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BEHAVIOUR OF STEEL FIBRE REINFORCED CONCRETE UNDER CYCLIC COMPRESSIVE LOADING

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ABSTRACT: An experimental study was carried out to investigate the behaviour of steel fibre reinforced concrete under cyclic compressive loading. Cylindrical specimens containing two volume fractions (one percent and two percent) of steel fibres and plain concrete specimens were tested under uniaxial monotonic and cyclic compressive loading to establish the stress-strain envelope curve, locus of common points and stability points. An analytical expression is established to represent these curves for SFRC. It was also observed that the permissible stress level depends on the plastic strain present in the material. The plastic strain curves are presented and a general form of second order equation is proposed to represent these curves.

Key words ; Fibre reinforced concrete, cyclic loading, envelope curve, common point, stability point, plastic strain

INTRODUCTION

A sizeable amount of research work(Sinha et.al,1964, Karsan and Jersa, 1969, Yankelevsky and Reinhardt,1987, Naraine and Sinha, 1989, Chaubey, and Sinha, 1991, Bahn and Hsu,1998 and Alshebani and Sinha,1999) has been reported on the behaviour of concrete and brick masonry under cyclic compressive loading and it has been established that concrete and brick masonry possess three fundamental stress-strain curves when subjected to cyclic loading. These three stress-strain curves are termed as the envelope stress-strain curve, the common point curve and the stability point curve. Fibre reinforced concrete is a relatively new material developed through extensive research and development during the last two decades. It has already found a wide range of practical applications and has been proved as reliable structural material having superior performance characteristics compared to conventional concrete . Incorporation of steel fibres in concrete has been found to improve several of its properties, primary cracking resistance, impact resistance, toughness and ductility(Romuldi and Batson, 1963, ACI Publication SP-44,1974, Barr and Noor, 1985, Otter, and Naaman1987, Sabapati and Achyutha,1989, H., Bayasi and Soroushion, 1991).For these reasons, fibre reinforced concrete can be used in structures that must withstand cyclic loading conditions. To use fibre reinforced concrete in such situations, its behaviour under cyclic loading is required to be investigated in depth. At present, very little research work is available on cyclic response of fibre reinforced concrete(Otter and Naaman1988, Paskova and Meyer,1997). The primary objective of this research is to investigate the stress-strain behaviour of fibre reinforced concrete under uniaxial cyclic compressive loading. Cylindrical specimens containing two volume fractions of steel fibres were tested under uniaxial compressive loading to establish stress-strain envelope curve, locus of common points and stability points. The common point is defined as the point of intersection of reloading portion of any cycle with the unloading portion of previous cycle. The stresses above common point produce additional strains while stresses below this point will result in the stress-strain path going into a loop. The common point descends and stabilises at lower bound called stability point. Mathematical expressions for the cyclic stress-strain curves are proposed.

EXPERIMENTAL PROGRAMME

Materials and mix proportions

In preparations of test specimens 43 grade ordinary Portland cement, natural river sand and stone aggregate were used. Concrete mix proportion adopted was 1:1.48:2.82(cement :sand :coarse aggregate)with water cement ratio of 0.5. The concrete mix was designed to achieve a 28-days cube strength of 20 Mpa. Steel fibres, at different volume fractions of one and two percent were mixed in concrete homogeneously. The steel fibres used were mild steel round straight wire with the diameter of 0.67 mm. and aspect ratio of 75. Longer size of fibre was chosen to reduce the number of fibres per Kg. of fibres to avoid problem of workability(Ramakrishnan and Josifek, 1987). While making the concrete mix with fibres water reducing admixture (conflo) was used to improve its workability. A total number of eighteen cylindrical specimens of size 150 mm (dia.) x 300 mm (length) were cast using standard steel moulds. These specimens were removed from moulds after 24 hours and cured for twenty eight days in water tank before testing. The cube compressive strength of concrete mix design mix was obtained as 29.1 Mpa and that of fibre mixes were obtained as 31 Mpa and 33.96 Mpa for one percent and two percent fibre mixes respectively.

Loading arrangement and Instrumentation

The cylindrical specimens were tested under uniaxial compressive loading. X-Y_1-Y_2 plotter was used to monitor displacement and applied load through linear variable differential transformers (LVDT) and a load cell respectively. Loading and unloading were controlled by a universal testing machine. A dial gauge was also connected over the length of specimen to check and record the measurement at peak load in each cycle of loading. Instrumentation and loading arrangement are shown in Fig.1.

Test Procedure

Three types of tests were conducted on each type specimens. Three specimens were tested for each type of test resulting in a total of twenty seven specimens being tested. The first type of test was conducted to establish stress-strain envelope curve, where load was increased steadily to failure. The second type of test was conducted to establish common points. In this test the specimens were tested under cyclic loading (Figs.2). In each cycle load was increased such that loading coincides approximately with the envelope stress-strain curve from the monotonic tests and reduced to zero. The common points were obtained as the intersection of reloading portion of any cycle with the unloading portion of previous cycle. In the ascending zone of the stress-strain curve the load histories were controlled by monitoring the incremental strain in each cycle so that the loading curve in each cycle attained the envelope curve. In the descending zone of the stress-strain curve, the load was released when the loading curve tended to descend. The stress-strain curve so obtained possessed a locus of common points (point C on Figs. 2). The object of third type of test was to establish stability points. In this type of test load was increased to point coinciding approximately with envelope curve and reduced to zero. The first cycle in each loop establishes common point. At this stage, when common point was established, loading and unloading with in the loop was repeated several times, number depended upon the reach of stability point, in such a way that at each time of repetition unloading was done when reloading curve intersected with initial unloading curve (Figs. 3).During loading -unloading process the point of intersection gradually descended (points C & D on Figs. 3). After a few numbers of cycles of loading and unloading within each loop this point of intersection stabilised at a lower bound (point S on Figs.3). Such lower bound points are termed as stability points. Once this point is stabilised further cycling led to the formation of a closed hysteresis loop and stability point would not further descend. After establishing stability point next cycle is chosen and same procedure is repeated.

