-direction reinforcement was 492 MPa. The cylinder compressive strength of the concrete was 37 MPa. The test specimen had displacement transducers at various orientations to measure the average strain of the element over a 1200 mm square central area.

The element was first loaded in the positive direction to a shear stress of +4.5 MPa (Fig. 1). At a shear stress of +2.0 MPa, significant diagonal cracking occurred and the stiffness of the element reduced. When the shear stress was reversed, perpendicular diagonal cracking occurred at a shear stress of −2.2 MPa. The element was subjected to a total of four complete cycles between +/− 4.5 MPa shear stress. The uncracked shear stiffness of the element was about $G = 12{,}000$ MPa, which corresponds to what is expected for the given concrete strength and rate of loading. After diagonal cracking, the shear stiffness of the cracked reinforced concrete element reduced to about $G = 1200$ MPa, or one-tenth of the uncracked stiffness. During the initial load cycles, the hysteresis loops were very stable and there was very little energy dissipated.

The element was then cycled between +/− 5.75 MPa shear stress. At this shear stress level, yielding occurred in the *y*-direction reinforcement near each peak, and the resulting accumulation of plastic strains in the *y*-direction reinforcement is shown in Fig. 2. The increase in *y*-direction strain due to yielding resulted in a corresponding increase in shear strain at each cycle and an increased "pinching" of the hysteresis loops. The accumulated *y*-direction plastic strain also resulted in concrete damage which further reduced the effective stiffness of the element. After six cycles of loading beyond the yield point of the *y*-direction reinforcement, the effective stiffness had reduced to about $G = 600$ MPa, which is one-twentieth of the uncracked stiffness. The membrane element failed by crushing of the concrete at the seventh load cycle due to damage resulting from the accumulated strains.

Further details of the response are examined more closely below for one cycle of loading. The load cycle chosen is in the middle of the yield cycles, specifically starting at the second positive yield peak and returning to the third positive yield peak (see Fig. 3a).

Fig. 3(b) shows the orientation of the minimum principal average strain during the selected cycle. At the peaks of the cycle, this orientation is about 32° from the *x*-direction. The average biaxial stresses in the concrete were calculated from the applied total shear stress using a bare-bar model for the reinforcing steel. Fig. 3(b) shows the orientation of the calculated principal compressive stress, indicating an orientation of about 38° from the *x*-direction at the peaks of the cycle. Thus at the peak stress levels, the principal compression stress angle and principal compression strain angle deviate by 6°. This deviation is similar to what has been observed at the same strain levels in monotonic shear tests of membrane elements with similar relative amounts of reinforcement, i.e. 3 to 1 ratio (Meyboom, 1987). The modified compression field theory (Vecchio and Collins, 1986), which can predict the monotonic shear response of reinforced concrete, assumes that the principal compression stress and principal compression strain angles coincide. As these angles do not deviate significantly near the peak stress, the MCFT gives a reasonable prediction of the envelope of reverse-cyclic response. It predicts a principal angle which is approximately the average of the two angles.

Fig. 3(b) indicates that the principal stress and strain angles deviate much more at low shear stress values. For instance, when the shear stress is zero (point A), the stress angle is 0°, while the strain angle is +20°. Similarly, when the shear strain is zero (point B), the strain angle is 0°, while the stress angle is −28°. This large deviation of angles is an important characteristic of the cyclic response of reinforced concrete and must be accounted for. In their finite element formulation, Stevens et al. (1991) assumed that the principal direction of the concrete stress increment coincided with the principal direction of the strain increment.

The measured concrete stress-strain relationship is examined in Fig. 3(c) in terms of the minimum principal compression stress versus the minimum principal average strain. The Vecchio-Collins (1986) softened stress-strain relationship agrees well with the observed response at high shear stress values when the principal stress and principal strain are approximately in the same direction. In the low stress region (near point B), the minimum strain becomes tensile as re-loading occurs, while the minimum concrete stress remains compressive. The resulting "bulge" in the curve is a significant deviation from the typical stress-strain relationship of concrete. In previously developed analytical models for reverse-cyclic shear, complex empirical stress-strain functions have been used to mimic this effect.

