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Effects of loading rate on the behaviour of reinforced concrete coupling beams

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ABSTRACT

This paper presents the preliminary test results of six identical rectangular concrete coupling beams, diagonally reinforced and subjected to monotonic and reversed cyclic loading, using two different loading rates. These rates were slow or quasi-static loading, and fast, simulating earthquake induced high-strain-rate loading. Compared to the test results for slow rate of loading, the fast rate of loading resulted in consistently, but moderately, higher strengths (less than 10%), small increases in initial stiffness and no significant change in ductility of the specimens. Failure of all specimens was precipitated by buckling of the secondary reinforcement and concrete crushing.

INTRODUCTION

In seismic design of coupled shear walls, the goal is to design the coupling beams such that the beams yield before the walls, thereby minimizing wall damage. Current seismic design provisions (ACI 1989; CSA 1984) have been developed primarily on the basis of results from quasi-static tests. The loading rates for such tests are substantially lower than those corresponding to the dynamic conditions expected in earthquake vibrations. Experiments to date, as reviewed by Fu et al. (unpublished), have shown that under dynamic conditions reinforced concrete members may exhibit brittle failure modes, with less hysteretic energy absorption. Also, the formation of plastic hinges may occur at higher than anticipated loads, thereby overloading some parts of the structure.

The behaviour of a diagonally reinforced coupling beam depends primarily on the behaviour of the diagonal steel. The concrete stabilizes the diagonal compression bars, but has little additional influence on the behaviour of the beam (Park and Paulay, 1975). Information from existing literature on the

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effects of rate of loading on the tensile behaviour of steel has been reviewed by Fu et al. The yield and ultimate strengths, the modulus of elasticity, the yield strain, the strain at which strain hardening begins, as well as the length of the yield plateau in the stress-strain diagram of steel, all increase at higher rates of loading, but the modulus of elasticity and the percentage elongation at failure remain roughly unchanged.

Experimental studies of diagonally reinforced coupling beams has been limited to static loading (Park and Paulay, 1975; Barney et al, 1980). This paper reports the preliminary results of an experimental program investigating the behaviour of diagonally reinforced coupling beams, tested using slow and fast loading rates, in monotonic and reversed cyclic loading.

TEST PROGRAM

Six diagonally reinforced concrete beams, with identical geometric and material properties, were tested in this study. The beams were similar in size and detailing, to coupling beams used in buildings with coupled shear walls. The beams were designed for seismic loading in accordance with the seismic design provisions of the Canadian Standards Association - Design of Concrete Structures for Buildings, 1985 - Chapter 21: Special Provisions for Seismic Design.

All specimens had a 1100 mm prismatic test region, with a cross section 300 mm by 400 mm. Main reinforcement was placed diagonally and each diagonal consisted of four M20 bars. The M20 bars were enclosed by 6 mm diameter rectangular hoops, at 100 mm spacing. Outside hoop dimensions were 120 mm by 120 mm. Figure 1 shows the dimensions and reinforcement details of the specimens. For all specimens, the yield strength of the diagonal reinforcement was 405 MPa, and the concrete strength was 26.7 MPa. Secondary reinforcement of the beams was provided within the test region for confinement of the concrete. It consisted of six longitudinal M10 bars and 6 mm diameter stirrups, at 100 mm spacing. The yield strengths of the M10 and 6 mm diameter bars were 400 MPa and 430 MPa respectively.

The cross section at both ends of the specimens was enlarged to 300 mm by 700 mm, to ensure proper load transfer at the beam ends and to ensure that failure was confined to within designated test region. The test set-up is shown in Figure 2. Load was transferred to the specimens through two odd-shaped, thick steel plate loading beams, attached to the enlarged ends of the beams by means of eighteen 25 mm diameter steel rods (yield strength 490 MPa) at each end. The external load was applied to the specimen through the free end of one of the loading beams, which was connected to a 500 kN capacity actuator, while the free end of the other loading beam was connected to a pinned joint. With this loading arrangement, each beam specimen was subjected to equal moments at the ends of the test region, and zero moment and pure shear at the mid-span.

Each beam was subjected to a different combination of load history and loading rate, as summarized in Table 1. For monotonic loading, the load on the specimen was steadily increased up to the static strength or dynamic strength of the specimen, depending on whether the rate of the load application was slow or fast. Incrementally cyclic loading was applied according to the load history shown in Figure 3, and simulated earthquake induced forces. The ductility ratio, referred to in Figure 3, is defined as the ratio of the displacement amplitude to the measured displacement at the static yield load (i.e., measured yield displacement for beam D1). The loading rate of the tests was measured in terms of the actuator displacement with respect to time (stroke control). For static tests, the external load was applied at a rate of 0.033 mm/sec. For dynamic tests, the rate of loading was 30 mm/sec, or approximately a thousand times faster than for the static tests. Beams D1, D2, D5 and D6 were tested monotonically. Beams D3 and D4 were subjected to reversed cyclic loadings. Beams D1, D4 and D6 were tested with slow or static loads, and beams D2, D3 and D5 were tested with fast or dynamic loads.

