

Significance of Variations in Wire and Coil Diameter

Wahl (1949) indicated that:-

- (a) a one per cent variation in the mean coil diameter of the spring changes its deflection by approximately 3 per cent.
- (b) a one per cent variation in wire diameter changes the deflection of the spring by approximately 4 per cent.

A cumulative variation in both the coil and wire diameter by only one per cent could cause a 7 per cent change in the load-deflection characteristic of the spring.

The expected variations in the deflection of characteristic of the 3 coils of Remanit .007" - .030", Elgiloy .007" - .030", Unitek Hi-T .008" - .036" , Unitek Permchrome Standard .008" - .036" and Elgiloy .008" - .036" were calculated according to the formula, Equation 29, derived by Wahl (1949) (see P. 66). The results are shown in Column 9 of Table 14 .

All springs exhibited an expected deflection greater than the nominal by a variable amount. The expected variations in between-coil deflection characteristic of the 3 coils of Remanit .007" - .030",

Unitek Hi-T .008" - .036" and Unitek Permachrome Standard .008" - .036" are small in comparison with the 3 coils of Elgiloy .008" - .036". As 4 sample springs from each of the 3 coils of Elgiloy .008" - .036" had been determined experimentally, such between-coil variations in the deflection characteristic of the springs will be further discussed at a later stage.

B. VARIATIONS IN THE NUMBER OF COILS IN A LENGTH OF SPRING

Table 15 shows the within and between-coil variations in the number of coils present in the 2 cm gauge length of the spring.

Column 3 of Table 15 shows the minimum number of coils found in each of the 4 tested sample springs.

Column 4, "variations", shows the within-coil maximum variation in the number of coils from Column 3.

Column 5, "within-coil variations, %", shows the within-coil maximum variations in the number of coils in any length of the springs.

Column 6 of Table 15 shows the maximum difference in the number of coils found between different coils of the same type of spring.

TABLE 15 VARIATIONS IN NUMBER OF COILS IN A GIVEN LENGTH OF THE SPRING

Column	1	2	3	4	5	6
	Type of Spring					
Manufacturer	Material	Dimension	Sample	Minimum no. of coils in every 2 cm length of spring.	Variations	Within-Coil Variation %
						Between-Coil Variations in no. of coils per 2 cm. length of spring
Unitek	Hi-T	.006"-.036"	Coil A	32	1	3.13
Rocky Mountain	Elgiloy	.007"-.036"	Coil A	43	2	4.65
Rocky Mountain	Elgiloy	.0056"-.022"	Coil A	48	1	2.08
Rocky Mountain	Elgiloy	.007"-.030"				
			Coil A	47	1	2.13
			Coil B	46	3	6.52
			Coil C	47	6	12.77
Dentaurum	Remanit	.007"-.030"				
			Coil A	32	6	18.75
			Coil B	33	5	15.15
			Coil C	36	5	13.88

TABLE 15 (cont'd)

Column	1	2	3	4	5	6
Type of Spring		Sample	Minimum no. of coils in every 2 cm length of spring	Variations	Within-Coil Variation %	Between-Coil Variations in no. of coils per 2 cm. length of spring
Manufacturer	Material					
Unitek	Hi-T	.008"-.036"				
		Coil A	32	less than 1	less than 3.03	
		Coil B	32	1	3.13	1.5
		Coil C	33	1	3.03	
Unitek	Perma-chrome Standard	.008"-.036"				
		Coil A	30	2	6.67	
		Coil B	30	less than 1	less than 3.33	.75
		Coil C	30	1	3.33	
Rocky Mountain	Elgiloy	.008"-.036"				
		Coil A	48	3	6.25	
		Coil B	48	1	2.08	.25
		Coil C	47	2	4.25	

Discussion

The S.A.E. limit for variations in active coils is $\pm \frac{1}{2}$ coil for every 10 coils. As only a limited number of coils of each type of spring has been tested, the results could only act as pointers.

With the exception of the 3 coils of Remanit .007" - .030" and one coil (Coil C) of Elgiloy .007" - .030", the within-coil variation in the number of coils per unit length of the tested springs varies from 2 to 7 per cent. Remanit .007" - .030" springs show an average variation of about 15 per cent.

For Elgiloy .008" - .036", Unitek Permachrome Standard .008" - .036" and Remanit .007" - .030", Elgiloy .007" - .030", the between-coil variation in the number of coils per 2 cm length of the spring is less than the within-coil difference. For Unitek .008" - .036", the between-coil variation is about the same magnitude as the within-coil variation.

As the total deflection of a compressed spring is proportional to the number of active coils present in the spring, these within and between-coil differences will affect the deflection of the spring accordingly. Variations in deflection of the spring will affect the load-deflection ratio of the spring and the force output from the spring at a given deflection.

C. CHANGE IN LENGTH OF SPRING WITH SOLID COMPRESSION

In the second and fourth cycle of loading, each sample spring was compressed solid. Upon unloading from solid compression, the spring was found to be unable to recover to its initial length. The average change in length (setage) of the 4 tested sample springs of each type is shown in Table 16.

The difference in length of any sample spring at the beginning and end of the second cycle of loading and unloading was the amount of setage of the spring after it had been compressed solid in the as-received condition. The setage was expressed as a percentage of its initial free length of the spring. (Column 3 of Table 16).

Due to this setage, the spring tested after the second unloading cycle had a different free length from its initial free length.

The new free length was obtained by subtracting the change in length of the spring after the second unloading cycle from its initial free length. Setage observed in the fourth cycle of loading was expressed as a percentage of its new free length in Column 4 of Table 16.

TABLE 16 SETTAGE OF SPRING WITH SOLID COMPRESSION

Column 1	2	3	4	5				
Type of Spring	Load to compress the spring solid Gm	As-received Condition		After Compressed Solid Once		Settage in as-received condition		
		Mean Settage percent	S.D.	S.E.	Mean Settage per cent		S.D.	S.E.
Unitek Hi-T .006"- .036"	211.2	5.60	.95	.548	1.16	.835	.482	4.83
Elgiloy .007"- .036"	183.2	3.24	.272	.157	0.46	.12	.069	7.04
Elgiloy .0056"- .022"	176.7	12.94	1.475	.852	0.83	.162	.093	15.59
Elgiloy .007"- .030"	233.2	7.85	1.294	.747	1.05	.55	.318	7.48
Remanit .007"- .030"	263.2	21.36	3.568	2.06	0.85	.21	.121	25.13
Unitek Hi-T .008"- .036"	578.2	3.92	.913	.527	0.81	.393	.227	4.84
Unitek Permachrome Standard .008"- .036"	478.2	15.22	2.125	1.227	1.57	.974	.562	9.69
Elgiloy .008"- .036"								153.
Coil A	210.7	2.86	.714	.412	0.62	.541	.312	4.61
Coil B	203.2	2.51	.843	.487	0.16	.142	.082	15.69
Coil C	203.2	3.10	.823	.475	0.17	.123	.071	18.24

Discussion

Settage observed by this method of investigation could have arisen from three sources. Firstly, friction between the 0.016 inch suspension wire and the collar of the scale pan-collar unit could cause an incomplete return of the spring to its initial position.

Secondly, statical hysteresis could cause a delay in the return of the spring to its initial length. As the spring was loaded and unloaded at fairly rapid successions there is insufficient time for the spring to adjust to room temperature. (See section on hysteresis).

Thirdly, there was plastic deformation of the spring material due to overstress.

The results were discussed with Dr. A. M. Brichta, Senior Lecturer of the Faculty of Mechanical Engineering, University of Sydney.

He pointed out the need to remove the scale pan and collar unit at the end of the second cycle of unloading to determine experimentally the new free length of the spring and the extent of the permanent set.

An additional series of experiments were carried out in accordance with

his suggestion. The procedure was the same as that described in the section on method except that the new free length was measured after the scale pan-collar unit and upper bracket stop had been removed from the suspension wire at the end of the second cycle of unloading. 4 sample springs from Remanit .007" - .030", 2 sample springs from Elgiloy .0056" - .022", Elgiloy .008" - .036" coil B, Unitek Permachrome Standard .008" - .036" and Unitek Hi-T .008" - .036", 1 sample spring from Elgiloy .007" - .030" and Elgiloy .007" - .036" were tested in this manner.

Results from this series of tests indicated that the measured free length was longer than that calculated by less than 0.1 millimetre. When a difference of this magnitude is expressed into percentage settage, taking an example of 0.1 mm difference in an initial free length of 20 mm, the percentage settage for this spring is affected by

$$\text{by } \frac{0.1}{20} \times 100\% = 0.5\%$$

All of the causative factors for settage were operative in the second and fourth cycle of loading. However, the observed mean percentage settage of the spring compressed solid in the as-received condition varied from 4.8 to 25 times greater than that observed after the spring had been compressed solid once. (Column 5 of Table 16). The mean percentage settage of the spring in the as-received condition was greater than three times its standard error.

It seems justified to conclude that for these preformed helical compression springs, cold "setting" the spring in the as-received condition by compressing it solid once will have removed nearly all the potential settage present. Considering the magnitude of the settage, only those present in Remanit .007" - .030", Unitek Permachrome Standard .008" - .036" and Elgiloy .0056" - .022" of about 21, 15 and 13 per cent respectively may be of any clinical significance.

D. HYSTERESIS

In this investigation, each sample spring was tested with four consecutive cycles of loading and unloading of the spring. Within each cycle, a loss of mechanical energy was evident from the area of the hysteresis loop formed by the loading and unloading curves of the spring.

Fig. 30 shows hysteresis loops formed by three consecutive loading and unloading of an Elgiloy .007" - .036" sample spring. It can be seen that the first load (13.2 grams) was accompanied by a larger than usual deflection. This was associated with a "take-up" in the ends of the spring. The first unloading load (83.2 grams) was accompanied by a delayed response in deflection, causing a slight curve at the upper end of the first unloading curve. The second

loading curve ascended almost parallel to the original loading curve between it and the first unloading curve. These were standard effects shown by all springs to varying degree.

The load-to-percentage-deflection rate (L-% D rate) of the spring shown in the second loading curve may be regarded as an average rate with the hysteresis effects removed. (Fig. 30-4).

Fig. 30-5 also shows that the second and third unloading curves of the spring practically coincided with each other. This phenomenon was also observed by Sweetser (see p. 92) in his torsion tests on mild steel. The L-% D rates of the spring shown by the second or third unloading curve become reproducible rates.

Additional examples of hysteresis loops formed by compressing sample springs solid and unloading thereof are shown in Figs. 37, 48, 55, 62, 71, 82, 101 and 102 in Appendix III.

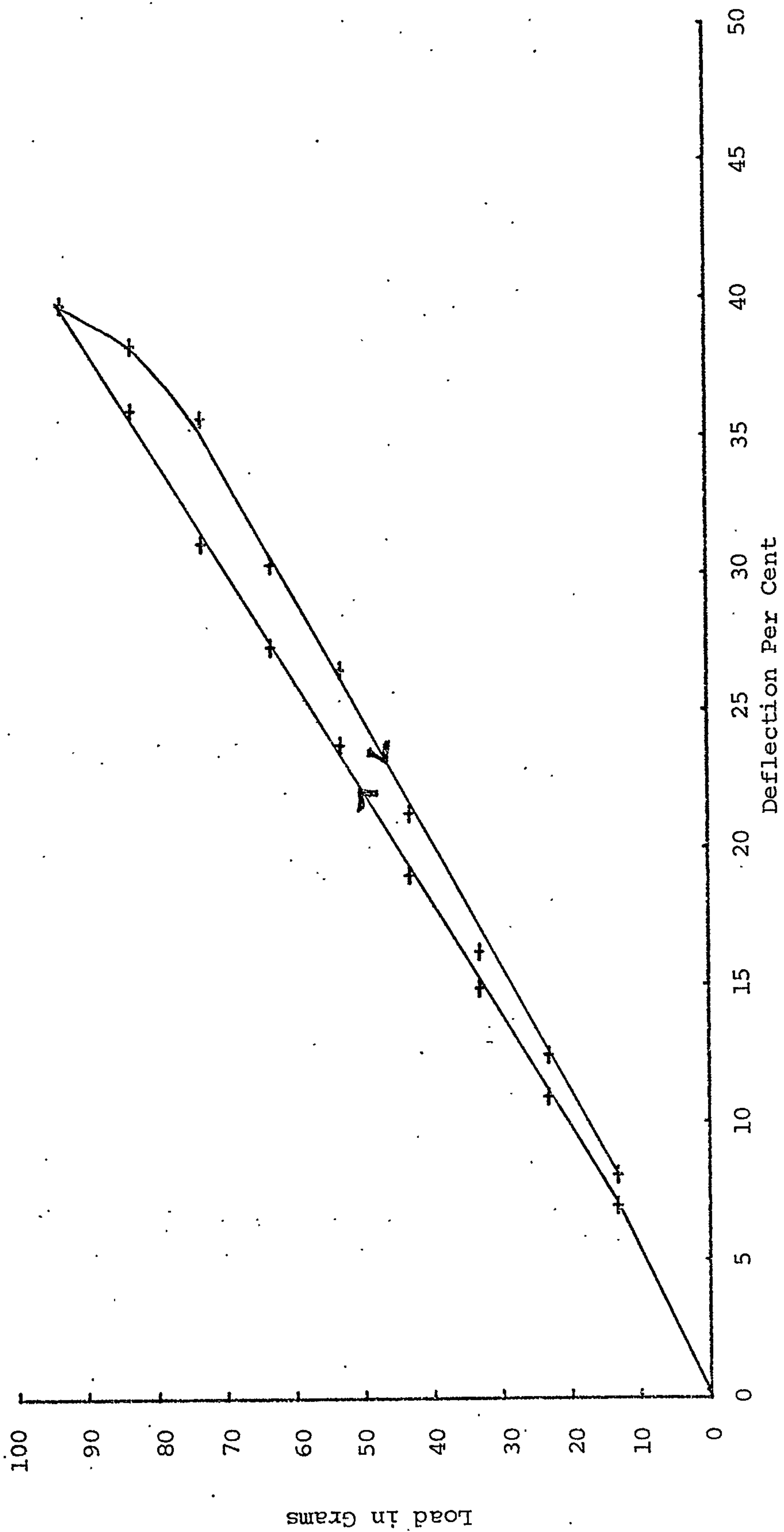


Fig. 30-1. Hysteresis Loop is seen between the first loading and unloading curves of an Elgiloy .007\" - .036\" open coil helical spring tested with 3 consecutive cycles of loading and unloading of the spring.

(Illustration continued on following page).

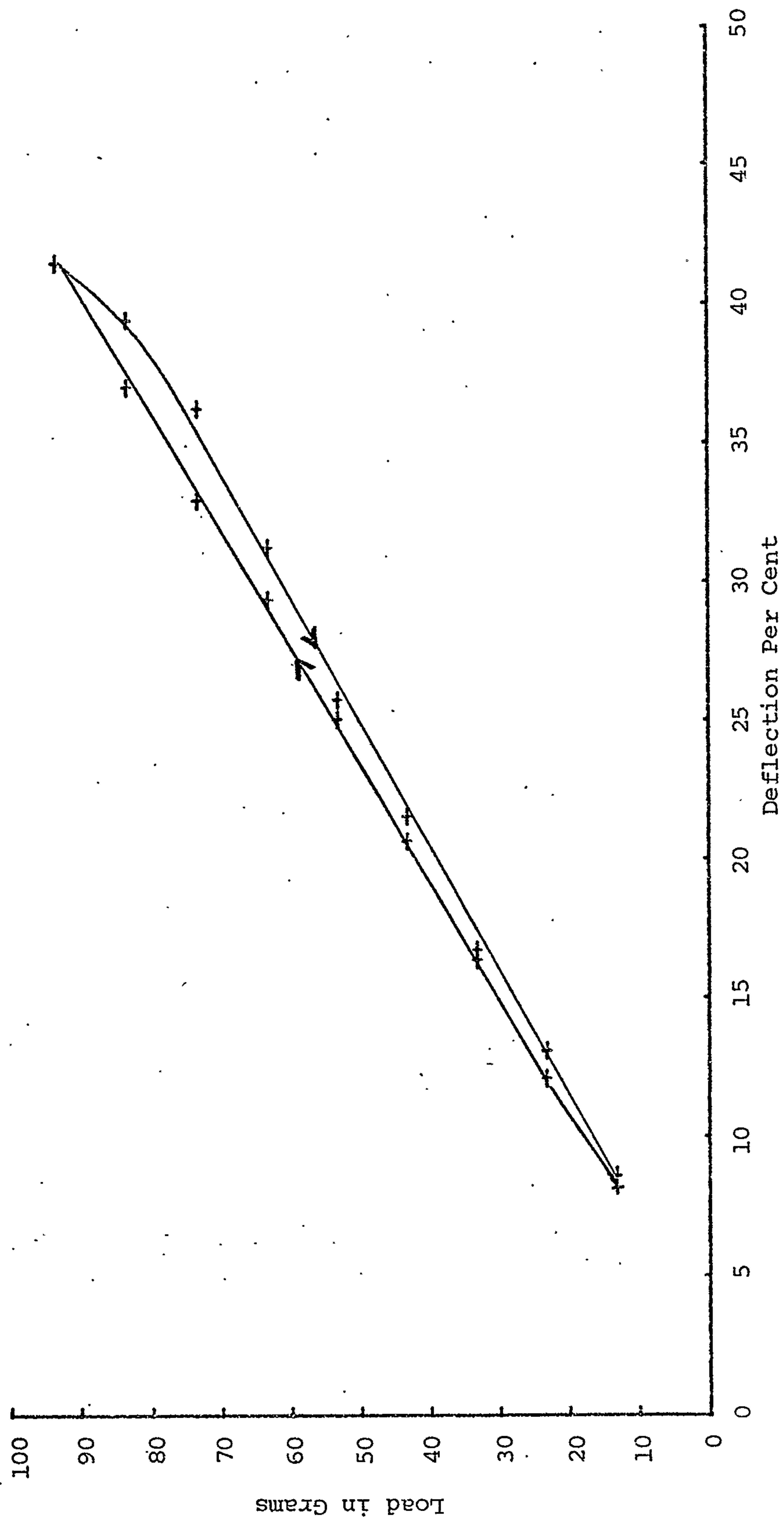


Fig. 30-2. The second loading and unloading curves of the same spring.

(Illustration continued on following page.)

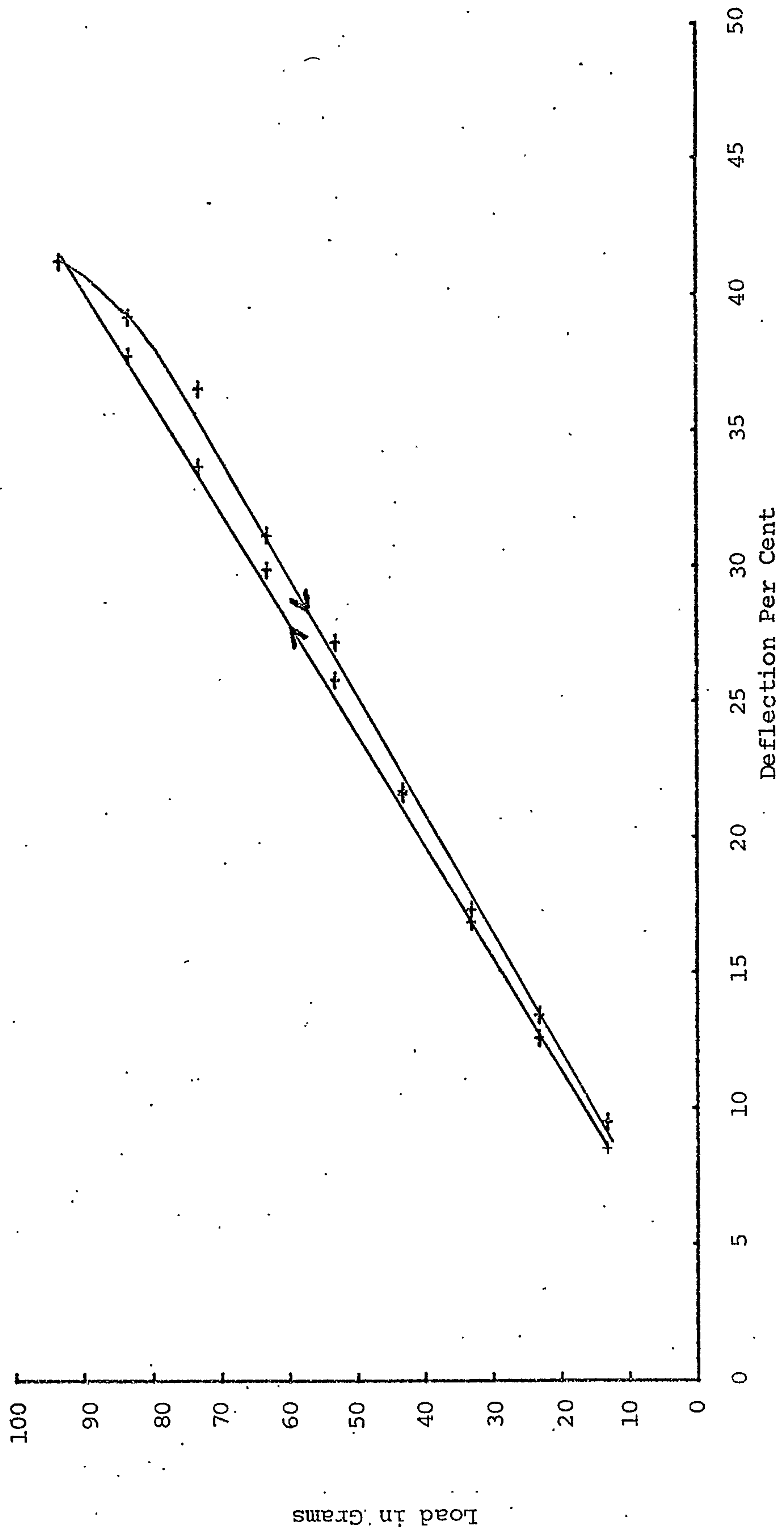


Fig. 30-3. The third loading and unloading curves of the same spring.

(Illustration continued on following page.)

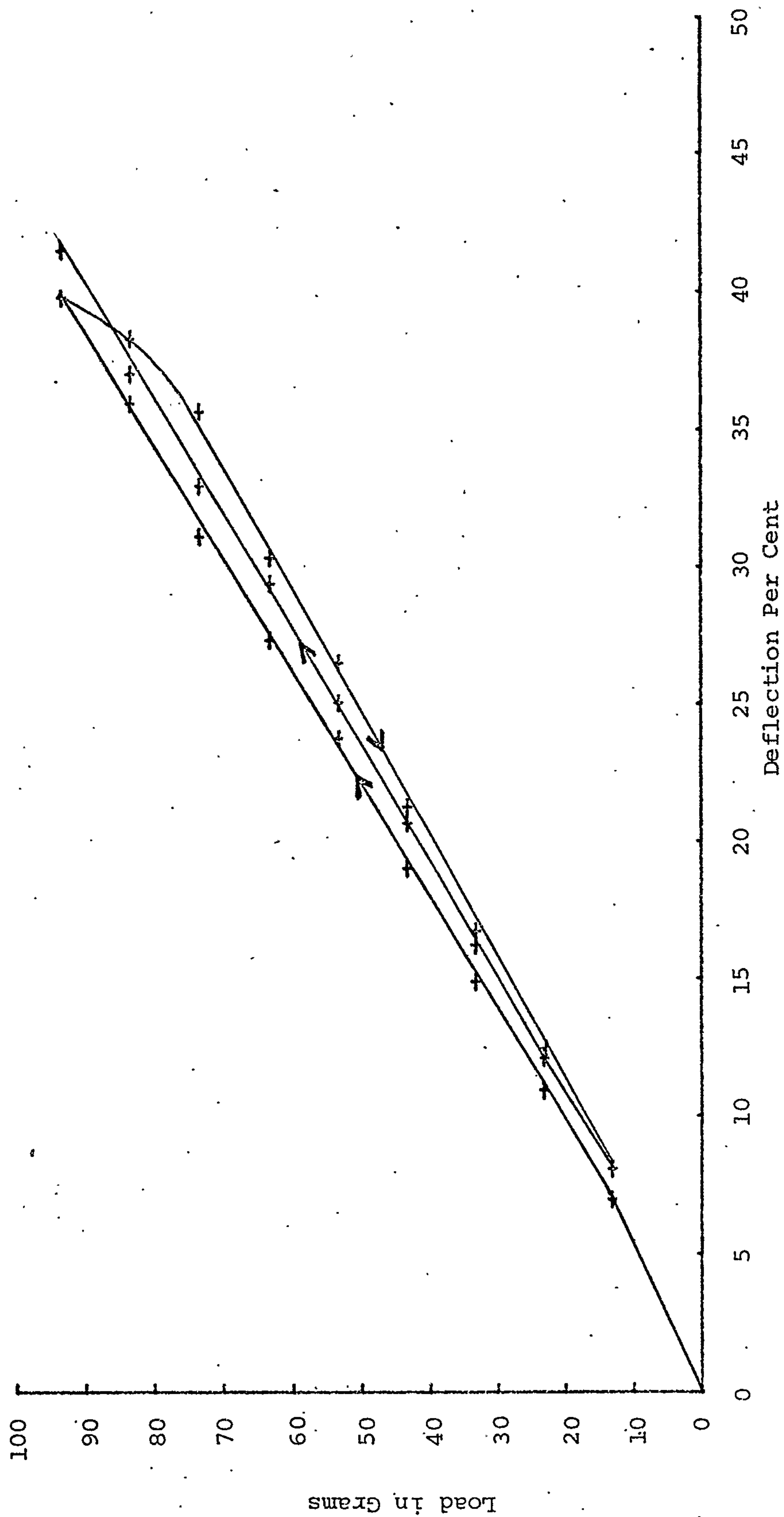


Fig. 30-4. Illustrating the second loading curve of the same spring in relation to its first loading and unloading curves.

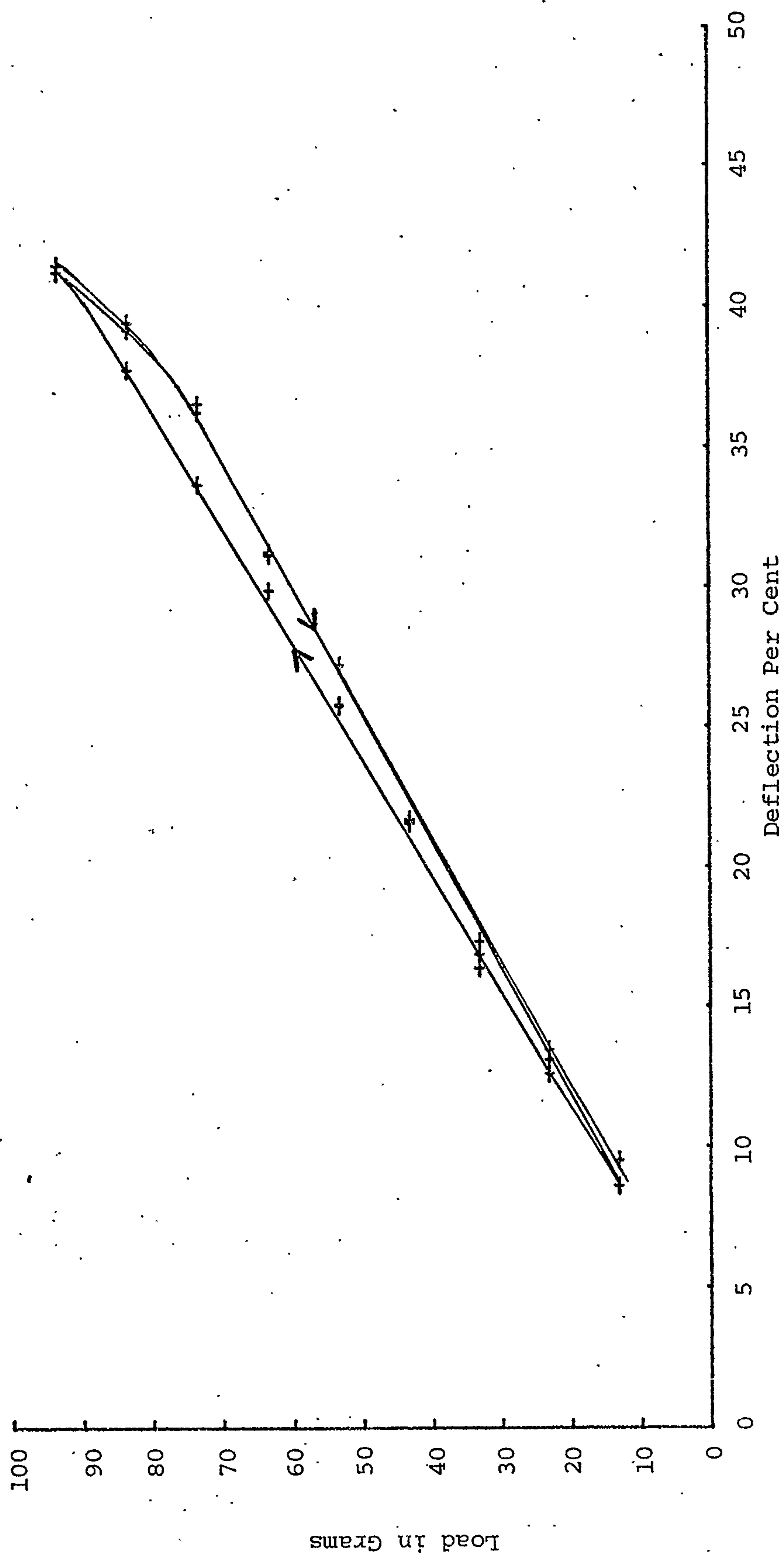


Fig. 30-5. Illustrating the third loading and unloading curves of the same spring in relation to the second unloading curve.

E. COMPARISON OF LOAD-TO-PERCENTAGE-DEFLECTION (L - %D)RATES ON UNLOADING

The load-to-percentage-deflection (L - %D) rates of the 8 types of springs on unloading from 93.2 grams in the as-received condition and after solid compression are shown in Table 17.

The L - %D rates of the 3 coils of Elgiloy .008" - .036" on unloading from 93.2 grams after solid compression are shown in Table 18.

In these tables, Column 2, "load", shows the range of load used to calculate its L - %D rate.

Column 3, "No. of Observations", shows the total pairs of load and corresponding percentage deflection data observed in the load range specified in Column 2 used to calculate its L - %D rate.

Each type of spring consisted of 4 sample springs. 5 pairs of data for each sample spring at 10 gram intervals were used. As seen in Fig. 30, the first unloading load, i.e., 83.2 grams, gave a delayed response in deflection. This reading was therefore not included in calculating the L - %D rate.

If a load, P , caused a deflection, δ , in a spring with a free length,

L, the percentage deflection of the spring at load P was calculated with the following formula:-

$$\% \text{ deflection} = \frac{\delta}{L} \times 100\%$$

Column 4, "Load/% Deflection, b", was obtained by calculating the linear regression coefficient, b, for the 20 pairs of load and corresponding percentage deflection data. This rate indicates the force output during unloading of the spring in grams per one per cent deflection of the spring.

Column 5, "Standard Error of b", shows the standard error of the L - %D rate.

Column 6, "t for b", shows the 't' value for statistical significance of regression coefficient, b.

Column 7, " $b \pm 3SE_b$ ", shows the 99.7 per cent confidence intervals of the L - %D rate of the spring.

Column 8, "Correlation Coefficient, r", shows the degree of relationship between the specified pairs of load and percentage deflection data.

Column 9, "t for r", shows the 't' value for statistical significance of "correlation coefficient".

Statistical formulae used for calculating linear regression coefficient b, standard error of b, correlation coefficient, r, and 't' tests are shown in Appendix I.

Graphic Representation of the L - %D Rates on Unloading

In order to compare visually the L - %D rates of these springs on unloading from 93.2 grams in the as-received condition and after solid compression, their regression coefficient, b, were plotted and are shown in Figs. 31 and 32 respectively.

Fig. 33 shows the spread of the L - %D rates of the 3 coils of Elgiloy .008" - .036" on unloading from 93.2 grams after the spring had been compressed solid once.

The L - %D rates below 30 grams were not graphed for comparison purposes because below this force level the load-to-percentage-deflection curves of these springs were non-linear.

TABLE 17 COMPARISON OF L-% D RATES ON UNLOADING IN AS-RECEIVED CONDITION AND AFTER SOLID COMPRESSION

As-received condition								
Column 1	2	3	4	5	6	7	8	9
Type of Spring	Load gm	No. of Observations	Load % Deflection b	Standard error of b	t for b	± 3 S.E. b	Correlation coefficient r	t for r
Unitek Hi-T .006"-.036"	73.2-33.2	20	1.55	0.068	22.94 ***	1.346-1.754	.983325	22.94 ***
Elgiloy .007"-.036"	73.2-33.2	20	1.98	0.054	36.36 ***	1.818-2.142	.993263	36.36 ***
Elgiloy .0056"-.022"	73.2-33.2	20	2.74	0.121	22.72 ***	2.377-3.103	.983006	22.72 ***
Elgiloy .007"-.030"	73.2-33.2	20	3.48	0.090	38.52 ***	3.210-3.750	.993989	38.52 ***
Elgiloy .008"-.036" (Coil B)	73.2-33.2	20	3.81	0.102	37.29 ***	3.504-4.116	.993589	37.29 ***
Remanit .007"-.030"	73.2-33.2	20	4.25	0.416	10.21 ***	3.002-5.498	.923471	10.21 ***
Unitek Permachrome Standard .008"-.036"	73.2-33.2	20	5.63	0.378	14.90 ***	4.496-6.764	.961771	14.90 ***
Unitek Hi-T .008"-.036"	73.2-33.2	20	5.51	0.365	15.09 ***	4.415-6.605	.962682	15.09 ***

Three asterisks indicate $p < 0.001$

TABLE 17 (cont'd)

After compressed solid once									
Column	1	2	3	4	5	6	7	8	9
Type of Spring		Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	b ± 3 S.E.	Correlation coefficient r	t for r
Unitek Hi-T .006"-.036"		73.2-33.2	20	1.37	0.059	23.30***	1.193-1.547	.983819	23.30***
Elgiloy .007"-.036"		73.2-33.2	20	1.91	0.033	57.48***	1.811-2.009	.997287	57.48***
Elgiloy .0056"-.022"		73.2-33.2	20	2.28	0.066	34.76***	2.082-2.478	.992631	34.75***
Elgiloy .007"-.030"		73.2-33.2	20	2.99	0.119	25.21***	2.633-3.347	.986135	25.21***
Elgiloy .008"-.036" (Coil B)		73.2-33.2	20	3.51	0.087	40.28***	3.249-3.771	.994499	40.28***
Remanit .007"-.030"		73.2-33.2	20	3.43	0.154	22.24***	2.968-3.892	.982282	22.24***
Unitek Permachrome Standard .008"-.036"		73.2-33.2	20	4.81	0.221	21.79***	4.147-5.473	.981564	21.79***
Unitek Hi-T .008"-.036"		73.2-33.2	20	5.20	0.286	18.18***	4.342-6.058	.973832	18.18***

TABLE 18 COMPARISON OF LOAD TO PERCENTAGE DEFLECTION RATES OF ELGILOY .008"-.036" ON UNLOADING
(AFTER COMPRESSED SOLID ONCE)

Column	1	2	3	4	5	6	7	8	9
Coil	Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	$\pm$ 3 S.E. b	Correlation coefficient r.	t for r	
Elgiloy .008"-.036" Coil A	73.2-33.2	20	2.71	0.110	24.53***	2.380-3.040	.985376	24.54***	
Elgiloy .008"-.036" Coil B	73.2-33.2	20	3.51	0.087	40.28***	3.249-3771	.994499	40.28***	
Elgiloy .008"-.036" Coil C	73.2-33.2	20	3.45	0.122	28.28***	3.084-3.816	.988936	28.28***	

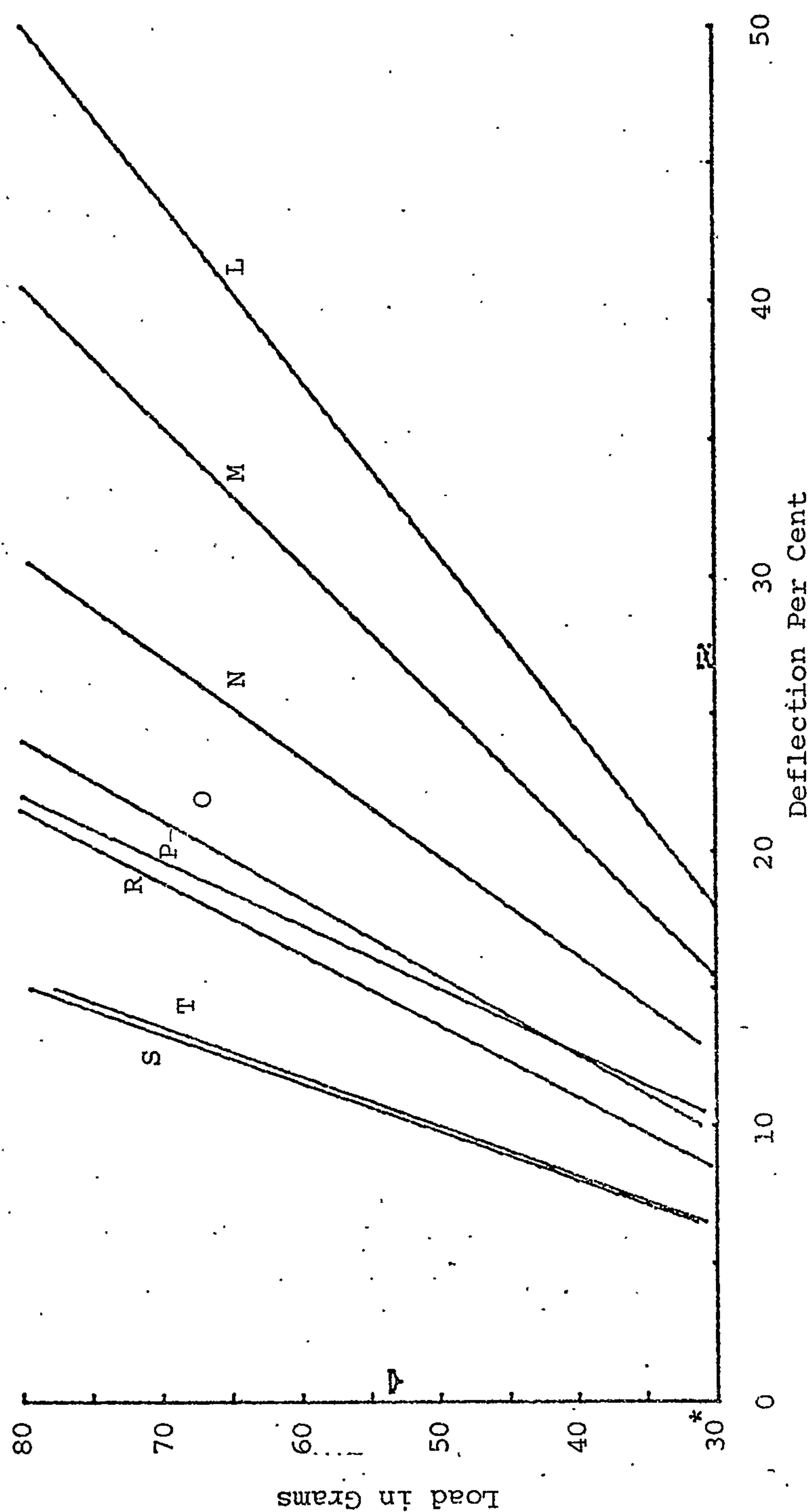


Fig. 31. Comparison of load-deflection regressions on unloading various types of open coil helical springs. (As-received condition).

L - Unitek Hi-T .006" - .036"
M - Elgiloy .007" - .036"
N - Elgiloy .0056" - .022"
O - Elgiloy .007" - .030"
P - Remanit .007" - .030"
R - Elgiloy .008" - .036"
S - Unitek PermaChrome Standard .008" - .036"
T - Unitek Hi-T .038" - .036"

* See P. 165

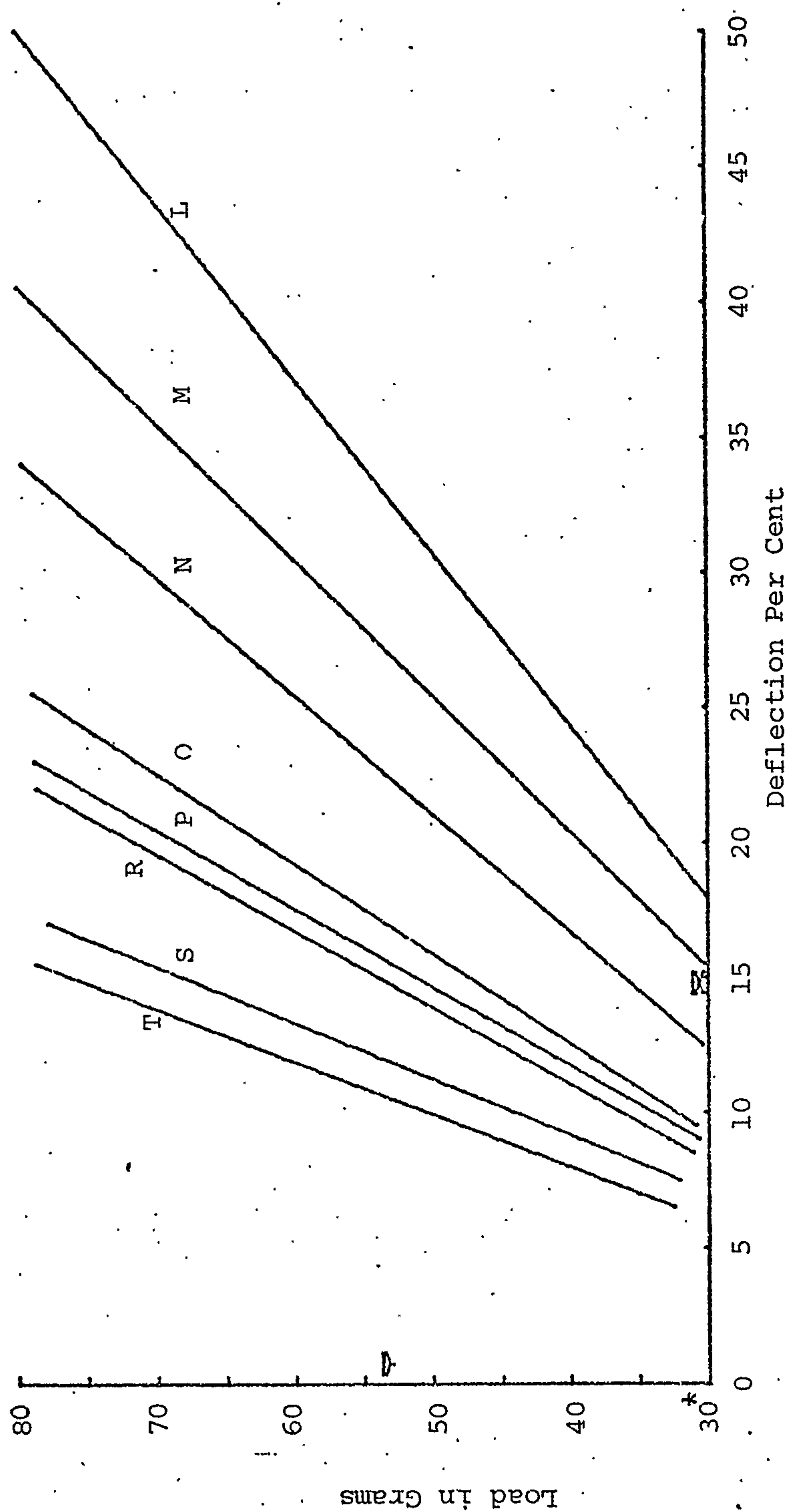


Fig. 32. Comparison of load-deflection regressions on unloading various types of open coil helical springs. (After compressed solid once.)

L - Unitek Hi-T .006" - .036"
 M - Elgiloy .007" - .036"
 N - Elgiloy .0056" - .022"
 O - Elgiloy .007" - .030"
 P - Remanit .007" - .030"
 R - Elgiloy .008" - .036"
 S - Unitek Permachrome Standard .008" - .036"
 T - Unitek Hi-T .008" - .036"

* See P. 165

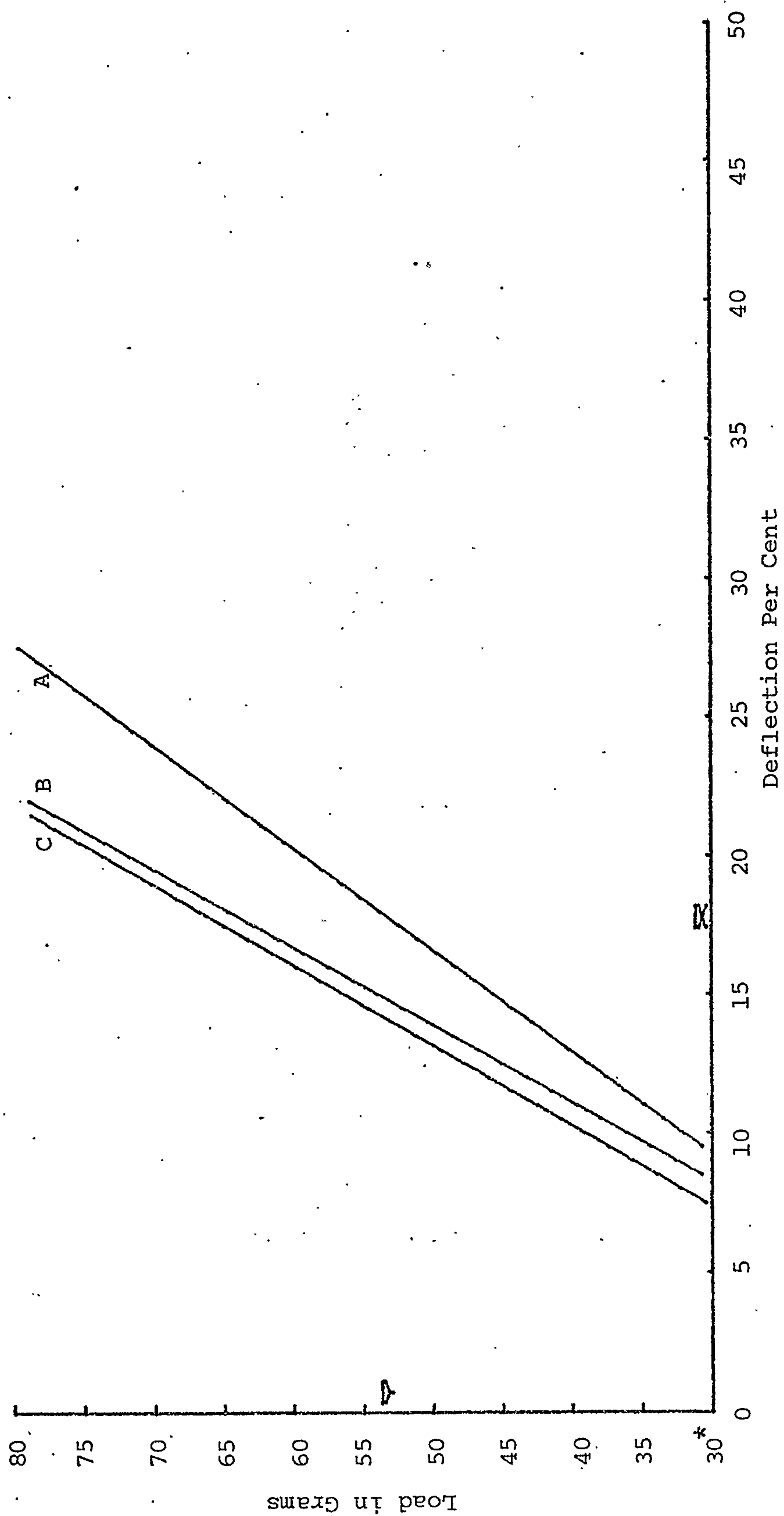


Fig. 33. Load-deflection regressions on unloading 3 coils of Elgiloy .008" - .036" open coil helical springs after they had been compressed solid once.

* See P. 165

F. LOAD TO PERCENTAGE DEFLECTION (L - %D) RATE ON LOADING

In this investigation, each sample spring was compressed solid in the second and fourth cycle of loading. The L - %D rates on loading each spring in the as-received condition and after the spring had been compressed solid once are shown in Tables 19, 20 and 21.

In these tables, Column 2, "load", shows the range of load used to calculate its L - %D rate.

Column 3, "No. of Observations", shows the total pairs of load and corresponding percentage deflection data observed in the load range specified in Column 2 used to calculate its L - %D rate.

Column 4, "Load/% Deflection, b", was obtained by calculating the linear regression coefficient, b, for the pairs of load and corresponding percentage deflection data as specified in Column 3.

For the determination of the load to deflection characteristic (spring rate) of a compression spring, S.A.E. limit specified that tests for spring rate should be carried out between 10 and 50 per cent of the total deflection. German Standard DIN 2095 (1973) mentioned that the spring rate must be tested in the range from 0.3 to 0.7 of the smallest permissible test length. (See sections

on the effect of coil pitch on the elastic range of deflection and manufacturing tolerance). In this investigation, the L - %D rate of the spring was determined by combining the two specifications and using load with corresponding percentage deflections within the 10 and 63 per cent of the total percentage deflection of the spring. This formed the basis for the load range specified in Column 2 and the number of observations specified in Column 3.

