5th Canadian Conf. Earthquake Engineering / Ottawa / 1987 / 5ème Conf. Canadienne Génie Sismique

Effects of unequal shear reversals on reinforced concrete beam performance

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ABSTRACT : The results of quasi-static cyclic load tests carried out on eight large scale reinforced concrete beam specimens are reported. The effects on beam performance of concrete strength, loading sequence variations and unequal shear reversals were investigated. A simple expression is proposed to reflect the effect of unequal shear reversals for seismic design.

1 INTRODUCTION

Most of the experimental work available in literature on seismic behaviour of reinforced concrete beams was carried out on rectangular beam specimens with equal top and bottom steel, subjected to equal moment and shear reversals. In the case of high shear in both directions, wide full-depth cracks are observed when the top and bottom flexural reinforcements yield progressively. These wide full-depth cracks reduce the interface shear transfer capacity and cause a detrimental overloading of the dowel mechanism. However, this is an extreme case, and in most of the actual structures reversals are far from being equal due to the effect of gravity loads, and bottom reinforcement is usually less than top reinforcement at critical support sections. Consequently, upward shear is smaller than downward shear although flexural yielding takes place in both directions. A less critical shear deterioration is therefore expected in cases of unequal shear reversals.

The main objective of the present work was to investigte experimentally the effects of shear ratio (i.e., ratio of maximum shear in either direction) on performance of reinforced concrete beams subjected to cyclic loading. However, effects of concrete strength and loading sequence variations were also studied.

2 EXPERIMENTAL WORK

2.1 Test specimens

Properties of test beams are summarized in Tables 1 and 2. These properties have been arranged in such a way to enable comperative studies on various parameters, based on the following considerations :

a. Beams 1A, 1B and 2A were designed to investigate effects of concrete strength variation.

b. In Beam 2B, unequal upward and downward shear was the result of unequal top and bottom steel. However, in 3B and 4A unequal shear was obtained by a special arrangement of loading (simultaneous application of upward and downward loads with different shear spans, Table 1). These beams together with the reference beam 2A were considered for the investigation of unequal shear effects.

c. Beams 3A and 3B had similar properties except mixed loading sequence (presence of one large amplitude deformation cycle preceding smaller ones, instead of the usual ever increasing deformation history) for 3A.

d. Beam 4B was designed as a T-beam. This beam is not included in the present paper.

2.2 Loading and supporting system

Eight cantilever test beams were arranged in pairs to form four units.

Table 1. Dimensions and reinforcement of test beams

Beam	Dimensions(mm) Longitudinal L	ℓ_1	ℓ_2	Sectional b	h	d	Reinforcement Longitudinal Top	Bottom	ρ'/ρ	Web Stirrups	Ties
1A	1800	1500	1500	200	500	439	5Ø20	5Ø20	1.0	Ø10/100	Ø6/100
1B	1800	1500	1500	200	500	439	5Ø20	5Ø20	1.0	Ø10/100	Ø6/100
2A	2000	1500	1500	200	500	439	5Ø20	5Ø20	1.0	Ø10/100	Ø6/100
2B	2000	1500	1500	200	500	439	5Ø20	3Ø20	0.6	Ø10/100	Ø6/100
3A	2500	1500	1850	200	500	439	5Ø20	5Ø20	1.0	Ø10/100	Ø6/100
3B	2200	1500	1900	200	500	439	5Ø20	5Ø20	1.0	Ø10/100	Ø6/100
4A	1800	1250	1600	200	500	439	5Ø20	5Ø20	1.0	Ø10/100	Ø6/100

Table 2. Material strengths and loading properties

Beam	Average Strength (MPa) f_c	f_y	Loading Sequence	Shear, $k = v_{max}/\sqrt{f_c}$ Up	Down	r
1A	33.2	311	Ever inc	0.27	0.25	0.92
1B	42.1	311	Ever inc	0.23	0.23	1.01
2A	37.6	306	Ever inc	0.23	0.23	1.00
2B	37.6	306	Ever inc	0.23	0.16	0.71
3A	35.6	306	Mixed	0.18	0.28	0.64
3B	35.6	306	Ever inc	0.18	0.28	0.64
4A	33.4	312	Ever inc	0.21	0.34	0.62

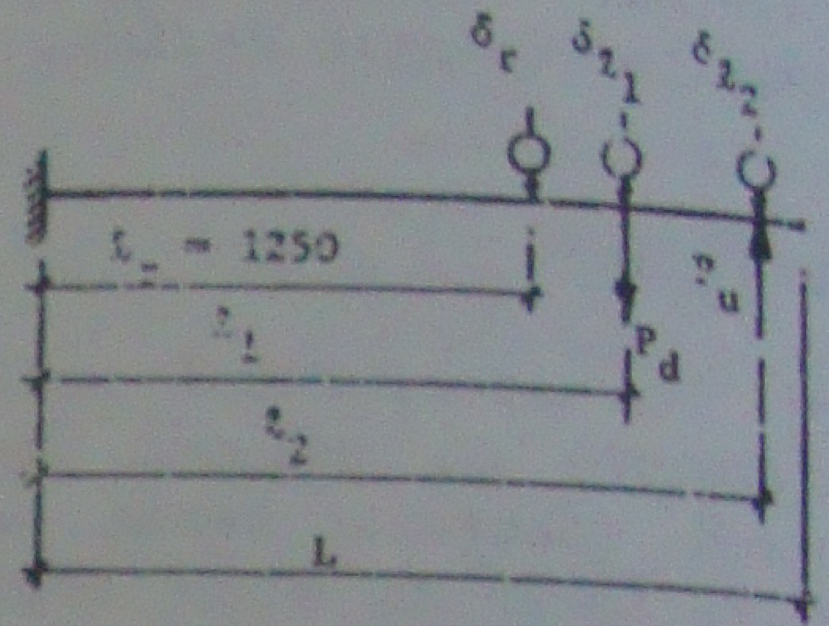

Table 3. Actual loading history for test beams

Beam	Loading Cycles						
1A	E1	E2	2D1	2D2	4D1	4D2	8D1
	8D2						
1B	E1	E2	2D1	2D2	4D1	4D2	6D1
	6D2	6D3	6D4	8D1	8D2		
2A	E1	E2	2D1	2D2	4D1	4D2	6D1
	6D2	6D3	6D4	4D3	4D4		
2B	E1	E2	2D1	2D2	4D1	4D2	6D1
	6D2	6D3	6D4	4D3	4D4		
3A	E1	E2	2D1	2D2	4D1	4D2	9D1
	6D1	6D2	6D3	6D4	8D1	8D2	
3B	E1	E2	2D1	2D2	4D1	4D2	6D1
	6D2	6D3	6D4	8D1	8D2	4D3	4D4
4A	E1	E2	2D1	2D2	4D1	4D2	6D1
	6D2	6D3	6D4	8D1	8D2		

