Energy Dissipation Characteristics of SFRC Under Cyclic Compressive Loading

Mukesh Shukla

Professor, Department of Civil Engineering, B.I.E.T. Jhansi

ABSRACT:*The most important aspect of structural performance under cyclic loading is the ability of the structure to adequately dissipate energy. The energy dissipation capacity has been used in the past as a measure of ability of a member to withstand cyclic inelastic loading or a damage indicator.Investigations reported in this paper aims at investigating Energy dissipation characteristics of steel fibre reinforced concrete(SFRC) under uniaxial 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 stress-strain envelope curve, locus of common points and stability points. The energy dissipation characteristics of SFRC were studied using the experimental cyclic stress-strain curves and compared with that of plain concrete. Energy dissipation curves are presented in forms of the EDT ratio versus the envelope strain and the EDT ratio versus the plastic strain at unloading. This study indicates that SFRC specimens possess more energy dissipation capacities than that of plain concrete specimens.*

KEY-WORDS :Cyclic loading, energy dissipation, SFRC, stress-strain curves.

1. INTRODUCTION

The behaviour of SFRC under uniaxial compressive loading for monotonic conditions has been extensively investigated by numerous researchers over a long period of time(Johnston,1974;Williamson ,1974**;**Salujaet al.,1992;Fanella & Naaman, 1985;Otter and & Naaman, 1986; Sabapati & Achyutha 1989; Otter & Naaman 1987). Cyclic actions may occur due to fluctuation of live load, especially when live load is the dominant gravity load. Design of structures having live load to dead load ratio needs to characterize the behaviour of building materials under cyclic loading. A sizeable amount of research work(Sinha et al.1964; Karsan & Jirsa 1965; Karsan 1986 Yankelevsky & Reinhardt 1987; Bahn & Hsu, 1998; Alshebani & Sinha 1999; Alshebani & Sinha 2000; Naranie & Sinha 1989 Choubey& Sinha 1991)has been reported on the behavior 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. The common point curve is a locus of common points where 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 where the point of intersection of the reloading curve and unloading curve descends and stabilizes at lower bound called the stability point.

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 severalofits properties, primary cracking resistance, impact resistance, toughness and ductility **[18-21, 6-7**]. 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 (**22-24)**. Investigations reported in this chapter aims at investigating the behaviour of steel fibre reinforced concrete under uniaxial 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 stress-strain envelope curve, locus of common points and stability points. The energy dissipation characteristics of the cyclic stress-strain curves are also discussed.

2.EXPERIMENTAL PROGRAMME

2.1 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. Theconcrete mix was designed to achieve 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 cut from mild steel round straight wire with the aspect ratio of 75. While making the concrete mix with fibres water-reducing admixture (CONFLO) was used to improve its workability. A total number of forty-eight cylindrical SFRC specimens and nine plain concrete specimens of size 150 mm (diameter) x 300 mm (length) were cast using standard steel moulds. Mixing of materials was done in tilting type mixer. Compaction was done by vibrating the moulds on vibrating table. Control cube specimens were also cast along with cylindrical specimens. These specimenswere removed from moulds after 24 hours and cured for twenty-eight days in water tank before testing. The cube compressive strength of concrete design mix was obtained as 29.1 MPa. Cube strength of fibre mixes were obtained as 31 MPa and 33.96 MPa for one percent and two percent fibre mixes respectively.

2.2 Loading Arrangement and Instrumentation

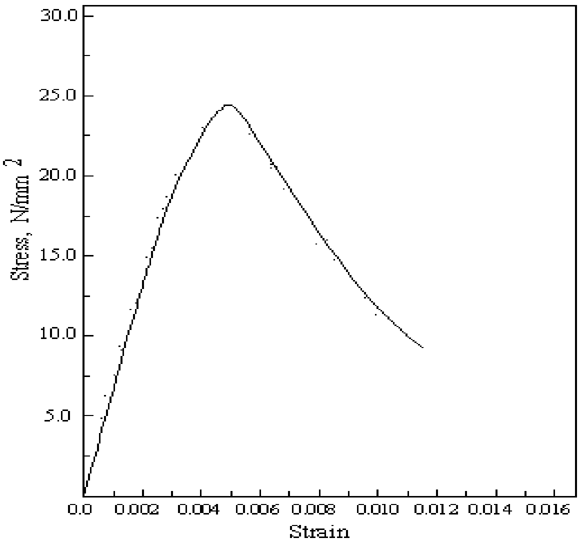
The cylindrical specimens were tested under uniaxial compressive loading. X-Y_1-Y_2 plotter was used to monitor displacement and applied load through linear variable differential transformers (LVDT) and a load cell respectively. Loading and unloading were controlled by a universal testing machine. A 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 PLATE 1.

