CHAPTER-4

RESULTS OF BEAM TESTS

4.1 General

In this chapter, behaviour of plain and fibre reinforced concrete deep beams and moderete deep beams subjected to two point loads at one third span is described. Static testing was carried out on forty beams consisting of five series. Each series consisting of eight beams. The objective of these tests was to provide an understanding of the behaviour of full depth fibre reinforced concrete section, half depth fibre reinforced concrete section and plain concrete beams with emphasis on the actual stresses developed in steel as well as in concrete. Observations were made for first cracking load, crack patterns, deflection, strain in steel and concrete, ultimate load and modes of failures. These provide a base for the analysis of steel fibre reinforced concrete deep beams and moderate deep beams.

4.2 Modes of Failure

(a) Crack patterns

To design a structure safely and rationally, thorough knowledge and understanding of crack patterns and modes of failure of such structure is highly essential. This obviously helps the designer to formulate the complete solution of many complicated concrete structures encountered in practice. In the past, large number of complicated structures were analysied by this approach.

Photographs of crack patterns and modes of failures of all the beams tested in this investigation are shown in **Plates [4 to 8]**. The cracks which are believed to be the cause of immediate failure of the beams are marked boldly. The cracks and points are marked to correspond to the load at which they appeared or propogated further until complete failure of the beam took place.

In all the tested beams, two types of cracks appeared in majority of the beams viz. flexural cracks and shear cracks. Flexure cracks appeared first in the region of maximum bending moment and initiated from the soffit of the beam. Shear cracks are normally inclined cracks, and originated from the bottom of the beam near to the support and propagated upwards towards loading point in shallow beams.

At higher loads, further cracks developed near the support and propagated towards the loading point. In all the beams which failed in shear, there was a considerable increase in the load before the formation of the second parallel crack. This crack is a diagonal crack which suddenly developed within the shear span. In some of the deeper beams having no web reinforcement, the appearance of these types of diagonal cracks was often accompained by a loud noise. This was simillar to Brazilian split cylinder test. These cracks initiated not from the support points but from the points somewhere D/3 to D/2 from the soffit and propagated upwards towards loading point as well as at the support point at a faster rate. Normally, the formation of such cracks is in the shear span (see **Fig.4.1**)[90,91] and is of the magnitude of 70% to 75% of the ultimate load. The formation of inclined crack eliminates the inclined principal stresses necessary to beam action and causes a redistribution of internal stresses which results in a tied arch action in which reinforcement acts as the tension tie and the portion of the concrete beam outside the inclined cracks acts as an arch rib in compression. The inclined diagonal cracks change the distribution of stress and strain.

For L/D ratios upto 2.0, shear cracks are more predominent than the flexure cracks. In this range,stresses are nonlinear. Due to redistribution of internal stresses which result in a tied arch action, in which the reinforcement acts as tension tie and portion beyond the inclined cracks acts as the arch rib in the beam.

Behaviour of deep beam with the typical effect of inclined cracks is shown in **Fig.4.4.**(44) Actual strain distribution is shown by solid lines. Theoretical strain distribution is shown by dotted lines. Once inclined cracks occured, strain in the steel reinforcement becomes uniform for the entire length and concrete strain tends to concentrate in mid span over the inclined crack.

In deep beams, very high stresses are generated in tension reinforcement near supports due to arch action. If special provisions are not made to anchor the bar at the support, the beam may fail in anchorage before reaching to their flexural or shear capacity.

The following modes of failures were observed in the beams which were tested. See **Fig.4.2.** (8)

(1) Diagonal tension failure by splitting the beam approximately along the line joining the load point and the support point. This type of failure was more common in most of the deep beams tested. See **Fig.4.3**.

(2) The inclined diagonal crack very often penetrates into the compression zone much higher above the neutral axis than a corresponding flexure crack as shown in **Fig.4.3**.

(3) The inclined diagonal crack causes the concentration of compressive stresses on the region above the crack. This may cause the crushing of concrete in the region of higher comrpessive stress concentration.

(4) Arch action causes higher stresses in the tensile steel near the supports which may cause anchorage or bond failure.

(b) Flexure Failures

Beams failed in flexure when the bending stresses in the region of high moment caused the concrete to crush in compression region after yielding of the longitudinal reinforcement. These types of failure were not common among deep beams. When L/D ratio is greater than 4.0 this type of failure is predominant. Normally flexure failure was observed in beams having L/D ratios between 5.0 and 6.0.

(c) Shear Failures

In shallow beams, shear failure is generally classified as diagonal tension failure and shear compression failure as showin in **Fig.4.3**. Failures in such beams begin with the formation of diagonal tension cracks as a result of combined bending and shearing stresses.

In deep beams, failure is some what different than that observed in moderate deep beams. In shear compression failure, parallel inclined cracks are formed. This gives the beam a "strut like" appearence between the load point and the support. Here failure occurs by the destruction of this strut. Sometimes, it occurs simultaneously with the formation of second parallel inclined crack.

Splitting failure is usually very common in deep beams without web reinforcement. In this type of failure, a diagonal crack suddenly originates from the inner edge of the supporting block and proceeds towards the outer edge of loading plate. After the formation of the diagonal crack, the beam fails by sudden splitting along the plane of this crack. The phenomenon of this failure is simillar to that of concrete cylinder under diametrical compressive load i.e. Brazilian split test.

(d) Flexural-Shear Failure

Flexural-shear failures are those in which the full strength of the beam has been developed in both. In this type of failure both flexural and inclined shear cracks are formed and well developed at the time of failure but major cause of failure is inclined shear crack. Thus, it is designated as flexural-shear failure.

(e) Bearing Failure

Bearing failure is due to high vertical stresses at the supports and load points because of local crushing of concrete.

(f) Load Deflection Characteristics

Deflections of all the beams were measured at midspan as well as under the load at the soffit of the beam. **Figures 4.5 to 4.20** show the total load versus central deflection for all the beams. The load deflections curves for the beams tested show two major stages. First stage is regarding elastic behaviour of the beam upto yield load (W_y). Second stage is inelastic behaviour after yield load and upto ultimate load. The portion of the load deflection curves upto yield load can be approximated by a straight line. A measure of the slope of the yielding portion can be given by the ratio of the ultimate load (W_u) to yield load (W_y). There was considerable deviation of the actual load deflection curve at beam yield, which is attibuted to cracking and sudden increase in deflection which beam could not sustain.

Ductility values $\frac{\nabla_u}{\nabla_y} = \mu$ for various ratios of L/D are given in **Table-4.1**.

(g) Steel Strains

Load-steel strain curve for the beams of each L/D ratios are shown in **Figs.4.21 to 4.28**. The initiation of the tension steel yield was easily identifiable from the sudden increase in the deflection rate. Strain in longitudinal tensile steel was measured by strain gauges bonded to the reinforcing bar in the neighbourhood of reaction at supports. For all beams having L/D

4.0, 5.0 and 6.0 the additional strain measurements were taken with a strain gauge bonded at the centre. Strains in steel measured at these points exhibited characteristic load-strain curve. It further showed an unstable erratic decreased slope. The end of this portion is designated as the inclined cracking load (W_c). Most of the strain gauges intended to measure the strains in steel failed or got damaged immediately after the tension steel started yielding. Regardless of the type of failure, the magnitude of strain in longitudinal steel at failure in most of the beams was slightly less than ~~steel yield strain.~~ The variation in steel strains in different series of beams of the same depth can be attributed to the gauges being on the line of crack or a little away from the line of crack. Typical Strains at various stages of loadings are given in tables of **Appendix-C**. Only eight tables matching with graphs are given. see **Figs. 4.21 to 4.28**.

(h) Inclined Cracking Load

For shallow beams, the formation of a diagonal crack is usually synonymous with the failure of the beams. It is for this reason that cracking load and ultimate load are the same in case of shallow beams. The diagonal cracking load is, therefore, a measure of shear strength of shallow beams which is the basis of shear design criteria of slender beams. However, in reinforced concrete deep beams, the situation is different. After the development of inclined crack, these beams can support an additional load before the ultimate shear capacity is reached. Thus additional shear capacity is observed in beams with web reinforcement.

Shear behaviour of fibrous concrete deep beams and moderate deep beams was one of the primary interests of this investigation. Previous research work (86, 89, 135, 137) established the use of inclined cracking load as a measure of the shear capacity of such beams. The inclined cracking load, as it is referred to in this study is defined similar to the definition of de Paiva and Siess (45). "An inclined cracking load is the load at which there is a sudden change in the tensile steel strain and the load versus steel strain curve decreases in slope and becomes straight to the beam yield".

All the test beams in this study exhibited the above definitive character of total load versus steel strain curve as described earlier. Inclined cracking load as derived from the curve is not the same as actual cracking load. A lower value is, therefore, taken as the inclined cracking load in all the cases. It is observed that the inclined cracking load was in all cases less than the ultimate load for these beams failing in shear modes.

In limit state method, control of crack width in structural member has become an important design consideration. It is found that the addition of fibres reduced the crack width. .Crack width variation with loads for beams having full depth fibres, half depth fibres and beams without fibres, are given in **Fig.4.29 to 4.36** for beams failing in flexure and flexural-shear.

(i) Reserve Strength Beyond Diagonal Cracking

It has already been mentioned that inclined cracking load for deep beams and moderate deep beams is not the ultimate shear capacity of the beams. Therefore, the strength of such beams beyond inclined cracking load can be termed as the reserve strength of the beams.

Reserve strength of beam can be defined as the ratio of difference of ultimate load and inclined cracking load to the inclined cracking load expressed as a percentage.

$$\text{Reserve strength} = \frac{W_u - Wc}{W_c} \times 100$$

Table-4.2 gives the relevant percentage of reserve strength of the beams tested. The percent of reserve strength varies from 0 to 200%. The variation in percentage of reserve strength can be attributed to the strength of the concrete, type of web reinforcement, and geometry of the specimen.

Ultimate shear capacity is more than the inclined cracking load. Close inspection of crack patterns shows that more dangerous cracks which caused failure of the beam are diagonal cracks which are formed in either of the shear span and not in the portion of the span of constant bending moment.

(j) Ultimate Load

Load was applied gradually in a continuous manner throughout the testing sequence by the machine. The failure load is termed as ultimate load. Ultimate load referred to in this investigation is defined as the load at which the indicator of the machine started returning back indicating that the beam could no longer sustain any further additional load. The ultimate loads thus measured are given in **Table-4.1**.

TABLE - 4.1

LOAD AND DEFLECTION CHARACTERISTICS OF TESTED BEAMS

Beam	L/D	W_c kN	W_y kN	W_u kN	∇Ycm	∇ucm	$\frac{\nabla u}{\nabla y} = \mu$
P60	1.0	170	--	261		--	--
F1.0 D60	1.0	298	295.0	500	1.46	2.44	1.672
H1.0 D60	1.0	270	259.0	444	1.88	3.25	1.720
F1.5 D60	1.0	300	312.5	510	1.60	3.12	1.950
H1.5 D60	1.0	270	256.7	450	1.85	3.30	1.780
P50	1.2	140	--	255		--	--
F1.0 D50	1.2	210	220.0	421	1.53	2.85	1.863
H1.0 D50	1.2	205	206.0	408	2.10	4.30	2.047
F1.5 D50	1.2	268	286.0	450	3.00	4.25	1.480
H1.5 D50	1.2	230	223.6	404	2.16	4.55	2.100
P40	1.5	83	--	203		--	--
F1.0 D40	1.5	150	155.0	360	1.08	2.84	2.629
H1.0 D40	1.5	141	152.0	353	1.26	3.15	2.500
F1.5 D40	1.5	163	168.0	366	1.34	2.98	2.228
H1.5 D40	1.5	133	148.0	334	1.18	3.02	2.540
P30	2.0	66	--	152		--	--
F1.0 D30	2.0	78	80.0	252	0.98	2.8	2.857
H1.0 D30	2.0	70	75.0	284	1.60	3.9	2.438
F1.5 D30	2.0	101	118.0	291	1.48	3.36	2.270
H1.5 D30	2.0	86	118.4	298	1.39	3.60	2.588

TABLE - 4.1 (Contd.)

Beam	L/D	W_c kN	W_y kN	W_u kN	∇Ycm	∇ucm	$\frac{\nabla u}{\nabla y} = \mu$
P20	3.0	22	--	72		--	--
F1.0 D20	3.0	26	34.5	157	0.95	3.38	3.557
H1.0 D20	3.0	24	28.0	184	0.98	3.54	3.612
F1.5 D20	3.0	29	35.0	170	1.18	3.65	3.093
H1.5 D20	3.0	27	38.0	187	0.98	3.70	3.781
P15	4.0	09	--	45		--	--
F1.0 D15	4.0	20	19.0	86	1.05	3.65	3.476
H1.0 D15	4.0	12	11.0	97	1.20	3.86	3.216
F1.5 D15	4.0	22	20.3	100	1.30	3.98	3.061
H1.5 D15	4.0	14	21.5	106	1.21	4.20	3.480
P12	5.0	08	--	24		--	--
F1.0 D12	5.0	09	09.0	52	0.86	4.60	5.168
H1.0 D12	5.0	09	10.0	64	0.91	4.48	4.923
F1.5 D12	5.0	16	14.0	61	1.03	4.30	4.184
H1.5 D12	5.0	12	11.1	69	1.02	4.35	4.248
P10	6.0	07	--	20		--	--
F1.0 D10	6.0	08	08.5	29	0.80	4.10	5.125
H1.0 D10	6.0	08	09.0	38	0.90	3.90	4.335
F1.5 D10	6.0	10	10.0	37	1.06	4.52	4.264
H1.5 D10	6.0	08	09.9	39	1.07	4.73	4.418

TABLE - 4.2

INCLINED CRACKING LOAD AND RESERVE STRENGTH OF TEST BEAMS

Beam No.	L/D	f_t N/mm^2	W_u kN	W_c kN	$\frac{W_u - W_c}{W_c} \times 100$	Mode of Failure
P60	1.0		26 1	17 0	53.52	Shear
F1.0 D60	1.0	4.02	50 0	29.8	67.78	Shear
H1.0 D60	1.0	3.68	44.4	27.0	64.44	Shear
F1.5 D60	1.0	4.23	51.0	30.0	70.00	Shear
H1.5 D60	1.0	3.84	45.0	27 0	66.66	Shear
P50	1.2		25.5	14 0	82.14	Flexure-Shear
F1.0 D50	1.2	4.02	42.1	21 0	100.40	Shear
H1.0 D50	1.2	3.68	40 8	20.5	99.00	Shear
F1.5 D50	1.2	4.23	45 0	26.8	67.91	Shear
H1.5 D50	1.2	3.84	40 4	23.0	75.62	Shear
P40	1.5		20.3	08.3	144.57	Flexure-Shear
F1.0 D40	1.5	4.02	36.3	15.0	140.00	Shear
H1.0 D40	1.5	3.68	35 3	14.1	150.30	Shear
F1.5 D40	1.5	4.23	36 6	16 3	124.53	Shear
H1.5 D40	1.5	3.84	33 4	13 3	151.12	Shear
P30	2.0		15 2	06 6	130.30	Flexure-Shear
F1.0 D30	2.0	4.02	25 2	07.8	223.00	Shear
H1.0 D30	2.0	3.68	28.4	07.0	305.70	Shear
F1.5 D30	2.0	4.23	29 1	10.1	188.11	Shear
H1.5 D30	2.0	3.84	29.8	08 6	246.51	Shear

TABLE - 4.2 (Contd.)

