# Behaviour of reinforced concrete beams under combined moment and shear reversal

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# IV

## Behaviour of Reinforced Concrete Beams under Combined Moment and Shear Reversal

Comportement des poutres en béton armé soumises à une inversion combinée du moment et de l'effort de cisaillement

Verhalten von Stahlbetonbalken unter kombinierter Momenten/Querkraft-Wechselbeanspruchung

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### INTRODUCTION

The behavior of a shear span under repeated reversal of loading has been studied by Brown and Jirsa (1) who concluded that the nonlinear behavior of reinforced concrete beams beyond yield is influenced by both Bauschinger effect and shear deformation. Therefore, it appears that seismic properties such as energy absorption capacity and stiffness degradation of a shear span will be influenced by the magnitude of nominal shear stress applied to the span. Furthermore, this nonlinear behavior will result in the development of regions which become critical during an earthquake due to the excessive inelastic deformations imposed (2). One critical region influenced by both shear and flexural stress is the region in a shear span immediately next to a column. Two shear spans and portions of columns as stubs form an interior component of a multi-story frame. Typical components of this type have been tested previously by others to obtain their force-deformation hysteretic behavior (3,4,5,6).

In this paper, the influence of shear span to depth ratio, a/d, amount of web reinforcement, and rate of loading on the seismic properties of reinforced concrete beams are examined. The experimental results for 12 specimens tested as simple beams using the component testing facility shown in Fig. 1 are presented.

### EXPERIMENTAL WORK

The testing facility used consists of a test frame and an hydraulically powered and electronically controlled actuator having a load rating of 75 kips statically and 50 kips dynamically and having a displacement range of ±6 inches. Ten of the 12 test specimens had a 9"x15" cross section and were reinforced longitudinally with four #7 bars (1.03%). The theoretical flexural capacity of this section is about 750 k-in and its effective depth, d, is 13 in. The maximum applied nominal shear stresss which depended on the a/d ratio was about $3.75\sqrt{f'_c}$. The stirrups used were #3 bars with spacings s=3.25", in accordance with the ACI and UBC building codes; i.e., s=d/4, and s=6"(7,8).

To investigate the dynamic properties of these beams, a prescribed triangularly shaped displacement-time signal was used which increased in amplitude after every four cycles of displacement at the same amplitude (Fig. 2). Continuous loading with constant velocity was applied to all the specimens. Initially, each specimen (except beam 1) was subjected to the 20 cycles of loading within the elastic limit. Subsequently, 20 more cycles of loading was applied which deformed the member beyond yield.

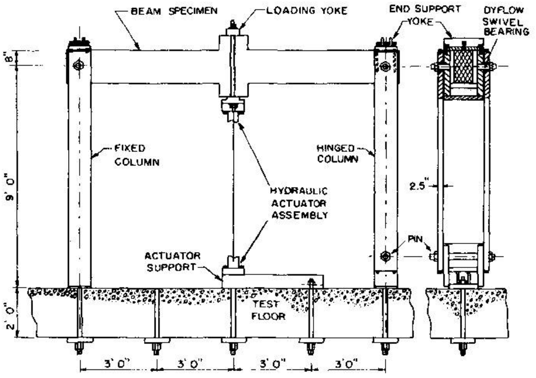

Fig. 1: Test Frame

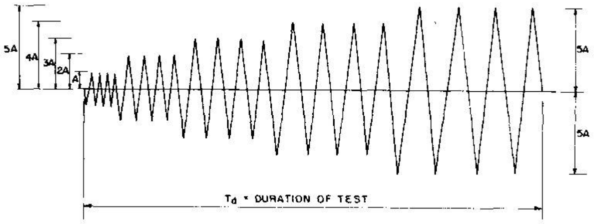

Fig. 2: Load Signal

Various electronic instruments were used to obtain load-deflection, moment-curvature, and steel strain time histories and also to obtain shear-deformation indices. Linear variable differential transformers (LVDT) in conjunction with amplifiers, power supplies and visicorders were used to measure and record all displacements. The displacement and corresponding load applied by the actuator were measured by a built-in LVDT and a load cell, respectively. Whenever possible, X-Y recorders were used to plot the load deflection relationships.