Plate 1. Instrumentation and loading arrangement

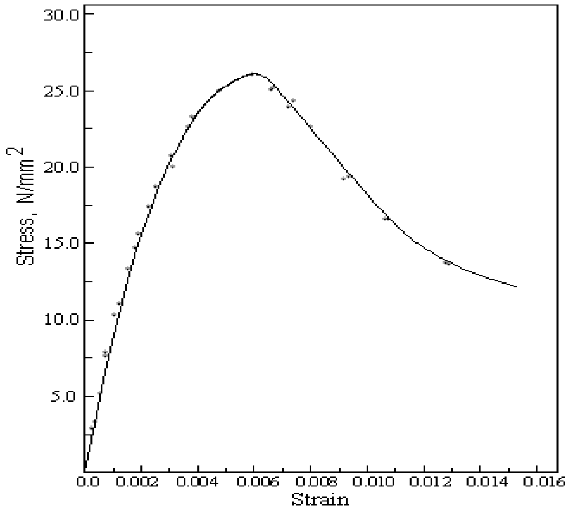
TEST PROCEDURE

Three types of tests were conducted on each type of specimen. Three specimens were tested for each type of test resulting in a total of twenty-seven specimens being tested.

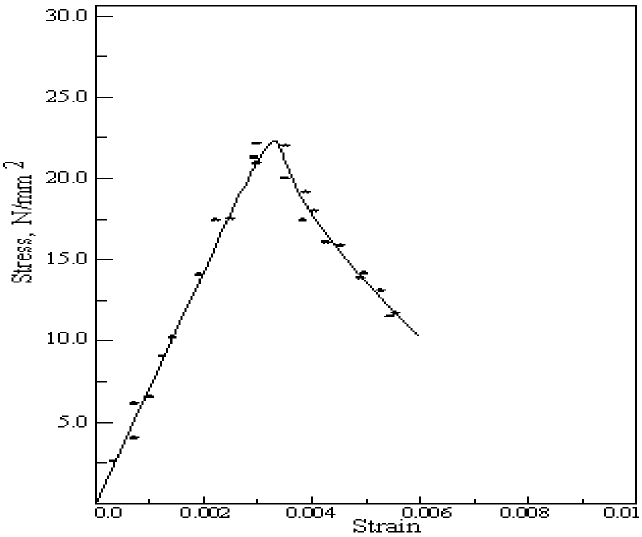
The first type of test was conducted to establish stress-strain envelope curve, where load was increased steadily to failure (Fig.1). The second type of test was conducted to establish common points. In this test the specimens were tested under cyclic loading (Fig.2). In each cycle load was increased 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 historieswere 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 Fig. 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 (Fig. 3). During loading -unloading process the point of intersection gradually descended (points C & D on Fig.3). After a few numbers of cycles of loading and unloading within each loop this point of intersection stabilized at a lower bound (point S on Fig 3). Such lower bound points are termed as stability points. Once this point was stabilized, further cycling led to the formation of a closed hysteresis loop and stability point wouldnotfurther descend. After establishing stability point next cycle is chosen and same procedure was repeated.