Beam No.	L/D	f_t N/mm²	W_u kN	W_c kN	$\frac{W_u - W_c}{W_c}$ x 100	Mode of Failure
P20	3.0		07.2	2.2	227.20	Flexure
F1.0 D20	3.0	4.02	15.7	2.6	503.80	Flexure-Shear
H1.0 D20	3.0	3.68	18.4	2.4	666.60	Flexure-Shear
F1.5 D20	3.0	4.23	17.0	2.9	486.20	Flexure-Shear
H1.5 D20	3.0	3.84	18.7	2.7	592.50	Flexure-Shear
P15	4.0		4.5	0.9	400.00	Flexure
F1.0 D15	4.0	4.02	8.6	2.0	333.00	Flexure-Shear
H1.0 D15	4.0	3.68	9.7	1.2	708.30	Flexure-Shear
F1.5 D15	4.0	4.23	10.0	2.2	354.50	Flexure-Shear
H1.5 D15	4.0	3.84	10.6	1.4	658.14	Flexure-Shear
P12	5.0		2.4	0.8	200.00	Flexure
F1.0 D12	5.0	4.02	5.2	0.9	447.00	Flexure
H1.0 D12	5.0	3.68	6.4	0.9	790.00	Flexure-Shear
F1.5 D12	5.0	4.23	6.1	1.6	281.00	Flexure
H1.5 D12	5.0	3.84	6.9	1.2	479.00	Flexure-Shear
P10	6.0		2.0	0.7	185.70	Flexure
F1.0 D10	6.0	4.02	2.9	0.8	262.50	Flexure
H1.0 D10	6.0	3.68	3.8	0.8	375.00	Flexure-Shear
F1.5 D10	6.0	4.23	3.7	1.0	270.00	Flexure
H1.5 D10	6.0	3.84	3.9	0.8	387.50	Flexure-Shear

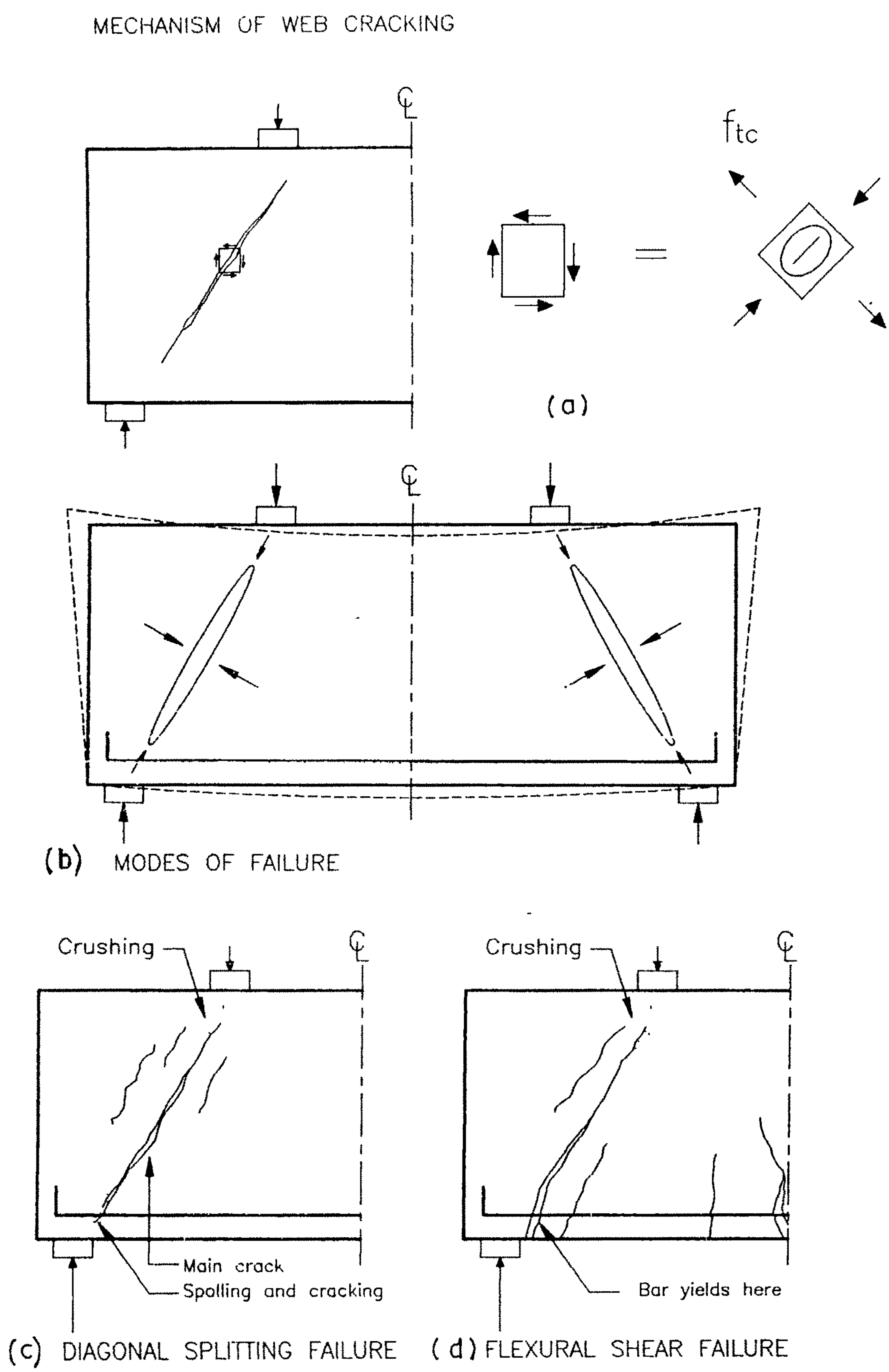
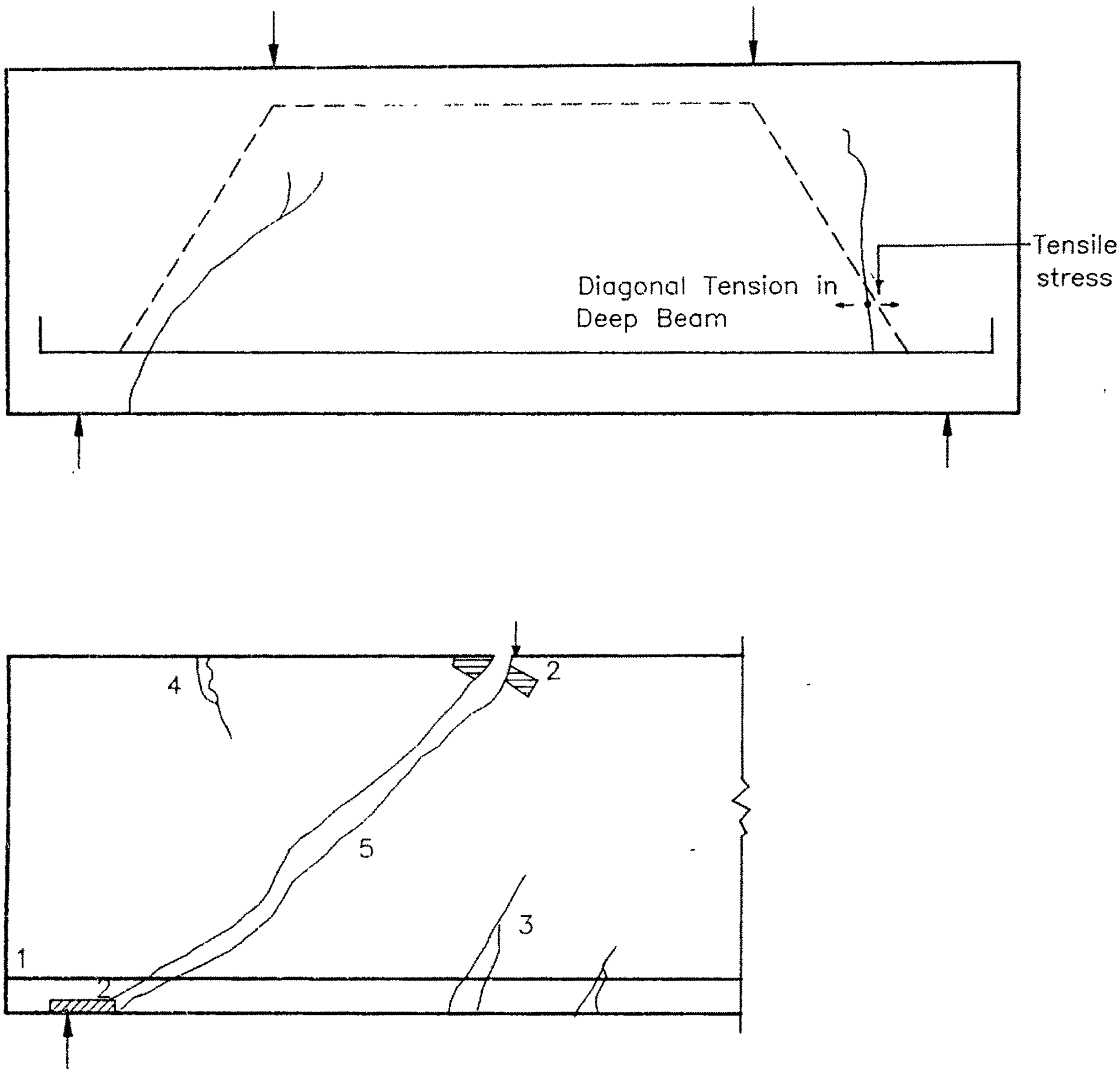


Fig. 4.1 MECHANISM OF FAILURE OF DEEP BEAMS



TYPES OF FAILURES

1 ANCHORAGE FAILURE
2 BEARING FAILURE OR CRUSHING FAILURE
3 FLEXURE FAILURE
4 ARCH RIB FAILURE
5 DIAGONAL SPLITTING FAILURE

Fig. 4.2 MODES OF FAILURES OF DEEP BEAMS.