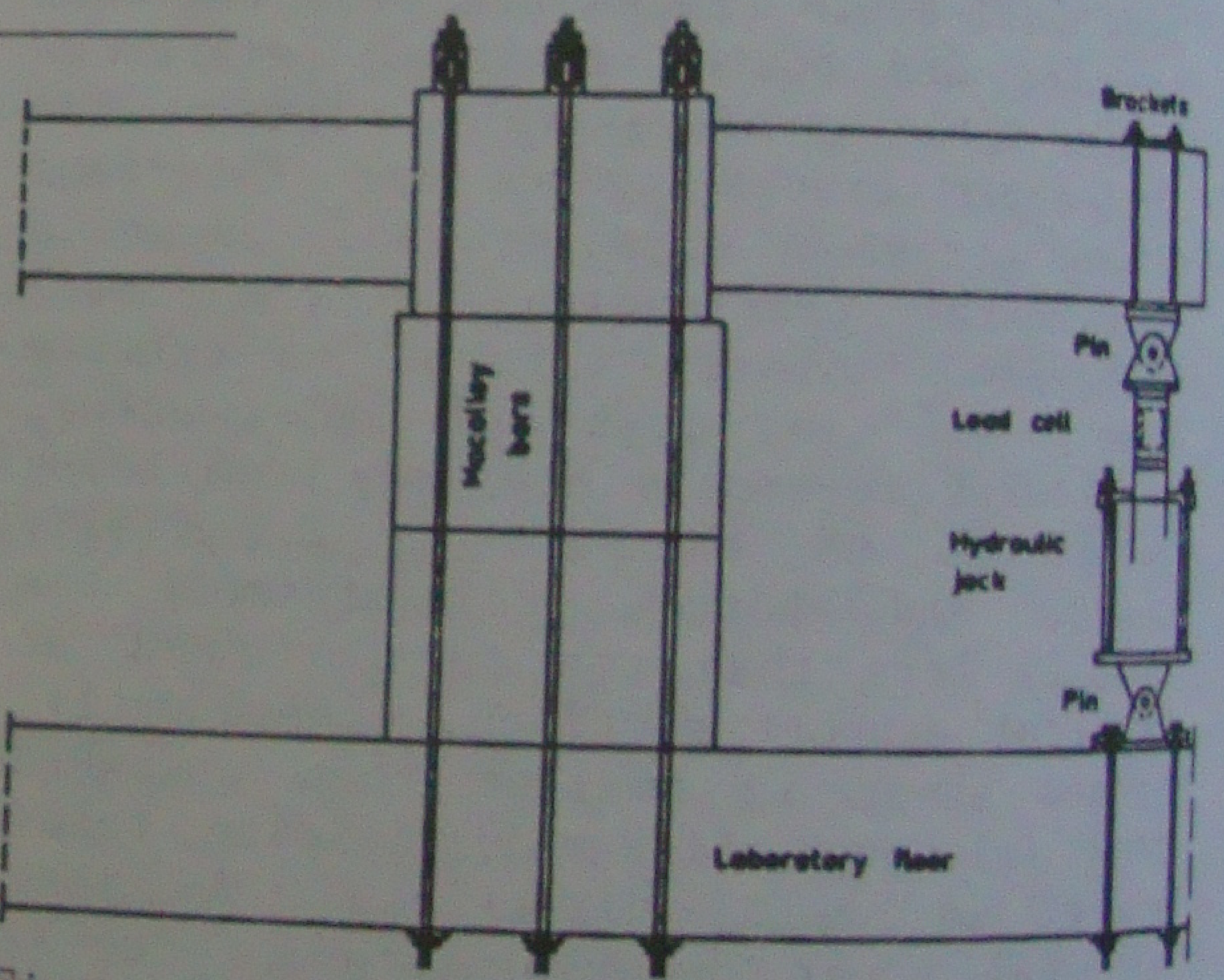

Figure 1. Loading and supporting system

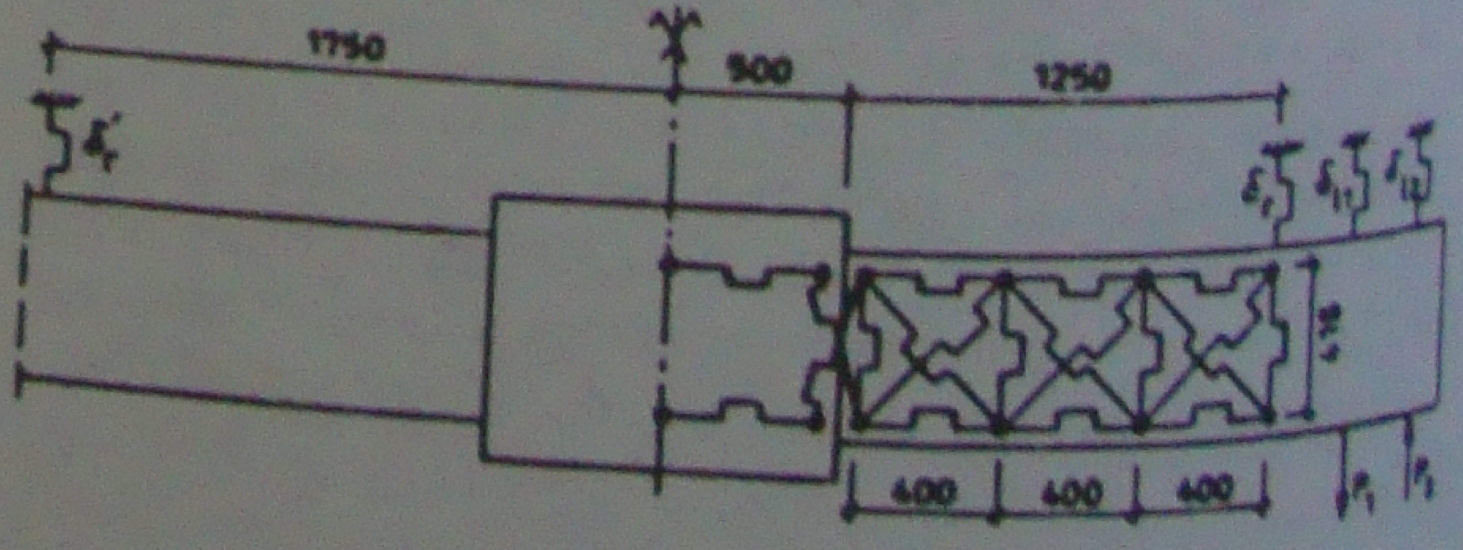

Figure 2. Clip gauge arrangement pattern

Each unit consisted of a very rigid central block and two test beams on either side. Prior to tests, central block was prestressed down to the strong floor with six Macalloy bars so that the central block acted as a very stiff column as shown in Figure 1. Load was applied to each beam through double acting hydraulic jacks with coupled load cells. As illustrated in Figure 1, the loading system was pin connected both to the floor and to the beam through a pair of brackets, so that accidental eccentricities could be minimized.

2.3 Instrumentation

Portal frame type clip gauges were used to measure a systematic pattern of displacements (Figure 2) which enabled the determination of, (i) deflections at the reference and loading points, (ii) flexural and shear deformations in four zones, (iii) rigid body rotation of the entire unit, (iv) contributions to the deflection of shear, flexure and rigid body rotation, (v) growth in length and growth in depth. Clip gauges were connected to studs which were welded to the longitudinal steel bars before casting. Gauge readings together with load cell readings were automatically recorded on punch tape which was directly fed to the computer for analysis.

2.4 Tests

Basic crack pattern in each beam was formed during the two initial elastic load cycles which extended to approximately 3/4 displacement ductility. These elastic cycles were generally followed by two 2D, two 4D and four 6D loading cycles based on reference point deflection. This basic loading sequence which was occasionally modified to some extent was based on the New Zealand code requirement of satisfactory performance for beams under four cycles of four displacement ductility and on the assumption of approximate equivalence of 4D in a usual structure to 6D in a cantilever beam. Actual loading history for each beam is given in Table 3.

In all beams, cracks formed in the initial elastic cycles, opened up during the inelastic cycles and the major diagonal cracks in the hinge zone became steeply inclined.

Spalling of concrete cover started generally in the 6D cycles, and growth in length and depth became evident. Sliding shear deformations were also evident at this stage.

Grinding action associated with sliding shear was observed generally, in the last 6D or 8D cycles, and this action ultimately caused the hinge zones to disintegrate.

3 DATA ANALYSIS

Raw data was reduced to obtain for each loading stage the values of (i) shear and bending moment, (ii) measured and calculated deflections at the reference and loading points, (iii) contributions of shear, flexure and rigid body rotation to deflection, (iv) rotation and curvature in each measurement zone, (v) growth in length and deph, and (vi) energy dissipation.

The processed data was then plotted in form of numerous curves illustrating the performance of each test beam. Data listing and detailed curves can be found in the UASE Report 268 . A few dimensionless quantities such as equivalent cycle stiffness and energy index etc. were introduced to form a reliable basis for comparison of beam performances. Only a few sets of curves representing the performance of beams could be included in the present paper. However, even this limited number of graphics is quite sufficient to illustrate the observations explained in the following section.

4 OBSERVATIONS

4.1 Concrete strength

Following observations regarding effects of concrete strength are made by comparison of Beams 1A, 1B and 2A :

a. In Figure 3, variation of the ratio of cycle peak load to yield load is plotted in order to have an indication of strength loss in beams made of concretes of different strength, otherwise identical. No significant effect is observed in E, 2D and 4D cycles;however, beyond 4D, a faster and earlier strength loss in poorer concrete is evident.

b. Ratio of shear deflection to total deflection is an indication of shear degradation. Variation of this ratio is presented in Figure 4 for three identical beams of different quality concrete. No significant difference is observed in the earlier cycles; but beyond 4D, higher shear degradation is obsedved in poorer concrete.

c. Equivalent cycle stiffness is an approximate measure of overall stiffness of the cycle. As shown in Figure 5, its variation indicates a similar tendency as regards stiffness degradation.

d. In Figure 6, shear deflections are plotted against energy dissipation. This variation is also a reliable indication of shear degradation. Observed tendency clearly supports the observation "b" given above.

4.2 Shear ratio

Four beams are compared in this respect. Beams 2B, 3B and 4A were similar in all respects (except one for each) to the reference beam 2A. 2B had unequal steel and therefore received unequal shear. In beams 3B and 4A unequal shear was obtained by a different arangement of the load. Nominal shear in 3B was of the same order as that of 2A, while it was somewhat higher for 4A with a similar shear ratio.

a. Strength degradation properties of 2A and 2B are very similar while the performance of 3B in this respect is superior (Figure 7). 4A lies between the two.

b. The same tendency is observed as regards shear degradation (Figures 8 and 10) and energy dissipation capacity (Figure 9).

New Zealand Code sets certain requirements for beams where the nominal shear stress exceeds a limiting value.However, these requirements are relaxed to a certain extent in the cases of unequal shear (i.e. $V_{up} < V_{down}$) as a result of significant gravity loading. The present relaxation method, known to be based purely on intuition is formulated in such a way to increase the limiting nominal shear stress value that brings the rather heavy requirements into action, using the expression,

$$v_u = (2 - r) \times 0.3 \sqrt{f_c} \quad \text{(MPa)} \tag{1}$$

where r is the shear ratio (between 0.2 and 1.0) and (2-r) is the factor through which relaxation is introduced. In the case of shear force being very small in