RATIONAL MODEL FOR SHEAR STRAIN REVERSAL

A model was developed to explain the mechanisms involved during the shear strain reversal when diagonal cracks in the previous loading direction close and diagonal cracks in the current loading direction open. The model is able to explain the "pinching" of the hysteresis loops, the deviation of the principal stress and principal strain angles, as well as the unusual "bulge" in the concrete stress-strain response (see Fig. 4).

The model is depicted in Fig. 5 using the three reference points shown in Fig. 3. At point A (Fig. 5a) the element has been unloaded and the shear stress is zero. As the x-direction reinforcement had not previously yielded, all of the strain is assumed to be elastic and has recovered. The elastic strains in the y-direction reinforcement have also recovered, however, significant accumulated plastic strains remain. The normal strain parallel to the open cracks is assumed to be zero. These three normal strain components define the complete biaxial strain state, which is summarized by the Mohr's circle shown in Fig. 5(a). At this point the shear strain is positive and the minimum principal strain is compressive. The sketch of the deformed membrane element illustrates that the cracks from the previous load cycle remain open at this point.

As shear stress is applied in the new direction of loading, the shear strain of the element reduces. At point B, the element is at the point of zero shear strain. Due to the applied shear stress, there are diagonal compression stresses in the concrete and associated tensile stresses in the reinforcement. The reinforcement stresses produce additional elastic strains in the x and y directions compared to point A. The diagonal compression stresses in the concrete cause the previous direction crack widths to reduce. An empirical crack closing model is used to relate the diagonal compression stress to the normal strain resulting from the reduced crack widths. Thus, the complete biaxial strain is defined by the x-direction elastic strain, y-direction elastic and plastic strains, and the normal strain in the previous crack direction. This strain state is shown in the Mohr's circle in Fig. 5(b). The opening of the current direction cracks is assumed to be a consequence of the other three strain components. At this point, the two sets of cracks are open an equal amount and the minimum principal strain is tensile. This corresponds to the point of maximum "bulging" shown in Fig. 3(b).

Once sufficient shear stress has been applied (point C), the previous direction cracks close completely due to the high diagonal compression normal to the cracks. At this point, the x-direction and y-direction strains have increased significantly due to additional elastic strains. From this point, the behaviour is similar to a membrane element under monotonic loading.

A computer program was written to implement the model described above. The results are presented in Fig. 4 for a single cycle of loading, corresponding to the experimental cycle shown in Fig. 3. The reference points A, B, and C are also shown on the analytical prediction. The analytical model tracks the accumulation of plastic steel strains. The concrete stress-strain relationship is linear for unloading and reloading, and the Vecchio-Collins (1986) softened parabola is used once the previous cracks have closed. Crack strains are considered explicitly, and are based on a fixed crack angle. The stress and strain angles are calculated independently, without any assumption linking the two together.

Fig. 5(a) indicates that the overall shear stress - shear strain behaviour is well predicted. The unloading in the model is simpler and more linear than actual, but the reloading curves and the envelope match well. The predicted principal compression stress angles and principal compression strain angles are shown in Fig. 5(b). These angles diverge similar to the experimental values during the shear strain reversal. Fig. 5(c) shows the predicted relationship between the concrete principal compression stress and the minimum principal strain. The unusual "bulge" observed in the experimental relationship is also present in the analytical prediction.