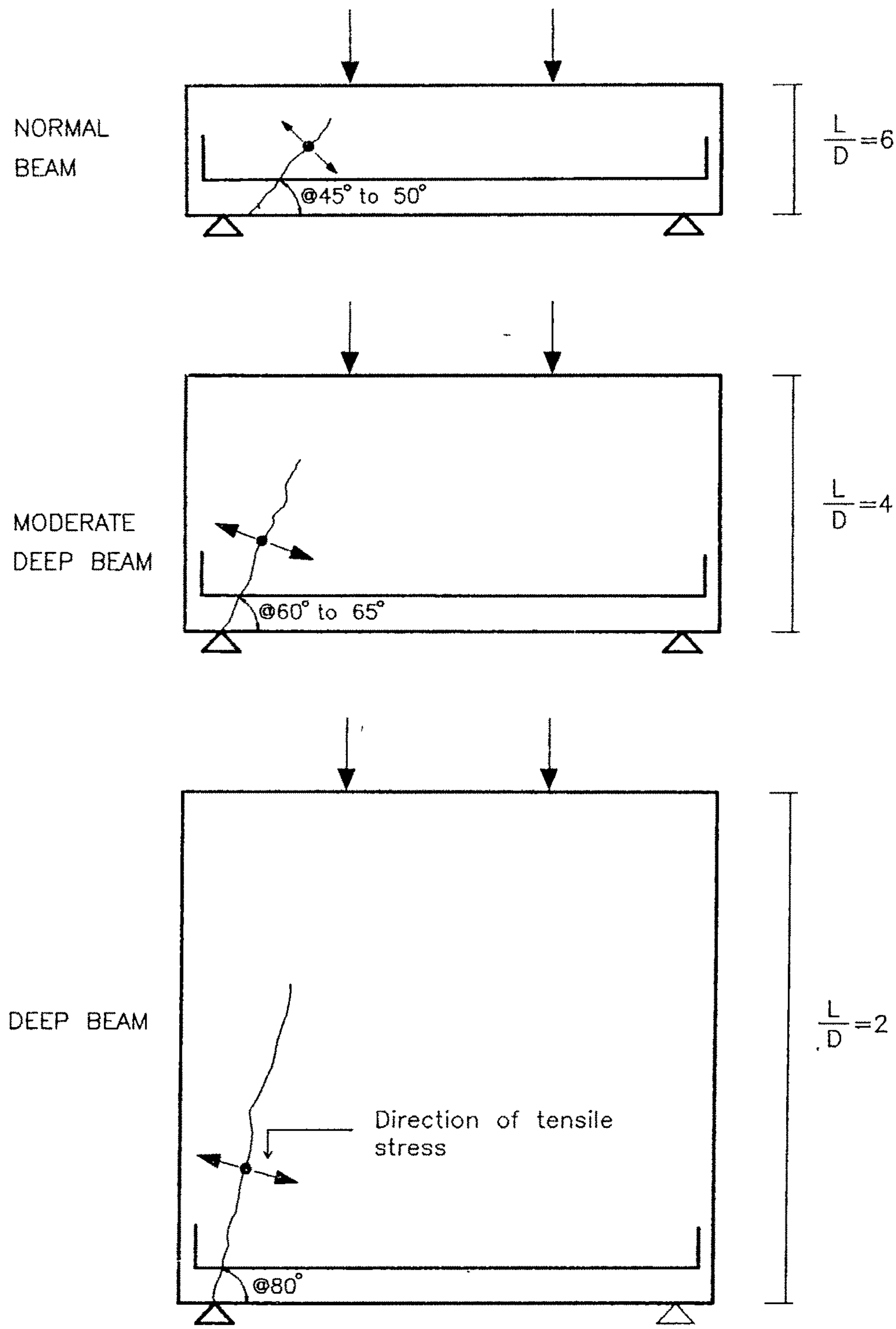


Fig. 4.3 DIAGONAL TENSION IN VARIOUS BEAMS

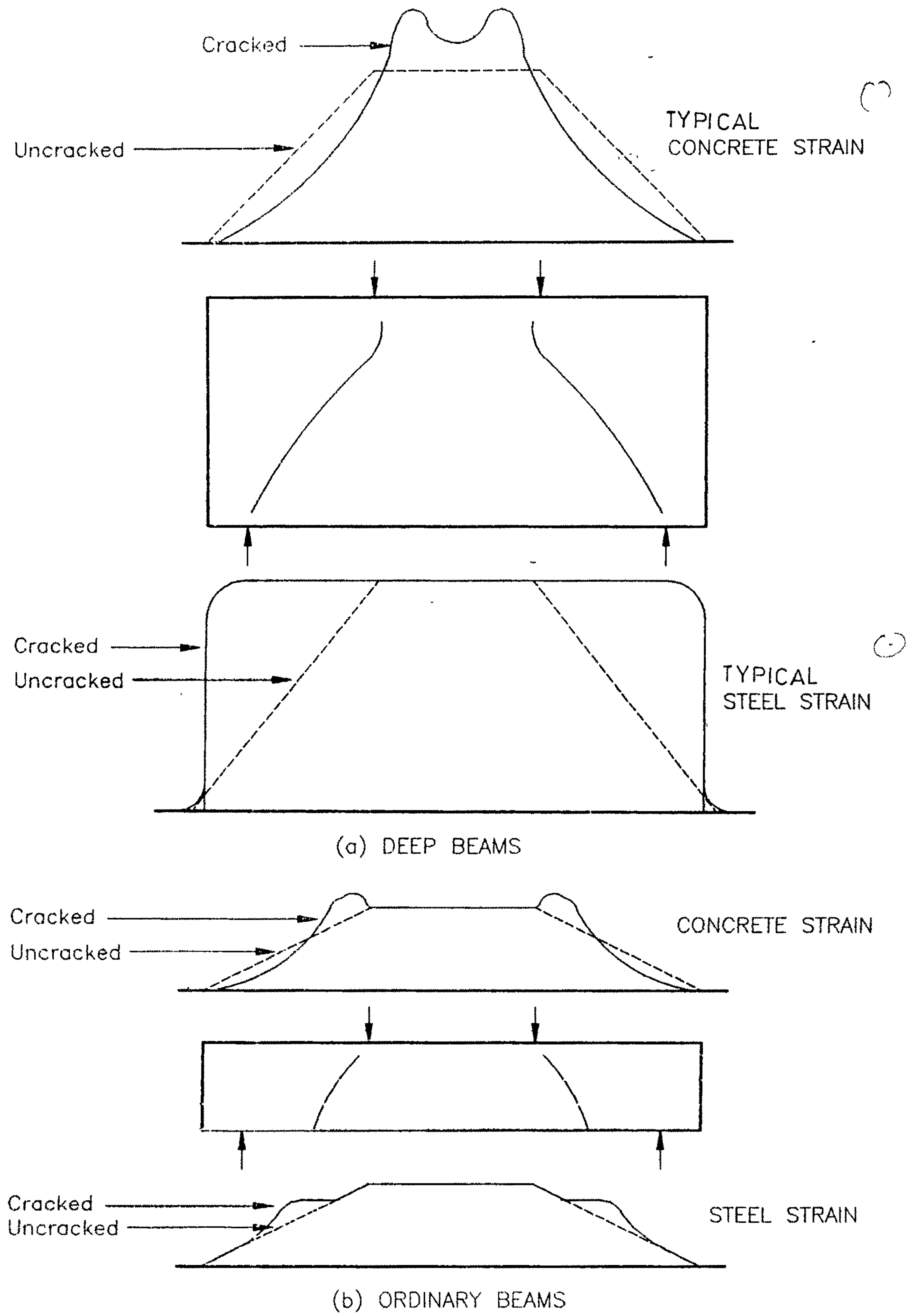


Fig. 4.4 EFFECT OF INCLINED CRACKING ON THE DISTRIBUTION OF STEEL & CONCRETE STRAINS.

