STRESS-STRAIN MODEL FOR GRADE 275 REINFORCING STEEL WITH CYCLIC LOADING

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ABSTRACT

The stress-strain relationship of Grade 275 steel reinforcing bar under cyclic (reversed) loading is examined using experimental results obtained previously from eleven test specimens to which a variety of axial loading cycles has been applied. A Ramberg-Osgood function is fitted to the experimental stress-strain curves to follow the cyclic stress-strain behaviour after the first load run in the plastic range. The empirical constants in the function are determined by regression analysis and are found to depend mainly on the plastic strain imposed in the previous loading run. The monotonic stress-strain curve for the steel, with origin of strains suitably adjusted, is assumed to be the envelope curve giving the upper limit of stress. The resulting Ramberg-Osgood expression and envelope is found to give good agreement with the experimentally measured cyclic stress-strain curves.

INTRODUCTION

Severe earthquake loading may cause structural elements to be subjected to cyclic (reversed) loading well into the inelastic range. It is well known that when steel is subjected to reversals of load after first yielding, the stress-strain curve becomes non-linear over much of the loading range due to the Bauschinger effect. Information on the stress-strain relationships for reinforcing steel is required to accurately predict the behaviour of structural concrete members under cyclic loading. Such stress-strain relationships are necessary in order to accurately determine the theoretical moment-curvature relationships for reinforced concrete members subjected to cyclic loading[1]. This leads to more precise determination of moment-curvature models for use in the non-linear dynamic analysis of reinforced concrete structures responding to severe earthquake motions. Also, such stress-strain data is needed to determine the tangent modulus of the steel at various levels of stress to check the likelihood of buckling of reinforcing bars in compression during cyclic loading.

Early work on the stress-strain behaviour of reinforcing bars subjected to cyclic loading was conducted by Singh, Gerstle and Tulin[2] who determined a simple empirical expression which represented the average of the family of measured reversed loading stress-strain curves. The expression is an experimental curve which is extended backwards to meet an initial elastic slope. In more recent work by Kent and Park[3,4] a form of the Ramberg-Osgood equation was used to follow the reversed loading branches of the stress-strain curve after the first yield excursion. Linear unloading curves parallel to the initial elastic slope were assumed. The parameters in the Ramberg-Osgood equation were determined empirically for Grade 275 reinforcing steel and were found to be a function of the actual yield strength, the plastic strain in the previous load run and the loading run number. This method using the Ramberg-Osgood equations was shown to generally lead to better accuracy than the method of Singh, Gerstle and Tulin[3,4]. Aktan, Karlsson and Sozen[5] have also used a form of the Ramberg-Osgood equations with empirical constants to define both the loading and unloading branches of the stress-strain curve and obtained good agreement with test results. They also devised an alternative idealisation consisting of sets of straight lines parallel to the elastic slope and inclined to it. Ma, Bertero and Popov [6] have also obtained close fit with experimental stress-strain data using a form of the Ramberg-Osgood equation.

The study described in this paper extends the existing work of Kent and Park [3,4]. The Ramberg-Osgood equations determined in that early work had been found to underestimate the stress at low strains and to overestimate the stress at high strains[3,4]. In this paper the experimental data collected by Kent and Park is reanalysed and the assumptions of that early procedure are re-examined in order to obtain a stress-strain model which fits the experimental data more closely. A more detailed account of this work may be seen elsewhere[7].

ENVELOPE STRESS-STRAIN CURVE FOR CYCLIC LOADING

Many investigators have shown that the envelope stress-strain curve for cyclic loading may be obtained from the appropriate part of the stress-strain curve for monotonic loading with the origin of coordinates suitably adjusted.

The monotonic stress-strain curve assumed in this study is the same as that proposed by Kent[3] and is illustrated in Fig. 1. The curve comprises three regions, which may be represented by the following equations using the notation of Fig. 1:

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Region AB : $\varepsilon_s \leqslant \varepsilon_y$

$$f_s = E_s \varepsilon_s \quad ..(1)$$

Region BC : $\varepsilon_y \leqslant \varepsilon_s \leqslant \varepsilon_{sh}$

$$f_s = f_y \quad ..(2)$$

Region CD : $\varepsilon_{sh} \leqslant \varepsilon_s \leqslant \varepsilon_{su}$

$$f_s = f_y \left\{\frac{m(\varepsilon_s - \varepsilon_{sh}) + 2}{60(\varepsilon_s - \varepsilon_{sh}) + 2} + \frac{(\varepsilon_s - \varepsilon_{sh})(60 - m)}{2(30q + 1)^2}\right\} \quad ..(3)$$

$$\text{where } m = \frac{(f_{su}/f_y)(30q + 1)^2 - 60q - 1}{15q^2} \quad ..(4)$$

$$\text{and} \quad q = \varepsilon_{su} - \varepsilon_{sh} \quad ..(5)$$

Eqs. 1 to 5 are similar to those obtained by Burns and Siess[8] except that they follow a generalised form for steel with different f_{su}/f_{sy} and ε_{su} values.