(a) One percent SFRC

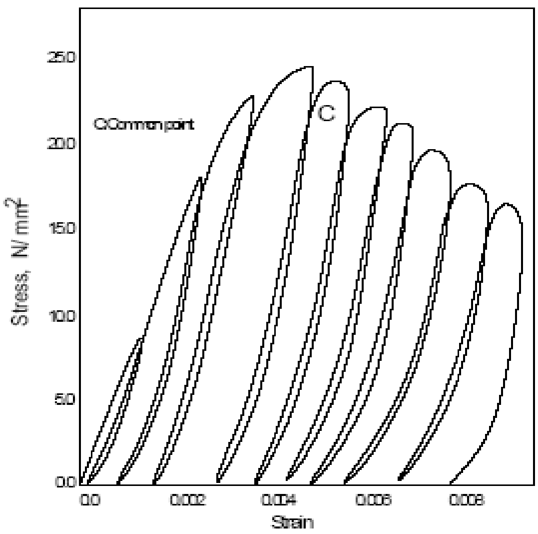


(b) Two Percent SFRC

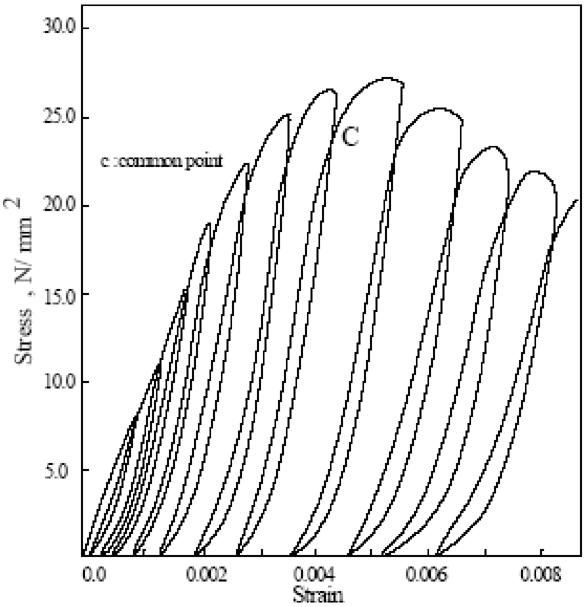


(c) Plain Concrete

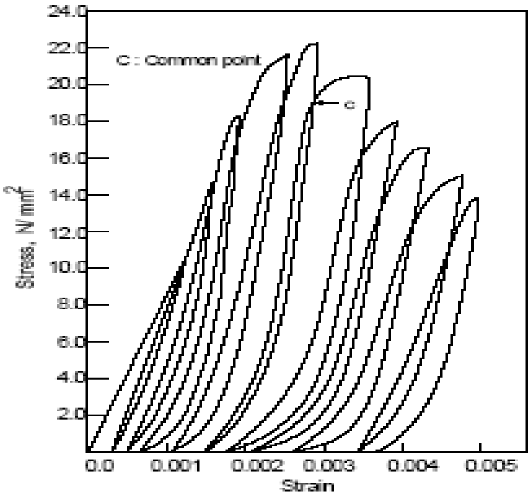
Fig.1 Stress-Strain Curves



(a) One Percent SFRC

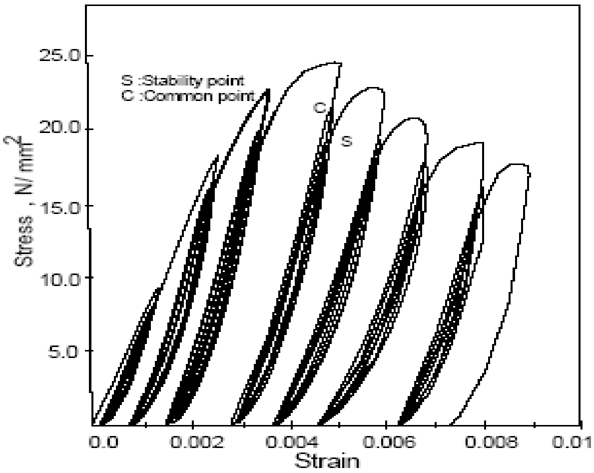


(b) Two percent SFRC

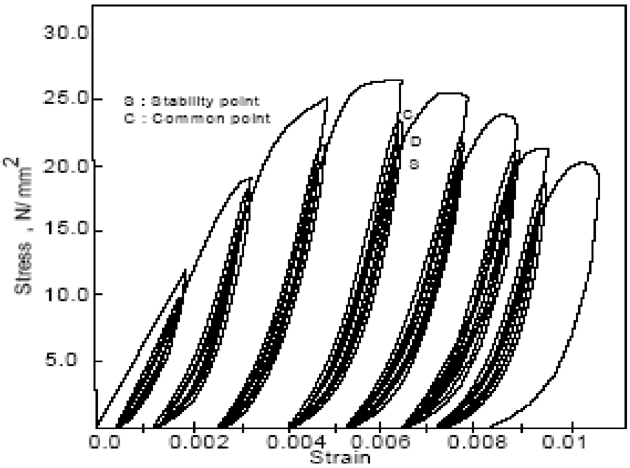


(C) Plain Concrete

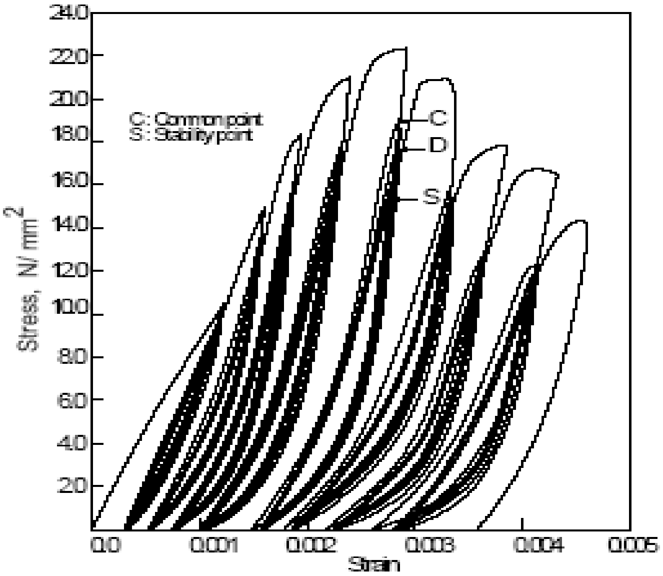
Fig.2. Test under cyclic loading for common points