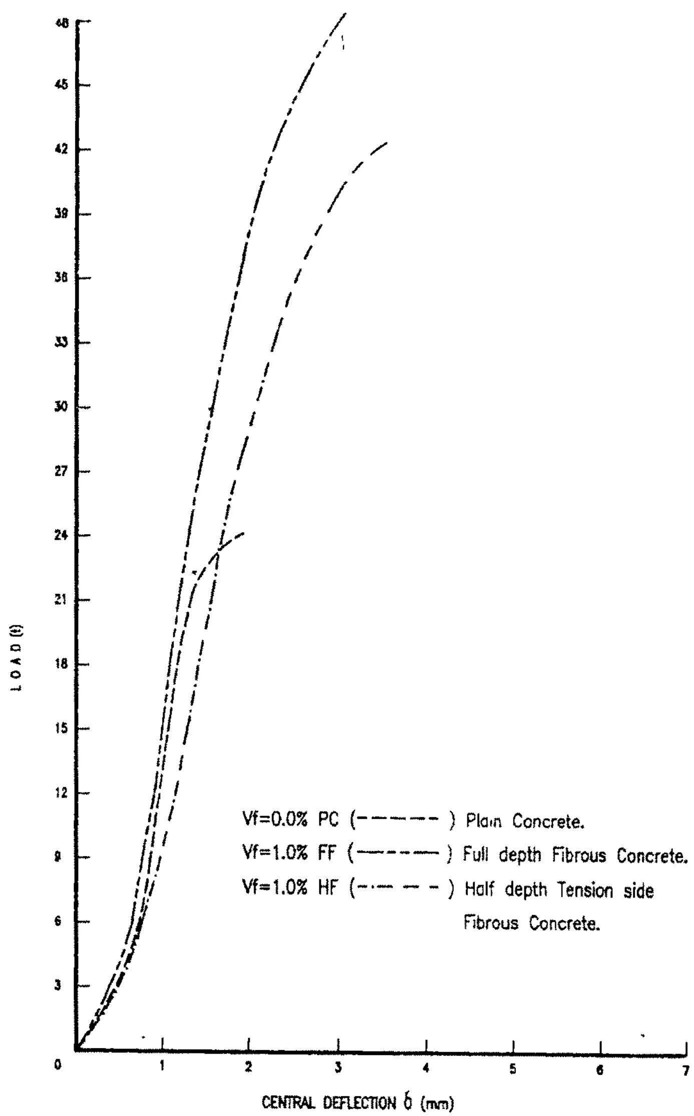


Fig.4.5 LOAD DEFLECTION CURVES FOR L/D=1.0 Series

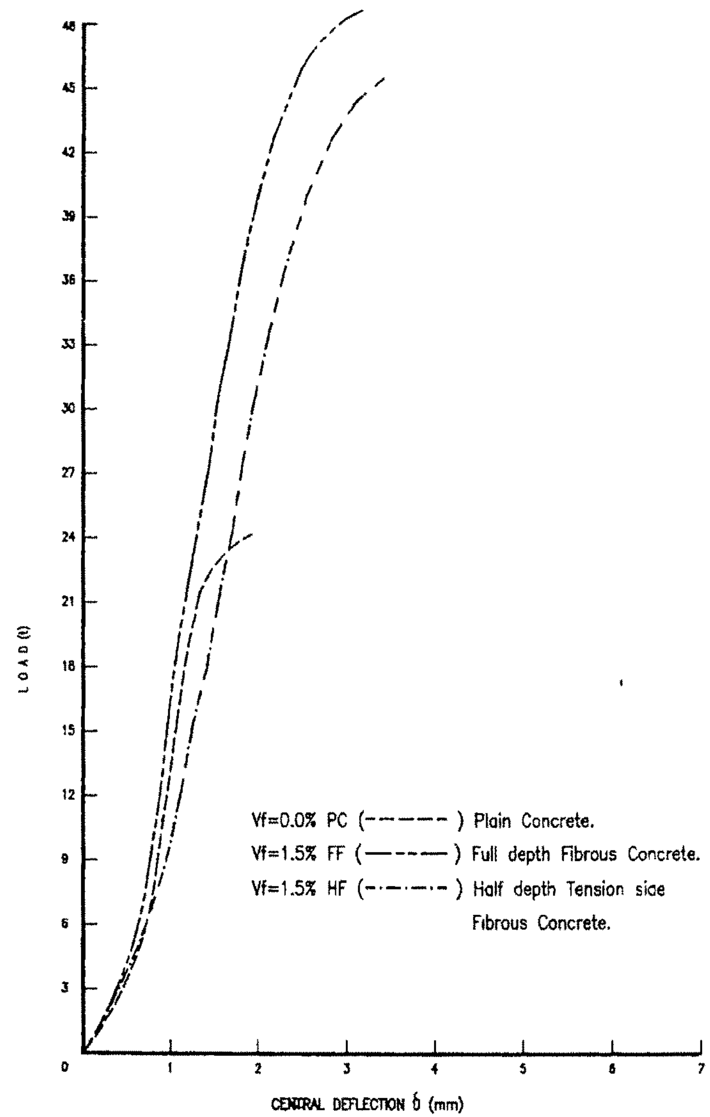


Fig.4.6 LOAD DEFLECTION CURVES FOR L/D=1.0 Series

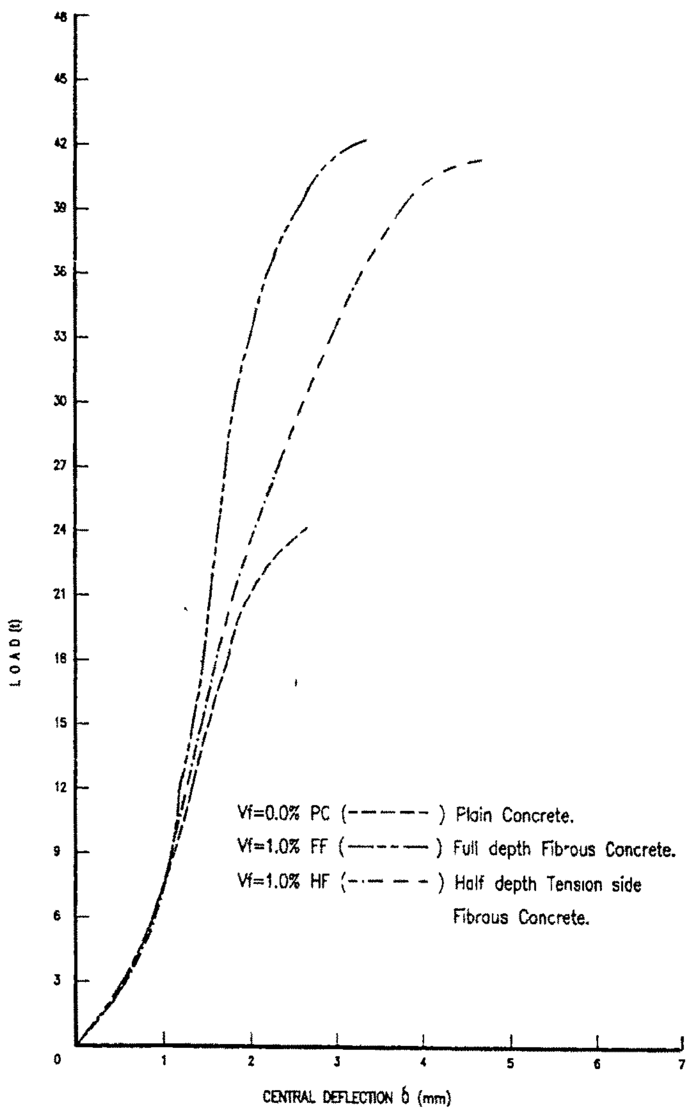


Fig.4.7 LOAD DEFLECTION CURVES FOR L/D=1.2 Series

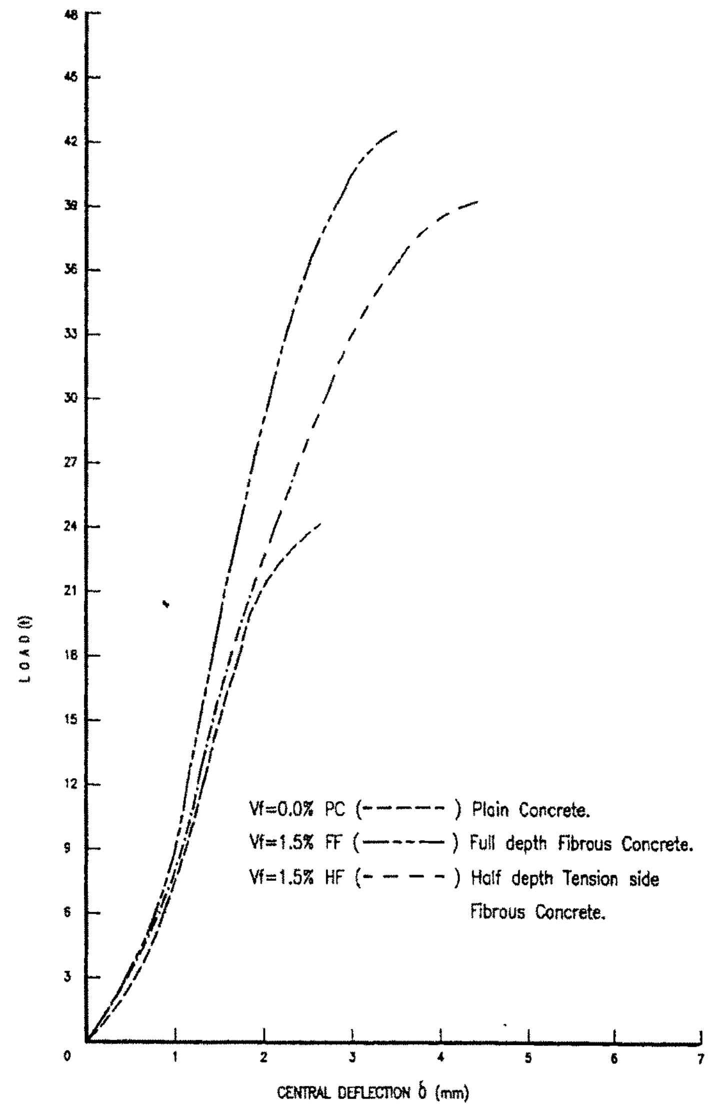


Fig.4.8 LOAD DEFLECTION CURVES FOR L/D=1.2 Series

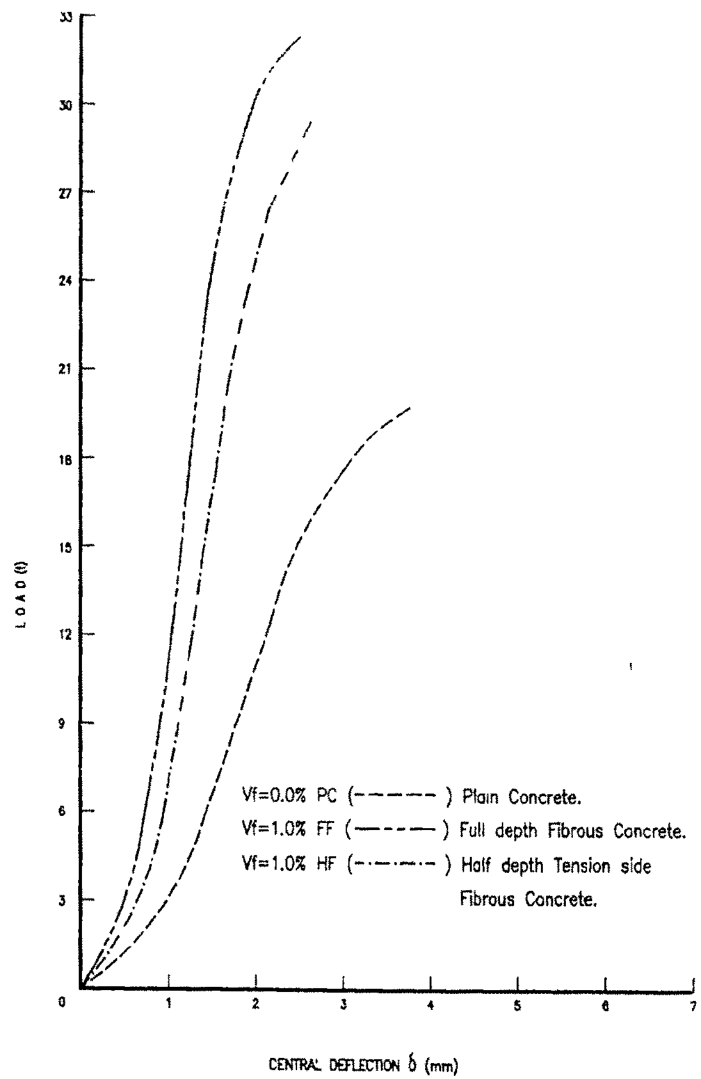


Fig.4.9 LOAD DEFLECTION CURVES FOR L/D=1.5 Series

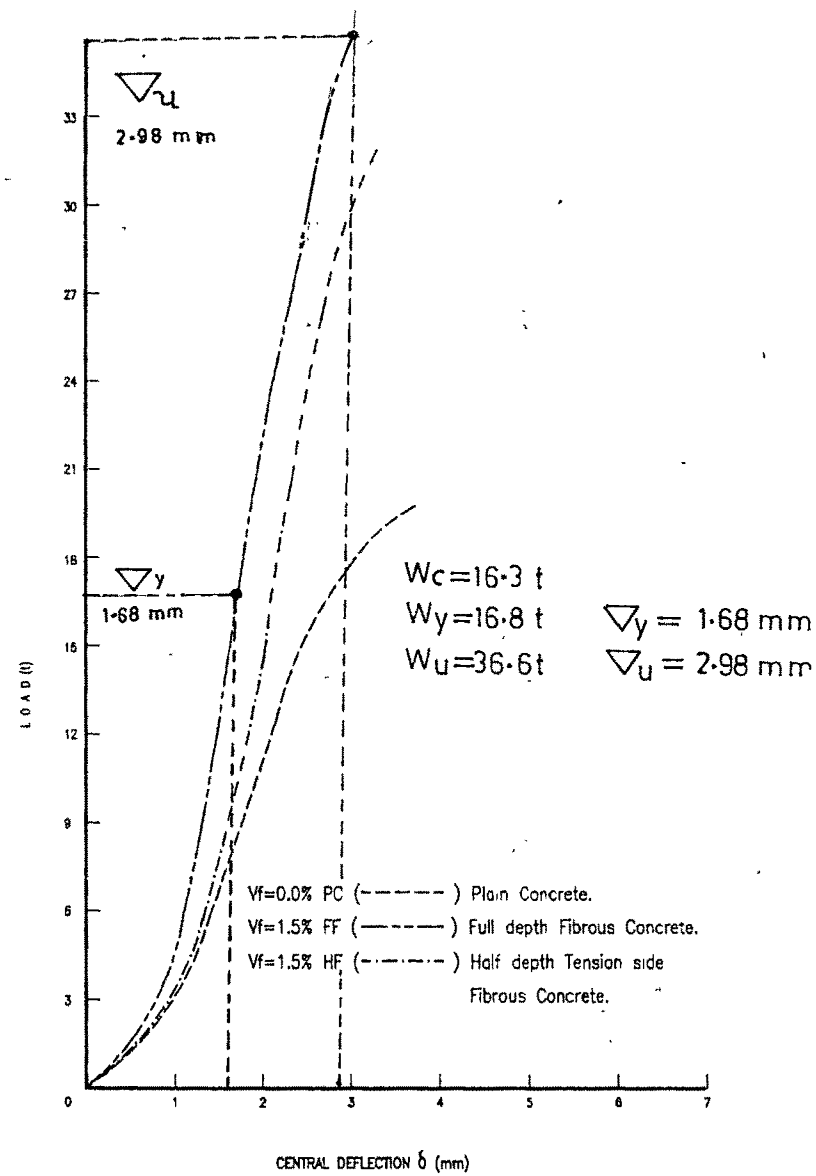


Fig.4.10 LOAD DEFLECTION CURVES FOR L/D=1.5 Series