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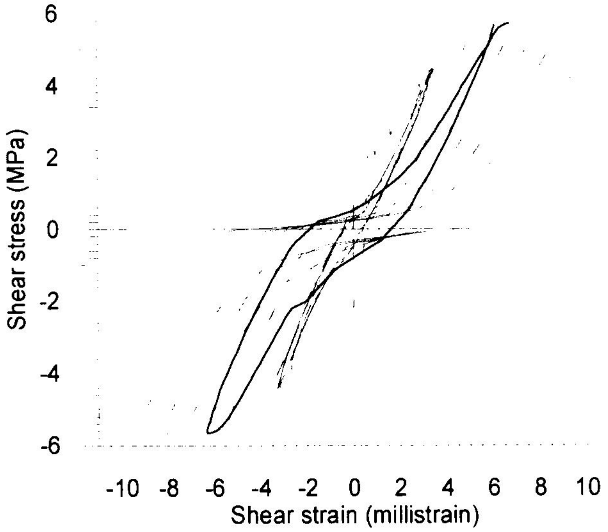

Fig. 1 - Shear response of membrane element

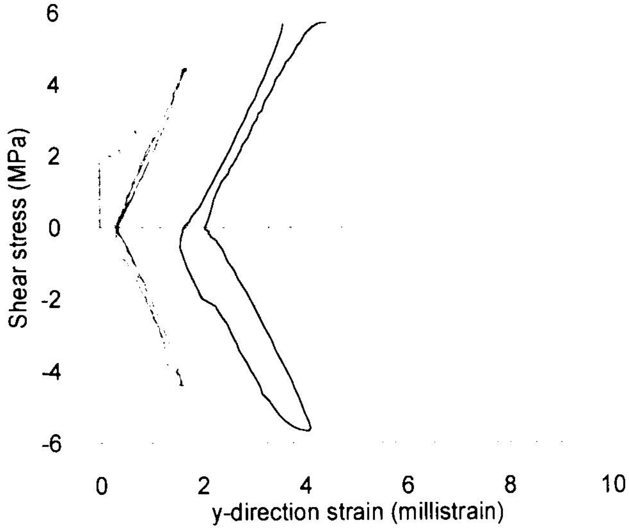