Table 1. Summary of load history and results of test specimens.

Beam	D1	D2	D3	D4	D5	D6
Type of Loading	M	M	C	C	M	M
Rate of Loading	S	F	F	S	S	F
Failure Loads (kN)						
CW Moments	307	330	327	314	248	303
CCW Moments	–	–	–329	–309	–329	–359

Note : M – monotonic; C – cyclic; S – 0.033 mm/sec; F – 30 mm/sec;
CW – clockwise (actuator pulling away from beam);
CCW – counterclockwise (actuator pushing down on beam);

To begin each test, the loading frame lower pin, which had a 1 mm clearance with the pin hole, was brought into bearing contact. By suspending the specimens freely from the actuator, their dead weight, together with the connecting steel plates, was found to be 40 kN. The starting zero-load and zero-displacement position for all specimens was set at half of the dead weight or ±20 kN, depending on whether the first cycle of load was applied in a clockwise or counterclockwise direction. Consequently, before loading, specimens D1 to D4 were suspended freely from the actuator and were subjected to a preload of 20 kN. Similarly, specimens D5 and D6 were subjected to a preload of –20 kN. The equivalent load of ±20 kN resulted in a relatively small measured displacement of between 1 mm and 1.5 mm. Therefore, the failure loads for individual specimens, as given in Table 1, have been adjusted accordingly, unless otherwise specified.

During each test, continuous time record of the applied load, displacements and strains were monitored. The external load applied to the beam specimen was measured by a load cell attached to the actuator. The displacements at the beam ends, and those along the test region, as well as the deformations of the concrete core at midspan of the beam, were measured using a total of 23 linear variable differential transducers (LVDT's). Steel strains were measured using twelve electrical resistance strain gauges attached to the main diagonal reinforcement and to the secondary transverse stirrups.

A PDP11 series mini-computer was used to control the load application through the MTS actuator and to perform data acquisition for each test.

RESULTS AND DISCUSSION

According to the Special Provisions for Seismic Design as outlined in CSA Standard CAN-A23.2-M84, both shear and flexure shall be resisted by the diagonal reinforcement in both directions. The maximum allowable shear force that the beam section can carry is equal to $A_s f_y (2 \times \sin a)$, where f_y is the yield strength, A_s the area of the diagonal reinforcement, and a the angle between the axis of the diagonal reinforcement and the longitudinal axis of the beam (equal to 17 degrees for the specimens herein). Using the area of steel of 1200 mm^2 for each diagonal, and the yield strength of 405 MPa, the calculated theoretical failure load of the beam specimens is 284 kN. With the exception of D5, all observed failure loads were greater than this value, as seen in Table 1.

The measured load-displacement curves, for all six specimens, are given in Figures 4(a) to (e). Specimens D1 and D2 were tested to failure under clockwise end moments. Specimens D3 and D4 were subjected to incremental cyclic clockwise and counterclockwise end moments. Specimens D5 and D6 were subjected to counterclockwise end moments upon failure, and then clockwise end moments for one complete cycle of loading.

Figures 4(d) and (e) compare the load-displacement response between specimens under monotonic loading and cyclic loading and the same rates of loading. Very little difference can be seen in either maximum load and stiffness, for D1 (307 kN) and D4 (314 kN), which were tested at a slow rate of loading, and for D2 (330 kN) and D3 (327 kN), which were tested at a fast rate of loading. The following compares pairs of specimens tested with the same type of loading, but different rates of loading.

Specimens D1 and D2

For D1, first flexural and diagonal shear cracks were observed at loads of 98 kN and 133 kN, respectively. As load increased, the diagonal cracks widened. The yield load was 217 kN at a displacement of 18.5 mm. Once the diagonal cracks started opening rapidly, the maximum load of 307 kN was reached, at a displacement of 35 mm. Failure of the beam was initiated by the large diagonal cracks, progressive crushing of the concrete in the compression zones, and eventual buckling of the secondary reinforcement (M10 bars) at the end of the test region. At the end of the test (70 mm displacement), large rotations at the beam ends were observed, and the residual load was 278 kN.

For D2, the time for initial loading to failure was only a few seconds. To ensure that failure had occurred before stopping the loading at the end of the test, the target final displacement was increased from the 70 mm for D1 to 90 mm for D2. D2 was loaded at a rate of a thousand times faster than for D1, and failed at 330 kN, at a displacement of 40 mm. Failure mechanism, buckling of secondary reinforcement and crushing of concrete, was similar to that observed for D1.

It should be noted that fewer cracks and less severe concrete crushing were observed at the end of the test for D2. The initial stiffness of the load-displacement curve for D2 is higher than for D1. The strain readings for D1 and D2 indicated that the diagonal reinforcement yielded prior to failure, and that steel strains for D2 were slightly higher than for D1 at any particular load level. Because only the secondary reinforcement buckled, D1 and D2 continued to carry substantial load after the maximum load had been reached, as indicated in Figure 4(a).