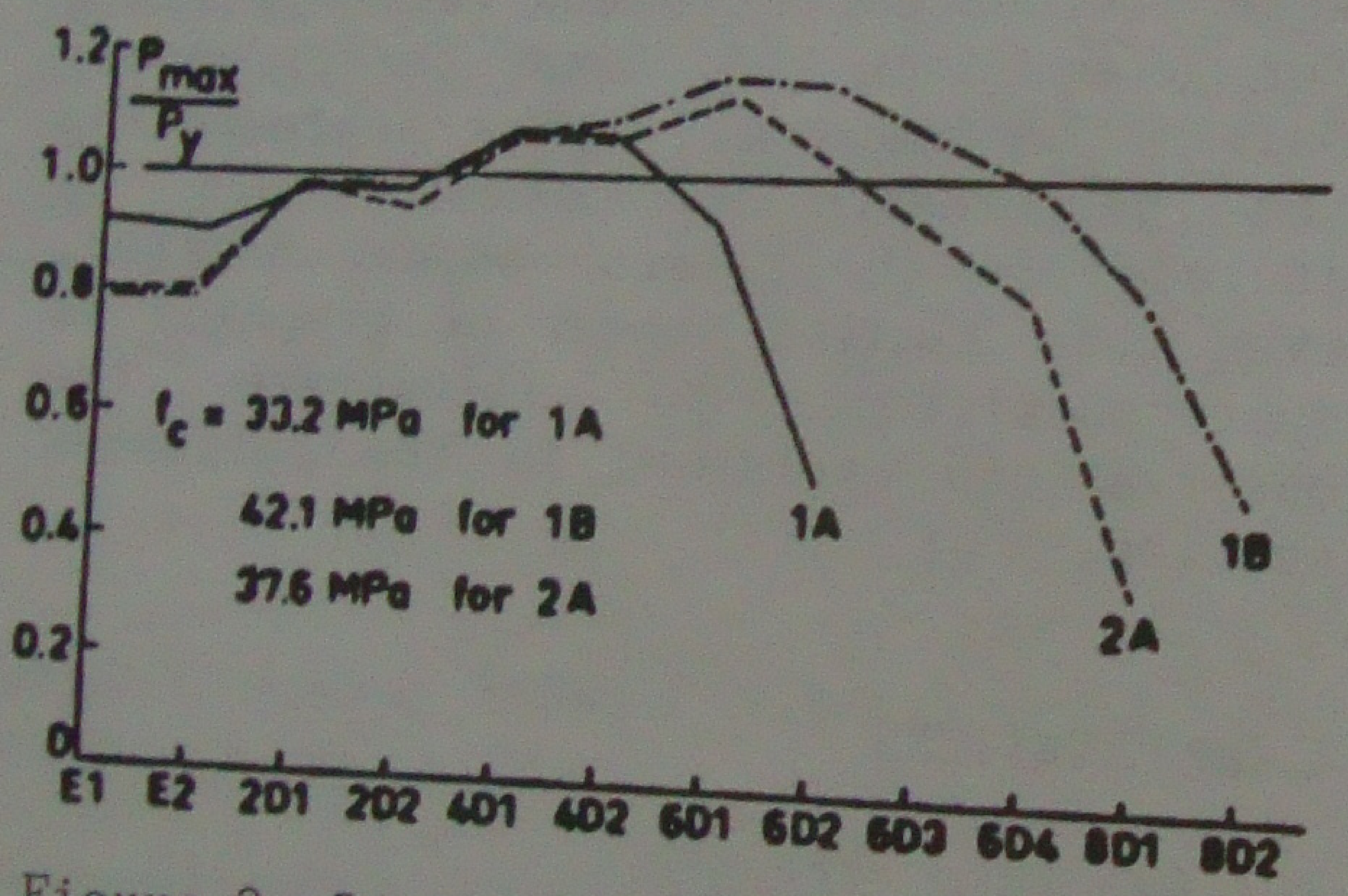

Figure 3. Strength loss

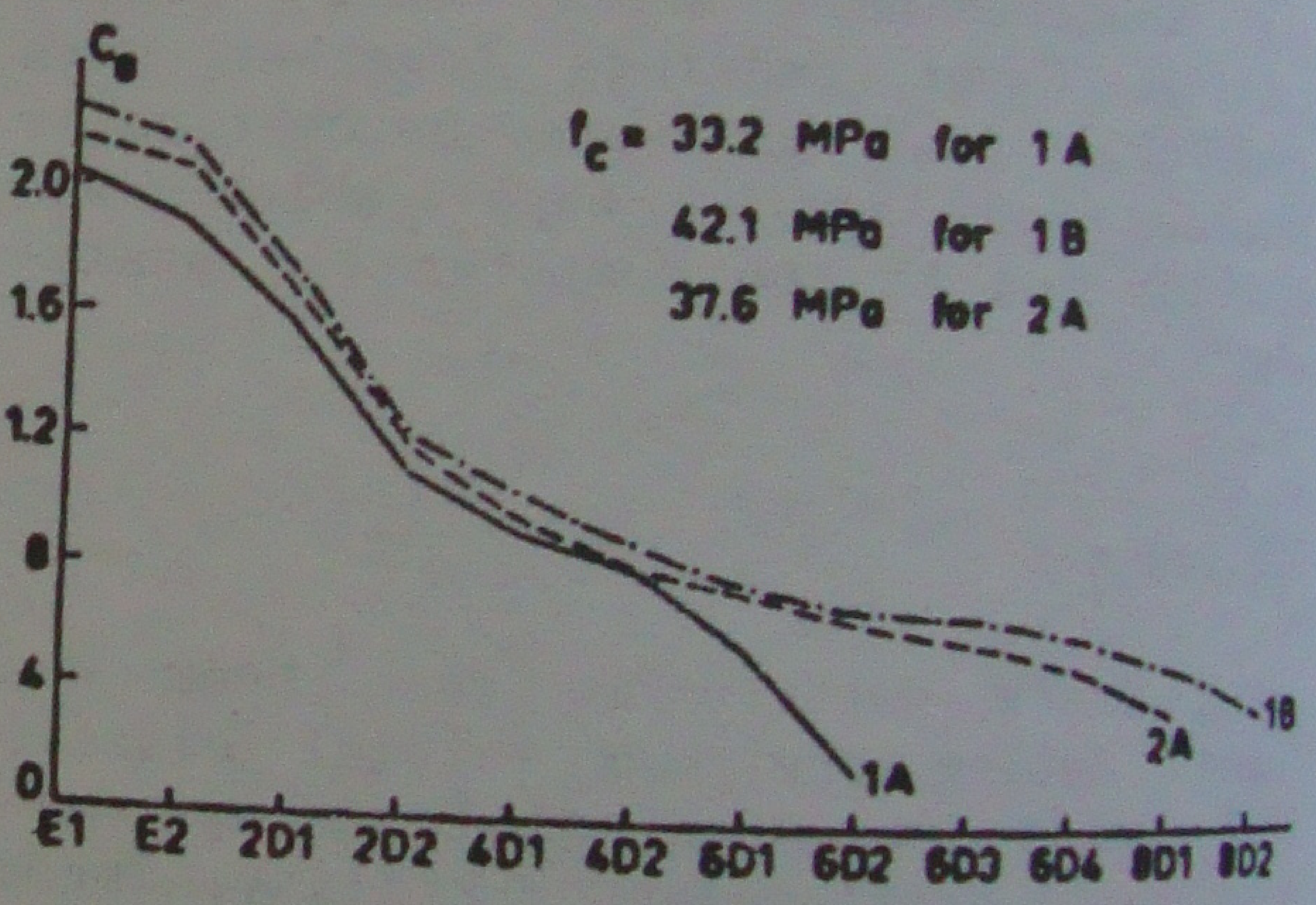

Figure 5. Equivalent cycle stiffness

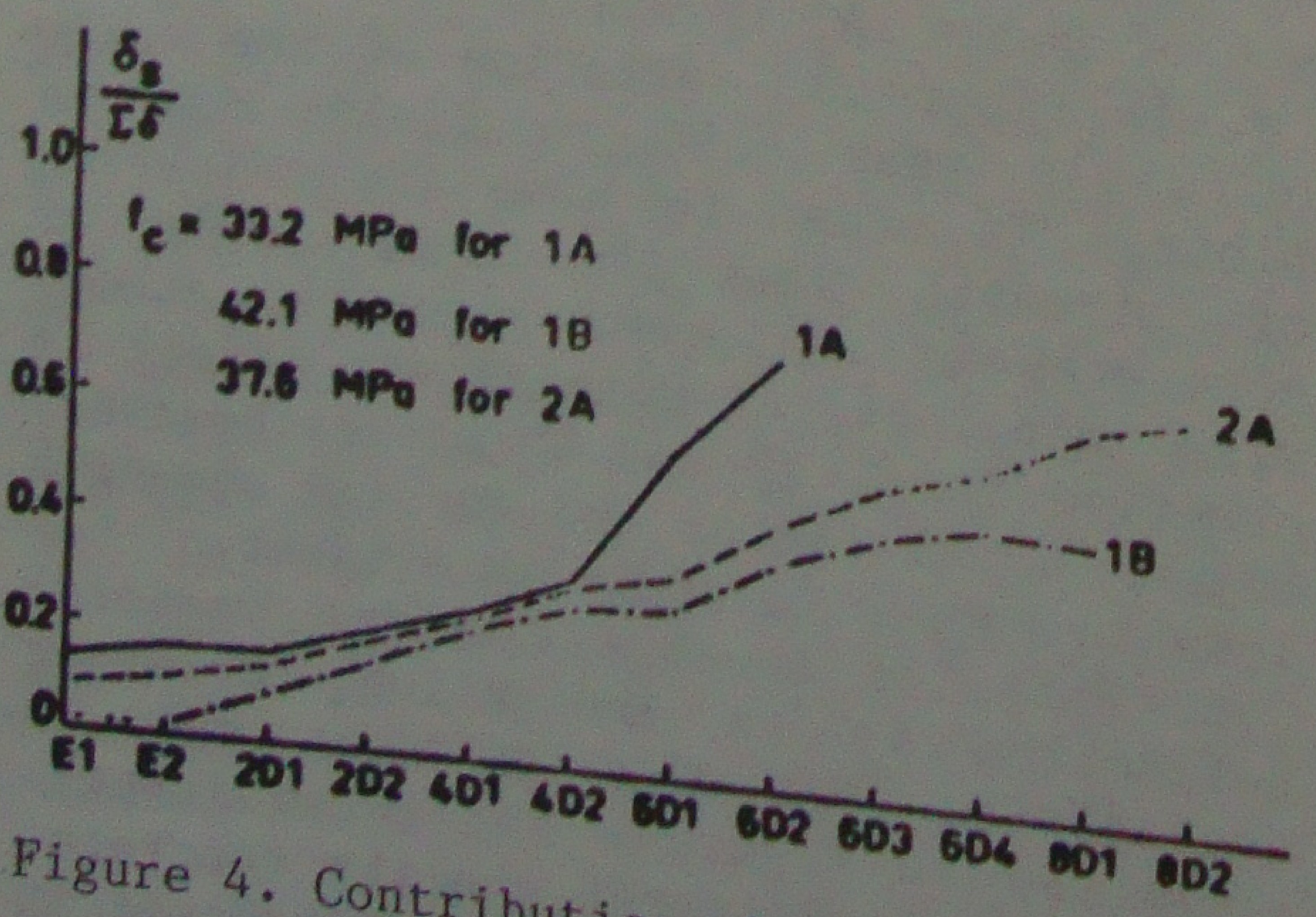

Figure 4. Contribution of shear to deflection

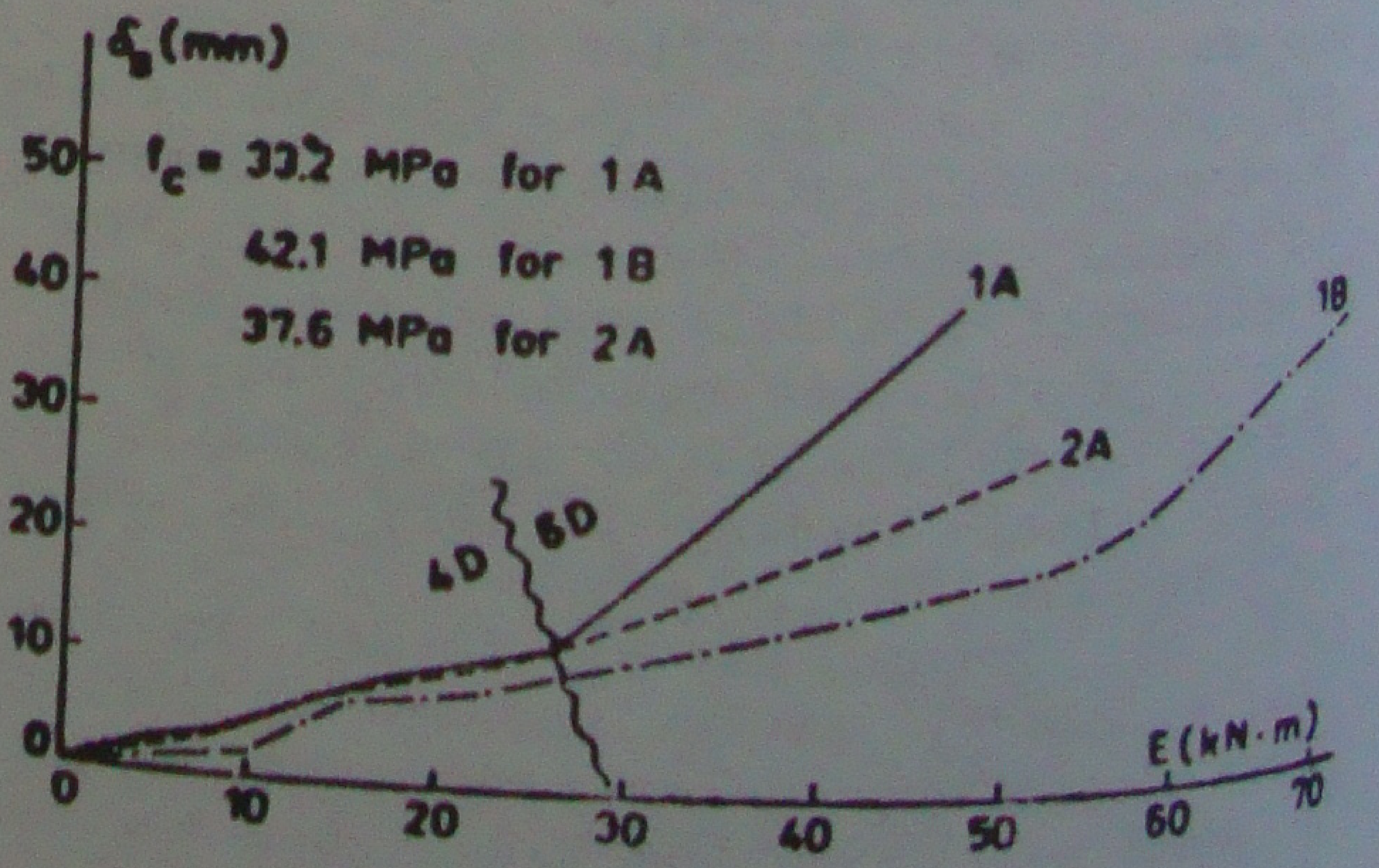

Figure 6. Energy-shear deflection

one direction, the limiting value is nearly doubled. This approach generally agrees with the behaviour observed during the tests. However in the case of unequal top and bottom reinforcement (beam 2B), improvement in performance is not significant, whereas the above expression indicates an improvement by a factor 1.4. This observation inspires a necessity to introduce the reinforcement ratio (ρ'/ρ) into the correction factor.

It is extremely difficult to establish a reliable and realistic measure for performance of a test beam. However, it should somehow be expressed considering (i) energy dissipation capacity, (ii) strength degradation properties, (iii) shear degradation properties and (iv) stiffness degradation properties observed during the tests. An overall evaluation of the performance of the four beams considered in all these respects, may lead to the conclusion that the performances of 2A, 2B and 4A are roughly of the same order, and can be taken as one unit of performance. The performance of 3B is obviously superior, and it can therefore be expressed as a coefficient (say 1.4) times one unit of performance. With all these rather debatable considerations, Table 4 was prepared to summarize the properties essential for comparison.

Table 4. Performance parameters

Beam	v_{max}	$\frac{V_{up}}{V_{down}}$	$\frac{\rho'}{\rho}$	Performance	α
2A	$\sim 1.0 v_o$	~1.0	1.0	~1.0U	1.0
2B	$\sim 1.0 v_o$	~0.6	0.6	~1.0U	1.0
3B	$\sim 1.0 v_o$	~0.6	1.0	~1.4U	1.4
4A	$\sim 1.4 v_o$	~0.6	1.0	~1.0U	1.4