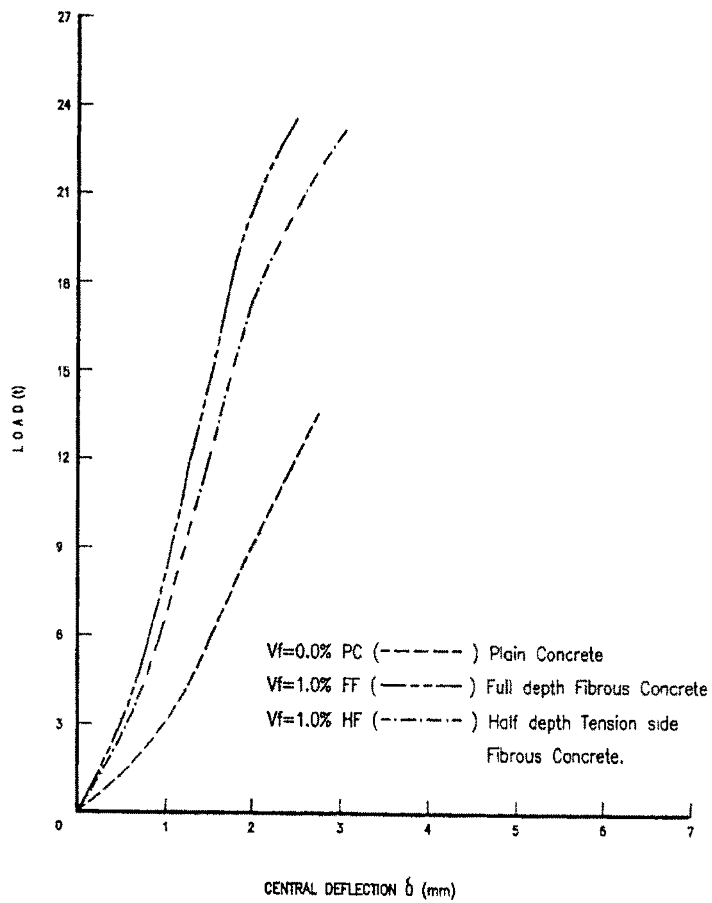


Fig.4.11 LOAD DEFLECTION CURVES FOR L/D=2.0 Series

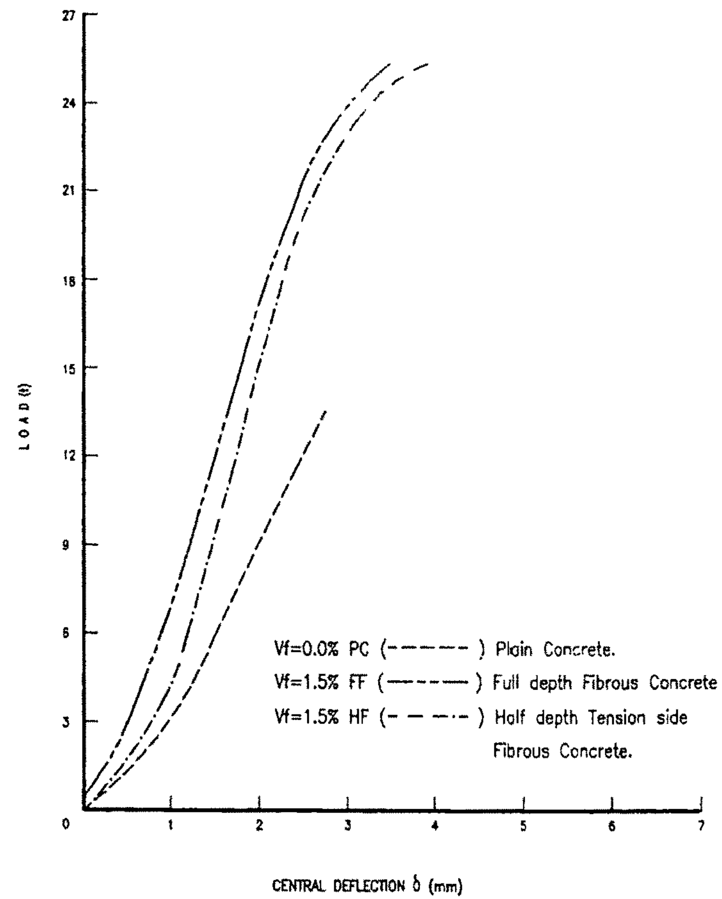


Fig.4.12 LOAD DEFLECTION CURVES FOR L/D=2.0 Series

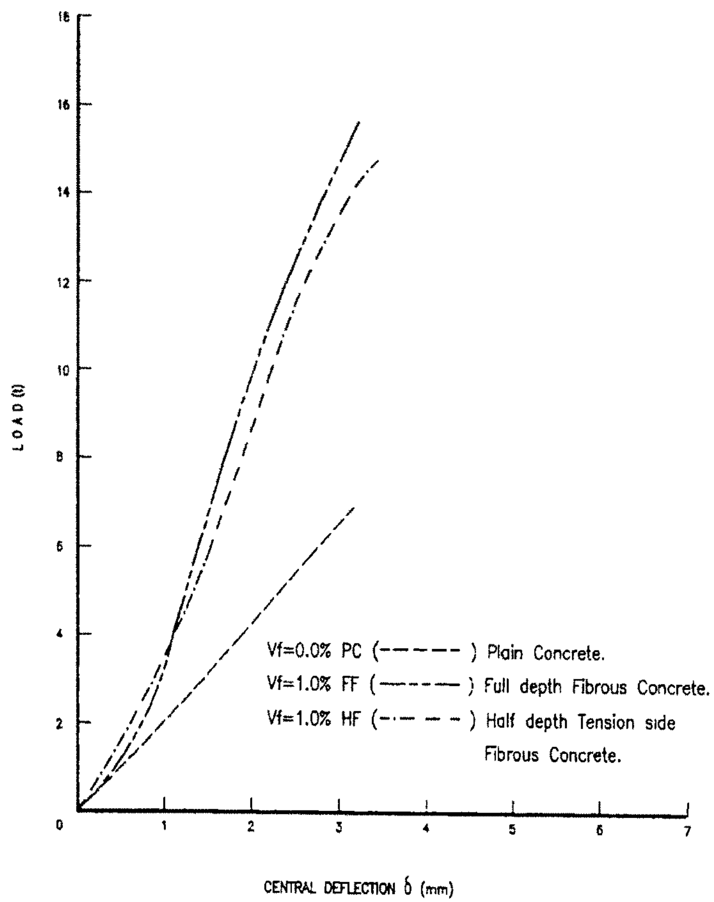


Fig.4.13 LOAD DEFLECTION CURVES FOR L/D=3.0 Series

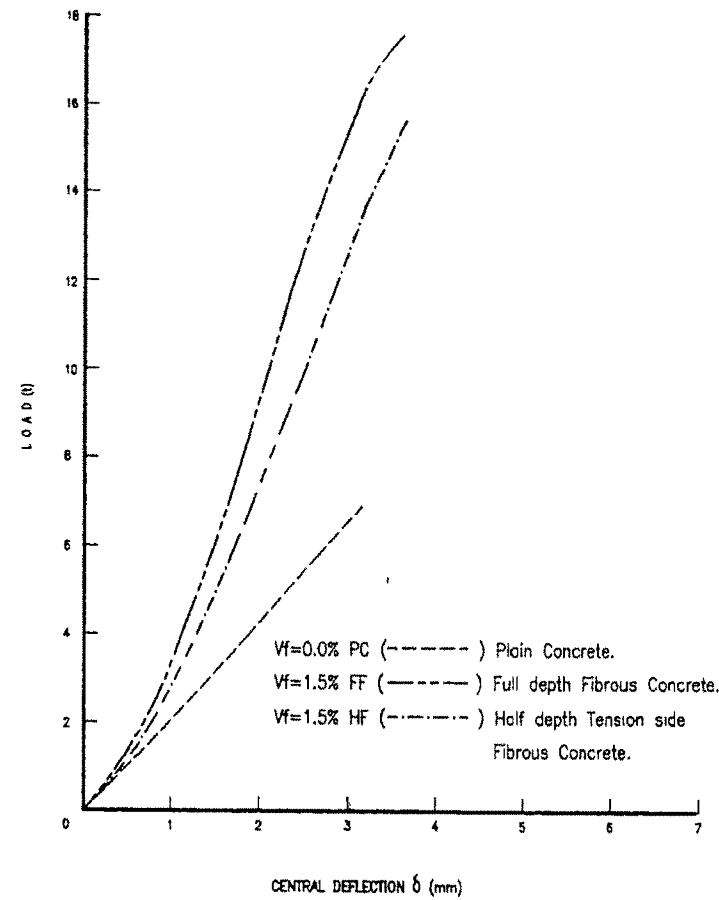


Fig.4.14 LOAD DEFLECTION CURVES FOR L/D=3.0 Series

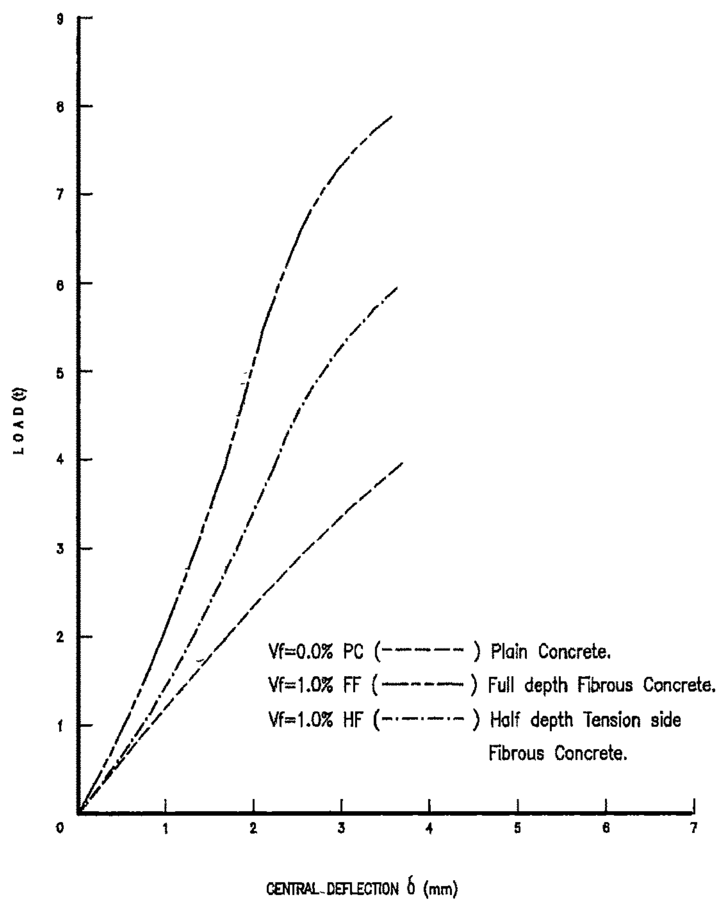


Fig.4.15 LOAD DEFLECTION CURVES FOR L/D=4.0 Series

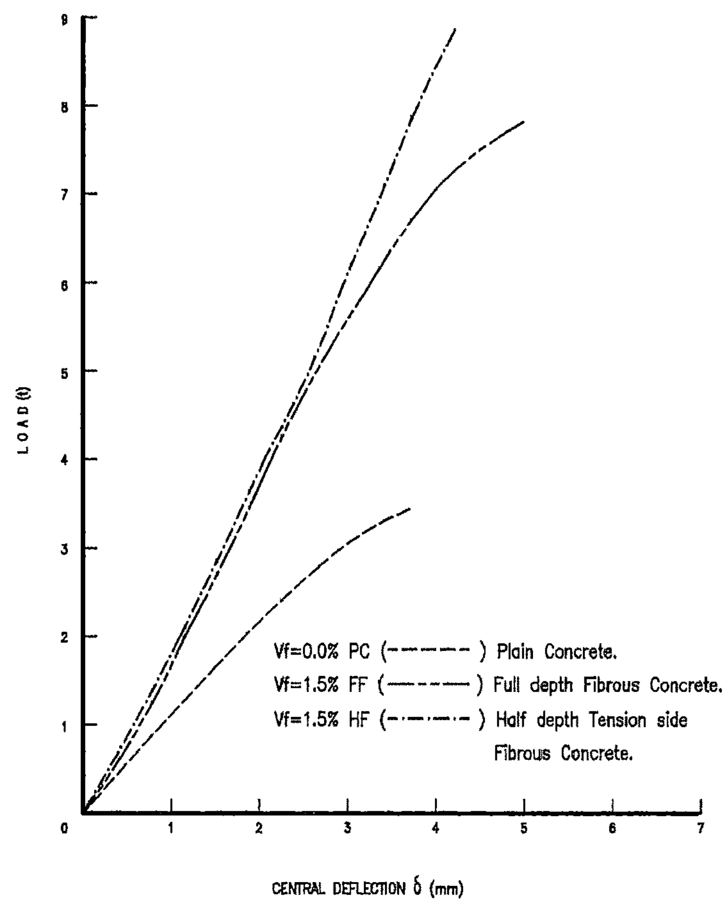


Fig.4.16 LOAD DEFLECTION CURVES FOR L/D=4.0 Series

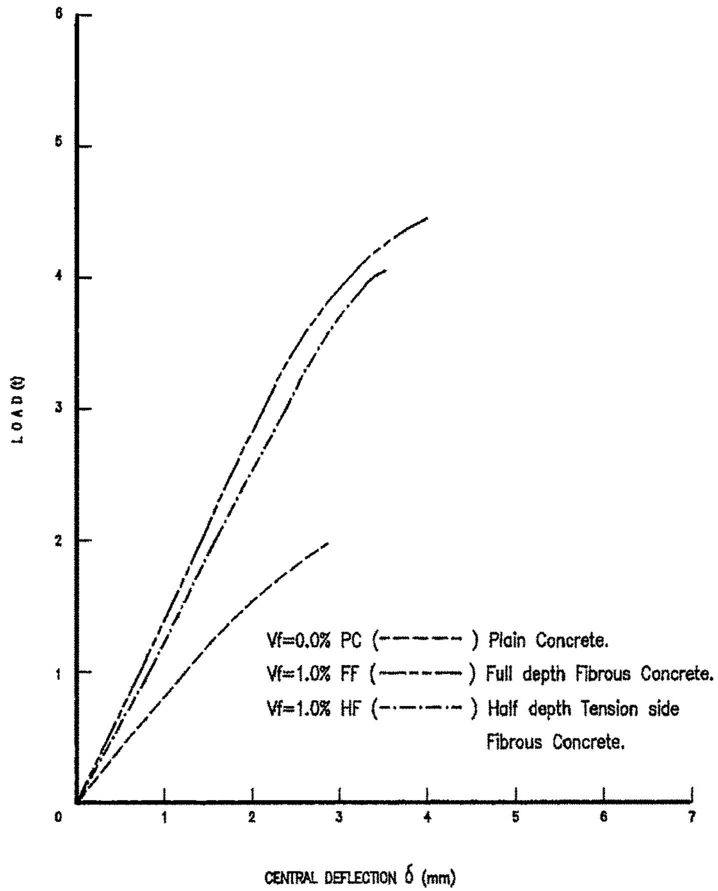