Specimens D3 and D4

Specimens D3 and D4 were subjected to greater than twelve cycles of loading and unloading (Figure 3). D3, under fast rate of loading, and D4, under slow rate of loading, followed identical loading history, such that direct comparison between the two specimens could be conducted. Both tests were stopped midway through cycle 13, when the specimens were found to have been badly damaged.

For D4, the first flexural and shear cracks were recorded at a load of 104 kN at cycle 1 (98 kN for D1) and 136 kN at cycle 4 (133 kN for D1). Before the maximum loads were reached at cycle 7, no new flexural cracks were found and the shear cracks lengthened, but did not visibly open. Maximum loads for clockwise and counterclockwise moments were 314 kN and 309 kN respectively. At the end of cycle 7, concrete in the compression zone started to spall, and many more shear cracks appeared, with shear cracks opening to about 5 mm. By the end of cycle 11, much of the concrete in the compression zone, between two large diagonal cracks, had fallen off. At the end of the test, all reinforcement within the exposed area, including the diagonal reinforcement in both directions, and the longitudinal and transverse secondary reinforcement were found to have buckled.

The first large diagonal crack, extending from the top of one end of the test region to bottom of the other end, was observed during cycle 7 of the clockwise end moments for D3. It was not until cycle 9, counterclockwise end moments, that the first large diagonal shear crack was visible. Maximum loads of 327 kN (314 kN for D4) and 329 kN (309 kN for D4) were obtained for clockwise and counterclockwise end moments, respectively. Failure of D3 was similar to that for D4, but exhibited fewer flexural and shear cracks. Figure 4(c) compares cycle by cycle the load-displacement response of D3 and D4. As for D1 and D2, the initial stiffness of the curves is greater for D3, which was tested with fast dynamic loads, than for D4, which was tested with slow static loads.

Specimens D5 and D6

Specimens D5 and D6 were loaded to failure under counterclockwise end moments, then unloaded and reloaded under clockwise end moments until failure. First flexural and diagonal shear cracks for D5 occurred at loads of 93 kN (98 kN for D1 and 104 kN for D4) and 136 kN (133 kN for D1 and 136 kN for D4), respectively. As load increased, more flexural cracks and shear cracks developed. At a load of 300 kN, and a displacement of 42 mm, diagonal shear cracks were approximately 5 mm wide and extended across the length of the test region. A maximum load of 329 kN was obtained at a displacement of 34 mm. At failure, the diagonal crack had opened to approximately 10 mm, along the entire length of the test region. Concrete crushing at the ends of test region, and buckling of both main diagonal reinforcement and secondary longitudinal and transverse reinforcement, were observed.

A maximum load of 359 kN at a displacement of 49 mm (329 kN at 34 mm for D5) was recorded for D6 under dynamic loading. At failure, no crushing of concrete occurred and shear cracks were generally long but had not significantly opened. Both D5 and D6 failure under counterclockwise end moments and were subsequently reloaded under clockwise end moments. Maximum loads reached in clockwise loading were 248 kN for D5 and 303 kN for D6. Figure 4(b) presents the load-displacement behaviour of the two specimens.

CONCLUSIONS

The experimental results were presented for six diagonally reinforced concrete coupling beams, subjected to different types and rates of loading. Slow static, fast dynamic, monotonic and cyclic loading tests were performed. It was found that specimens subjected to dynamic loads tended to carry somewhat higher loads and showed higher initial stiffness, than specimens subjected to static loads. Specimens under fast rate of loading also developed fewer and less severe cracks than specimens under slow rate of loading. Ductility was not significantly affected by the different rates of loading. These conclusions are consistent with the effect of loading rate on the behaviour of reinforcing steel, indicating that the behaviour of coupling beams is primarily a function of the steel rather than the concrete behaviour.

Code provisions adequately predict the behaviour and the failure load of the beams tested. Also, whether the loading was monotonic or cyclic appeared to have minimum effects on the behaviour of specimens. Failure of all specimens was precipitated by buckling of the secondary reinforcement and concrete crushing. Therefore, additional secondary steel may be required for concrete confinement, at the ends of the test region for the beams, or, for coupled shear walls, adjacent to the vicinity of load transfer between the wall and the beam.