TEST RESULTS AND EVALUATION

Stress -strain envelope curve

The peak points of the stress-strain curve under cyclic loading in test types 2 and 3 were found to lie approximately on the stress-strain curve obtained under monotonic loading. Therefore, the envelope curve was obtained by superimposing the peak stress-strain points under cyclic loading tests on the stress-strain curve under monotonic loading. Fig.4(a),(b) and (c) show all such peak points of the stress-strain curves under cyclic loading and envelope points under monotonic loading. The stress co-ordinate is normalised with respect to the peak stress of each specimen and strain co-ordinate is normalised with respect to axial strain when peak stress is attained. Fig.4(c) shows comparison of envelope curves for both types of SFRC and concrete specimens. Envelope curves for both types of SFRC specimens lie above the envelope curve for plain concrete specimens.

Common point and stability point curves

The common points obtained from the cyclic tests in test types 2 and 3 were normalized and plotted in Figs.3.7 (a), (b), and (c) for both types of SFRC specimens and plain concrete specimens. Comparison of common point curves for three types of specimens is shown in Fig.3.8. The stability points obtained from test type 3 are plotted in Figs. 3.9 (a), (b) and (c) for both types of SFRC specimens and plain concrete specimens respectively. Fig.3.10 shows comparison of stability point curves for all types of specimens. The common point and stability point curves for SFRC specimens lie above the plain concrete specimens.

Analytical curves

The general form given below can be used to obtain the envelope curve, the common point curve and the stability point curve for specimens having different volume fractions of steel fibres.

$$\sigma = (\beta / \alpha).\ \varepsilon^{S}.\exp.[(1-\varepsilon/\alpha).\varepsilon /(\alpha + S^{n})] \qquad [1]$$

where,

σ = Normalised stress
ε = Normalised strain

The parameter α represents the value of strain parameter at maxima and the variation of β accounts for the change in maxima of the envelope curve, the common point curve and stability point curve. The values of α and β for envelope curves are both unity. Using experimental data the values of α and β were plotted in α- β co-ordinate system and found suitable linear expression of α in terms of β for both types of specimens. These linear expressions are given below :

For one percent fibre specimens :

$$\alpha = 0.25\,\beta + 0.75 \qquad [2a]$$

For two percent fibre specimens:

$$\alpha = 0.245\,\beta + 0.755 \qquad [2b]$$

Parameter S can be regarded as shape factor and n being a constant to be determined from best fit curve. The values of these parameters are given in Table1. Analytical curves are drawn in Figs.4 to 8. These curves showed good agreement with test data as reflected by coefficient of determination R^2 given in Table1.

Table -1 Values of parameters β, S and n

Fibre Specimen →	Two Percent fibre				One Percent fibre			
Curves ↓	β	S	n	R^2	β	S	n	R^2
Envelope	1.0	0.64	1.289	0.99	1.0	0.75	4.819	0.98
Common Point	0.88	0.64	1.173	0.98	0.87	0.75	4.425	0.98
Stability Point	o.75	0.64	1.026	0.96	0.74	0.75	3.961	0.96

Stress-strain characteristics under cyclic loading

From the three types of tests conducted on cylindrical specimens under uniaxial compressive loading three distinct stress-strain curves were obtained namely envelope curve, common point curve and stability point curve. From these tests it was evident that test type 2 gives upper bound points while test type 3 gives lower bound points. These upper bound points and lower bound points are termed as common points and stability points respectively. Stresses above the common point produce additional strains whereas stresses below the common point produce a stress-strain path going into a close loop and forming loci of other common points until it stabilises at a lower locus of points (point S in Figs.3).

Permissible stress level

The stability point curve can be a useful aid in defining the permissible stress limit under uni axial compressive loading where reductions of compressive strength due to effect of repeated loading have to be taken in to account. If the peak stress of the repeated load is higher than the peak of the stability point curve ($\sigma > \sigma_s$), repeated cycles will result in the accumulation of strain and will gradually produce failure, as strains grow as a result of number of cycles. If the peak level of repeated load is less than the peak load of stability point curve ($\sigma < \sigma_s$), the repeated cycles of load will cause accumulation of plastic strains till it coincides with stability point curve at 1 (Fig.10). Further cycling will follow the same path and plastic strain stabilises at ε_1. In defining the permissible stress level for repeated loadings, the level of plastic strain present in the material has to be considered (Choubey and Sinha, 1994). If repeated loading is done from an initial state of plastic strain such that its value (ε_3) is larger than the plastic strain associated with unloading from strain ratio on peak of stability curve, then stability point will exist at stress level below the peak of stability point (i.e. on the descending portion of stability point curve). In such cases stability point strain can be determined from relationship between plastic strain and stability point strain. Corresponding to stability point strain , stability point stress can be obtained. At plastic strains lower than the residual strain associated with unloading from the strain ratio on the peak of the stability point curve, the peak of the stability point curve can be used to define permissible stress.