(a)One Percent SFRC



(b) Two Percent SFRC



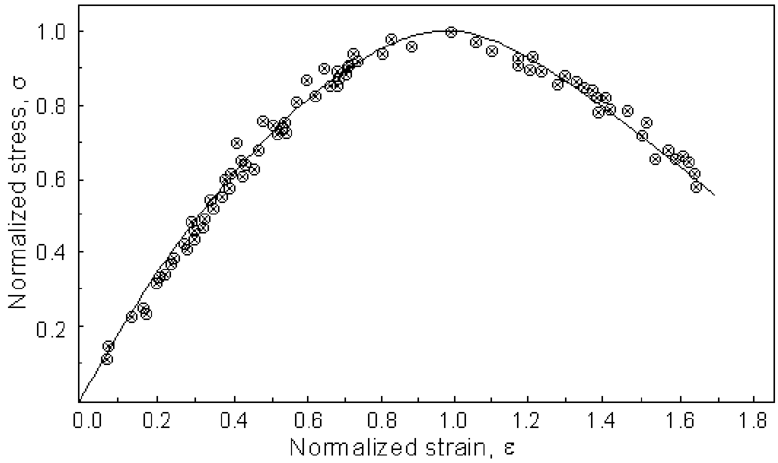
(c) Plain Concrete

Fig.3.Test under cyclic loading for stability points

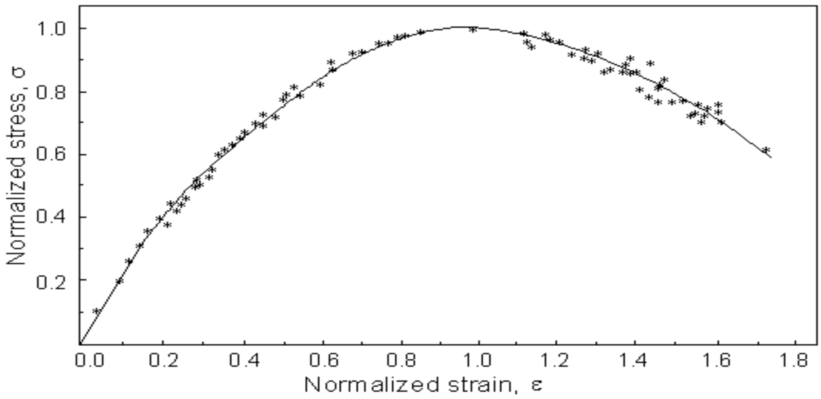
TEST RESULTS AND EVALUATION

Stress-Strain Curves

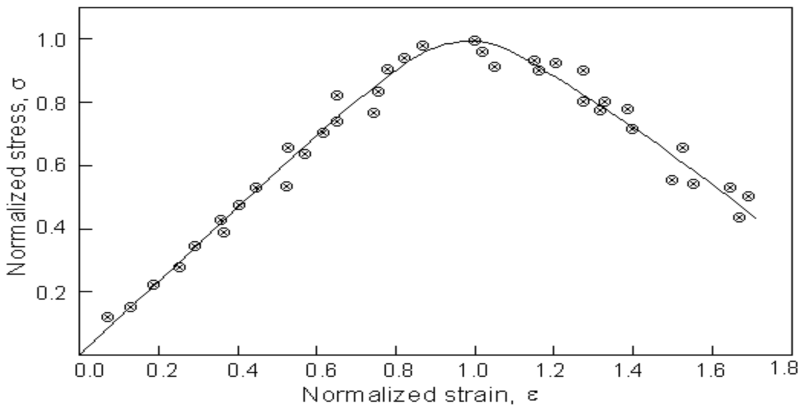
Envelope stress –strain curves, common pointsstress-strain curves and Stability points Stress-strain curvesare plotted in fig.4 to fig.6. The Stress co-ordinate is normalized with respect to the peak stress of each specimen and strain co-ordinate is normalized with respect to axial strain when peak stress is attained.



