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Reversed cyclic axial loading tests on reinforced concrete members

Stuart Bristowe[1], William D. Cook[2] and Denis Mitchell[3]

ABSTRACT

A series of full-scale, reversed cyclic loading tests were conducted at McGill University to aid in the development of constituitive relationships for predicting the seismic response of concrete elements. The specimens were constructed using normal (30 MPa) and high-strength (70 MPa) concretes. For each concrete strength, three specimens were constructed; one detailed as a beam (R = 2 and 4), the second as a nominally ductile column (R = 2) and the third as a ductile column (R = 4). The complete cyclic response in tension and compression of each of the specimens was determined. These experimental results provide useful data for developing constituitive relationships for the prediction of the reversed cyclic responses of high-strength and normal-strength concrete elements.

INTRODUCTION

While some research has been done on the monotonic behaviour of high-strength concrete members, little research is available on the reversed cyclic loading response of such members. This together with the increased use of high-strength concrete led to the development of new provisions in the 1994 CSA Standard (CSA, 1994), which limit the concrete strength for seismic design. For ductile and nominally ductile members the specified compressive strength, f'_c, used in seismic design is limited to 55 MPa.

EXPERIMENTAL PROGRAMME

This testing programme was conducted to investigate the effect of high-strength concrete on the response of members subjected to reversed cyclic tension and compression, with varying amounts of transverse reinforcement which represents different ductility levels for both beams and columns. In reality a structural member is not subjected to pure axial loading, but in beams and columns portions of the member are subjected to reversals of tension and compression. The details of the six specimens are presented below.

<u>Nominally Ductile and Ductile Beams (R = 2 and 4)</u>

Figure 1(a) shows the dimensions and reinforcing details of a specimen with typical "beam details". The clear height of the specimen was taken as four times the cross-sectional width, b. Uniform axial loading was assumed to occur over a length of 3b in the central portion of the specimen. The cover thickness for these specimens was taken as 30 mm which satisfies interior exposure conditions for a beam. The confinement details of the transverse reinforcement for a beam are based on considerations of required shear capacity, as well as confinement requirements. In choosing the details for the prototype beam it was assumed that the confinement requirements controlled the choice of the transverse reinforcement. Furthermore, it was assumed that the prototype beam was sufficiently deep such that the d/4 spacing limit did not control the spacing of the confinement hoops. The spacing, s, of the hoops was governed by the bar buckling requirements, resulting in a required hoop spacing of 156 mm ($8d_b$) for both the normal-strength (30 MPa - N1) and high-strength concrete (70 MPa - H1) specimens.

The corbels at each end of the specimen were designed using the strut and tie method for the critical tension loading case. The transverse reinforcement was continued through the corbel to provide adequate confinement of the longitudinal bars in this region for the compressive cycles. Additional reinforcement was placed within the corbels to ensure that these areas remained elastic during the entire testing procedure.

[1] Ph.D. candidate, Department of Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke St. W., Montreal, Quebec, H3A 2K6.

[2] Research Engineer, Department of Civil Engineering and Applied Mechanics, McGill University.

[3] Professor, Department of Civil Engineering and Applied Mechanics, McGill University.

Nominally Ductile Columns (R = 2)

The reinforcement details of a specimen with typical "column details" are given in Fig. 1(b). The cover thickness for these elements had to be increased to 40 mm to provide a two hour fire rating. Square and diamond-shaped hoops were provided to ensure lateral support of each longitudinal bar, resulting in an effective area of confinement of 341 mm^2 in each principal direction of the section. For a nominally ductile column, the confinement requirements are determined by using 50% of the spacing limits given in Clause 7.6.5.2. The resulting spacing, s, for the normal-strength concrete specimen (N2) was 156 mm ($8d_b$). For concrete strengths greater than 50 MPa, Clause 7.6.5.2 reduces the above spacing by 25 %, resulting in a required spacing of 117 mm for the high-strength concrete specimen (H2).

