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Effects of beam width on the cyclic behavior of reinforced concrete

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ABSTRACT

Lateral force resisting concrete frames in regions of moderate seismic risk are generally designed to dissipate applied energy through the formation of plastic hinges in the beam elements. Previous research strongly suggests that, in addition to load history, applied shear stress, and nominal stirrup strength, member width also influence hinge performance. To facilitate a better understanding of the effects of beam width on the inelastic behavior of reinforced concrete members subjected to severe seismic loading, four lightly reinforced specimens were fabricated and tested. The performance of these specimens is compared to those of narrow beams fabricated and tested in a similar manner. This study indicates that, for specimens with the same flexural strength, nominal concrete strength, and stirrup spacing, an increase in beam width improves beam performance under cyclic load.

INTRODUCTION

Failures in reinforced concrete frames subjected to moderate earthquakes are minimized when energy is dissipated through the formation of plastic beam hinges. An understanding of the factors influencing beam performance is necessary if a structure's integrity is to be maintained throughout the duration of the seismic loading.

Numerous studies have been undertaken to determine the influence of various parameters on the hysteretic behavior of reinforced concrete beams. This research indicates that load history, applied shear stress, and nominal stirrup strength significantly affect hinge performance. Unfortunately, the development of a consistent measure of cyclic performance has been complicated due to variations in design and test parameters within and between studies.

Several measures of cyclic performance have been proposed for which the goal has been to characterize the net effect of variations in member properties and testing techniques. These measures include the Work Index and Modified Work Index, I_w and I'_w, respectively (Gosain,

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Brown and Jirsa 1977), the Energy Index, I_E (Hwang 1982), the Energy Dissipation Index, D_i (Nmai and Darwin 1984), and the Normalized Energy Index, I_{EN} (Ehsani and Wight 1990).

Previous research by Darwin and Nmai (1986) and Hanks and Darwin (1988) suggests that beam width may have a substantial influence on energy dissipation and cyclic performance. An increase in beam width reduces the maximum applied shear stress, which significantly affects member response and should increase the number of cycles to failure.

The purpose of this research is to investigate the influence of beam width on the cyclic behavior of lightly reinforced concrete beams. The results from the experimental portion of this study are compared to those of previous research (Nmai and Darwin 1984) using narrow beams. Beam hinge performance is based on an evaluation of the energy dissipated and the Energy Dissipation Index, D_i.

EXPERIMENTAL INVESTIGATION

Four cast-in-place reinforced concrete specimens were fabricated with a beam width of 15 in. and overall depth of 18 in.. Reinforcement ratios, ρ, of 0.34% (Beam H-1, H-3, and H-4) and 0.51% (Beam H-2) were used. Other details of the beam dimensions and properties are shown in Table 1 and Fig. 1. Nominal stirrup strength, $v_s = A_v f_{vy}/(bs)$, (A_v = total area of stirrup, f_{vy} = yield strength of stirrup, b = beam width, and s = stirrup spacing) was about 78 psi in all beams. The maximum applied shear stress, $v_m = V_m/(bd)$, (V_m = maximum shear force, and d = effective depth), varied from 64 to 105 psi depending on the area of flexural steel.

All specimens were fabricated with two layers of #4 bars as negative moment reinforcement, A_s (top steel). Beams H-1, H-2 and H-3 contained one layer of #4 bars as positive moment reinforcement, A_s' (bottom steel), while Beam H-4 was fabricated with two layers of #4 bars as A_s'. Transverse reinforcement was fabricated from 7/32 in. nominal diameter smooth rod and welded to form a closed hoop. The first stirrup was placed at 1 in. from the vertical face of the formed column, subsequent stirrups were spaced at 3 5/8 in. centers. The flexural reinforcement of the beam was welded to a 3/4 in. bearing plate to prevent anchorage failure within the column (Fig. 1).

The specimens were post-tensioned to a structural floor and the ends of the beams were loaded using a 110 kip capacity hydraulic actuator. Throughout testing, specimens were subjected to constant nominal displacement ductility factors, μ, ranging from 4.3 to 8.5 (Table 1) in both positive and negative bending. Strains in the longitudinal and transverse reinforcement were measured with foil gages. Beam tip displacement and displacements at various locations in the beam and column were measured with linear variable differential transformers, LVDT's.