## TEST RESULTS

Only typical results will be presented herein. In Table 1, certain properties of the beams are presented including yield deflections, yield strengths, maximum applied loads and average nominal shear stresses.

TABLE 1 PROPERTIES OF SPECIMENS AND THEIR APPLIED LOADS

| BEAM | a/d | $f'_c$ | $f_y$ | s | $\Delta_y$ in | | $F_y$ kips | | $F_{max}$ kips | | $v_u/\sqrt{f'_c}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psi | ksi | in | + | - | + | - | + | - | (avg) |
| 1 | 5.10 | 2640 | 52.4 | 6.00 | .57 | .64 | 22.8 | 26.9 | 23.0 | 27.5 | 1.75 |
| 2 | 5.10 | 4750 | 52.4 | 6.00 | .48 | .50 | 23.3 | 24.7 | 24.0 | 27.5 | 1.75 |
| 5 | 5.10 | 4060 | 51.8 | 3.25 | .55 | .51 | 25.2 | 29.5 | 23.0 | 28.0 | 1.75 |
| 6 | 5.10 | 4060 | 51.8 | 3.25 | .50 | .51 | 20.8 | 24.7 | 23.0 | 28.0 | 1.75 |
| 7 | 3.70 | 4650 | 51.8 | 6.00 | .35 | .33 | 38.3 | 36.3 | 32.0 | 34.0 | 2.25 |
| 9 | 3.70 | 4250 | 51.8 | 3.25 | .35 | .36 | 37.3 | 36.6 | 32.0 | 36.0 | 2.25 |
| 10 | 3.70 | 4250 | 51.8 | 3.25 | .35 | .35 | 30.3 | 32.1 | 32.0 | 36.0 | 2.25 |
| 11 | 2.31 | 4590 | 50.1 | 3.25 | .22 | .21 | 59.4 | 59.7 | 59.0 | 60.0 | 3.75 |
| 12 | 2.31 | 4590 | 50.1 | 3.25 | .23 | .21 | 57.5 | 53.2 | 59.0 | 60.0 | 3.75 |

A typical elastic load-deflection diagram is seen in Fig. 3 for beam No. 6. Load-deflection diagrams for beams Nos. 5,9, and 12 are seen in Figs. 4,5 and 6, respectively. A typical moment-curvature diagram is seen in Fig. 7 for beam No. 9. Typical strain histories for the same beam are seen in Fig. 8. Typical shear force-shear deformation index $\alpha$ is seen in Fig. 9 for beam No. 12. This index is defined as the chord rotation angle calculated from the relative displacements between the stub and a cross section 11" away from its outer face. The instrumentation used and the state of beam No. 12 after testing are seen in Fig. 10.

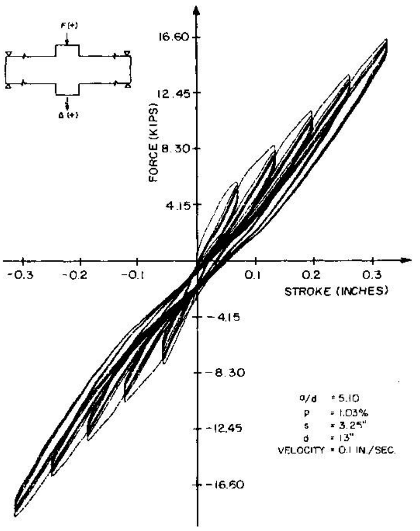

Fig. 3 Elastic Hysteresis Loops (Beam 6)

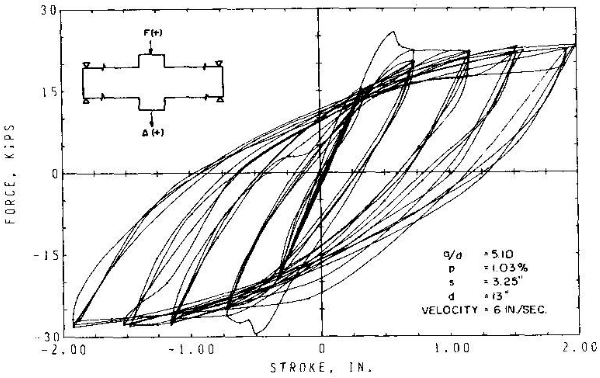

Fig. 4 Inelastic F - Δ Hysteresis Loops (Beam 5)