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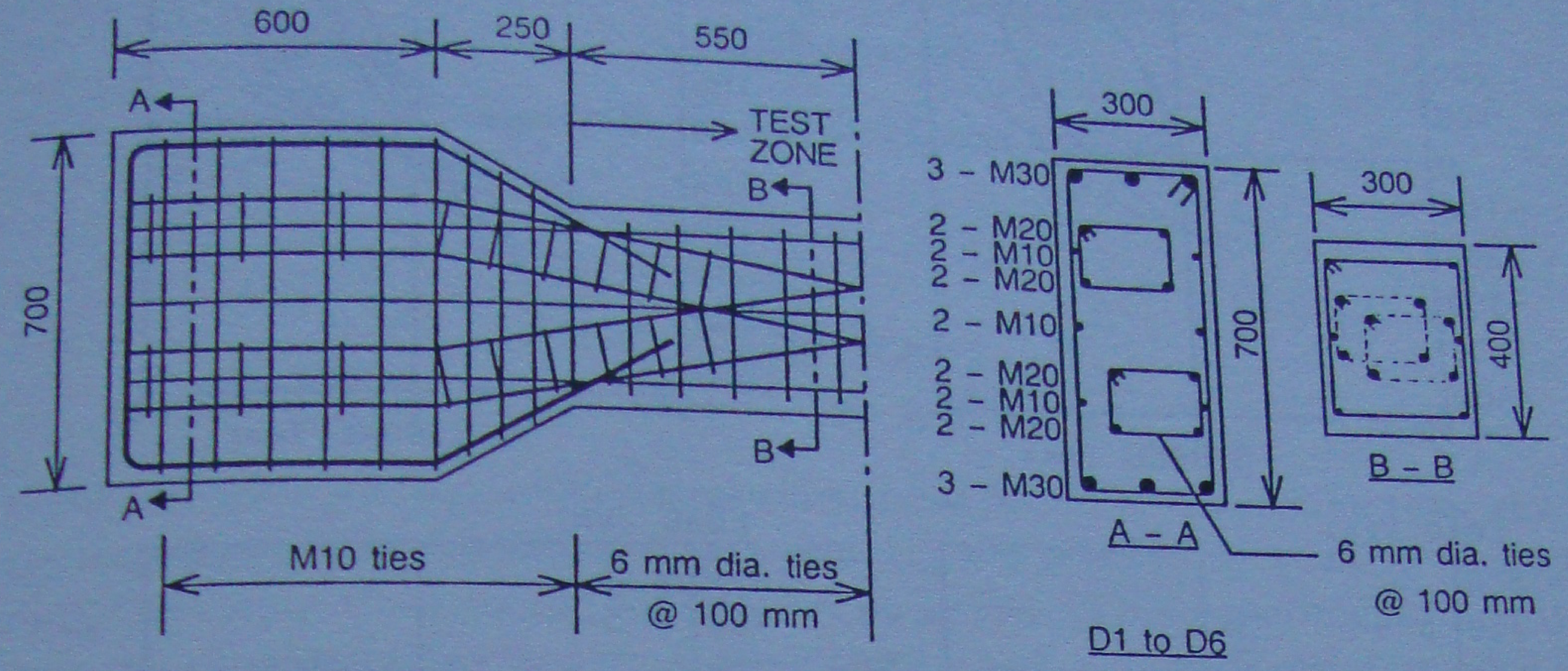