Column 5 shows the force input into the spring in grams per one per cent deflection of the spring.

Columns headed "Standard Error of b", "t for b", "Correlation Coefficient, r", and "t for r" have the same meaning as that of Table 17. Values under these headings were calculated from the data specified in Columns 2 and 3.

Graphic Representation of the L - %D Rates on Loading

Actual point to point observations of load and percentage deflection of each sample spring for the second (as-received condition) and fourth (after compressed solid once) cycle of loadings were plotted (Figs. 37 to 108 in Appendix III).

As mentioned above, the inter-relationship between load and percentage

deflection of each spring was determined by the line of best fit calculated from the load and percentage deflection data within the 10 and 63 per cent of the total percentage deflection of the spring. The standard deviation of the load from the line of best fit, $SDy.x$, was also calculated. (See Appendix II).

The line of best fit was depicted on the graph by the linear regression line. The slope of the regression line is the $L - \%D$ rate of the spring.

On each graph the name of the sample spring is shown together with its $L - \%D$ rate, b , the standard deviation of the load from the regression line $SDy.x$ and the standard error of b .

With the provision of these plots and Tables 19, 20 and 21, the reader is provided with an opportunity of studying each tested spring and to decide for himself the following:-

- (1) the linear portion of the $L - \%D$ curve of the spring;
- (2) the maximum elastic limit or apparent proportional limit of the spring when it is loaded in the as-received condition and after it has been compressed solid once;
- (3) which way he would like to use his springs.

(Text continued on page 183).

TABLE 19 LOAD TO PERCENTAGE DEFLECTION RATE ON LOADING

As-received Condition								
Column	1	2	3	4	5	6	7	8
Type of Spring	Sample	Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r	t for r
Elgiloy .007"- .036"	A 1	33.2-63.2	4	2.16	.009	250.37***	.999984	249.99***
	A 2	33.2-93.2	7	2.38	.026	92.53***	.999708	92.50***
	A 3	33.2-93.2	6	2.18	.028	78.57***	.999676	78.54***
	A 4	63.2-113.2	4	2.34	.157	14.92**	.995536	14.92**
Elgiloy .0056"- .022"	A 1	43.2-83.2	5	3.67	.066	55.77***	.999518	54.76***
	A 2	43.2-83.2	5	2.92	.038	76.40***	.999743	76.38***
	A 3	23.2-73.2	6	3.03	.087	34.96***	.998368	34.97***
	A 4	53.2-103.2	4	3.08	.107	28.71**	.998789	28.71**
Elgiloy .007"- .030"	B 1	33.2-93.2	4	3.93	.052	75.59***	.999825	75.58***
	B 2	33.2-93.2	4	3.79	.085	44.61***	.999498	44.61***
	B 3	33.2-103.2	5	3.91	.102	38.48***	.998988	38.47***
	B 4	33.2-93.2	4	3.80	.057	66.55***	.999774	66.50***
			* indicates	0.05 < p < .01				
			***	p ≤ 0.01				
			***	p < .001				

* indicates 0.05 < p < .01
 *** p < 0.01
 *** p < .001

TABLE 19 (Cont'd)

As-received Condition								
Column	1	2	3	4	5	6	7	8
Type of Spring	Sample	Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r	t for r
Remanit .007-.030"	A 1	33.2-93.2	4	5.54	0.176	31.51**	.998995	31.52**
	A 2	33.2-93.2	4	5.03	0.153	32.92***	.999078	32.91***
	A 3	33.2-93.2	4	4.93	0.037	133.21***	.999944	133.62***
	A 4	33.2-103.2	5	5.75	0.168	34.19***	.998719	34.19***
Unitek Hi-T .008"-036"	A 1	63.2-103.2	4	6.21	0.105	59.37***	.999716	59.32***
	A 2	93.2-173.2	5	6.36	0.132	48.29***	.999357	48.27***
	A 3	53.2-128.2	6	6.39	0.189	33.84***	.998258	33.84***
	A 4	33.2-98.2	5	5.73	0.127	45.22***	.999267	45.20***
Unitek Permachrome Standard .008"-036"	A 1	53.2-153.2	5	5.50	0.083	65.86***	.999654	65.82***
	A 2	93.2-153.2	4	5.36	0.052	102.42***	.999905	102.59***
	A 3	93.2-153.2	4	5.83	0.061	96.334***	.999892	96.21***
	A 4	93.2-153.2	4	5.93	0.158	37.51 ***	.999290	37.50***

TABLE 19 (Cont'd)

As-received Condition								
Column	1	2	3	4	5	6	7	8
Type of Spring	Sample	Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r	t for r
Unitek Hi-T .006"-.036"	A 1	33.2-93.2	4	2.00	0.016	124.93***	.999936	124.99***
	A 2	33.2-93.2	4	2.14	0.108	19.81**	.997461	19.81**
	A 3	33.2-93.2	4	1.92	0.043	44.38***	.999493	44.39***
	A 4	33.2-93.2	4	2.13	0.035	60.49***	.999727	60.51***

TABLE 20 LOAD TO PERCENTAGE DEFLECTION RATE ON LOADING

After Compressed Solid Once								
Column	1	2	3	4	5	6	7	8
Type of Spring	Sample	Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r	t for r
Elgiloy .0071.036"	A 1	33.2-63.2	4	2.39	.104	22.95**	.998107	22.95**
	A 2	33.2-63.2	4	2.25	.064	35.19***	.999194	35.21***
	A 3	33.2-93.2	6	2.17	.051	42.34***	.998886	42.33***
	A 4	63.2-103.2	3	2.10	.160	13.17*	.997129	13.17*
Elgiloy .0056".022"	A 1	43.2-83.2	5	2.69	.179	15.03***	.993429	15.03***
	A 2	43.2-83.2	5	3.14	.069	45.82***	.999286	45.80***
	A 3	23.2-73.2	6	2.93	.056	52.57***	.999277	52.56***
	A 4	53.2-93.2	3	2.92	.096	30.38*	.999459	30.38*
Elgiloy .007".030"	B 1	53.2-123.2	4	3.41	.043	78.67***	.999838	78.55***
	B 2	53.2-123.2	4	3.61	.099	36.31***	.999242	36.31***
	B 3	53.2-123.2	4	3.81	.019	195.55***	.999974	196.11***
	B 4	33.2-93.2	4	3.70	.085	43.40***	.999470	43.41***

TABLE 20 (cont'd)

After Compressed Solid Once							
Column	1	2	3	4	5	6	8
Type of Spring	Sample	Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r
Remanit .007"-.030"	A 1	53.2-133.2	4	4.31	0.120	35.84***	.999222
	A 2	53.2-133.2	4	3.34	0.080	41.89***	.999430
	A 3	53.2-133.2	4	3.67	0.027	137.59***	.999947
	A 4	53.2-143.2	5	3.94	0.086	45.71***	.999283
Unitek Hi-T .008"-.036"	A 1	53.2-173.2	4	6.36	0.131	48.66***	.999578
	A 2	93.2-173.2	5	6.02	0.101	59.65***	.999579
	A 3	63.2-153.2	4	6.33	0.266	23.79**	.998238
	A 4	63.2-168.2	5	5.96	0.102	58.40***	.999560
Unitek Permachrome standard .008"-.036"	A 1	53.2-153.2	5	5.52	0.168	32.84***	.998612
	A 2	93.2-153.2	4	5.64	0.075	74.89***	.999822
	A 3	93.2-173.2	4	4.74	0.055	85.51***	.999863
	A 4	93.2-153.2	4	5.28	0.338	15.62**	.995925

TABLE 20 (Cont'd)

After Compressed Solid Once								
Column	1	2	3	4	5	6	7	8
Type of Spring	Sample	Load gm	Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r	t for r
Unitek Hi-T .006"-.036"	A 1	33.2-73.2	5	2.09	0.102	20.47***	.996439	20.47***
	A 2	33.2-73.2	3	2.27	0.010	218.24**	.999990	223.60**
	A 3	33.2-73.2	3	1.86	0.058	31.87*	.999508	31.86*
	A 4	33.2-73.2	3	1.81	0.011	159.78**	.999980	158.11**

TABLE 21 LOAD TO PERCENTAGE DEFLECTION RATE ON LOADING ELGILOY .008"-.036"

As-received Condition								
Column	1	2	3	4	5	6	7	8
Coil		Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r	t for r
A 1		33.2-73.2	5	3.598	.051	70.41***	.999697	70.34***
A 2		33.2-73.2	5	4.087	.169	24.21***	.997449	24.20***
A 3		33.2-93.2	4	3.392	.374	9.06*	.988043	9.06*
A 4		33.2-93.2	4	3.705	.068	54.79***	.999667	54.78***
B 1		33.2-73.2	5	4.495	.103	43.82***	.999219	43.80***
B 2		23.2-73.2	6	4.416	.135	32.82***	.998147	32.81***
B 3		33.2-93.2	4	4.162	.084	49.76***	.999596	49.73***
B 4		33.2-93.2	4	4.371	.103	42.41***	.999444	42.39***
C 1		33.2-83.2	5	4.143	.083	49.78***	.999395	49.76***
C 2		33.2-73.2	5	4.254	.043	99.66***	.999849	99.65***
C 3		33.2-93.2	4	4.127	.084	49.34***	.999589	49.31***
C 4		33.2-93.2	4	4.644	.061	75.69***	.999825	75.58***

TABLE 21

After Compressed Solid Once.								
Column	1	2	3	4	5	6	7	8
Coil		Load gm	No. of Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r	t for r
A 1		33.2 73.2	5	3.296	.095	34.60***	.998749	34.60***
A 2		33.2-93.2	4	3.973	.096	41.43***	.999417	41.39***
A 3		53.2-123.2	4	3.662	.042	88.04***	.999871	88.03***
A 4		53.2-113.2	4	3.598	.052	69.02***	.999790	68.99***
B 1		33.2-113.2	5	4.024	.048	83.31***	.999783	83.12***
B 2		33.2- 93.2	4	4.059	.070	58.18***	.999704	58.11***
B 3		53.2-123.2	4	4.196	.078	54.00***	.999657	53.98***
B 4		53.2-123.2	4	4.119	.097	42.42***	.999444	42.39***
C 1		33.2-113.2	5	4.184	.066	62.83***	.999620	62.80***
C 2		33.2-113.2	5	4.009	.136	29.54***	.999285	29.54***
C 3		53.2-123.2	4	4.327	.126	34.37***	.999155	34.38***
C 4		53.2-123.2	4	4.703	.095	49.70***	.999595	49.67***

G. COMPARISON OF LOAD TO PERCENTAGE DEFLECTION RATES ON LOADING

A visual examination of the load versus percentage deflection curve of each of the sample springs (Figs. 37 to 108 in Appendix III) revealed that the inter-relationship between load and percentage deflection of Unitek Hi-T .006" - .036", Elgiloy .007" - .036" loaded in the as-received condition and of Elgiloy .0056" - .022", Elgiloy .007" - .036", Remanit .007" - .030", Unitek Hi-T .008" - .036", Unitek Permachrome Standard .008" - .036" and 3 coils of Elgiloy .008" - .036" loaded after they had been compressed solid once, was more consistent over a longer range of the total percentage deflection of the spring. For each type of spring, the L - %D rate under these conditions is summarized in Table 22.

Column 2 of this table headed "Load Range" shows the range of load selected from the individual L - %D curves (Figs. 37 to 108) for the calculation of its L - %D rate.

Column 3 headed "No. of Observations" shows the total pairs of load and corresponding percentage deflection data from the 4 sample springs, observed in the load range specified in Column 2, used to calculate its L - %D rate.

Column 4, "Load/% Deflection", shows the L - %D rate of the spring

TABLE 22

COMPARISON OF LOAD TO PERCENTAGE DEFLECTION RATES ON LOADING

Column	1	2	3	4	5	6	7	8	9	10
Type of Spring	Load range gm	No of Observations	Load % deflection b	Standard error of b	t for b	Correlation coefficient r	t for r	Condition of loading		
Unitek Hi-T .006"- .036"	33.2-93.2	16	2	0.077	25.90***	1.77-2.23	.989724	25.90***	As received	
Elgiloy .007"- .036"	33.2-113.2	16	2.31	.044	52.16***	2.18-2.44	.997437	52.16***	As-received	
Elgiloy .0056"- .022"	33.2-103.2	16	2.84	.052	54.94***	2.68-2.996	.997689	54.94***	184	
Elgiloy .007"- .030"	53.2-143.2	16	3.63	.059	61.78***	3.45-3.81	.998171	61.78***	1	
Elgiloy .008"- .036"	33.2-135.2	16	4.07	.052	78.35***	3.91-4.23	.998862	78.36***		
Remanit .007"- .030"	53.2-143.2	16	3.58	0.242	14.77***	2.85-4.31	.969362	14.77***	After compressed	
Unitek Hi-T .008"- .036"	53.2-173.2	16	5.95	0.235	25.36***	5.25-6.66	.989292	25.36***	solid once	
Unitek Permachrome Standard .008"- .036"	53.2-153.2	16	5.13	0.185	27.82***	4.58-5.69	.991076	27.82***		

TABLE 22 (cont'd)

Type of Spring	Load range gm	No of Observations	Load % deflection	Standard error of b	t for b	b $\pm$ 3 S.E.	Correlation coefficient r	t for r	Condition of loading
Elgiloy .008"-.036" Coil A	33.2-123.2	17	3.35	0.216	15.49***	2.702-3.998	.970126	15.49***	After compressed
Elgiloy .008"-.036" Coil B	33.2-123.2	17	4.09	0.059	68.93***	3.913-4.267	.998425	68.93***	solid once
Elgiloy .008"-.036" Coil C	33.2-123.2	17	4.43	0.168	26.32***	3.926-4.934	.989349	26.32***	

Three asterisks indicate $p < 0.001$

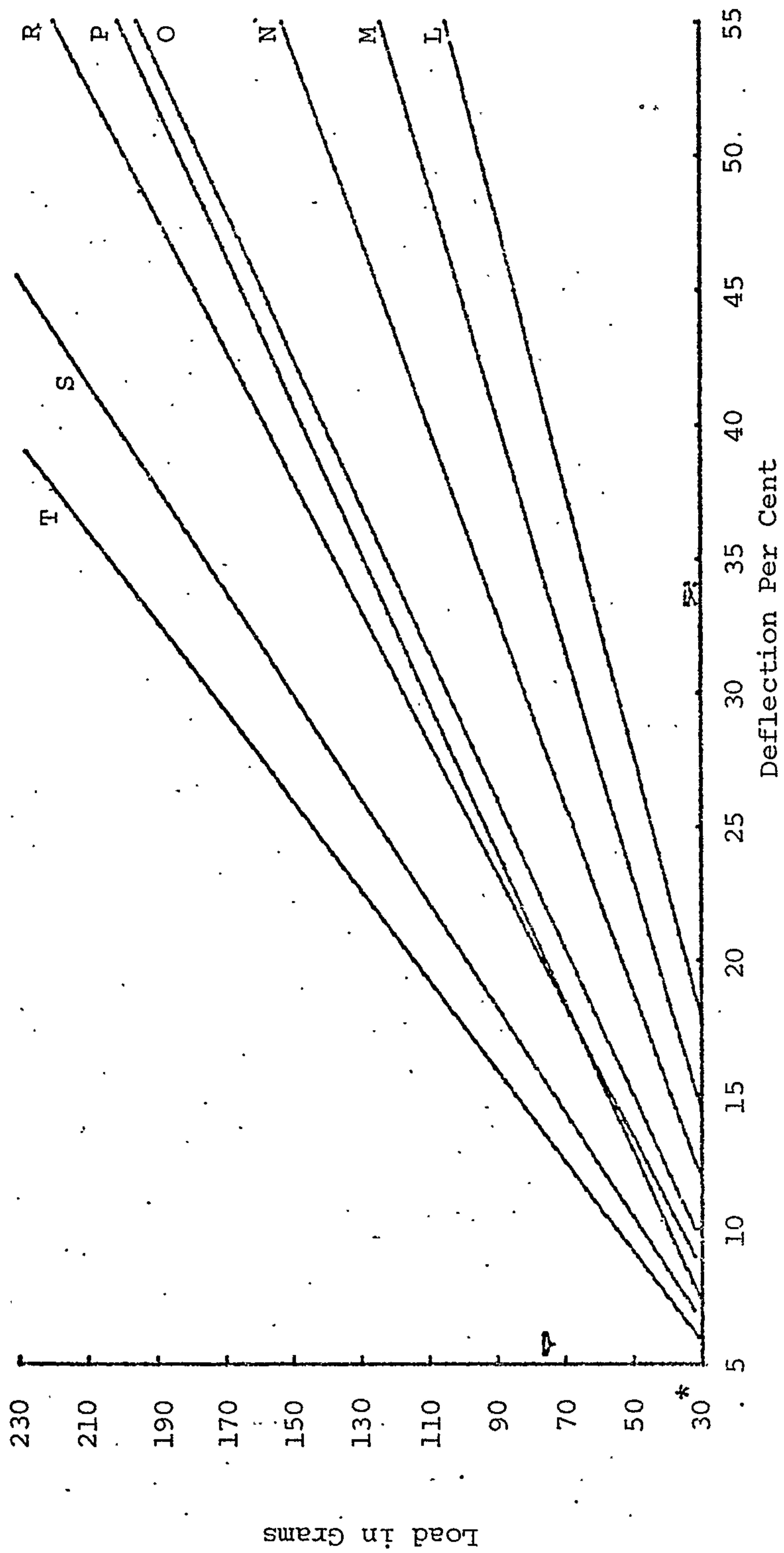


Fig. 34. Comparison of load-deflection regressions on loading various types of open coil helical springs.

L - Unitek Hi-T .006" - .036"

M - Elgiloy .007" - .036"

N - Elgiloy .0056" - .022"

O - Elgiloy .007" - .030"

P - Remanit .007" - .030"

R - Elgiloy .008" - .036"

S - Unitek Permchrome Standard .008" - .036"

T - Unitek Hi-T .008" - .036"

* See P. 165.

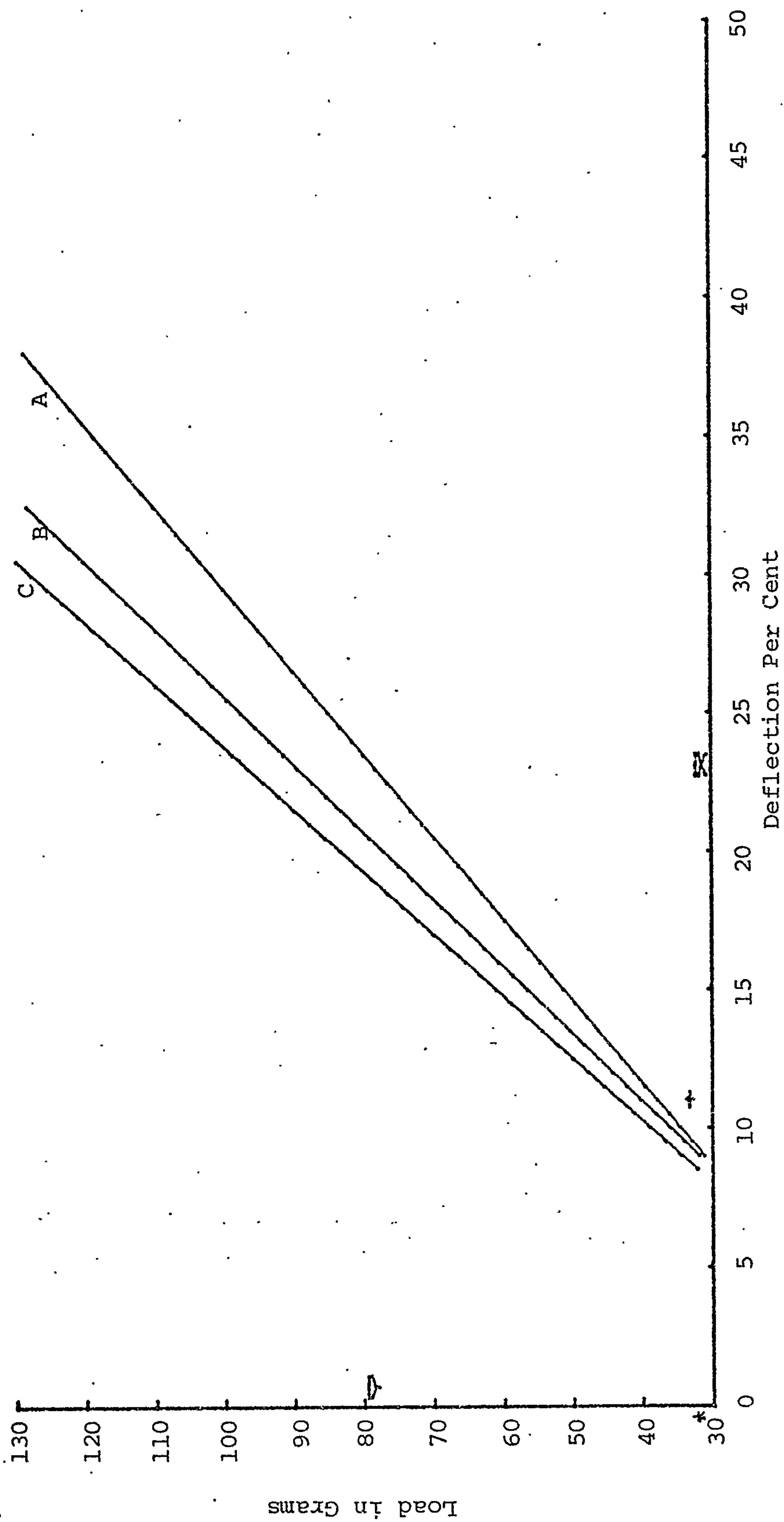


Fig. 35. Load-deflection regressions on loading 3 coils of Elgiloy .008" - .036" open coil helical springs after they had been compressed solid once.

* See P. 165

obtained by calculating the regression coefficient, b , of the line of best fit for the data specified in Columns 2 and 3.

Columns headed "Standard Error of b ", " t for b ", " $b \pm 3SEb$ ", "Correlation Coefficient, r ", and " t for r " have the same meaning as that of Table 17. Values under these headings were calculated from the data specified in Columns 2 and 3.

For visual comparison of their $L - \%D$ rates, their line of best fit were plotted and are shown in Figs. 34 and 35.

Discussion

Load to Percentage Deflections Rates on Loading and Unloading

The results shown in Tables 19, 20 and 21 indicate that the inter-relationship between load and percentage deflection of the spring within 10 and 63 per cent of its total deflection is linear.

The regression coefficient calculated from the combined load and percentage deflection data of the 4 sample springs, being representative of each type of spring, also exhibits a linear $L - \%D$ rate. The ' t ' value for the $L - \%D$ rates on loading or unloading each type of spring was above the 0.1 per cent level (Tables 17 and 22).

The correlation coefficients for the load and percentage deflection of these springs on unloading from 93.2 grams in the as-received condition varied from 0.923 to 0.993 and after solid compression from 0.973 to 0.997 (Table 17). On loading these springs the correlation coefficient for load and percentage deflection also varied from 0.969 to 0.998. (Table 22).

From these correlation coefficients it would appear that despite buckling, load and percentage deflection of the spring approach a perfect positive relationship.

The L - %D rates on unloading the springs after they had been compressed solid once are lower than that in their as-received condition (Table 17).

The L - %D rates on loading and unloading these springs can be compared by using the 99.7 per cent confidence intervals of the rates given in Column 7 of Tables 17 , 18 and 22.

The L - %D rates on unloading after solid compression of Unitek Hi-T .006" - .036", Elgiloy .007" - .036", Elgiloy .0056" - .022" and Elgiloy .007" - .030" are different from each other. Sections from Remanit .007" - .030", Elgiloy .007" - .030" and Elgiloy .008" - .036" may have similar rates. Unitek Hi-T and Permachrome

Standard .008" - .036" may also have similar rates but are different from that of Elgiloy .008" - .036" (Table 17).

Graphic comparison of the mean rates of these springs is shown in Fig. 32.

Of the three coils of Elgiloy .008" - .036", Coil B and C have similar L - %D rates which are different from Coil A (Table 18 and Fig. 33).

A comparison of the L - %D rates on loading these springs (Table 22) indicates that:-

- (a) Sections from Unitek Hi-T .006" - .036" and Elgiloy .007" - .036" may have similar rates.
- (b) Elgiloy .007" - .036", Elgiloy .0056" - .022", Elgiloy .007" - .030" and Elgiloy .008" - .036" have different rates.
- (c) Sections from Remanit .007" - .030" may have L - %D rate similar to Elgiloy .0056" - .022", Elgiloy .007" - .030" and Elgiloy .008" - .036".

- (d) For Unitek Hi-T and Permachrome Standard .008" - .036", their rates may be similar but are different from that of Elgiloy .008" - .036".

Graphic comparison of the mean rates of these springs is shown in Fig. 34.

Thus the L - %D rate either on loading or unloading the spring may be used for comparison purposes. Table 23 summarised the L - %D rates shown in Table 17 and 22.

The progressive increase in their mean L - %D rates follows generally the same order as that derived theoretically, (see P. 38) from a consideration of the wire and core diameters of the springs.

Although springs from different manufacturers have the same nominal wire and core diameters, the actual number of coils present in the 2 cm test length of the springs differs considerably. Such difference could have caused the observed difference between the theoretical and experimental results.

In order to reduce the difference observed in the number of coils (turns) present in the 2 cm test length and to compare them on a more valid ground, the new L - %D rates on loading these springs

TABLE 23

Summary of Load to Percentage Deflection Rates (gm %)

Type of Spring	As-received Condition		After Compressed Solid Once	
	Unloading	Loading	Unloading	Loading
Unitek Hi-T .006"-.036"	1.55	2	1.37	
Elgiloy .007"-.036"	1.98	2.31	1.91	
Elgiloy .0056"-.022"	2.74		2.28	2.84
Elgiloy .007"-.030"	3.48		2.99	3.63
Remanit. .007"-.030"	4.25		3.43	3.58
Elgiloy .008"-.036"	3.81		3.51	4.07
Unitek Hi-T .008"-.036"	5.63		5.20	5.95
Unitek Permachrome Standard .008"-.036"	5.51		4.81	5.13

if they had the same number of turns were calculated. The method used for this conversion is shown in the Appendix II.

The results of this conversion is shown in Table 24 . The observed L - %D rate per turn of the spring under such hypothetical condition conforms more closely to the theoretically predicted results. Quantitatively, the values found in this investigation is higher than that of the predicted.

This analysis indicates that the L - %D rates of Remanit and Unitek springs could be improved if their manufacturers had wound their springs more closely.

It also indicates that the L - %D rates of orthodontic helical compression springs can be predicted quantitatively. Formulae used for such prediction were discussed in Chapter 2.

TABLE 24

Comparison of Theoretical and Observed Load to Percentage Deflection Rate Per Turn of The Spring Using .007"-.036" As a Base Line for Comparison.

Type of Spring	Theoretical load to deflection rate per turn of spring	Theoretical load to deflection rate per turn after adjustment for higher modulus of rigidity of Elgiloy	Observed load to percentage deflection per turn of spring
Unitek Hi-T wire .006"-.036"	.583	.547	.63
Elgiloy .007"-.036"	1	1	1
Elgiloy .0056"-.022"	1.531	1.531	1.547
Remanit .007"-.030"	1.557	1.479	1.664
Elgiloy .007"-.030"	1.557	1.557	1.901
Unitek Permachrome Wire .008"-.036"	1.583	1.485	1.835
Unitek Hi-T wire .008"-.036"	1.583	1.485	1.933
Elgiloy .008"-.036"	1.583	1.583	1.995

TABLE 25

ABSOLUTE AND RELATIVE VARIABILITY OF LOAD TO PERCENTAGE DEPLETION RATES

Type of Spring	As-received Condition			After Compressed Solid Once			t test for difference between b_1 and b_2
	Mean load % deflection b_1	S.D. of b_1	Coefficient of Variation	Mean load % deflection b_2	S.D. of b_2	Coefficient of Variation	
Unitek Hi-T .006"- .036"	2.05	.106	5.17	2.01	.213	10.6	.336
Elgiloy .007"- .036"	2.27	.111	4.89	2.23	.124	5.56	.449
Elgiloy .0056"- .022"	3.18	.337	10.6	2.92	.184	6.3	1.33
Elgiloy .007"- .030"	3.86	.073	1.89	3.63	.169	4.66	2.442
Remanit .007"- .030"	5.31	.396	7.46	3.82	.411	10.76	5.25**
Elgiloy .008"- .036" coil A	3.7	.293	7.92	3.63	.275	7.58	.325
Elgiloy .008"- .036" coil B	4.36	.145	3.33	4.1	.078	1.9	3.183*
Elgiloy .008"- .036" coil C	4.29	.24	5.59	4.31	.294	6.82	- .079
Unitek Permachrome Standard .008"- .036"	5.66	.269	4.75	5.3	.399	7.53	1.496
Unitek Hi-T .008"- .036"	6.17	.305	4.94	6.17	.207	3.35	.027

** significant at $p < .005$ * significant at $.01 < p < .05$

H. VARIABILITIES OF LOAD TO PERCENTAGE DEFLECTION RATES

Table 25 contains the L - %D rates on loading each type of spring in the as-received condition and after solid compression. These were the average rate of the 4 sample springs from one coil of each type of spring.

When an orthodontic helical compression spring is used to deliver a force, the clinician is only interested in the unloading rate of the spring. However, the rate of unloading depends on the level of maximum stress in the spring at the time of unloading and on the loss of mechanical energy in a loading and unloading cycle. (Sayre 1931, Carson 1933, Timoshenko 1968). By comparing the L - %D rate of the loading curve, both of the above-mentioned variables would be avoided. When there is minimum loss in mechanical energy, the unloading curve would be the same as the loading curve. With loss in mechanical energy, the L - %D rate on unloading would be smaller than that of the loading curve (see Chapter 5 and P. 156).

Absolute variability and relative variability of the L - %D rates on loading each type of spring are shown in Table 25 under the columns headed "S.D. of b" and "Coefficient of Variation" respectively. Statistical formulae used to calculate standard deviation, S.D., and

coefficient of variation are presented in Appendix I.

Discussion

Relative variability of the $L - \%D$ rate within the same coil varies from 2 to 10 per cent. This rate scatters around the specification (± 5 per cent) of the S.A.E. tolerance limit for the deflection characteristic of coil springs with outside diameters up to 0.0625 inch. (See section on tolerance limit). According to Wahl (1949) and Berry (1961) such variability is within the expected values for the load-deflection characteristics of commercial helical compression springs.

With the exception of Remanit .007" - .030" and Elgiloy .008" - .036" (Coil B only), the observed difference between the $L - \%D$ rates of the springs in the as-received condition and after solid compression is not statistically significant.

The $L - \%D$ rates of Remanit .007" - .030" and Elgiloy .008" - .036" (Coil B only) are significantly lowered by compressing the springs solid. For Remanit .007" - .030", with solid compression, this rate is reduced by approximately 28 per cent.

I. BETWEEN COIL AND WITHIN COIL VARIATIONS OF LOAD TO
PERCENTAGE DEFLECTION RATE

In the discussion of the observed wire and core diameters of the tested springs (P. 147), it was shown that among the springs, the deflection characteristics of the 3 coils of Elgiloy .008" - .036" were expected to exhibit the greatest between-coil variations.

The L - %D rates of the 4 sample springs from each of the 3 coils of Elgiloy .008" - .036" had been determined experimentally. The results were analysed for (a) between-coil and within-coil variations of the L - %D rates on loading these springs and (b) the variations of these rates between loading (activating) the spring in the as-received condition and after solid compression.

The method used was that described by Snedecor (1959) using an analysis of variance of the observed L - %D rates.

Table 26 shows the completed analysis of variance of the L - %D rates of the springs loaded in the as-received condition and after solid compression.

The variance ratio, F, is 0.4754. Thus the 2 types of activation (compressing the spring in the as-received condition and after solid compression) do not significantly affect the L - %D rates

TABLE 26

Analysis of Variance of the Load to Percentage Deflection Rates with Two Types of Activation (activated in the as-received condition and after solid compression).

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares
Total	23	3.078	
Activations	1	.0651	.0651
Individuals	22	3.0129	.13695

$$F = .4754$$

of Elgiloy .008" - .036" open coil helical springs.

Table 27 shows the completed analysis of the components of variance. Each component in the sub-sample was included among those in the sample above it. The parameters estimated from the samples tested were calculated as indicated.

The variance ratio, F , for statistical significance of the between-coil variations of the $L - \%D$ rate is 11.048. It is beyond the 1 per cent point.

The variance ratio, F , for the within-coil variations of the $L - \%D$ rate is 2.9498. It is beyond the 5 per cent point.

Evidently for the 3 coils of Elgiloy .008" - .036", their $L - \%D$ rates vary both from sample springs to sample springs taken from different sections of the same coil and from one coil to another.

From the component analysis of the mean square of the coil, mean $L - \%D$ rate, it is clear that the coil to coil variations of the $L - \%D$ rate are far greater than that among the same coil or between the rates in the as-received condition and after solid compression of the spring.

TABLE 27

Completed Analysis of the Components of Variance of Load
to Percentage Deflection Rates

Source of Variation	Degree of Freedom	Mean Square	Parameters Estimated
Coils	2	.966325	$\sigma^2 + n\sigma_B^2 + bn\sigma_A^2$
Sections	9	.087466	$\sigma^2 + n\sigma_B^2$
Determinations	12	.029651	σ^2

$$n = 2 \quad b = 4 \quad a = 3 \quad S^2 = .029651 \text{ estimates } \sigma^2$$

$$S_B^2 = \frac{(.087466 - .029651)}{2} = .0289 \text{ estimates } \sigma_B^2$$

$$S_A^2 = \frac{(.966325 - .087466)}{8} = .1099 \text{ estimates } \sigma_A^2$$

Where a refers to coil, b to sections from which the sample
springs were taken.

σ_A = Coil component of variance

σ_B = section component of variance

σ = determination component of variance

n = 2 determinations (as-received after solid compression).

Thus more information on the $L - \%D$ rates may be obtained by decreasing the number of time consuming determinations per section of the same coil, because they have a small component, and increasing the number of coils. Fewer determinations of the rate on each of more coils of Elgiloy .008" - .036" would increase precision.

This analysis of variance of the $L - \%D$ rates of the 3 coils of Elgiloy .008" - .036" confirms the conclusion derived from a theoretical analysis of the observed wire and coil diameters of the springs that they were expected to show a greater between-coil variation in the deflection characteristic of the spring. It also suggests that such theoretical analysis may be used to plan future experimental design.

J. APPARENT PROPORTIONAL LIMIT OF THE SPRING

The method that I used to determine the apparent proportional limit (A.P.L.) of the spring was to draw a line parallel to the graphed linear regression line at either +3 or -3 standard deviation of the load, $SDy.x$, from the regression line. This line cuts the load vs. percentage deflection curve at a fairly definite point. The load and percentage deflection at this point were taken to be the load and percentage deflection of the spring at its A.P.L.

TABLE 28 Values obtained for Load and Percentage Deflection at the Apparent Proportional limit (A.P.L.) and Percentage Deflection at Solid Length of the Spring

Type of Spring	Condition of loading	Mean load at A.P.L. gm	S. D.	Mean Percentage deflection at A.P.L.	S. D.	Mean Percentage deflection at solid length	S. D.	Max. activation length as % of available space.
Unitek .006"-.036" Hi-T	As-received	114.5	10.599	57.85	4.895	74.45	0.238	137.25
Elgiloy .007"-.0036"	As-received	117.15	15.915	51.2	5.536	58.73	1.35	104.92
Elgiloy .0056"-.022"		139.15	26.931	49.25	8.061	56.1	4.647	97.04
Elgiloy .007"-.030"	After compressed	158.33	12.248	43.97	2.965	51.88	.714	78.48
Remanit .007"-.030"	solid once	179.75	22.867	47.48	6.168	54.83	1.696	90.4
Unitek .008"-.036" Hi-T		320.25	33.53	52.43	4.006	64.5	.727	110.22
Unitek .008"-.036" Permachrome Standard		226.25	53.483	44.07	8.112	61.73	.574	78.79
Elgiloy .008"-.036" Coil A		136.75	6.076	39.3	3.477	46.85	.666	64.74
Coil B		175.5	4.123	43.5	.668	45.55	.311	76.99
Coil C		167.75	26.361	39.26	5.429	44.83	.31	64.64

After examining the graphs (Figs. 37 to 108 in Appendix III), it became apparent that the inter-relationship of load and percentage deflection of Unitek Hi-T .006" - .036" and Elgiloy .007" - .036" loaded in the as-received condition were more consistent over a longer range of percentage deflection of the spring. For Elgiloy .0056" - .022", Elgiloy .007" - .030", Remanit .007" - .030", Unitek Hi-T .008" - .036", Unitek Perma-chrome Standard .008" - .036" and the 3 coils of Elgiloy .008" - .036", the observed inter-relationship between load and percentage deflection were more consistent when they were loaded after solid compression.

For each spring the A.P.L. was determined for the condition where it showed a better performance.

Results from the 4 sample springs of each coil were averaged. The mean load and percentage deflection at the A.P.L. and the mean percentage deflection at solid compression together with their standard deviations are shown in Table 28.

Discussion

It is not possible to discuss the strength of the different spring materials as the apparent proportional limits of these springs do not reflect the true strength of the material. Instead it gives an

indication of the elastic deformation range of the spring with a linear $L - \%D$ rate.

For "Elgiloy" springs, the mean load at APL increases in a stepwise manner from 117 grams for Elgiloy .007" - .036" to 139 grams for Elgiloy .0056" - .022", 158 grams for Elgiloy .007" - .030" and 170 grams for Elgiloy .008" - .036". For the three coils of Elgiloy .008" - .036", the mean loads at their apparent proportional limits vary by 30 to 40 grams.

Both Elgiloy .007" - .030" and Remanit .007" - .030" have a similar load at the APL.

Unitek Hi-T .008" - .036" has a much higher load at its APL when compared with Elgiloy .008" - .036" with Unitek Permachrome Standard .008" - .036" in between.

These findings agree with Johnson (1941) and Born (1955) that a spring with the same core size but of a smaller diameter wire exerts less force.

The mean percentage deflection at the APL of these springs varies from 40 to 57 per cent of the total length of the spring.

K. CLINICAL APPLICATION OF THE APPARENT PROPORTIONAL LIMIT

Once the percentage deflection of the spring at its APL is known, provided that the space available for the spring is also known, the maximum free length of the spring when compressed into the available space exerting a force equal to the force at its APL can be easily determined.

Consider the following example:-

A spring L units long has a percentage deflection of X per cent at its APL. (Fig. 36)

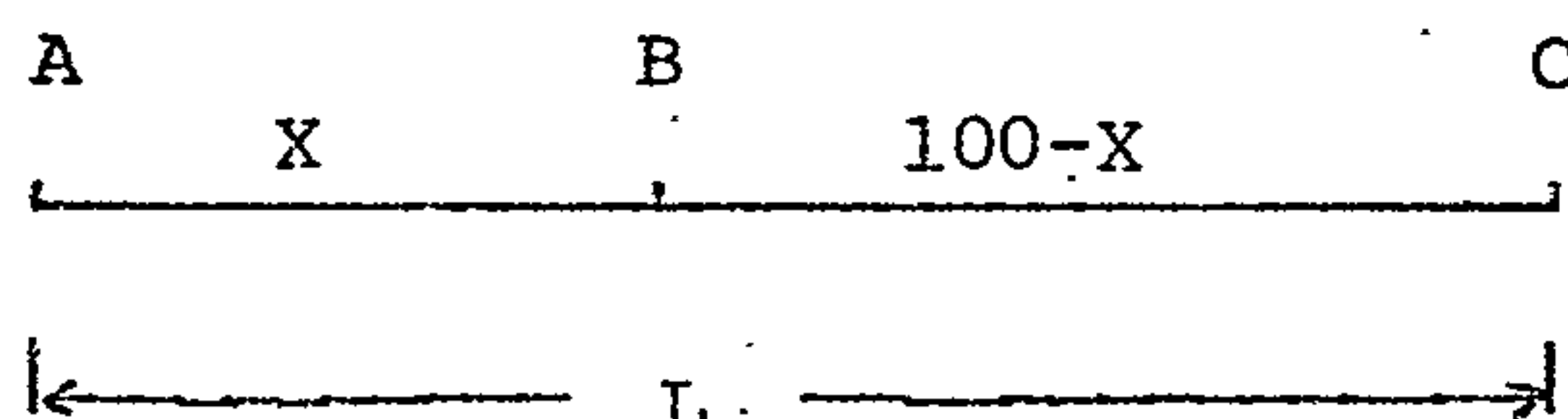


Fig. 36. Spring of length L compressed into a known available space, BC .

When the spring is compressed from AC to BC , it would have reached its APL and exerted a force equal to the force at its APL.

This example illustrates that the maximum free length of the spring, L, may be considered to have 2 component sections. It has a basic section, BC, which is as long as the available space. It has a second section, AB, which when compressed into the available space would activate the spring to its APL. This section is referred to as the "maximum activation length". The clinician is likely to be interested in knowing what is the length of this maximum activation length of the spring.

As the distance from B to C is known, the distance from A to B can be expressed as a percentage of the available space. Thus,

$$AB = \left(\frac{X}{100 - X} \right) \times 100\% \text{ of the available space}$$

In order to calculate AB, the only data required is the percentage deflection of the spring at its APL.

The "maximum activation length" required to activate the spring to its APL for any available space, expressed as a percentage of this space has been calculated for the 8 types of springs investigated. The results are shown under the column headed "Max. Activation Length as % of Available Space" in Table 28.

Knowing the "maximum activation length", the factor of safety suggested by Wahl (1949) and Burstone (1975) is the difference in length of the spring between the actual length used and this "maximum activation length". The factor of safety in the spring can therefore be assessed quite easily.

It is interesting to note that the "maximum activation length" of the spring can be of such a large percentage of the available space for the spring. Knowing the "maximum activation length" of the spring and the force it exerts, the actual force applied in any situation varies in direct proportion to the ratio of actual length used: "maximum activation length". With the correct choice, a spring may be activated to a large deflection and yet it will exert a force within the biological force limit for effective tooth movement.

SUMMARY AND CONCLUSIONS

Numerous designs of preformed orthodontic helical compression springs as available in the market create a need for selection. From theoretical considerations of the dimensions of these springs, five designs showing lowermost load to deflection rates were selected for further experimental evaluation. These springs were selected from 3 manufacturers and made of three types of stainless steel wires and a cobalt-chromium alloy wire. The designs varied in wire size (.0056in., .006 in., .007 in., and .008 in.) and internal coil diameter (.022 in., .030 in. and .036 in.)

The springs were tested in compression on a 0.016" wire acting as a mandrel.

From the tests values were obtained for:-

- (a) wire diameter, outside coil diameter and number of coils per two centimeter length of the spring;
- (b) the load-to-percentage-deflection rates on loading and unloading the spring in the as-received condition and after solid compression;
- (c) the load and percentage deflection at the apparent proportional limit of the spring in the as-received condition and after solid compression.

- (d) the change in length of the spring with solid compression.

The results showed that:-

- (1) The measured diameters of the wires of various types of Rocky Mountain and Unitek springs were within their stated tolerance limits. The between-coil variations of wire diameter of Rocky Mountain springs were 0.05 per cent. For Unitek springs, the between-coil variations of wire diameter were from 0.09 to 0.2 per cent.

The observed inside coil diameters of Unitek springs were 8 to 10 per cent in excess of their nominal sizes and exceeded the tolerance limits stated by their manufacturer. Dentaurem springs were about 3 per cent larger than their nominal sizes and just exceeded the stated tolerance limits. Rocky Mountain springs showed a larger between-coil variations in the inside coil diameter than either Unitek or Dentaurem springs.

The effect of the cumulative variations in the wire and coil diameter was to increase the deflection of the spring over the nominal by a variable amount. The expected variations in between-coil deflection characteristics of Dentaurem and Unitek springs were small in comparison with

the 3 coils of Elgiloy .008" - .036" open coil helical spring.

The within-coil variations in the number of turns per unit length of the spring varied from 2 to 7 per cent, except Remanit .007" - .030" which showed an average variation of 15 per cent. The between-coil variations in the number of turns were less than the within-coil difference except Unitek Hi-T .008" - .036" which showed a slightly greater variation in the number of turns in between-coil than within-coil.

- (2) Loss of mechanical energy was evident with each cycle of loading and unloading of the spring. The rate of unloading of the spring was affected by the level of stress in the spring at the time of unloading and the presence of any other frictional forces.

The load-to-percentage-deflection rates on loading and unloading of these springs were linear for specific ranges of load.

Despite buckling of the spring with an initial load of 13.2 grams, the load-to-percentage-deflection of the spring approached a perfect positive relationship.

- (3) Cold "setting" of the springs by compressing them solid once indicated that nearly all of the potential settage present in the springs was removed.

Solid compression of Remanit .007" - .030", Unitek Permachrome Standard .008" - .036" and Elgiloy .0056" - .022" showed a settage of 21, 15 and 13 per cent respectively.

With the exception of Remanit .007" - .030", the load-to-percentage-deflection rates of the springs were not significantly lowered by compressing the springs solid before putting them to service. Cold "setting" of Remanit .007" - .030" open coil helical spring reduced its load-to-percentage-deflection rate by approximately 28 per cent.

With the exception of Unitek Hi-T .006" - .036" and Elgiloy .007" - .036", all of the springs after cold settage showed that the inter-relationship between load and percentage deflection was more consistent over a longer range of the percentage deflection of the spring. After solid compression, the apparent proportional limits of Unitek Hi-T .006" - .036" and Elgiloy .007" - .036" were lowered.

- (4) Unitek Hi-T .006" - .036", Elgiloy .007" - .036", Elgiloy .0056" - .022", Elgiloy .007" - .030", Remanit .007" - .030", Elgiloy .008" - .036", Unitek Permachrome Standard .008" - .036" and Unitek Hi-T .008" - .036" showed a sequential increase in their respective load-to-percentage-deflection rates upon unloading.

On loading Unitek Hi-T .006" - .036", Elgiloy .007" - .036", Elgiloy .0056" - .022", Remanit .007" - .030", Elgiloy .007" - .030", Elgiloy .008" - .036", Unitek Permachrome Standard .008" - .036" and Unitek Hi-T .008" - .036", a sequential increase in their respective load-to-percentage-deflection rates was also evident.

Qualitatively this sequential increase in their load-to-percentage-deflection rates was in agreement with a theoretical analysis of their nominal wire and core diameters.

- (5) The within-coil relative variability of their load-to-percentage-deflection rates ranged from 2 to 10 per cent.

Component analysis of variance of the 3 coils of Elgiloy .008" - .036" open coil helical spring indicated that the load-to-percentage-deflection rates of these springs varied from section to section of the same coil and from coil to

coil. The coil to coil difference was greater than the within-coil difference. This conclusion is the same as that obtained from a theoretical analysis of the observed wire and coil diameters of the spring. It suggests that theoretical analysis of the observed wire and coil diameters may be used to help plan future experimental design.

- (6) The load-to-percentage-deflection rates of Remanit .007" - .036", Unitek Hi-T .006" - .036", Unitek Hi-T .008" - .036" and Unitek Permachrome Standard .008" - .036" could be lowered if their manufacturers had wound their springs more closely.
- (7) The percentage deflections and loads at the apparent proportional limit of these springs varied from 40 to 57 per cent and 114 to 320 grams respectively.

A method of determining the length of the spring when compressed into a given space will activate the spring to its apparent proportional limit has been suggested. This length consists of the available space plus a length ("maximum activation length") of the spring which is to be compressed into the available space. The "maximum activation length" for the tested springs varied from 64 to 137 per cent

of the available space..

As only a limited number of coils of each type of spring has been tested, the results could only act as pointers.

APPENDIX ISTATISTICAL METHODSNOTATIONS FOR THE SECTION ON STATISTICS

X data	-	Relative deflection in per cent
Y data	-	force or load in grams
N	-	number of observations
Σ	-	sum of
d.f.	-	number of degrees of freedom
$\bar{x}$	-	mean of X data
$\bar{y}$	-	mean of Y data
SD or σ	-	standard deviation
CV	-	Coefficient of Variation
SE	-	Standard error
t	-	't' ratio
Ho	-	null hypothesis
r	-	Correlation coefficient
$\sqrt{\quad}$	-	square root
b	-	Regression coefficient or slope
$SD_{y \cdot x}$	-	standard deviation of y from the regression line.
p	-	probabilities

Standard deviation (Barnard 1976)

Standard deviation, SD, is a measurement of variability of a series of measurements. It is the best estimate of the amount of deviation of individual measurements around the mean of the universe from which the sample was drawn. It is defined as the square root of the variance which is the mean of the squares of all deviations from the arithmetic mean of the series. It is calculated with the formula:-

$$SD = \sqrt{\frac{\sum x^2 - \frac{(\sum x)^2}{N}}{N - 1}}$$

where $\sum$ means the sum of, x the individual measurements of the series, N the number of measurements and $N-1$ the degrees of freedom.

Standard deviation gives some indications of the limit within which measurements from other similar samples from the same universe would fall. Approximately 99.73 per cent of measurements will be found in a range of 3 SD on either side of the mean.