The monotonic stress-strain curve has been shown in tests by Leslie[9] to approximately describe the envelope stress-strain curve for cyclic loading providing the cyclic straining occurs either all in the tensile region or all in the compression region. This is also evident from the work of Aktan, Karlsson and Sozen[5]. For more symmetrical tension - compression straining (i.e. approximately equal strain excursions in tension and compression in each cycle) the monotonic stress-strain curve approximately describes the envelope curve only if the origin of the monotonic curve is displaced horizontally.

In this study it will be assumed that the stress-strain envelope for cyclic loading is the same as the stress-strain curve for monotonic loading, except that the origin is translated horizontally during loading such that the new origin is $(\varepsilon_{zmx},0)$ for tensile loading (see Fig. 2), where

$$\varepsilon_{zmx} = \varepsilon_o - \frac{f_o}{E_s} \quad ..(6)$$

where ε_o is the maximum compressive strain and f_o is the stress at the maximum compressive strain. For compressive loading the modified origin is $(\varepsilon_{zmn},0)$, where

$$\varepsilon_{zmn} = \varepsilon_o - \frac{f_o}{E_s} \quad ..(7)$$

where ε_o is the maximum tensile strain and f_o is the stress at the maximum tensile strain. The assumed envelope is shown in Fig. 2. Note that when the origin is displaced it must always be in the directions shown in Fig. 2. For example, the current stress envelope for tensile loading must always commence at the original origin (0,0) or to the left of it as shown in Fig. 2. Thus for repeated loading of the same sign the origin of the envelope always remains at (0,0). The steel stresses are not permitted to exceed the envelope values during loading.

STRESS-STRAIN CURVE FOR CYCLIC LOADING

Assumed Form of Stress-Strain Relationship

For cyclic loading at stresses less than the envelope values, the following modified form of the Ramberg-Osgood function is assumed to give the stress-strain curve after the first yeild excursion

$$\varepsilon_s - \varepsilon_o = \frac{(f_s - f_o)}{E_s}\left\{1 + \left|\frac{f_s - f_o}{f_{ch} - f_o}\right|^{r-1}\right\} \quad ..(8)$$

where ε_s, f_s are the strain and stress values at the point on the stress-strain curve; ε_o, f_o are the strain and stress values at the beginning of the stress-strain curve; f_{ch} is the characteristic stress; E_s is the value of the modulus of elasticity from the initial elastic loading run and r is the Ramberg-Osgood parameter. Eq. 8 is assumed to give the cyclic stress-strain curves which lie within the envelope values (see Fig. 2).

The characteristics of the Ramberg-Osgood function, Eq. 8, are illustrated in Fig. 3. It is noted that values of r between 1 and ∞ give a range of sweeping curves which vary between a straight line when r = 1 to a bilinear relationship with initial slope E_s when r = ∞.

Regression Analysis for f_{ch} and r

Kent and Park[3,4] have reported the results of tests on eleven specimens of Grade 275 (f_y = 316 to 339 MPa) deformed steel reinforcing bars. The chemical composition of the steel complied with NZSS 1693:1962[10]. The specimens were of bar size No. 4,5,6 and 7 (12.7, 15.9, 19.0 and 22.2 mm diameter, respectively). In the region of the strain measurement the specimens had been machined to a smaller diameter. The loads were applied statically and axially, taking considerable care to ensure that eccentricity of load did not become significant during the loading runs. A variety of loading cycles was applied to study a range of initial strains and unloading and reloading sequences. The maximum compressive strains applied were much smaller than the maximum tensile strains applied, in order that the strain histories would be similar to that of flexural reinforcing steel at a plastic hinge region in a reinforced concrete beam with cyclic (reversed) flexure.

The stress-strain results of each of the cyclic loading runs of the eleven test specimens were reanalysed in the present study by a regression analysis in order to obtain more accurate values for f_{ch} and r than had been obtained previously. To perform this analysis Eq. 8 was first made linear in r and f_{ch}[7], using the first three terms of the Taylor series as described by Draper and Smith[11]. Then a general regression analysis was conducted to determine f_{ch} and r for each cyclic load run of each specimen so that the sum of the squares of the differences between the experimentally measured strain and the strain predicted by Eq. 8 at particular stress levels was minimized[7]. The results of this regression analysis for f_{ch} and r are shown in Table 1, where f_{ch} is shown as a function of the steel yield strength f_y. The steel yield strength was measured in the first yield excursion.

The method used by Kent and Park[3,4] to linearise the Ramberg-Osgood function for regression analysis was to take logarithms on both sides of a rearranged Eq. 8. However in this approach, when f_{ch} and r were determined by minimizing the sum of the squares of the differences between the experimental results and those predicted by Eq. 8, the difference used was in fact the difference between the logarithms of the experimental and predicted deviation from the line through point (ε_o, f_o) with slope E_s. For low stress values the logarithms will be large negative numbers tending towards infinity as the deviation from this line tends towards zero. The effect of this was to weight disporportionately the lower stress values, and thus to fit mainly the lower stress values. As a result, the previous expressions derived by Kent and Park[3,4] did not fit the experimental curves very well once a significant amount of plastic strain had been imposed.