Plastic strain curves

Plastic strain may be considered as an index of deterioration and is related to permissible stress level. Therefore, it is important to relate the plastic strain with the envelope, common point and stability point strains. The non-dimensional plastic strain ε_p, at the end of unloading of any cycle is plotted against the non-dimensional envelope strain,ε_e, at the beginning of the cycle in Figs.11(a), (b) and (c). The plastic strain is non-dimensionalised with respect to the strain when peak load is attained for each specimen. Other curves of non-dimensional plastic strain at unloading versus the non-dimensional common point strain and the non-dimensional stability point strain are shown in Figs. 12(a), (b) and (c) and 13(a), (b) and (c) respectively.

Using experimental data, the least squares method was applied to determine the equations of these curves for SFRC specimens. It is found that these curves can be represented by second order parabolic equations. The general form of the equation is given below.

$$\varepsilon_p = a_1 \varepsilon + b_1 \varepsilon^2 \quad (3)$$

The parameter ε refers to ε_e, ε_c, or ε_s depending on the plastic strain curve being referred ; ε_p, ε_e, ε_c and ε_s are the non-dimensional plastic strain, envelope strain, common point strain and stability point strain respectively. The values of coefficients a_1 and b_1 are given in Table3.2 for each curve fitted to both types of SFRC specimens. The coefficients of determination R2 given in Table-2 indicate good degree of fit of second order curves with experimental data.

Comparison of these plastic strain curves for SFRC and concrete specimens is shown in Figs11 (d), 12(d) and 13(d). These curves for two percent SFRC specimens lie little over that for one percent fibre specimens and concrete specimens. This shows that two percent specimens undergo for lesser residual strains compared to that of one percent fibre specimens and concrete specimens at unloading from same strain ratios.

Table-2 Values of coefficients a_1 , b_1 and coefficient of determination R^2 in plastic strain curves

Fibre specimen→	Two percent fibre			One percent fibre		
Curves ↓	a_1	b_1	R^2	a_1	b_1	R^2
ε_p versus ε_e	0.142	0.421	0.99	0.07	0.444	0.99
ε_p versus ε_c	0.195	0.370	0.99	0.131	0.394	0.99
ε_p versus ε_s	0.210	0.360	0.99	0.194	0.342	0.99

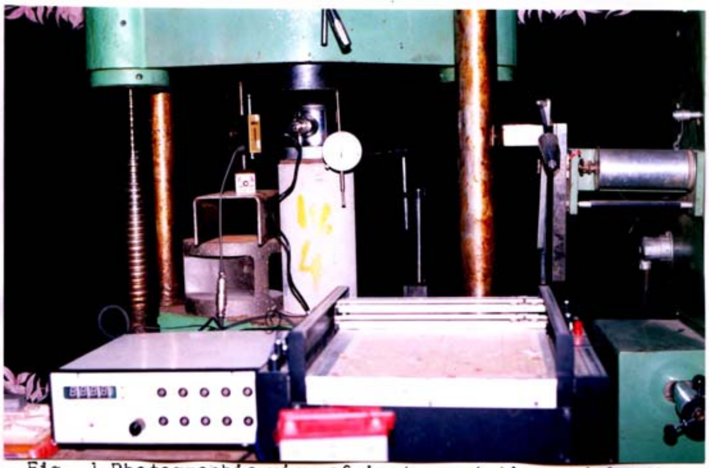

Fig. 1 Photographic view of instrumentation and loading

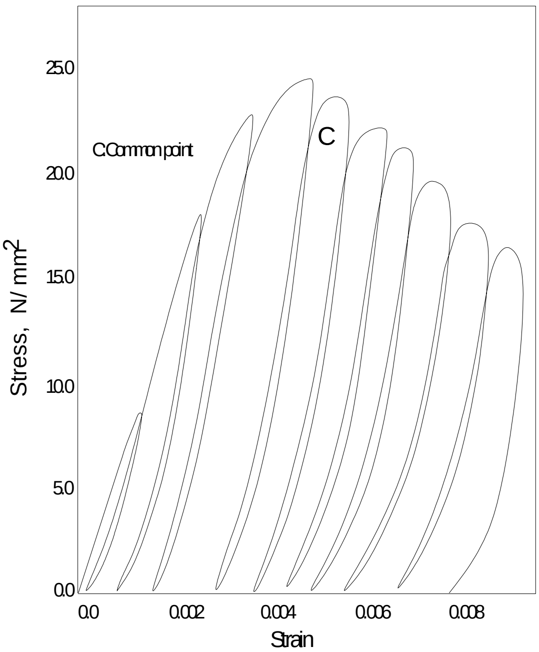

FIG.2(a) TEST UNDER CYCLIC LOADING FOR COMMON POINTS

(One percent SFRC)

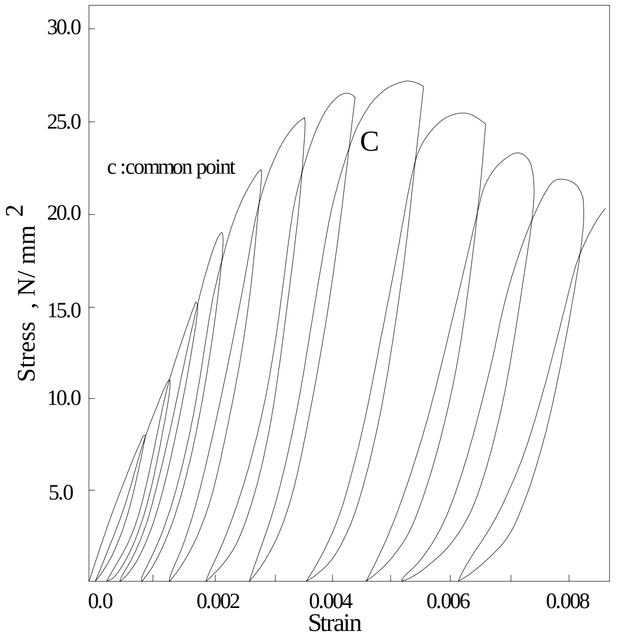

FIG.2(b) TEST UNDER CYCLIC LOADING FOR COMMON POINTS
(Two percent SFRC)