TEST RESULTS

Studies relative to beam hinge behavior generally incorporate energy dissipated by the specimen into the measure of cyclic performance. Energy dissipated is the area bounded by the load-displacement plot for each hysteresis loop. Fig. 2 is a representative plot of the hysteresis loops for Beam H-3. A summary of the principle experimental results for the beams of this study is presented in Table 1.

EVALUATION OF TEST RESULTS

Energy dissipated, E, is a function of the number of cycles required to cause failure. To eliminate ambiguity in the definition of failure, several researchers have defined the energy dissipated by a member as the summation of energy for cycles in which the maximum load, P_n, is at least 75% of the yield load, P_y (i.e. $P_n \geq 0.75P_y$). The influence of beam width on the cumulative energy dissipated by a member can be obtained by comparing the results of specimens fabricated with different widths, yet similar flexural reinforcement, effective depth, stirrup spacing, concrete strength, and load history. Beams F-2 and F-3 tested by Nmai and Darwin (1984) and H-1 and H-2 of this study provide for direct comparison.

By comparing the energy dissipated for Beam F-2 ($b = 7.5$ in., $\rho = 1.02\%$, $A_s'/A_s = 0.5$, $\mu = 5.1$, $E = 169$ inch-kips) and H-2 ($b = 15$ in., $\rho = 0.51\%$, $A_s'/A_s = 0.5$, $\mu = 5.3$, $E = 315$ inch-kips) for all cycles in which $P_n \geq 0.75P_y$, it can be seen that the 86% increase in E for H-2 may be attributed to the increase in beam width. Similarly, a 22% increase in E for Beam H-1 ($b = 15$ in., $\rho = 0.34\%$, $A_s'/A_s = 0.5$, $\mu = 4.3$, $E = 245$ inch-kips) as compared to F-3 ($b = 7.5$ in., $\rho = 0.69\%$, $A_s'/A_s = 0.5$, $\mu = 4.4$, $E = 201$ inch-kips) also results from the larger beam width.

The increase in energy dissipated is primarily attributed to the reduction in the maximum applied shear stress. However, increased beam widths also improve confinement of the core concrete and thus delay buckling of the compression reinforcement which may increase both the number of cycles to failure and the energy dissipated.

Since the cyclic behavior of a member depends upon both strength and displacement ductility factor, energy dissipation alone is not a viable means in which to evaluate inelastic performance. One measure of cyclic performance which appears to provide a consistent evaluation of a wide range of design parameters is the Energy Dissipation Index, D_i, developed by Nmai and Darwin (1984). The Energy Dissipation Index is expressed as

$$D_i = \frac{\sum E}{0.5P_y\Delta_y[1 + (\frac{A_s'}{A_s})^2]} \qquad (1)$$

in which $\sum E$ is the summation of the energy dissipated for cycles where $P_n \geq 0.75P_y$, P_y and Δ_y = initial yield load and yield deflection in negative bending, A_s' = area of bottom steel, and A_s = area of top steel. The normalizing term $0.5P_y\Delta_y[1+(A_s'/A_s)^2]$ approximates the total elastic energy at yield for both negative and positive bending at the near and far ends, respectively, of a full span beam in a frame subjected to lateral displacement.

Nmai and Darwin (1984) show that the contribution of nominal stirrup strength, concrete strength and maximum applied shear stress correlate well with D_i. Their results, based on a linear regression analysis of selected data, show that these design parameters, expressed in the form $(v_s f_c')^{0.5}(v_m)^{-1.5}$, provide a reasonably good estimation, or prediction, of D_i. The dominance of the applied shear stress, and subsequently the influence of beam width, is evident, as seen by the relatively large magnitude of the v_m exponent.