Coefficient of Variation (Barnard 1976)

The variability of two sets of measurements is compared by the

coefficient of variation, CV, which relates the size of the standard deviation of the series to its mean. It is calculated as follows:-

$$CV = \frac{SD}{\text{Mean}} \times 100 = \frac{SD}{\bar{X}} \times 100$$

Standard Error (Garn 1958)

The standard error, SE, of the mean describes the expected deviation of means of like samples. The formula for standard error is:-

$$SE = \frac{SD}{\sqrt{N - 1}}$$

Standard error gives an indication of the limits within which means of other similar samples would fall. 3 standard errors on either side of the mean includes approximately 99.73 per cent of all other means of similar samples.

The Student's 't' Test (Garn 1958)

For observed difference between means of two series.

The 't' test of statistical significance of an observed difference

between the means of two series of measurements is calculated by relating the observed difference to the standard error of the difference.

Standard error of the difference is the square root of the sum of the squares of the standard errors of the two means.

$$\text{Thus, } t = \frac{\text{Difference between observed means}}{\text{Standard error of Difference}}$$

$$= \frac{\bar{x}_1 - \bar{x}_2}{\left[\left(\frac{N_1 SD_1^2 + N_2 SD_2^2}{N_1 + N_2 - 2} \right) \left(\frac{N_1 + N_2}{N_1 N_2} \right) \right]^{1/2}}$$

When interpreting this 't' value from the 't' table, the number of degrees of freedom for the two groups is two less than the total number of measurements in the two groups being compared.

Correlation Coefficient (Leaver and Thomas 1974)

Correlation coefficient, r , is a measure of the degree of relationship between two characteristics in a series of observations. It is calculated with the formula:-

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\left(\sum X^2 - \frac{(\sum X)^2}{N}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{N}\right)}}$$

Regression Coefficient

Regression coefficient, b , is "the amount of change that will on the average take place in one characteristic when the other characteristic changes by a unit". (Barnard 1976). It is depicted graphically by the slope of the linear regression line.

It is calculated with the formula:-

$$b = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sum X^2 - \frac{(\sum X)^2}{N}} \quad (\text{Snedecor 1959})$$

Test of Statistical Significance of Regression Coefficient

(Snedecor 1959)

If there is no definite correlation between the two characteristics, the regression coefficient, b , for the regression of one characteristic on the other would be zero. The t -test may be used to determine if b is significantly different from zero. The t ratio is calculated for $(n-2)$ degrees of freedom from

$$t = \frac{b}{\text{standard error of } b} = \frac{b}{SE_b}$$

The standard error of b is calculated with the formula:-

$$SE_b = \frac{1}{\sum X^2 - \frac{(\sum X)^2}{N}} \sqrt{\frac{\left[\sum X^2 - \frac{(\sum X)^2}{N} \right] \left[\sum Y^2 - \frac{(\sum Y)^2}{N} \right] - \left[\sum XY - \frac{(\sum X)(\sum Y)}{N} \right]^2}{N - 2}}$$

The ' t ' value is then interpreted from the ' t ' table for the probabilities of the ' t ' value being due to chance.

Test of Statistical Significance of Correlation Coefficient

(Leaver and Thomas 1974)

The significance of the correlation coefficient is determined by calculating t for $(N-2)$ degrees of freedom using the following formula:-

$$t = r \left(\frac{N - 2}{1 - r^2} \right)^{\frac{1}{2}}$$

The t value is then interpreted from the 't' table for the probabilities of the t value being due to chance.

The Null Hypothesis

The Null Hypothesis is that "no difference exists, that the observed difference is no greater than that which could be observed between any pair of samples drawn from the same universe, where we would expect the true difference to be zero and the observed difference one that was due to chance". (Barnard 1976).

In using a test of significance, the null hypothesis is first defined. One then determines whether the null hypothesis can be rejected and at what level of confidence or p (probability) value. (Garn 1958).

APPENDIX II

Method of Determining the Offset Line from the Regression Line

Regression Coefficient, b , is calculated with the formula:-

$$b = \frac{\sum xy - \frac{\sum x \sum y}{N}}{\sum x^2 - \frac{(\sum x)^2}{N}}$$

The standard deviation of y from regression $SDy.x$ is calculated from the formula described by Leaver and Thomas (1974)

$$SDy.x = \sqrt{\frac{\left[\sum x^2 - \frac{(\sum x)^2}{N} \right] \left[\sum y^2 - \frac{(\sum y)^2}{N} \right] - \left[\sum xy - \frac{\sum x \sum y}{N} \right]^2}{\left[\sum x^2 - \frac{(\sum x)^2}{N} \right] (N-2)}}$$

Approximately 99.73 per cent of experimental data will be found within the range of 3 $SDy.x$ on either side of the regression line.

A line drawn parallel to and offset at 3 $SDy.x$ from the regression line will cut the load-percentage deflection curve at a definite point. The curve immediately beyond this definite point represents a real deviation from linearity between load and percentage deflection. The confidence limit for this statement is 99.73 per cent.

Method Used to Standardize the Number of Active Coils for Comparison of L - %D Rates

Method used to compare the load to percentage deflection rates of the tested springs assuming that they all had the same number of active coils in the 2 cm gauge length of the spring.

The deflection δ of a helical spring is given by equation (1) as

$$\delta = \frac{64 P R^3 n}{G d^4}$$

Rearranging the terms,

$$\frac{P}{\delta} = \frac{G d^4}{64 R^3 n}$$

For springs of the same dimension, the load-deflection ratio is therefore inversely proportional to the number of active coils of the spring. If the load to deflection ratio and the number of active coils in the spring are known, the load-deflection ratio of another spring of the same dimension but of a different number of active coils can be calculated. Since,

$$\frac{P_1}{\delta_1} \propto \frac{1}{n_1}$$

where $\frac{P_1}{\delta_1}$ is a known load-deflection ratio for a spring with n_1 coils.

Therefore,

$$\frac{\frac{P_1}{\delta_1}}{\frac{P_2}{\delta_2}} \propto \frac{\frac{1}{n_1}}{\frac{1}{n_2}}$$

where $\frac{P_2}{\delta_2}$ is an unknown load-deflection ratio for a spring of

the same dimension, but with n_2 coils.

Hence,

$$\frac{P_2}{\delta_2} \propto \frac{n_1}{n_2} \times \frac{P_1}{\delta_1}$$

$\frac{P_1}{\delta_1}$ is a known quantity for the tested springs with n_1 turns and

is tabulated in Tables 6, 7, 8, 9, 10, 11, 12 and 13 in Appendix III.

In mathematical symbols, this load to percentage deflection, b , is

$$b = \frac{P}{\frac{\delta}{L} \times 100}$$

where L is the length of the spring, P is the load and δ the deflection.

Rearranging the terms,

$$\frac{P}{\delta} = \frac{b \times 100}{L}$$

If this spring has n_2 turns the load-deflection ratio $\frac{P_2}{\delta_2}$ becomes

$$\frac{P_2}{\delta_2} \propto \frac{n_1}{n_2} \times \frac{P_1}{\delta_1}$$

$$\propto \frac{n_1}{n_2} \times \frac{b \times 100}{L}$$

Using the average number of coils observed in the 2 cm test length of Elgiloy .007" - .036" as the basic number of coils presumed to be present in each type of spring, their new load to percentage

deflection rates can be calculated and compared with each other
and with Elgiloy .007" - .036".

APPENDIX III

TABLE 6

Observed Dimensions of Unitek Hi-T .006"-.036" Sample Springs

Unitek Hi-T .006"-.036"	Wire diameter mm	Outside coil diameter mm	No. of turns	Free length of specimen mm	Pitch height mm
A 1	.1508	1.3235	32	20.235	0.6323
A 2	.1505	1.327	32	20.246	0.6327
A 3	.1513	1.3208	33	20.355	0.6168
A 4	.1508	1.325	33	20.11	0.6094
Average	.1509	1.3241	32.5	20.2365	0.6228

TABLE 7

Observed Dimensions of Eligiloy .007"-.036" Sample Springs

Elgiloy .007"-.036"	Wire diameter mm	Outside coil diameter mm	No of turns	Free length of specimen mm	Pitch height mm
A 1	.173	1.3475	45	20.325	0.4517
A 2	.174	1.3502	45	20.30	0.4511
A 3	.173	1.3482	44	20.117	0.4572
A 4	.174	1.3490	43	20.34	0.4730
Average	0.1735	1.3487	44.25	20.271	0.4583

TABLE 8

Observed Dimension of Eligiloy .0056"-.022" Sample Springs

Elgiloy .0056"-.022"	Wire diameter mm	Outside coil diameter mm	No. of turns	Free length of specimen mm	Pitch height mm
A 1	.1385	.887	49	20.55	0.4194
A 2	.1373	.895	49	20.524	0.4189
A 3	.138	.893	48	20.467	0.4264
A 4	.139	.897	48	20.297	0.4229
Average	.1382	0.893	48.5	20.460	0.4219

TABLE 9

Observed Dimensions of Elgiloy .007"-.030" sample springs

Elgiloy .007"-.030"	Wire diameter mm	Outside coil diameter mm	No. of turns	Free length of specimen mm	Pitch height mm
A 1	.178	1.1611	49	20.224	0.4127
A 2	.1752	1.1476	48	20.061	0.4179
A 3	.1747	1.144	49	20.157	0.4114
A 4	.1765	1.1627	49	20.279	0.4139
Average	0.1761	1.1539	48.75	20.180	0.4140
B 1	.176	1.133	49	20.064	0.4095
B 2	.176	1.1365	48	20.065	0.4180
B 3	.176	1.137	46	20.101	0.4370
B 4	.176	1.134	49	20.119	0.4106
Average	0.176	1.1351	48	20.087	0.4188
C 1	.176	1.134	53	20.082	0.3789
C 2	.1762	1.1245	49	20.056	0.4093
C 3	.1757	1.1355	49	20.307	0.4144
C 4	.176	1.128	47	20.164	0.4290
Average	0.176	1.1305	49.5	20.152	0.4079

TABLE 10

Observed Dimensions of Remanit .007"-.030" Sample Springs

Remanit .007"-.030"	Wire diameter mm	Outside coil diameter mm	No. of turns	Free length of specimen mm	Pitch height mm
A 1	.174	1.134	35	19.907	0.5688
A 2	.174	1.135	38	20.04	0.5274
A 3	.174	1.1356	36	20.23	0.5619
A 4	.174	1.136	32	20.22	0.6319
Average	.174	1.135	35.25	20.099	0.5725
B 1	.1748	1.1382	37	19.951	0.5392
B 2	.1746	1.1357	38	20.22	0.5321
B 3	.176	1.135	33	20.111	0.6094
B 4	.1738	1.134	34	20.735	0.6099
Average	0.1748	1.1357	35.5	20.254	0.5727
C 1	.1748	1.1365	36	20.353	0.5654
C 2	.1738	1.1335	36	20.317	0.5644
C 3	.175	1.136	38	20.247	0.5328
C 4	.1748	1.142	41	20.104	0.4903
Average	.1746	1.137	37.75	20.255	0.5382

TABLE 11

Observed Dimensions of Unitek Hi-T .008"-.036" Sample Springs

Unitek Hi-T .008"-.036"	Wire diameter mm	Outside coil diameter mm	No. of turns	Free length of specimen mm	Pitch height mm
A 1	.205	1.426	32	20.415	0.6380
A 2	.206	1.4288	32	20.367	0.6365
A 3	.208	1.422	32	20.171	0.6303
A 4	.207	1.424	32	20.062	0.6269
Average	0.2065	1.4252	32	20.254	0.6329
B 1	.2062	1.4264	32	20.169	0.6303
B 2	.2065	1.4143	33	20.082	0.6085
B 3	.2063	1.4308	32	20.226	0.6321
B 4	.2065	1.417	33	20.154	0.6107
Average	.2064	1.4221	32.5	20.158	0.6204
C 1	.207	1.428	34	20.208	0.5944
C 2	.2065	1.425	33	20.179	0.6115
C 3	.2068	1.4248	33	20.206	0.6123
C 4	.207	1.4248	34	20.368	0.5991
Average	0.2068	1.4257	33.5	20.240	0.6043

TABLE 12

Observed Dimensions of Unitek Permachrome Standard .008"-.36"
Sample Springs

Unitek Permachrome Standard .008"-.036"	Wire diameter mm	Outside coil diameter mm	No. of turns	Free length of specimen mm	Pitch height mm
A 1	.2068	1.396	32	20.065	0.6270
A 2	.2065	1.399	31	20.538	0.6625
A 3	.206	1.40	30	20.234	0.6745
A 4	.2058	1.4005	30	20.162	0.6721
Average	0.2063	1.3989	30.75	20.250	0.6590
B 1	.2065	1.4018	30	20.058	0.6686
B 2	.206	1.404	30	20.205	0.6735
B 3	.207	1.397	30	19.97	0.6657
B 4	.206	1.4033	30	20.096	0.6699
Average	0.2064	1.4015	30	20.082	0.6694
C 1	.206	1.4023	31	20.12	0.6490
C 2	.206	1.4074	30	20.017	0.6672
C 3	.2063	1.4036	30	20.362	0.6787
C 4	.2065	1.405	30	20.19	0.6730
Average	0.2062	1.4046	30.25	20.172	0.6670

TABLE 13

Observed Dimensions of Elgiloy .008"-.036" Sample Springs

Elgiloy 008"-.036"	Wire diameter mm	Outside coil diameter mm	No. of turns	Free length of specimen mm	Pitch height mm
A 1	.198	1.3795	51	20.401	0.4000
A 2	.1982	1.3758	48	20.079	0.4183
A 3	.1978	1.3798	47	19.95	0.4245
A 4	.1985	1.382	48	20.278	0.4225
Average	0.1981	1.3793	48.5	20.177	0.4163
B 1	.198	1.332	49	20.286	0.4140
B 2	.198	1.3287	49	20.187	0.4120
B 3	.1985	1.332	48	20.347	0.4239
B 4	.198	1.328	48	20.273	0.4224
Average	.1981	1.3302	48.5	20.273	0.4181
C 1	.1985	1.3265	49	20.238	0.4130
C 2	.1978	1.3242	49	20.214	0.4125
C 3	.1976	1.3171	48	20.024	0.4172
C 4	.198	1.322	47	20.161	0.4290
Average	.198	1.3225	48.25	20.159	0.4179

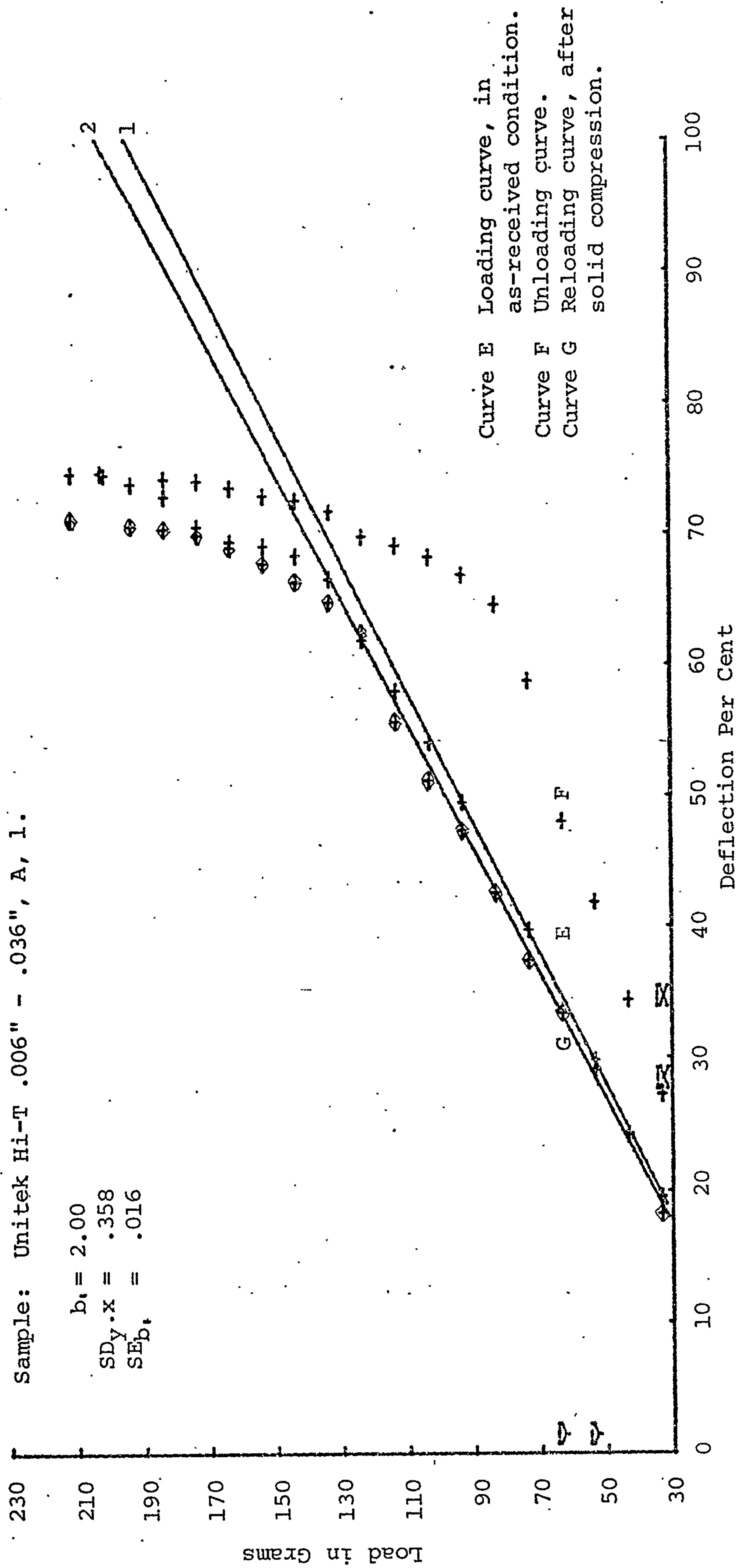


Fig. 37. Load-deflection regression of Unitek Hi-T .006" - .036" open coil helical spring loaded in as received condition (1) and after solid compression (2).

Sample: Unitek Hi-T .006" - .036", A, 2.

$b = 2.14$
 $SD_{y \cdot x} = 2.252$
 $SE_b = .108$

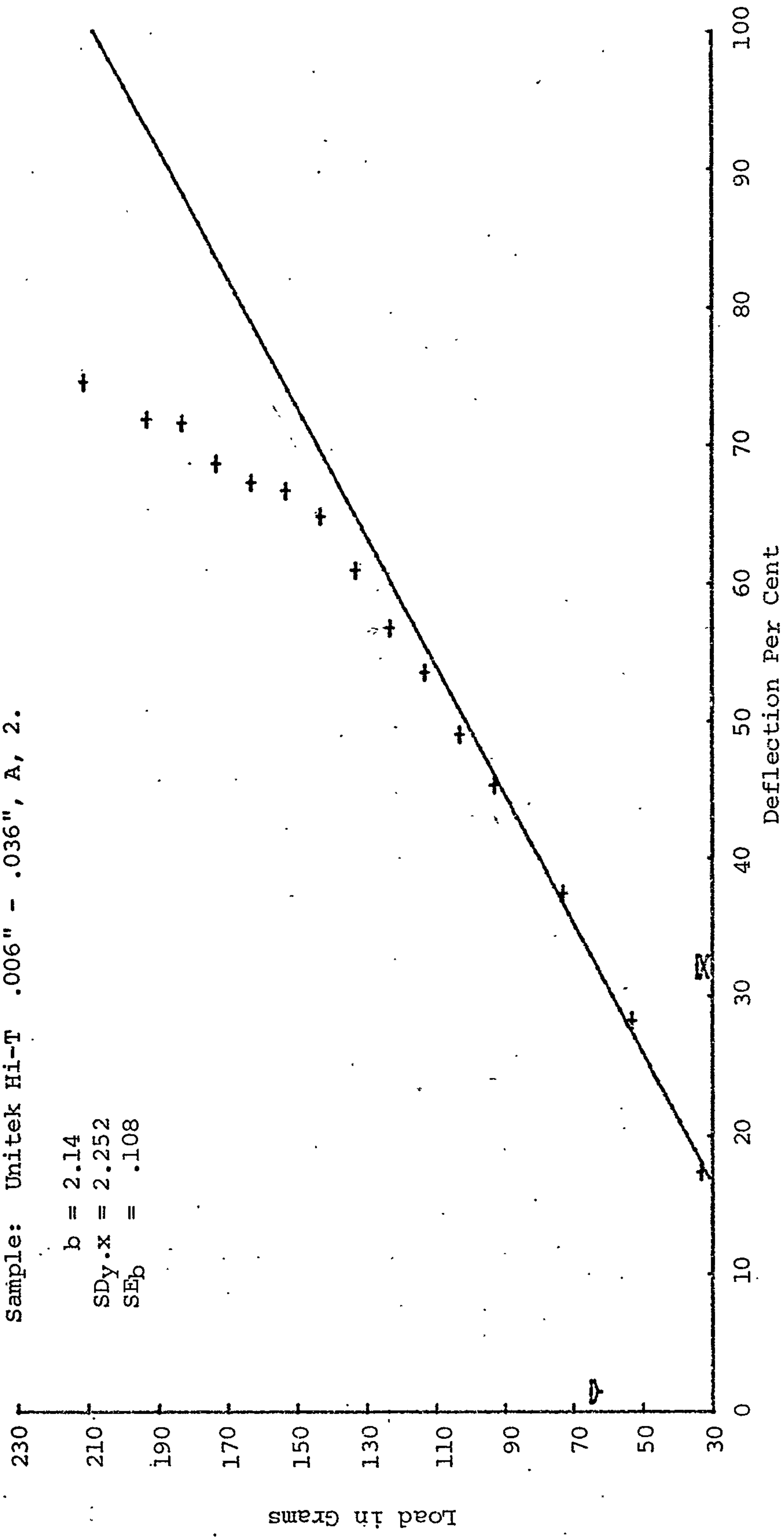


Fig. 38. Load-deflection regression of Unitek Hi-T .006" - .036" open coil helical spring loaded in as-received condition.

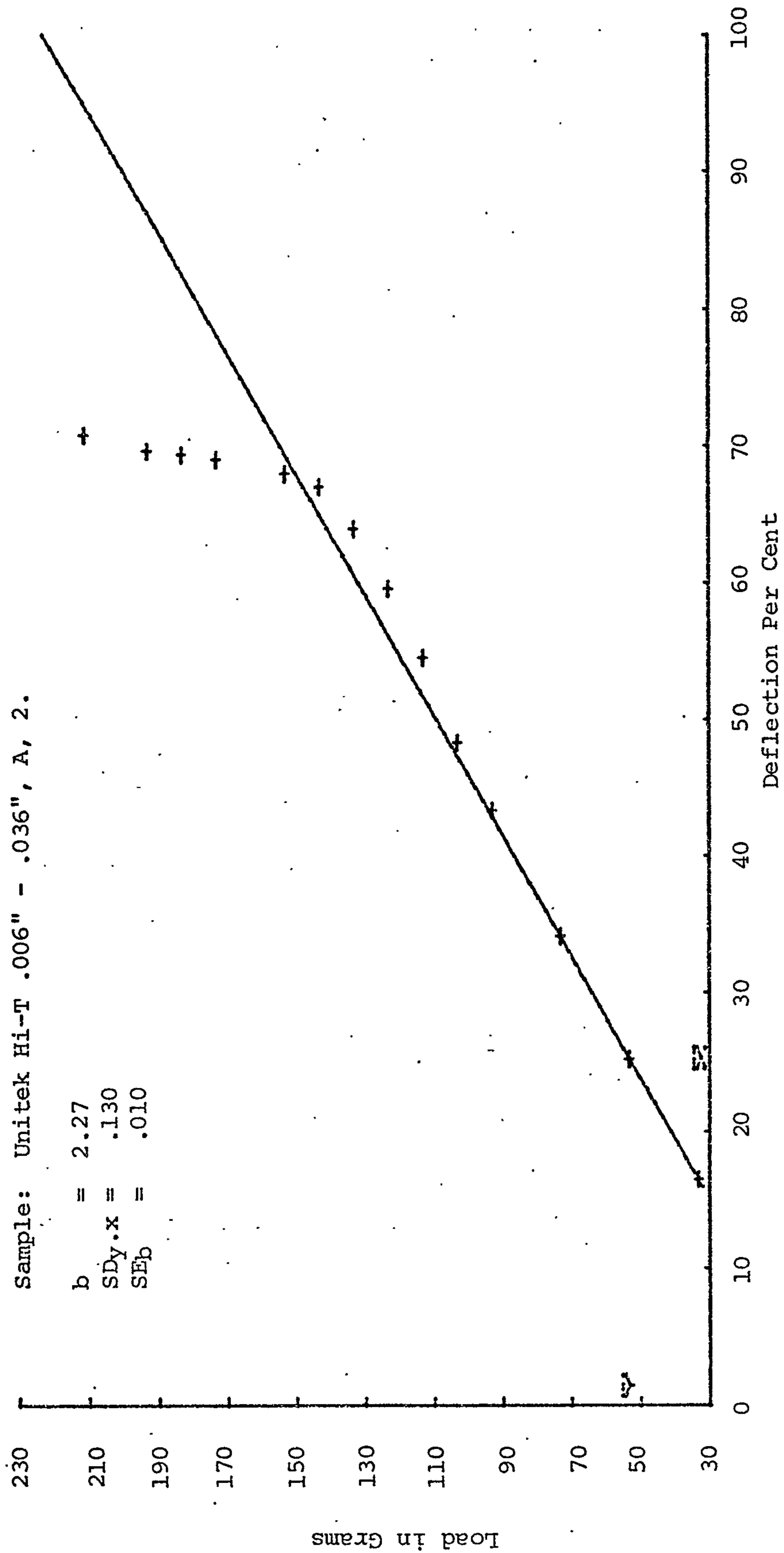


Fig. 39. Load-deflection regression of Unitek Hi-T .006"-.036" open coil helical spring loaded after it had been compressed solid once.

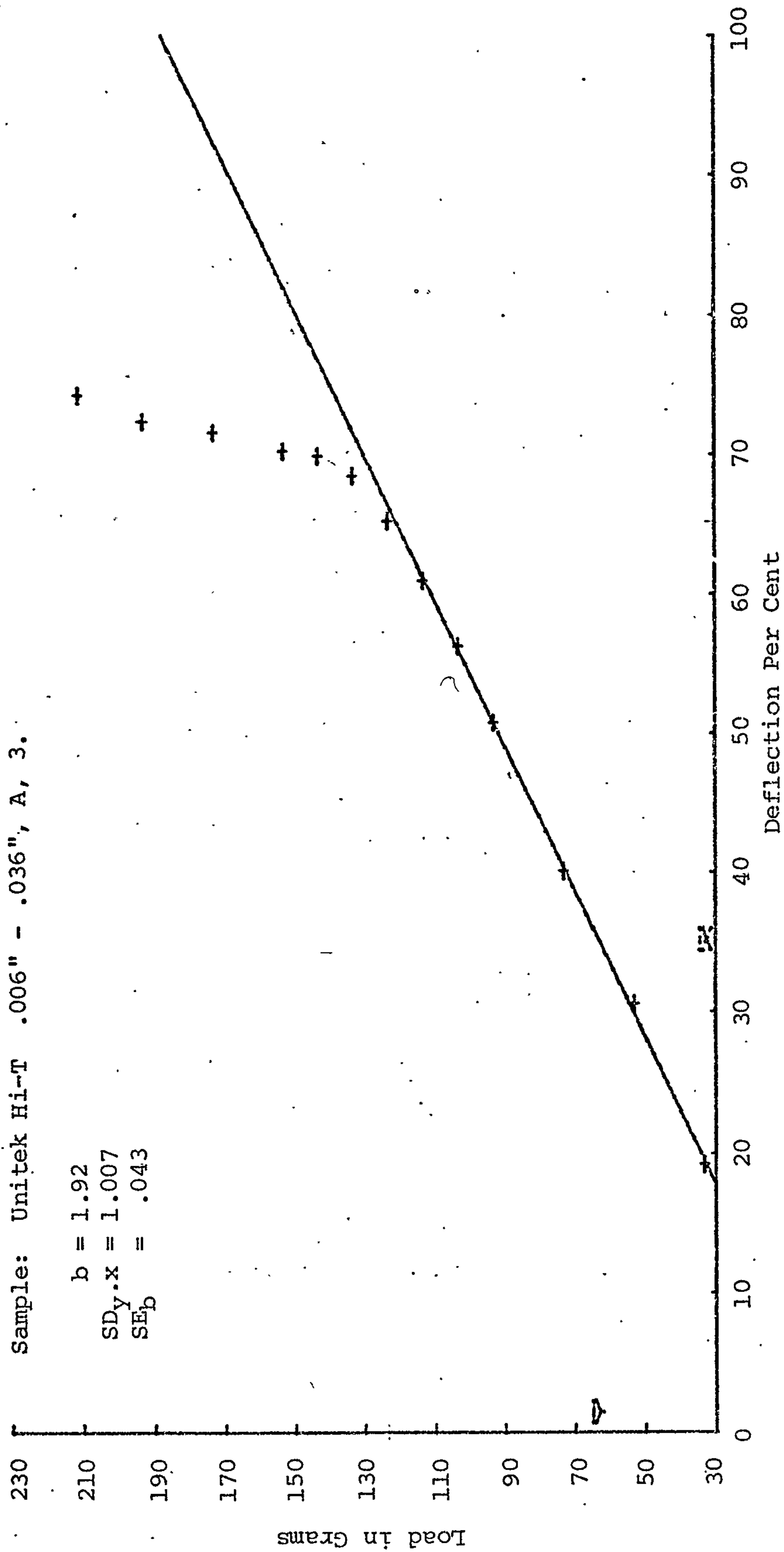


Fig. 40. Load-deflection regression of Unitek Hi-T .006" - .036" open coil helical spring loaded in as-received condition.

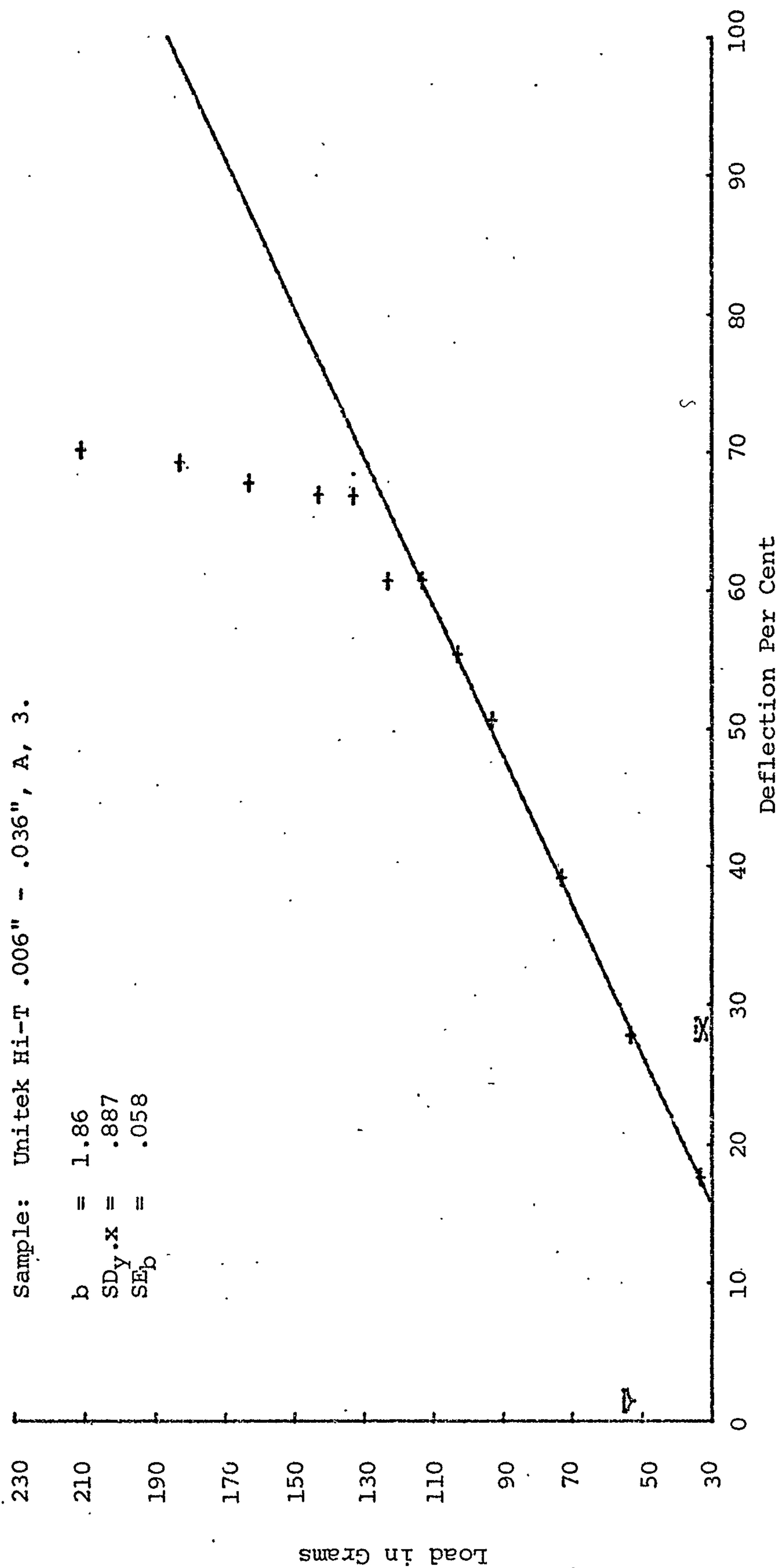


Fig. 41. Load-deflection regression of Unitek Hi-T .006" - .036" open coil helical spring loaded after it had been compressed solid once.

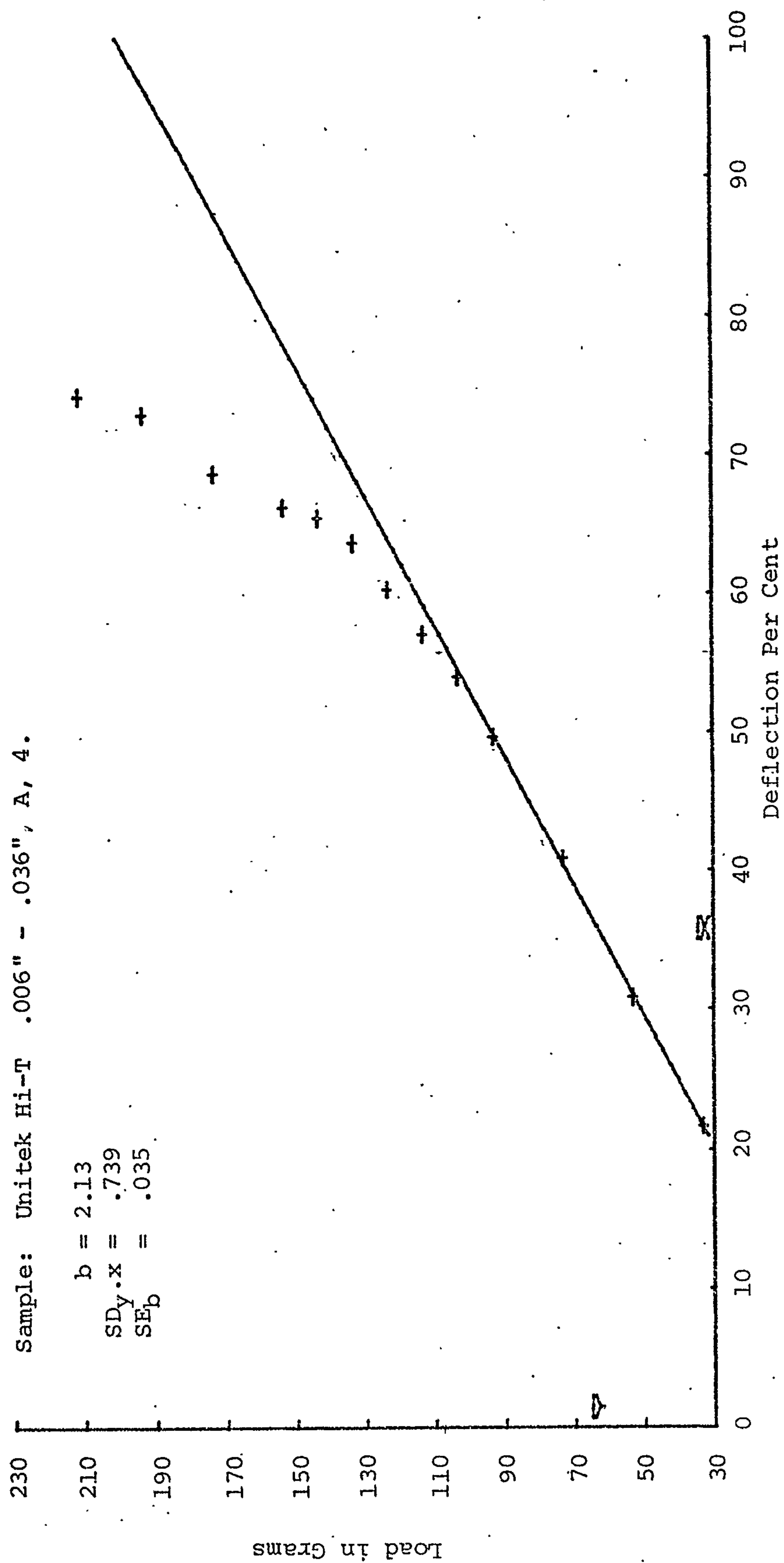


Fig. 42. Load-deflection regression of Unitek Hi-T .006" - .036" open coil helical spring loaded in as-received condition.

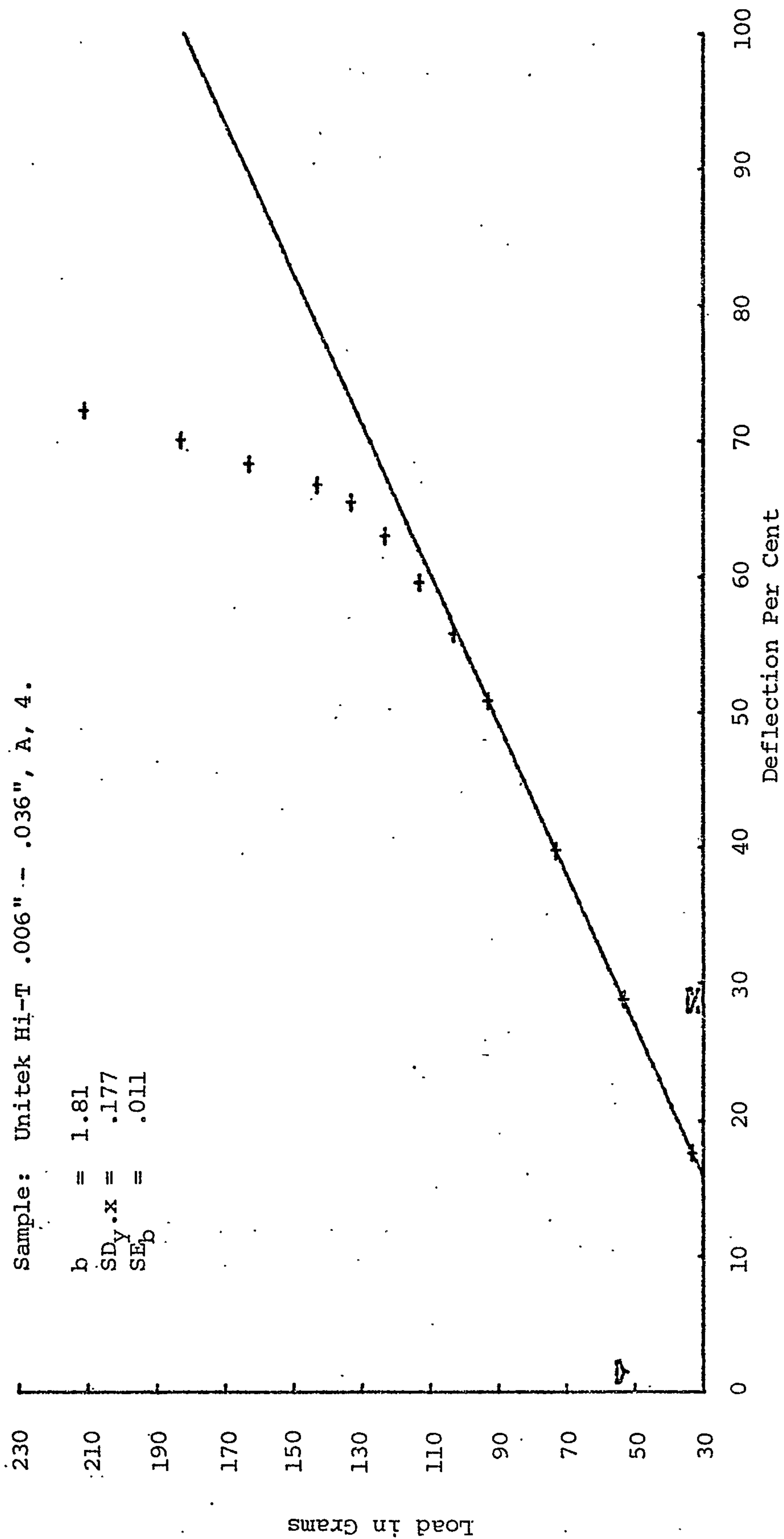


Fig. 43. Load-deflection regression of Unitek Hi-T .006" - .036" open coil helical spring loaded after it had been compressed solid once.

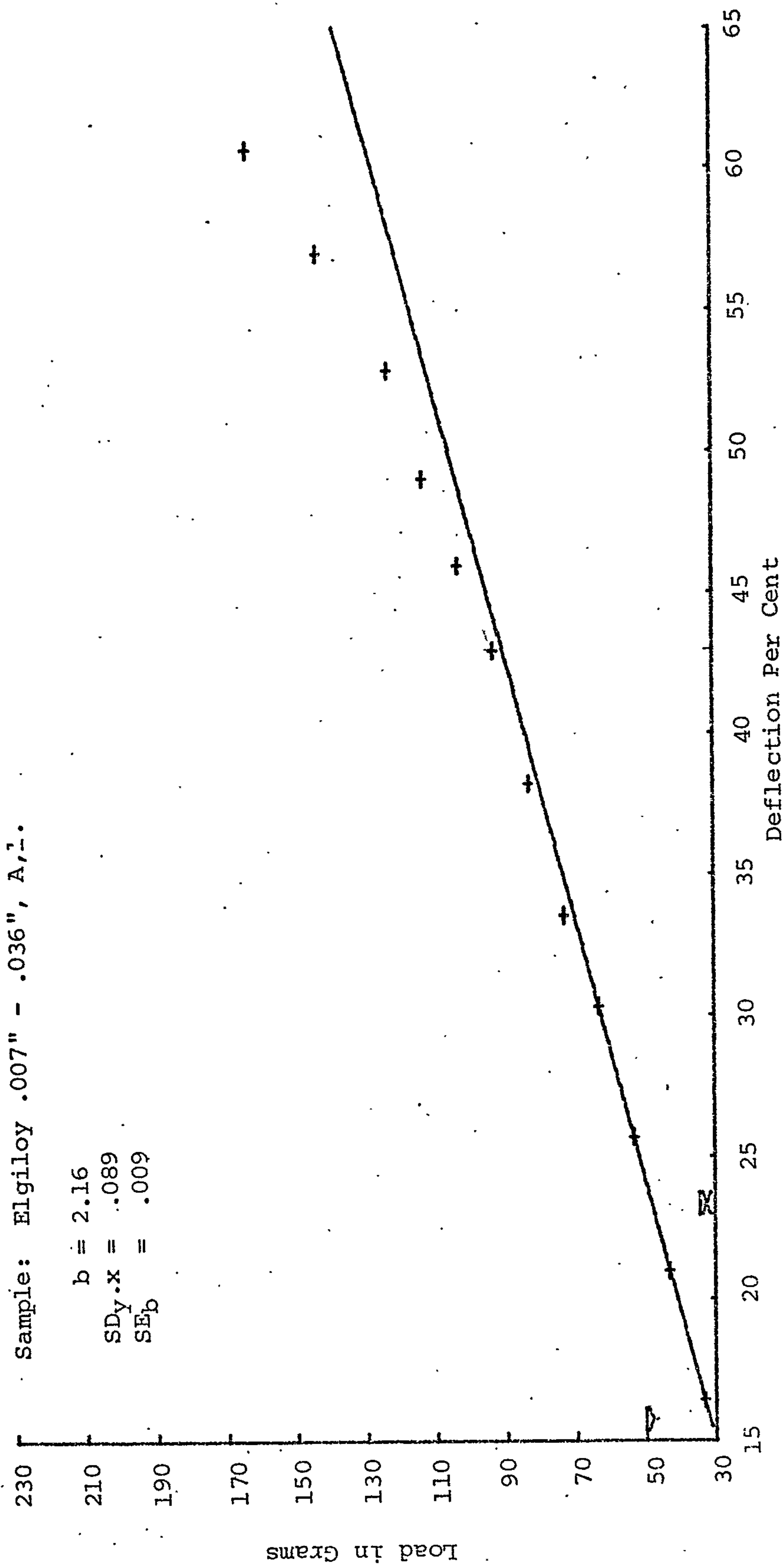


Fig. 44. Load-deflection regression of Elgiloy .007" - .036" open coil helical spring loaded in as-received condition.

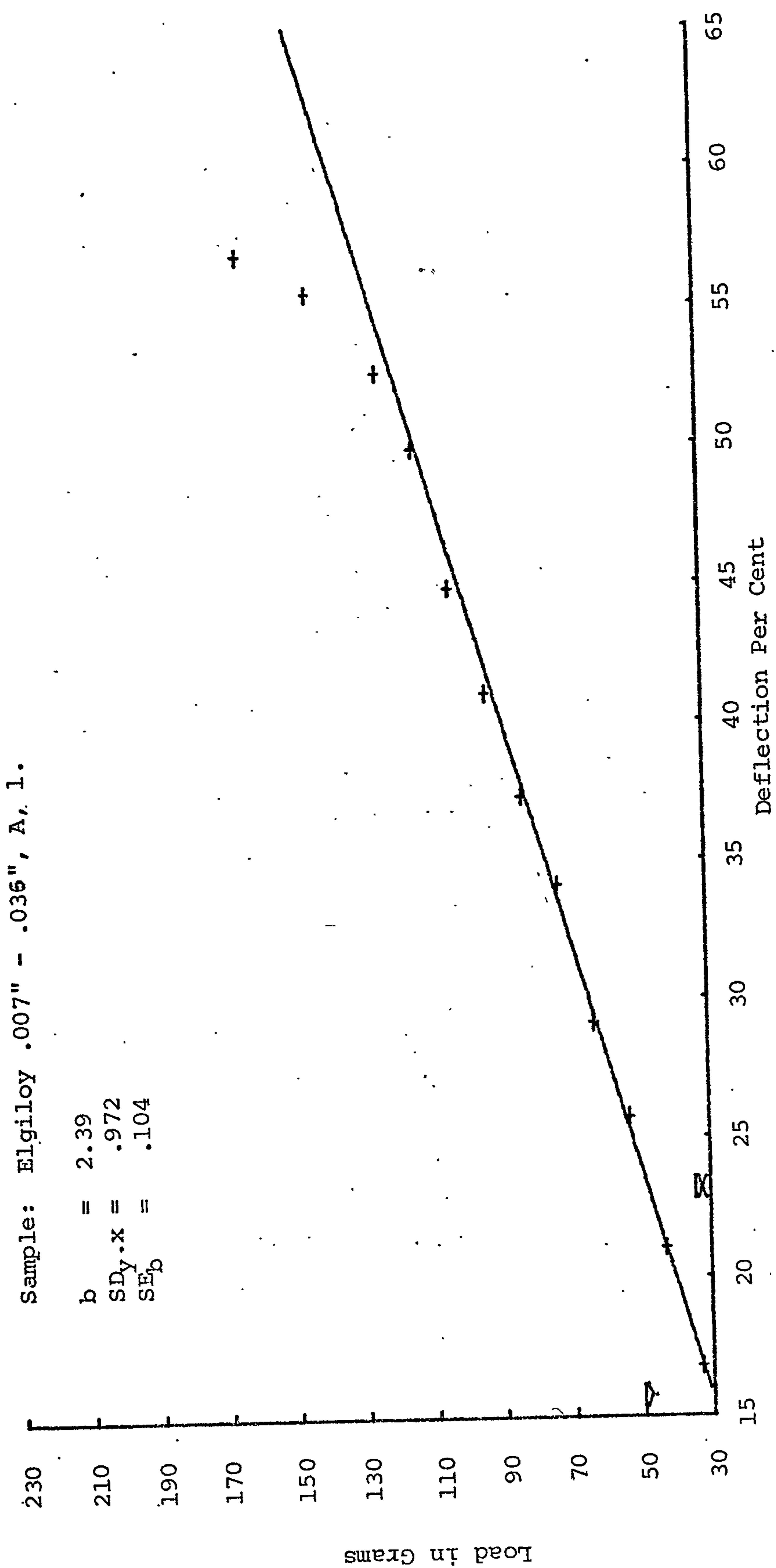


Fig. 45. Load-deflection regression of Elgiloy .007" - .030" open coil helical spring loaded after it had been compressed solid once.