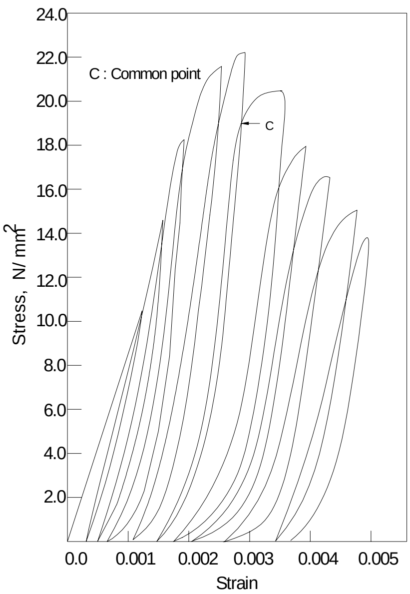

FIG.2(c) TEST UNDER CYCLIC LOADING FOR COMMON POINTS
(Plain concrete)

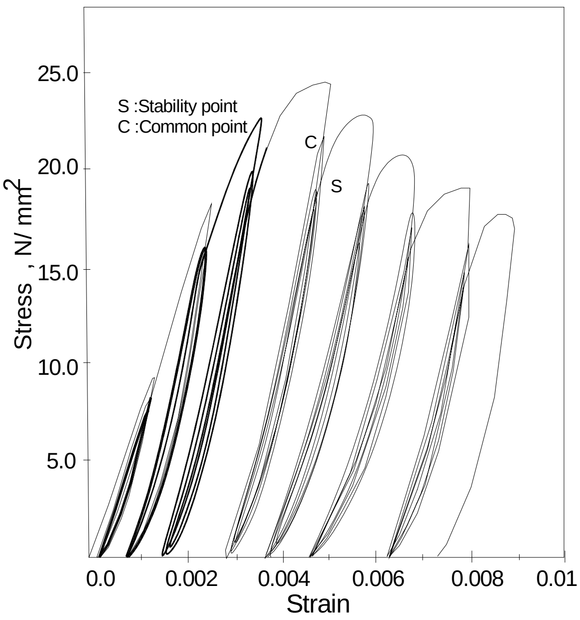

FIG.3(a) TEST UNDER CYCLIC LOADING FOR STABILITY POINTS
(One percent SFRC)

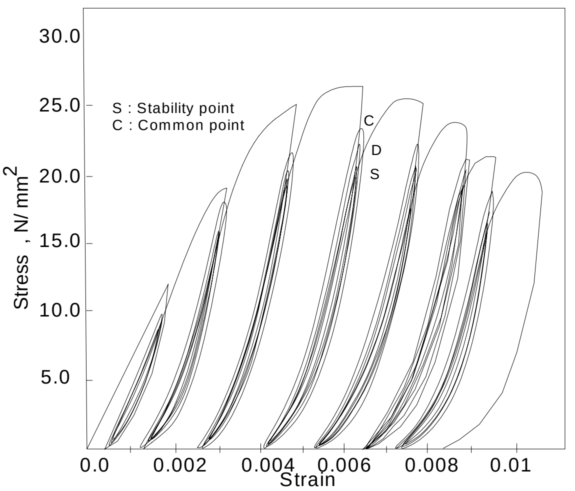

FIG.3(b) TEST UNDER CYCLIC LOADING FOR STABILITY POINTS
(Two percent SFRC)

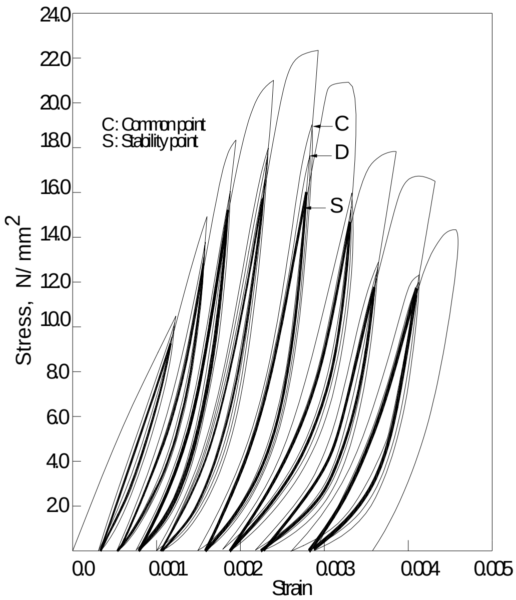

FIG.3(c) TEST UNDER CYCLIC LOADING FOR STABILITY POINTS
(Plain concrete)

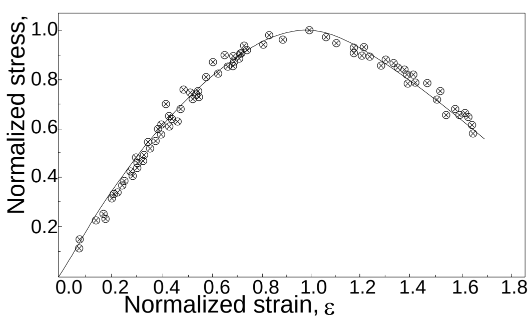

FIG.4(a) ENVELOPE STRESS-STRAIN CURVE (1%SFRC)