The influence of increased beam width on D_i is seen by performing a linear regression analysis on the data for Beams F-2 & H-2 and F-3 & H-1. The regression of D_i on $(v_s f_c')^{0.5}(v_m)^{-1.5}$ results in a best fit equation of

$$D_i = 81.8[(v_s f_c')^{0.5}(v_m)^{-1.5}] + 13 \tag{2}$$

with a correlation coefficient, r = 0.957 (Fig. 3). A comparison of D_i values in Fig. 3 for Beams F-2 and H-2 (A_s = 6#4 and A_s' = 3#4) and Beams F-3 and H-1 (A_s = 4#4 and A_s' = 2#4) suggests that an increase in beam width appears to be more effective at increasing D_i as the amount of flexural reinforcement increases.

The relationship represented in Eq. 2 appears to be independent of variations in μ and A_s'/A_s on D_i for specimens with similar stirrup spacing, effective depth, and f_c'. When Beam F-1 (b = 7.5 in., ρ = 1.03%, A_s'/A_s = 0.5, μ = 3.9, E = 287 inch-kips) from the research by Nmai and Darwin (1984) and Beams H-3 (b = 15 in., ρ = 0.34%, A_s'/A_s = 0.5, μ = 8.5, E = 178 inch-kips) and H-4 (b = 15 in., ρ = 0.34%, A_s'/A_s = 1.0, μ = 4.7, E = 507 inch-kips) of this study are included in the analysis of the specimens shown in Fig. 3, the best fit equation becomes

$$D_i = 84.9[(v_s f_c')^{0.5}(v_m)^{-1.5}] + 12 \tag{3}$$

with r = 0.972. Fig. 4 shows the seven data points represented by Eq. 3. As this figure illustrates, there is a positive correlation of data represented by the best fit line for specimens fabricated with widths of 7.5 or 15 in., $3.9 \leq \mu \leq 8.5$, and A_s'/A_s of 0.5 or 1.0. For the range of data previously discussed, Eq. 3 provides a reasonably consistent prediction of D_i. Both Figs. 3 and 4 indicate that an increase in D_i may be obtained by increasing the nominal stirrup strength and concrete strength and decreasing the maximum applied shear stress. For the range of data analyzed in this study, the most effective means in which to improve D_i appears to be obtained through an increase in beam width.

CONCLUSIONS

For beams with similar flexural strength, stirrup spacing, and concrete strength, an increase in beam width increases the energy dissipation capacity. The increase in energy dissipated by the member appears to be primarily the result of a decrease in maximum applied shear stress. Increased beam widths improve concrete confinement and delay buckling of the compression reinforcement. As a result, the number of cycles to failure and the energy dissipation capacity of the member are increased.

The Energy Dissipation Index, D_i, appears to be a consistent measure of cyclic performance. Improvements in D_i may be readily obtained by increasing the width of reinforced concrete beams.

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Table 1. Beam properties and principle experimental results

Beam	H-1	H-2	H-3	H-4
Length, L (in.)	68	68	68	68
Height, h (in.)	18	18	18	18
Width, b (in.)	15	15	15	15
Effective depth, d (in.)	15.69	15.81	15.63	15.75
Effective depth, d_1 (in.)	16.81	16.88	16.69	15.75
Core width, b_c (in.)	13.0	13.0	13.0	13.0
Core depth, d_c (in.)	15.91	16.03	15.85	15.97
Shear span, a (in.)	60	60	60	60
a/d	3.8	3.8	3.8	3.8
Top reinforcement ratio, ρ (%)	0.34	0.51	0.34	0.34
Top reinforcement, A_s	4#4	6#4	4#4	4#4
Bottom reinforcement, A_s'	2#4	3#4	2#4	4#4
A_s'/A_s	0.5	0.5	0.5	1.0
Yield str. of flex. reinf. (ksi)	66.4	66.4	66.4	71.7
Stirrup diameter (in.)	0.222	0.222	0.222	0.222
Stirrup spacing, s (in.)	3.6	3.6	3.6	3.6
f_{vy} (ksi)	56.6	55.5	54.3	54.3
v_s (psi)	81	79	77	77
v_m (psi)	64	105	74	76
f_c' (psi)	4200	4400	4120	4060
Slump (in.)	3.25	4.0	2.0	4.0
Yield load (kips)	12.8	20.9	13.0	14.8
Maximum load (kips)	15.1	24.8	17.4	18.0
Yield deflection (in.)	0.30	0.34	0.24	0.37
Maximum deflection (in.)	1.29	1.80	2.04	1.73
Displacement ductility factor, μ	4.3	5.3	8.5	4.7
Number of cycles:				
$P_n \geq 0.75P_y$	13	7	4	17
Total	21	13	5	21
Cumulative Energy Dissipated (inch-kips):				
Cycles where $P_n \geq 0.75P_y$	245	315	178	507
Energy Dissipation Index, D_i	102	71	91	93