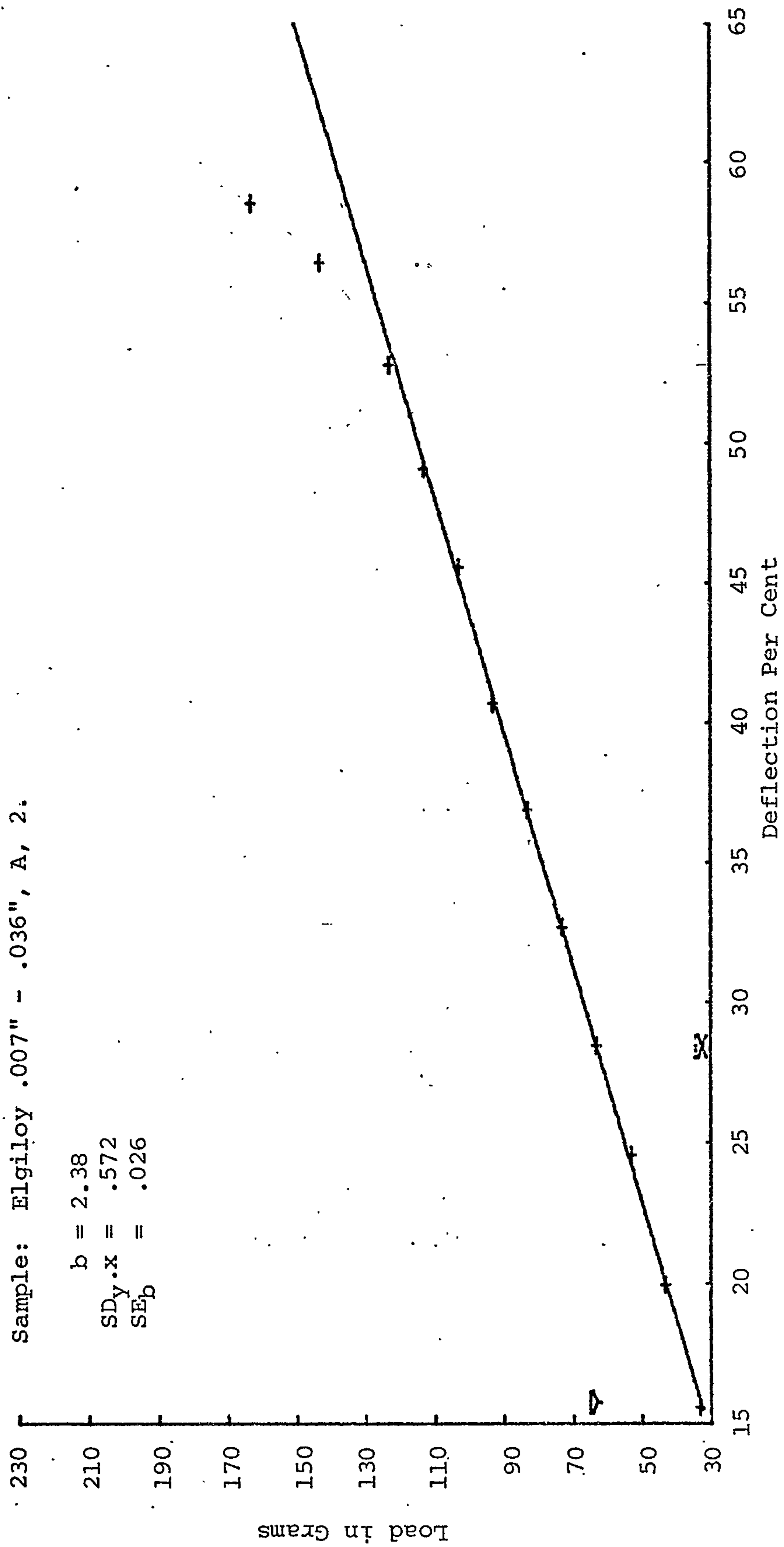


Fig. 46. Load-deflection regression of Elgiloy .007" - .036" open coil helical spring loaded in as-received condition.

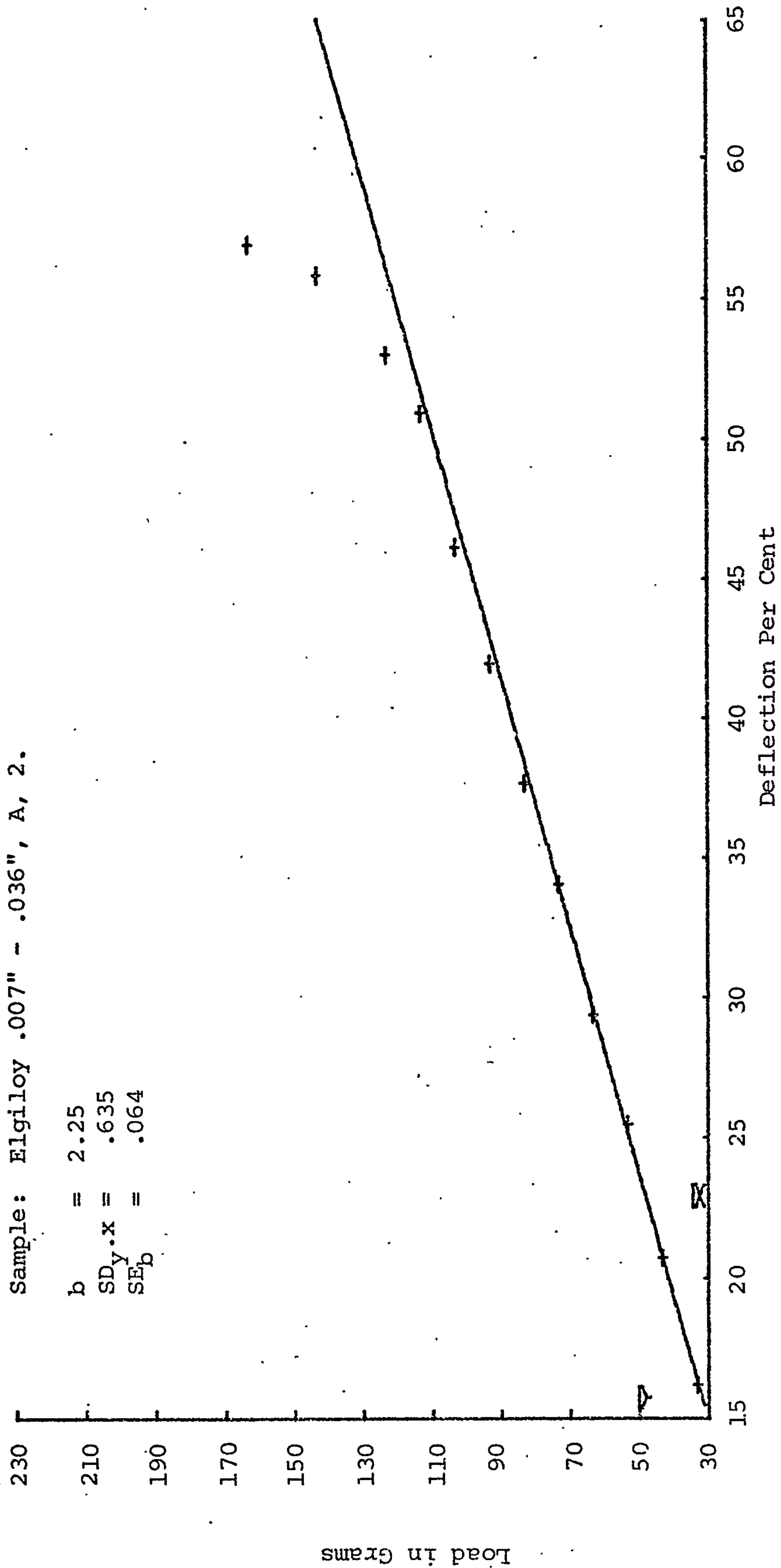


Fig. 47. Load-deflection regression of Elgiloy .007" - .036" open coil helical spring loaded after it had been compressed solid once.

Sample: Elgiloy .007" - .036", A, 3.

$b_1 = 2.18$

$SDY \cdot x = .615$

$SEb_1 = .028$

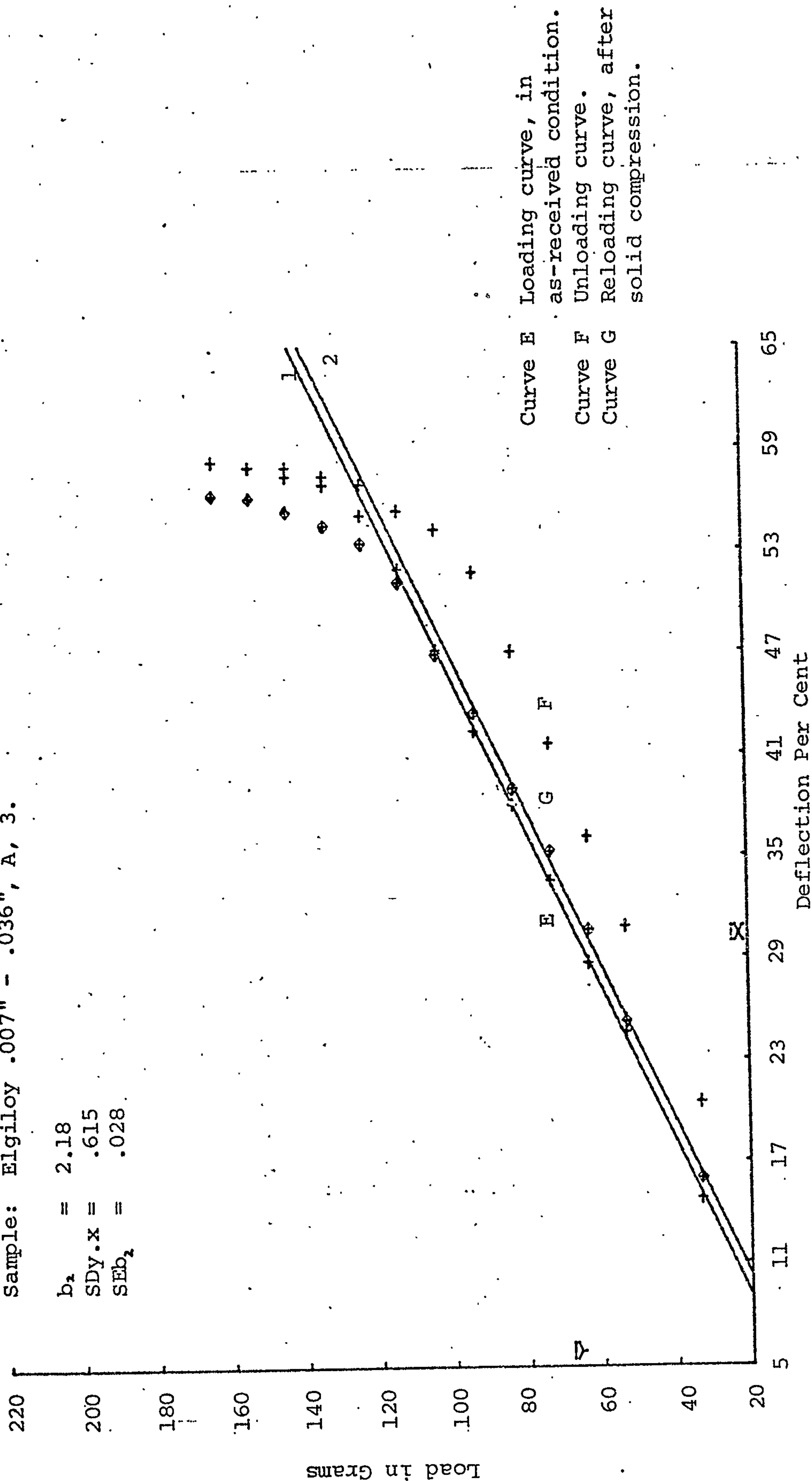


Fig. 48. Load-deflection regressions of Elgiloy .007" - .036" open coil helical spring loaded in as-received condition (1) and after solid compression (2)

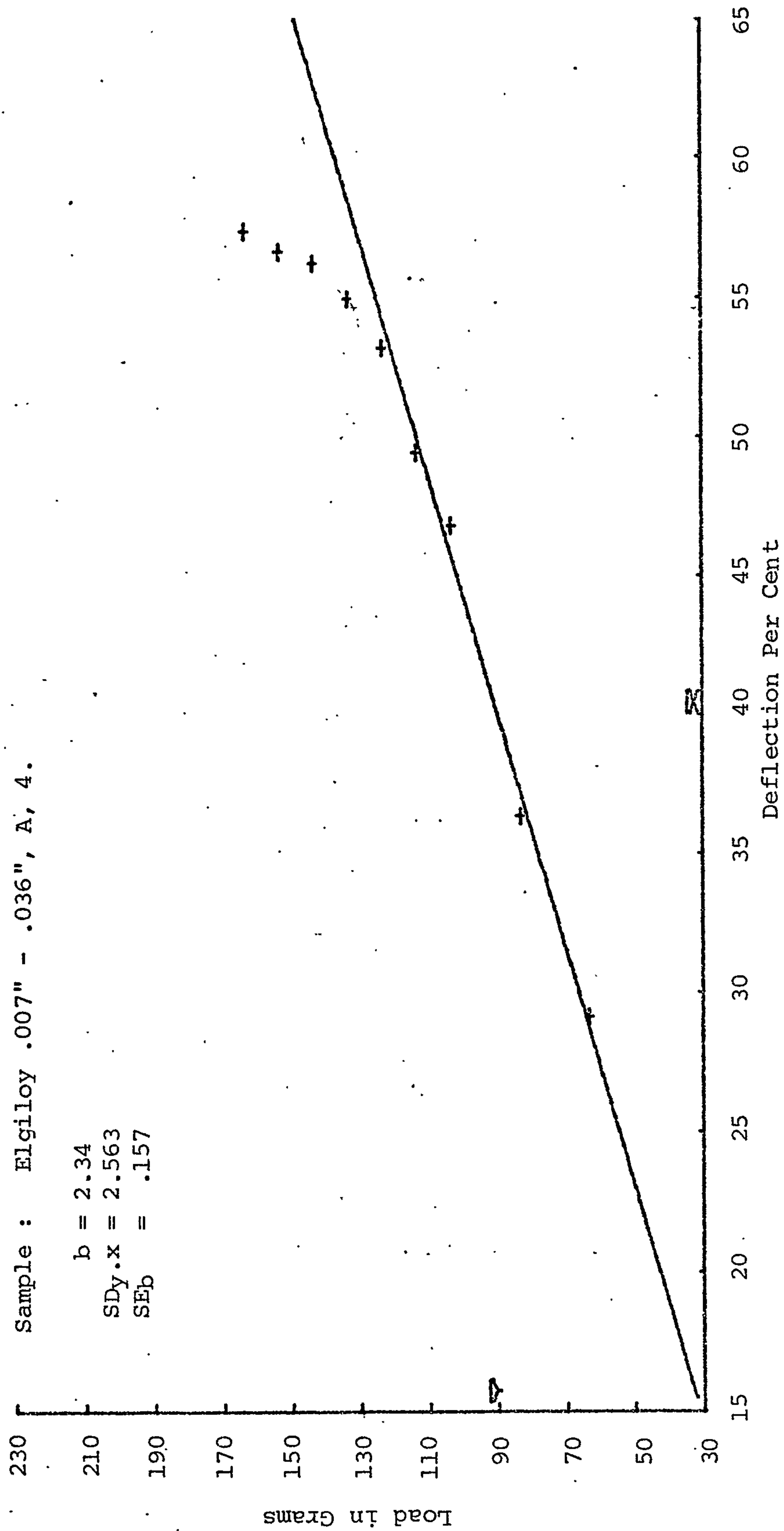


Fig. 49. Load-deflection regression of Elgiloy .007" - .036" open coil helical spring loaded in as-received condition.

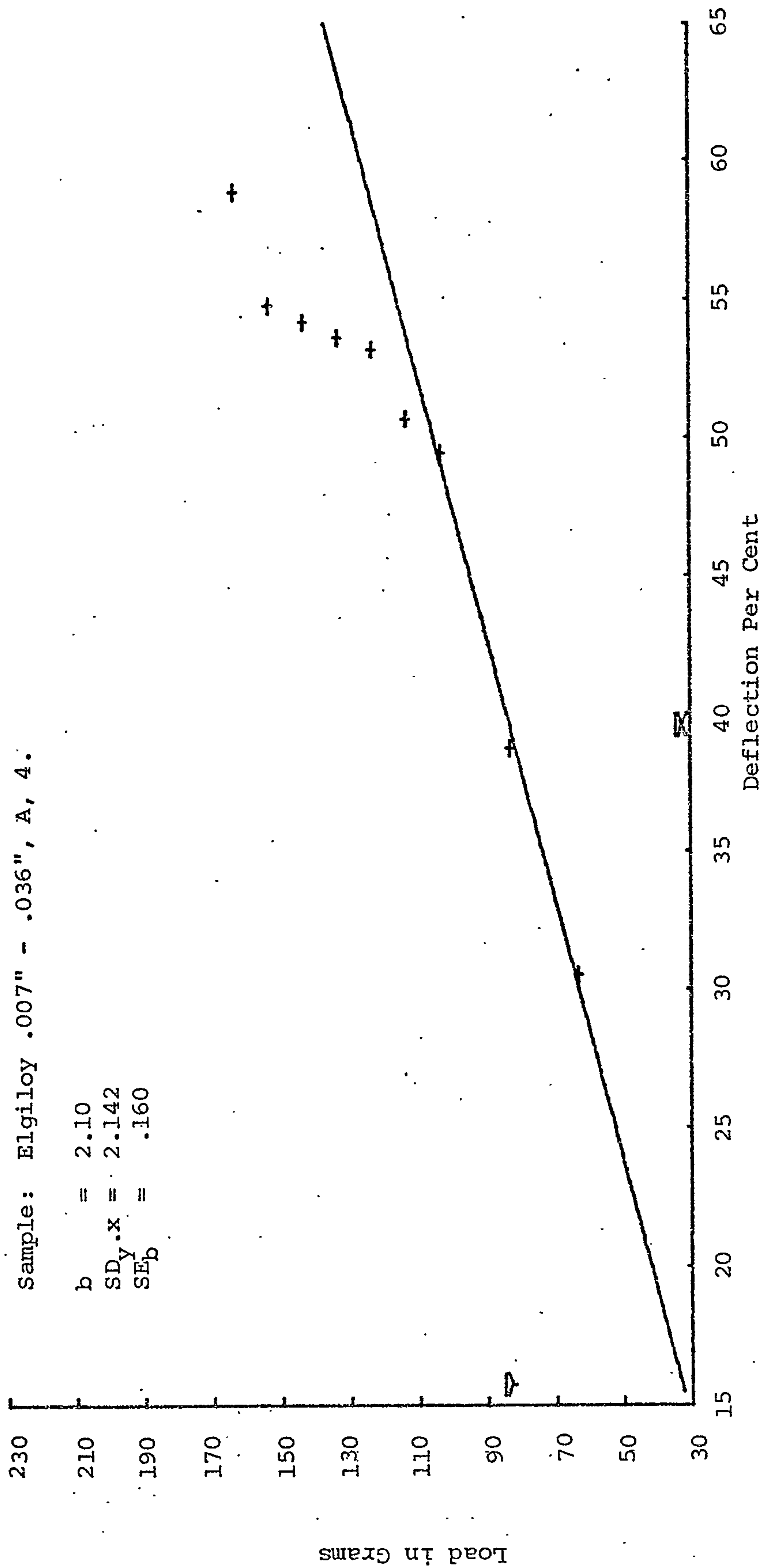


Fig. 50. Load-deflection regression of Elgiloy .007" - .036" open coil helical spring loaded after it had been compressed solid once.

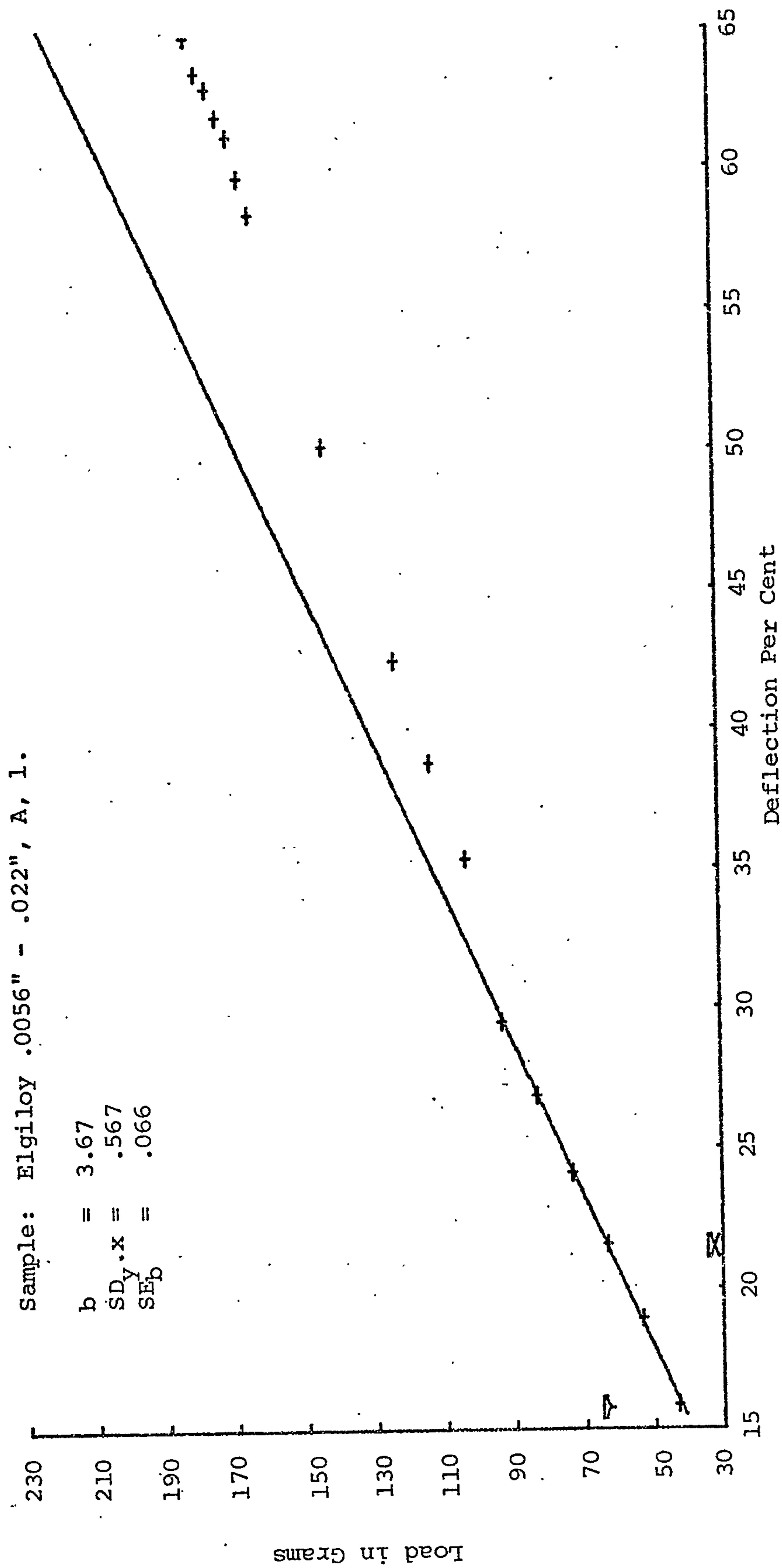


Fig. 51. Load-deflection regression of Elgiloy .0056" - .022" open coil helical spring loaded in as-received condition.

Sample: Elgiloy .0056" - .022", A, 1.

$b = 2.69$
 $SD_{y \cdot x} = 2.090$
 $SE_b = .179$

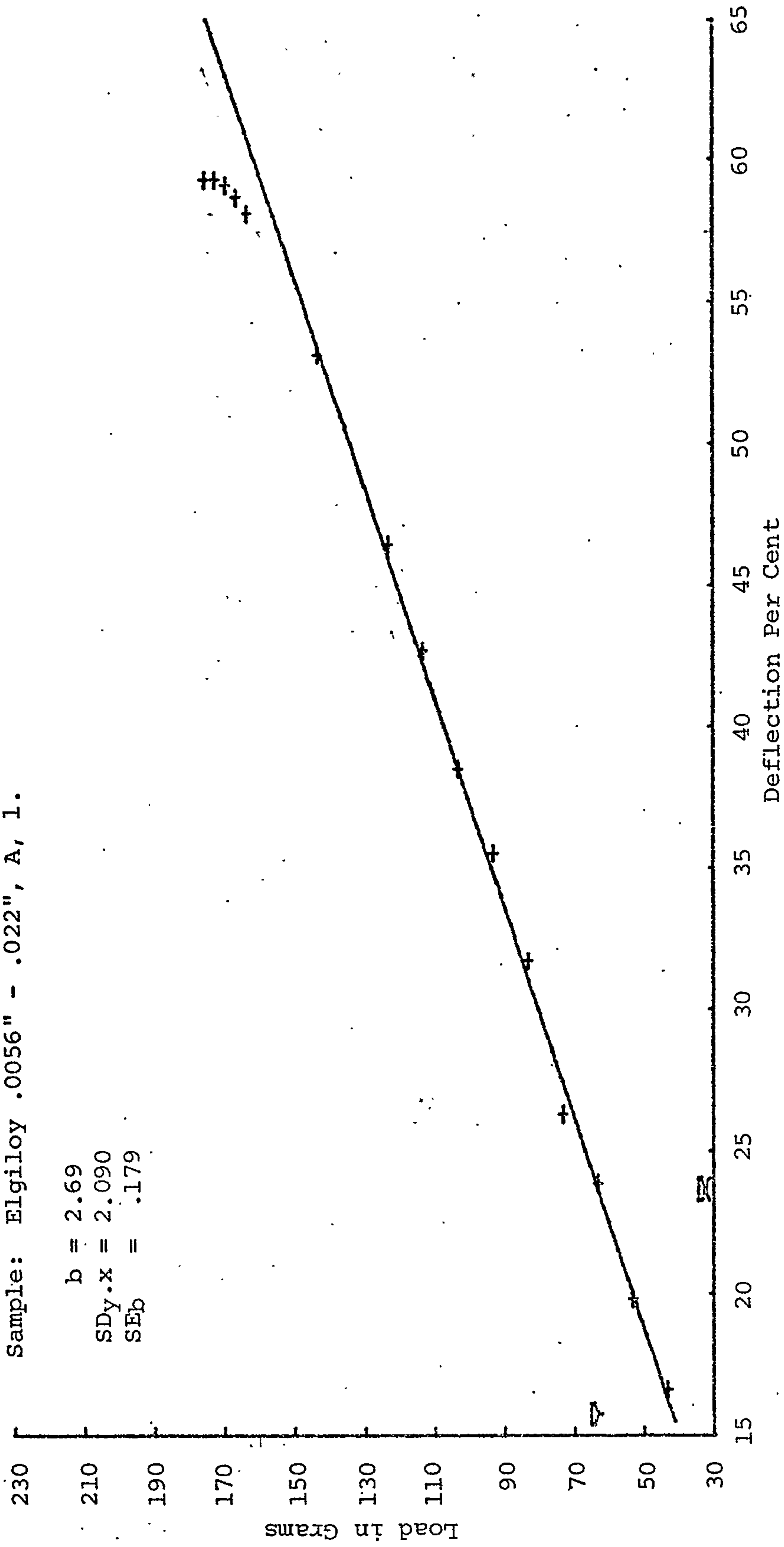


Fig. 52. Load-deflection regression of Elgiloy .0056" - .022" open coil helical spring loaded after it had been compressed solid once.

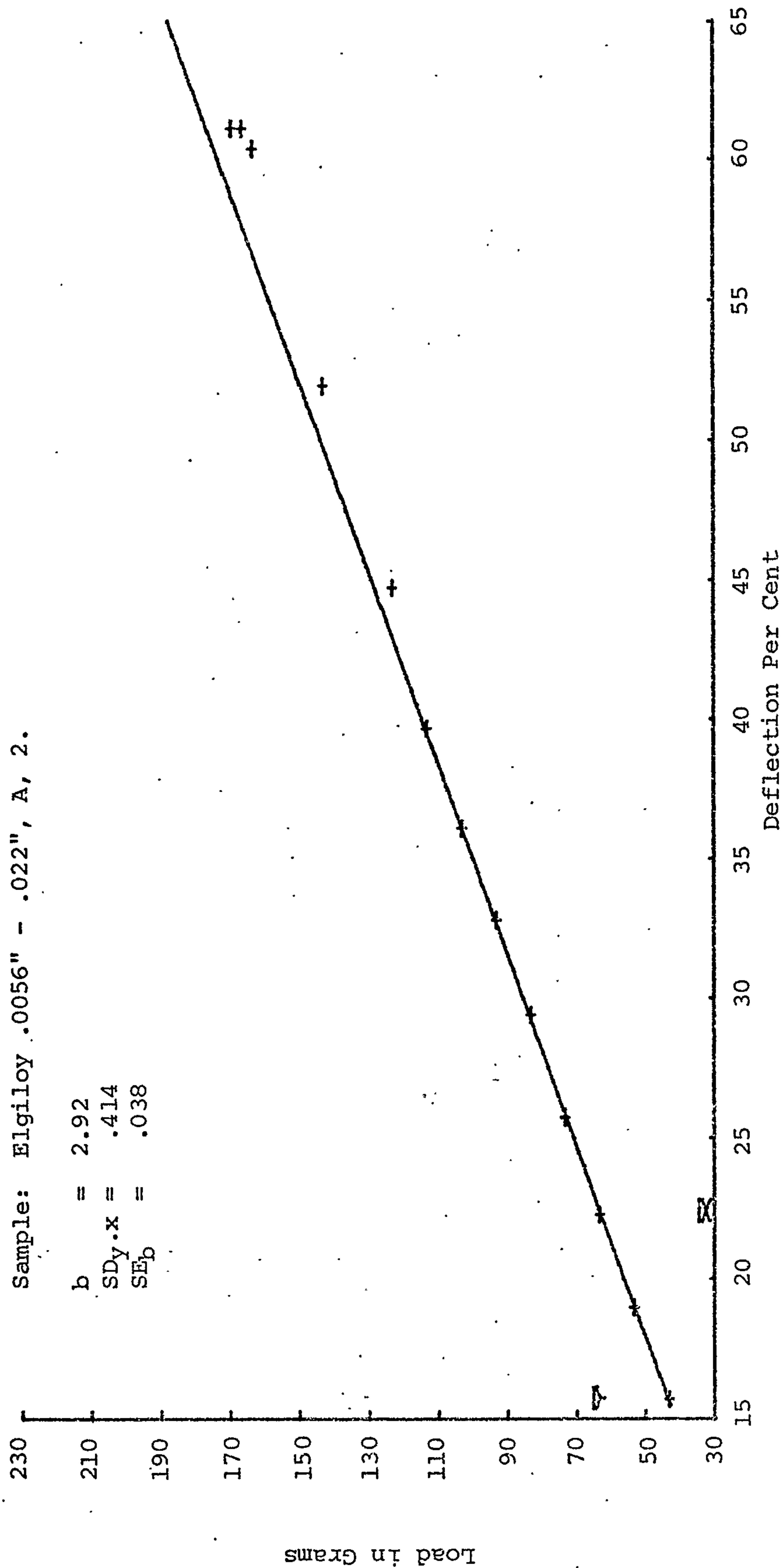


Fig. 53. Load-deflection regression of Elgiloy .0056" - .022" open coil helical spring loaded in as-received condition.

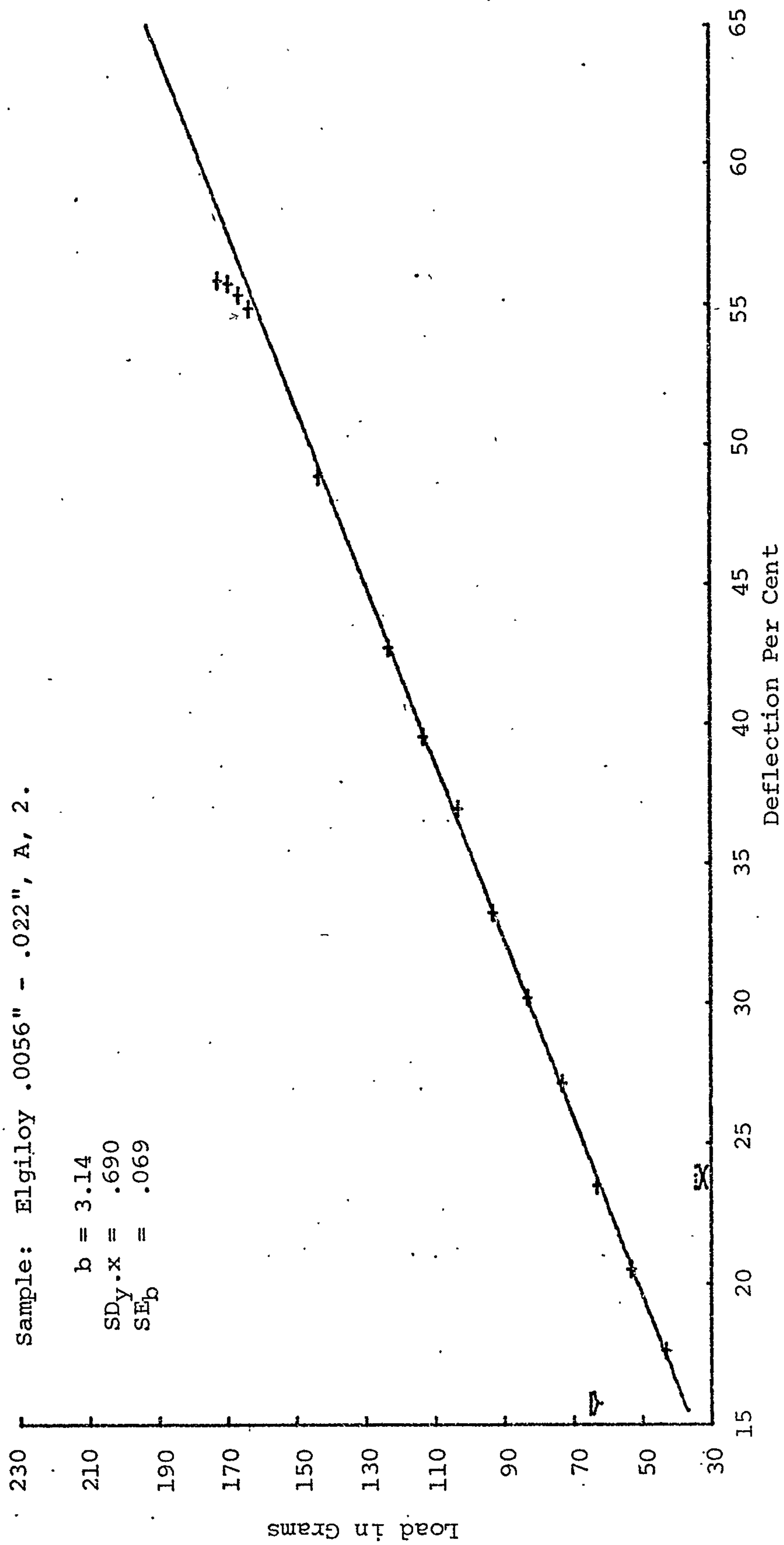


Fig. 54. Load-deflection regression of Elgiloy .0056" - .022" open coil helical spring loaded after it had been compressed solid once.

Sample: Elgiloy .0056" - .022", A, 3.

$b_2 = 2.93$
 $SDy \cdot x = .795$
 $SEb_2 = .056$

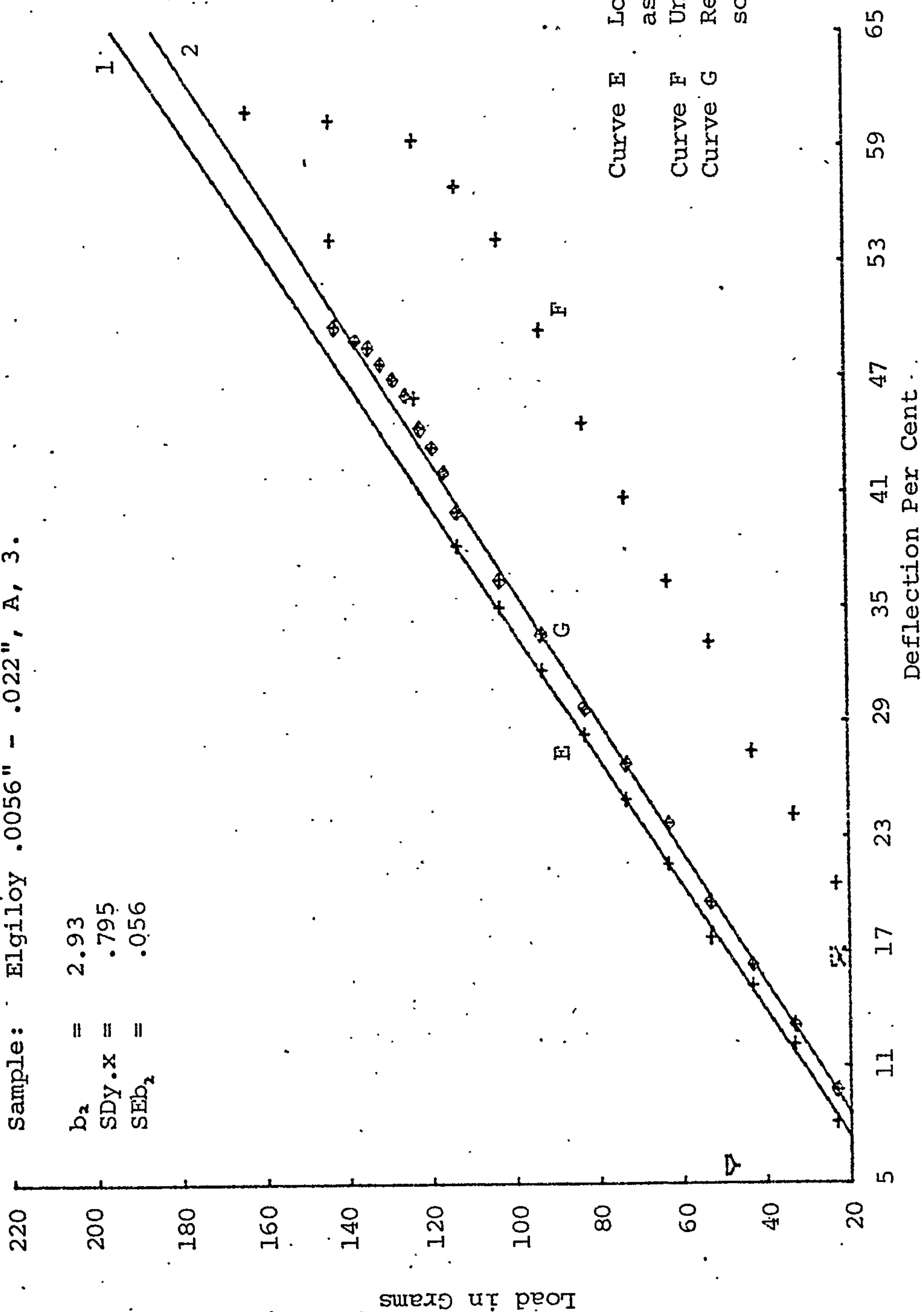


Fig. 55. Load-deflection regressions of Elgiloy .0056" - .022" open coil helical spring loaded in as-received condition (1) and after solid compression (2).

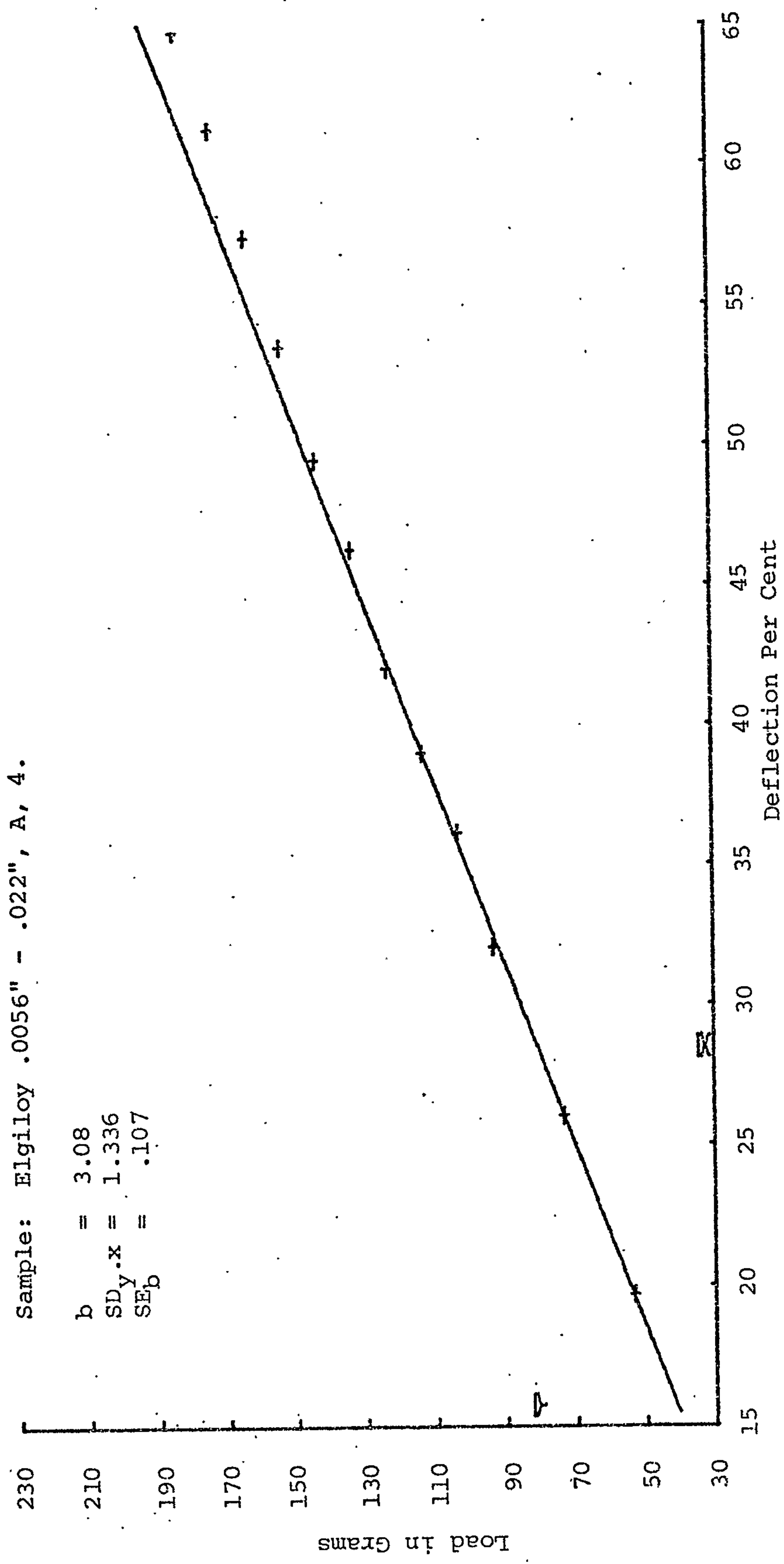


Fig. 56. Load-deflection regression of Elgiloy .0056" - .022" open coil helical spring loaded in as-received condition.

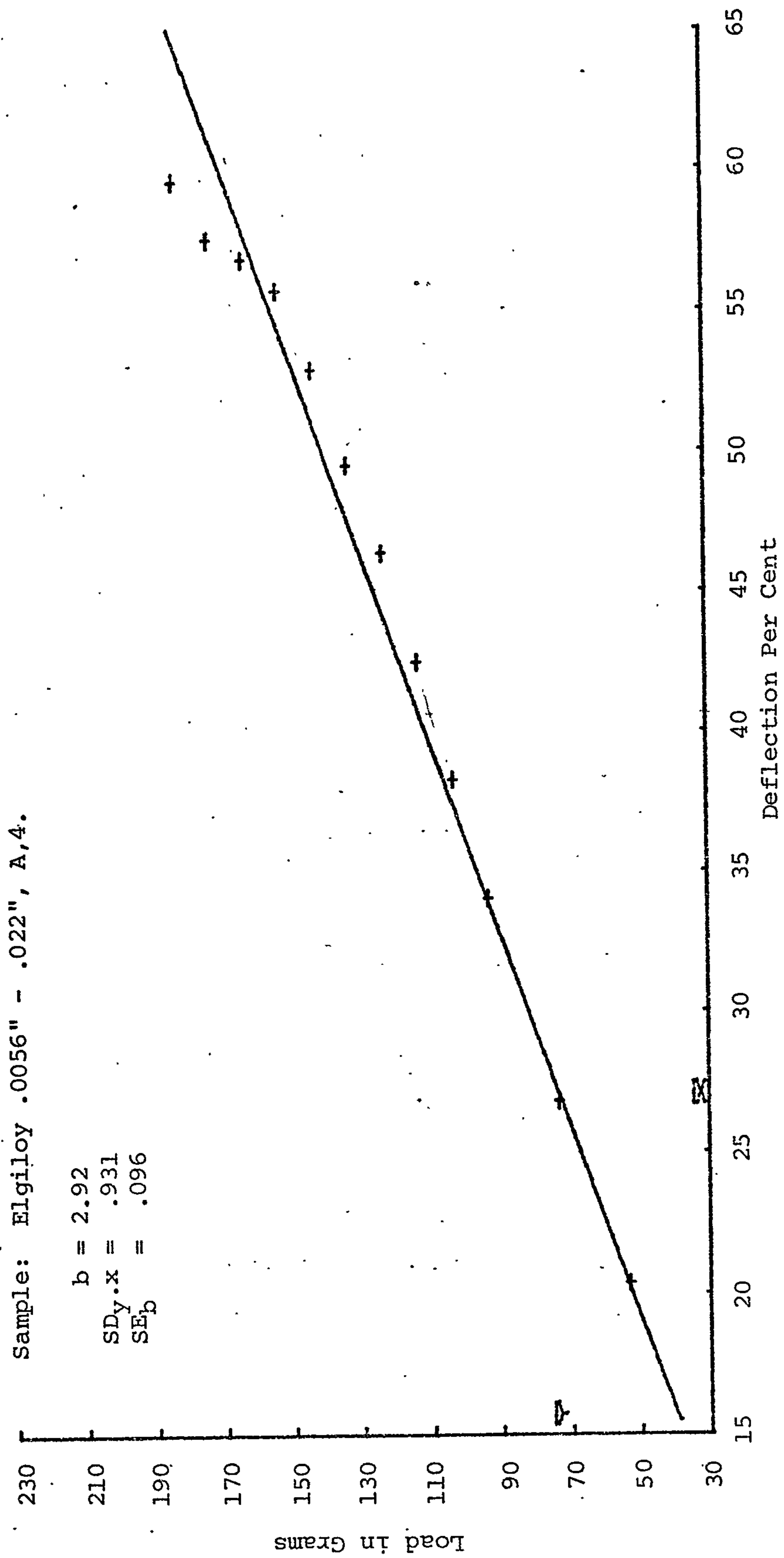


Fig. 57. Load-deflection regression of Elgiloy .0056" - .022" open coil helical spring loaded after it had been compressed solid once.

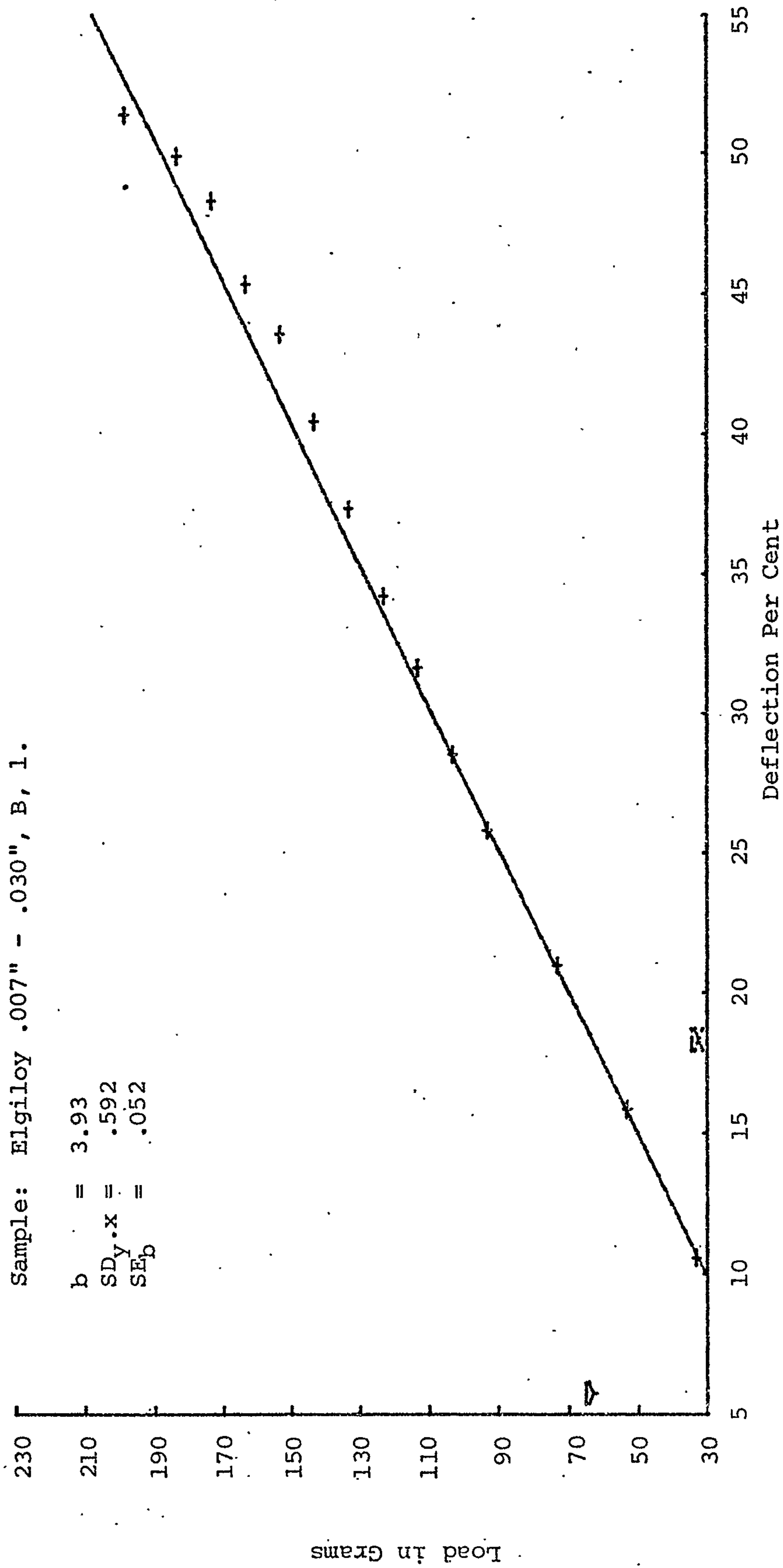


Fig. 58. Load-deflection regression of Elgiloy .007" - .030" open coil helical spring loaded in as-received condition.