(a) One Percent SFRC

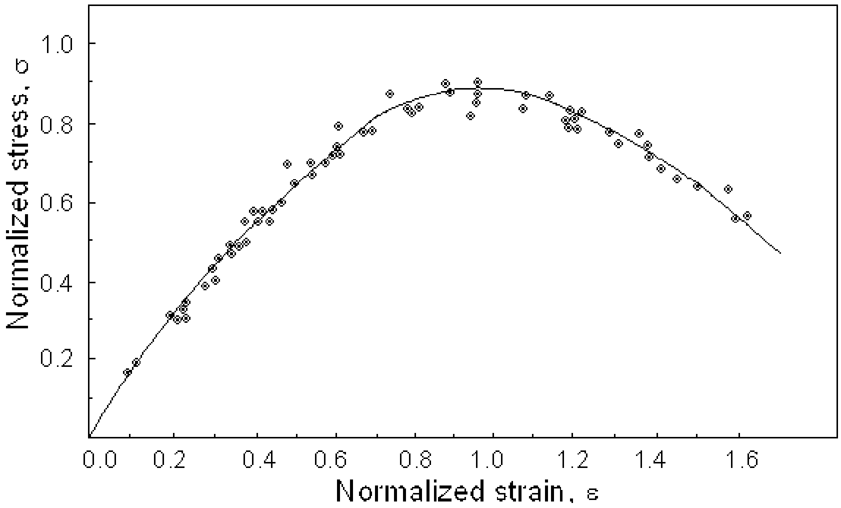


(b) Two Percent SFRC

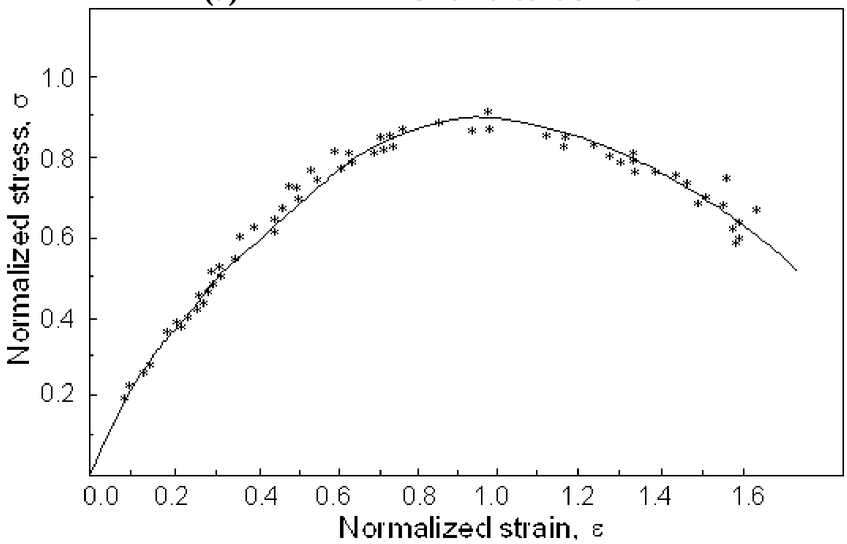


(c) Plain Concrete

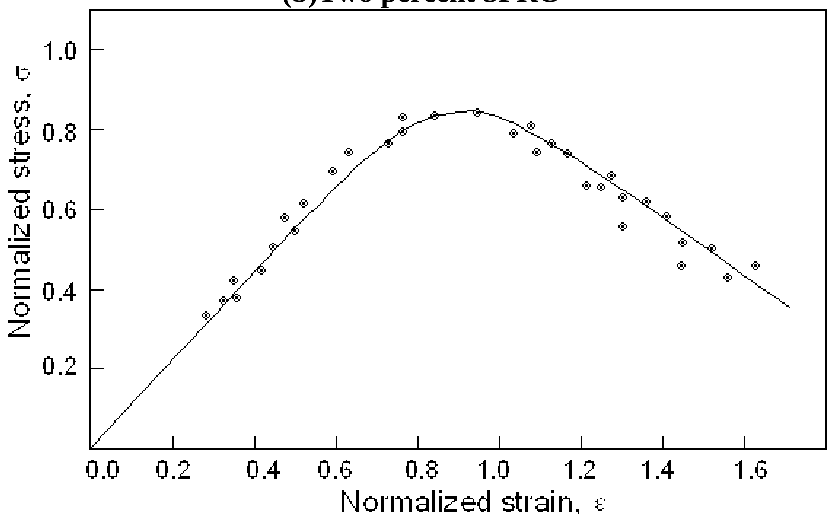
Fig.4 Envelope Stress –Strain Curves



(a) One Percent SFRC

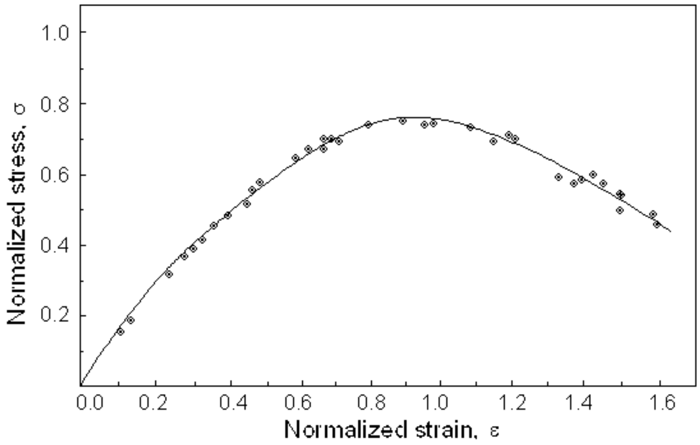


(b)Two percent SFRC

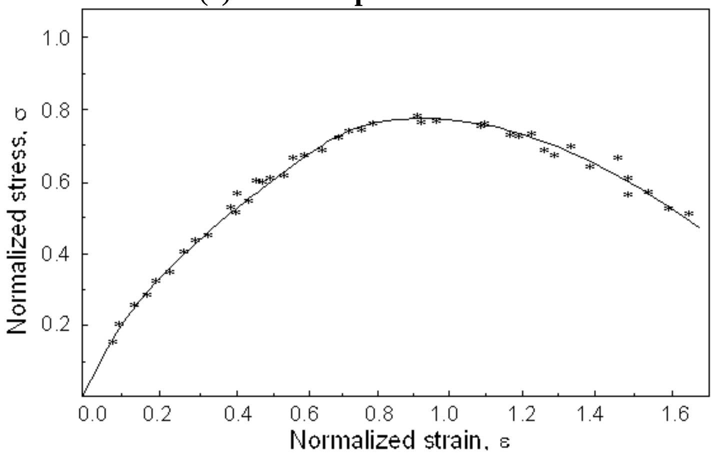


(c) Plain Concrete

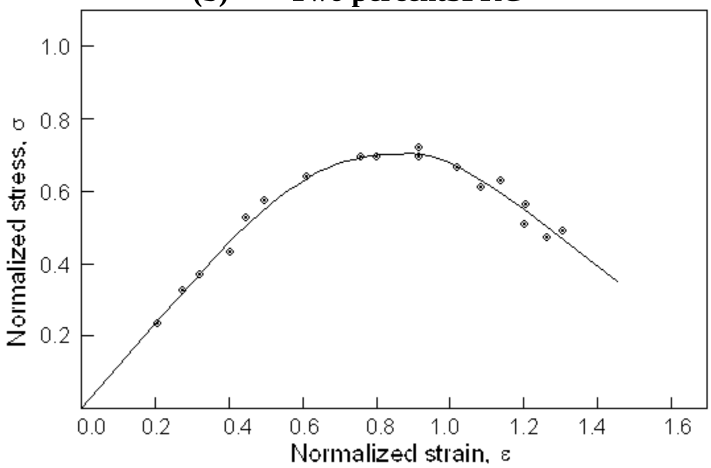
Fig.5 Common Points Stress-Strain Curves



(a) **One percentSFRC**



(b) Two percentSFRC



(c) Plain concrete

Fig.6.Stability Points Stress-Strain Curves

ENERGY DISSIPATION

Perhaps the most important aspect of structural performance under cyclic loading is the ability of the structure to adequately dissipate energy. The energy dissipation capacity has been used in the past as a measure of ability of a member to withstand cyclic inelastic loading or a damage indicator**[25-29]**.The energy dissipation ratio, EDT, is used in the present study to express the energy dissipated per cycle of loading/unloading. The EDT ratio is defined as the ratio of the energy dissipated to the total stored energy per cycle of loading/unloading. Fig.7 shows diagrammatically to determine the EDT ratio for a typical loading/unloading cycle. The areas under the curves were determined using digital planimeter. To make precise measurement each area was measured three times and average values were used to determine the EDT values for each cycle of loading/unloading. Figures 8(a), (b) and (c) show the curves of EDT versus the non-dimensional envelope strain for both types of SFRC and concrete specimens. For two percent fibre specimens the EDT ratio increases approximately linearly to a value of approximately 0.38, corresponding to an envelope strain ratio of approximately 0.3, after which it increases non linearly to a value of approximately 0.7, corresponding to an envelope ratio of approximately 1.2. The EDT values then decrease to a value of approximately 0.55 corresponding to envelope strain ratio of approximately 2.0. For one percent SFRC specimens, the EDT ratio increases approximately linearly to a value of 0.33,corresponding to an envelope strain ratio of approximately 0.32, after which it increases non-linearly to a value of approximately 0.63 corresponding to an envelope strain of approximately 1.14. The EDT ratio then decreases to a value of approximately 0.45 corresponding to an envelope strain of approximately 2.0. For concrete specimens, the EDT ratio increases approximately linearly to a value of 0.33, corresponding to an envelope strain ratio of approximately 0.4, after which it increases non-linearly to a value of 0.58 corresponding to an envelope strain ratio of approximately 1.2 after which it decreases sharply.