As a result of the above discussion, Equation 1 can be modified as,

$$v_u = \alpha \times 0.3 \sqrt{f_c} \quad \text{(MPa)} \qquad (2)$$

where $\alpha = 2 - \frac{r}{\beta}$ $\quad 1.0 \leq \alpha \leq 1.8$

$r = V_{up}/V_{down}$ $\quad 0.2 \leq r \leq \beta$

$\beta = \rho'/\rho$ $\quad 0.5 \leq \beta \leq 1.0$

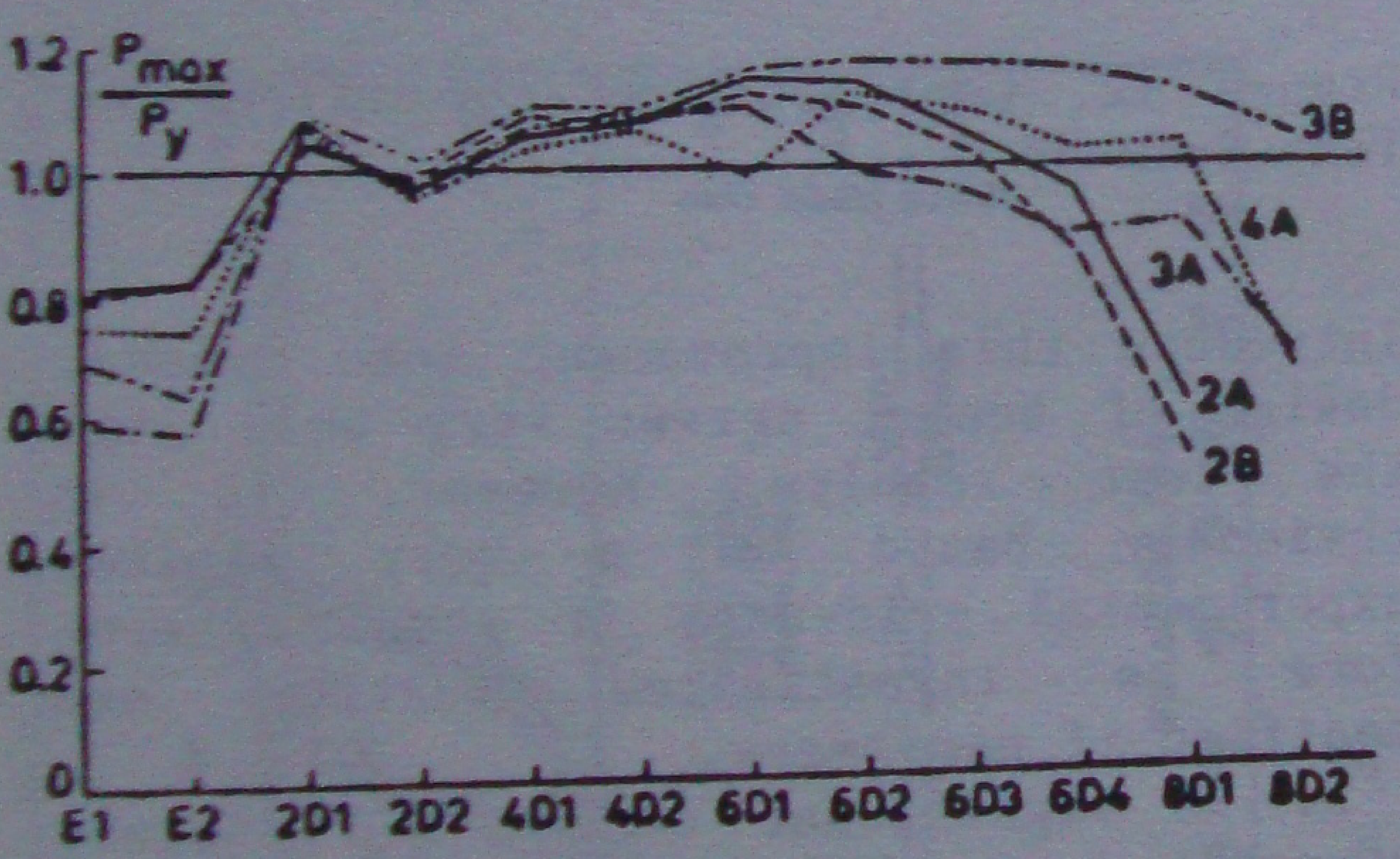

Figure 7. Strength loss

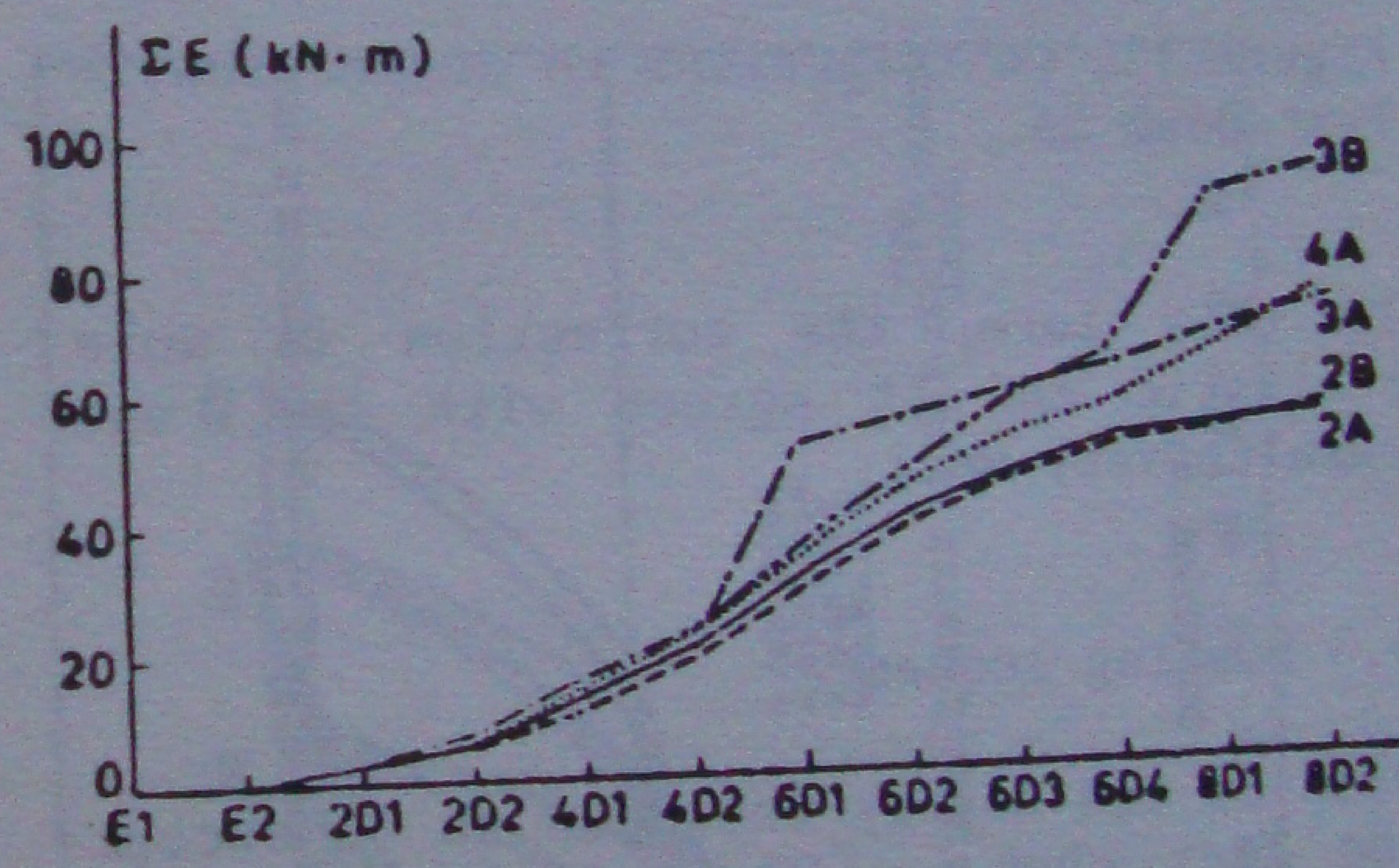

Figure 9. Energy dissipation (integral)