Fig. 2 - Accumulation of y-direction strain

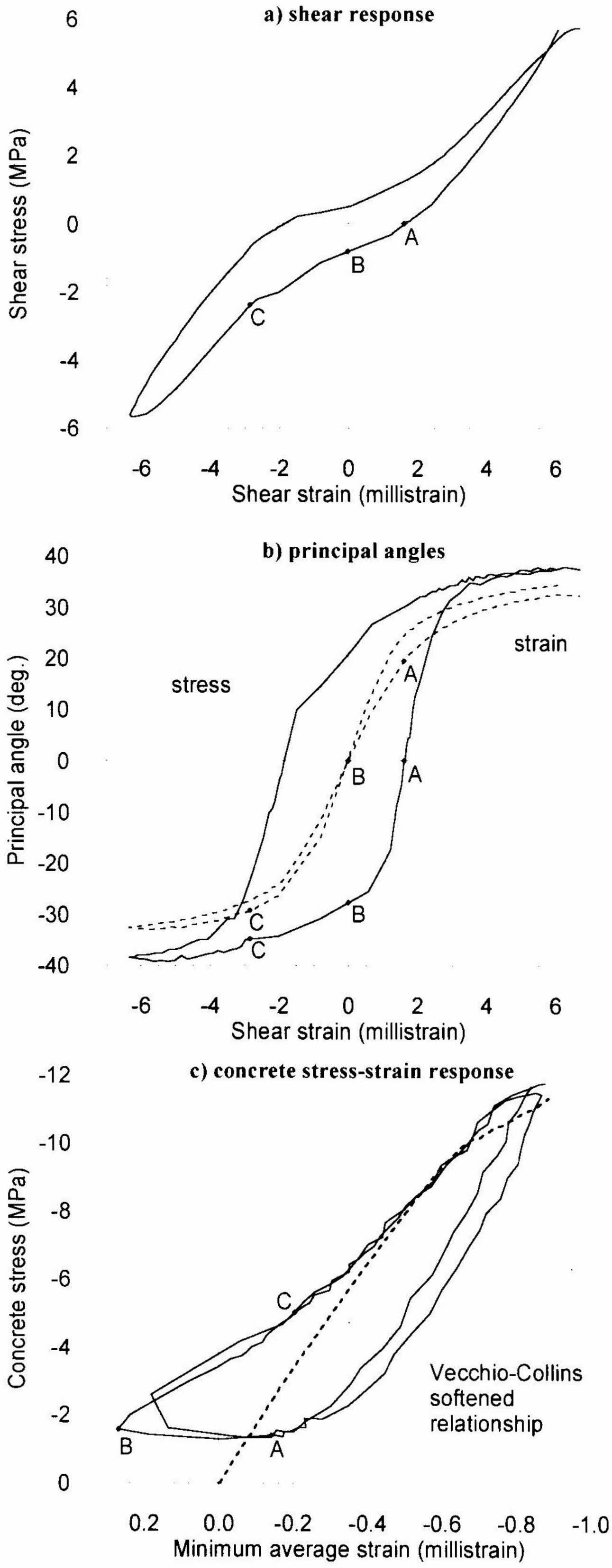

Fig. 3 - Experimental data, single cycle