Empirical Equation for the Characteristic Stress, f_{ch}

By plotting the values of the ration f_{ch}/f_y given in Table 1 against the possible dependent variables it was observed that the value of f_{ch}/f_y in each loading run was apparently dependent on the plastic strain imposed in the previous loading run, ε_{pl}. The trend was for the ratio f_{ch}/f_y to decrease with increasing prior plastic strain. The values for the ratio of f_{ch}/f_y from Table 1 are shown plotted against ε_{pl} in Fig. 4. Because of the wide scatter of points there seemed little purpose in seeking too complicated an empirical equation to fit these points and a linear relationship relating f_{ch}/f_y to ε_{pl} was fitted, weighted according to the inverse of the stress standard deviation for the particular loading run. The following relationship was obtained

$$f_{ch} = f_y\ (0.973 - 9.806\ \varepsilon_{pl}) \qquad ..(9)$$

for within the range $0 < \varepsilon_{pl} < 0.025$, and is shown plotted in Fig. 4. The values for the ratio f_{ch}/f_y given by Eq. 9 for each of the cyclic loading runs of the eleven test specimens are shown in Table 1.

Empirical Equation for the Ramberg-Osgood Parameter, r

Using the values for f_{ch} given by Eq. 9, a second regression analysis was performed to find the best value of r for the stress-strain results of each of the cyclic loading runs of the eleven test specimens. To perform this analysis Eq. 8 was first made linear in r using the Taylor series, as described by Draper and Smith[11]. Then general regression analysis was conducted to determine r for each cyclic load run for each specimen so that the sum of the squares of the differences between the experimentally measured strain and the strain predicted by Eq. 8 at particular stress levels was minimised[7]. The results of this second regression analysis for r are shown in Table 1.

The values for r so determined were then plotted against various possible dependent factors. It was observed that r was apparently dependent on the plastic strain imposed in the previous loading run, ε_{pl}, and that the correlation of r with other possible variables was poor. Fig. 5 shows the values of r plotted against ε_{pl}. The observation that r shows reasonable correlation with ε_{pl} is different to that made previously by Kent and Park[3,4], who had observed that r was apparently dependent on the number of previous post-elastic loading runs and whether the loading run number was odd or even. Nevertheless there was significant scatter in their plotted data, and it was based on less accurate f_{ch} values than the present data. Hence in the present work r will be assumed to be related to ε_{pl} alone.

An empirical relationship relating r to ε_{pl} was fitted using the values of r obtained from the second regression analysis, weighted according to the inverse of the stress standard deviation for the particular loading run. The following relationship was obtained

$$r = 12.33 + \frac{45.07}{\exp(1000\varepsilon_{pl})} - \frac{9.77}{\log_e(1000\varepsilon_{pl} + 2)} \qquad ..(10)$$

for within the range $0 < \varepsilon_{pl} < 0.025$, and is shown plotted in Fig. 5.

Application of Cyclic Stress-Strain Equations

The proposed model for the cyclic stress-strain behaviour is described by Eqs. (1) to (10). Eqs. (1) to (5) define the monotonic stress-strain curve and hence apply to the first loading run into the post-yield range. Subsequent reversed loading runs are described by Eqs. (8,), (9) and (10), with the stipulation that the stress level reached should not exceed that given by the current stress envelope described by the monotonic stress-strain curve with the zero stress origin given by either Eq. (6) or (7). In order to allow for small stress reversals which do not significantly effect the stress-strain history, it was further assumed that if the plastic strain imposed in a loading run is small (less than 0.0005), then on reloading the new loading curve is only continued until the previous loading curve in that direction is reached and then the previous loading curve is followed. The constraints on the cyclic stress-strain relationships are illustrated in Fig. 6.

COMPARISON OF EXPERIMENTAL RESULTS WITH PROPOSED CYCLIC STRESS-STRAIN MODELS

Figs. 7 to 10 compare the stress-strain curves derived from the model presented in this paper and the model of Kent and Park [3,4] with the experimental stress-strain curves. The curves derived from the stress-strain models were calculated between the experimental strain values at which stress reversals took place.

In Figs. 7 to 10 the tensile stress and strain are initially in the first quadrant, and the cyclic (tension - compression) stresses applied to the test specimens were such as to cause much greater tension strains than compressive strains. This test loading was used in order to approximately simulate the strain history in a longitudinal reinforcing bar in a plastic hinge region of reinforced concrete beam subjected to cyclic flexure. In such a beam if cracking of concrete and yielding of tension steel occurs due to bending moment applied in one direction, when the directon of bending moment is reversed these open cracks will remain in what is now the concrete "compression zone" and will only close if the force in the tension steel is large enough to yield the steel in compression. If the cracks in the compression zone do close, the concrete in the compression zone will prevent the development of extremely high compressive strains in the steel, as is evident from the neutral axis position in the section, whereas when the steel is yielding in tension, extremely high tensile strains can develop, as is evident from wide cracks in the concrete[1]. Hence the strains in the reinforcing bars will occur mainly in the tension range.

The curves of Figs. 7 to 10 illustrate the degree of accuracy with which the derived stress-strain models fit the experimental behaviour. Generally, the stress-strain curves derived using the model presented in this paper follow the experimental curves with good accuracy, and the accuracy achieved is significantly better than that from the curves derived using the model of Kent and Park which tends to overestimate the stress at high strains and to underestimate the stress at low strains.