Ductile Columns (R = 4)

The detailing of these specimens, representing ductile prototype columns, was the same as the nominally ductile columns, however the design of the confinement reinforcement was governed by Clause 21.4.4.2. The spacing of the hoops is a function of the member dimensions, the area of the transverse reinforcement and the material properties of the concrete and the hoop steel. The resulting hoop spacing for the normal-strength concrete specimen (N3) was 82 mm. If 400 MPa reinforcement were used for the high-strength concrete specimen (H3) the spacing of the hoops would be extremely small. Therefore, high-strength steel was used for the confinement of the 70 MPa specimen. The resulting spacing of the hoops was 58 mm.

Test Setup and Instrumentation

These axially loaded specimens were tested using a 11 400 kN MTS testing machine. Each specimen was post-tensioned to the base plate and the main piston of the machine through conduits cast in the corbels. The reversed cyclic loading of the specimens was computer controlled at a specified strain rate.

The overall applied load and deflection of each specimen was measured by the load cell and extensometer of the MTS testing machine. Linear voltage differential transducers (LVDT's) were used to measure the axial strain at each corner in the central 1500 mm of the specimen. Five additional LVDT's, having gauge lengths of 300 mm, were used to record the local axial strains on the back face of each specimen. Electrical resistance gauges were glued to selected longitudinal bars at their mid height and on selected hoops at the mid height of the specimen to measure the strains in the steel.

Loading Procedure

Under the action of reversing loads, the extreme fibres in a beam or a column experience alternating peak compressive and tensile strains. A prototype beam was designed and the full monotonic flexural response of this section was calculated. At selected ductilities of the response, the strain distribution over the depth of the beam was determined assuming that plane sections remain plane. At each of these ductility levels the strains in the tensile steel (ε_s) and the extreme compressive fibre (ε_c) were determined, (see Fig. 2). This analysis gave target strains for the axially loaded specimens. The specimens were subjected to a uniform tensile strain, ε_s, during the tension cycle and the corresponding compressive strain, ε_c, during the compression cycle, to simulate realistic reversed cyclic loading.

A prototype column was also designed and the monotonic flexural response was determined assuming a constant applied compressive load of $0.2A_g f_c'$ (735 kN and 1715 kN for the normal and high-strength concrete specimens, respectively). The axially loaded column specimens were tested using the strains determined in a similar manner to that stated above.

SPECIMEN RESPONSES

Ductile and Nominally Ductile Beams

The load-deflection responses of Specimens N1 and H1 are given in Figs. 3(a) and 3(b). The top right quadrant of each graph indicates a tensile load and an elongation of the specimen. The compressive response of Specimen N1 was essentially linear until the crushing of the concrete, when there was a dramatic loss in the load carrying capacity of the specimen. There was no post-crushing resistance of this specimen due to the severe spalling of the concrete cover, buckling of the longitudinal bars and the deterioration of the concrete core of the specimen. The mid-side bars underwent severe buckling due to the lack of restraint.

The response of Specimen H1 was similar to that of N1, however once the peak compressive strain was reached the cover concrete spalled in an explosive nature.

Nominally Ductile Columns

The load-deflection responses of Specimens N2 and H2 are given in Figs. 3(c) and 3(d). The initial response of Specimen N2 was similar to the response of the normal-strength concrete Specimen N1, until signs of crushing of the concrete were observed. A considerable post-peak loading resistance was evident, maintaining approximately 67% of the peak load, however this diminished rapidly as the core concrete of the specimen deteriorated. This specimen failed with the buckling of the longitudinal reinforcement.

The response of Specimen H2 was similar to high-strength Specimen H1 and at the peak compressive load the cover concrete spalled abruptly. For this specimen only 33% of the peak load was obtained during the post-peak response. This specimen failed due to crushing of the core concrete and the buckling of the longitudinal reinforcement.