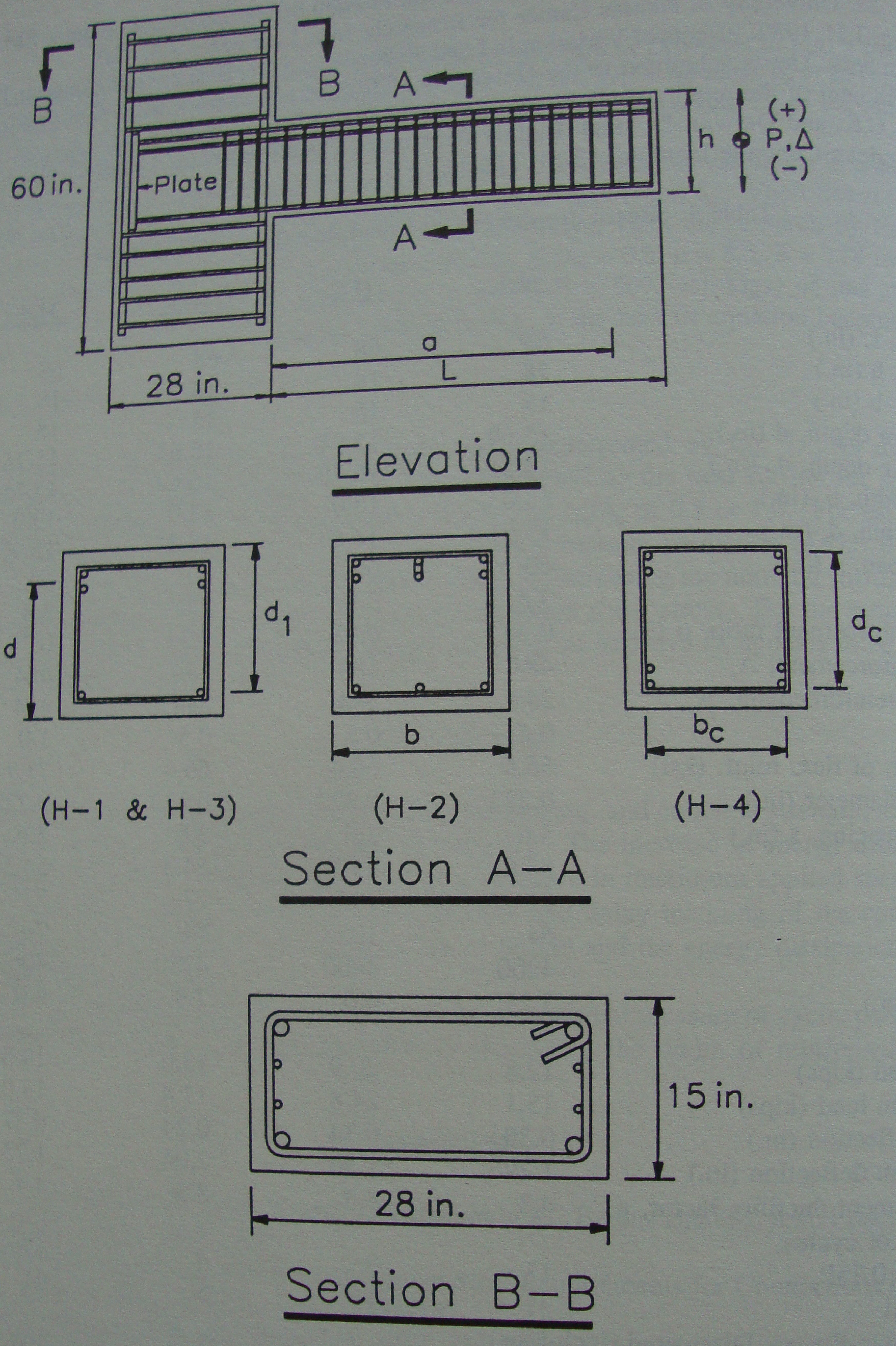

Figure 1. Test specimen and reinforcing details