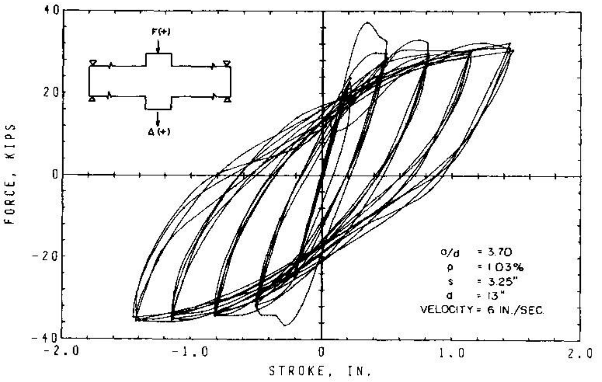

Fig. 5 Inelastic F - Δ Hysteresis Loops (Beam 9)

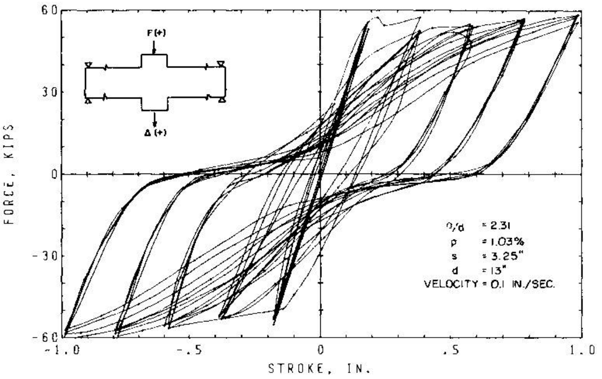

Fig. 6 Inelastic F - Δ Hysteresis Loops

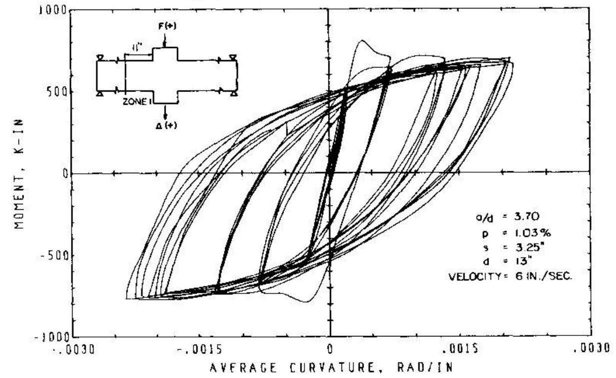

Fig. 7 M - ψ Hysteresis Loops (Beam 9)

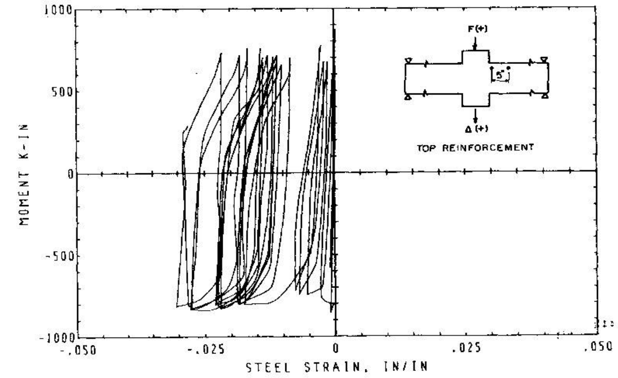

Fig. 8 Steel Strain History (Beam 9)

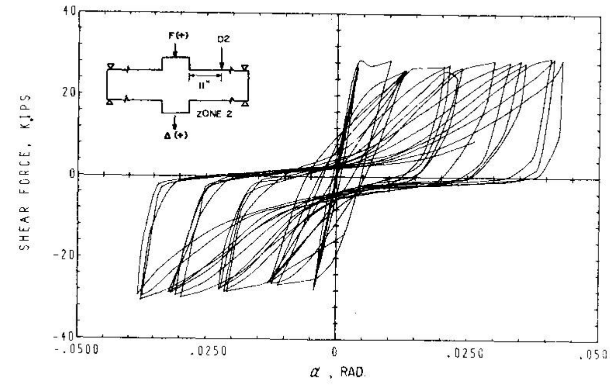

Fig. 9 Shear Deformation Index (Beam 12)