Ductile Columns

Figures 3(e) and 3(f) show the cyclic responses of Specimens N3 and H3. These specimens performed similarly to Specimens N2 and H2 up to the peak load. A dramatic difference between the responses is evident by comparing the post-peak performances of each specimen. The normal-strength concrete specimen achieved 85% of the peak load and displayed good ductility. The post peak load corresponds to a core concrete compressive stress of 55 MPa, due to the excellent confinement provided. Failure occurred when a longitudinal bar ruptured due to low cycle fatigue. At large compressive strains the core concrete started to deteriorate and the longitudinal bars buckled.

Specimen H3 also displayed good post peak resistance, reaching 81% of the peak load, which corresponds to a stress of 107 MPa on the core concrete. The spalling of the cover concrete was not abrupt, possibly due to the prevention of buckling of the longitudinal bars by the closely spaced hoops. At the completion of the test the core concrete displayed signs of crushing and the longitudinal bars were buckling and two of the high-strength steel hoops ruptured due to the lower rupture strain of the high-strength, cold-rolled reinforcement.

Photographs of the normal-strength and high-strength concrete specimens at failure, are given in Figs. 4 and 5, respectively.

DEVELOPMENT OF BEHAVIOURAL MODELS

The effect of buckling of the longitudinal reinforcement was critical for the compressive response of each of these specimens, and hence an additional series of tests on the tensile and compressive cyclic response of individual reinforcing bars was conducted. These tests involved varied length to diameter ratios of the bars and also varied loading histories. The two loading histories selected simulated the induced straining of the longitudinal bars in reinforced concrete beams and columns subjected to reversed cyclic loading. The goal of this research programme is to develop behavioural models for reversed cyclic loading. These models will take into account the influence of concrete strength, amount of transverse reinforcement, bar buckling and strain hardening of the reinforcing steel. These specimens provide basic data for the response of members under pure axial loading. The behavioural model developed will be extended to predict responses under combined loading.

ACKNOWLEDGEMENTS

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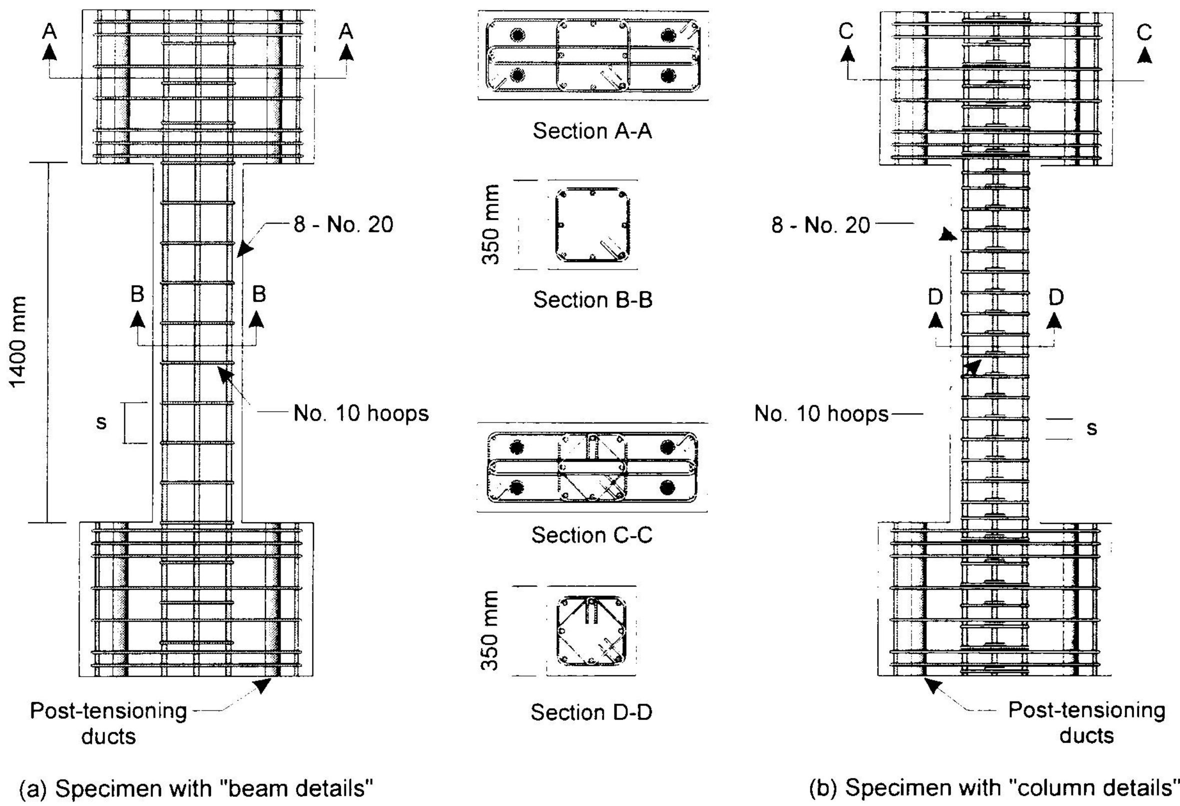