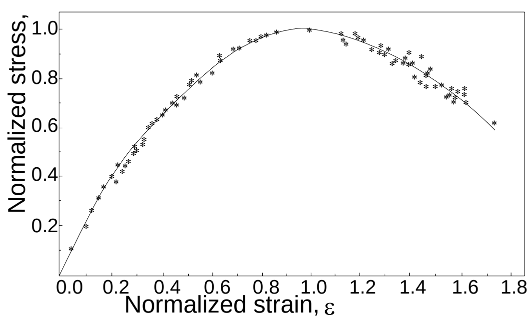

FIG.4(b)ENVELOPE STRESS-STRAIN CURVE (2% SFRC)

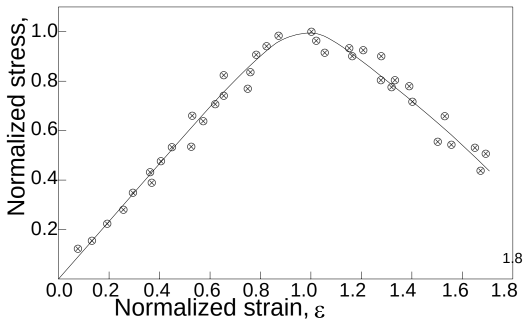

FIG.4(c) ENVELOPE STRESS-STRAIN CURVE (Plain concrete)

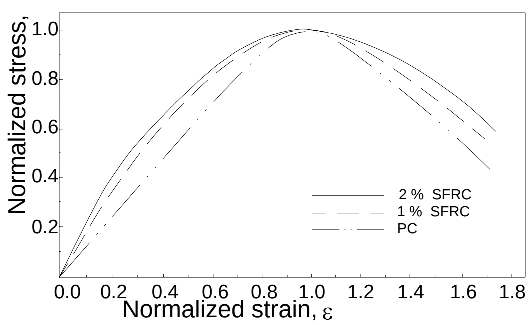

FIG.5 COMPARISON OF ENVELOPE STRESS-STRAIN CURVES

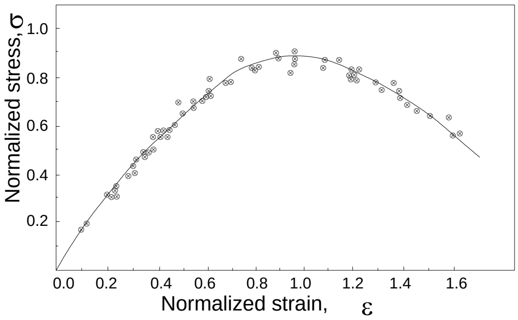

FIG.6(a) COMM0N POINT STRESS-STRAIN CURVE (1%SFRC)

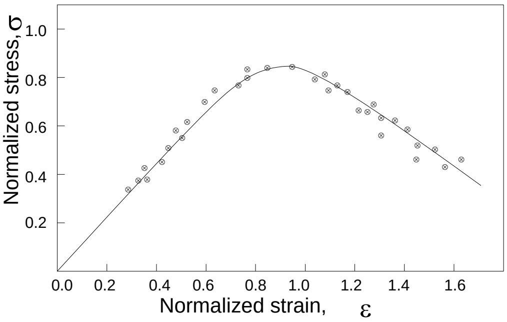

FIG.6(c) COMM0N POINT STRESS-STRAIN CURVE (Plain concrete)

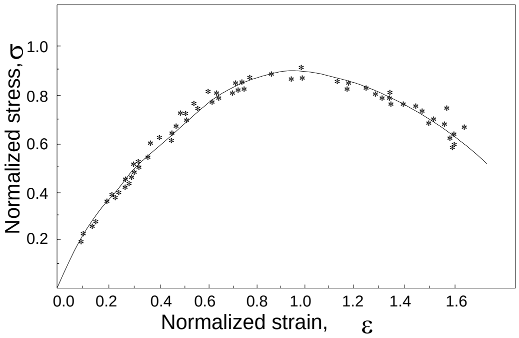

FIG.6(b) COMM0N POINT STRESS-STRAIN CURVE (2%SFRC)

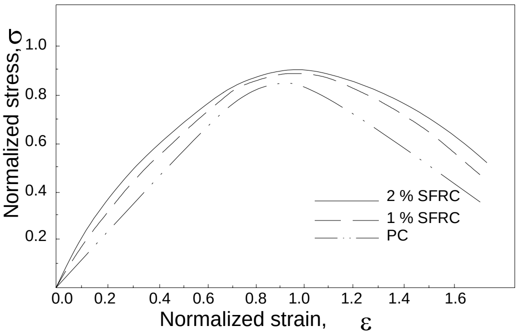

FIG.7 COMPARISON OF COMM0N POINT CURVES

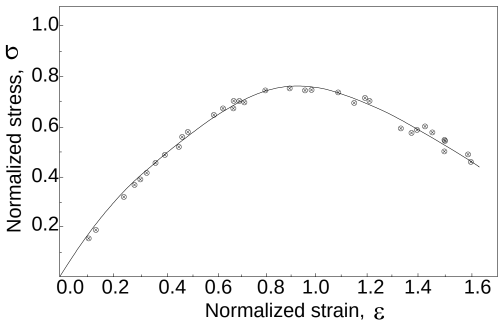

FIG.3.8(a) STABILITY POINT STRESS-STRAIN CURVE (1%SFRC)