It should be noted that the use of an accurate stress-strain model for steel is important because if the difference between the predicted and experimental stresses immediately prior to stress reversal is large, the predicted curve becomes out of phase with the experimental curve and significant errors can arise.

It should also be emphasized that the empirical equations for the proposed cyclic stress-strain model have been derived from experimental results obtained from steel reinforcing bars with strains imposed mainly in the tension region, for maximum imposed strains less than that at the commencement of strain hardening, for steels with a yield strength in the range 316 to 339 MPa (46 to 49 ksi), and for slow (static) strain rates. Further tests are required, particularly to investigate the effect of high rates of loading such as in a structure subjected to seismic ground motions, and to investigate the possible change in steel mechanical properties due to strain ageing after cyclic loading in the inelastic range.

APPLICATION OF THE CYCLIC STRESS-STRAIN MODEL

The proposed model for the stress-strain behaviour of cyclically loaded reinforcing steel in the inelastic range emphasizes that after the first yield excursion the yield stress of steel as usually defined loses its significance since the stress-strain curve becomes nonlinear over much of the loading range. The proposed stress-strain model has three main applications. The first application is the determination of the theoretical moment-curvature characteristics of reinforced concrete members subjected to cyclic flexure[1,12]. It has been found previously[1] that for large portions of the moment-curvature loop after the first yield excursion the shape of the moment-curvature loop is very dependent on the shape of the stress-strain curve for the steel. A second application is the determination of the buckling loads of reinforcing bars in reinforced concrete members with cyclic flexure. It is evident that after the first yield excursion of the longitudinal steel the tangent modulus of the steel at stresses less than the initial yield strength can be considerably lower than the modulus of elasticity of the steel and that this could lead to buckling of bars at lower levels of compressive stress than expected from monotonic loading tests. A third application is the calculation of the stresses in reinforcing bars from the strain histories measured during cyclic loading.

CONCLUSIONS

Equations defining the stress-strain characteristics of Grade 275 steel reinforcing bars under cyclic (reversed) loading after the first yield excursion have been presented using the Ramberg-Osgood function with empirical constants which depend on the plastic strain in the previous loading run. The stress-strain curve for monotonic loading, with suitably adjusted origin of co-ordinates, is used to describe the envelope which the steel stresses cannot exceed. The stress-strain model is shown to be capable of describing cyclic stress-strain curves with good accuracy.

ACKNOWLEDGEMENTS

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NOTATION

The following symbols are used in this paper:

E_s = modulus of elasticity of steel obtained from the monotonic loading curve

f_{ch} = characteristic stress used in Ramberg-Osgood function

f_o = steel stress at beginning of a loading curve

f_s = steel stress

f_y = yield strength of steel obtained from the monotonic loading curve

r = Ramberg-Osgood parameter

ε_o = steel strain at beginning of a loading run

ε_{pl} = plastic strain in steel produced in previous loading run

ε_s = steel strain

ε_{sh} = steel strain at commencement of strain hardening obtained from the monotonic loading curve

ε_{su} = ultimate steel strain obtained from the monotonic loading curve

ε_y = steel strain at the yield strength obtained from the monotonic loading curve

ε_{zmn} = strain origin for steel stress-strain envelope for compressive loading

ε_{zmx} = strain origin for steel stress-strain envelope for tensile loading

TABLE 1: RESULTS OF ANALYSIS FOR f_{ch} and r

Specimen (3,4)	Loading Run Number	From First Regression Analysis		f_{ch}/f_y given by Eq. 9	r given by Second Regression Analysis and Eq. 9
		f_{ch}/f_y	r		
6	1	1.040	11.403	0.902	6.360
8	1	0.977	15.584	0.940	11.944
	2	1.013	48.185	0.928	21.066
	3	0.733	9.966	0.770	11.842
9	1	1.377	6.368	0.956	17.330
	2	1.076	50.708	0.966	15.023
	3	0.883	10.140	0.860	9.018
11	1	0.856	10.988	0.938	9.330
12	1	0.831	10.601	0.879	9.012
	2	0.993	53.201	0.960	31.450
17	1	1.118	6.301	0.919	8.434
	2	1.007	53.381	0.967	14.263
	3	0.946	8.895	0.951	8.815
	4	1.007	41.262	0.968	14.197
	5	0.896	8.430	0.950	7.622
	6	1.003	24.032	0.966	13.280
	7	0.923	6.814	0.946	6.563
	8	0.823	37.740	0.964	29.671
20	1	0.810	12.147	0.917	9.384
	2	0.986	45.693	0.967	54.991
	3	0.828	10.488	0.957	8.014
	4	1.016	21.807	0.967	30.907
	5	0.817	10.935	0.959	8.051
	6	1.010	20.842	0.967	29.460
	7	0.791	10.786	0.957	7.489
	8	1.031	14.918	0.966	24.625
	9	0.824	9.743	0.958	6.000
21	1	1.657	6.562	0.961	19.454
	2	1.049	60.000	0.970	9.027
	3	2.125	6.000	0.965	15.976
	4	1.073	39.527	0.969	9.988
	5	1.408	7.960	0.964	18.797
	6	1.058	60.000	0.969	8.267
	7	1.069	13.865	0.966	19.550
	8	1.066	59.429	0.969	19.341
25	1	0.915	10.035	0.929	10.585
	2	0.996	35.505	0.923	20.083
	3	0.737	9.705	0.758	10.253
29	1	1.388	6.002	0.954	13.375
	2	1.046	60.000	0.967	7.445
	3	1.093	6.624	0.947	9.282
	4	1.043	36.968	0.962	7.410
	5	0.951	8.390	0.941	8.650
	6	1.055	23.590	0.959	6.832
	7	0.913	7.405	0.944	6.773
	8	1.031	42.870	0.955	11.565
30	1	1.436	6.916	0.964	19.543
	2	1.463	7.324	0.963	60.000
	3	1.475	7.780	0.967	16.168
	4	1.075	60.000	0.966	10.887