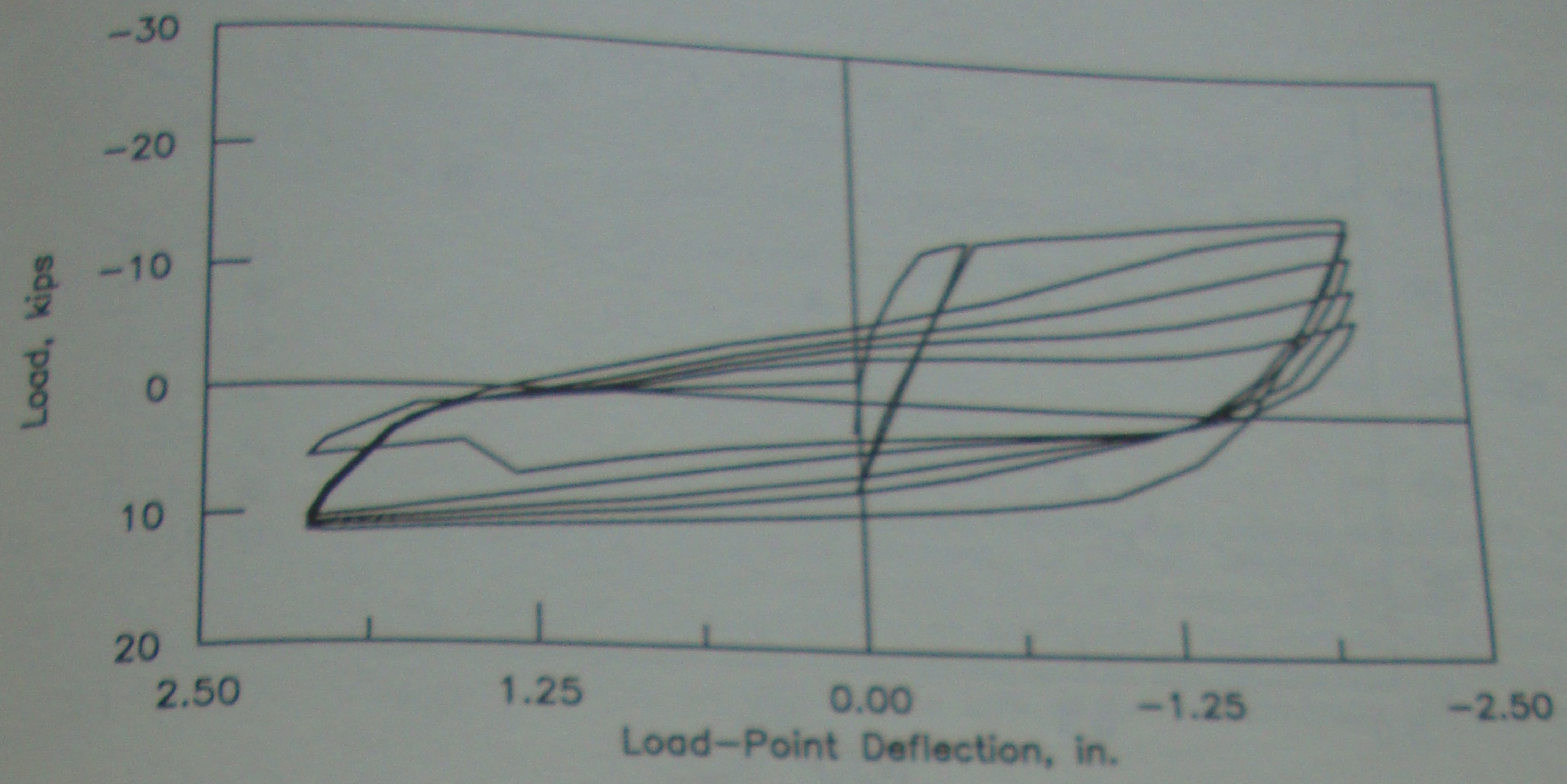

Figure 2. Load-deflection curve, Beam H-3