Figure 1. Details of specimens

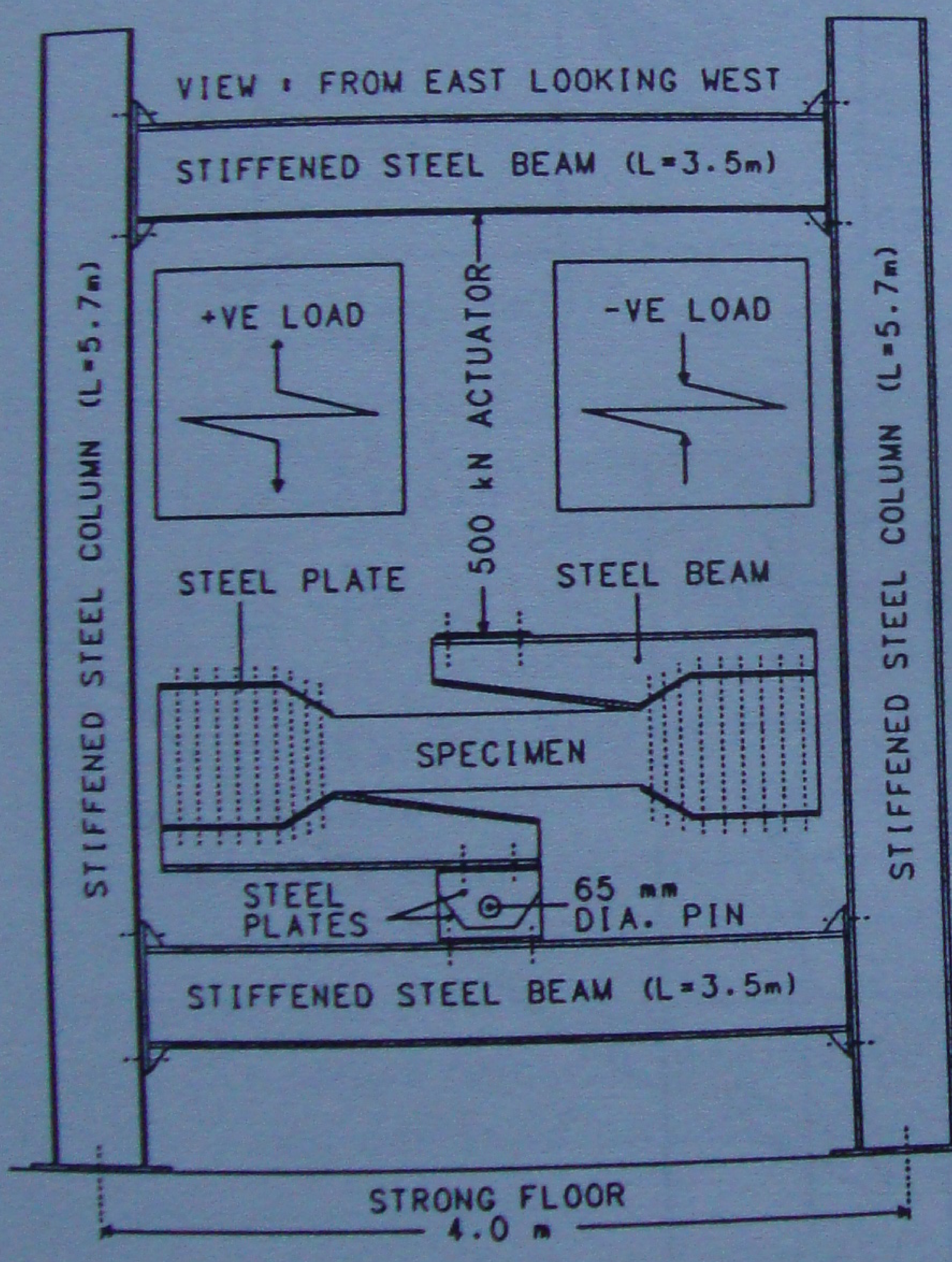


Figure 2. Test set-up