Note: Loading runs were numbered 0,1,2,3,...., where first yield occurs at run number 0, the first post-elastic stress reversal is run number 1, the second post-elastic stress reversal is run number 2, etc.

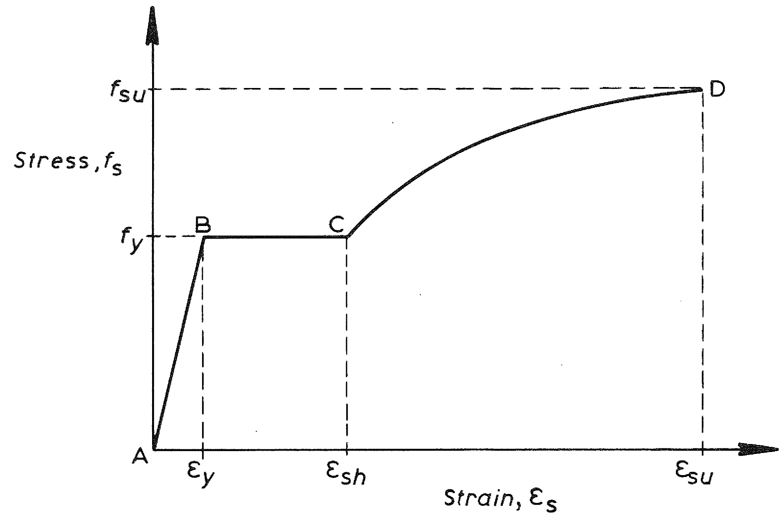

FIGURE 1: MONOTONIC STRESS-STRAIN RELATIONSHIP FOR STEEL

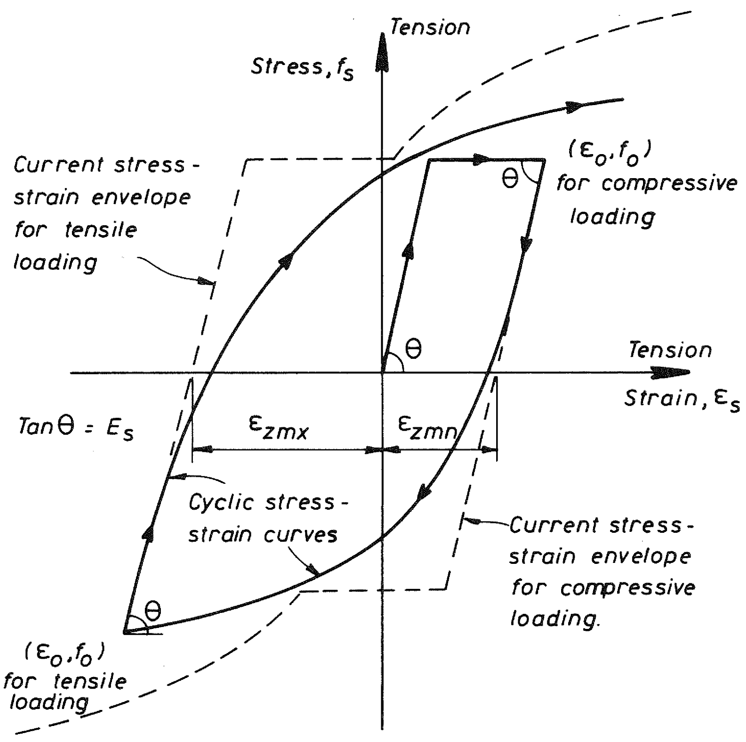