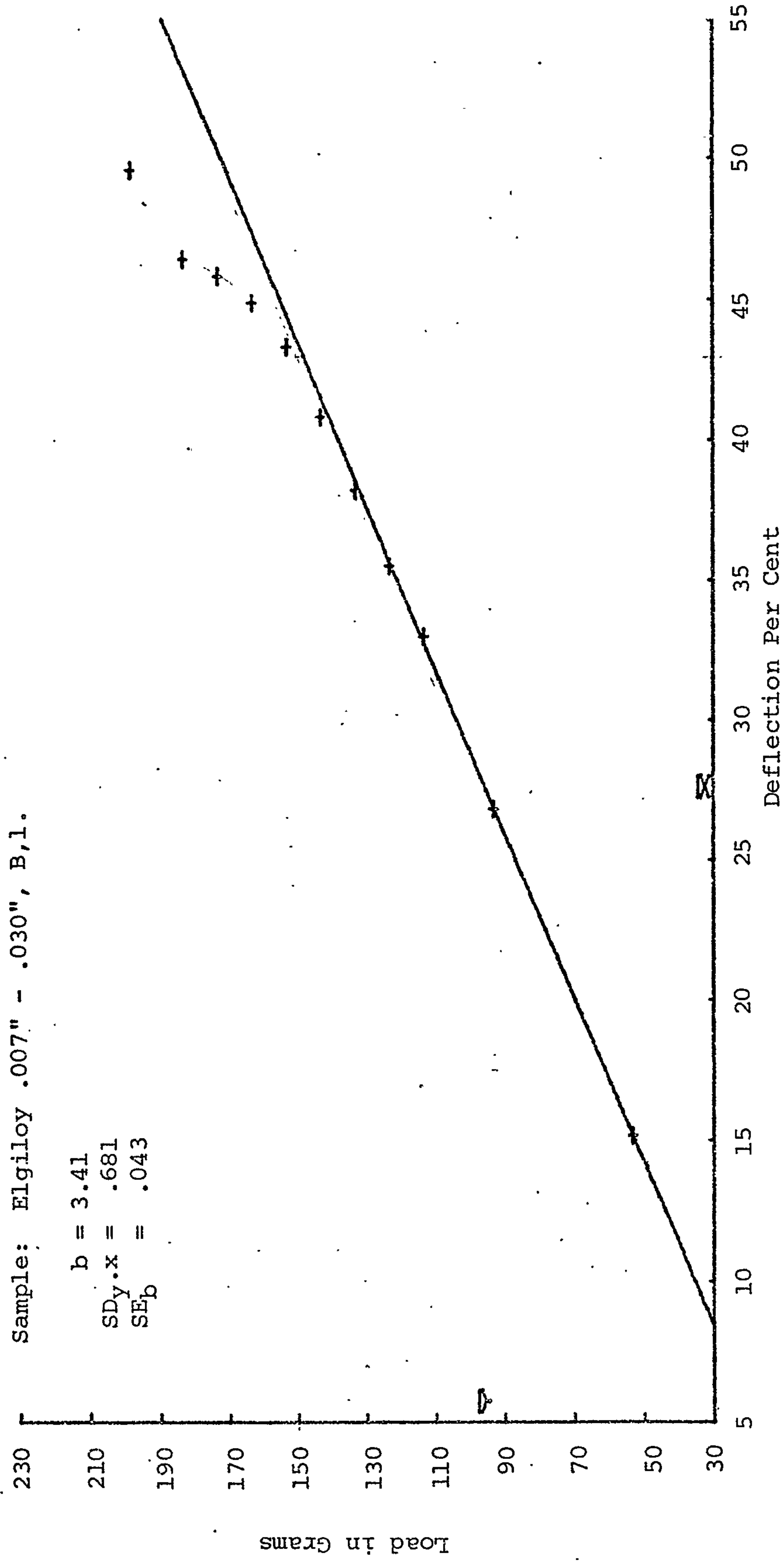


Fig. 59. Load-deflection regression of Elgiloy .007" - .030" open coil helical spring loaded after it had been compressed solid once.

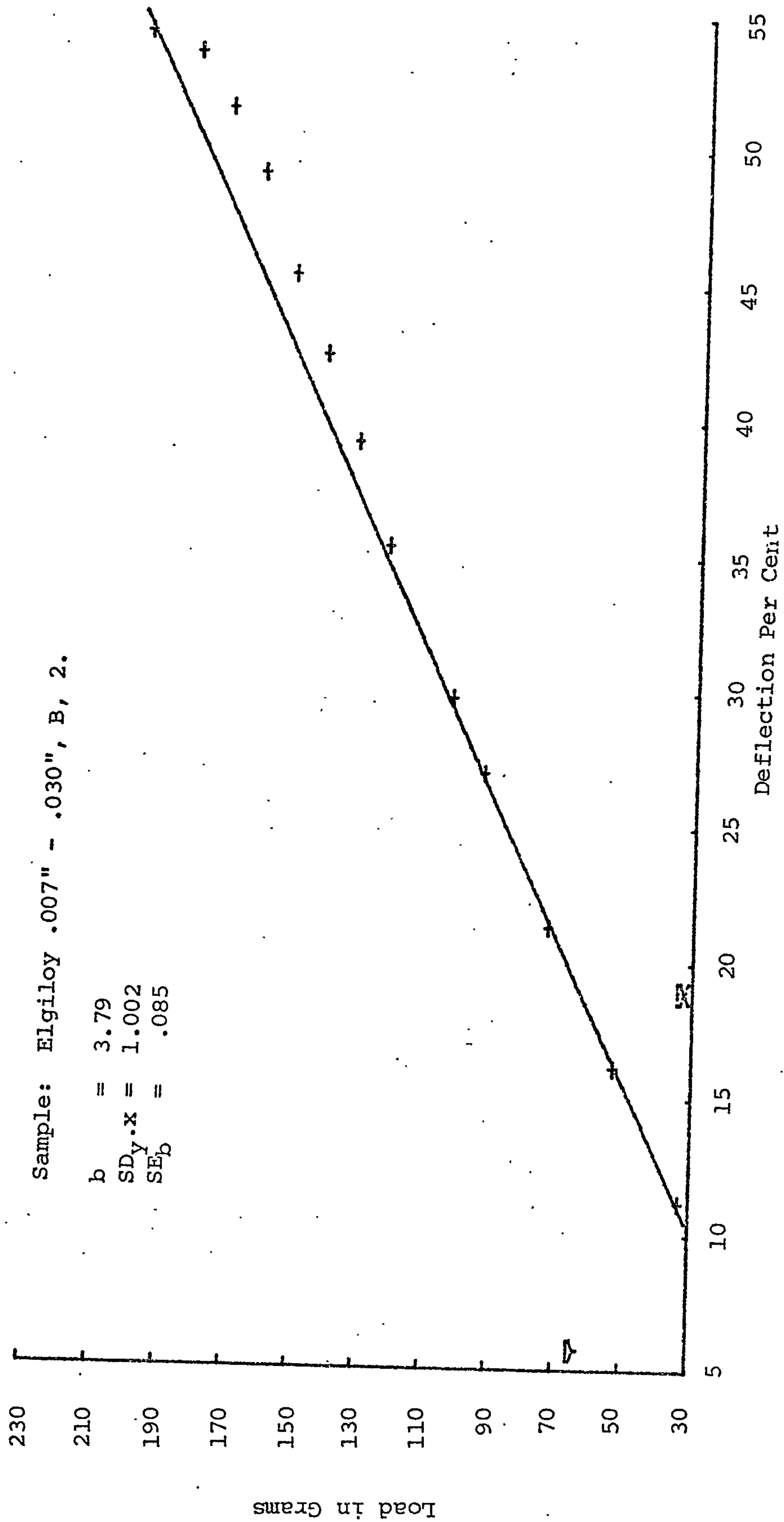


Fig. 60. Load-deflection regression of Elgiloy .007" - .030" open coil helical spring loaded in as-received condition.

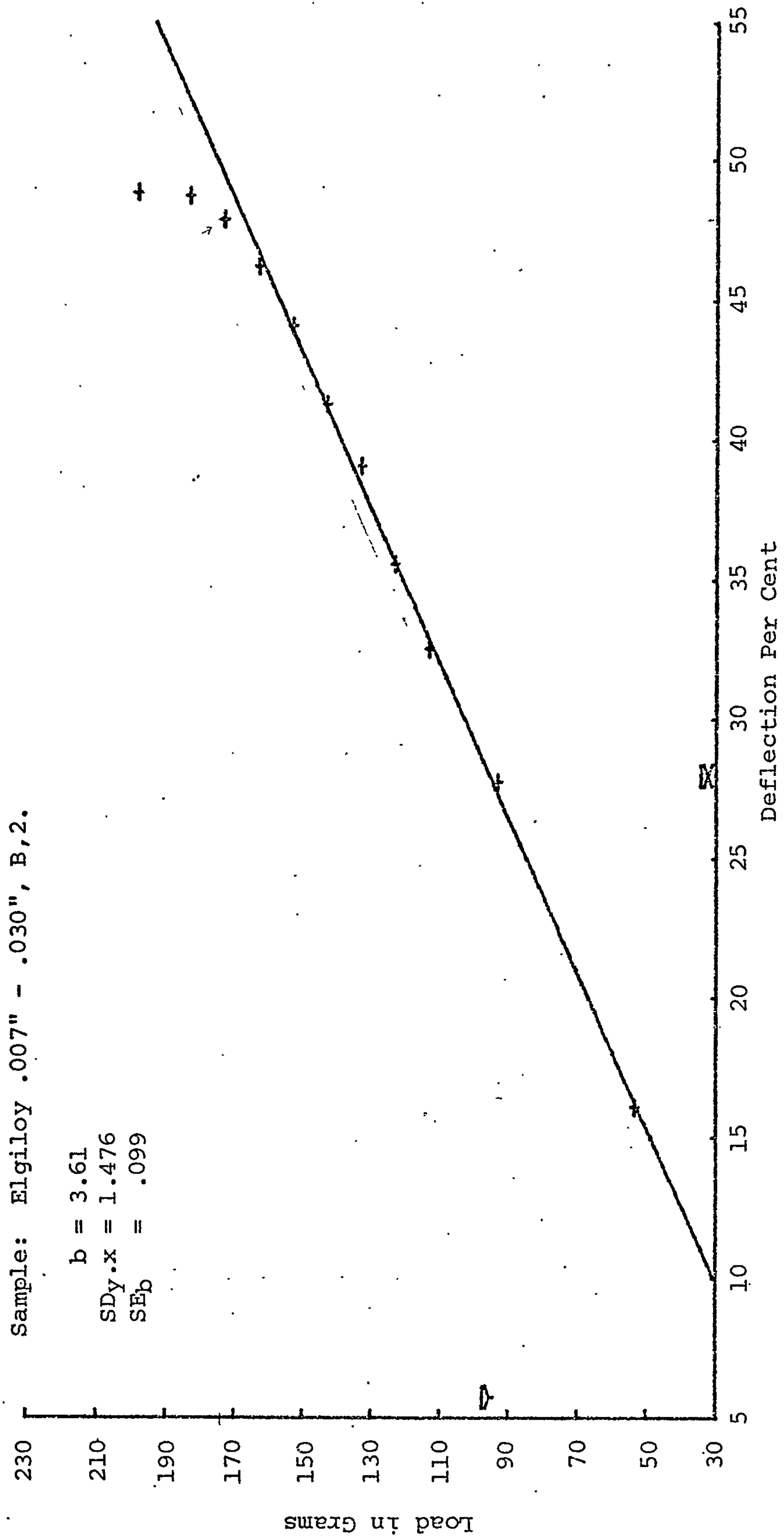


Fig. 61. Load-deflection regression of Elgiloy .007" - .030" open coil helical spring loaded after it had been compressed solid once.

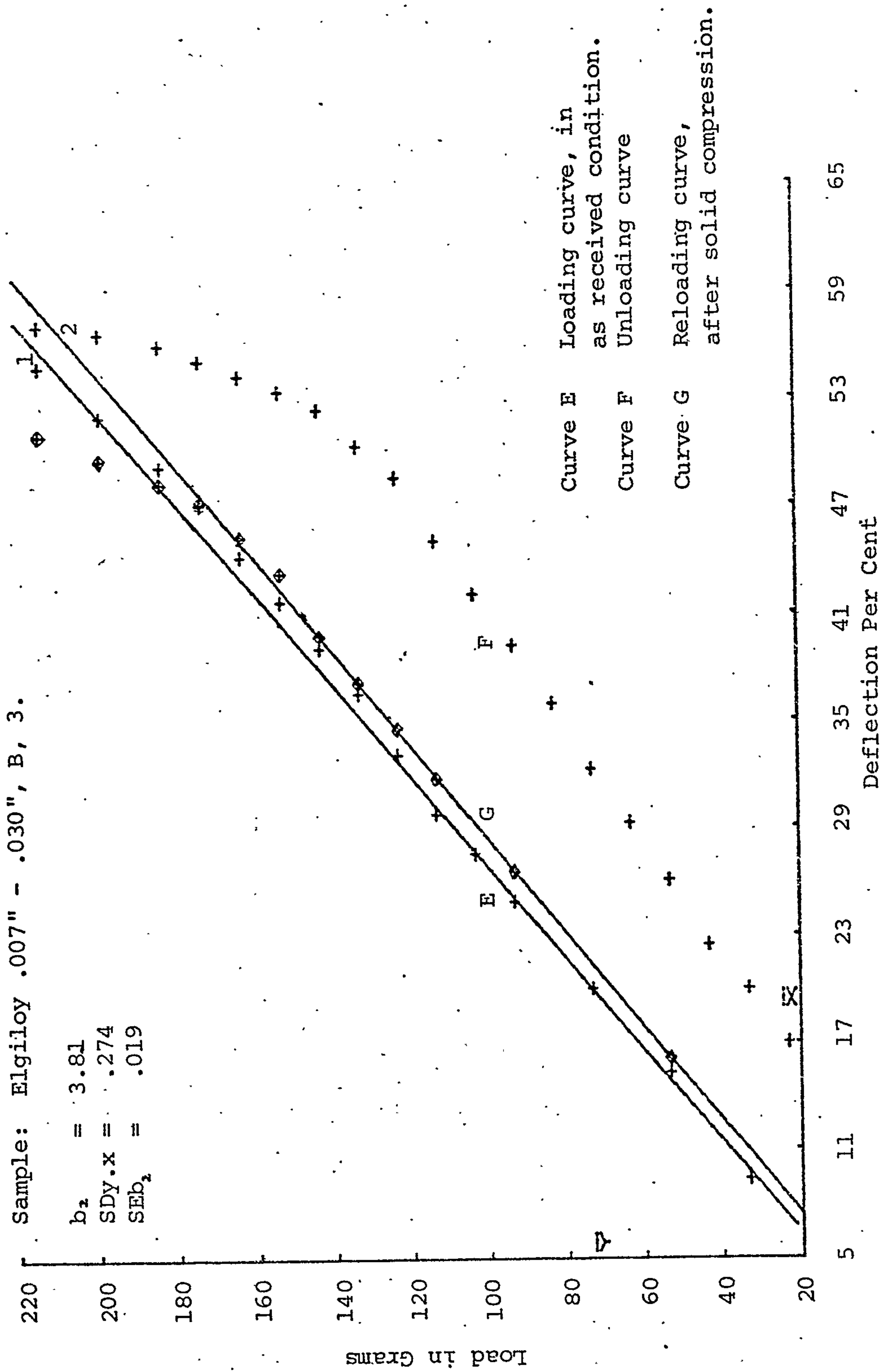


Fig. 62. Load-deflection regressions of Elgiloy .007" - .030" open coil helical spring loaded in as-received condition (1) and after solid compression (2).

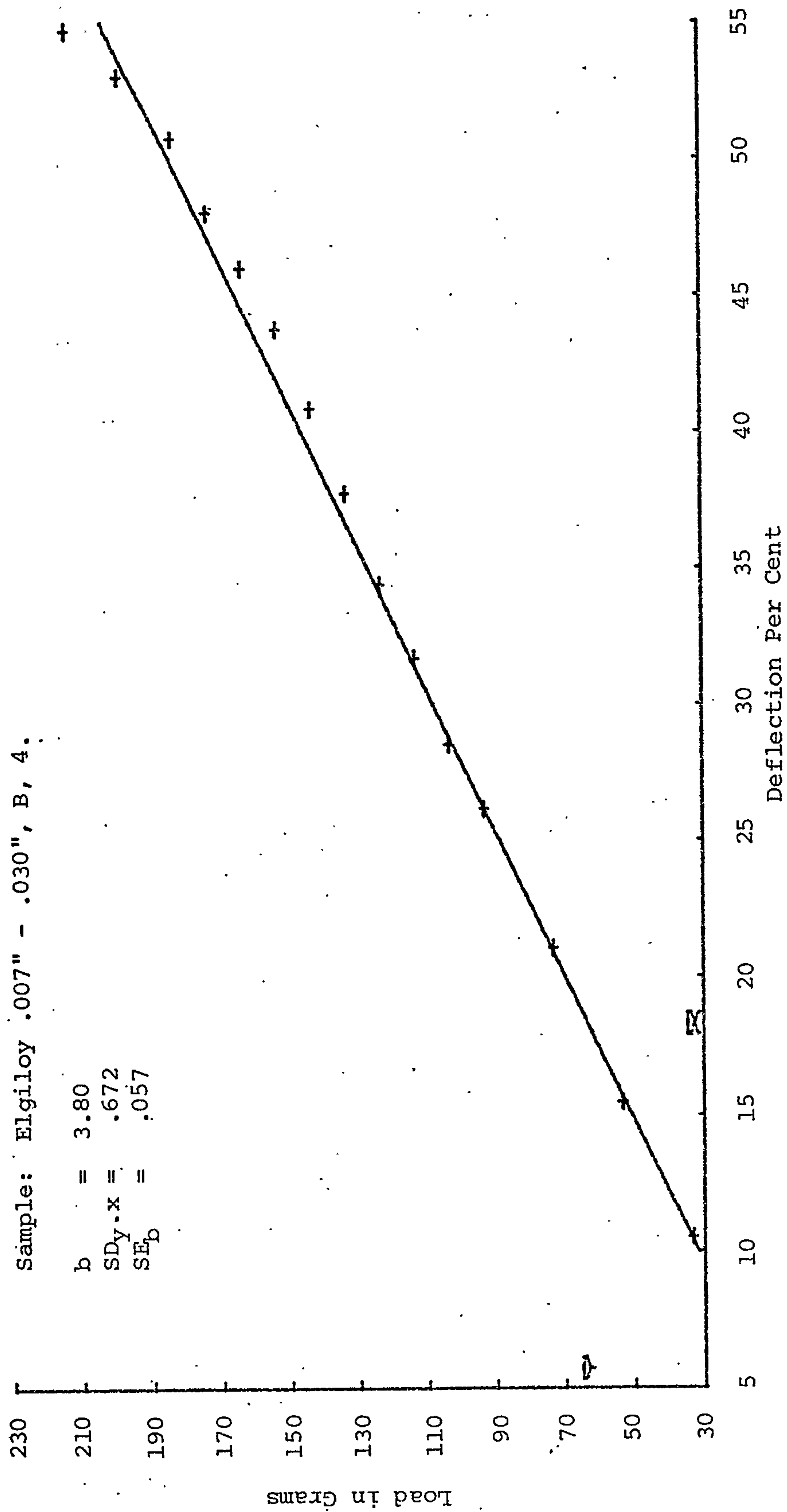


Fig. 63. Load-deflection regression of Elgiloy .007" - .030" open coil helical spring loaded in as-received condition.

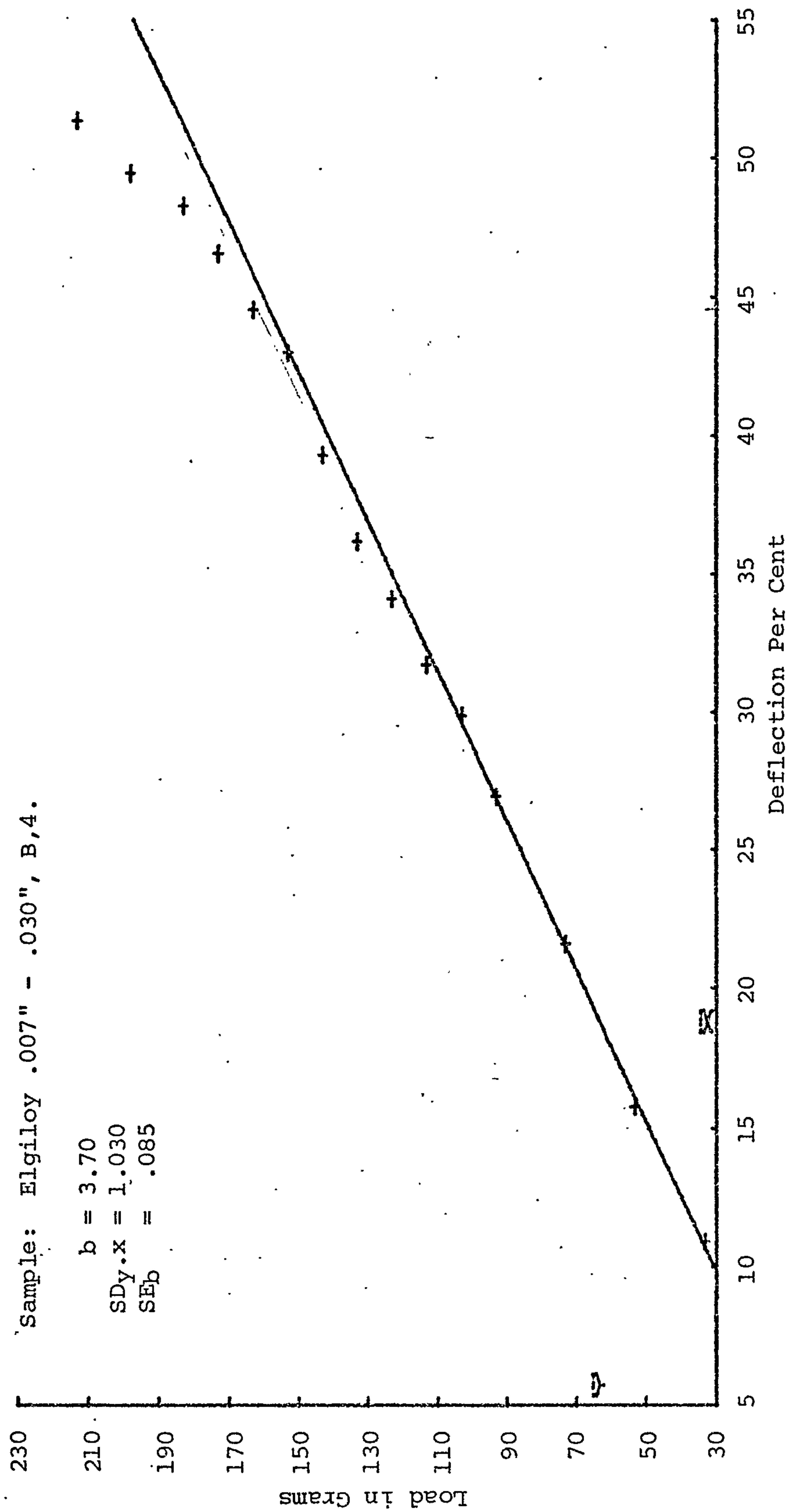


Fig. 64. Load-deflection regression of Elgiloy .007" - .030" open coil helical spring loaded after it had been compressed solid once.

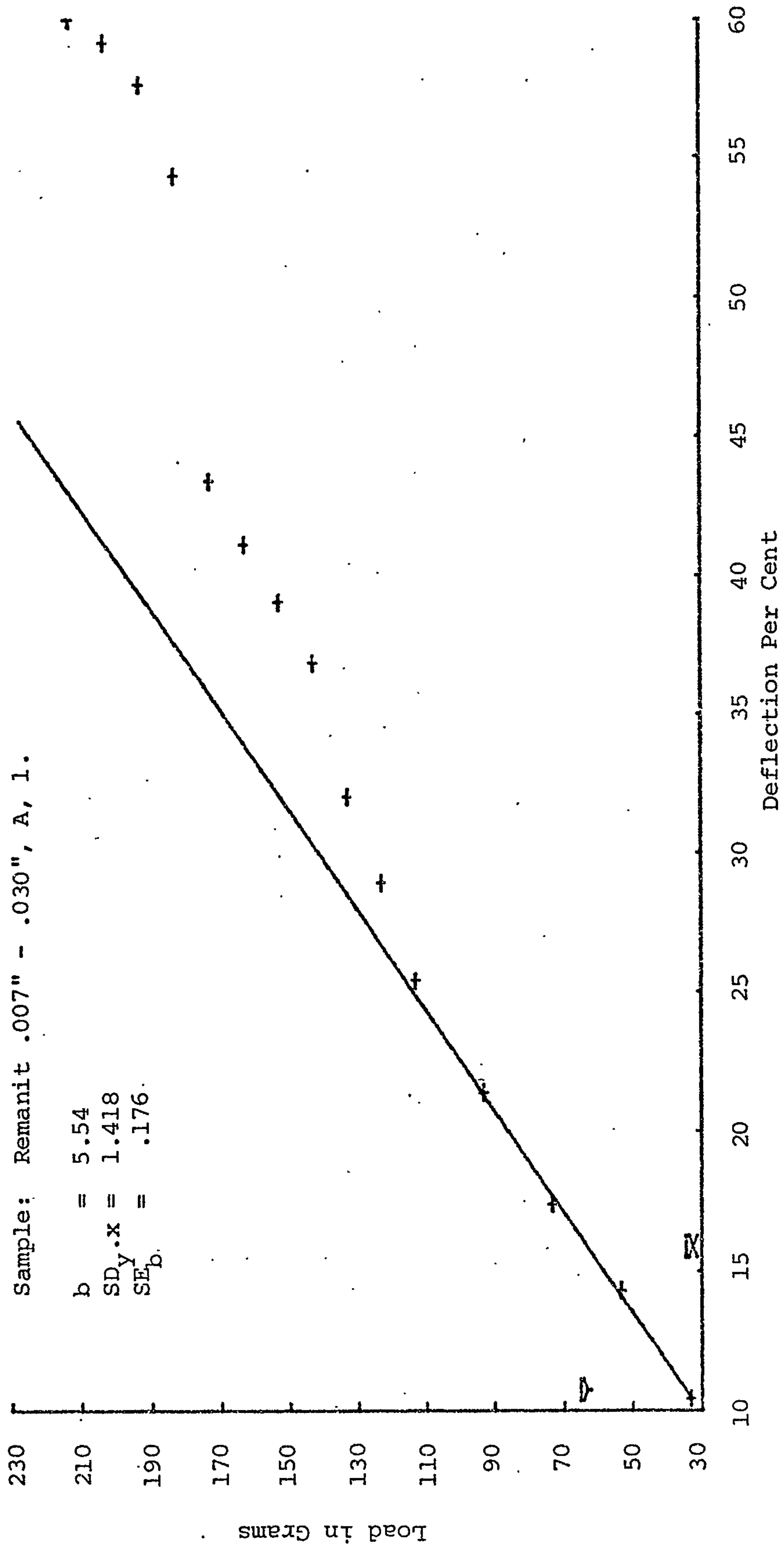


Fig. 65. Load-deflection regression of Remanit .007" - .030" open coil helical spring loaded in as-received condition.

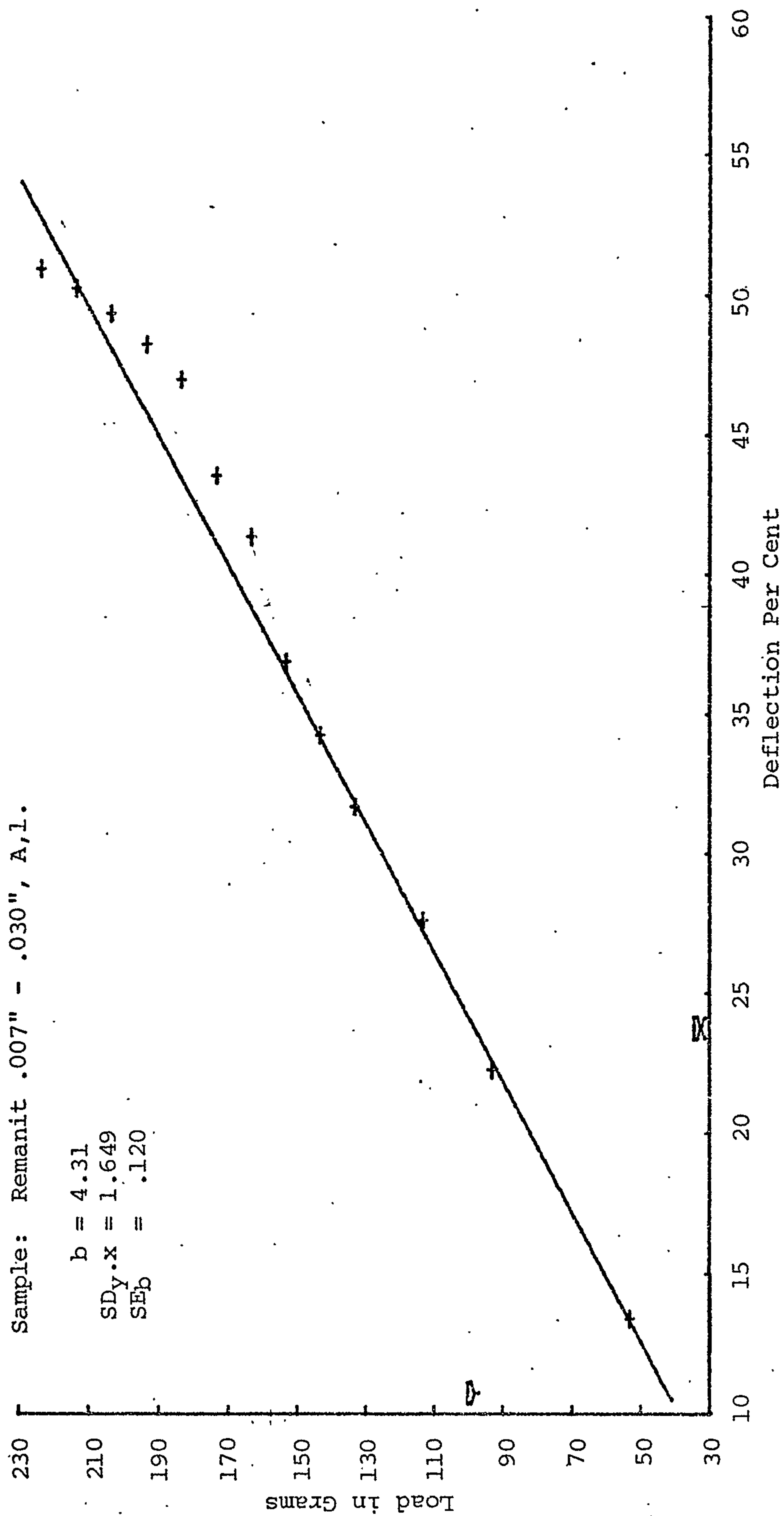


Fig. 66. Load-deflection regression of Remanit .007" - .030" open coil helical spring loaded after it had been compressed solid once.

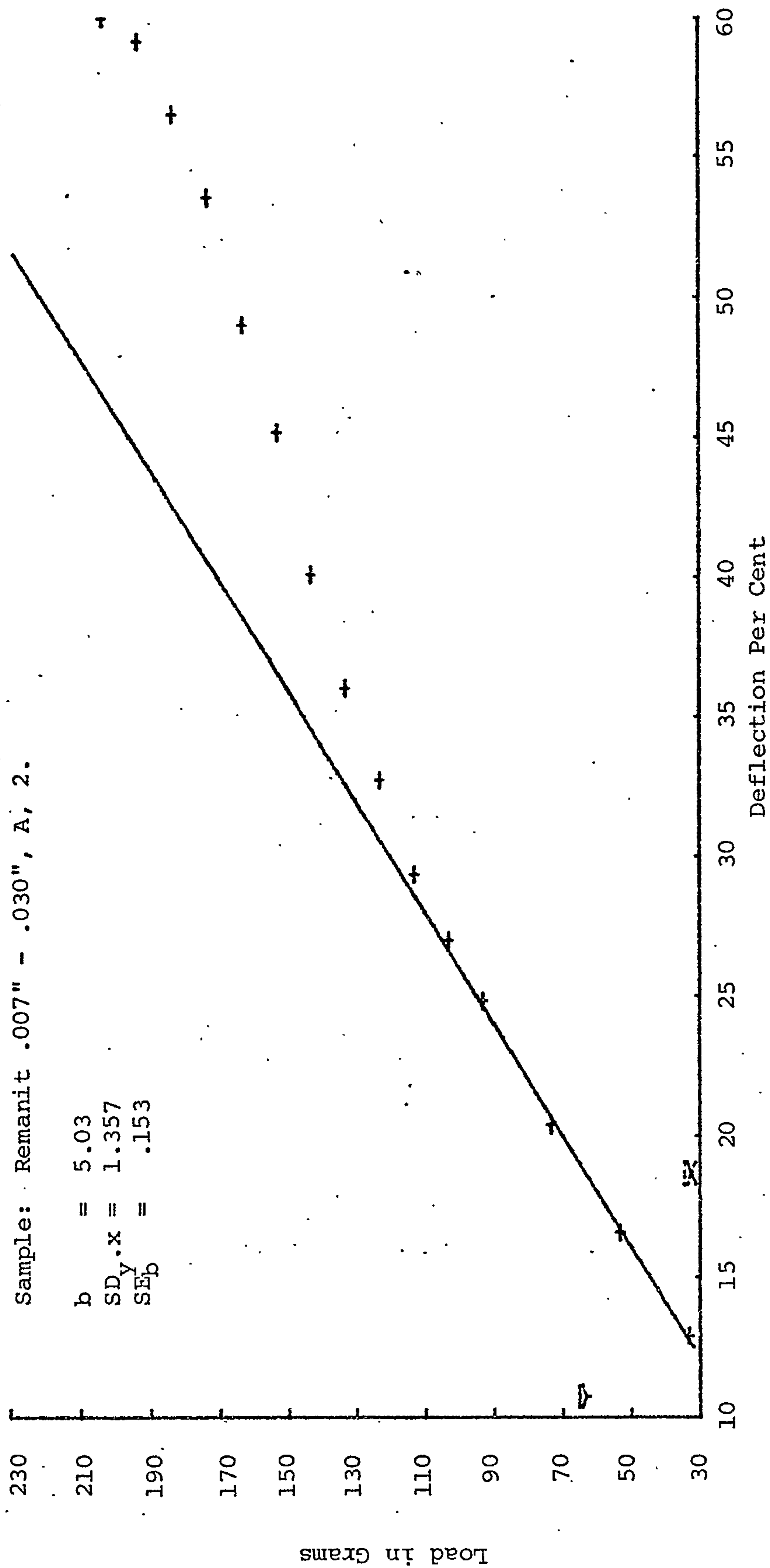


Fig. 67. Load-deflection regression of Remanit .007" - .030" open coil helical spring loaded in as-received condition.

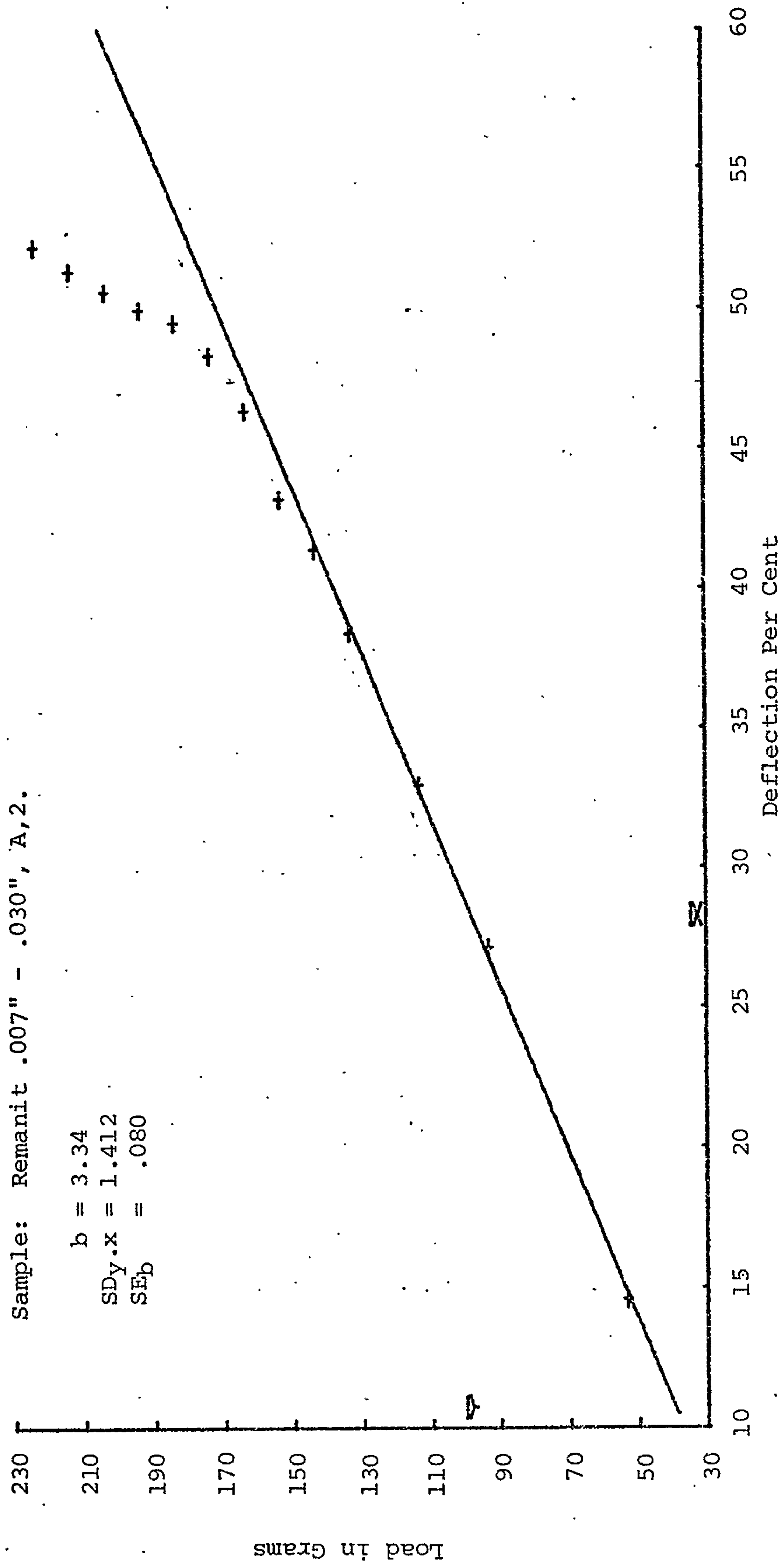


Fig. 68. Load-deflection regression of Remanit .007" - .030" open coil helical spring loaded after it had been compressed solid once.

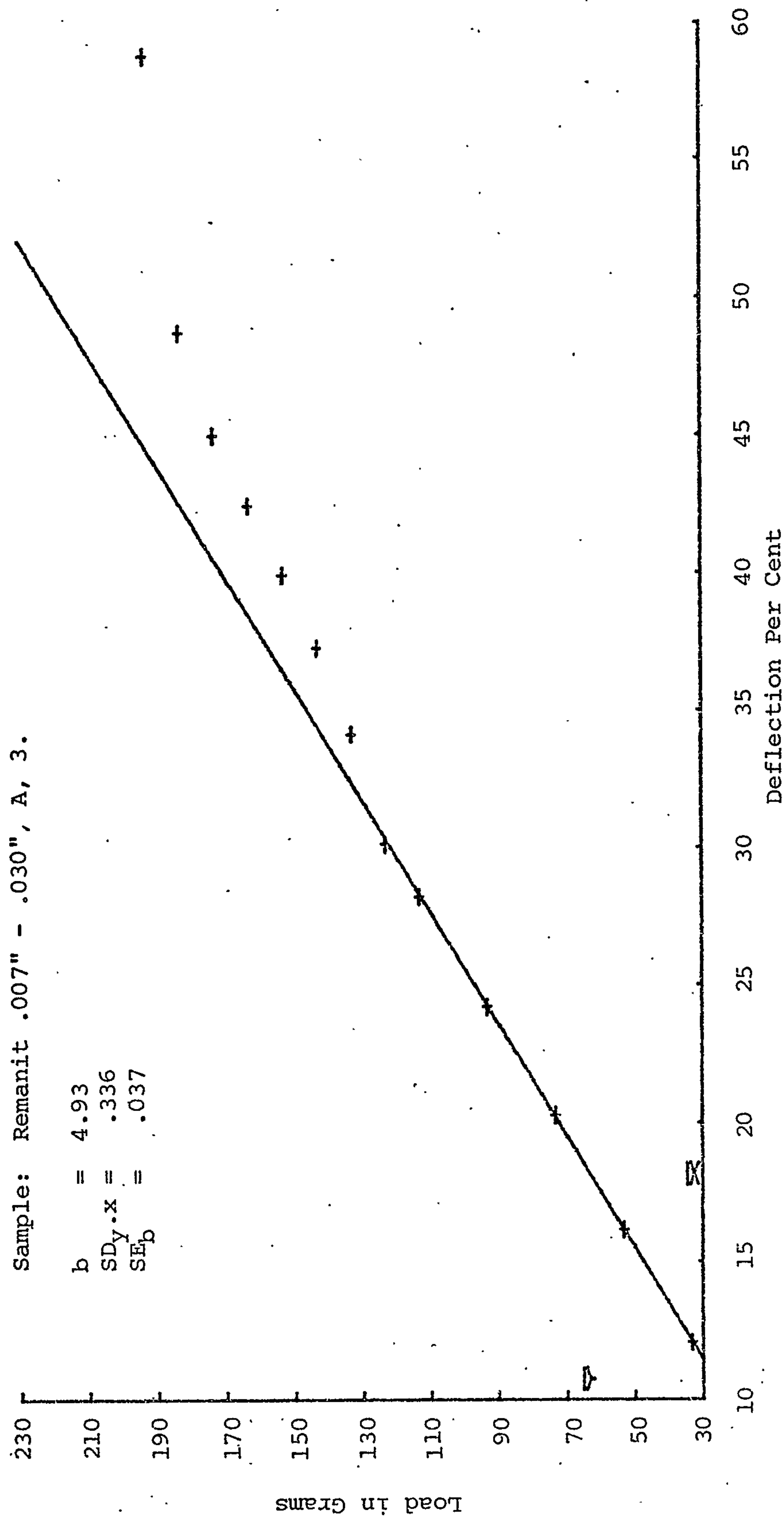


Fig. 69. Load-deflection regression of Remanit .007" - .030" open coil helical spring loaded in as-received condition.

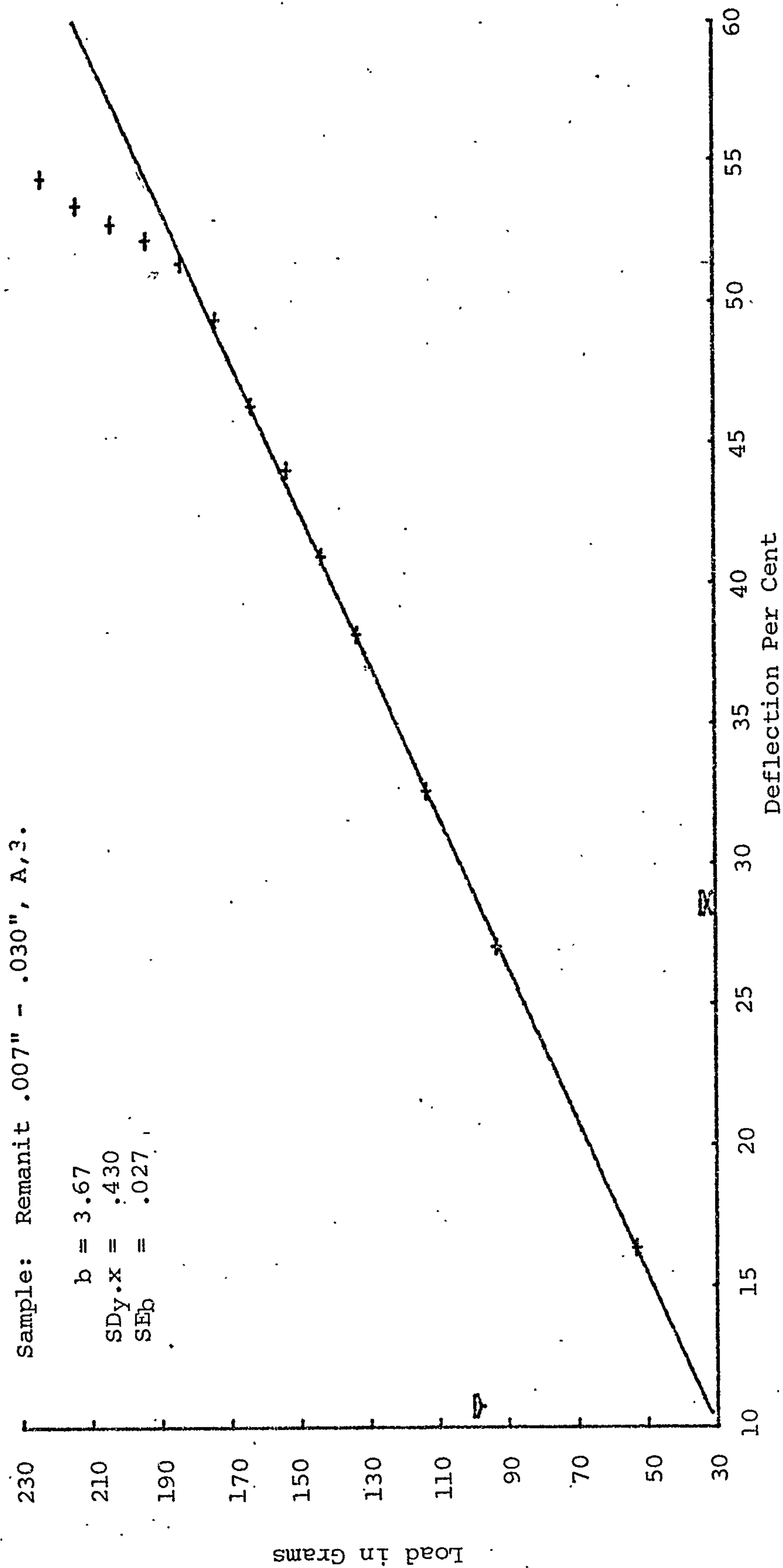


Fig. 70. Load-deflection regression of Remanit .007" - .030" open coil helical spring loaded after it had been compressed solid once.