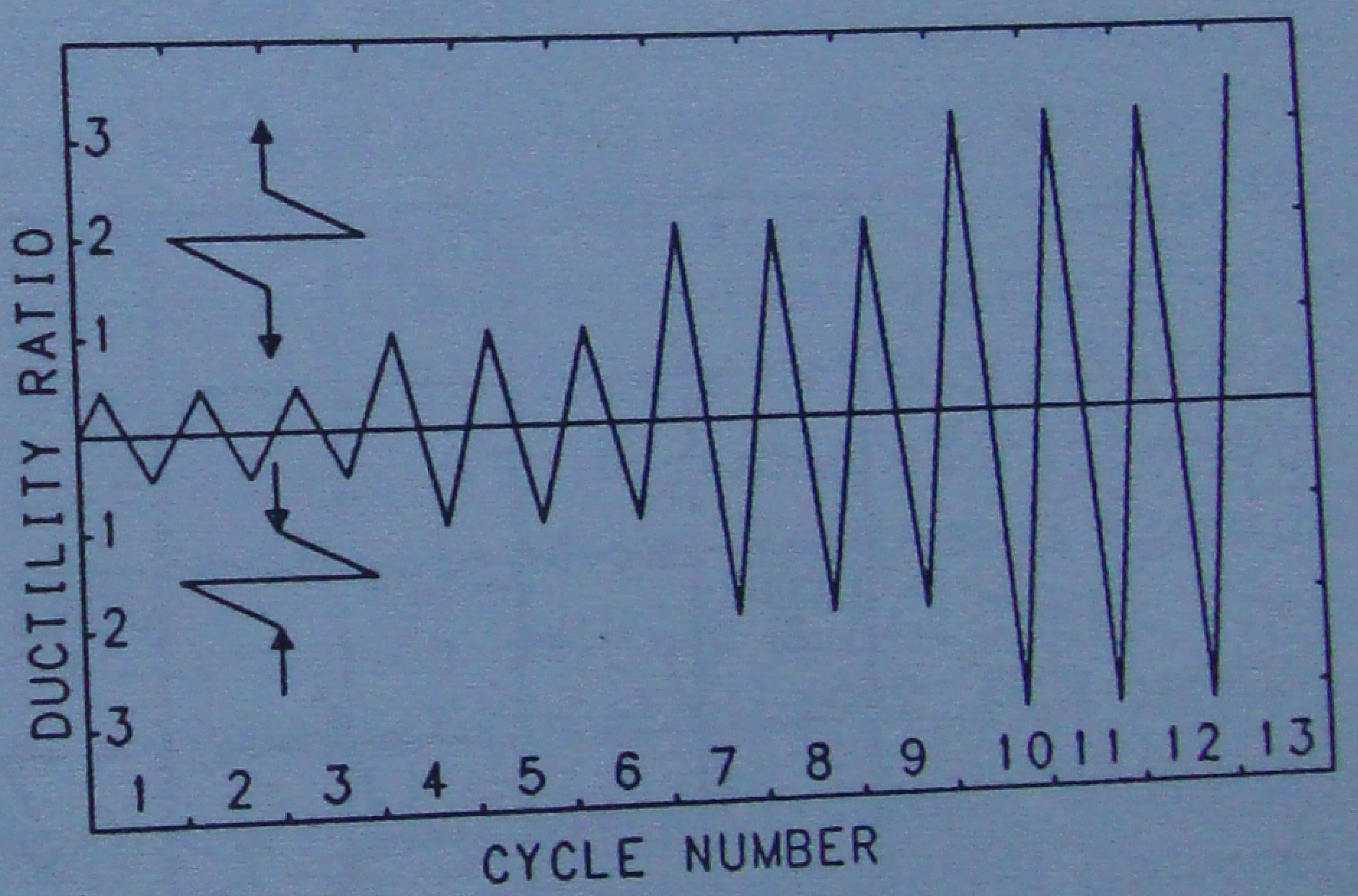
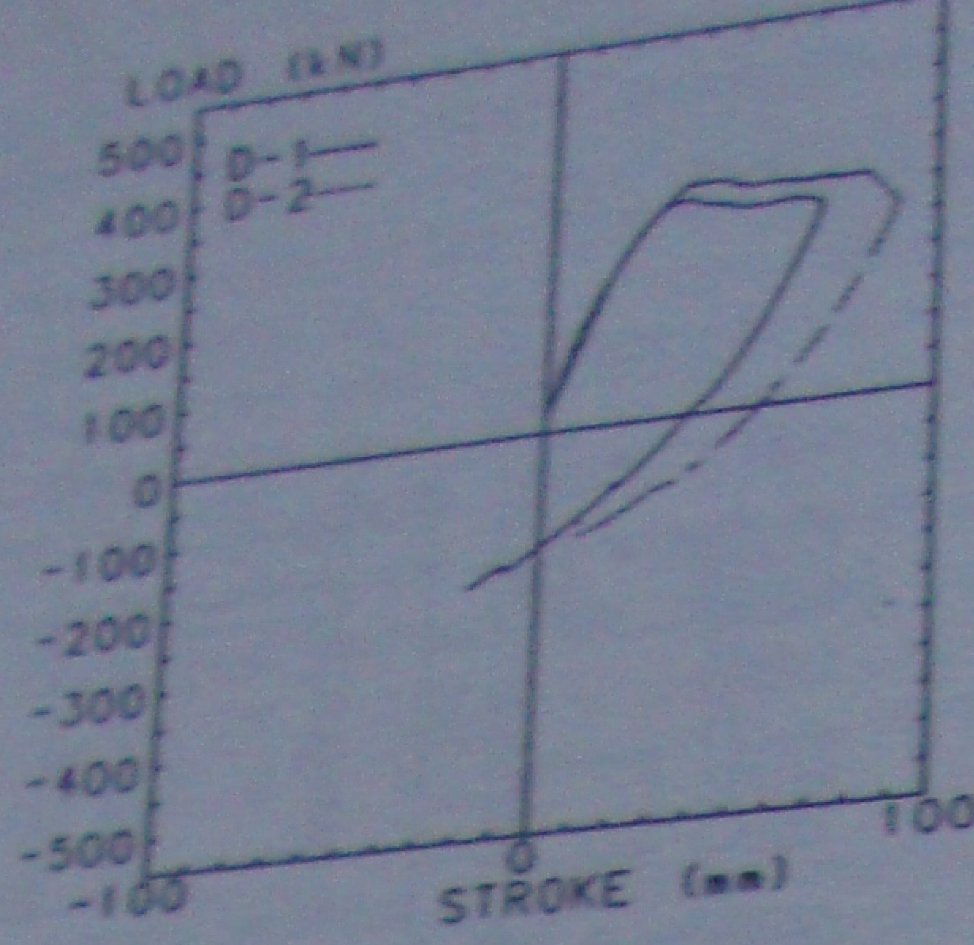