Figure 1 Reinforcing details of axial specimens

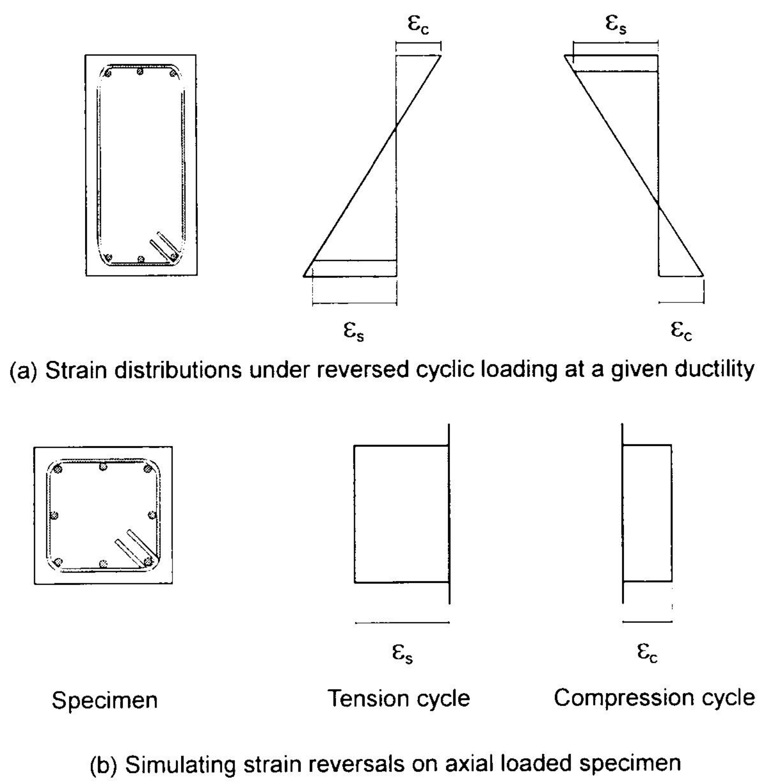

Figure 2 Simulation of reversing strains for axial loaded specimens