Fig.4.17 LOAD DEFLECTION CURVES FOR L/D=5.0 Series

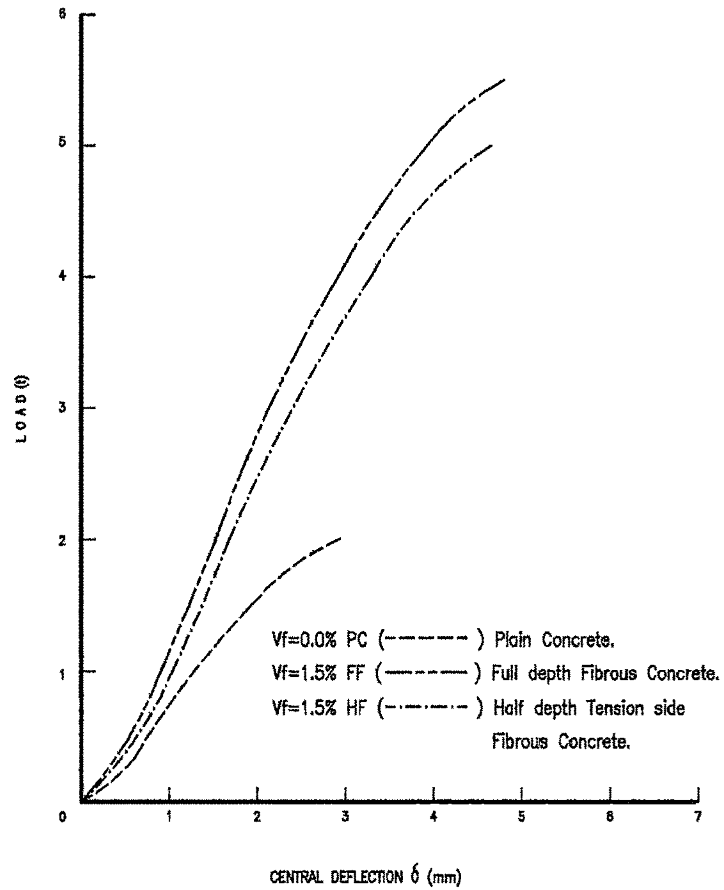


Fig.4.18 LOAD DEFLECTION CURVES FOR L/D=5.0 Series

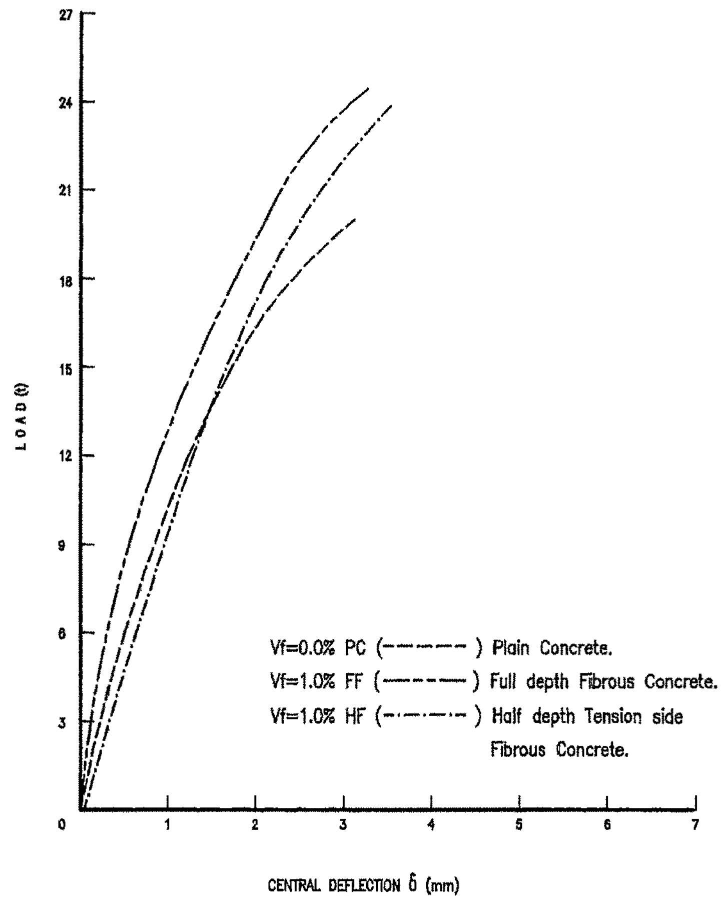


Fig.4.19 DEFLECTION CURVES FOR L/D=6.0 Series

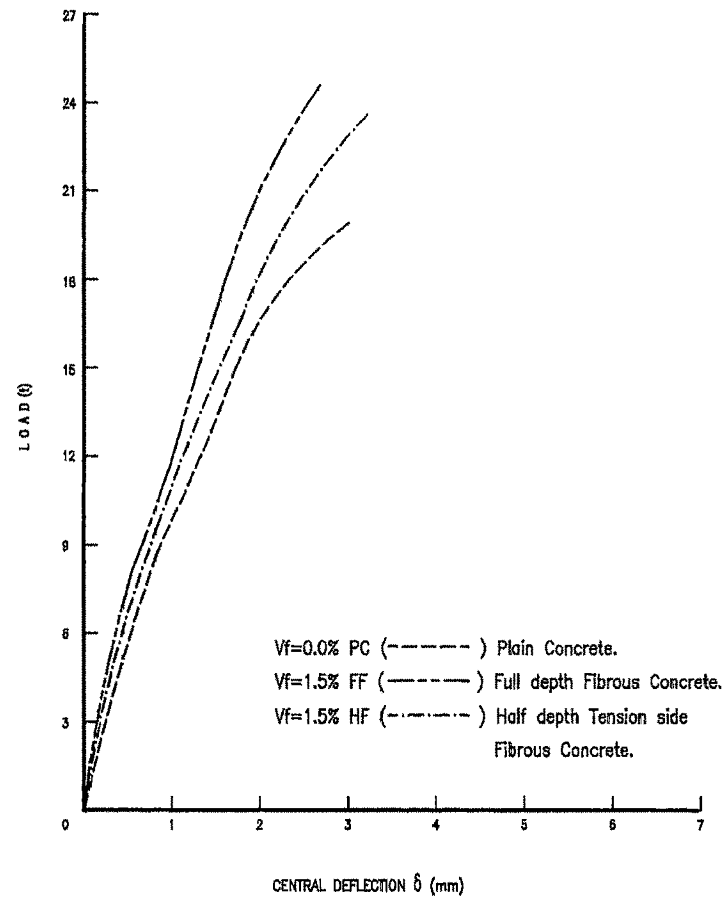


Fig.4.20 LOAD DEFLECTION CURVES FOR L/D=6.0 Series

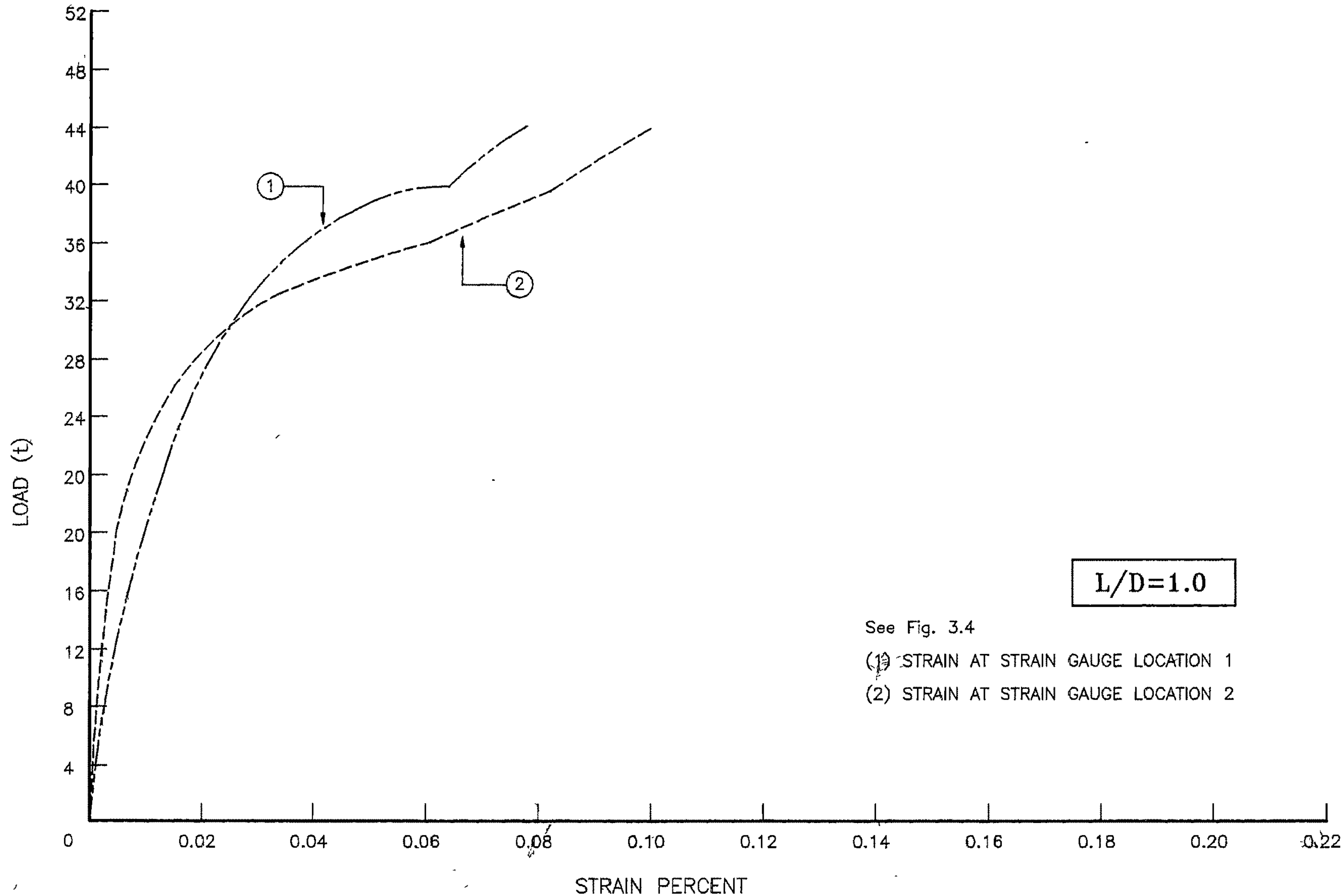


Fig. 4.21 LOAD VERSUS STEEL STRAIN FOR BEAM F 1.5 D 60

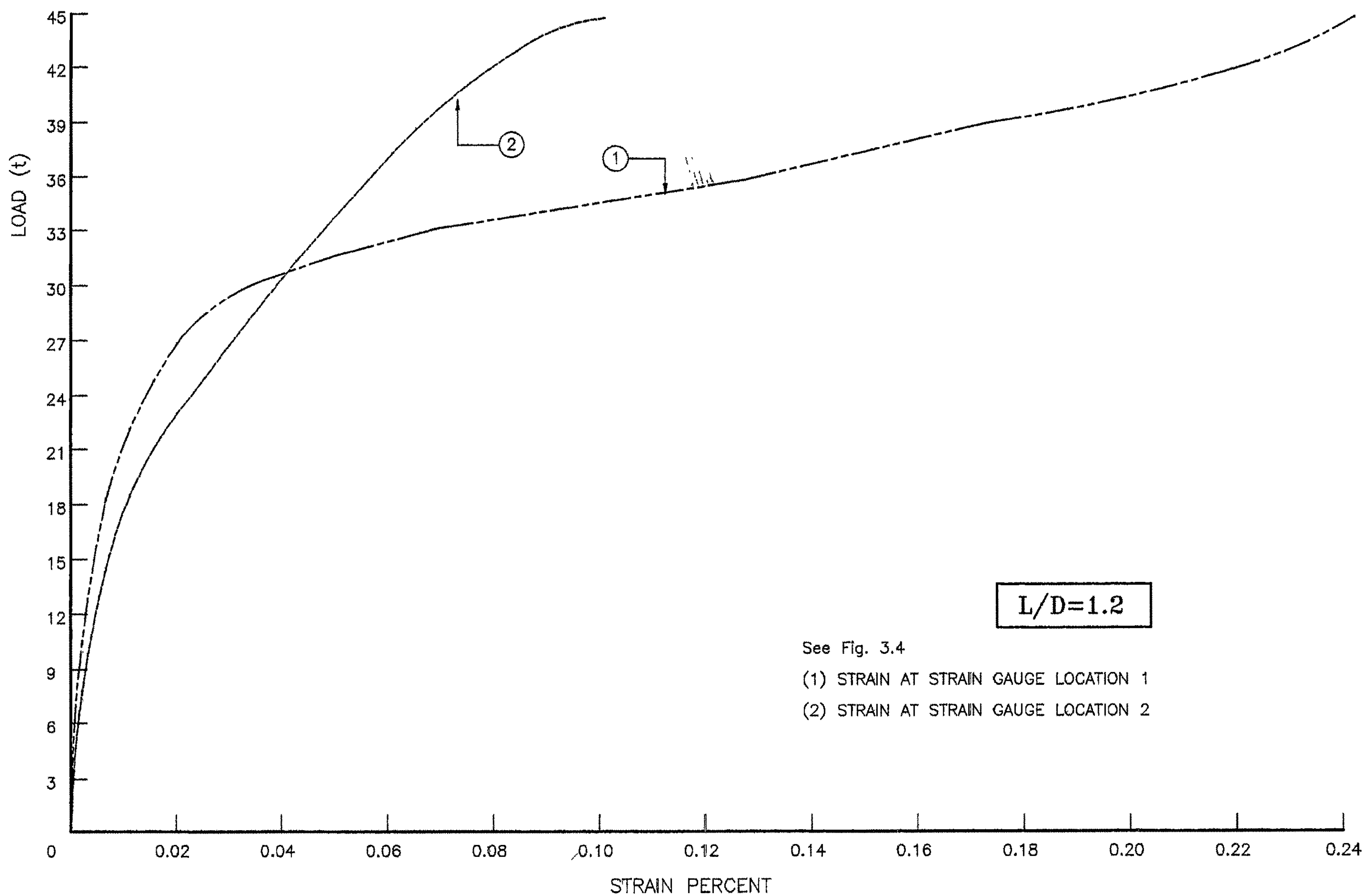


Fig. 4.22 LOAD VERSUS STEEL STRAIN FOR BEAM F 1.5 D 50

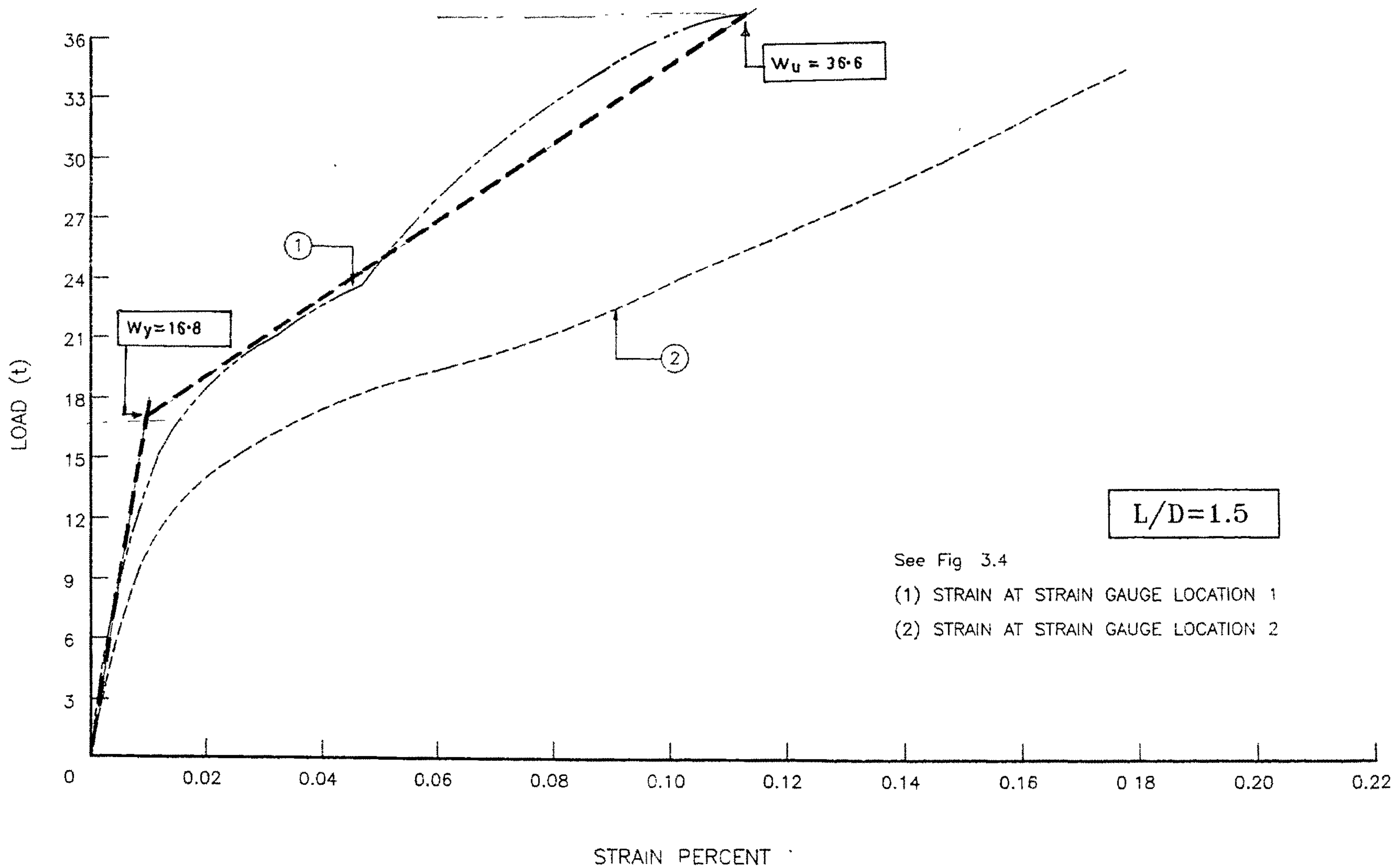