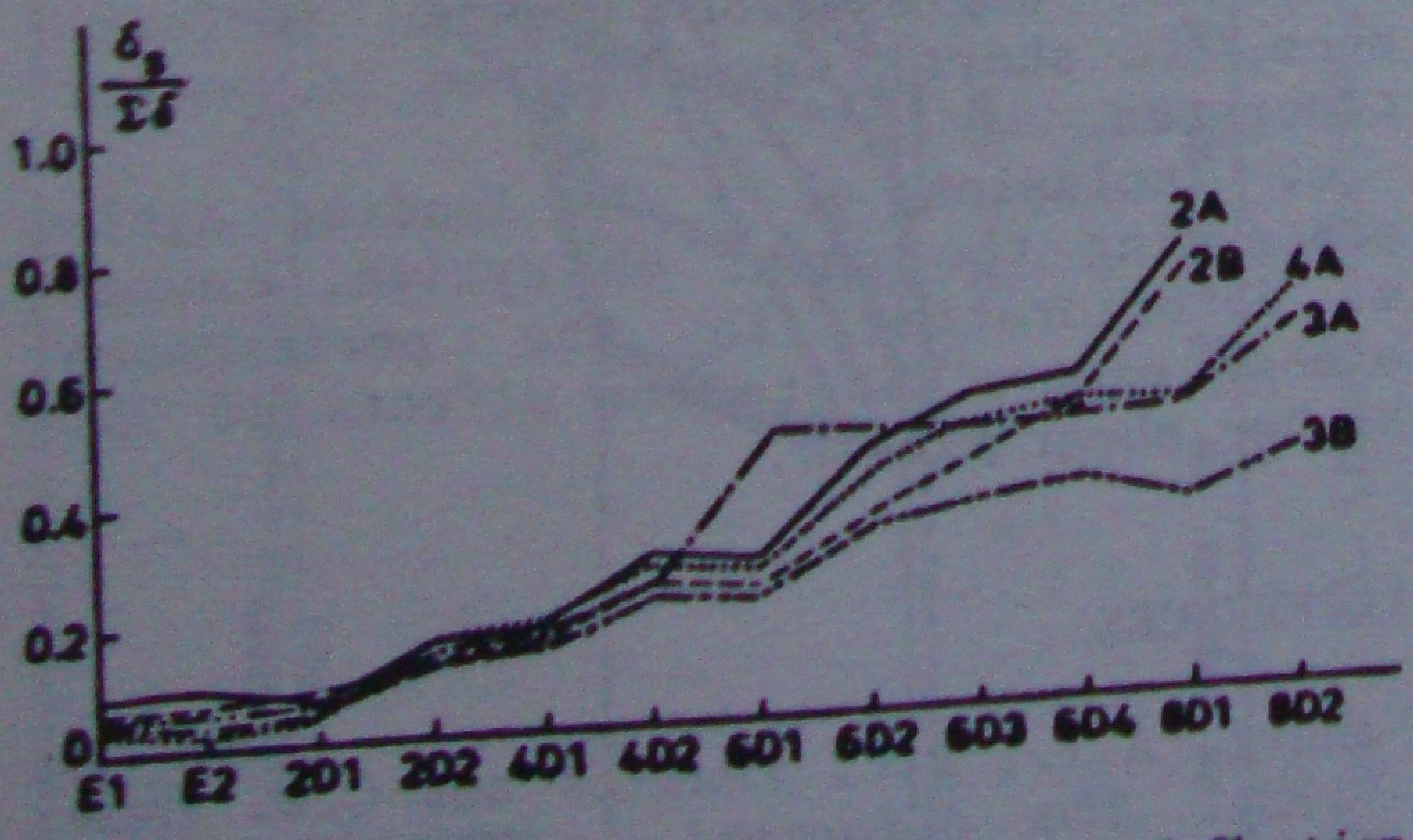

Figure 8. Contribution of shear to deflection

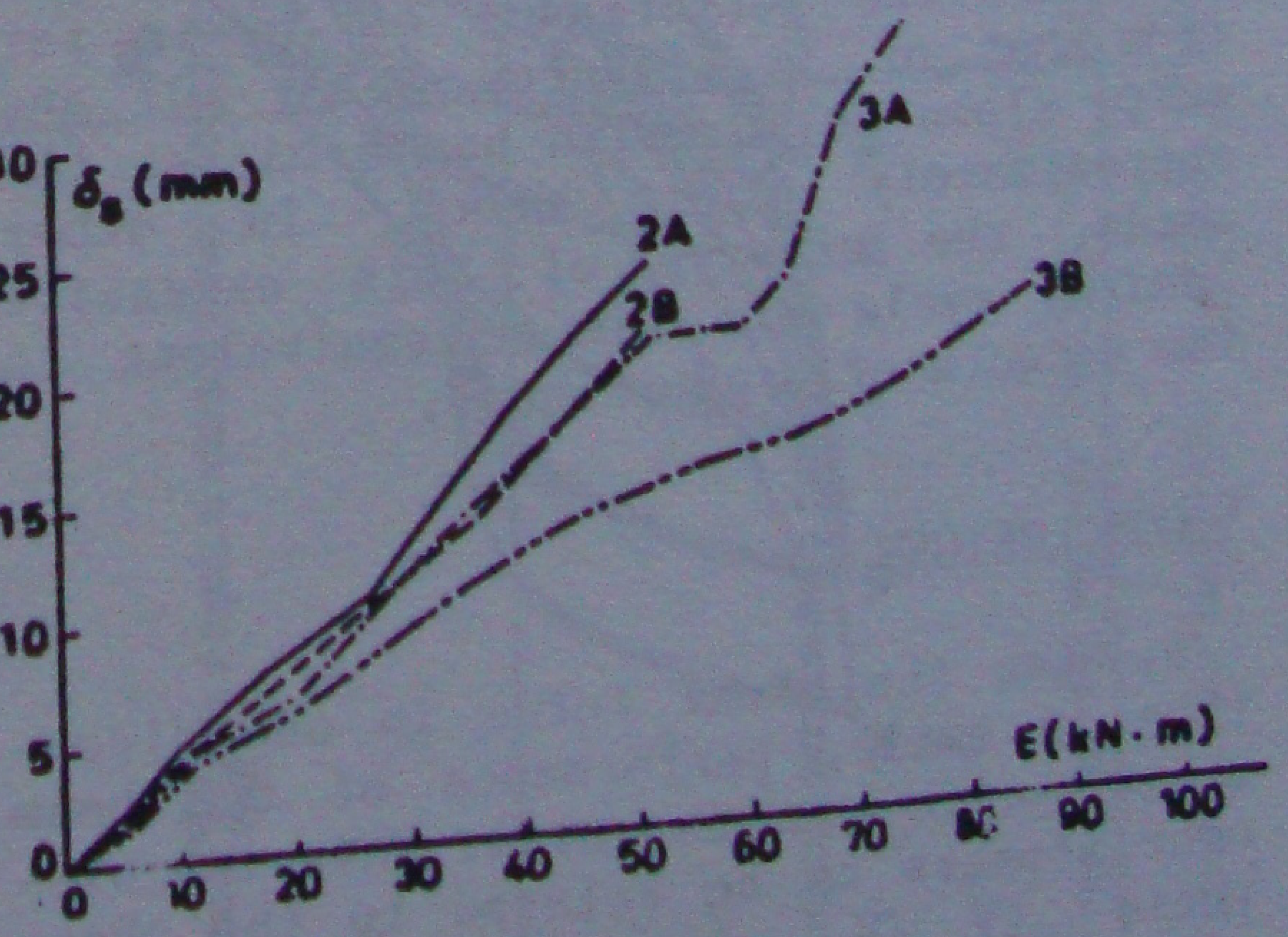

Figure 10. Energy shear deflection

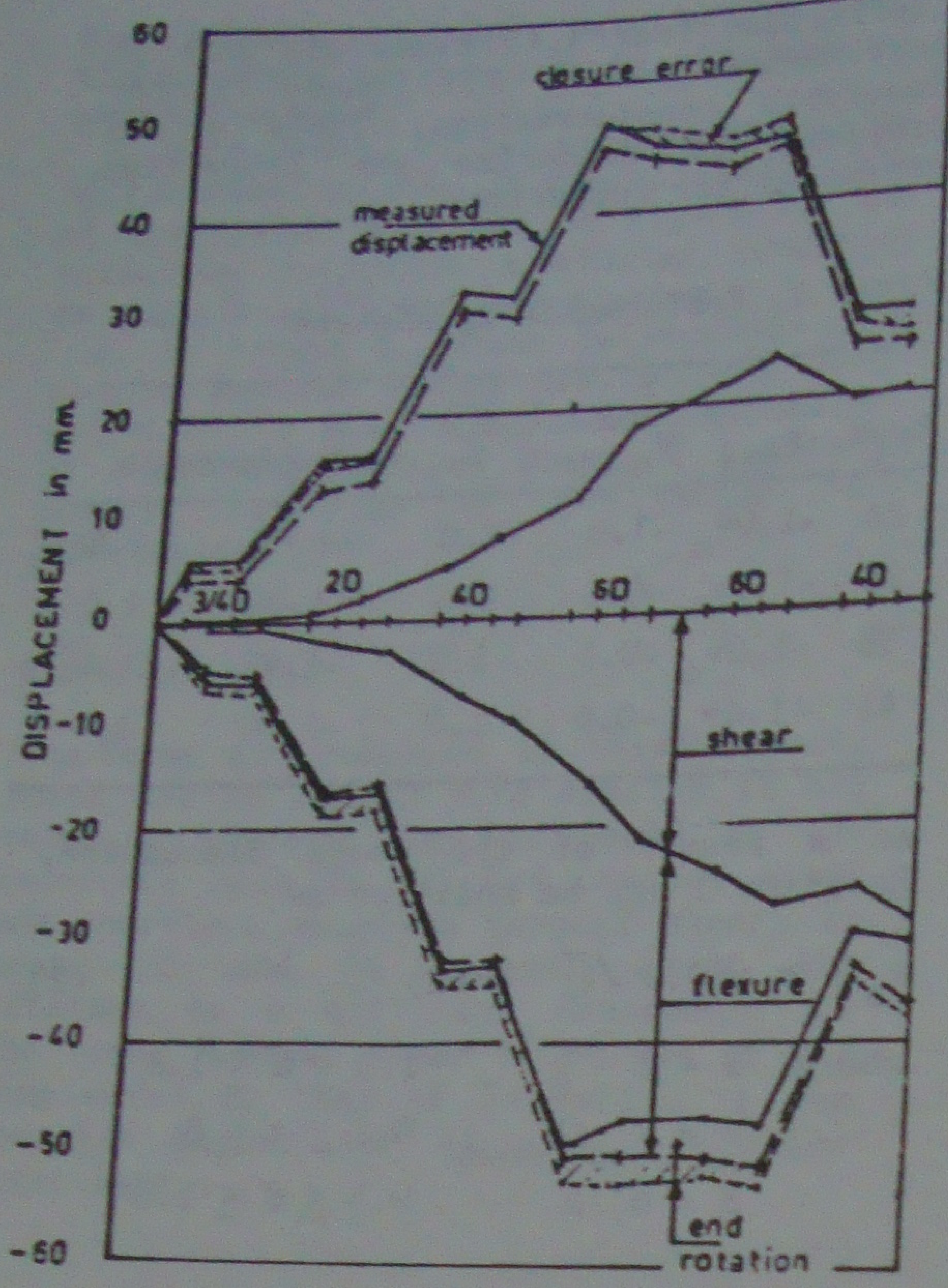

Figure 11. Contributions to deflection, Test Beam 2A

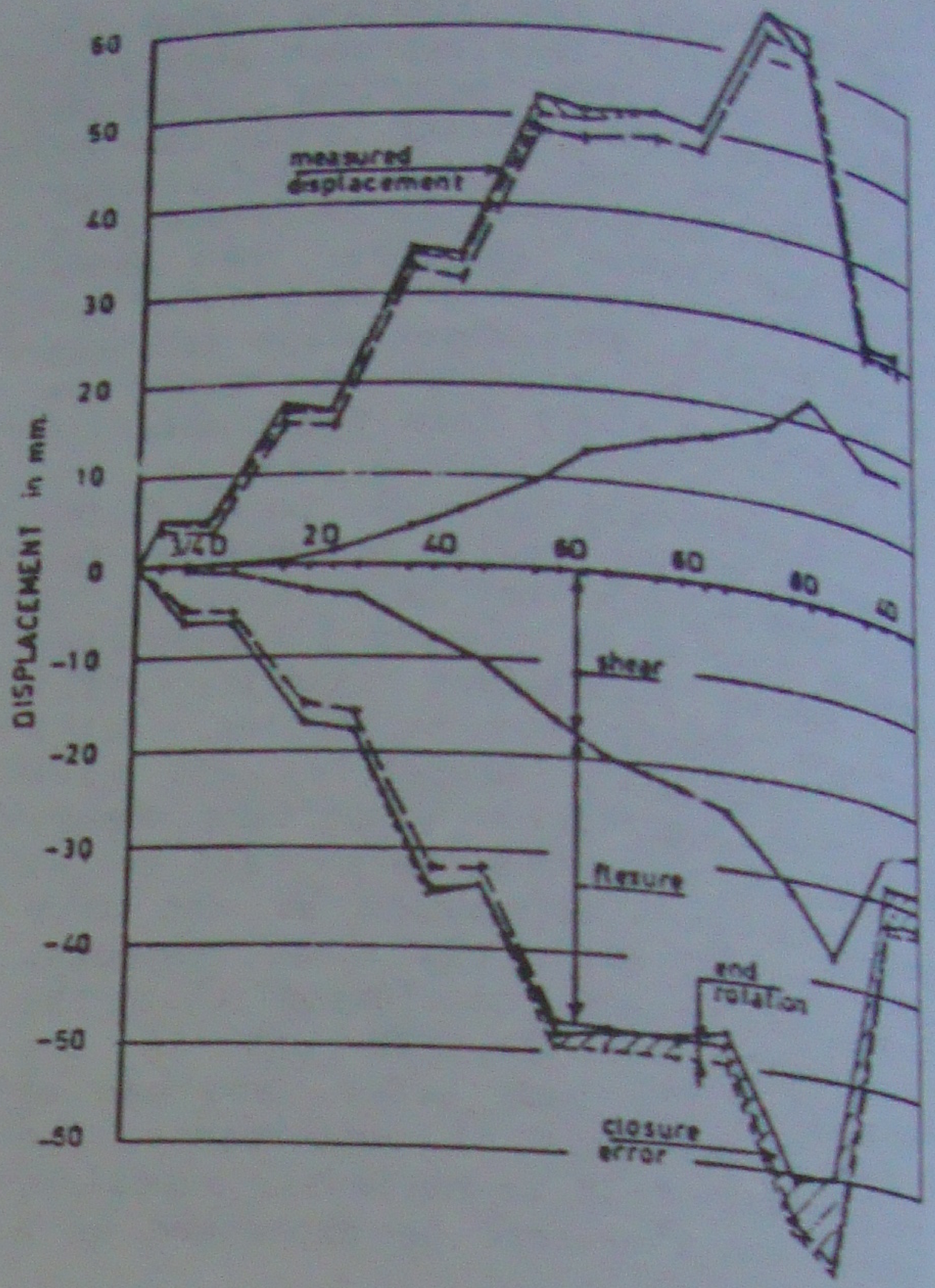

Figure 12. Contributions to deflection, Test Beam 3B

In this form, the correction is more realistic and it agrees with the test results very well.

4.3 Loading sequence

Beam 3A was nearly the same as 3B except the fact that, a 9D cycle preceded 6D cycles applied to this beam. As a result of this, the performance of 3A is far from that of 3B (Figures 7 to 10) and quite close to 4D which had a higher (by approximately 25%) shear. In other words, the effects of this excessive loading cycle are almost equivalent to the effects of higher shear.

5 CONCLUSIONS