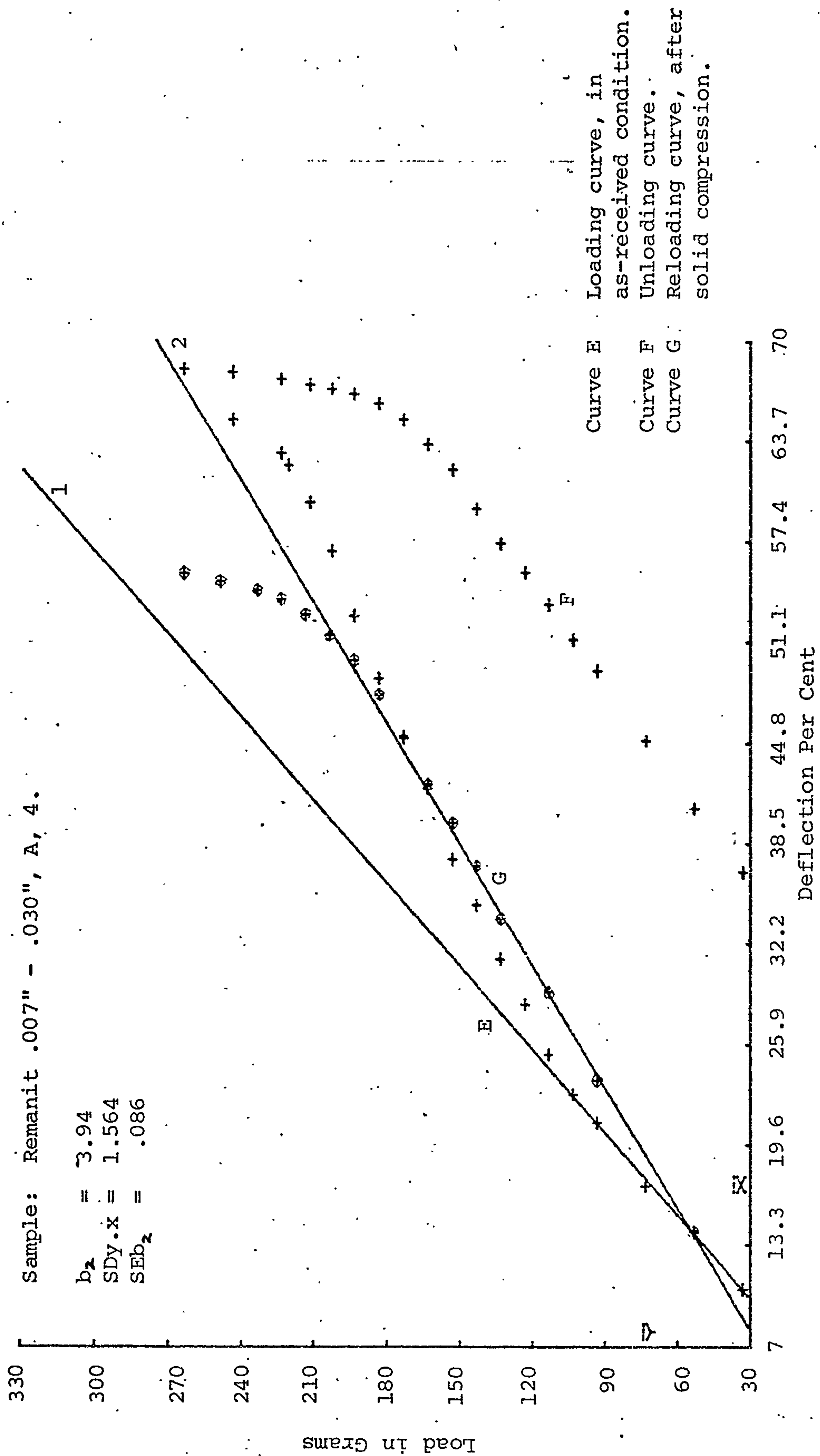


Fig. 71. Load-deflection regressions of Remanit .007" - .030" open coil helical spring loaded in as-received condition (1) and after solid compression (2).

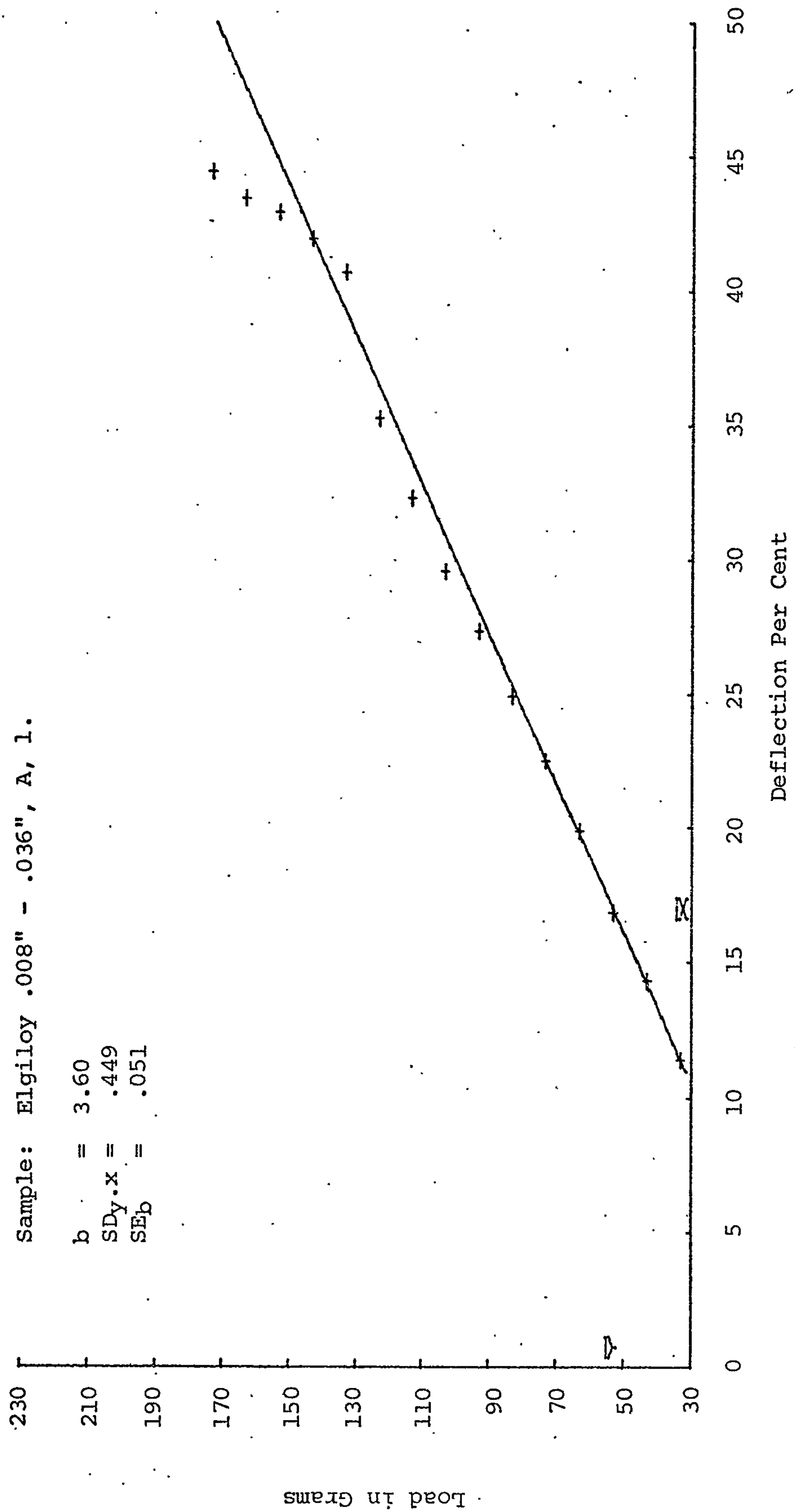


Fig. 72. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

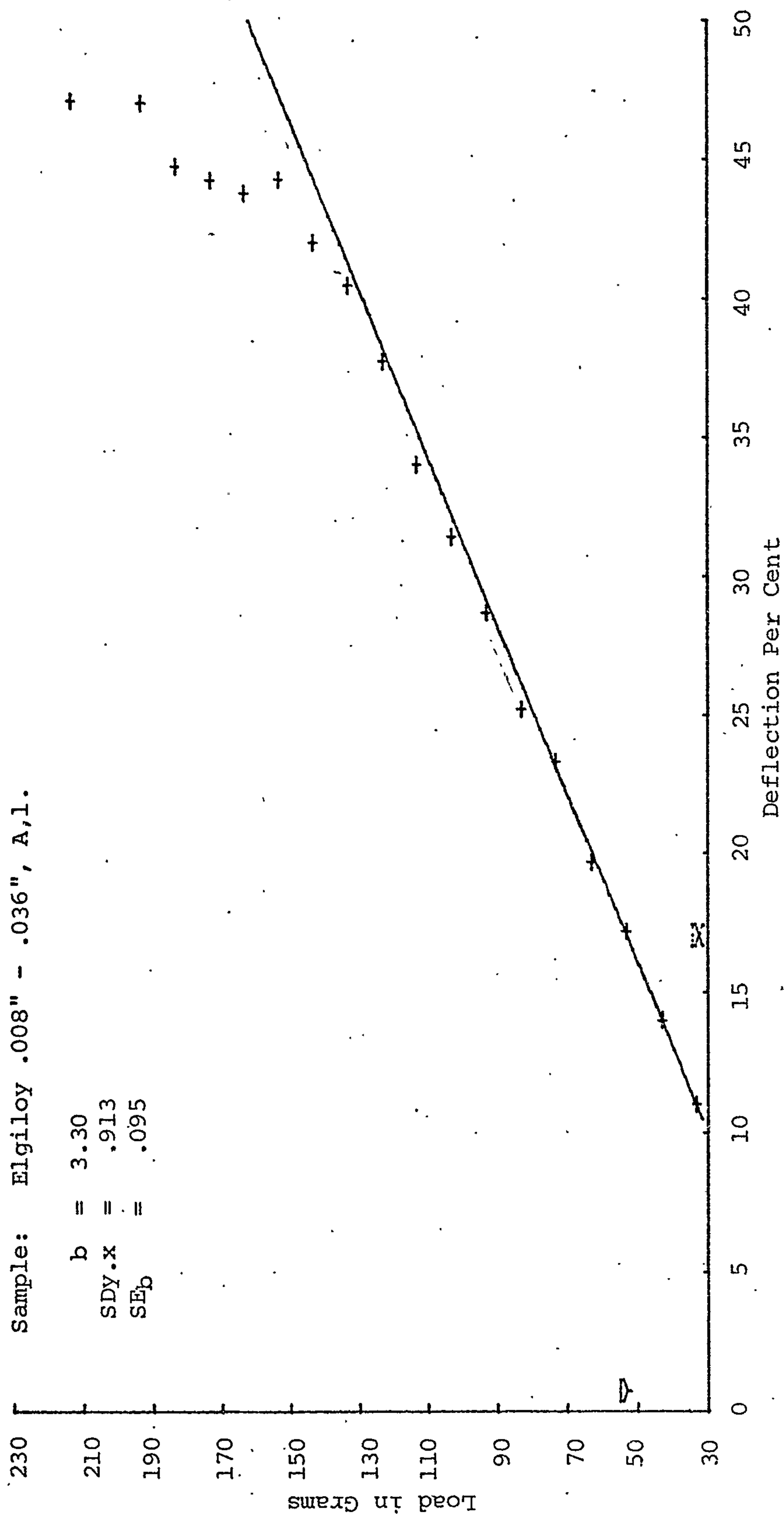


Fig. 73. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

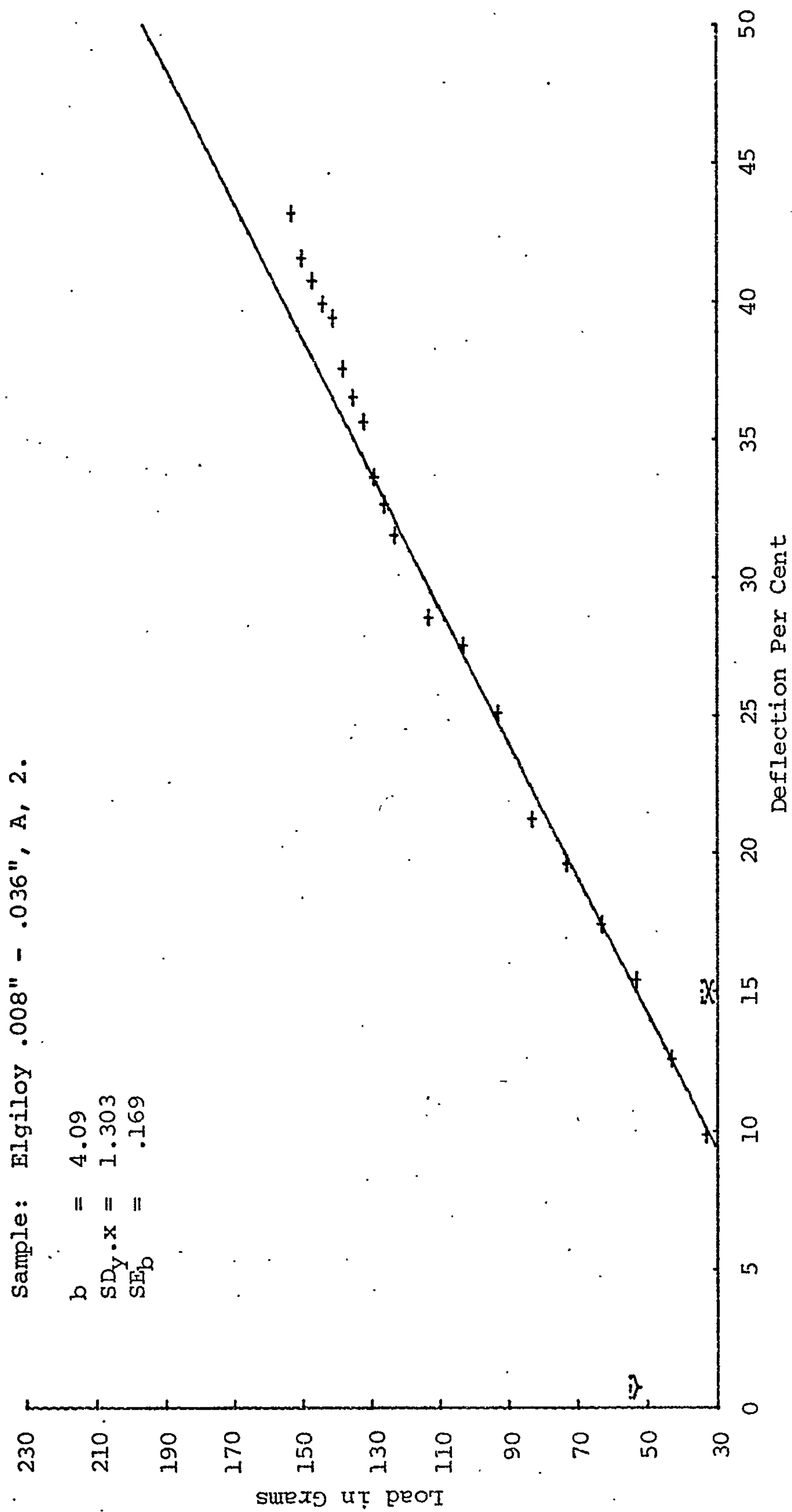


Fig. 74. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

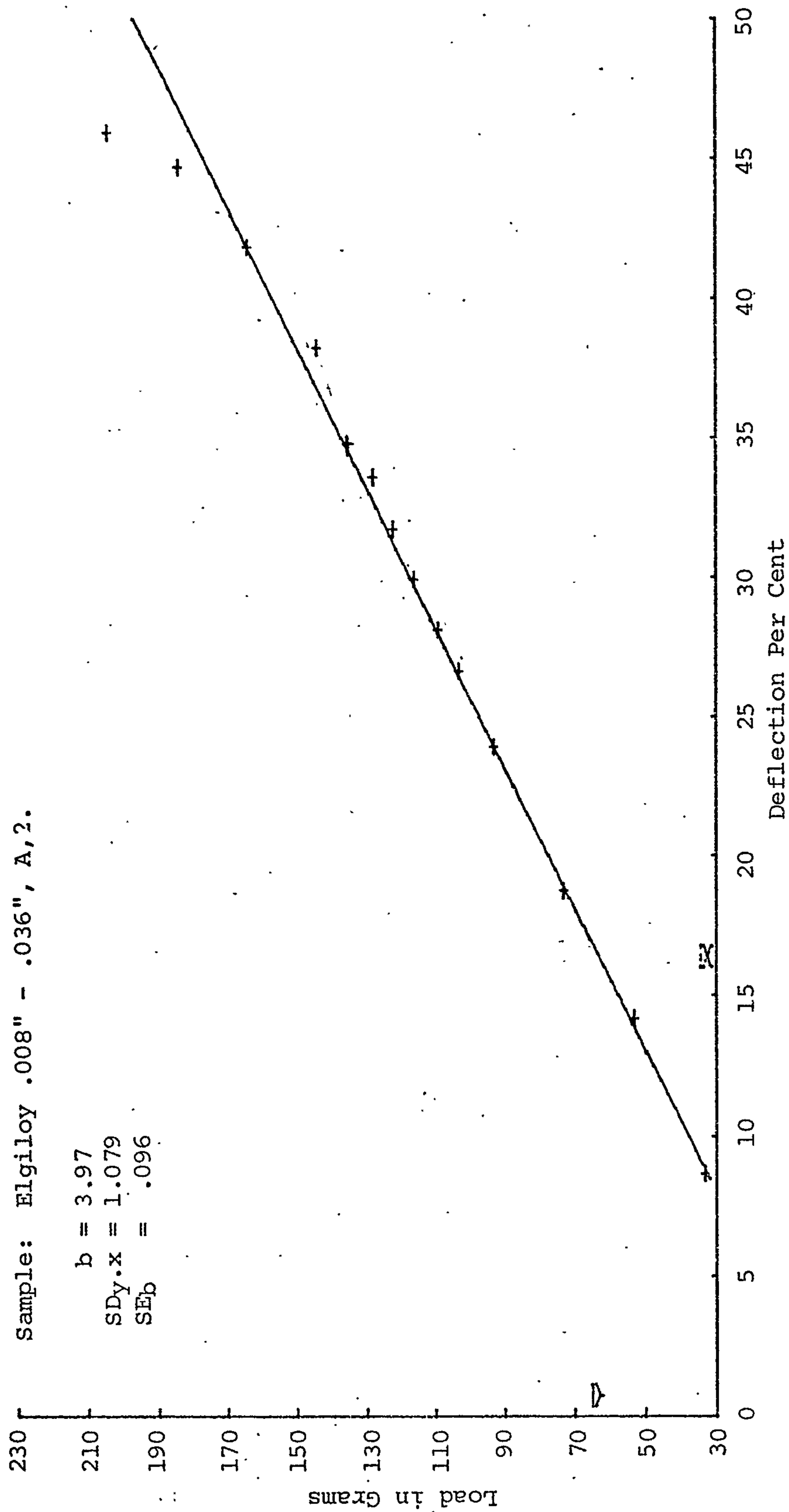


Fig. 75. Load-deflection regression of Elgiloy .008" - .036" open coil hilical spring loaded after it had been compressed solid once.

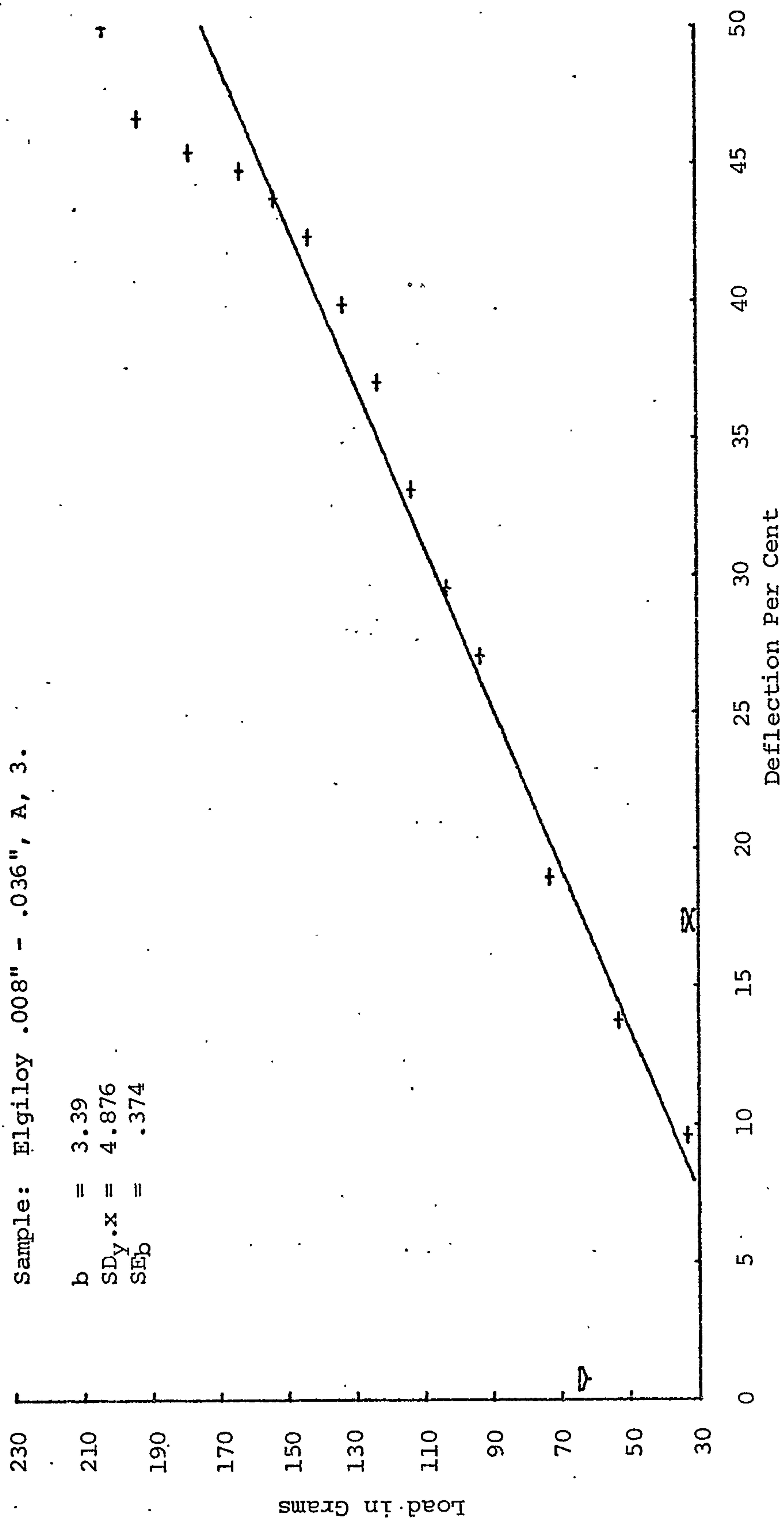


Fig. 76. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

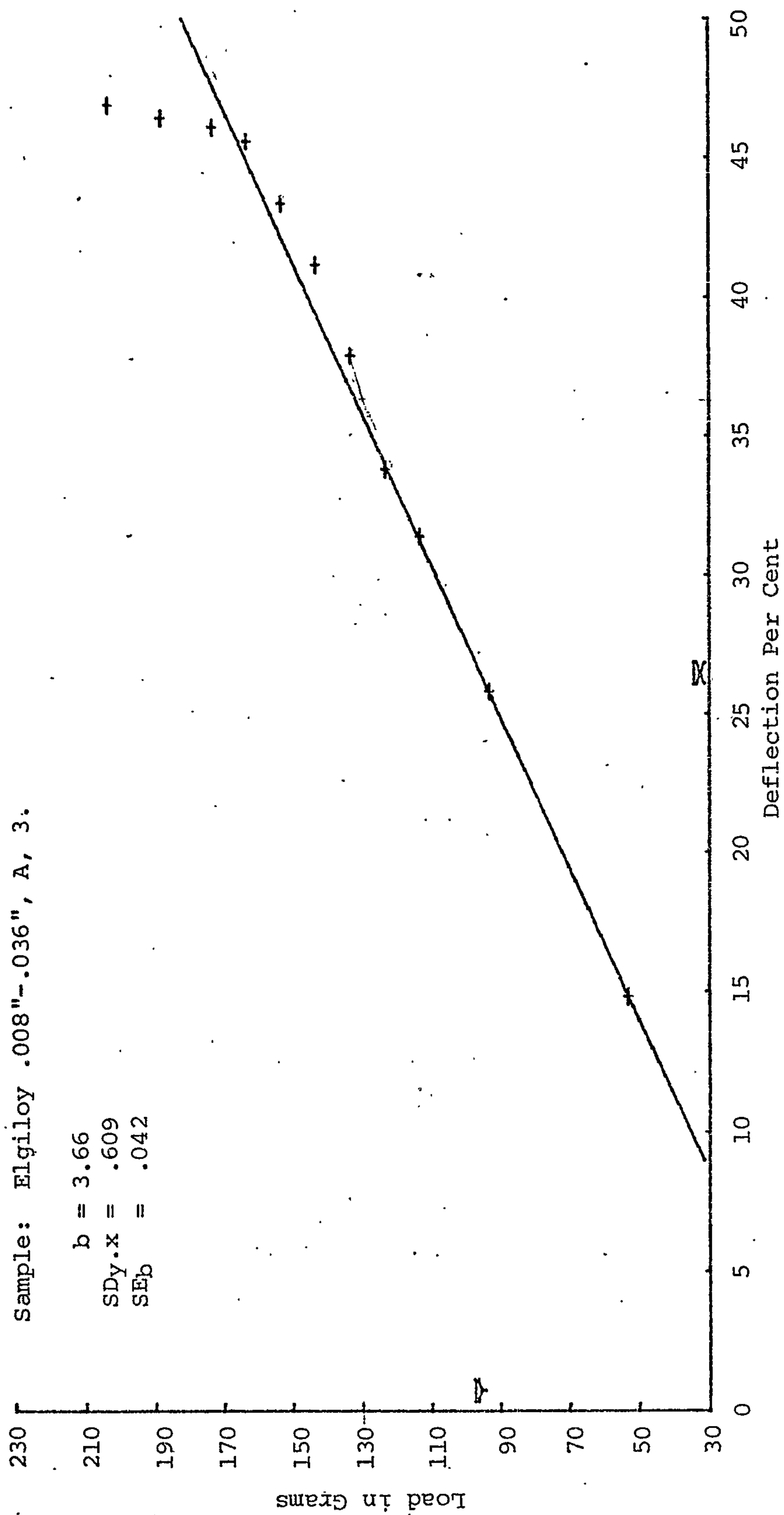


Fig. 77. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

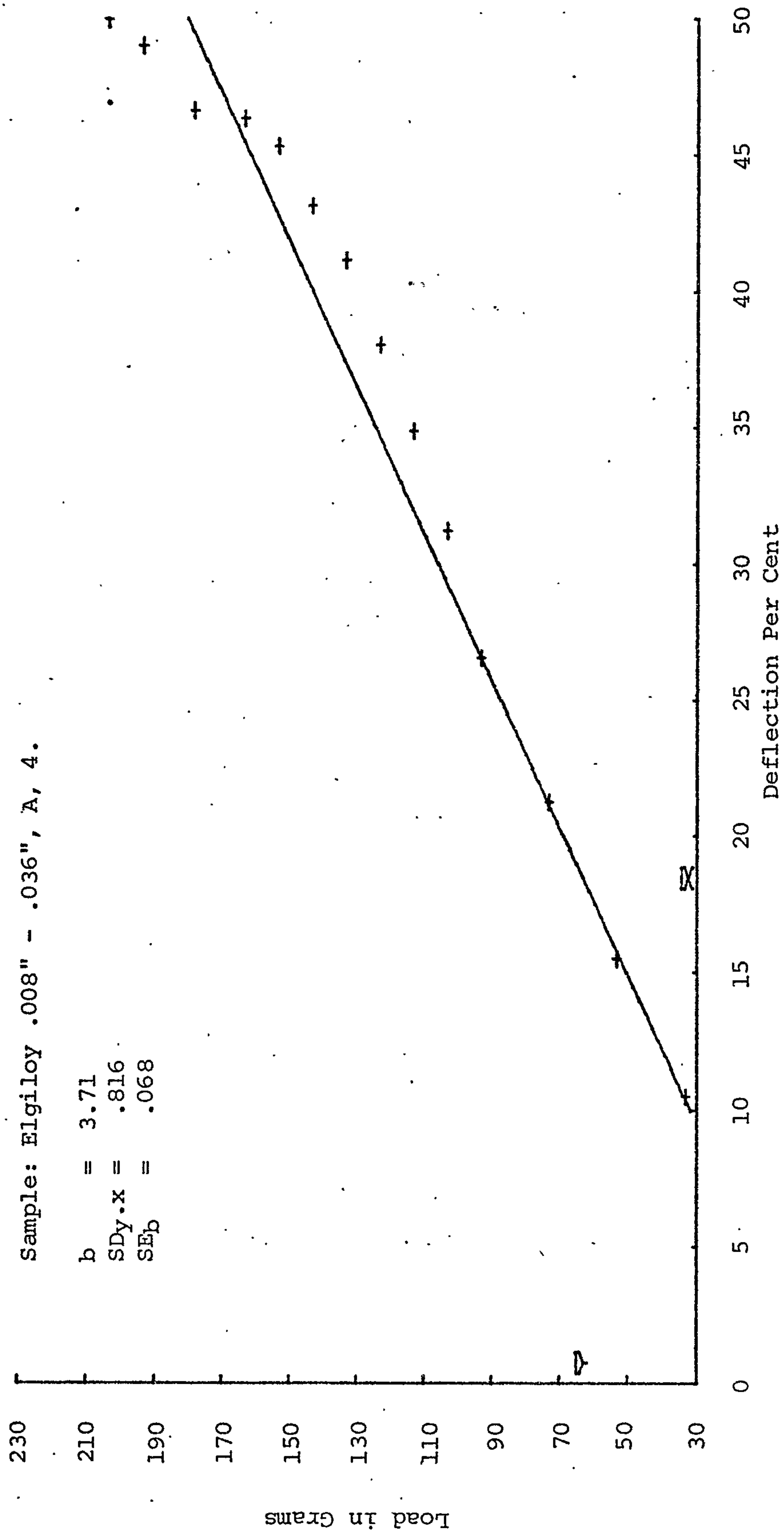


Fig. 78. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

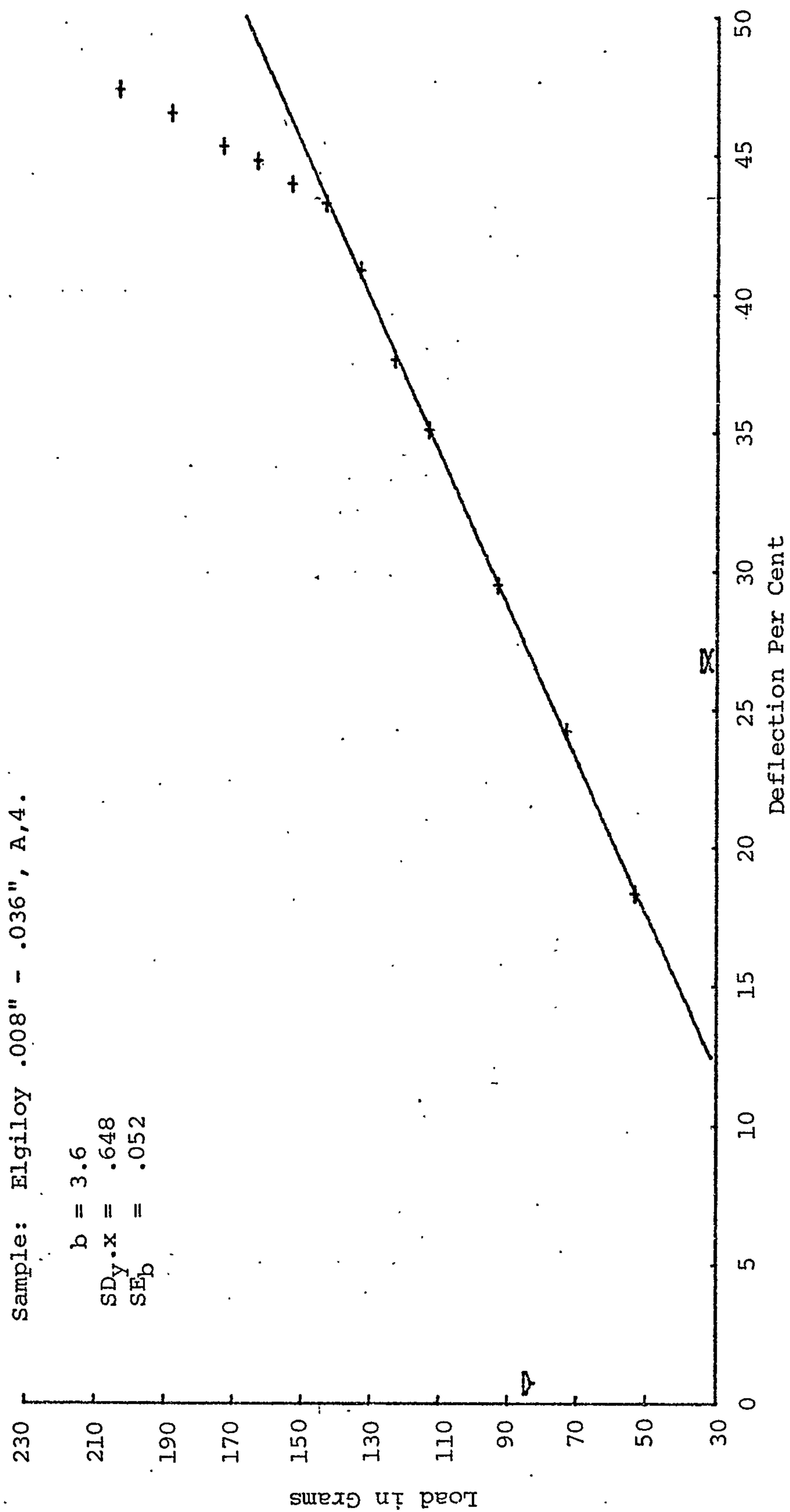


Fig. 79. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

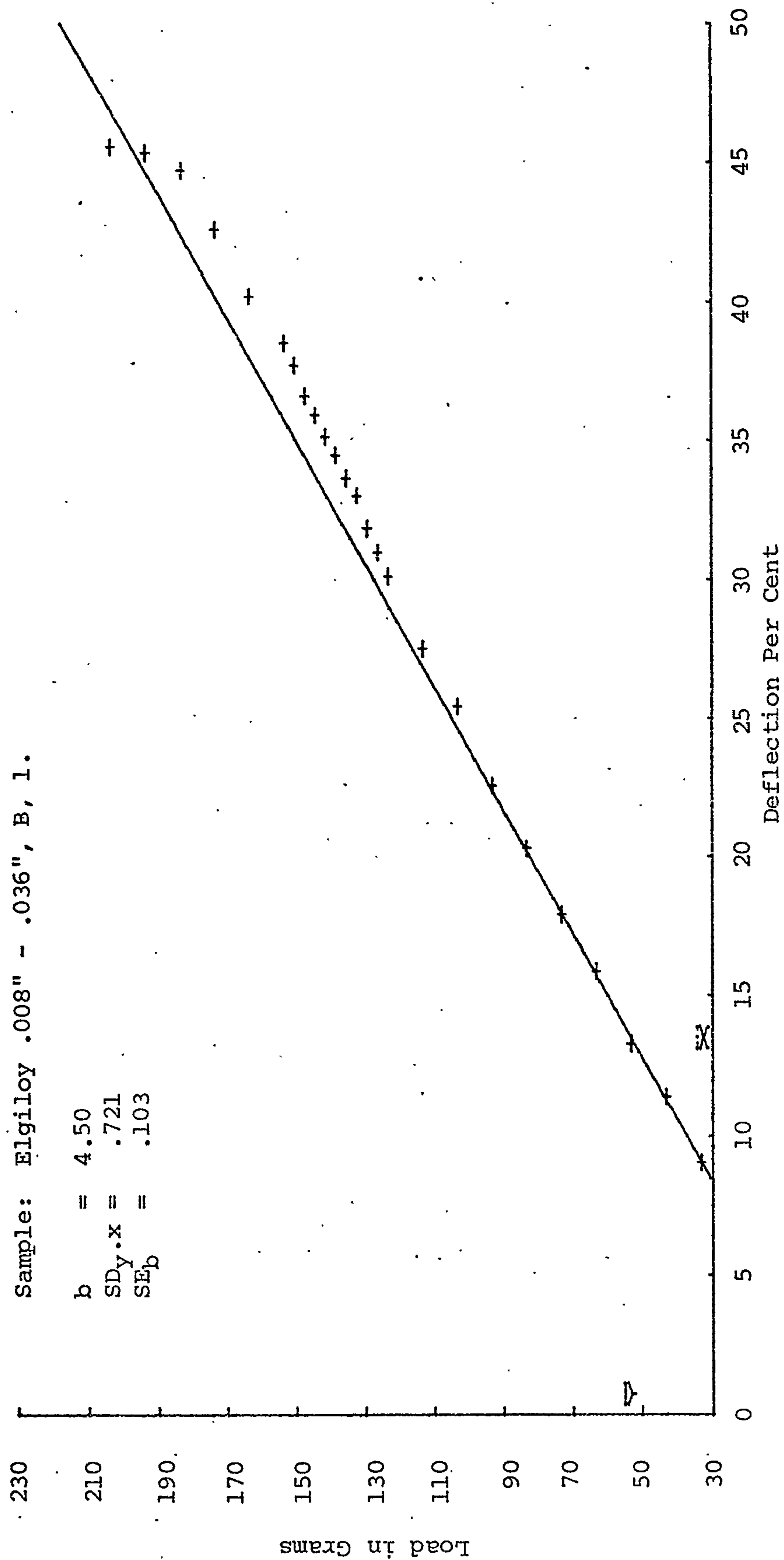


Fig. 80. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

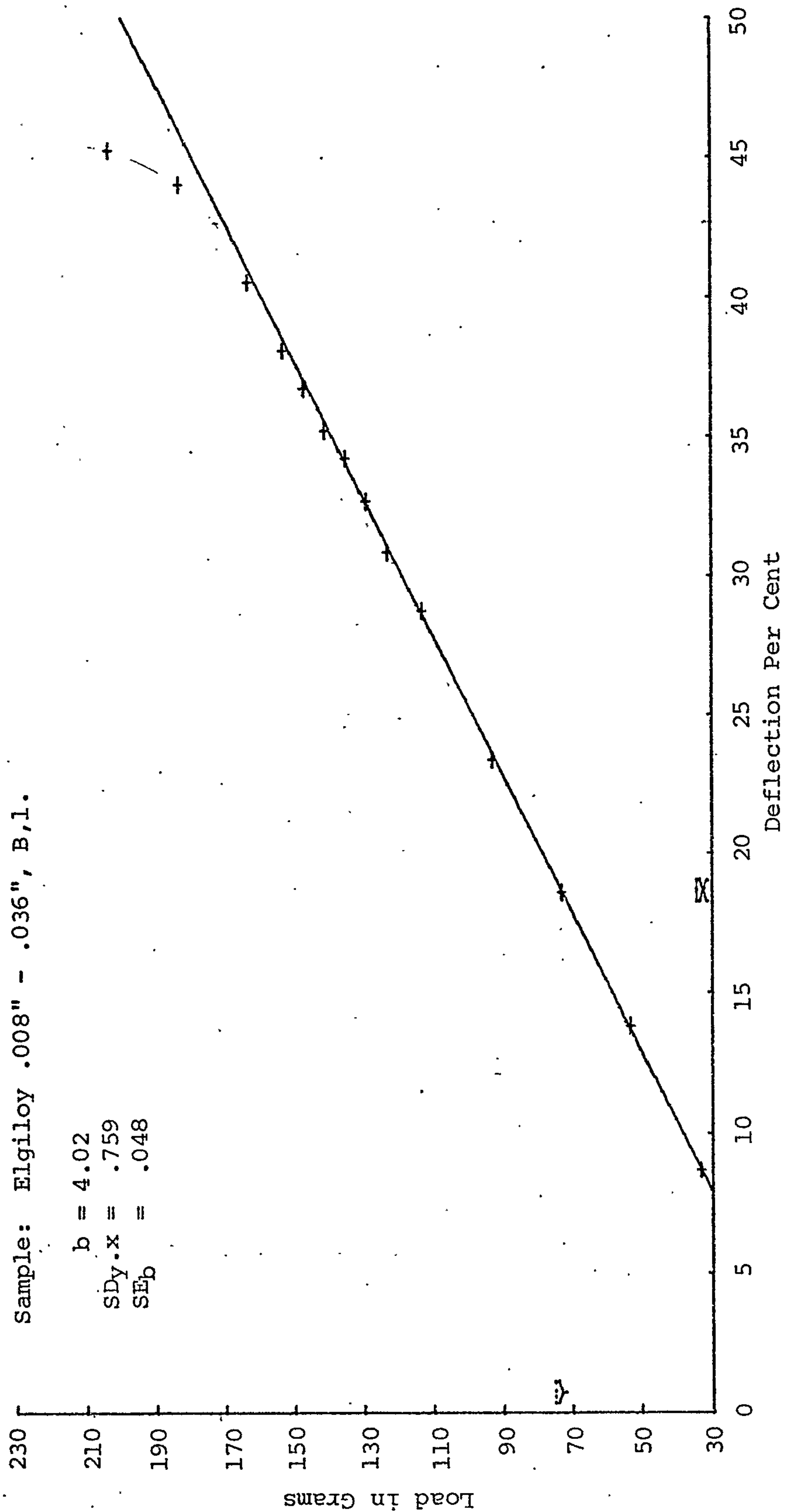


Fig. 81. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

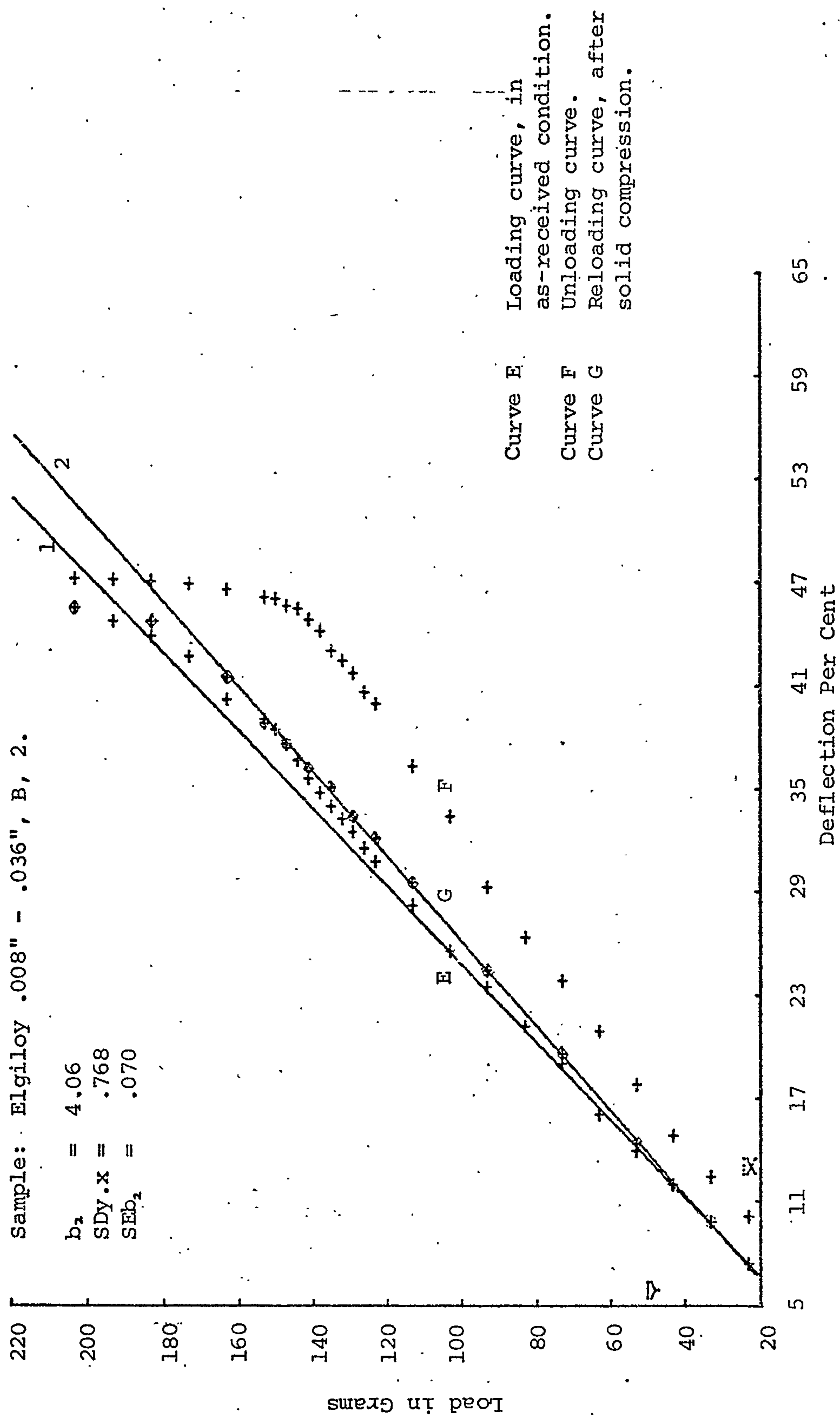


Fig. 82. Load-deflection regressions of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition (1) and after solid compression (2).