Fig. 4.23 LOAD VERSUS STEEL STRAIN FOR BEAM F 1.5 D 40

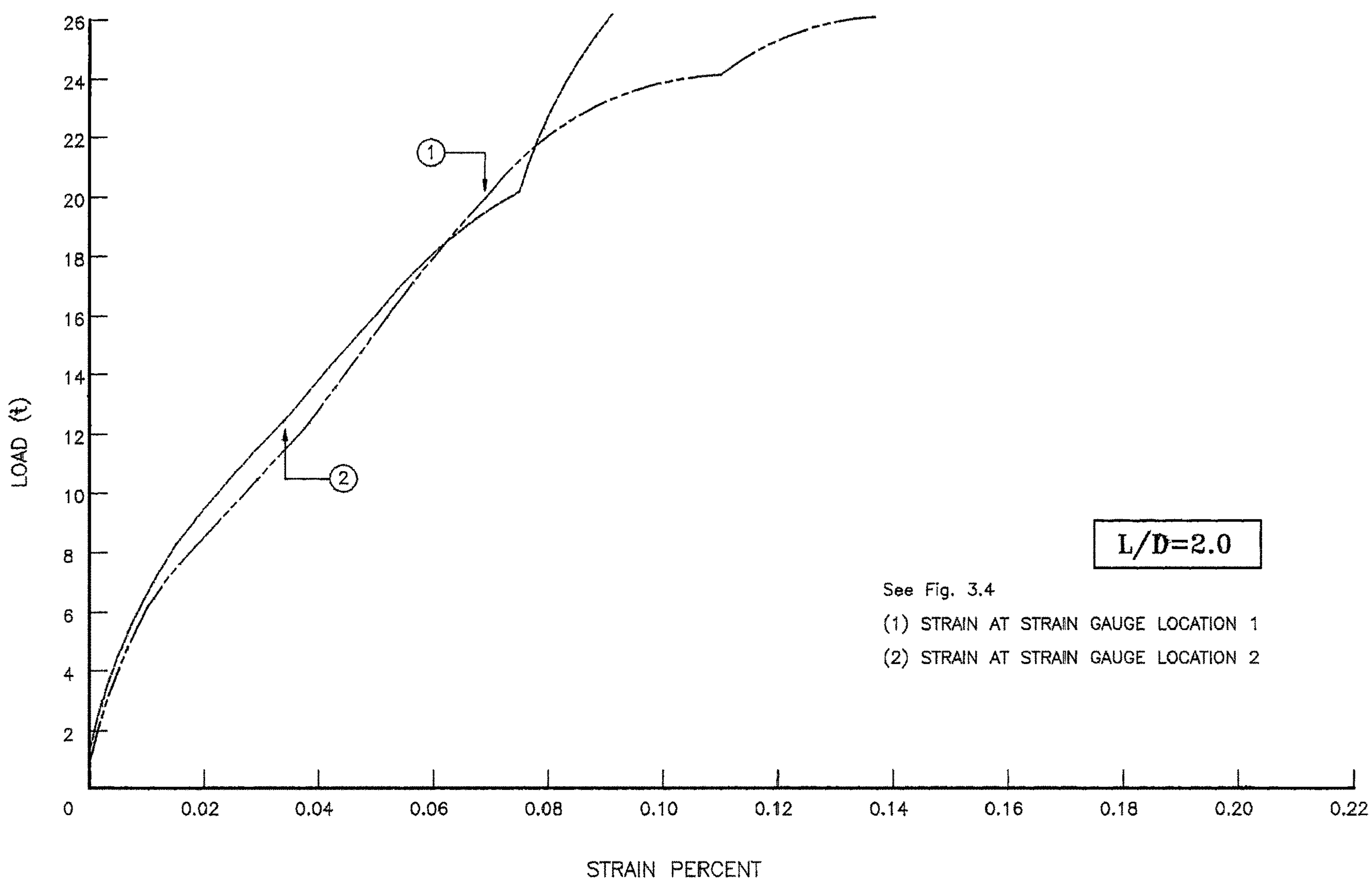


Fig. 4.24 LOAD VERSUS STEEL STRAIN FOR BEAM F 1.5 D 30

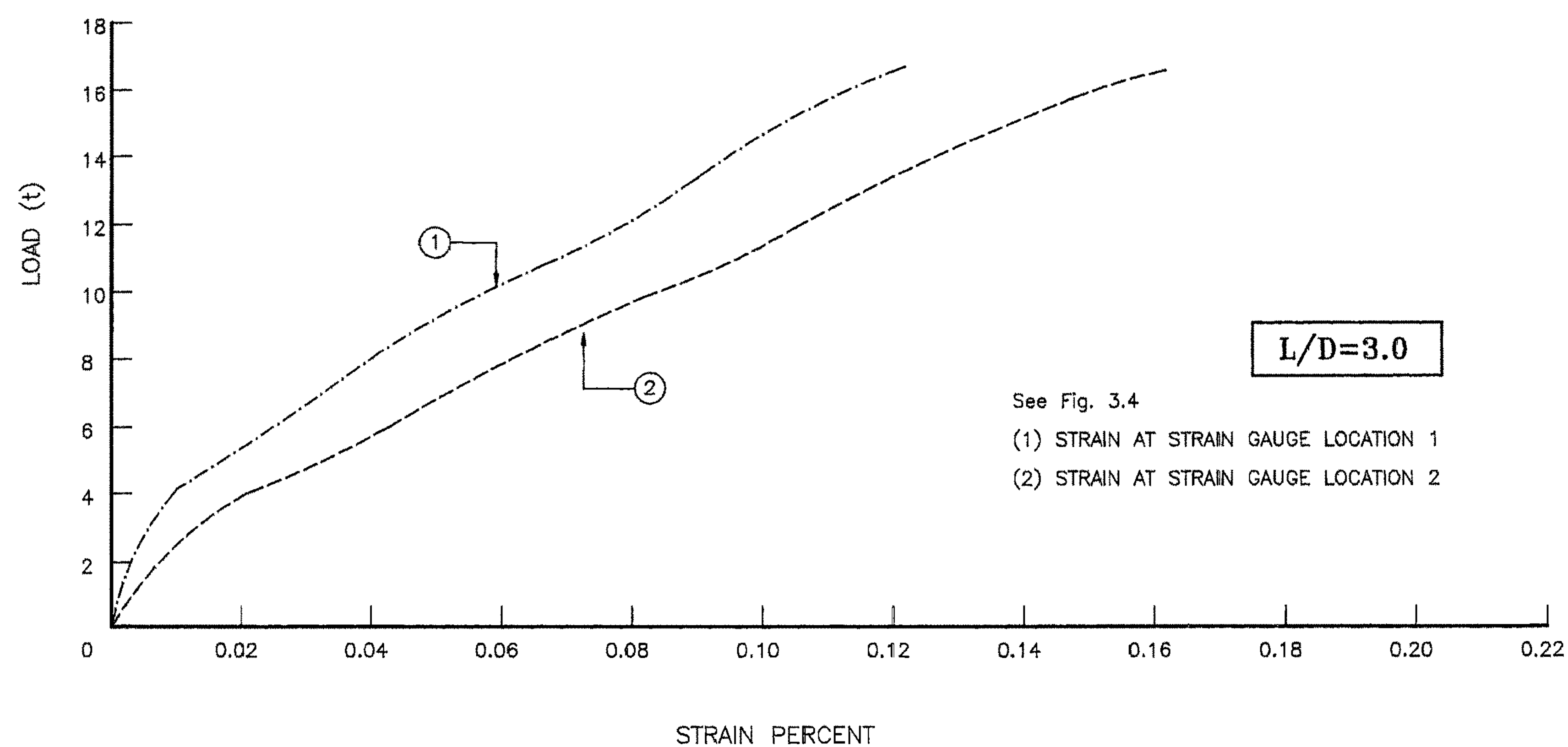


Fig. 4.25 LOAD VERSUS STEEL STRAIN FOR BEAM F 1.5 D 20

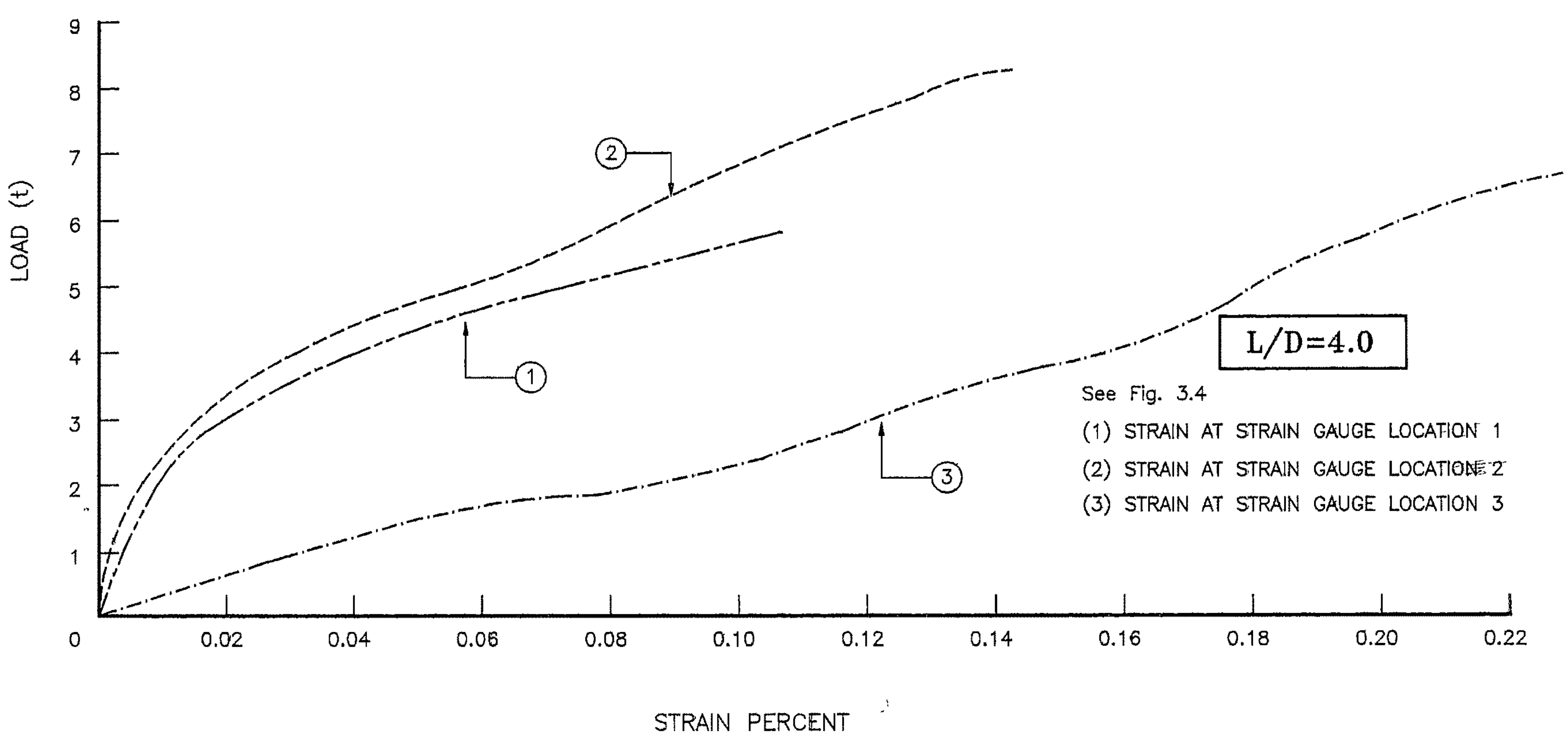


Fig. 4.26 LOAD VERSUS STEEL STRAIN FOR BEAM F 1.5 D 15

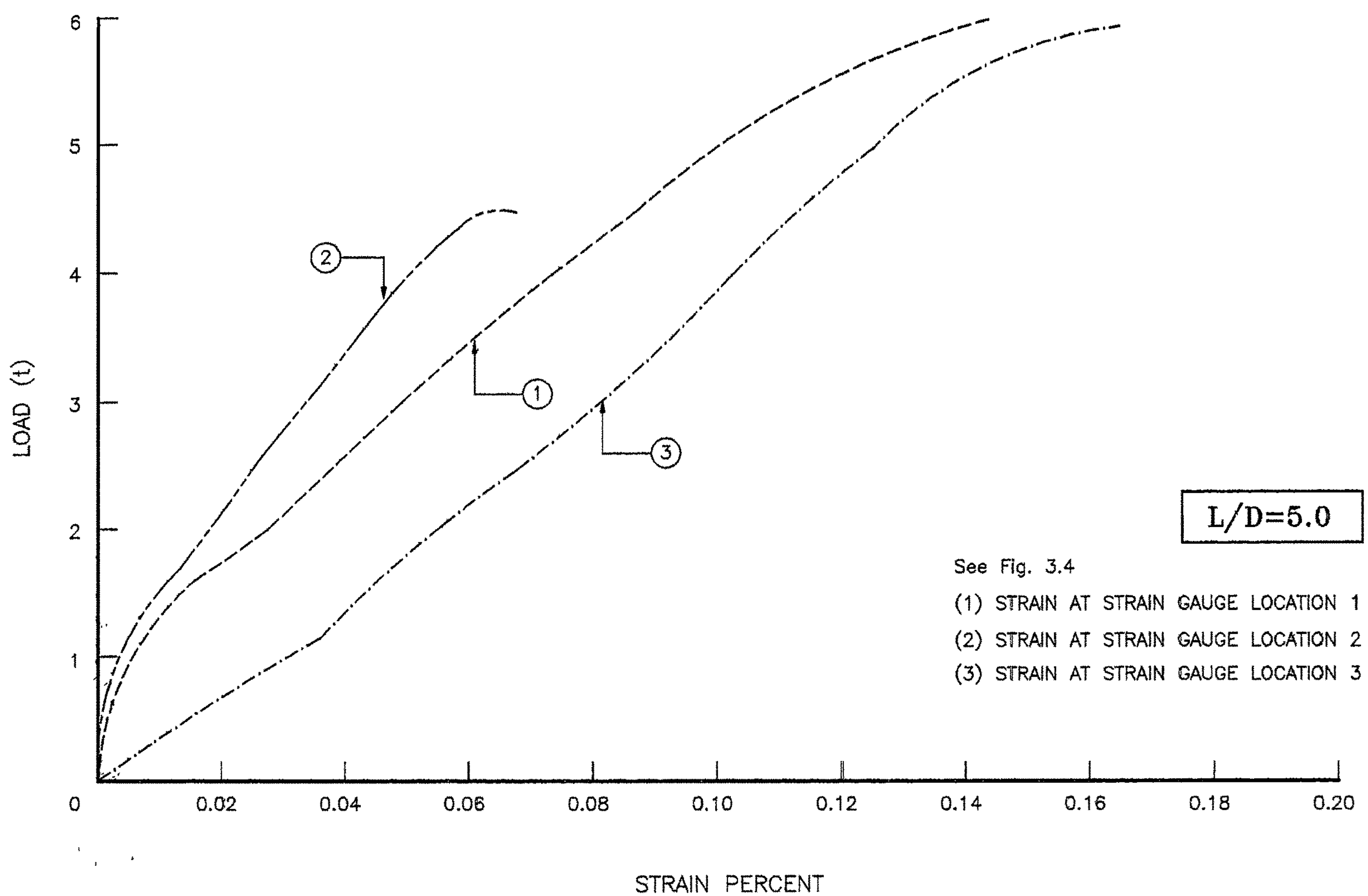


Fig. 4.27 LOAD VERSUS STEEL STRAIN FOR BEAM F 1.5 D 12

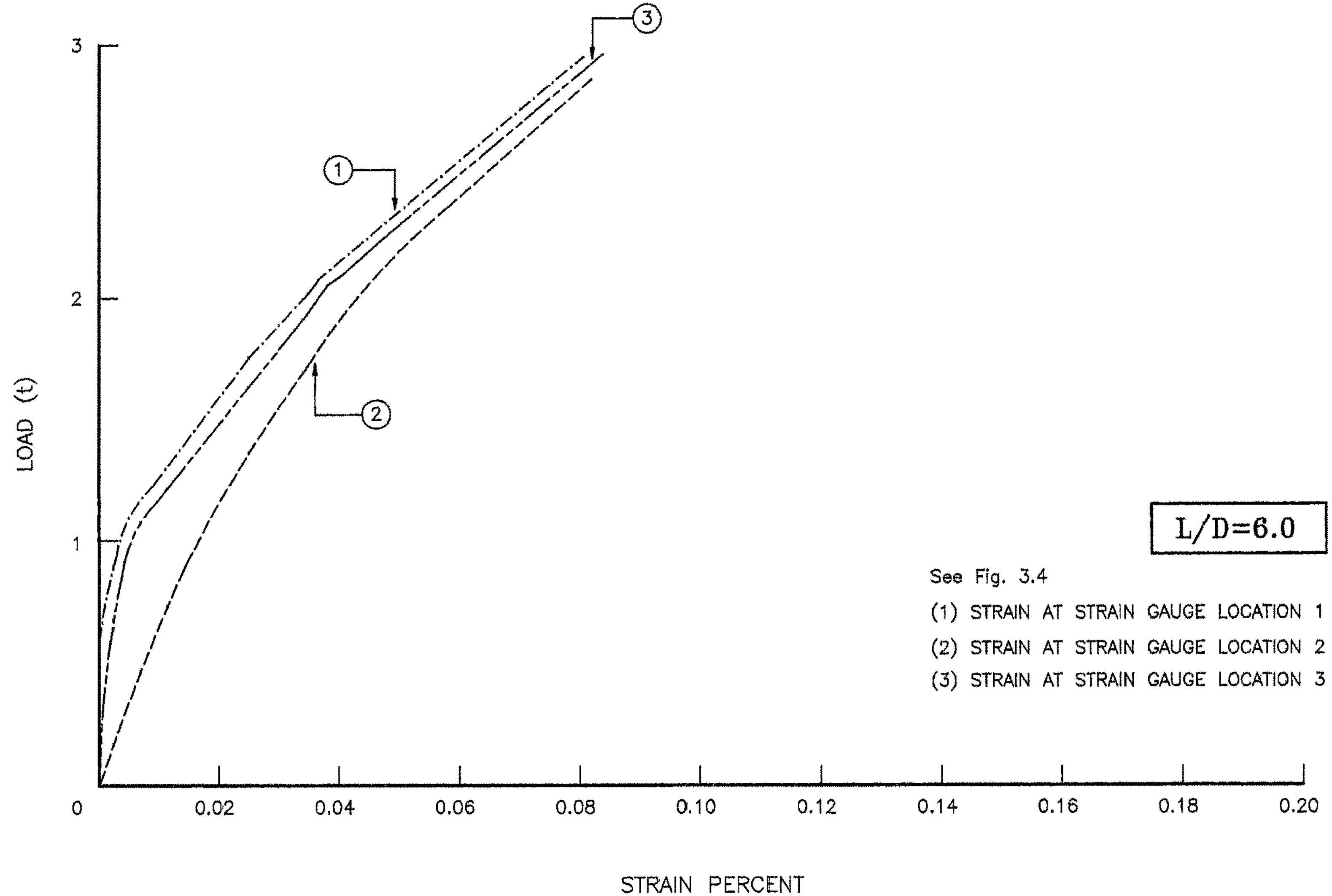
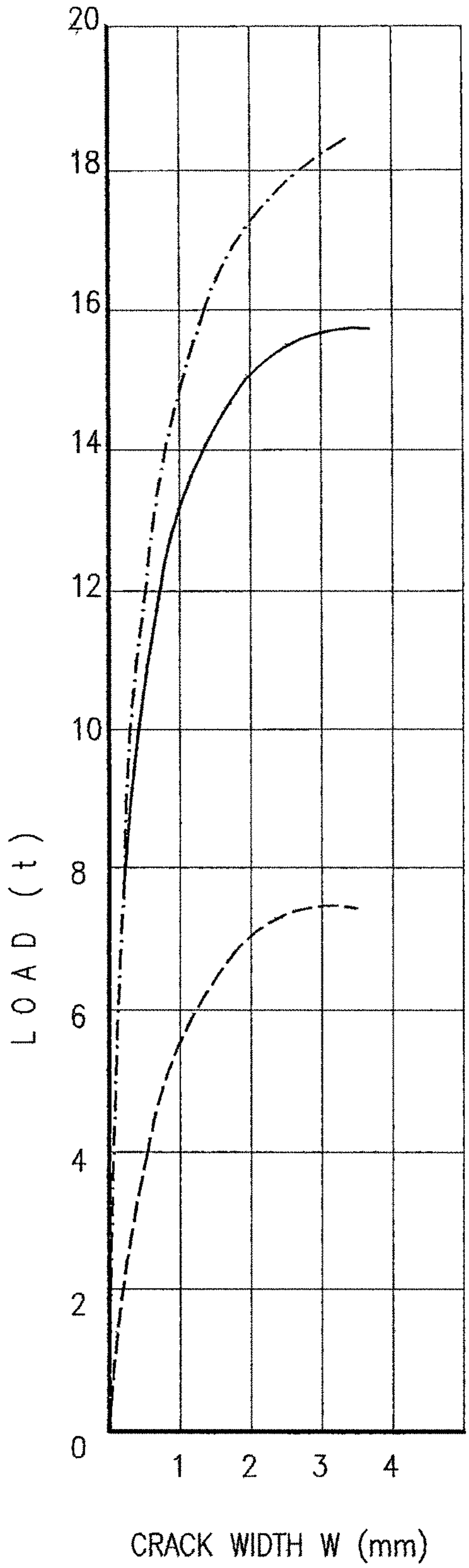
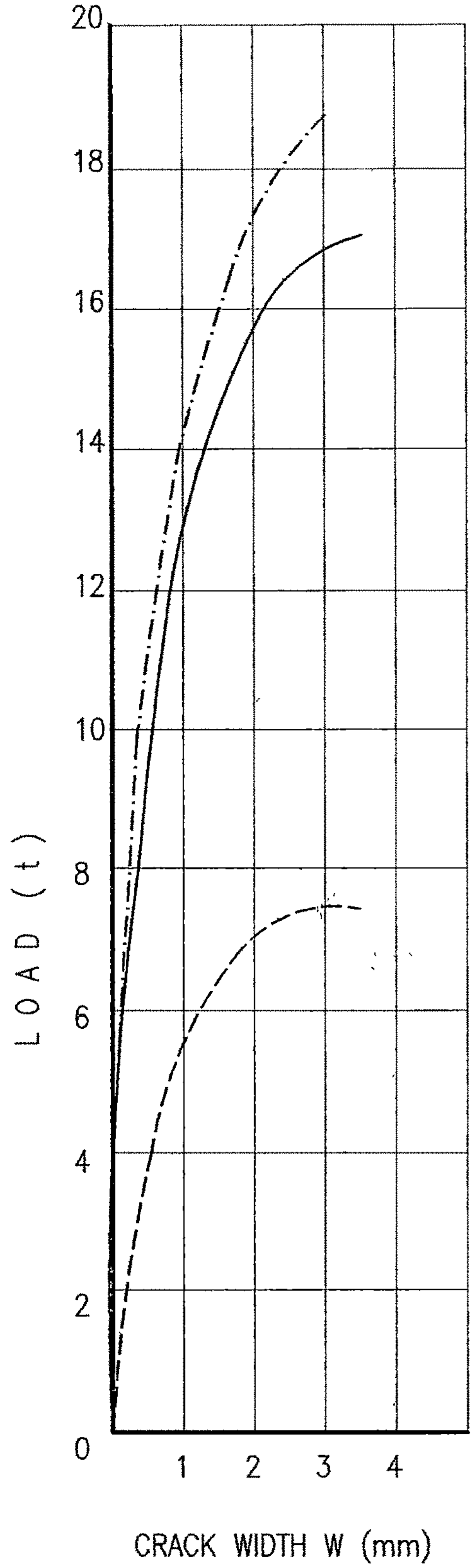