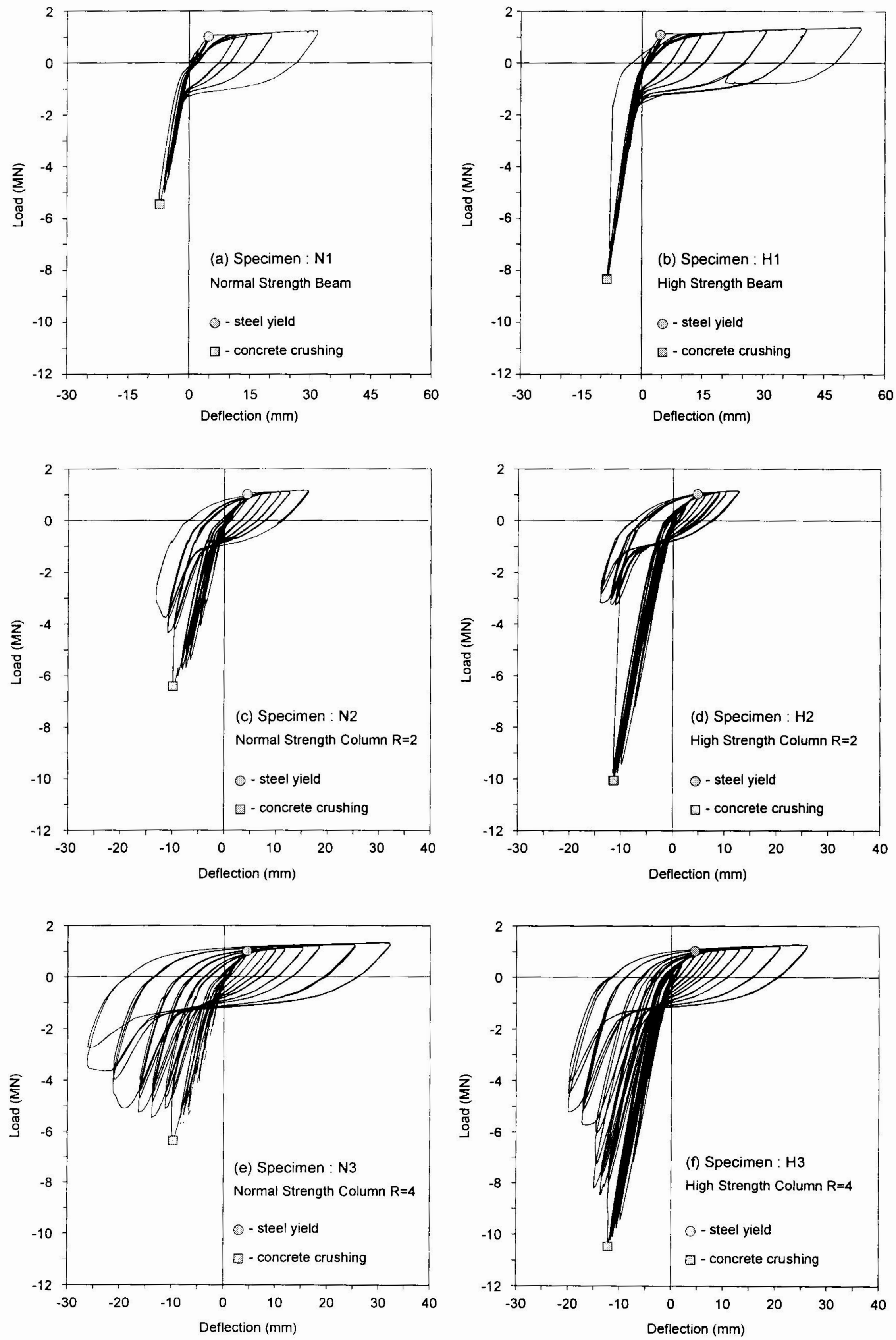

Figure 3 Hysteretic responses of axially loaded specimens

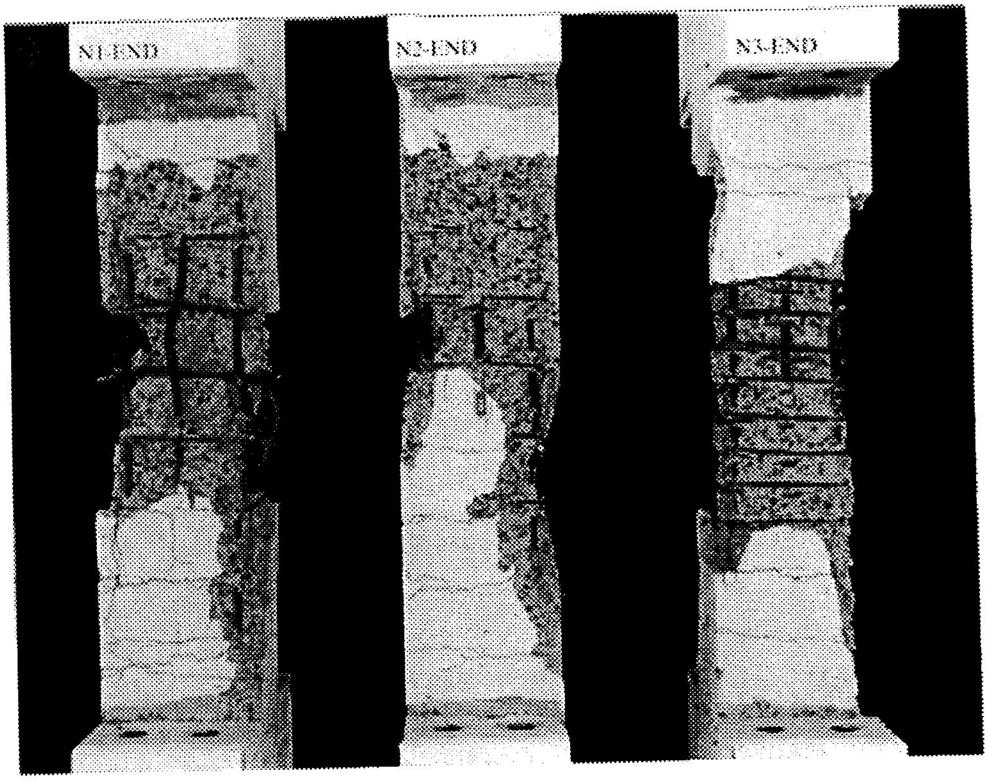