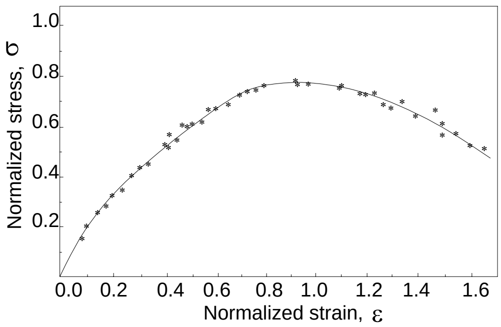

FIG.3.8(b) STABILITY POINT STRESS-STRAIN CURVE (2%SFRC)

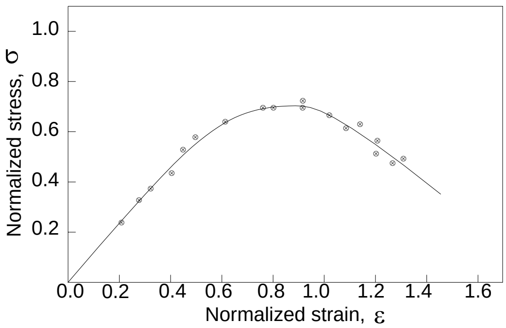

FIG.3.8(c) STABILITY POINT STRESS-STRAIN CURVE (Plain concrete)

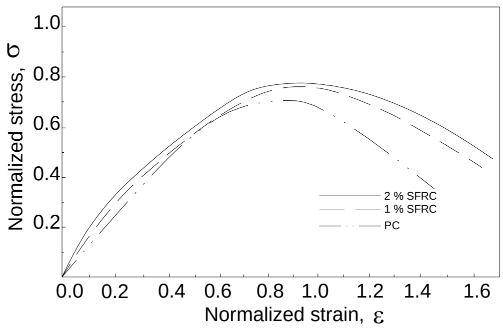

FIG.9COMPARISON OF STABILITY POINT CURVES

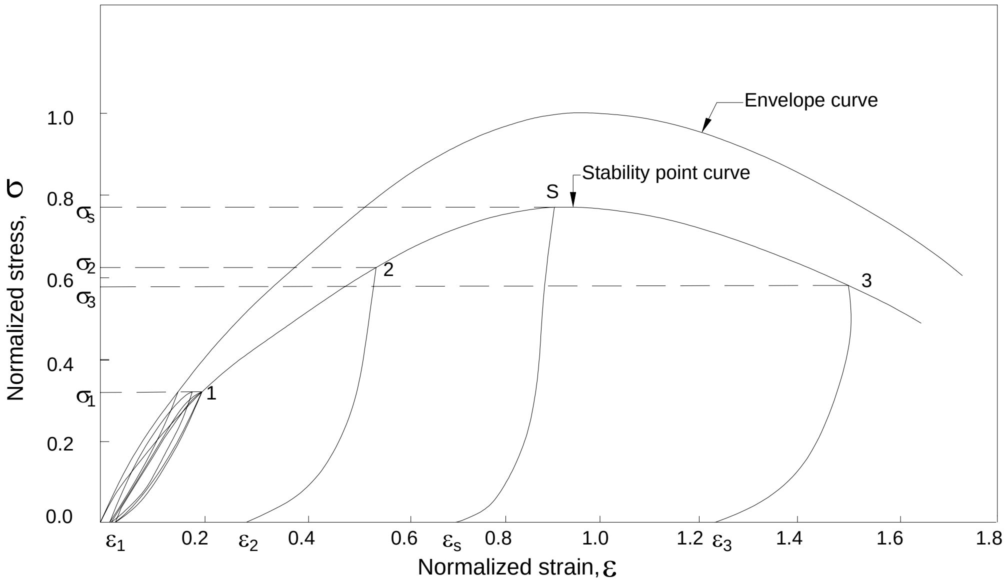

FIG.10 PERMISSIBLE STRESS LEVEL

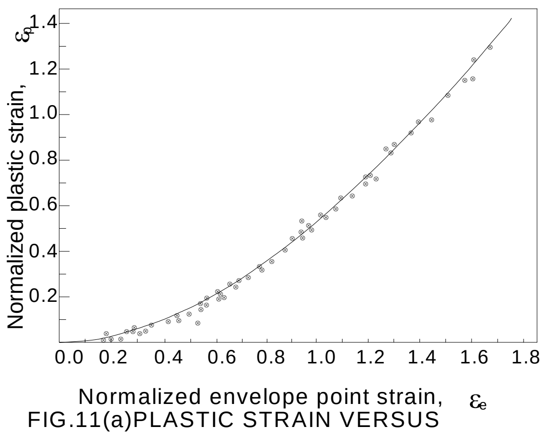

FIG.11(a)PLASTIC STRAIN VERSUS ENVELOPE STRAIN CURVE (1%SFRC)

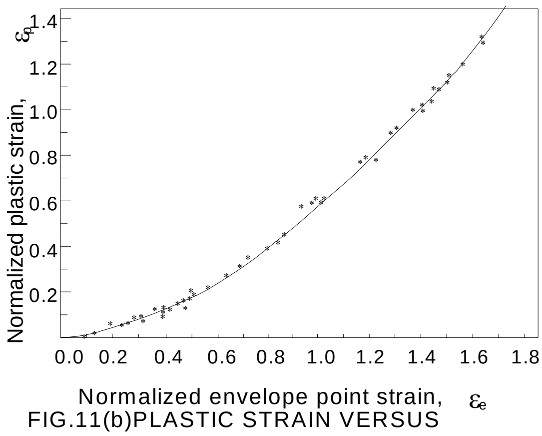

FIG.11(b)PLASTIC STRAIN VERSUS ENVELOPE STRAIN CURVE (2%SFRC)