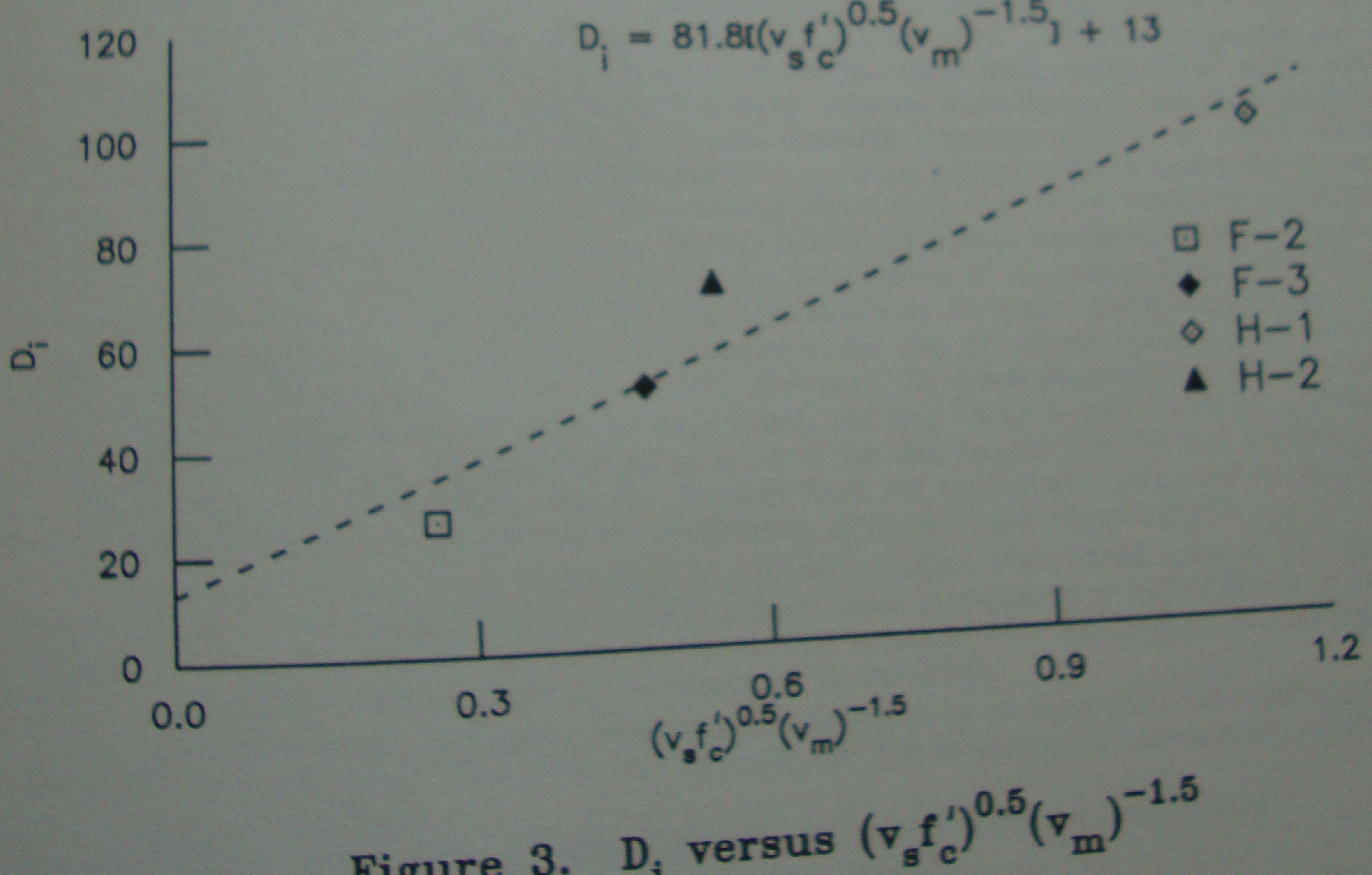

Figure 3. D_i versus $(v_s f'_c)^{0.5}(v_m)^{-1.5}$