FIGURE 2: STRESS-STRAIN ENVELOPE FOR CYCLIC LOADING

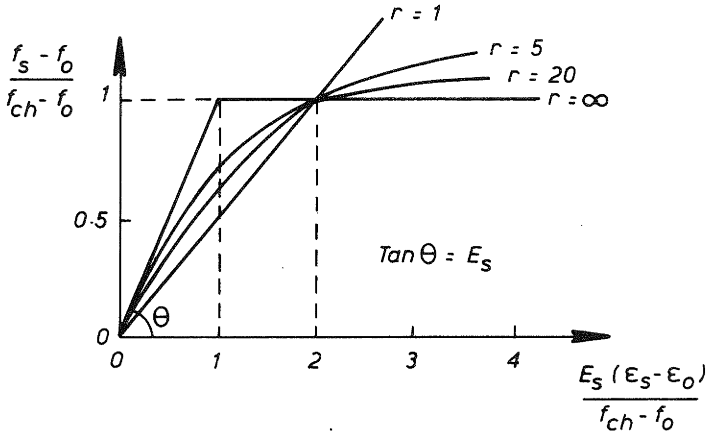

FIGURE 3: CURVES GIVEN BY RAMBERG-OSGOOD FUNCTION EQ. 8

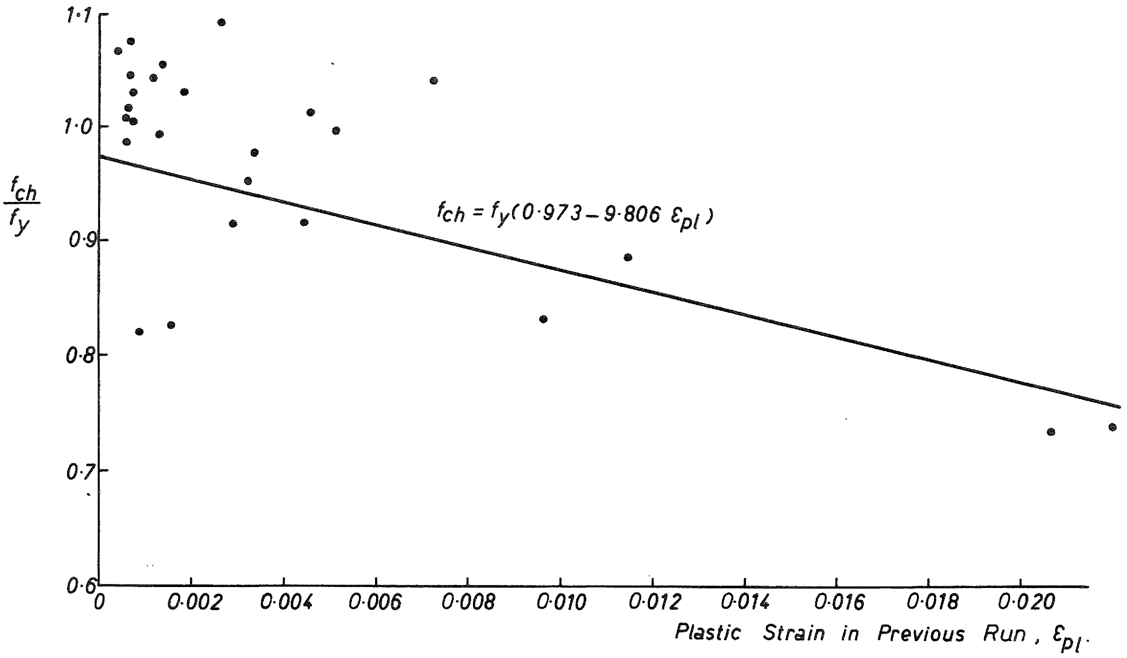

FIGURE 4: RELATIONSHIP BETWEEN CHARACTERISTIC STRESS f_{ch} AND PLASTIC STRAIN IMPOSED IN PREVIOUS LOADING RUN ε_{pl}

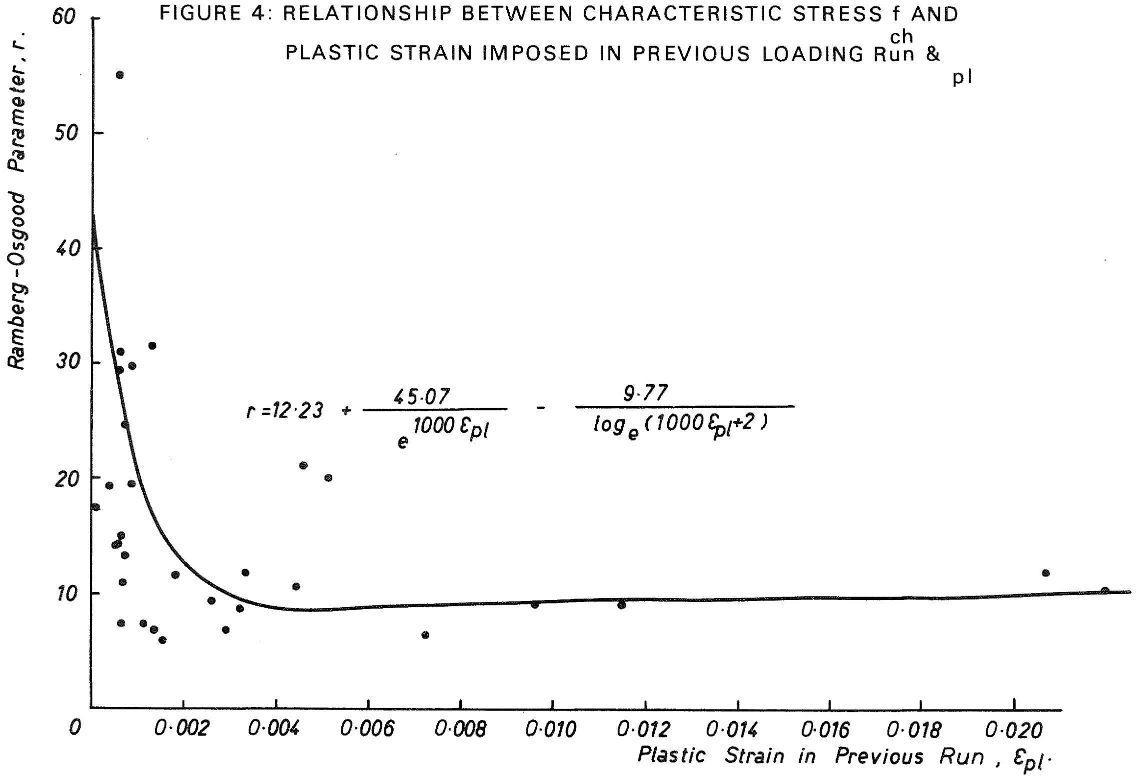