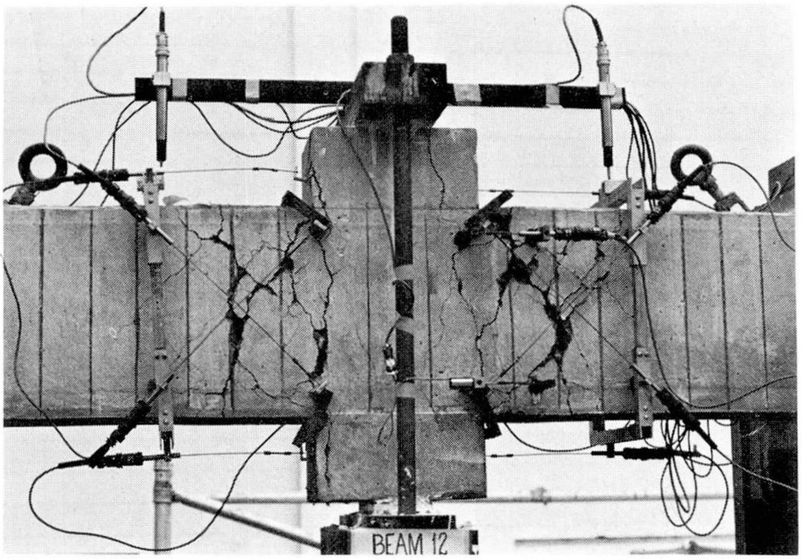

Fig. 10: Beam 12 After Test

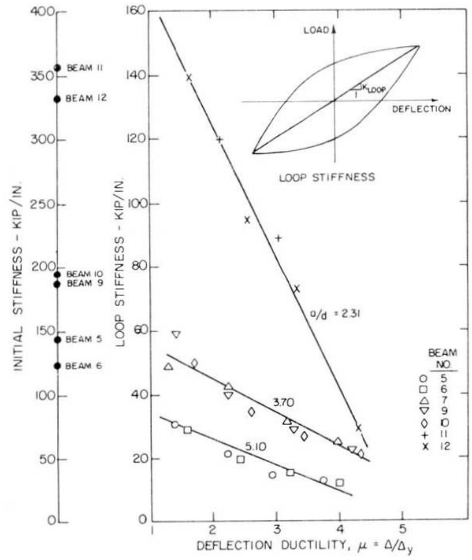

Fig. 11: Loop Stiffness Degradation

ANALYSIS OF TEST RESULTS

As observed in Fig. 3, deflection cycling within the elastic limit results in hysteresis loops which decrease in area by as much as 50% even when the cycling is repeated at a constant amplitude of deflection.

Except for increases in yield strengths by as much as 20%, no significant differences existed in the hysteresis loops of similar beams tested under dynamic and quasi-static conditions. The increase in yield strength influences energy absorption only for the cycle during which yielding takes place.

An important characteristic of reinforced concrete beams is the continuous deterioration of stiffness with increasing amplitudes of deflection or ductility. The deterioration of the instantaneous stiffness is exhibited by the hysteresis loops. Shear pinching can significantly influence instantaneous stiffness. Therefore, in such cases the elasto-plastic Ramberg-Osgood, or Clough's degrading stiffness models (9) are not applicable.

A more refined "loop stiffness" can be defined as the ratio of the sum of the maximum loads to the sum of the maximum displacements. This stiffness is especially appropriate for the beams tested since equal top and bottom reinforcements have been used and symmetrical displacements have been applied. A summary of the loop stiffness versus deflection ductility is seen in Fig. 11. As observed, loop stiffness deterioration is more significant for beams with smaller a/d ratios.

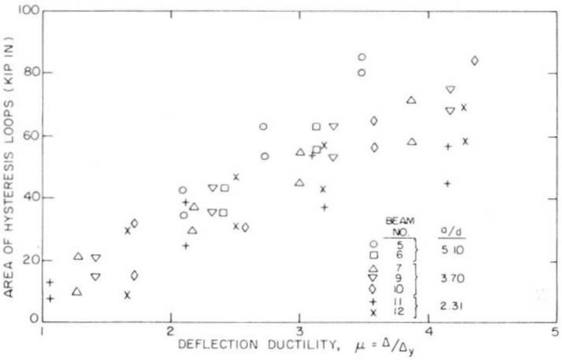

Fig. 12: Energy Absorption

Energy absorption is one of the most important properties directly linked to damping constants used in dynamic analyses. Using well defined cyclic loadings, energy absorption capacities were carefully measured in this investigation. Areas of the hysteresis loops obtained are summarized in Fig. 12. Except for increasing energy absorption with increasing ductility, no significant trend can be observed.