a. When the shear force in one direction is small, performance of the beam under cyclic load improves. This improvement appears to be related to the shear ratio (V_{up}/V_{down}) and reinforcement ratio (ρ'/ρ). Equation 2 proposed to introduce this improvement into seismic design of beams, agrees very well with the test results. However, it is obviously based on a very limited experimental evidence; it should therefore be investigated further and modified if necessary.

b. No significant effect of concrete strength variation was observed in the earlier cycles. However, beyond 4D cycles, faster and earlier strength loss higher shear degradation and higher stiffness degradation (poorer performance, in short) was observed in poorer concretes.

c. Inclusion of a 9D loading cycle preceeding the usual 6D cycles, caused a deterioration in the performance almost equivalent to the effects of 25% higher shear stress.

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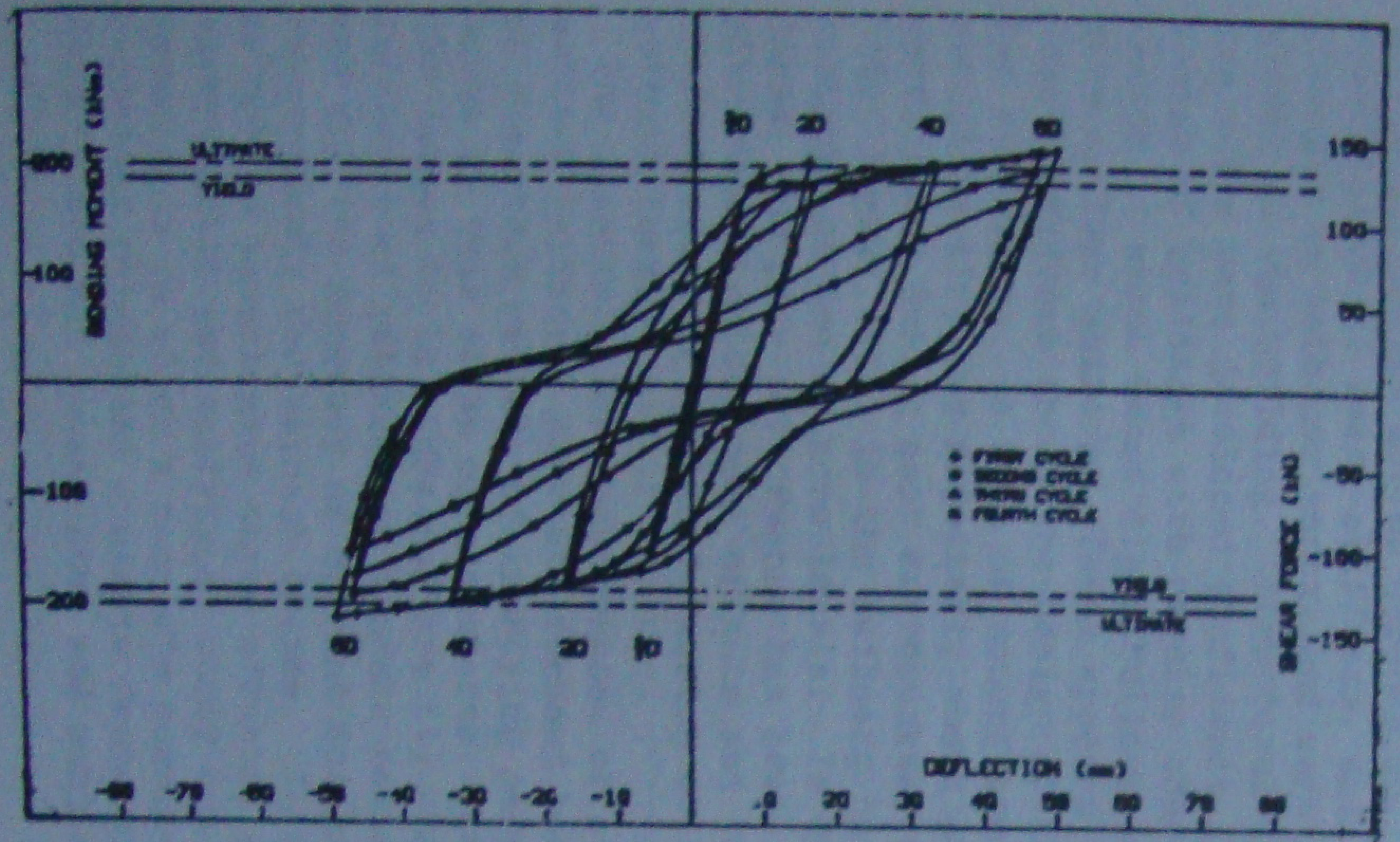