FIGURE 5: RELATIONSHIP BETWEEN RAMBERG-OSGOOD PARAMESTER r AND PLASTIC STRAIN IMPOSED IN PREVIOUS LOADING RUN ε_{pl}

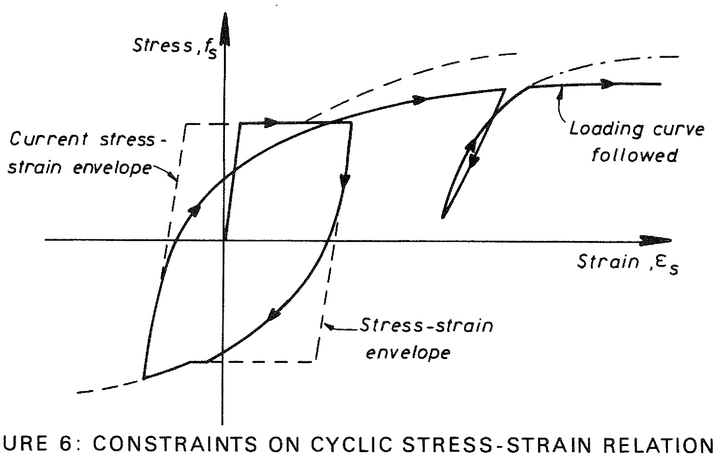

FIGURE 6: CONSTRAINTS ON CYCLIC STRESS-STRAIN RELATIONSHIPS

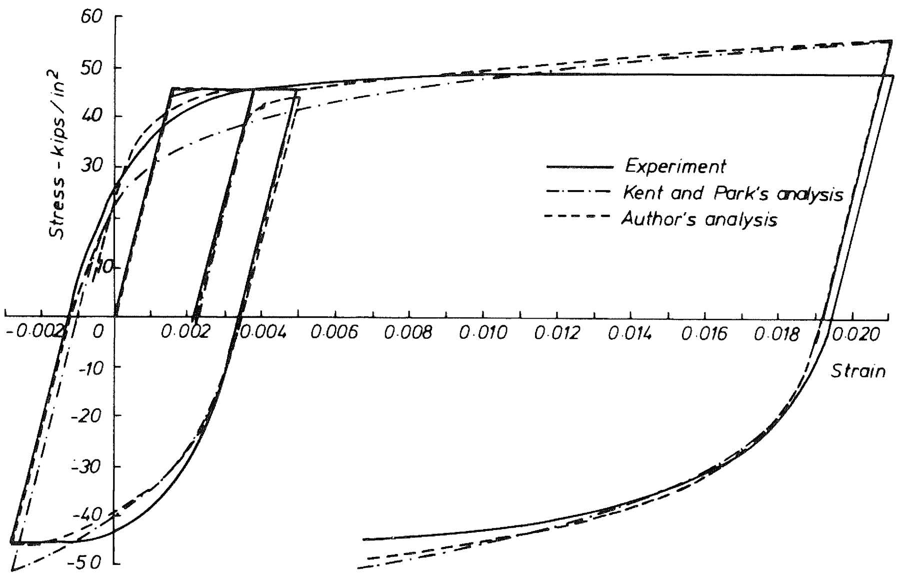

FIGURE 7: COMPARISON OF PREDICTED AND EXPERIMENTAL STRESS-STRAIN CURVES FOR STEEL SPECIMEN 8 (1 kip/in^2 = 6.89 MPa)

