SOME RECENT RESEARCH IN NEW ZEALAND INTO ASPECTS OF THE SEISMIC RESISTANCE OF PRESTRESSED CONCRETE FRAMES

by

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SYNOPSIS

The results of an investigation into the seismic resistance of prestressed and partially prestressed concrete frames are described. The experimental part of the project involved the testing of ten near full scale beam-interior column assemblies under static cyclic loading to obtain information for seismic design. Theoretical moment-curvature studies were conducted to established section properties that would lead to ductile behaviour. Non-linear dynamic analyses of single degree of freedom systems were conducted using accurate idealizations for the load-displacement loops to compare the behaviour of prestressed, partially prestressed and reinforced concrete systems responding to severe earthquakes.

INTRODUCTION

Prestressed concrete has been widely used for structures carrying gravity loads but has not had the same acceptance for structural systems which resist seismic loads. Part of this caution in the use of prestressed concrete for earthquake resistant structures has been due to the paucity of experimental and theoretical studies of prestressed concrete structures subjected to seismic type loading. In the past there has been a lack of detailed building code provisions for the seismic design of prestressed concrete. For example, the building code of the American Concrete Institute, ACI 318-71 (1), contains special provisions for the seismic design of reinforced concrete structures but does not have corresponding provisions for prestressed concrete. However the Seismic Committee of the NZ Prestressed Concrete Institute has recently prepared a set of design recommendations (2), and the FIP Commission on Seismic Structures is currently preparing design recommendations (3).

Previous research in this area has been conducted at the University of Canterbury by Blakeley (4) with Park. This paper briefly summarizes further research work completed by the authors (5).

TESTS ON BEAM-INTERIOR COLUMN JOINTS

Ten beam-interior column plane frame assemblies were tested under static cyclic loading (5). The beams had an 18 in by 9 in (457 mm by 229 mm) section and the columns had a 16 in by 12 in (406 mm by 305 mm) section. Each test unit represented the joint region of a plane frame extending approximately between the points of contraflexure of the members. Fig. 1 shows a unit under test. The columns were subjected to an axial load and the beam and column ends were loaded to simulate the shears and bending moments induced by seismic loading. The columns were designed to have a greater flexural strength than the beams and hence plastic hinging was expected to occur in the beams. As an example of the test results, Fig. 2 shows the measured load-deflection characteristics and the observed damage

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of Unit 4 which had a prestressed beam containing three tendons [one at the top, one at mid depth and one at the bottom of the section, giving a uniform prestress of 1123 psi (7.74 MPa)]. Fig. 3 shows the measured load-deflection characteristics of Unit 7 which had a partially prestressed beam containing nonprestressed steel [at the top and bottom of the section] and three prestressed tendons [one in the top, one at mid depth and one at the bottom of the section, giving a uniform prestress of 675 psi (4.65 MPa)], and with approximately the same flexural strength as Unit 4. The inelastic deformations of the units was due to plastic hinge rotation in the beams and the improved performance of Unit 7 compared with Unit 4 was due to the nonprestressed steel acting as compression reinforcement in the plastic hinge regions.

The tests illustrated the need for closely spaced stirrups placed with minimum cover in the plastic hinge regions of beams to avoid excessive loss of flexural capacity caused by reduction of the concrete section when crushing of unconfined concrete commences. Units 4 and 7 contained No. 3 (9.5 mm dia.) stirrups at $3\frac{1}{2}$ in (89 mm) centres. It is recommended that in beam plastic hinge zones the spacing of stirrups should not exceed 4 in (102 mm) or $\frac{1}{4}$ of the effective depth, as is recommended for reinforced concrete in Appendix A of ACI 318-71 (1). The tests also indicated the value of nonprestressed compression steel in maintaining flexural capacity after concrete crushing, and in increasing the energy dissipation, providing bond failure does not occur through the joint core.