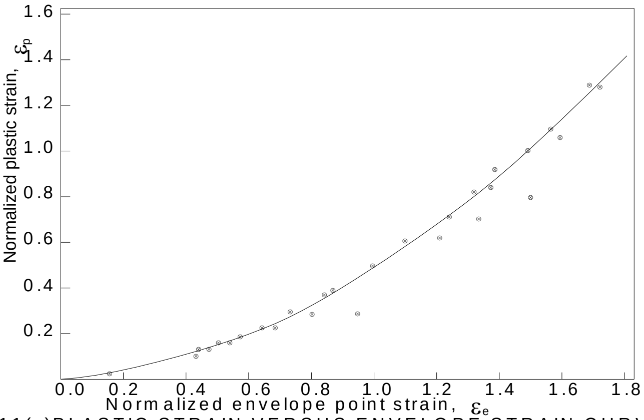

FIG.11(c)PLASTIC STRAIN VERSUS ENVELOPE STRAIN CURVE (Plain concrete)

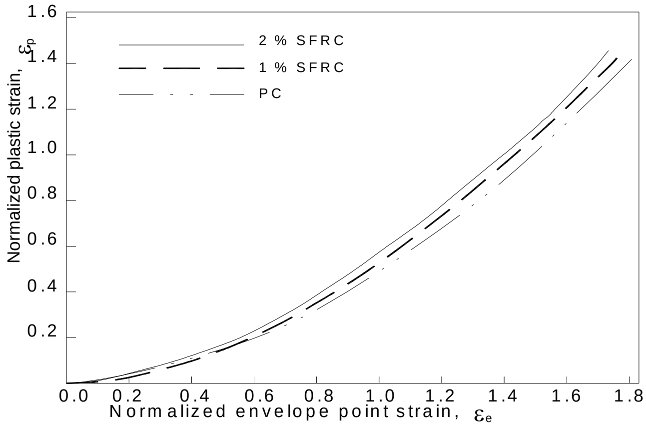

FIG.11(d)COMPARISON OF PLASTIC STRAIN VERSUS ENVELOPE STRAIN CURVES

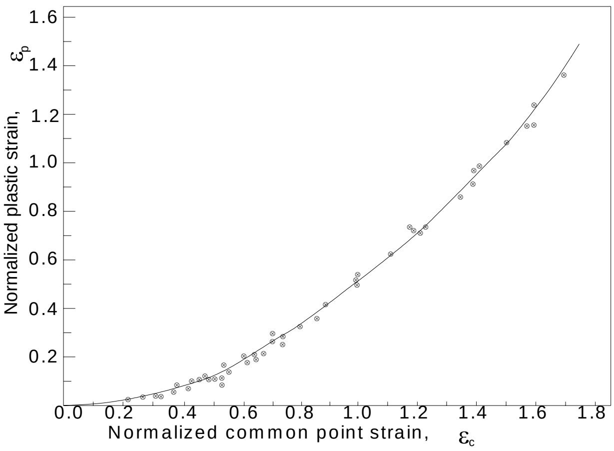

FIG.12(a) PLASTIC STRAIN VERSUS COMMON POINT CURVE (ONE PERCENT SFRC)

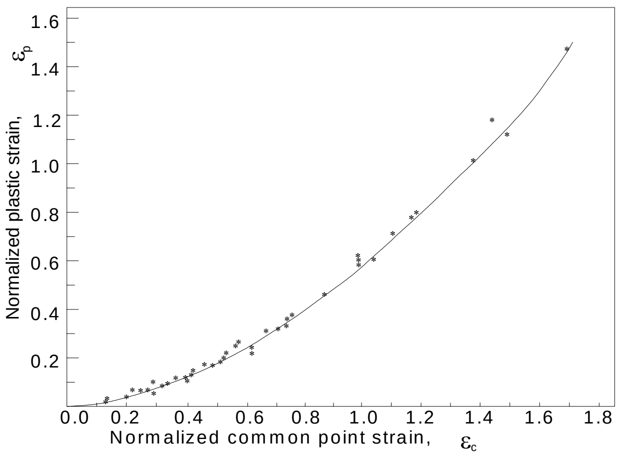

FIG.12(b) PLASTIC STRAIN VERSUS COMMON POINT CURVE (TWO PERCENT SFRC)

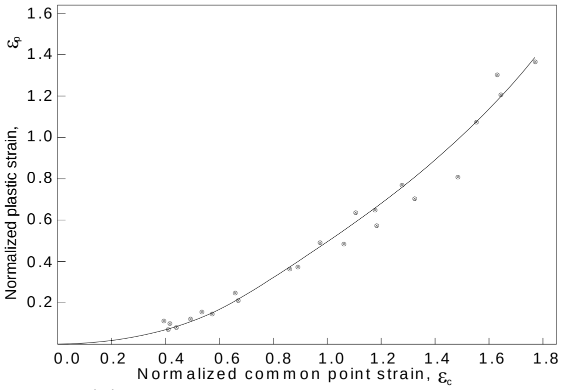

FIG.12(C) PLASTIC STRAIN VERSUS COMMON POINT STRAIN CURVE (PLAIN CONCRETE)