Fig. 4.28 LOAD VERSUS STEEL STRAIN FOR BEAM F 1.5 D 10

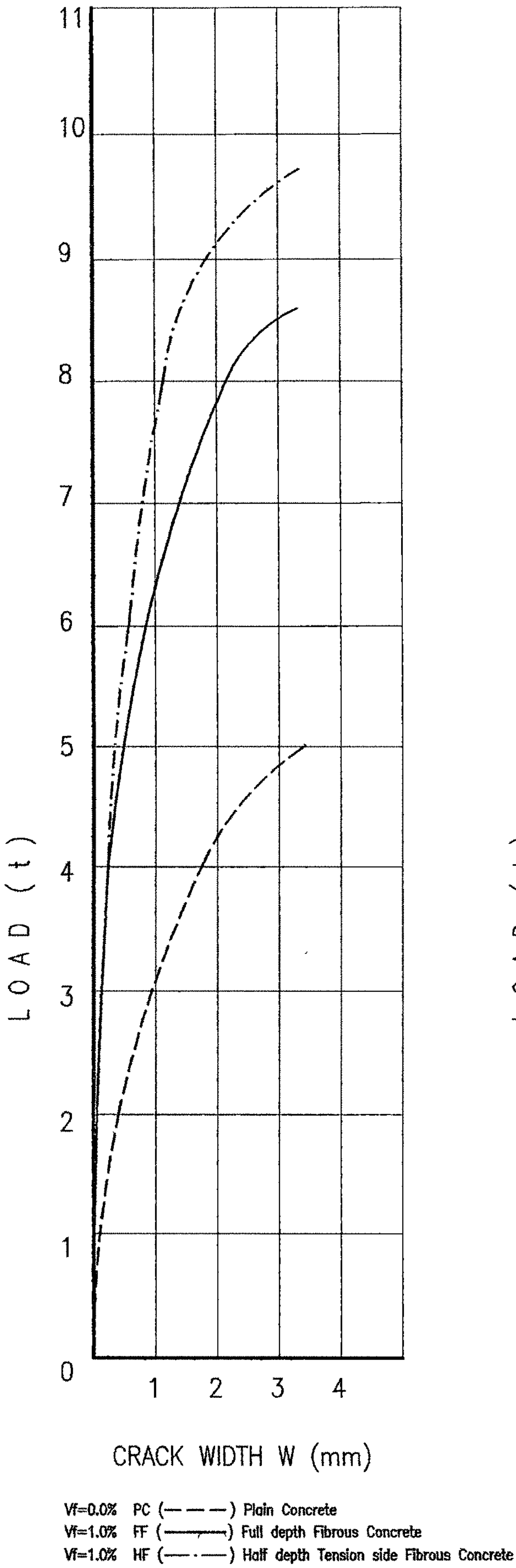


Vf=0.0% PC (— — — —) Plain Concrete
Vf=1.0% FF (————) Full depth Fibrous Concrete
Vf=1.0% HF (—·—·—) Half depth Tension side Fibrous Concrete



Vf=0.0% PC (— — — —) Plain Concrete
Vf=1.5% FF (————) Full depth Fibrous Concrete
Vf=1.5% HF (—·—·—) Half depth Tension side Fibrous Concrete

Fig.4.29–30 LOAD–CRACK WIDTH CURVES FOR L/D =3.0 Series



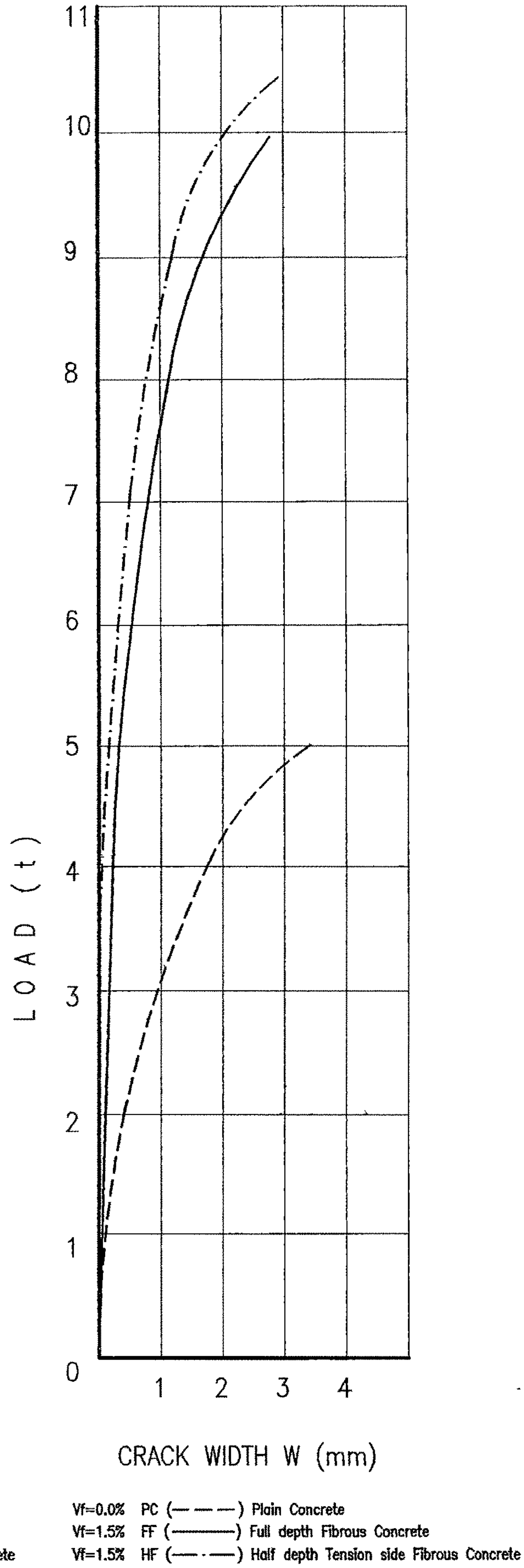
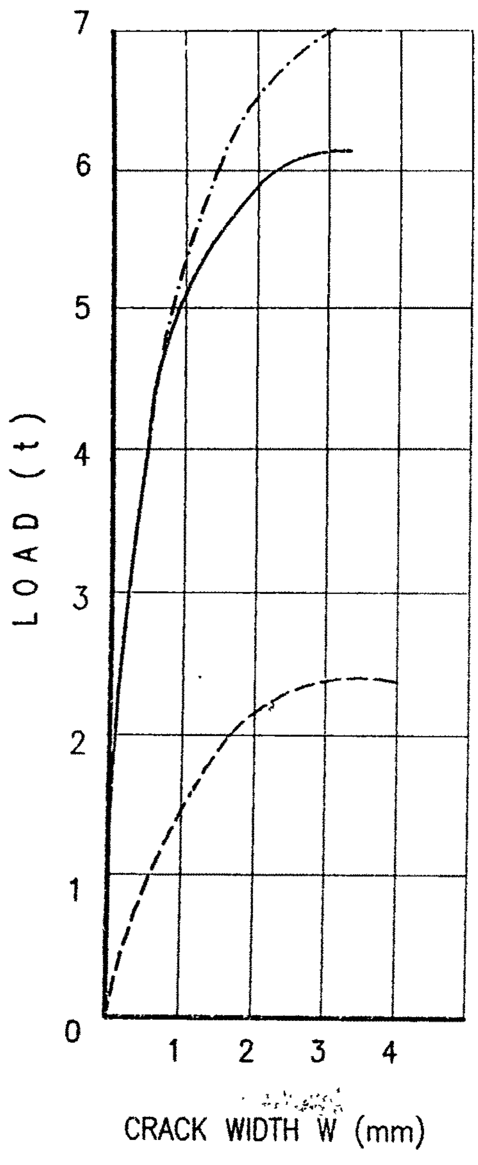
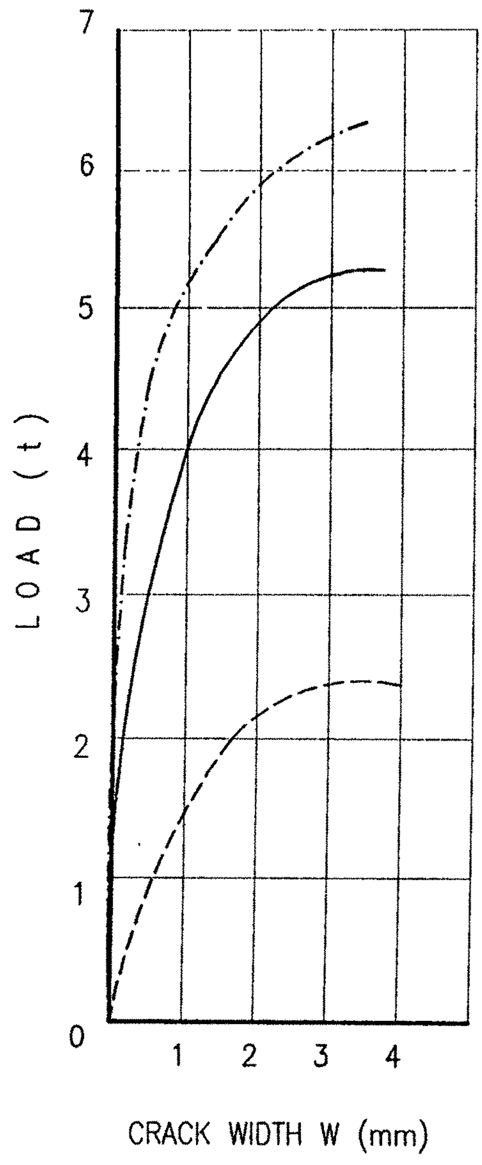


Fig.4.31−32 LOAD−CRACK WIDTH CURVES FOR L/D =4.0 Series



Vf=0.0% PC (— — —) Plain Concrete
Vf=1.0% FF (————) Full depth Fibrous Concrete
Vf=1.0% HF (— · —) Half depth Tension side Fibrous Concrete



Vf=0.0% PC (— — —) Plain Concrete
Vf=1.5% FF (————) Full depth Fibrous Concrete
Vf=1.5% HF (— · —) Half depth Tension side Fibrous Concrete

Fig.4.33–34 LOAD–CRACK WIDTH CURVES FOR L/D =5.0 Series

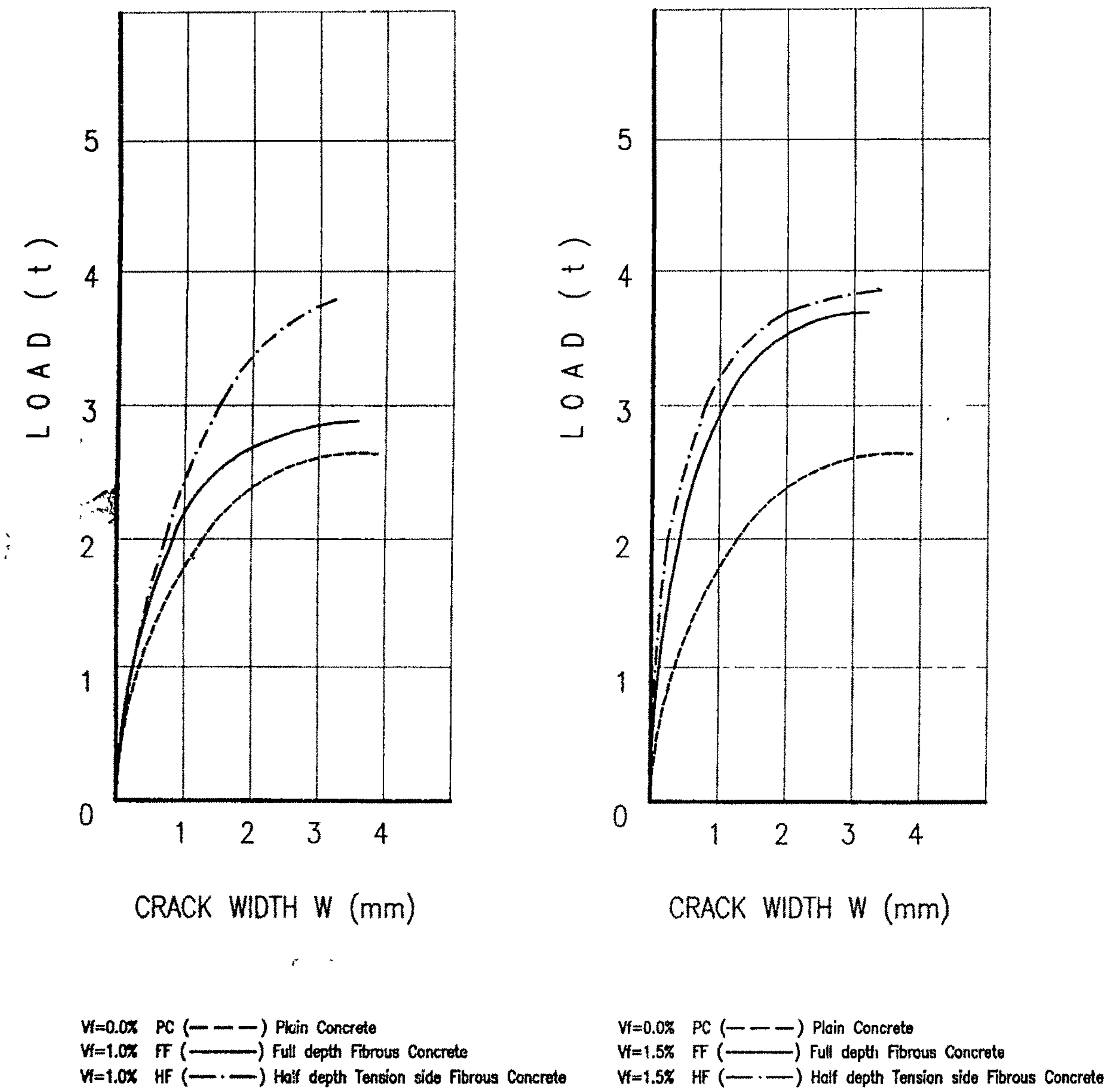


Fig.4.35−36 LOAD−CRACK WIDTH CURVES FOR L/D =6.0 Series