A critical aspect of the test results was the beam-column joint core behaviour. Transverse shear reinforcement (hoops) in the joint core had been designed using the method recommended for reinforced concrete in Appendix A of ACI 318-71 (1). In all the units tested the beams reached at least 95% of their theoretical flexural strength in the first inelastic loading cycle accompanied by yielding of the joint core hoops in some units. For those units in which the joint core hoops yielded, further inelastic loading cycles resulted in a degradation of the joint core shear strength due to repeated opening and closing of diagonal tension cracks in alternating directions. In these units the shear strength of the joint core governed the strength of the unit and the inelastic deformation of the unit occurred mainly in the joint core, leading to severe damage which would be difficult to repair. Thus the approach of Appendix A of ACI 318-71 for joint core shear design cannot be regarded as being adequate for plane frames subjected to intense cycles of seismic loading. In those units without a prestressing tendon at mid depth joint core shear failure always occurred illustrating the benefit to joint core behaviour to be gained from the presence of a central tendon. The test results from the ten test units and a suggested joint core design procedure may be seen reported in detail elsewhere (5,6).

THEORETICAL MOMENT-CURVATURE CHARACTERISTICS OF PRESTRESSED AND PARTIALLY PRESTRESSED CONCRETE SECTIONS

The available flexural ductility of a section is illustrated by the shape of the moment-curvature ($M - \phi$) curve. The $M - \phi$ curve obtained for monotonic loading gives a good approximation for the envelope curve for cyclic loading providing strength degradation due to concrete damage is not significant. Theoretical $M - \phi$ curves can be obtained using idealized stress-strain relationships for concrete and steel by satisfying the requirements of strain compatibility and equilibrium for the section while incrementing the extreme fibre strain (7,5). Fig. 4 shows typical monotonic M - ϕ curves obtained from a section with various contents of eccentrically placed prestressing steel. Consideration of these and other M - ϕ curves led to the recommendation that for reasonable ductility for seismic design the depth of the rectangular compressive concrete stress block at ultimate moment should not be greater than 0.2 of the section overall depth (5).

It is of interest to compare the monotonic M - ϕ curves for sections with different arrangements of prestressing steel. In seismic design moment reversals will require many sections to have both negative and positive moment strength and hence tendons will often exist near both extreme fibres of the section and near mid depth. Fig. 5 shows theoretical M - ϕ curves for the section with up to five tendons symmetrically distributed down the depth. The total prestressing steel content is the same for each of the five cases, being 0.00696 of the gross concrete section. For the case of all steel concentrated in a single central tendon, N = 1, the moment capacity is more sensitive to a deterioration of the compressed concrete and a significant reduction of moment capacity occurs at high curvatures. However there is little difference in the moment capacity for two or more tendons and such sections are able to maintain near maximum moment capacity at high curvatures. Therefore two or more tendons are to be preferred.

To obtain a better indication of the performance of sections subjected to seismic loading M - ϕ curves for cyclic flexure are necessary. Such theoretical M - ϕ curves can be obtained using idealized cyclic stress-strain curves for concrete and steel obtained from experimental data. The theoretical cyclic M - ϕ curves can be obtained by dividing the section into a number of discrete horizontal elements and tracing the M - ϕ loop by incrementing the extreme fibre strain and satisfying strain compatibility and equilibrium (7,5). The effect of buckling of prestressing steel at high compressive strains can be taken into account using a tangent modulus approach. Figs. 6 and 7 show compared computed theoretical and measured experimental cyclic M - ϕ curves for the beams in the plastic hinge regions of Units 4 and 7. Good accuracy results from the theoretical approach but the amount of computer time used is considerable. The theoretical and experimental curves indicated that the inclusion of non-prestressed steel in a prestressed section results in a fattening of the M - ϕ loops and thus can considerably increase the hysteretic energy dissipation.

The cyclic M - ϕ loops can be idealized for use in dynamic analyses to save computational time. The idealized model for reinforced concrete suggested in this study is based on the Ramberg Osgood relationship (Fig. 8a) and that for prestressed concrete is based on a series of straight lines (Fig. 8b). These two models can be combined to model partially prestressed sections (Fig. 8c). Such idealizations, with empirical factors to define the exact shape of the loops, give good agreement with measured experimental cyclic M - ϕ curves (5) and are suitable for use in non-linear dynamic analyses.