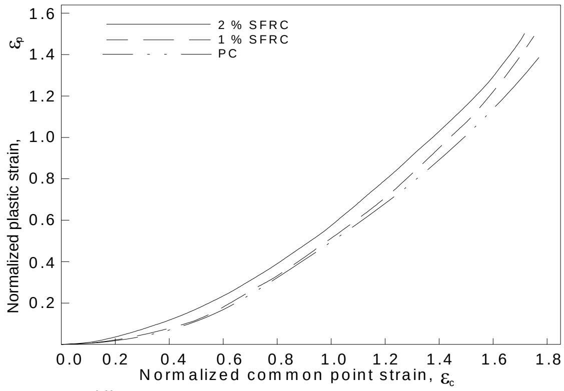

FIG.12(d) COMPARISION OF PLASTIC STRAIN VERSUS COMMON POINT STRAIN CURVES

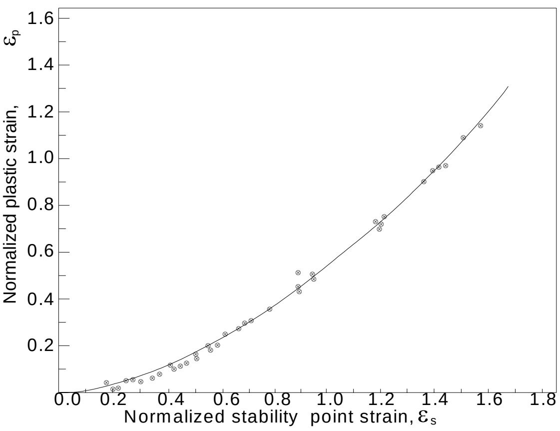

FIG.13(a) PLASTIC STRAIN VERSUS STABILITY POINT STRAIN CURVE(1%SFRC)

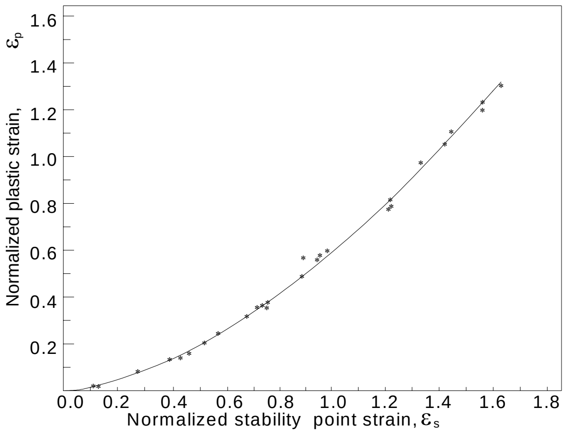

FIG.13(b) PLASTIC STRAIN VERSUS STABILITY POINT STRAIN CURVE(2%SFRC)

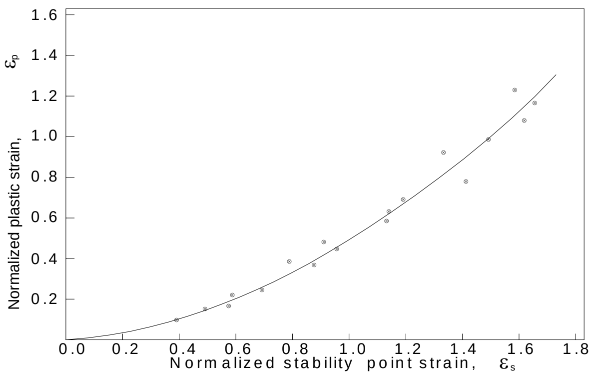

FIG.13(c) PLASTIC STRAIN VERSUS STABILITY POINT STRAIN CURVE (Plain concrete)

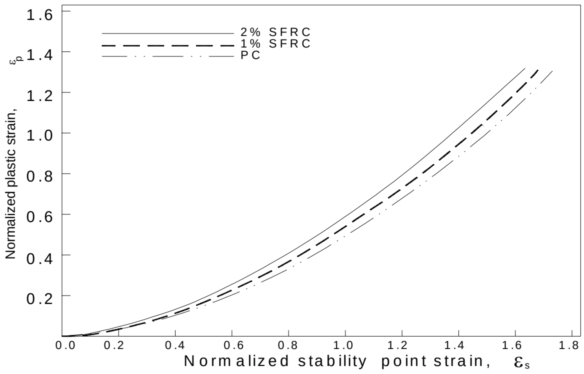

FIG.13(d) COMPARISON OF PLASTIC STRAIN VERSUS STABILITY POINT STRAIN CURVES

CONCLUSIONS

The following conclusions are drawn from the study conducted on steel fibre reinforced concrete and plain concrete specimens tested under uniaxial compressive loading.

1. The envelope stress-strain curve under cyclic loading coincides with stress-strain curve under monotonic loading.
2. The cyclic stress-strain history possesses locus of common points and locus of stability points.
3. Analytical expression has been developed to express envelope, common point and stability point stress- strain curves in non-dimensional form for SFRC specimens for uniaxial cyclic compressive loading .
4. The plastic strain level present in the material is a prime factor in defining the permissible stress level where reductions of compressive strength due to effect of repeated loadings have to be taken into account .
5. The use of stability point curve in defining the permissible stress level was discussed and it was pointed out that the stress at the peak of the stability point curve can be used to define the permissible stress level, if initial plastic strain is lower than the plastic strain associated with unloading from the peak of stability point curve. If repeated loading is done from an initial state of plastic strain in the material such that this value is larger than the residual strain (plastic strain) associated with unloading from the peak of stability point curve, then the stability point will exist at a stress level below the peak of the stability curve i.e. on the descending portion of stability point curve and stress corresponding to this point defines the permissible stress level. When peak stress of load cycle is greater than the peak stress of stability point curve, repeated cycles lead to failure due to accumulation of plastic strain.
6. The plastic strain curves of the plastic strain at unloading versus the envelope strain, the common point strain and stability point strain follow second order parabolic equations.

Notations

σ : Normalised stress
ε : Normalised strain
εp : Normalised plastic strain SFRC : Steel fibre reinforced concrete

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