Figure 4 Photograph of normal-strength specimens at failure

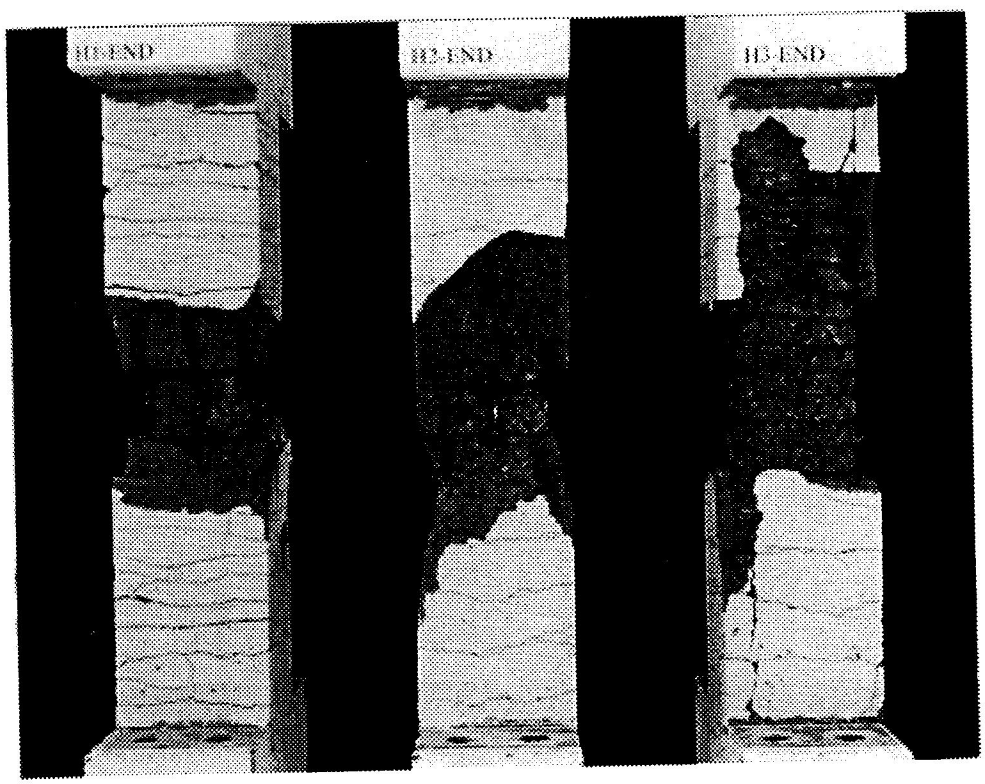

Figure 5 Photograph of high-strength specimens at failure