Figure 3. Cyclic loading history

(a)



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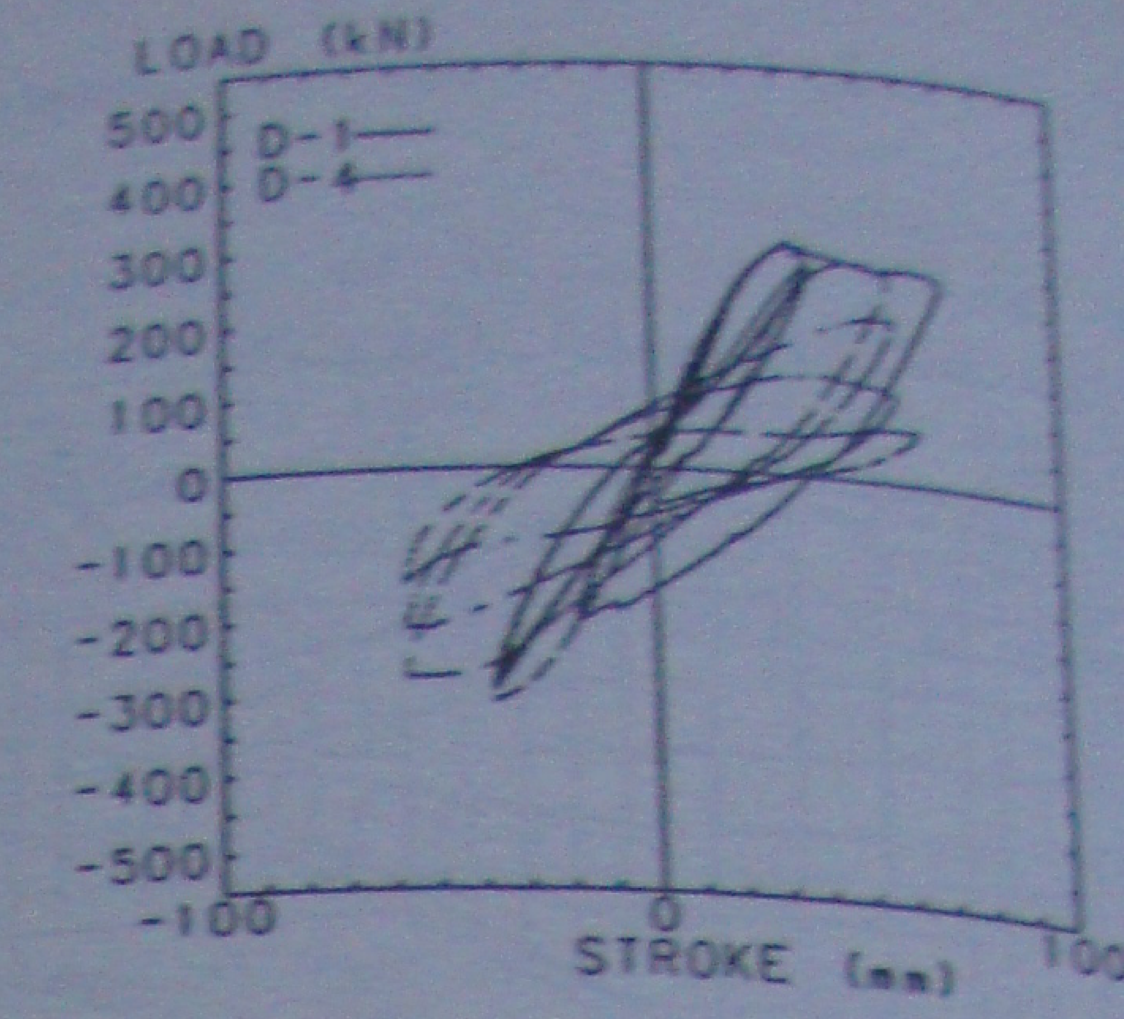