EARTHQUAKE RESPONSE OF SIMPLE CONCRETE SYSTEMS

A comparative study was made of the response of prestressed, partially prestressed and reinforced concrete single degree of freedom systems to the

El Centro 1940 N-S component earthquake and artificial earthquakes A-2 and B-2 (8). The displacement response was calculated using a step-by-step numerical integration method (5). The idealized non-linear cyclic load-displacement loops used were of similar shape to the idealized cyclic $M - \phi$ loops of Fig. 8. The strength of the systems was calculated for the seismic loading given by New Zealand building codes. The maximum displacement of the prestressed concrete system was on average found to be 1.3 times that of the reinforced concrete system with the same strength, damping ratio and initial stiffness. This difference in response is due to the smaller hysteretic energy dissipation of the prestressed concrete system compared with the reinforced concrete system. However this displacement ratio showed wide variation from the average value of 1.3, ranging between 0.7 and 2.4 for the range of cases studied of damping ratio 0.02 to 0.10 and initial period 0.3 to 2.1 seconds. This displacement ratio is of interest when comparing the ductility demands of prestressed and reinforced concrete systems, and the possible non-structural damage due to the earthquake.

CONCLUSIONS

The present study, along with previous studies, gives clear evidence that properly detailed prestressed concrete frames will give satisfactory seismic load resistance. The results of these studies have been incorporated in the design recommendations of the Seismic Committee of the New Zealand Prestressed Concrete Institute (2).

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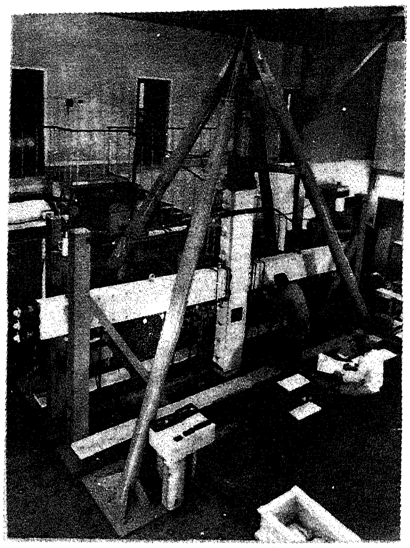

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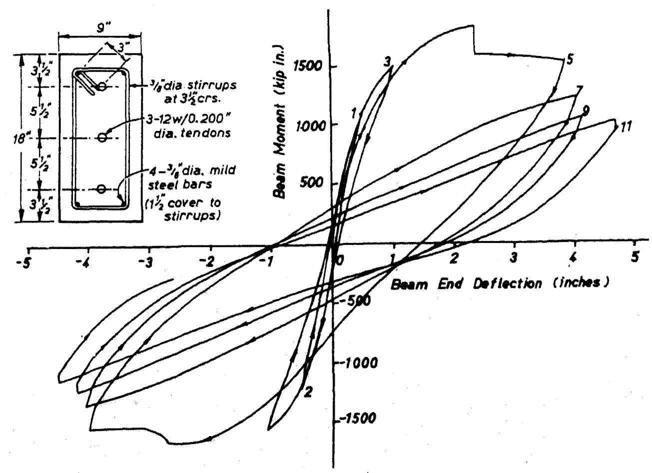
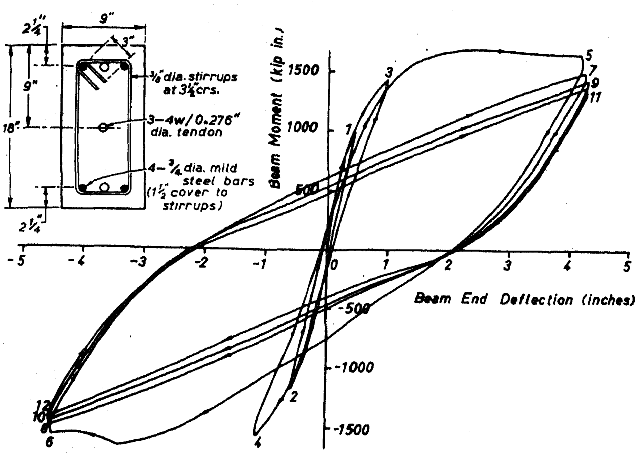
Fig. 1 Unit in Test Frame During Testing.



Unit 4 at Maximum Deflection (End of loading run 12)

Fig. 2 Unit 4 : Beam Moment at Column Face Versus Beam End Deflection.



Unit 7 at Maximum Deflection (End of loading run 12)

Fig. 3 Unit 7 : Beam Moment at Column Face Versus Beam End Deflection.