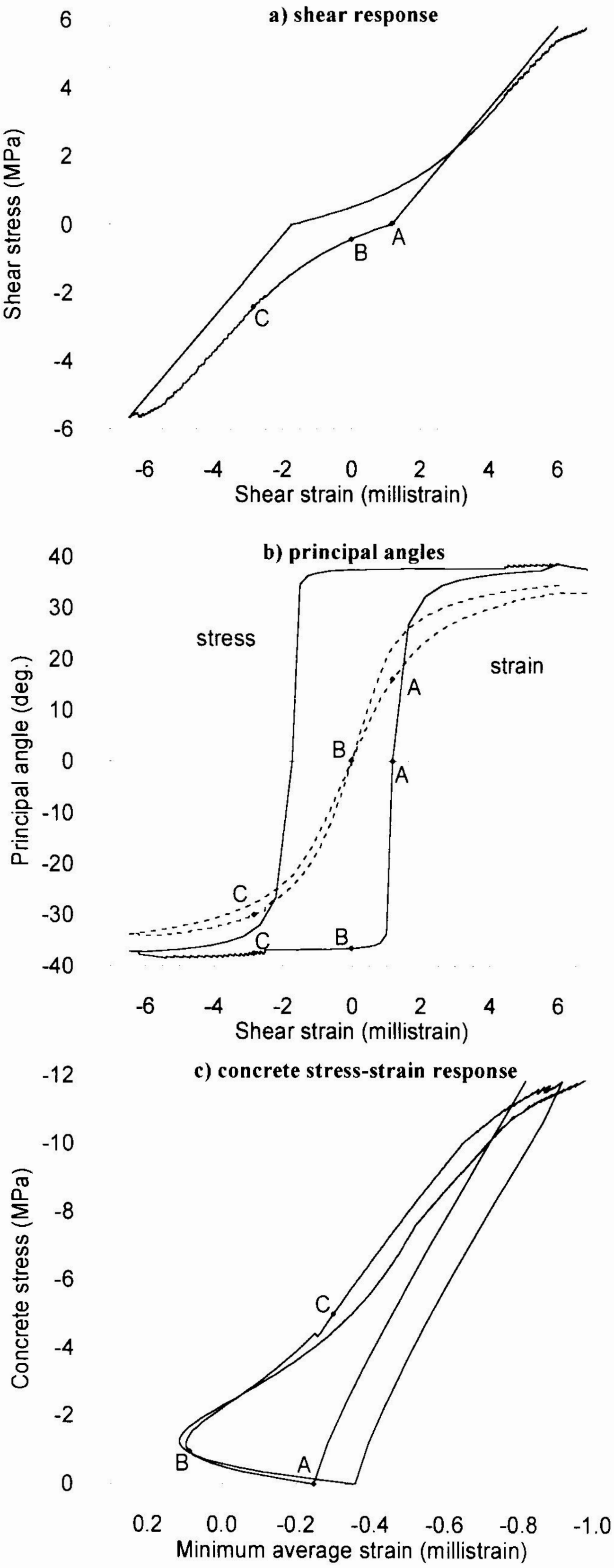

Fig. 4 - Analytical prediction, single cycle

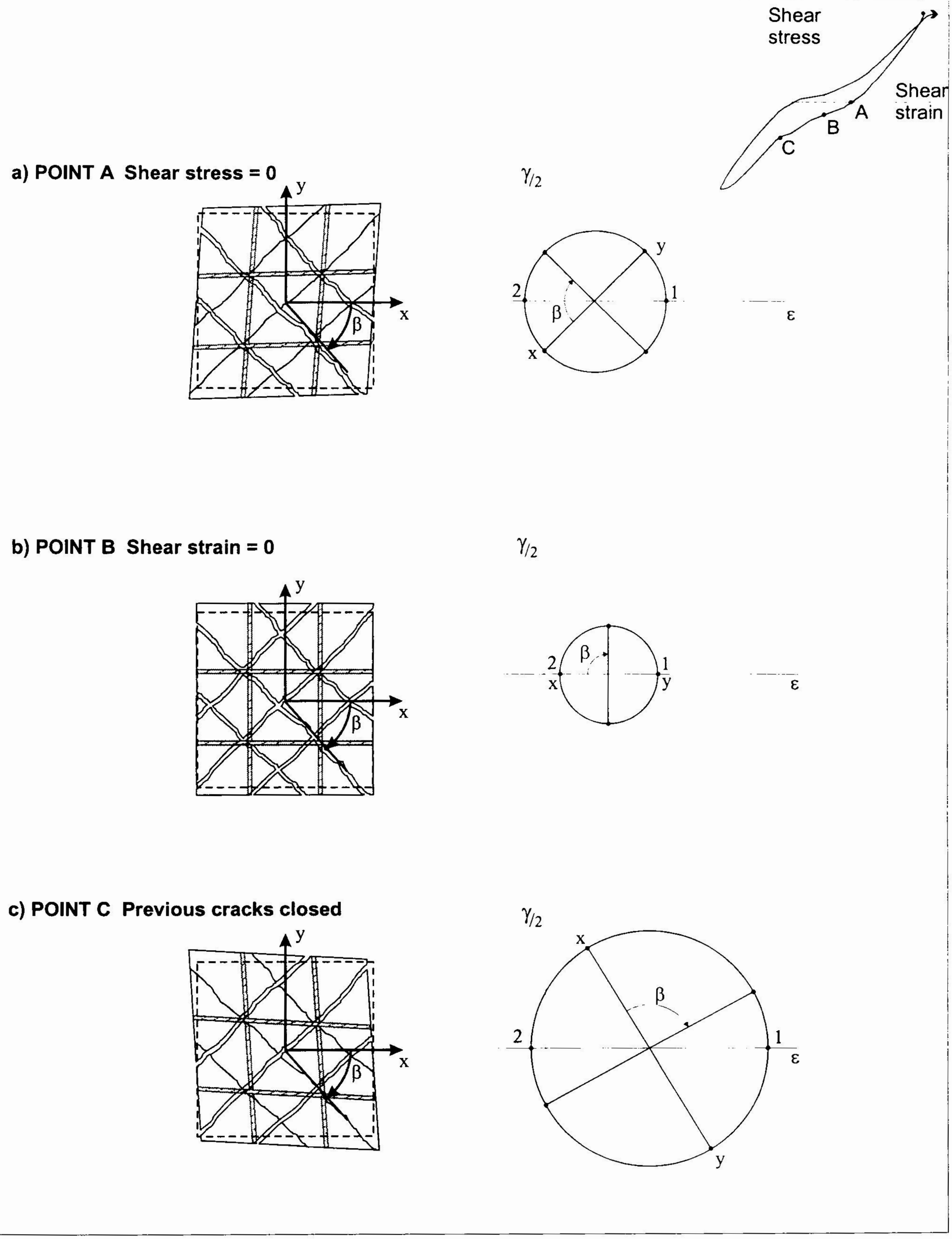

Fig. 5 - Rational model for shear strain reversal