The relatively high rate of increase of the EDT ratio at the initial stages of cyclic loading can be associated with the formation of micro-cracks in concrete. Subsequently, the rate of increase of EDT ratio decreases which may be associated with widening of the micro-cracks. The initial portion of the EDT versus ε_e can be associated with the elastic response of the material, since the formation of micro cracks does not result in much accumulation of plastic strain. For two percent and one percent specimens, the initial linear portion of the EDT curve exists up to an envelope strain ratio of approximately 0.3 and 0.32 respectively. For concrete specimens, the initial linear portion of the EDT curve exists to an envelope ratio of approximately o.4. From the envelope stress-strain relation presented in section 3.3.5, envelope strain ratios of 0.3 for two percent specimens and 0.32 for one percent specimens correspond to stress ratios of 0.53 and 0.51 for two percent and one percent SFRC specimens respectively. From the envelope stress-strain curve for concrete stress ratio corresponding to envelope strain ratio of 0.4 is approximately 0.43. Therefore, from the energy dissipation characteristics it can be hypothesized that a stress of 0.53 σ_m, and 0.51σ_m can be used as the elastic limit for two percent and one percent SFRC specimens respectively. This limit for concrete can be used as 0.43σ_m. The envelope stress-strain curves are also observed to be approximately linear up to a stress ratio of 0.53 and 0.51 for two percent and one percent SFRC specimens respectively. Plastic (residual) strain ratio corresponding to envelope strains ratios of 0.3 for two percent SFRC and 0.32 for one percent SFRC are determined as .08 and .067 respectively from plastic strain curves of plastic strain versus envelope strain curves. These low levels of plastic strain confirm an approximate elastic response of material. Fig.9 shows a comparison of EDT ratios for both types of SFRC specimens and concrete specimens.. For specimens with two percent fibres the EDT values are typically higher than those for specimens with one percent fibres. These values for SFRC specimens are substantially higher than those for concrete specimens.