Figure 13. Load-Deflection, Test Beam 2A

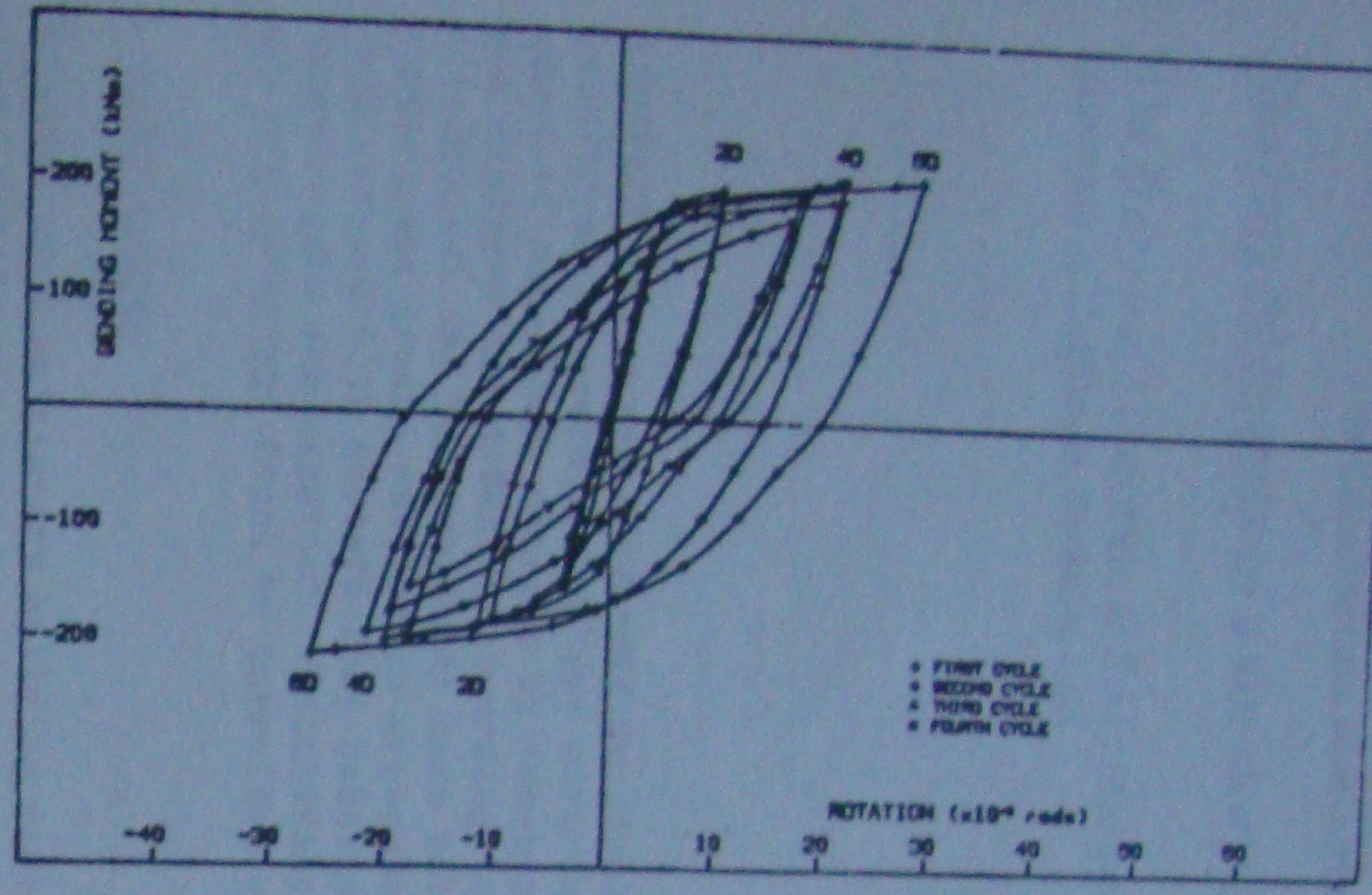

Figure 14. Moment-Rotation, Test Beam 2A

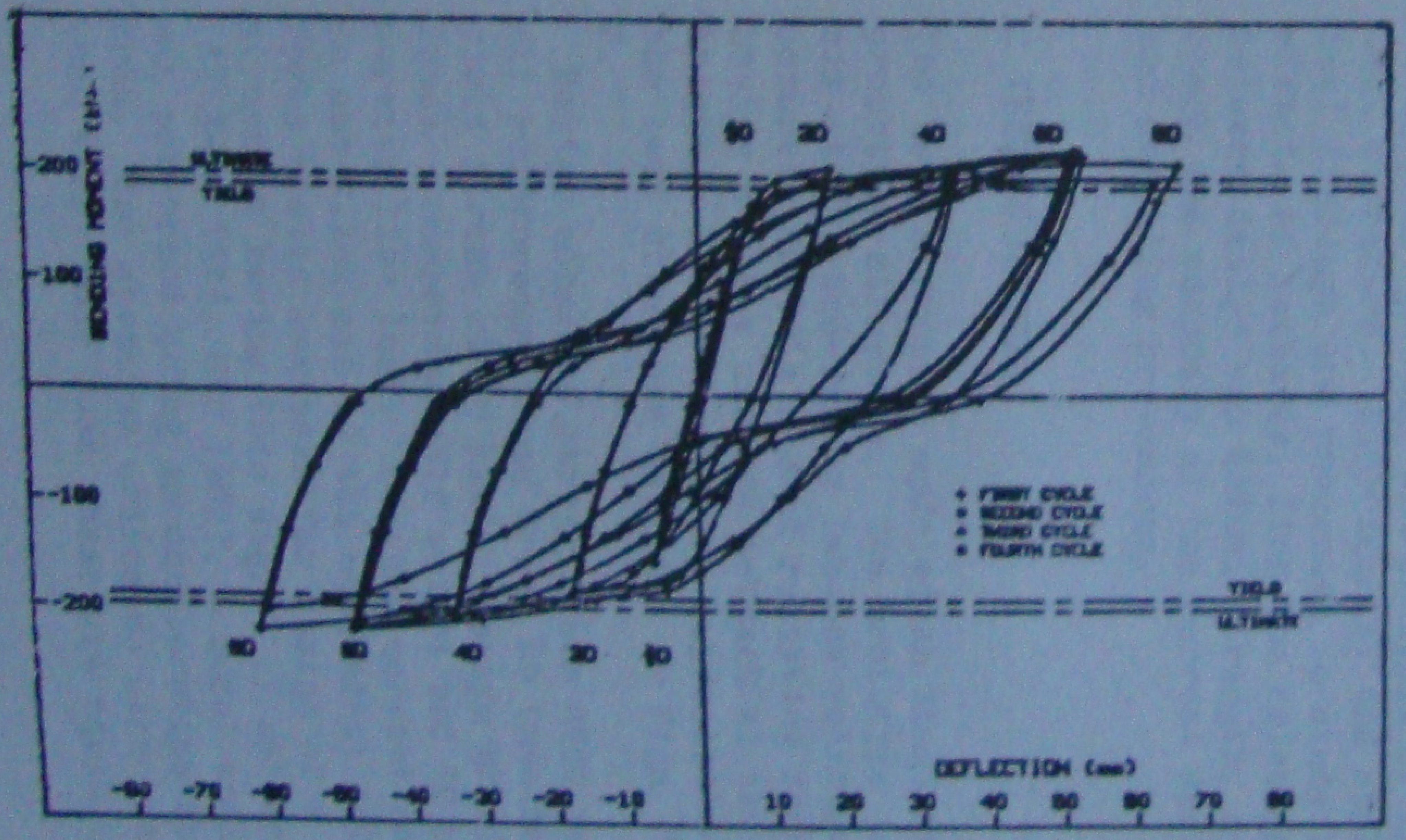

Figure 15. Load-Deflection, Test Beam 3B

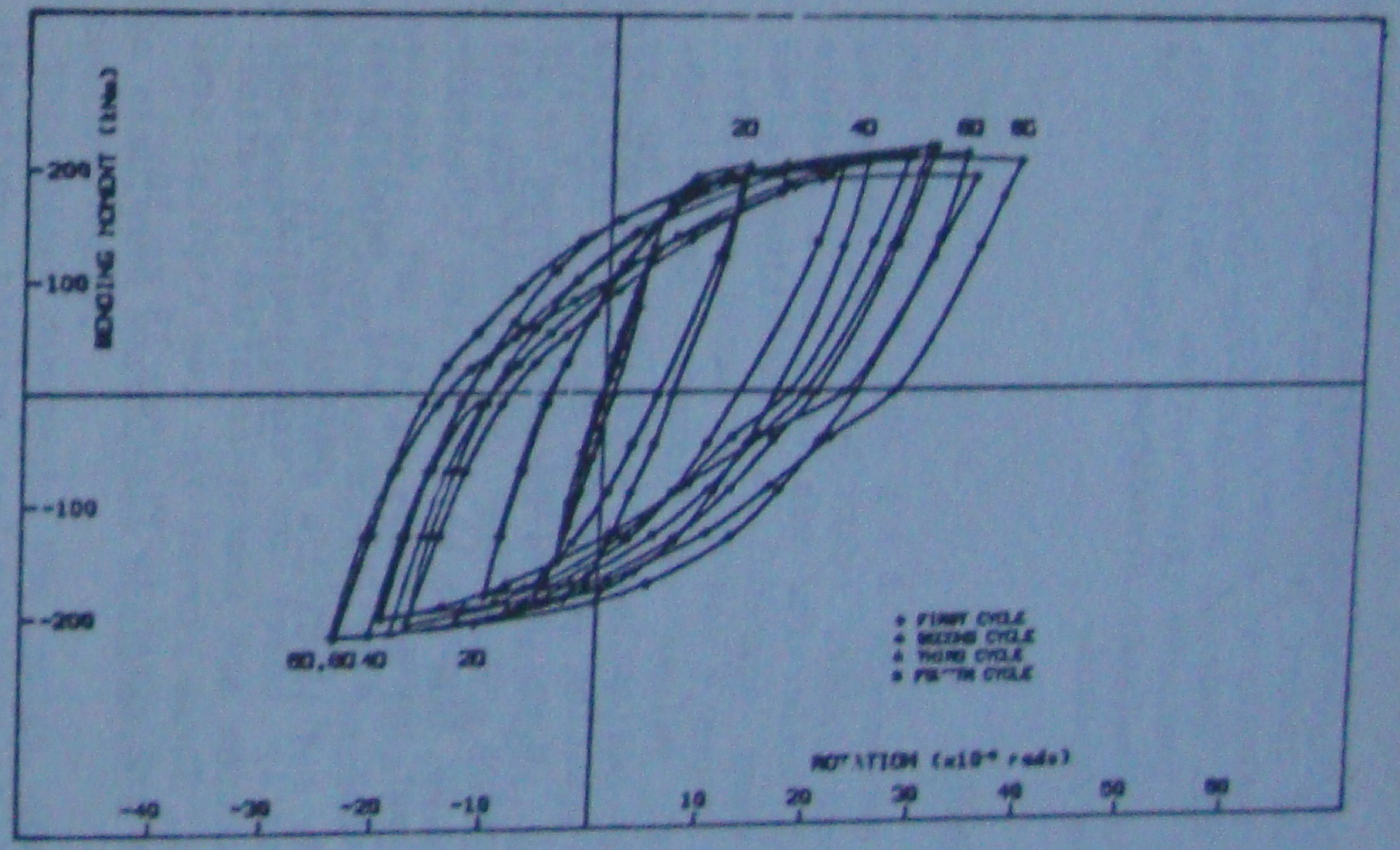

Figure 16. Moment-Rotation, Test Beam 3B

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APPENDIX

In paragraphs 4.1.b and 4.2.b of the present paper, contribution of shear to total deflection was used as a measure of shear degradation. Variations given in Figures 4 and 8 were based on experimental values of flexural deflection, shear deflection and deflection due to end rotation measured at the reference point. More detailed pictures of the variation of these contributions are given in Figures 11 and 12 for two typical test beams.

Energy dissipation and equivalent cycle stiffness calculations were naturally based on experimental load-deflection and moment-rotation relationships. These curves for two typical test beams are given in Figures 13 to 16.