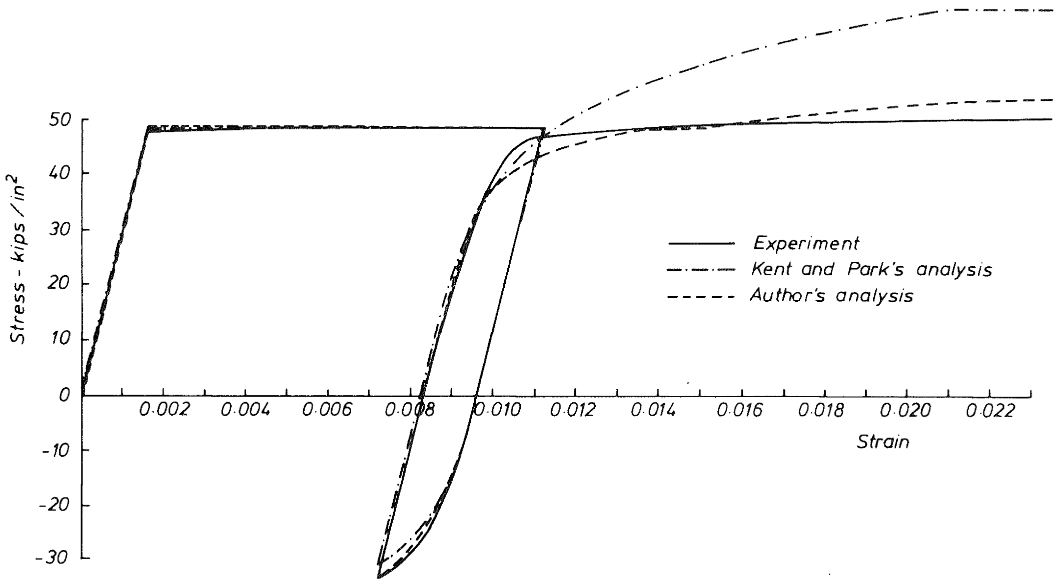

FIGURE 9: COMPARISON OF PREDICTED AND EXPERIMENTAL STRESS-STRAIN CURVES FOR STEEL SPECIMEN 9 (1 kip/in^2 = 6.89 MPa).

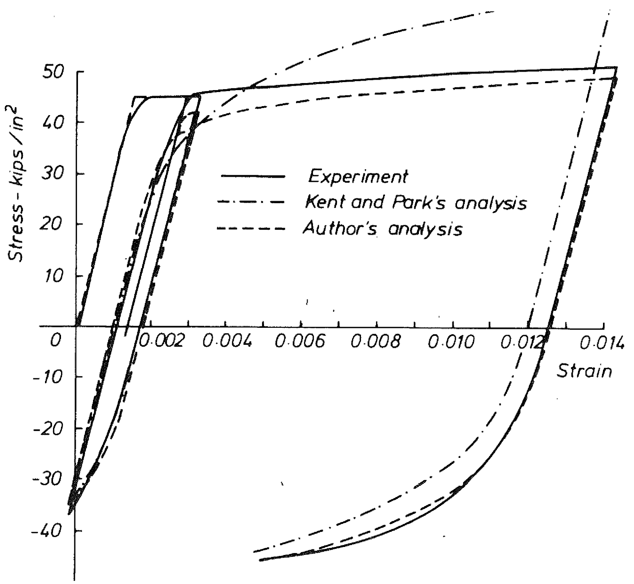

FIGURE 8: COMPARISON OF PREDICTED AND EXPERIMENTAL STRESS-STRAIN CURVES FOR STEEL SPECIMEN 9 (1 kip/in^2 = 6.89 MPa)

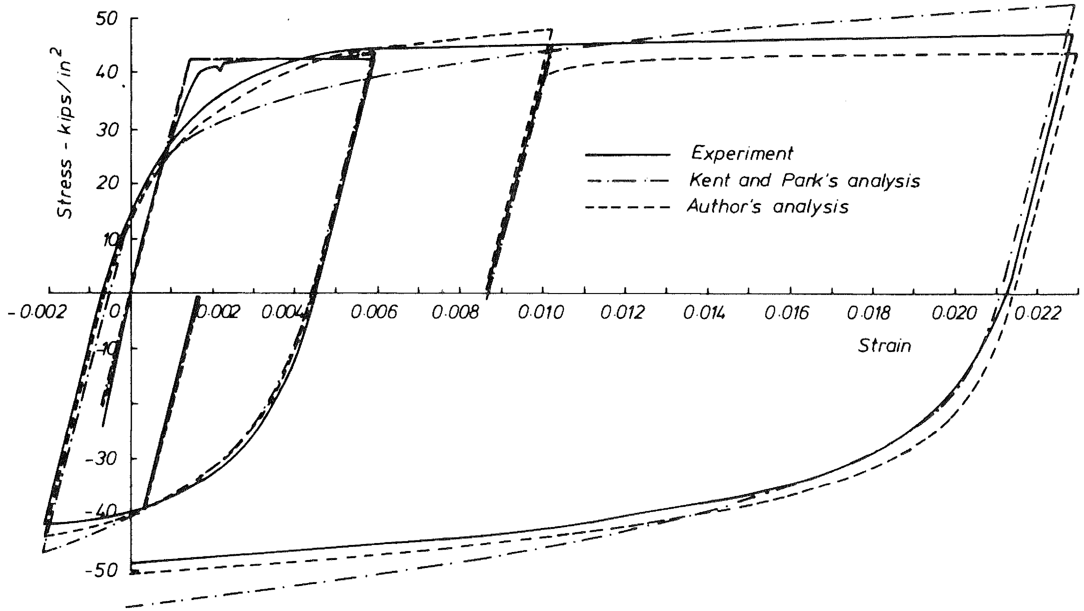

FIGURE 10: COMPARISON OF PREDICTED AND EXPERIMENTAL STRESS-STRAIN CURVES FOR STEEL SPECIMEN 25 (1 kip/in^2 = 6.89 MPa).