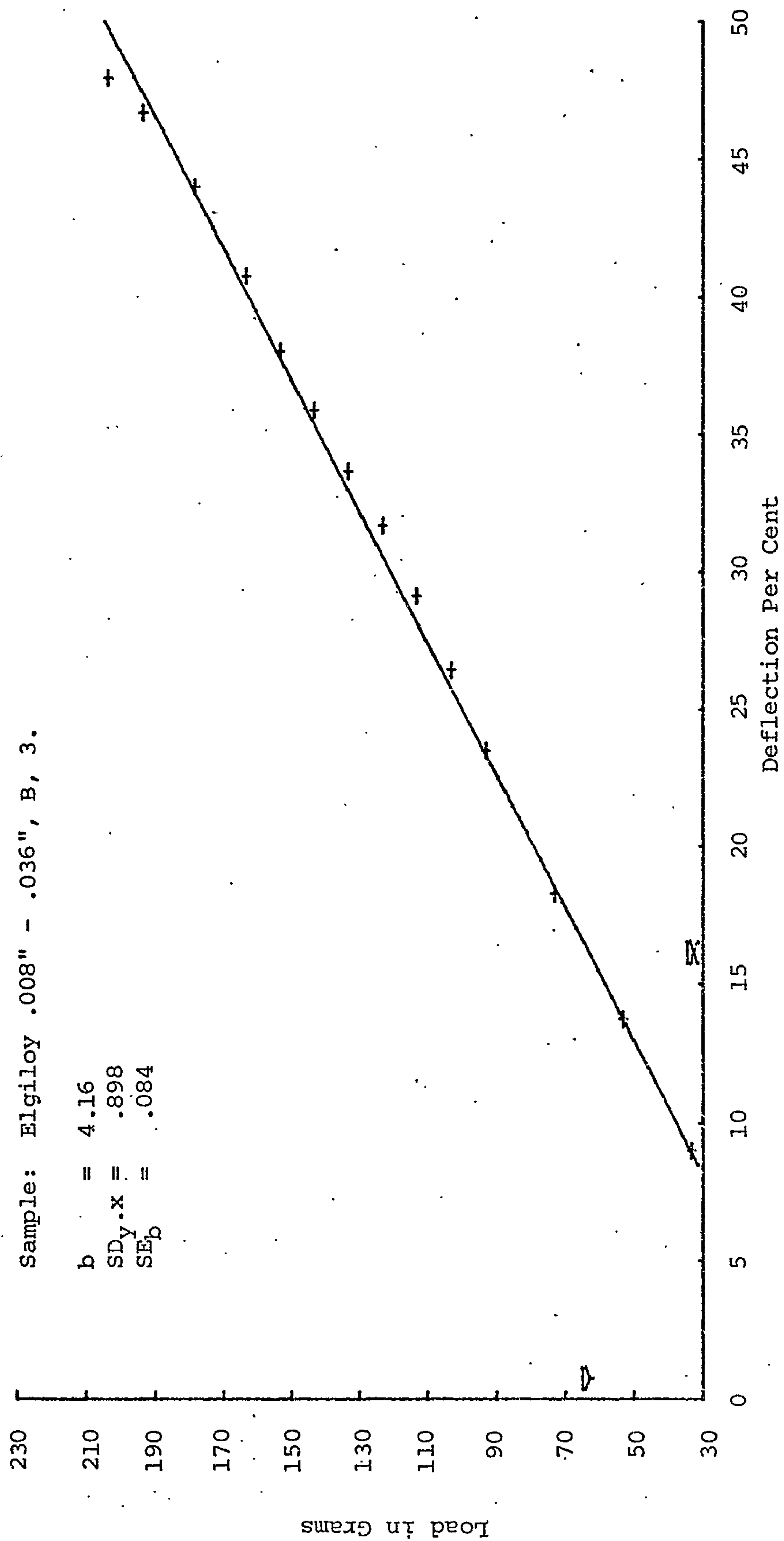


Fig. 83. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

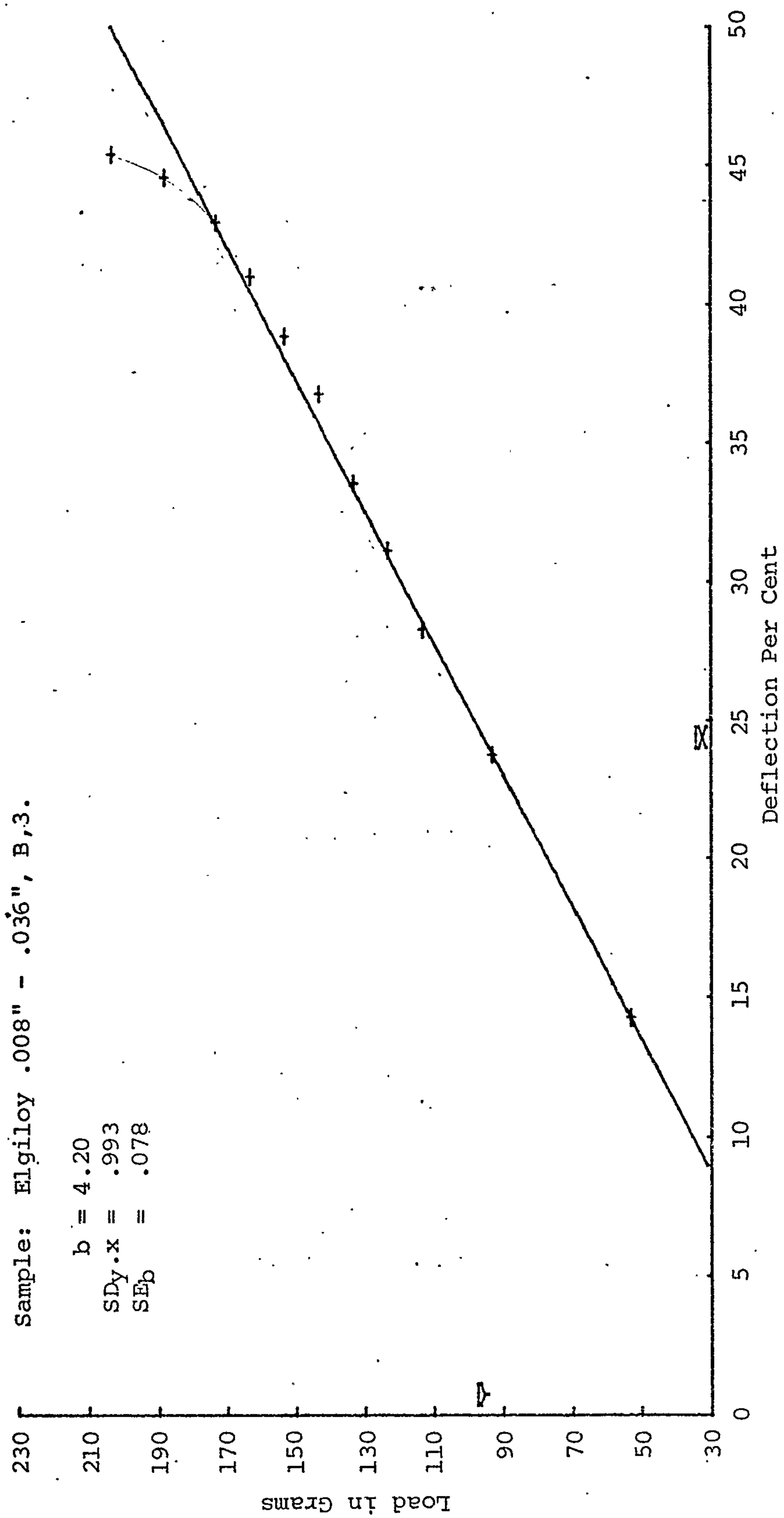


Fig. 84. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

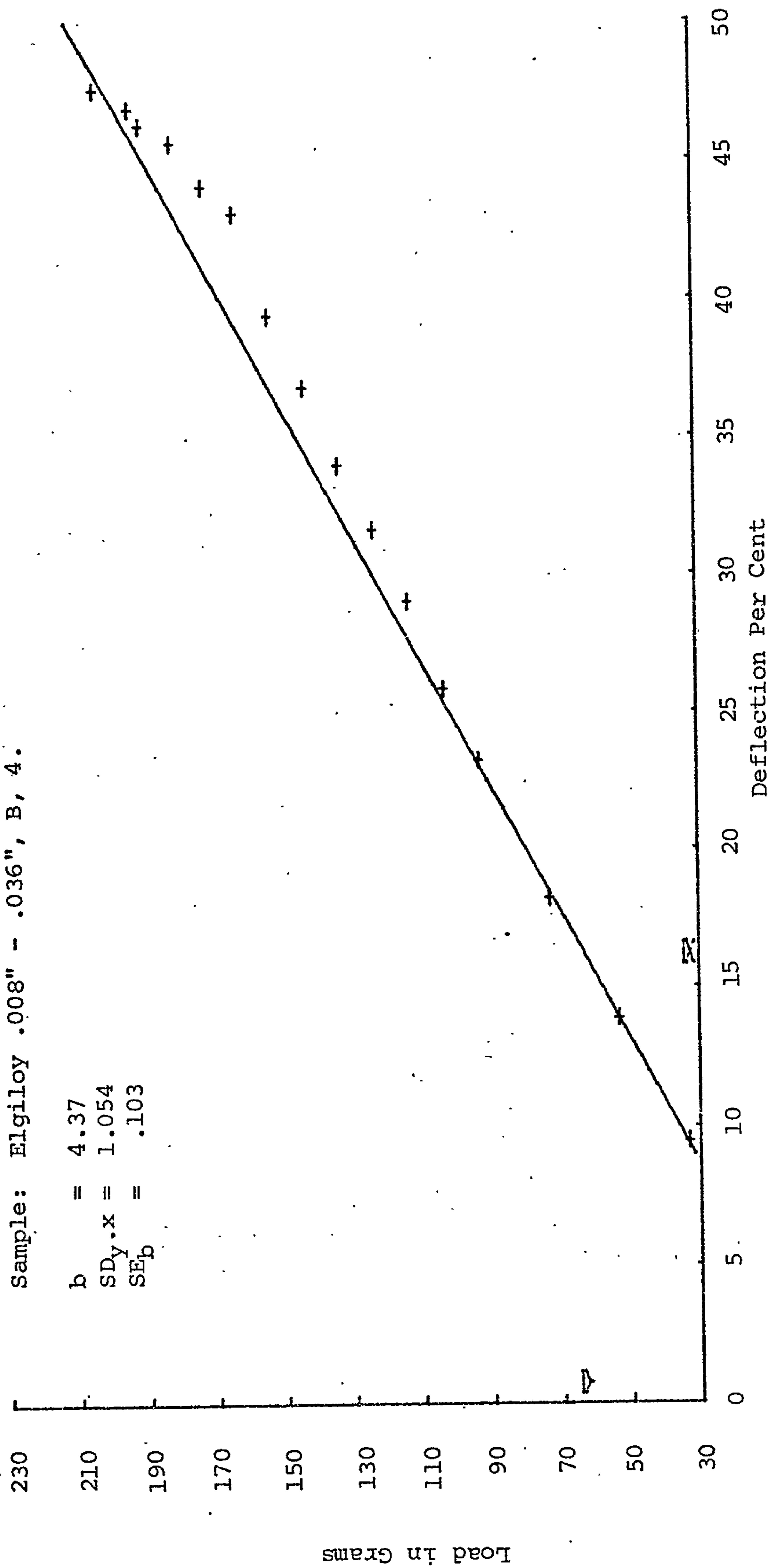


Fig. 85. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

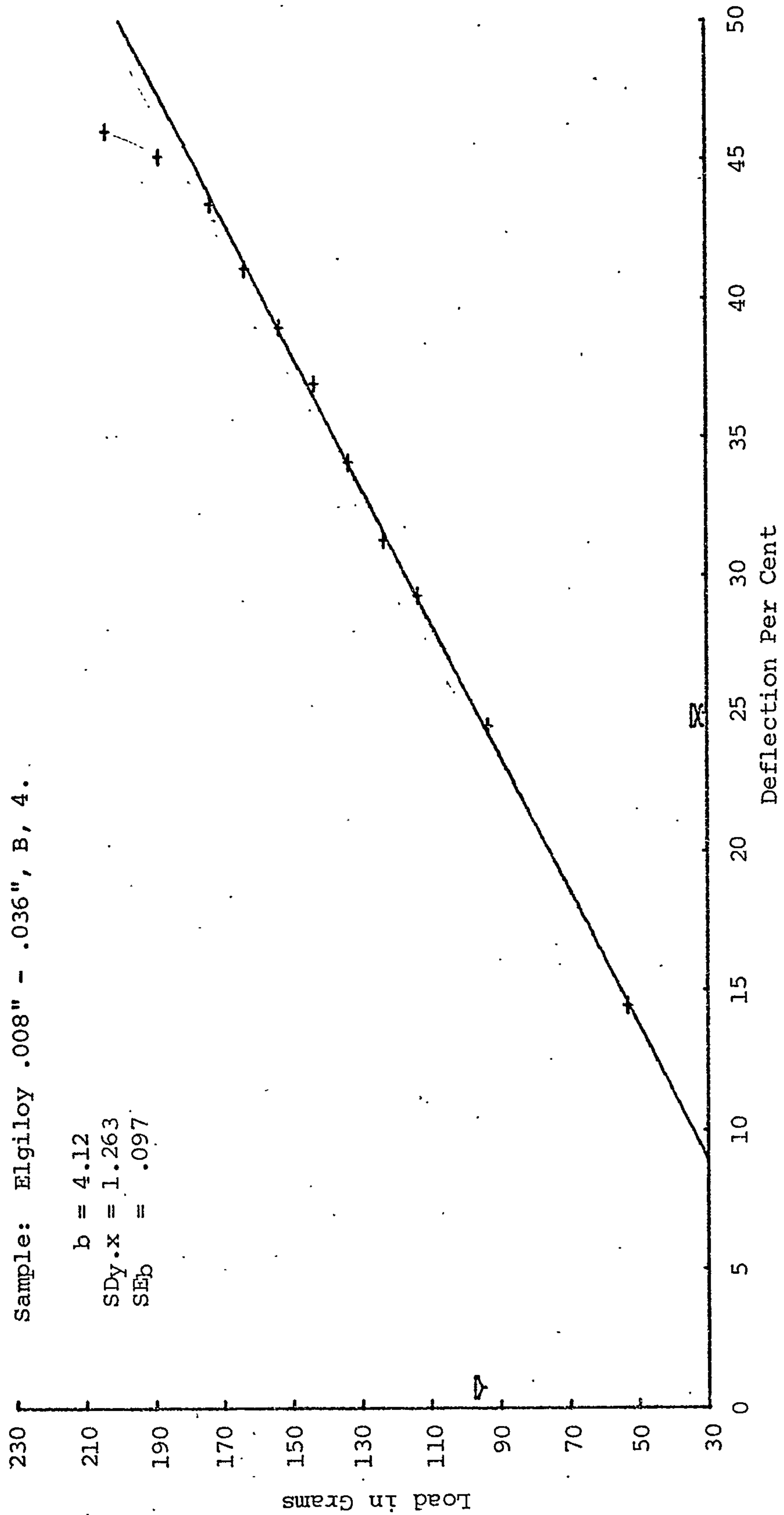


Fig. 86. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

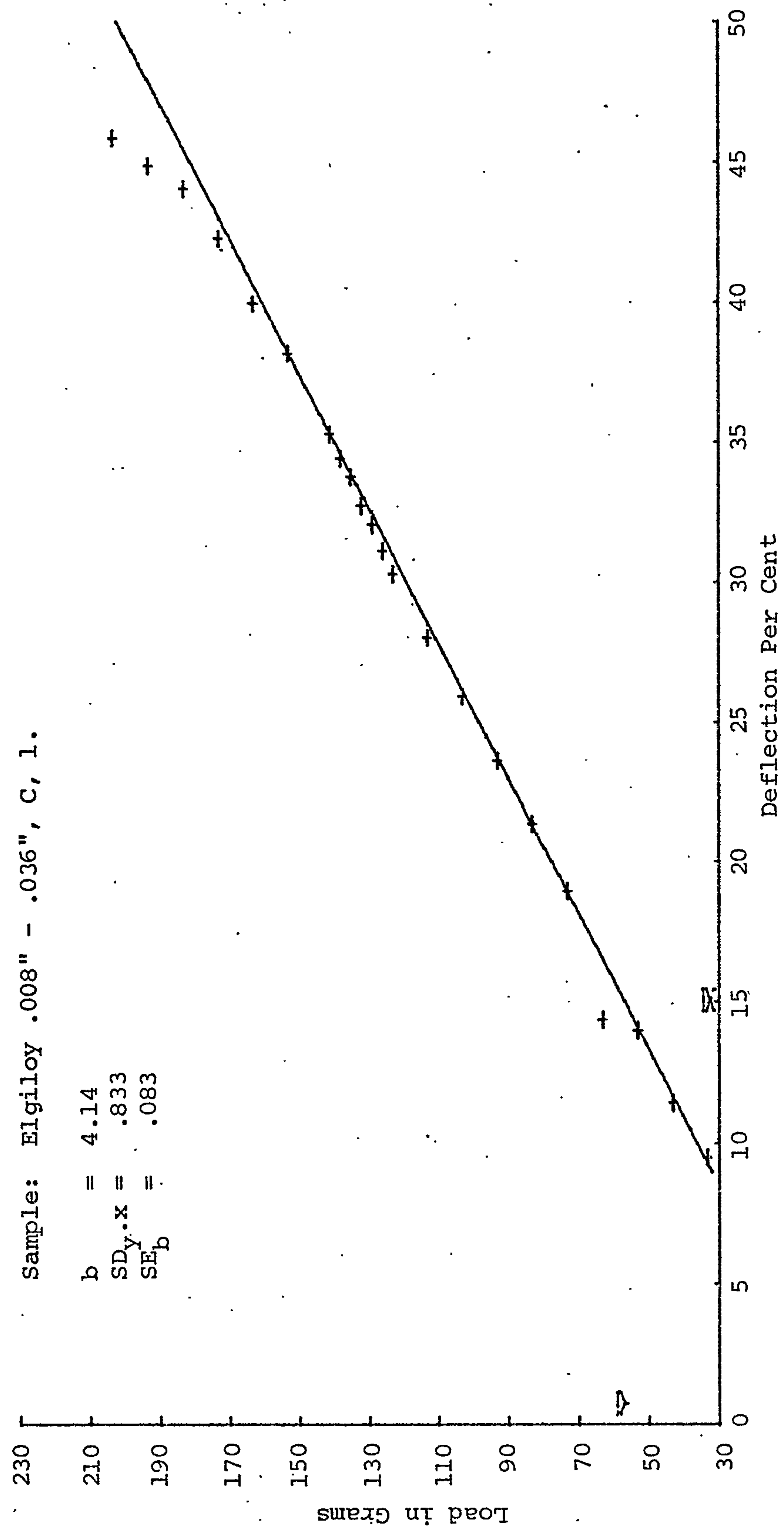


Fig. 87. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

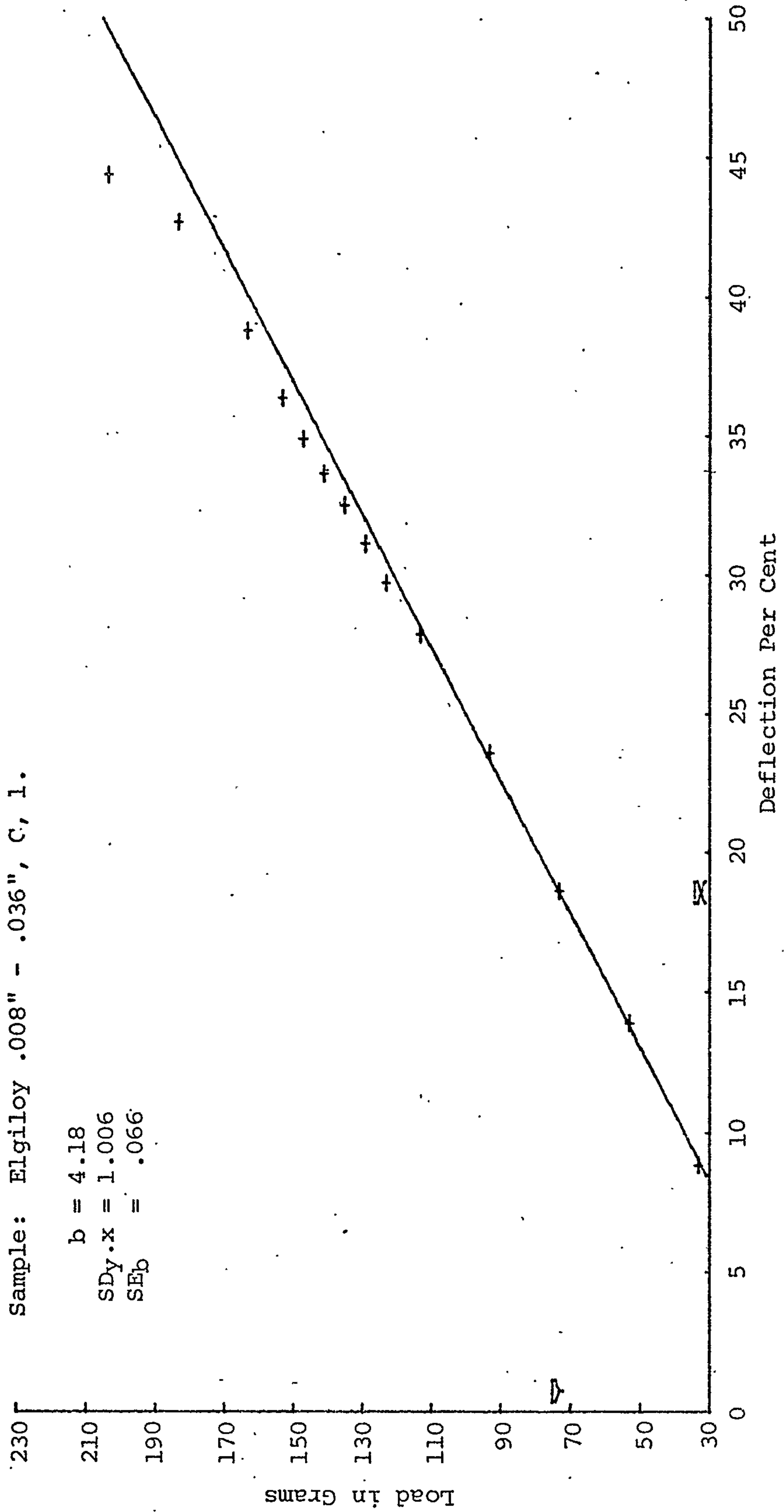


Fig. 88. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

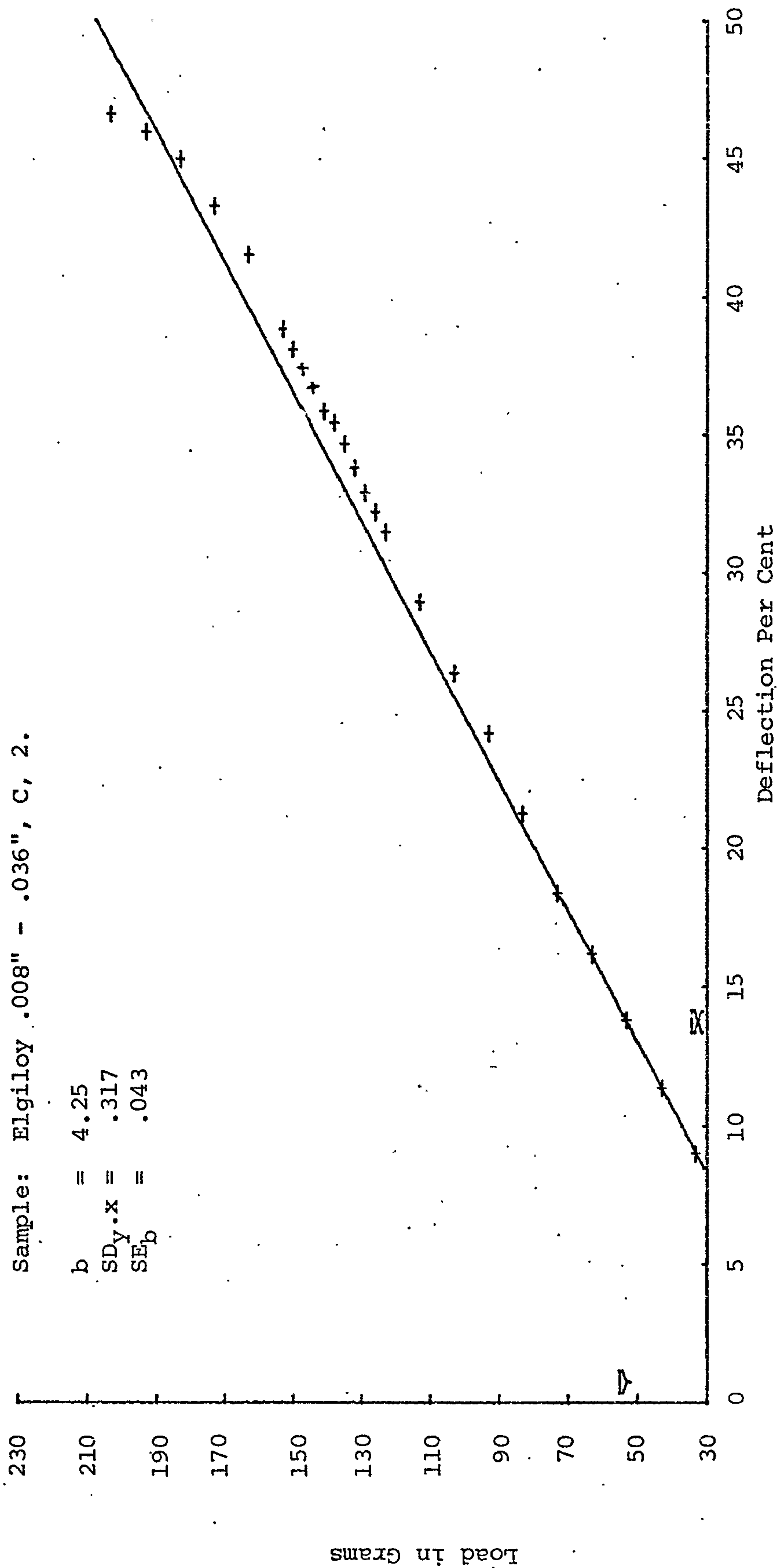


Fig. 89. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

Sample: Elgiloy .008" - .036", C,2.

$b = 4.01$
 $SD_{y \cdot x} = 2.137$
 $SE_b = .136$

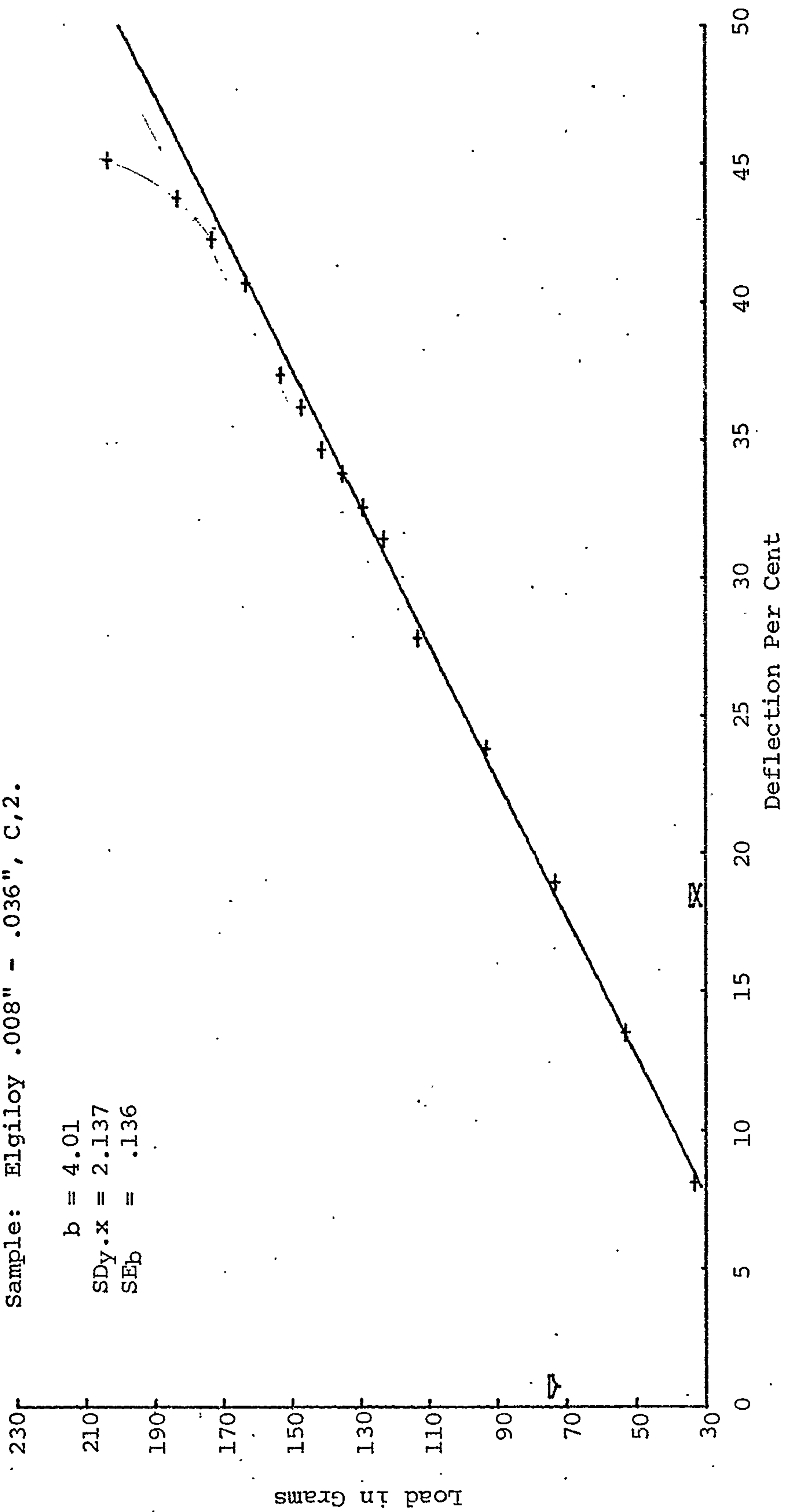


Fig. 90. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

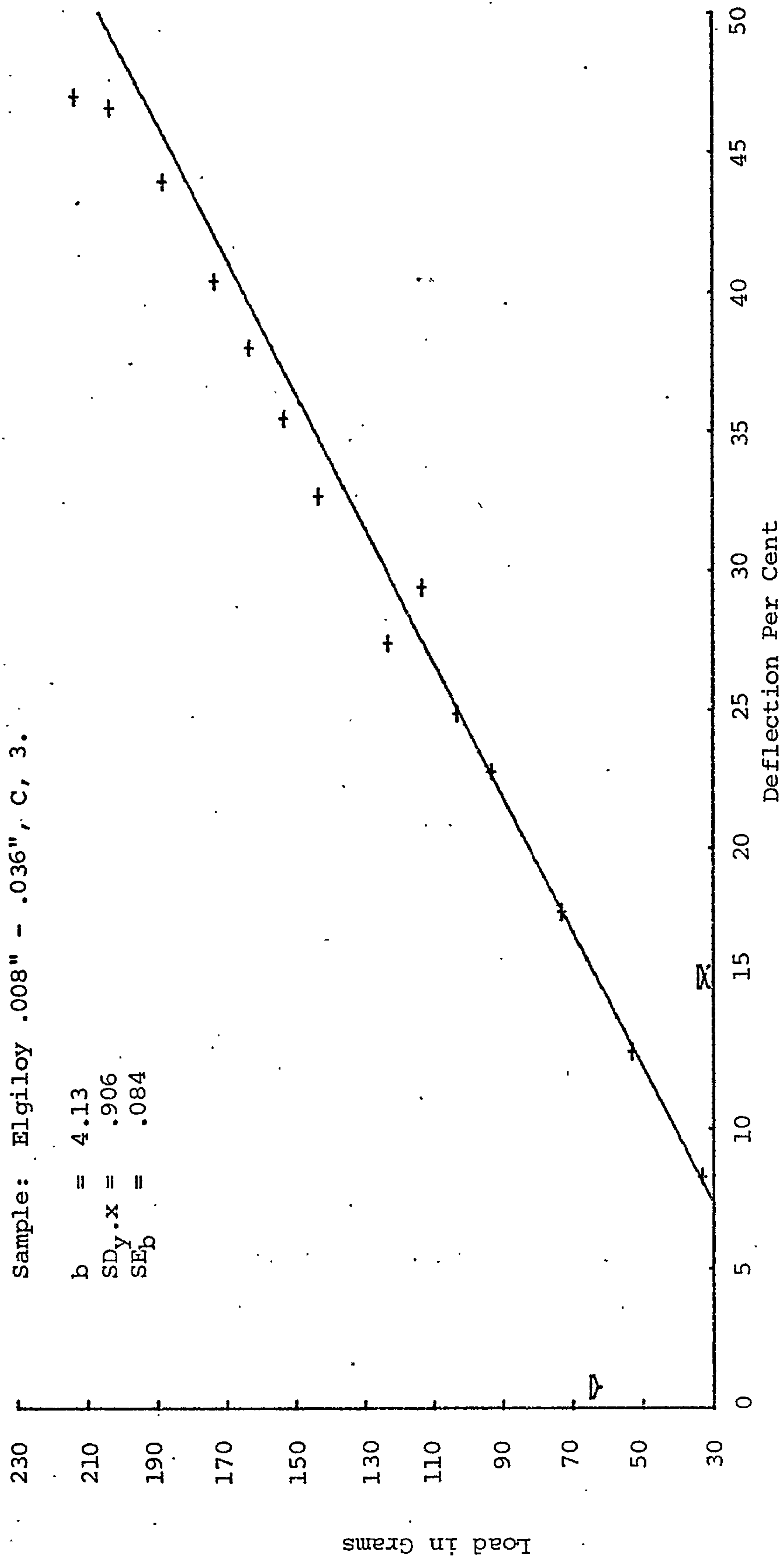


Fig. 91. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

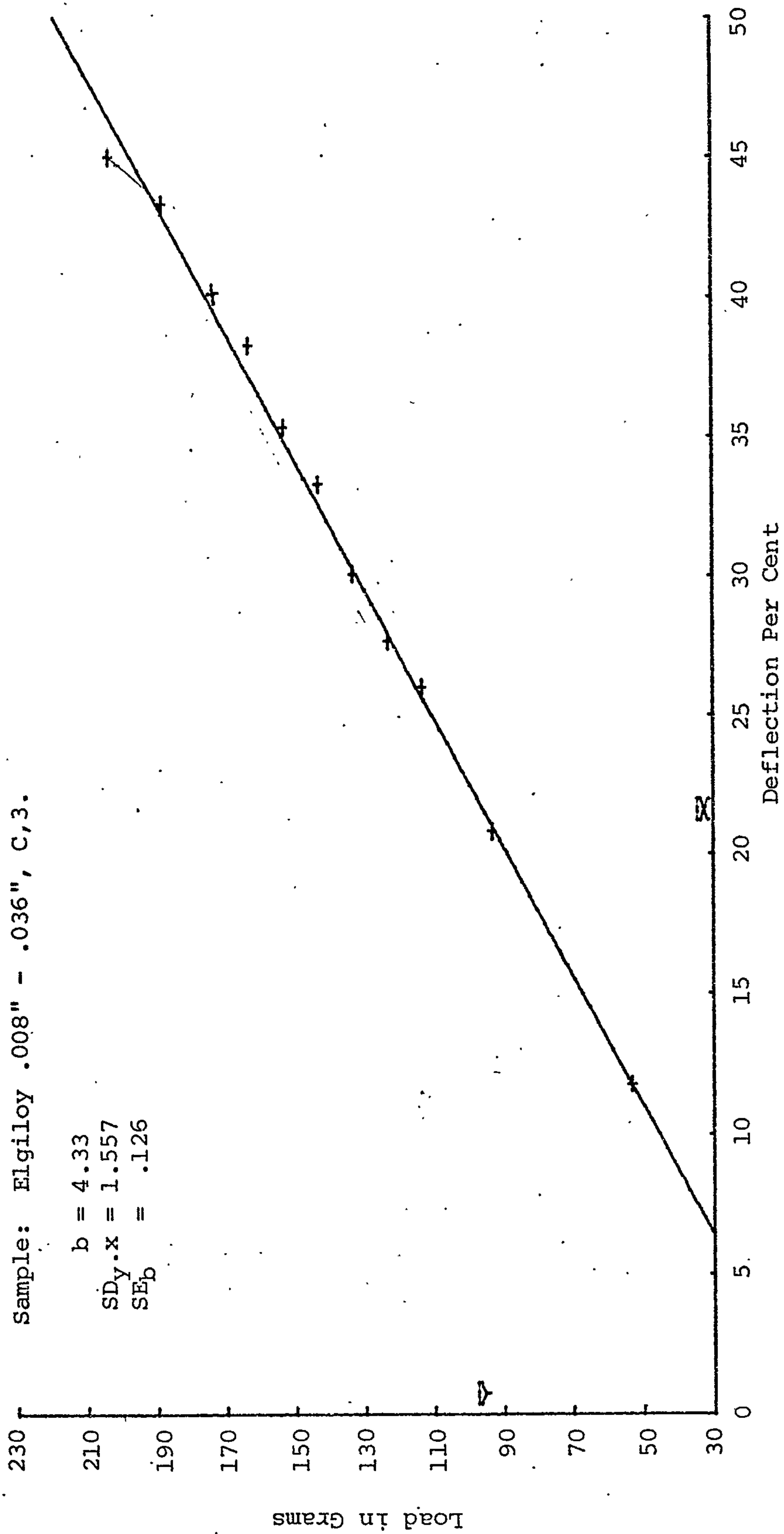


Fig. 92. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

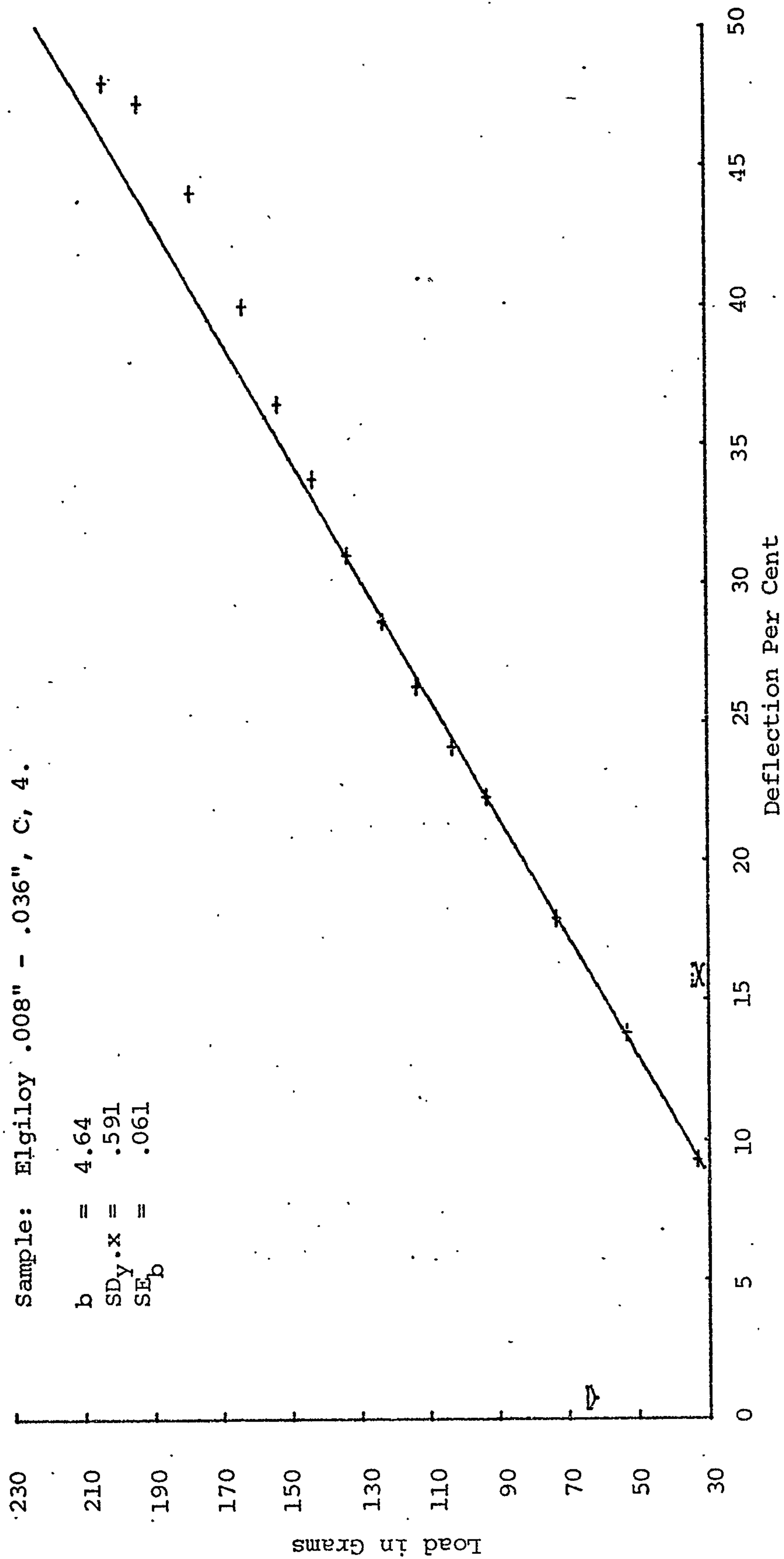


Fig. 93. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded in as-received condition.

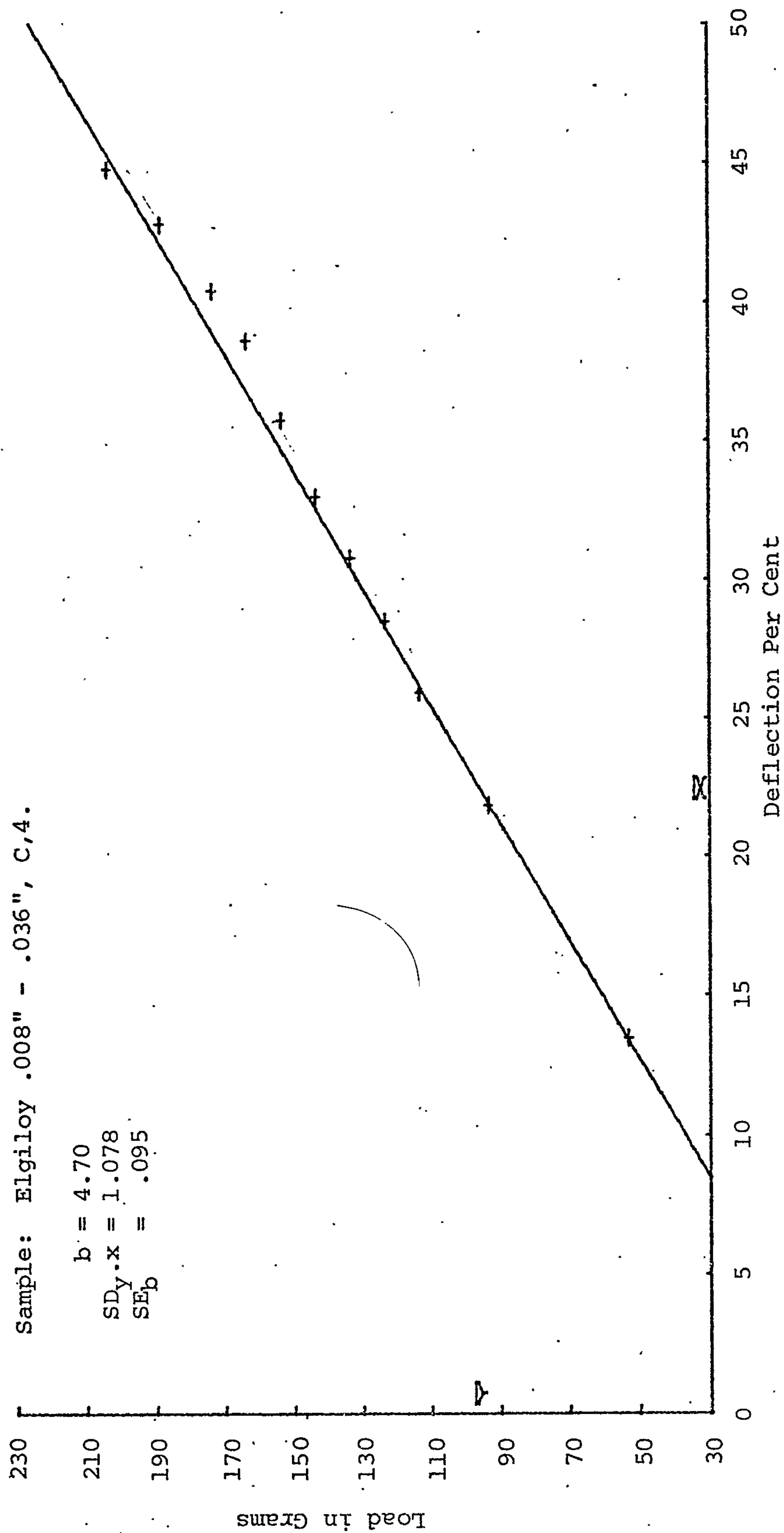


Fig. 94. Load-deflection regression of Elgiloy .008" - .036" open coil helical spring loaded after it had been compressed solid once.

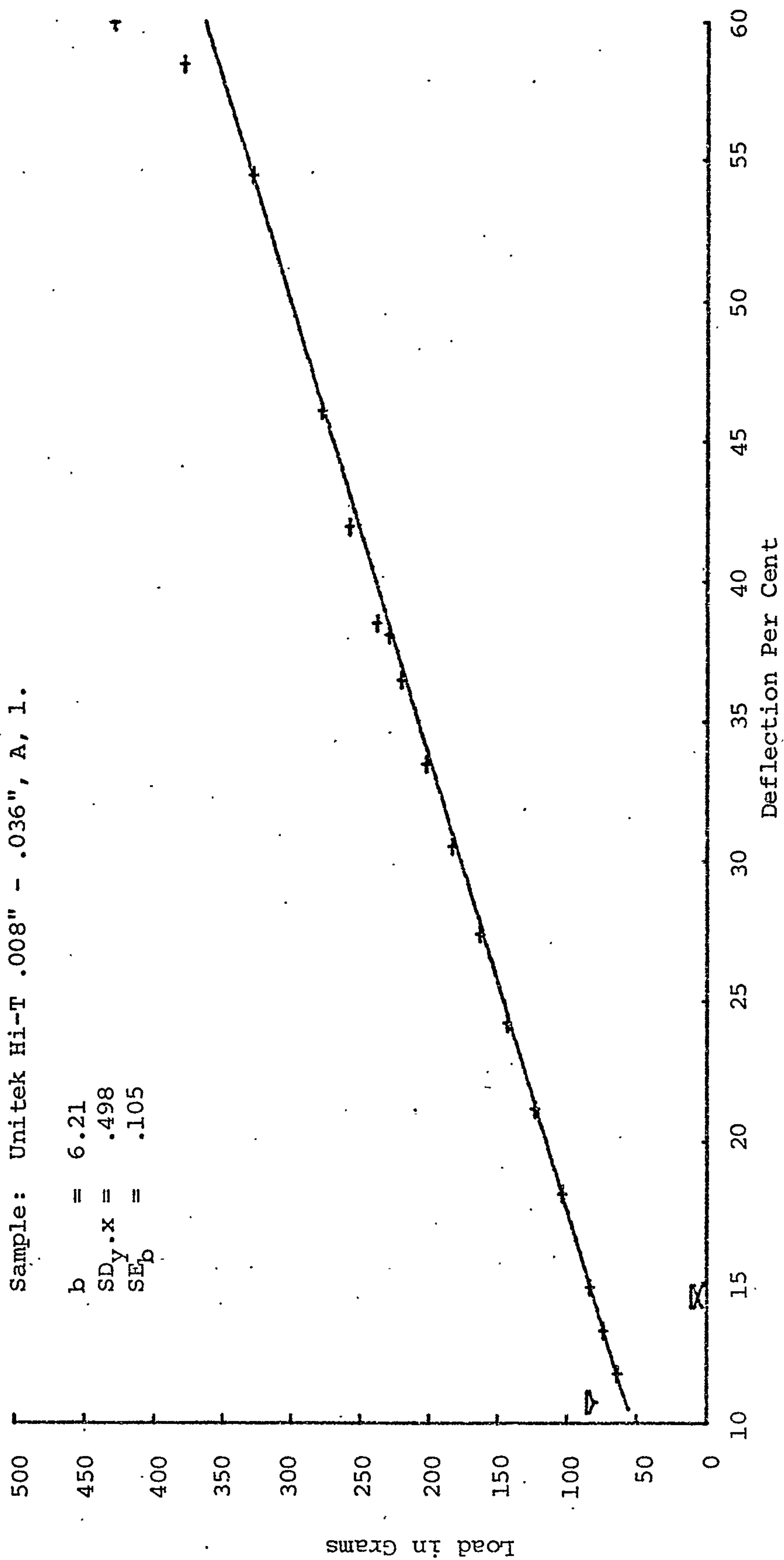


Fig. 95. Load-deflection regression of Unitek Hi-T .008" - .036" open coil helical spring loaded in as-received condition.

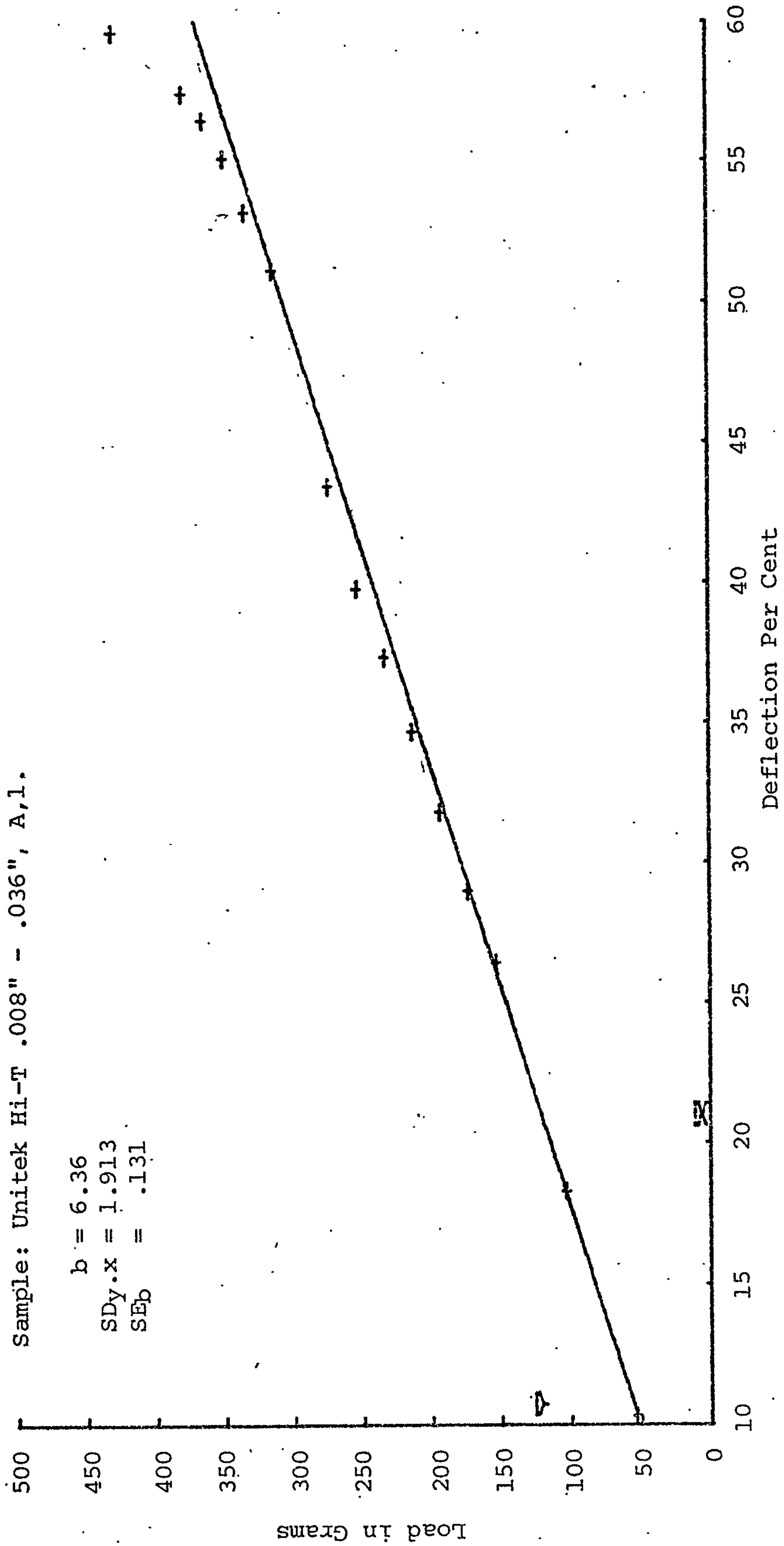


Fig. 96. Load-deflection regression of Unitek Hi-T .008" - .036" open coil helical spring loaded after it had been compressed solid once.