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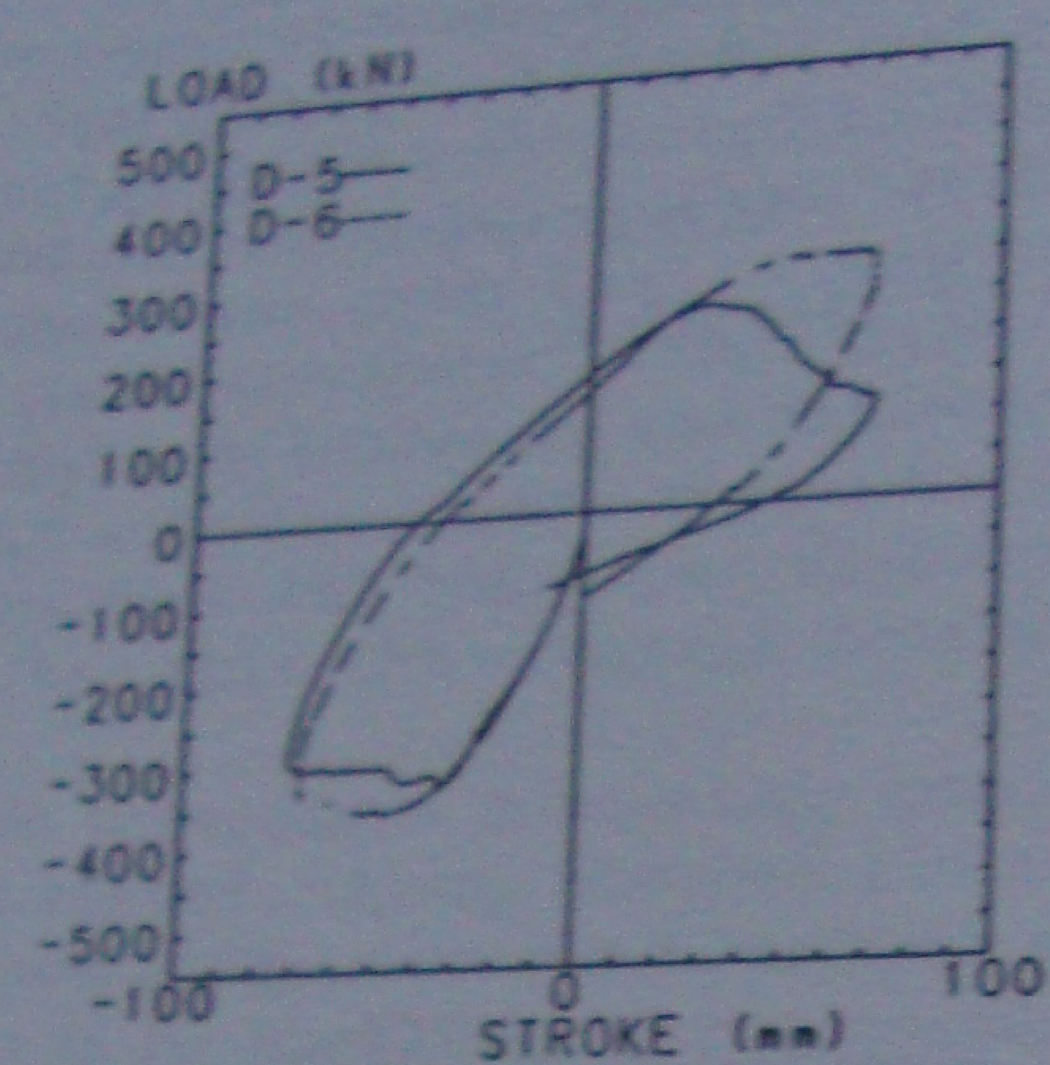
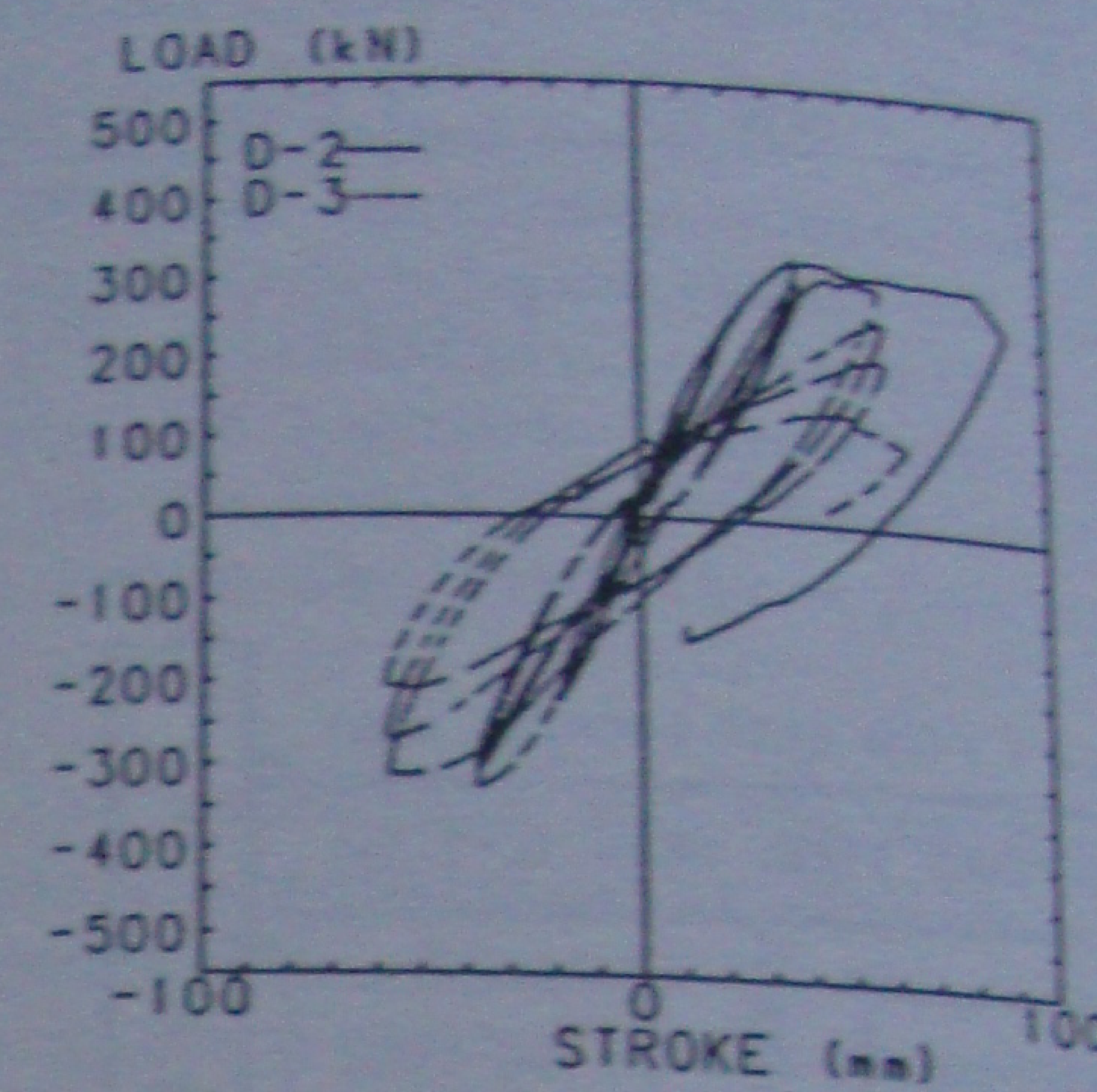


(e)



(c)

Figure 4. Load displacement curves

(a) D1 and D2
(b) D5 and D6
(c) D3 and D4
(d) D1 and D4
(e) D2 and D3