Figures 10(a), (b) and (c) show the graphs of EDT ratio versus the non-dimensional plastic strain at unloading for both types of SFRC specimens and concrete specimens. From these curve it is again observed that at early stage of cyclic loading, the relatively high rate of increase of the EDT is obtained. As pointed out before, this high rate of increase can be associated with the formation of micro-cracks. The formation of these micro-cracks does not result in much accumulation of plastic strain. For two percent SFRC, the point at which the EDT versus plastic strain curve begins to become non-linear (i.e. begins to deviate from the initial linear portion) occurs at a value of plastic strain of approximately 0.17. For one percent SFRC the corresponding value of plastic strain is approximately 0.15 and this value for concrete is approximately 0.2. The point where non-linearity in plastic strain begins to occur can be interpreted as the point in the loading history denoting the beginning of the process of deterioration of the micro-cracks in the material. Based on the empirical plastic strain curves, for two percent SFRC, the value of plastic strain of 0.17 corresponds to a value of envelope strain of approximately 0.50 and the latter corresponds to an envelope stress ratio of 0.76. Similarly, for one percent SFRC the value of plastic strain of 0.15 corresponds to a value of envelope strain of approximately 0.51 and the latter corresponds to an envelope stress ratio of 0.74. Plastic strain of 0.2 for plain concrete corresponds to envelope strain value of approximately 0.62 and from envelope curves latter corresponds to an envelope stress ratio of approximately 0.7. Hence, from the energy dissipation characteristics, it can be hypothesized that these stress ratios can be used as damage indicator of the material. These stress ratios are also in close proximity with the peak stress ratios predicted by the stability point curves for both types of specimens. Fig 11 shows a comparison of EDT versus plastic strain ratio curves of both types of specimens. Here, again it is found that curve of two percent fibre specimens lie above the curve of one percent fibre specimens and concrete specimens.

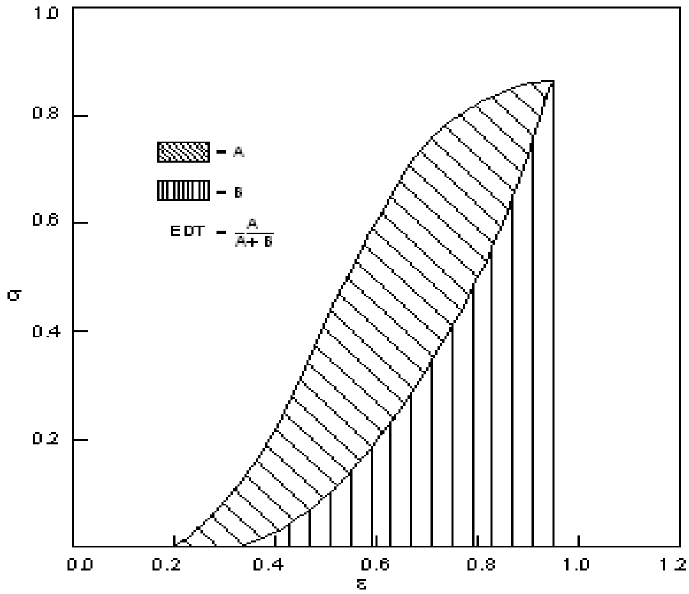
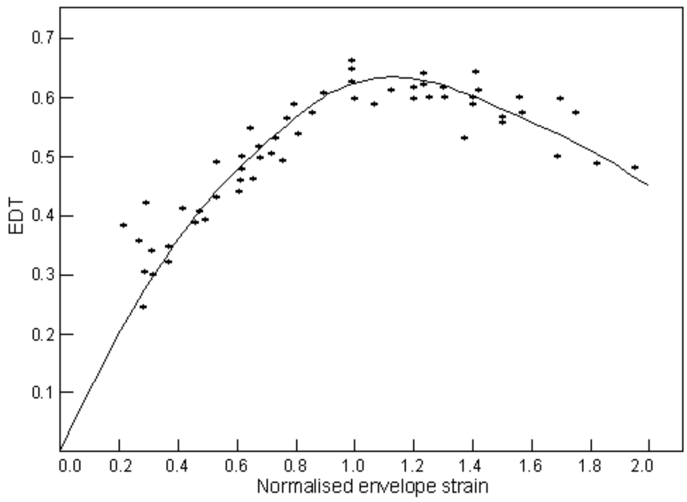
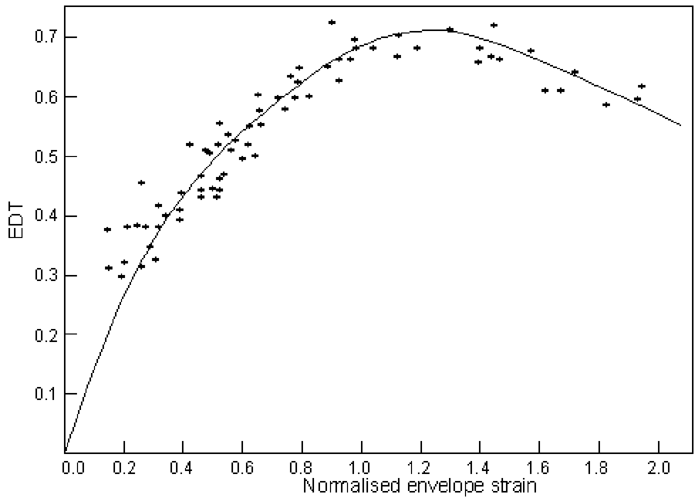