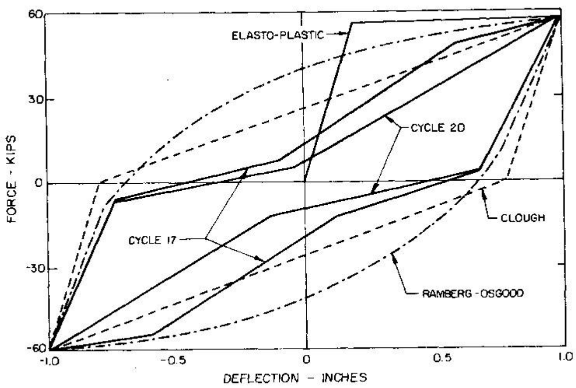

Fig. 13: Effect of Shear Pinching

When cycled at the same amplitude, energy absorption has significantly decreased after four cycles. Individually, however, shear pinching in each beam can be very important. For example, in ig. 13, the areas of hysteresis loops 17 and 20 of beam No. 12 are 65% and 54.5% respectively, of the area of the loop described in Clough's degrading stiffness model. Thus, it can be seen that shear pinching can significantly reduce energy absorption capacity.

While recent codes (7,8) recommend the use of #3 stirrups at d/4 spacing, it is observed for the beams tested that no significant differences of energy absorption or stiffness deterioration exist between beams with stirrup spacing of 3.25" (d/4) or 6". Therefore, the d/4 spacing requirement should be relaxed for beams with normal range of nominal shear stresses.

## CONCLUSIONS

The only observed influence of dynamic loading is an increase in yield strength. No other strain rate effects are observed. Energy is dissipated within and beyond the elastic limit. The areas of hysteresis loops decrease continuously when cycled under load reversals at the same amplitude. The energy absorption increases with an increase in ductility. Stiffness deterioration is more significant in shear span with smaller a/d ratios. Shear pinching in shear spans must be represented in mathematical models in order to correctly characterize their seismic behavior. For low nominal shear stresses it appears that the d/4 spacing requirement for web reinforcement in critical regions should be relaxed.

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## SUMMARY

The behavior of reinforced concrete components simulating interior beams and column stubs is investigated. Stirrup spacing, shear span to depth ratio and loading velocity were varied in order to study their influences on energy absorption and stiffness degrading properties of beams so all beams were loaded by hydraulically powered, electronically controlled actuator. Load-deflection and other pertinent relationships are discussed in terms of energy absorption, stiffness deterioration, strength and deflection ductility.

## RESUME

On étudie le comportement d'éléments en béton armé simulant des poutres intérieures et des tronçons de colonne. L'espacement des étriers, le rapport de la portée de cisaillement à la hauteur et la vitesse de charge ont été variés pour étudier leurs influences sur l'absorption d'énergie et sur la perte de rigidité des poutres. Toutes les poutres ont été chargées par un servomoteur actionné hydrauliquement et contrôlé électroniquement. On discute ensuite les courbes charge-déformation ainsi que d'autres relations intéressantes en termes d'absorption d'énergie, de perte de rigidité, de résistance et de déformabilité.

## ZUSAMMENFASSUNG

Man untersucht das Verhalten von Stahlbetonteilen, welche Balken und kurze Säulenstücke darstellen, Die Bügelanordnung, das Verhältnis von Spannweite zur Höhe und die Belastungsgeschwindigkeit wurden variiert, um ihre Einflüsse auf die Energieabsorption und steifigkeitsreduzierenden Eigenschaften der Balken zu studieren; alle Balken wurden hydraulisch beladen und elektronisch überwacht. Die Lastverformungsabhängigkeit und andere signifikante Verhältnisse werden in Form von Energieabsorption, Steifigkeitsabnahme, Widerstand und Verformungsduktilität vesprochen.