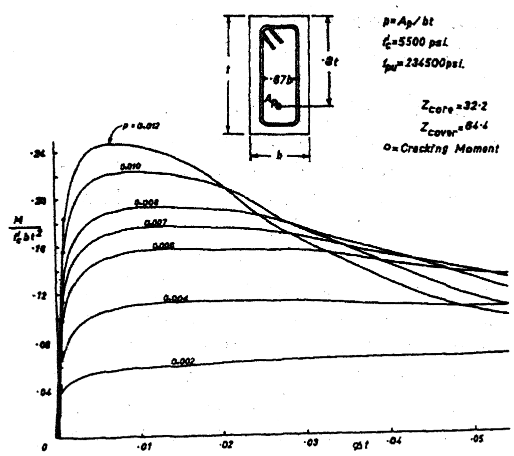


Fig. 4 Moment-Curvature Curves For Section With Various Contents of Eccentrically Placed Prestressing Steel

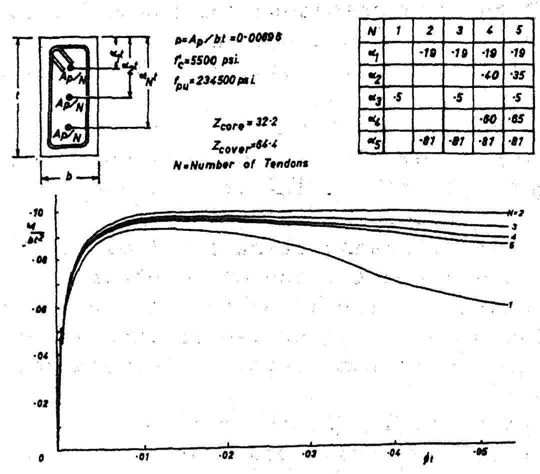


Fig. 5 Moment-Curvature Curves For Section With Various Numbers of Symmetrically Placed Prestressing Tendons

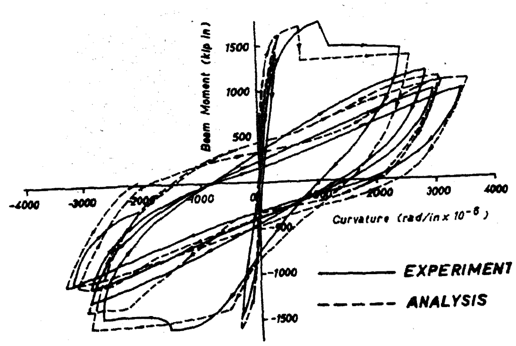


Fig. 6 Unit 4 : Theoretical and Experimental Moment-Curvature Curves

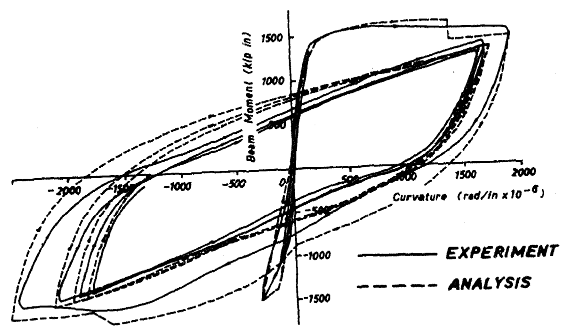


Fig. 7 Unit 7 : Theoretical and Experimental Moment-Curvature Curves

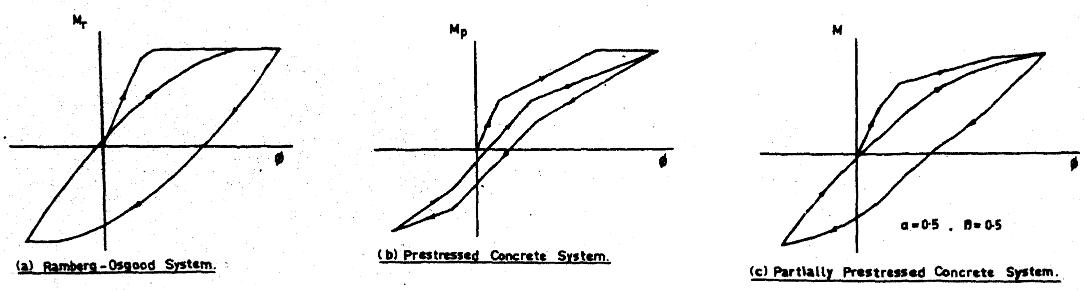


Fig. 8 Moment-Curvature Idealization For Reinforced, Partially Prestressed and Prestressed Concrete Sections