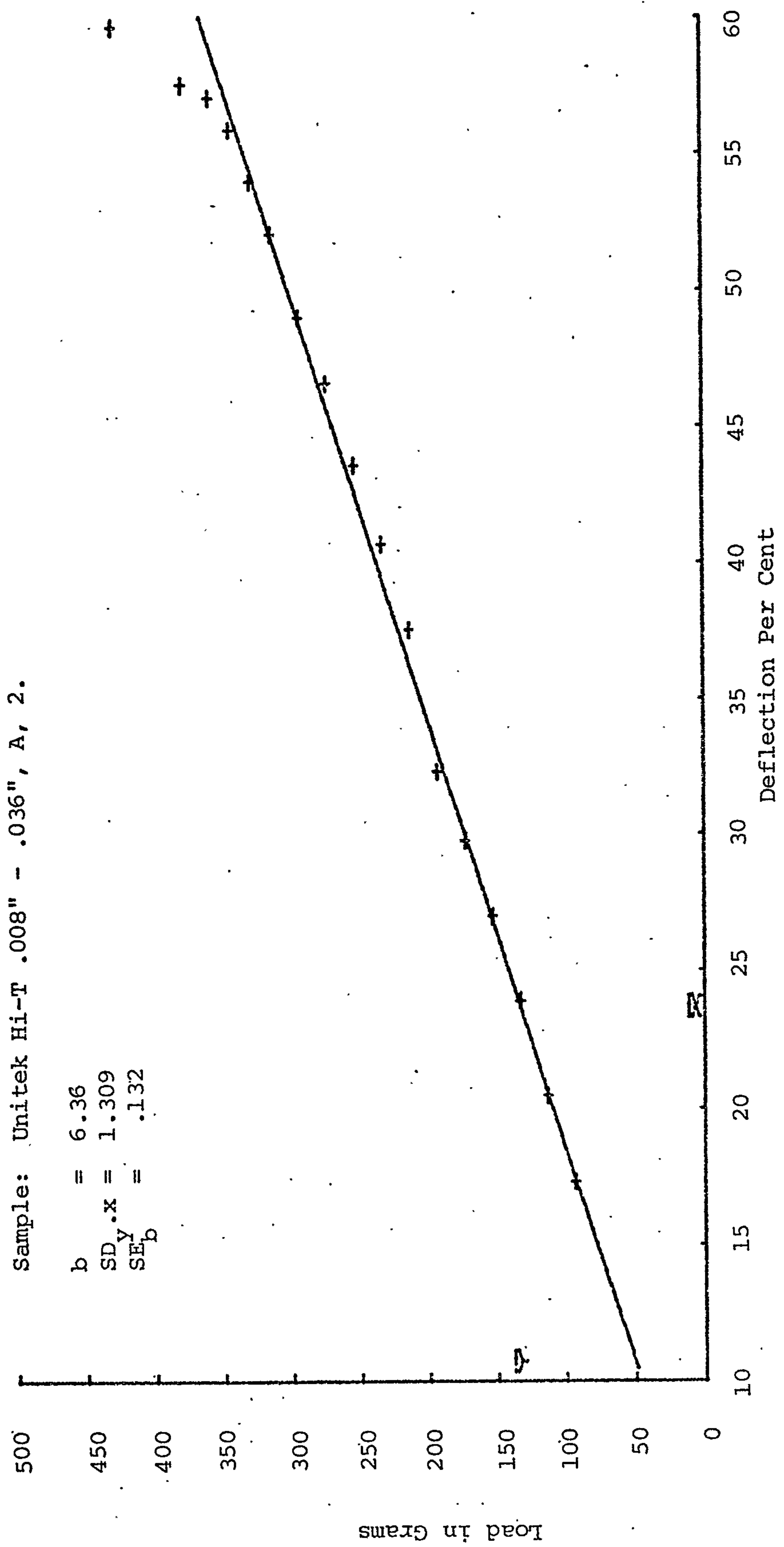


Fig. 97. Load-deflection regression of Unitek Hi-T .008" - .036" open coil helical spring loaded in as-received condition.

Sample: Unitek Hi-T .008" - .036", A,2.

$b = 6.02$

$SD_{y \cdot x} = 1.060$

$SE_b = .101$

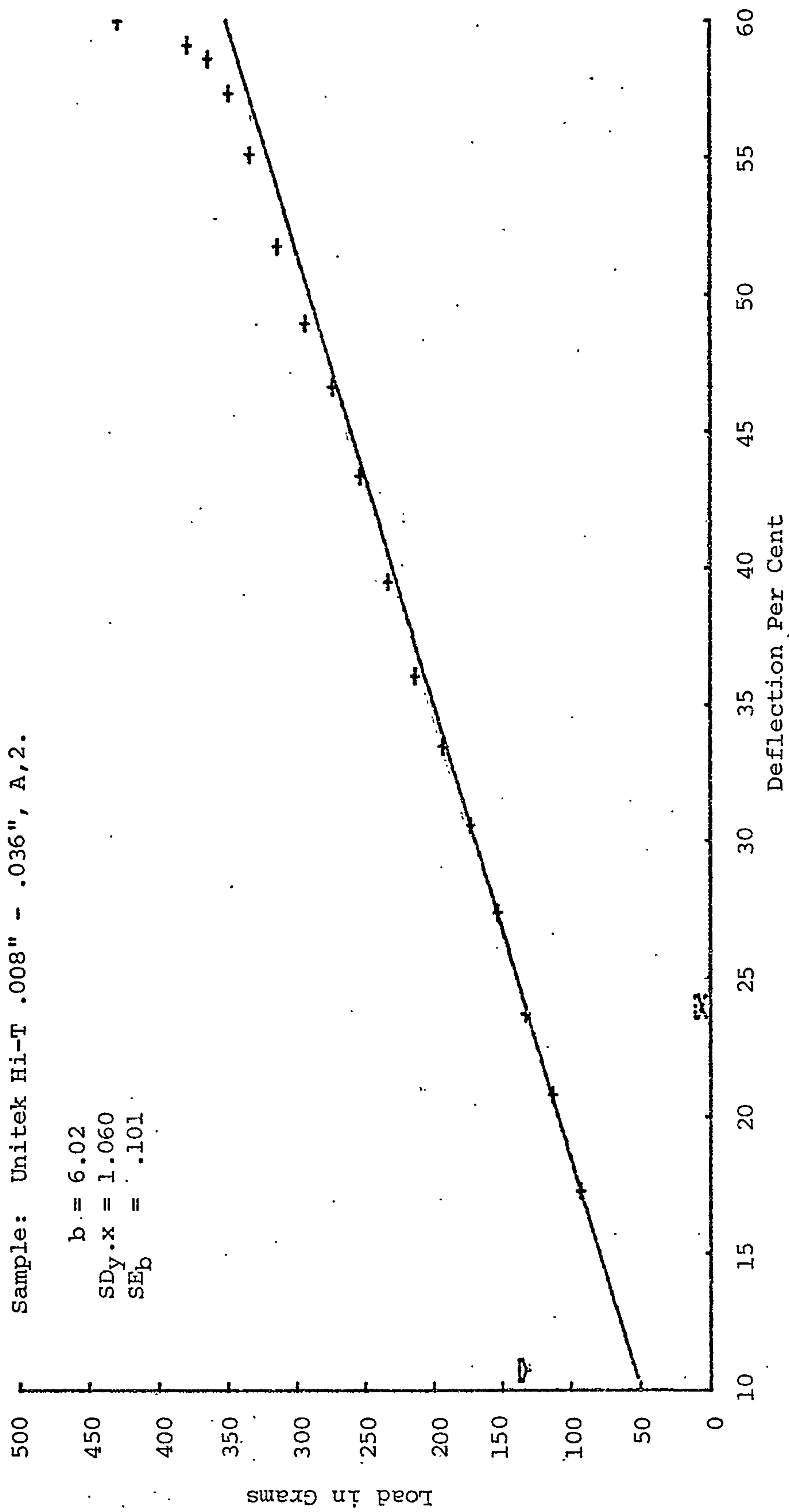


Fig. 98. Load-deflection regression of Unitek Hi-T .008" - .036" open coil helical spring loaded after it had been compressed solid once.

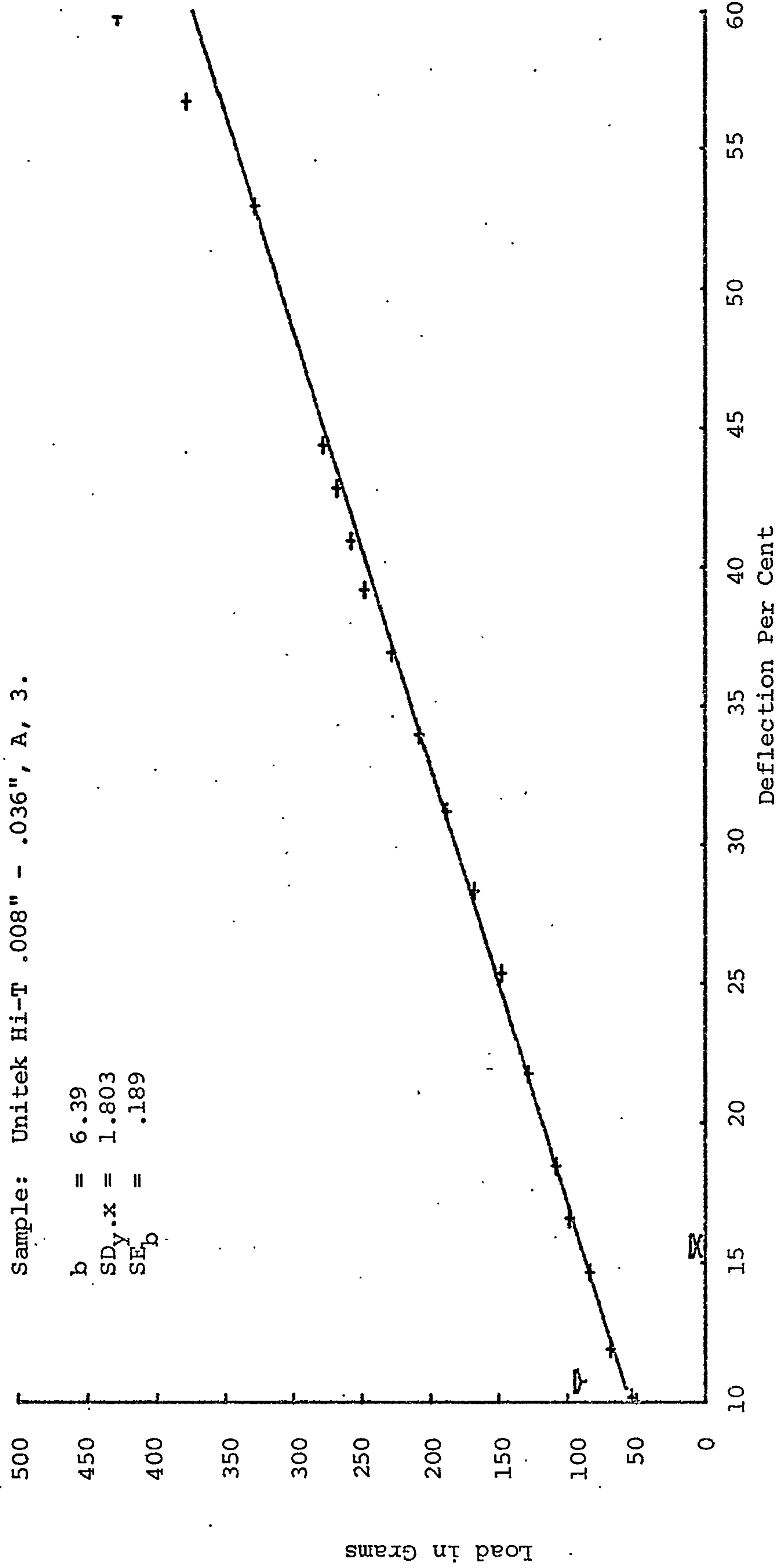


Fig. 99. Load-deflection regression of Unitek Hi-T .008" - .036" open coil helical spring loaded in as-received condition.

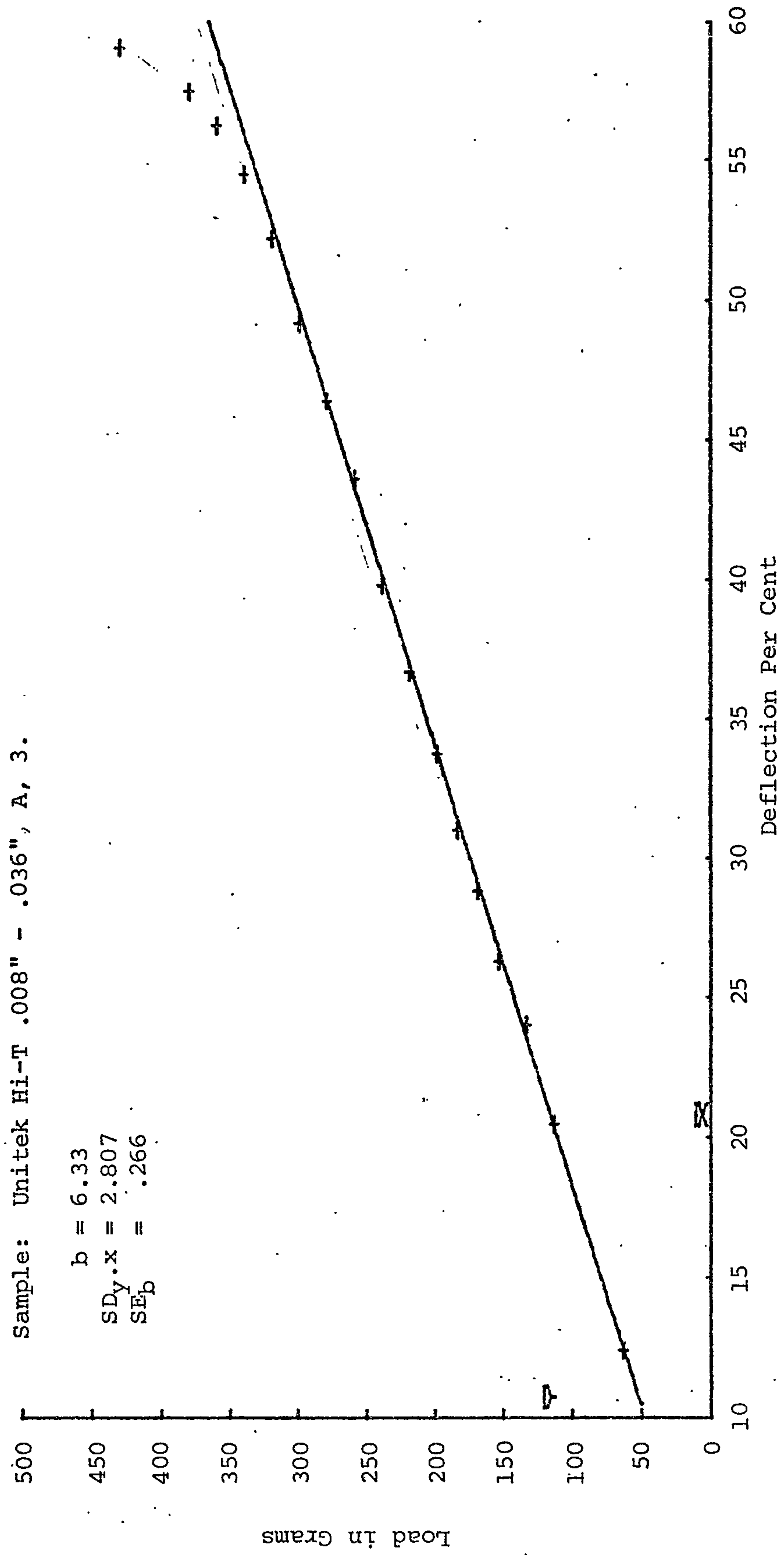


Fig. 100. Load-deflection regression of Unitek Hi-T .008" - .036" open coil helical spring loaded after it had been compressed solid once.

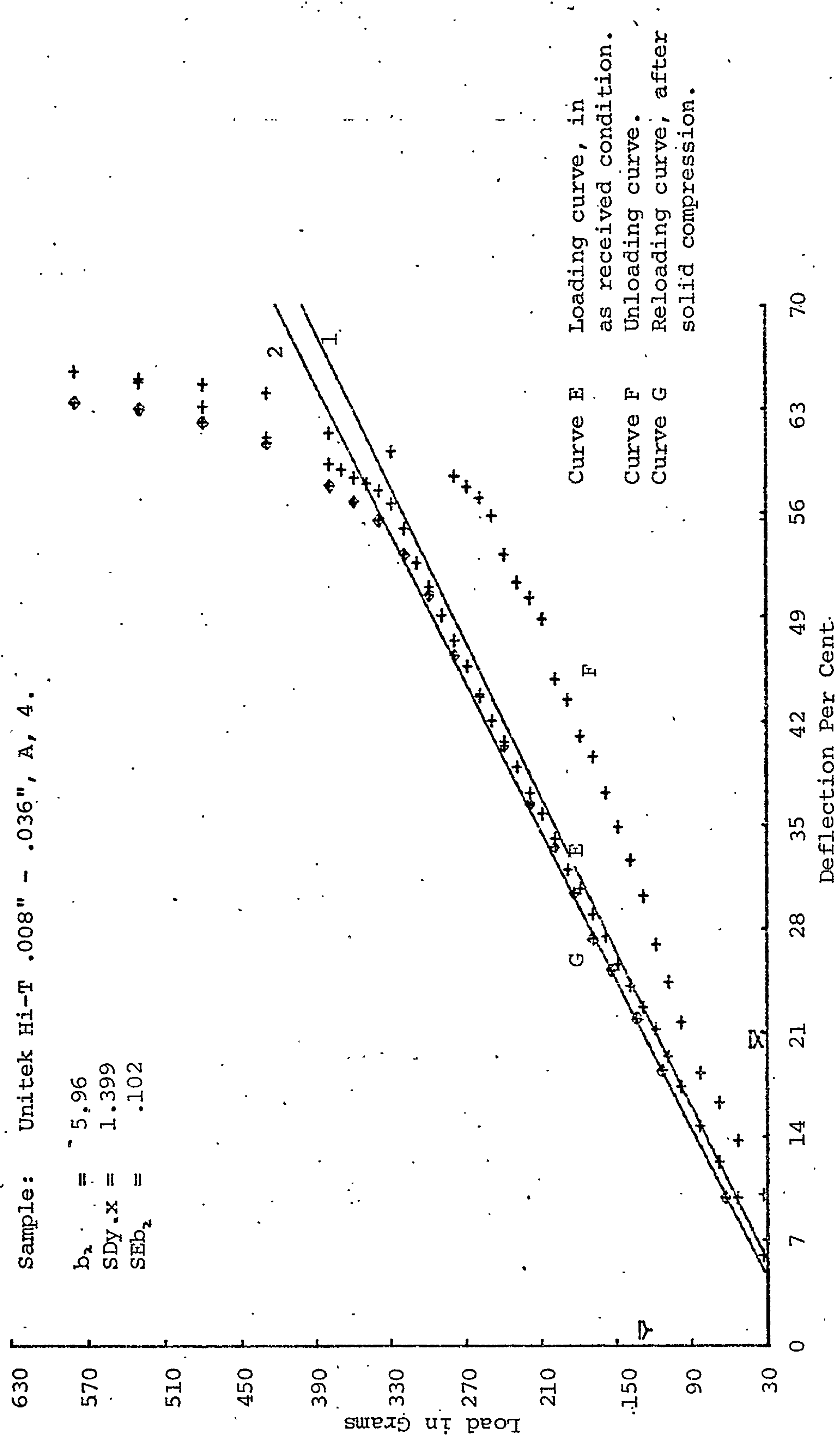


Fig. 101. Load-deflection regressions of Unitek Hi-T .008" - .036" open coil helical springs loaded in as-received condition (1) and after solid compression (2)

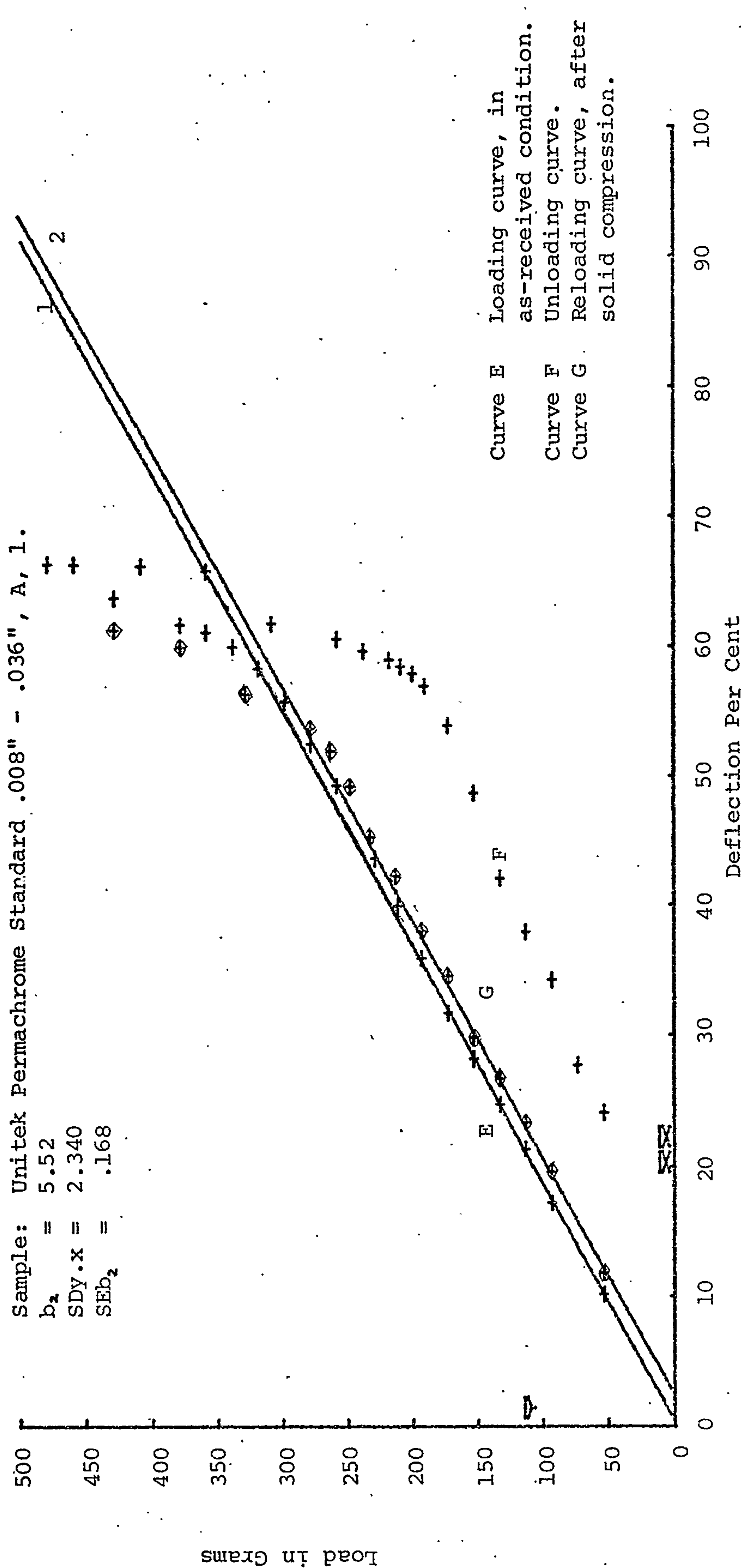


Fig. 102. Load-deflection regression of Unitek Permachrome Standard .008" - .036" open coil helical spring loaded in as-received condition (1) and after solid compression (2).

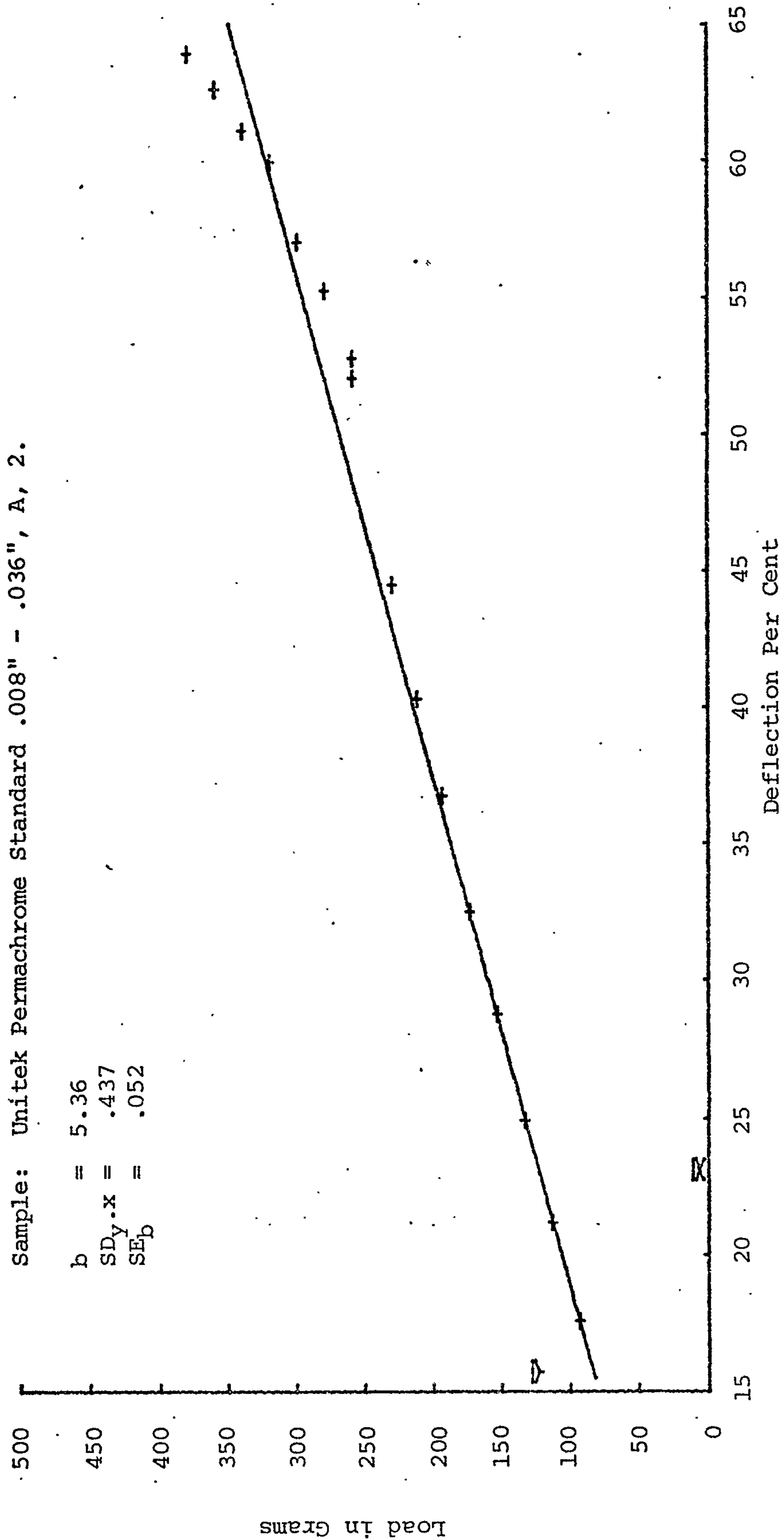


Fig. 103. Load-deflection regression of Unitek Permachrome Standard .008" - .036" open coil helical spring loaded in as-received condition.

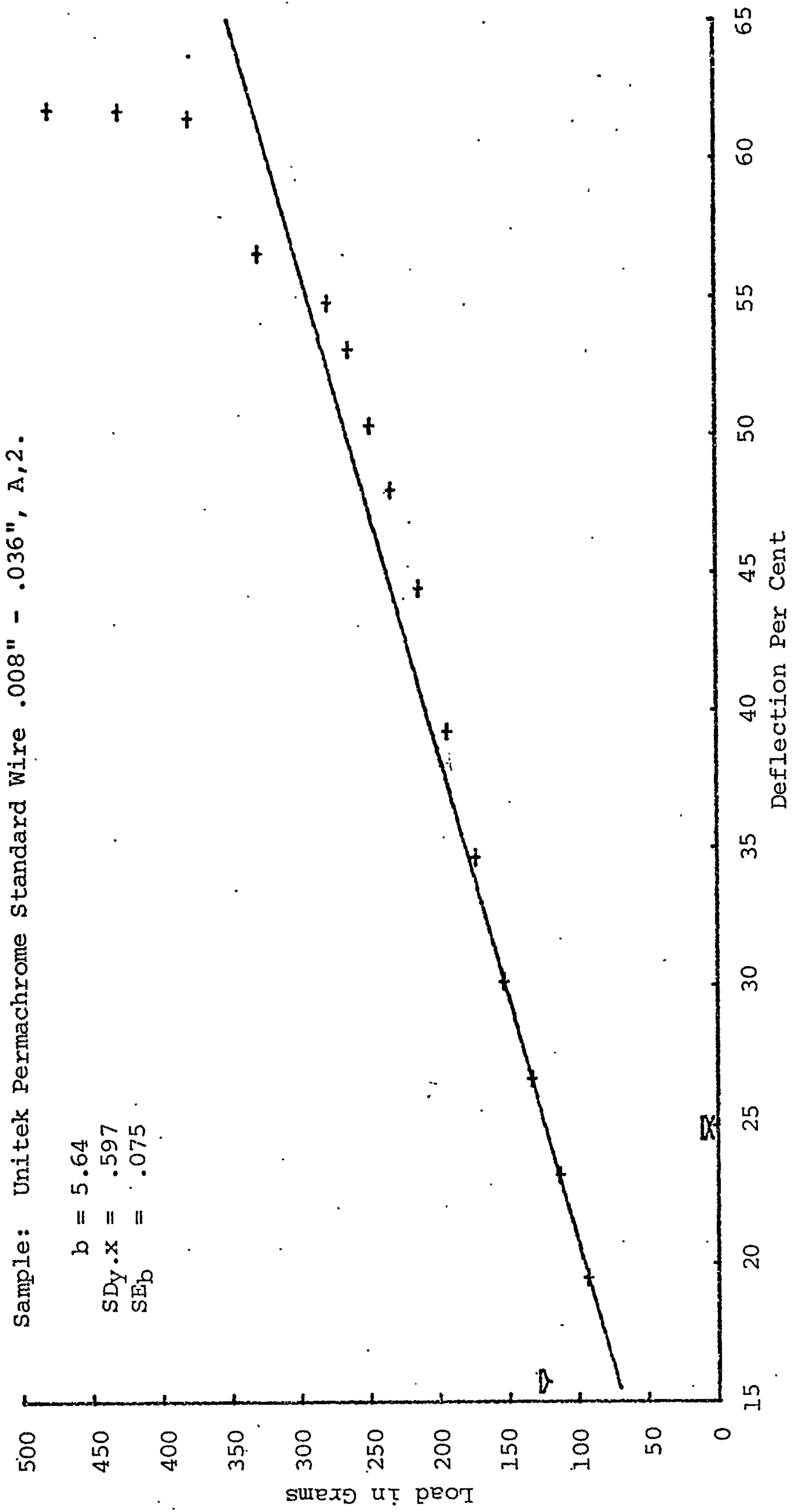


Fig. 104. Load-deflection regression of Unitek Permachrome Standard Wire .008" - .036" open coil helical spring loaded after it had been compressed solid once.

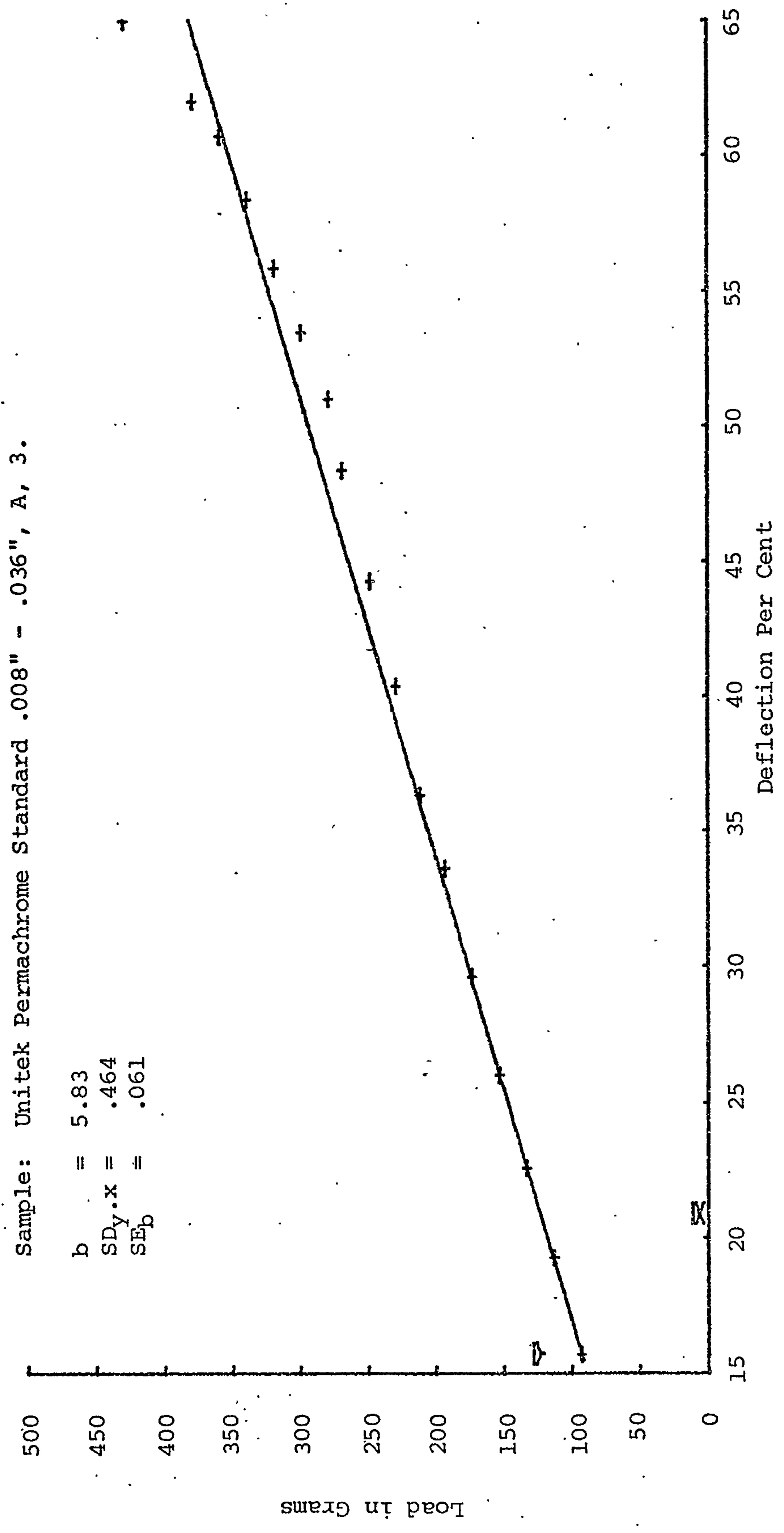


Fig. 105. Load-deflection regression of Unitek Permachrome Standard .008" - .036" open coil helical spring loaded in as-received condition.

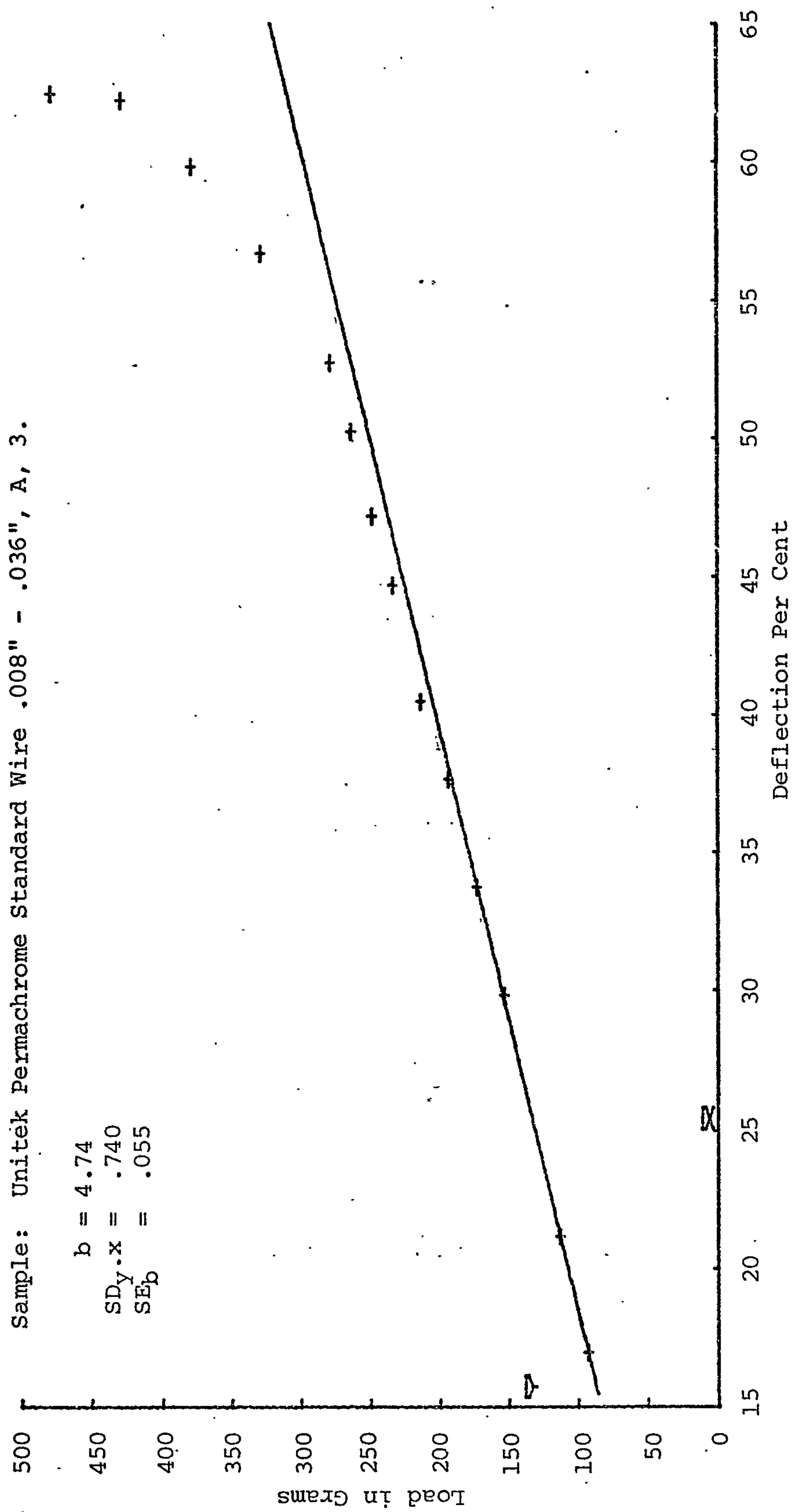


Fig. 106. Load-deflection regression of Unitek Permachrome Standard Wire .008" - .036" open coil helical spring loaded after it had been compressed solid once.

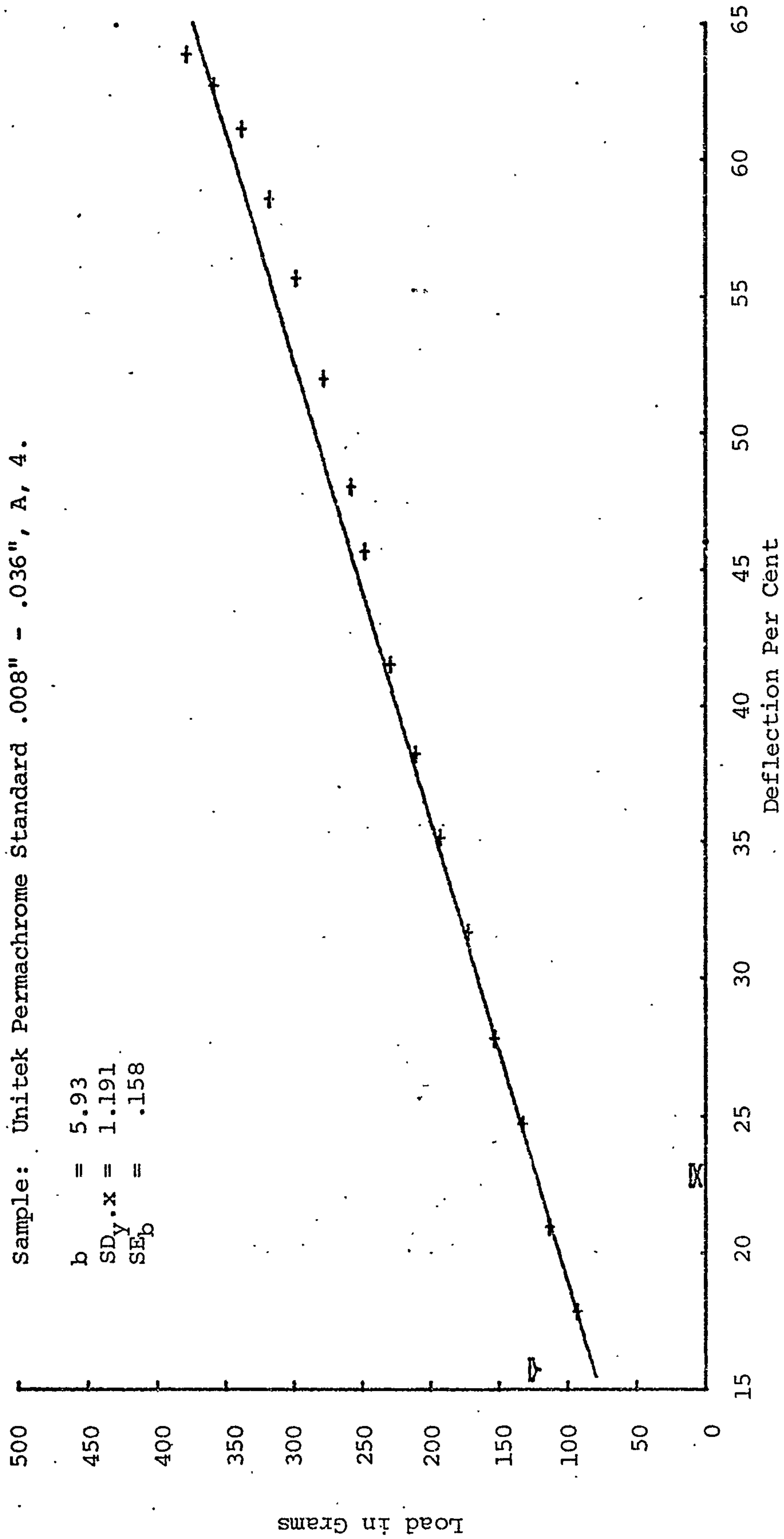


Fig. 107. Load-deflection regression of Unitek Permachrome Standard .008" - .036" open coil helical spring loaded in as-received condition.

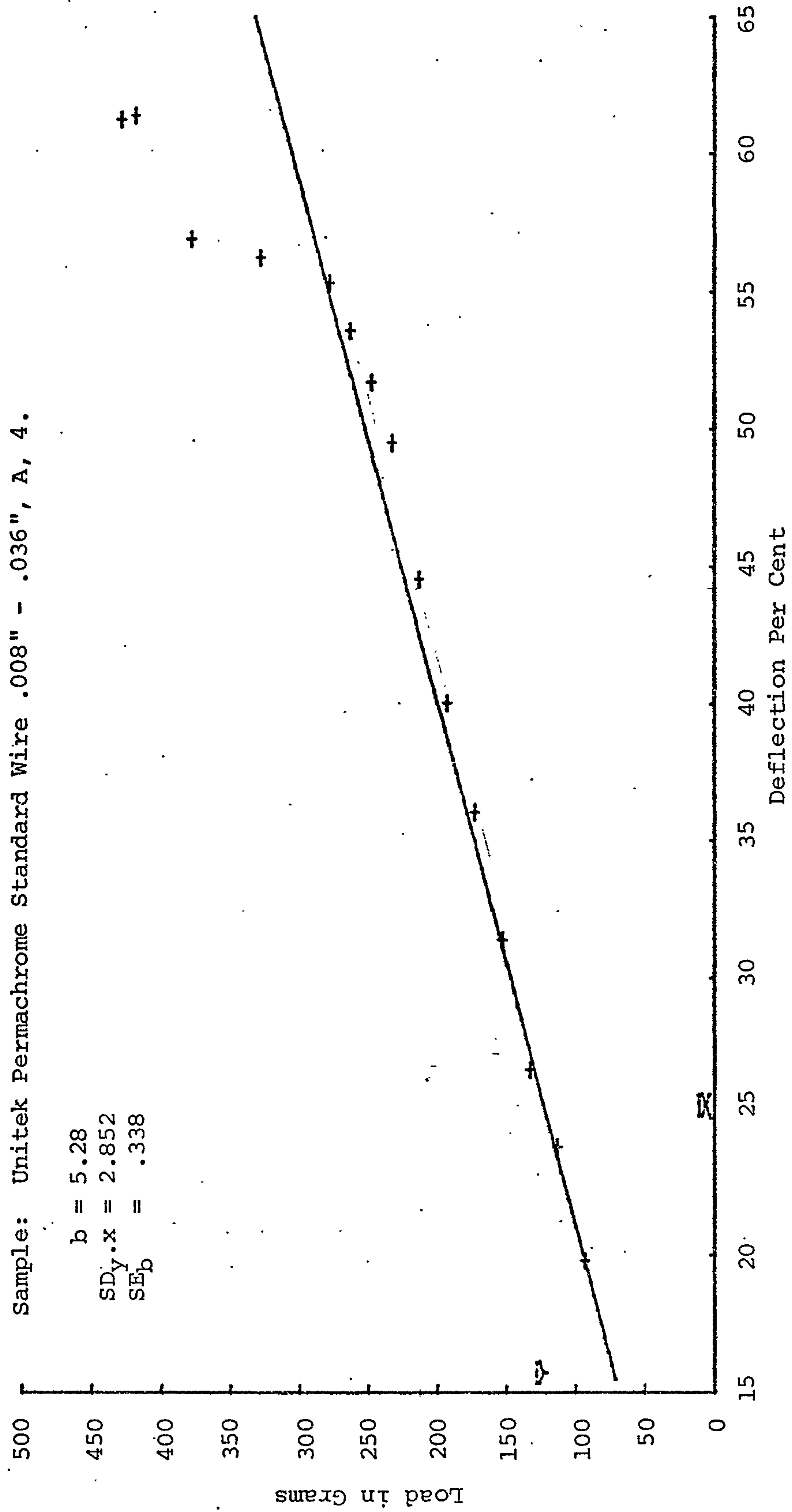


Fig. 108. Load-deflection regression of Unitek Permachrome Standard Wire .008" - .036" open coil helical spring loaded after it had been compressed solid once.

APPENDIX IV

Informations on the Experimental Compression Springs Supplied by
Their Manufacturers (Personal Communication)

Dentaurum Remanit Opon Coil Springs

Composition

The springs are made from a spring steel corresponding to a material listed in the German Standard DIN 17224 (1968) as material No. 4310. The essential composition given by Firma Dentaurum is: carbon 0.15 per cent; chromium 16.0 - 18.0 per cent; nickel 7.0 - 9.0 per cent. These figures indicated that the wire is an austenitic 18-8 stainless steel wire.

Mechanical Properties

The only mechanical property stated by the company is the modulus of elasticity: $20,000 \text{ kg/mm}^2$.

The tensile strength specified in German Standard DIN 17224 (1968) for wires made of material No. 4310 into diameters up to 0.2 mm is 235 to 260 kg/mm^2 , and into diameters over 0.2 mm to 0.4 mm is 225 to 250 kg/mm^2 . The modulus of rigidity is $7500 \pm 200 \text{ kg/mm}^2$ and the modulus of elasticity is $19,400 \pm 500 \text{ kg/mm}^2$. The recommended heat treatment temperature is 380 C for 30 minutes.

Details of Manufacture

Heat treatment of the springs is done before it is formed. The sizes of the springs are manufactured to empirical data. The manufacturing tolerance for core diameter is ± 0.02 mm.

Unitek Hi-T and Permachrome Standard Open Coil SpringsComposition

The composition of Permachrome Standard wire stated by Unitek is:-
carbon 0.15 per cent max.; manganese 2.00 per cent max.; silicon 1.00 per cent max.; phosphorus 0.040 per cent max.; sulphur 0.030 per cent max.; chromium 17.00 - 19.00 per cent and nickel 7.00 - 10.00 per cent. The remainder of content is iron. These figures indicate that Permachrome Standard wire is a 18-8 type 302 stainless steel wire.

The composition of Hi-T is given as:-

carbon 0.142 per cent; manganese 1.00 per cent; phosphorus 0.027 per cent; sulphur 0.013 per cent; silicon 0.32 per cent; chromium 15.65 per cent; nickel 4.38 per cent; molybdenum 2.68 per cent; copper 0.12 per cent and nitrogen 0.124 per cent. The remainder of content is iron. These figures indicate that Hi-T is a 15-5 precipitation-hardening stainless steel wire.

Mechanical Properties

The yield strength for Hi-T wires varies according to drawn wire size.

As an example of yield strength of Hi-T wires, the company gives the

yield strength for 0.012 inch diameter wire as 350/395,000 psi.

The tensile strength is 395/430,000 psi. The yield for Permachrome is 325/380,000 psi.

The modulus of elasticity is 29 M psi and the modulus of rigidity is 10.5M psi.

Elongation in a 2 inch gauge length varies from 1 to 2 per cent.

Details of Manufacture

Springs made from Permachrome are not heat treated. Springs made from Hi-T wire are stress relief heat treated at 800°F for 15 minutes after forming.

The manufacturing tolerance for wire diameters is $\pm .00025$ in. The tolerances for the coil inside diameters are $\pm .001$ in. for sizes .020 in. to .022 in. and $\pm .002$ in. for sizes .030 in. to .039 in. The distance between adjacent coils is .015 in. $\pm .002$ in.

Rocky Mountain "Red Elgiloy" Open Coil SpringsComposition

The springs are made of unheat treated "Red Elgiloy". The nominal composition of "Elgiloy" is as follows:-

cobalt 40%; chromium 20%; nickel 15%; molybdenum 7%; manganese 2%; carbon 0.15%; beryllium 0.04% and the remainder is iron.

Mechanical Properties

The ultimate tensile strength is 340,000 psi, the yield strength 310,000 psi, shear yield 210,000 psi, modulus of elasticity 28,500,000 psi and the torsional modulus is 11,200,000 psi. The recommended heat treatment temperature is 900°F (482°C).

Details of Manufacture

The manufacturing tolerance for wire diameter is $-.0002$ in. and $+0$. The distance between adjacent coils is the diameter of wire used $\pm .001$ inch.

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