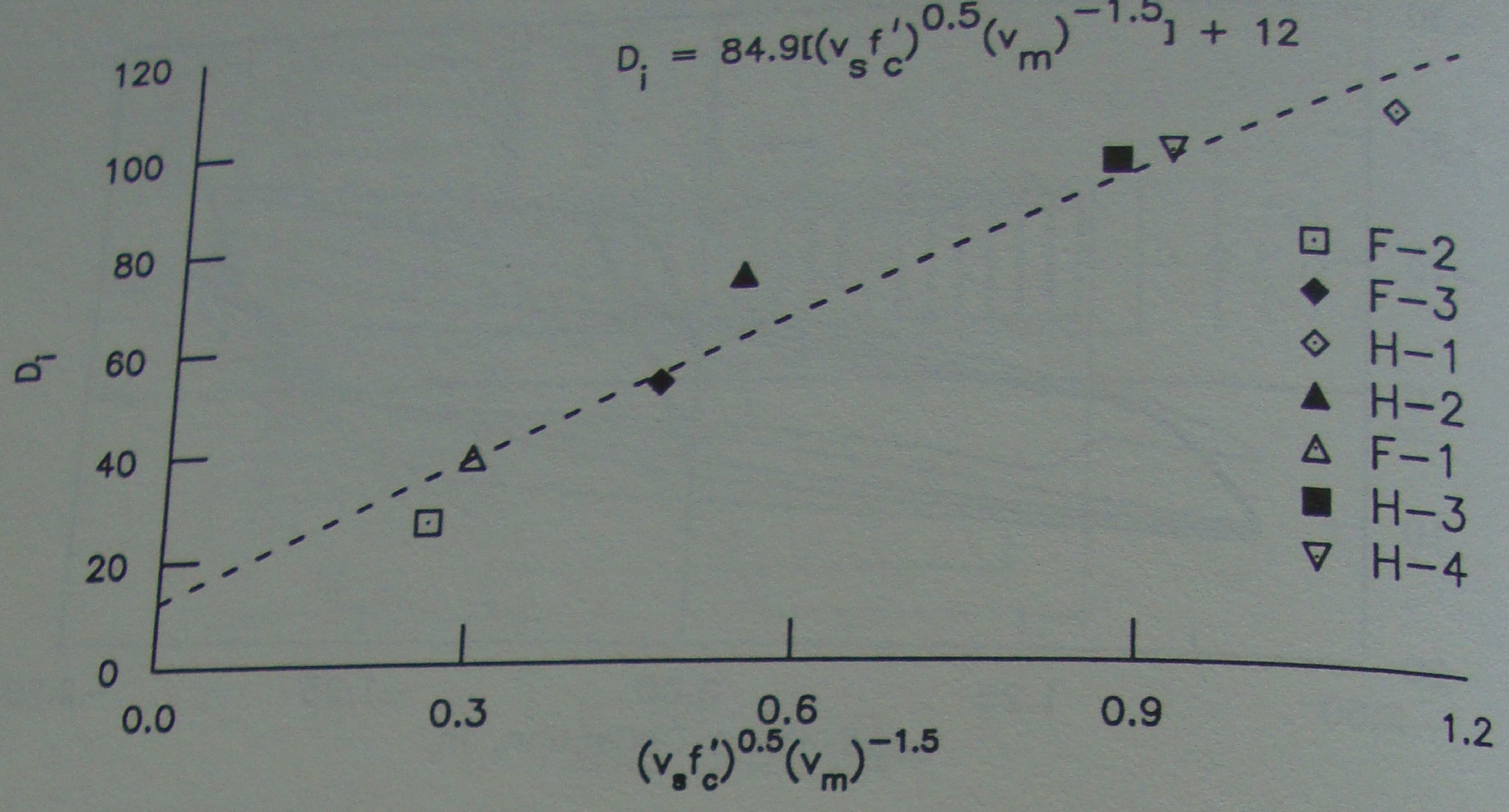

Figure 4. D_i versus $(v_s f_c')^{0.5}(v_m)^{-1.5}$