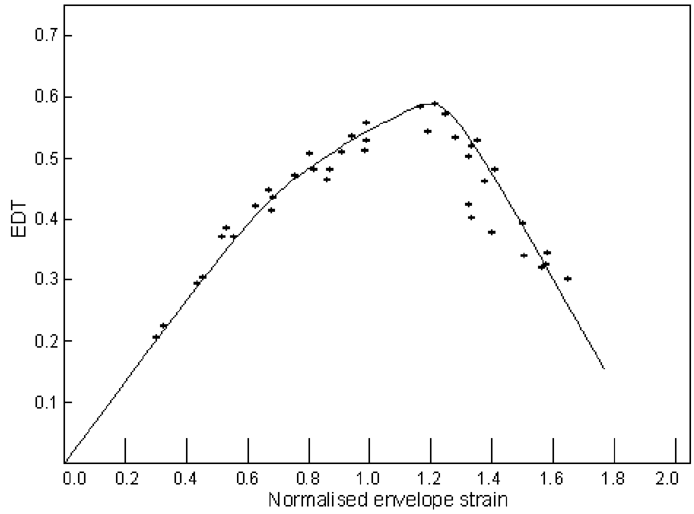
Fig.7.DETERMINATION OF EDT RATIO



(a) One Percent SFRC



(b) Two Percent SFRC



(c) Plain Concrete

Fig.8 EDT Versus Envelope Strain Curves

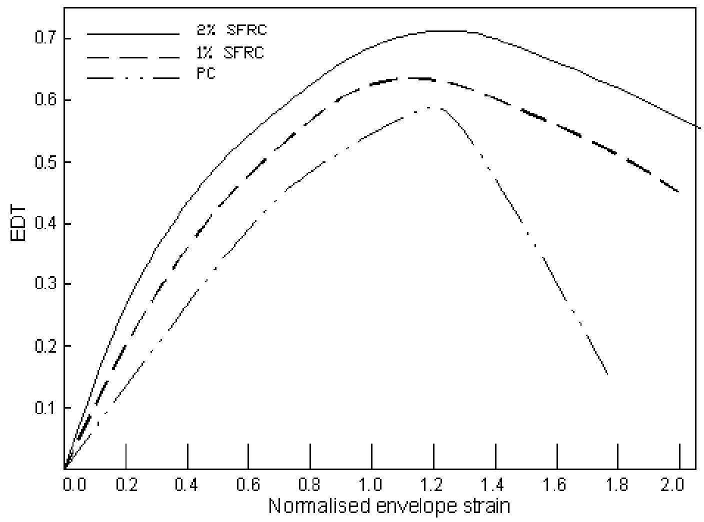
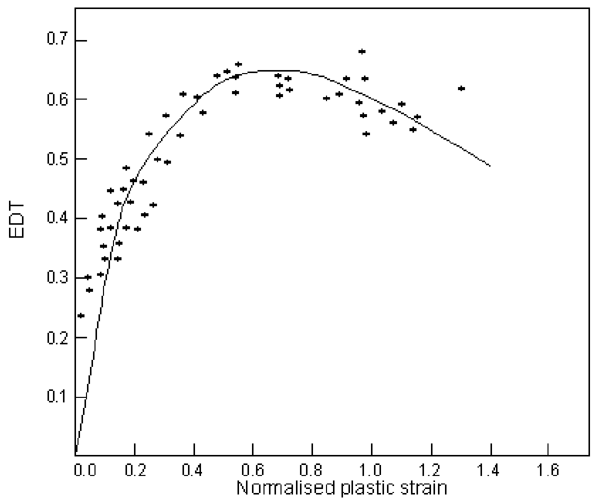
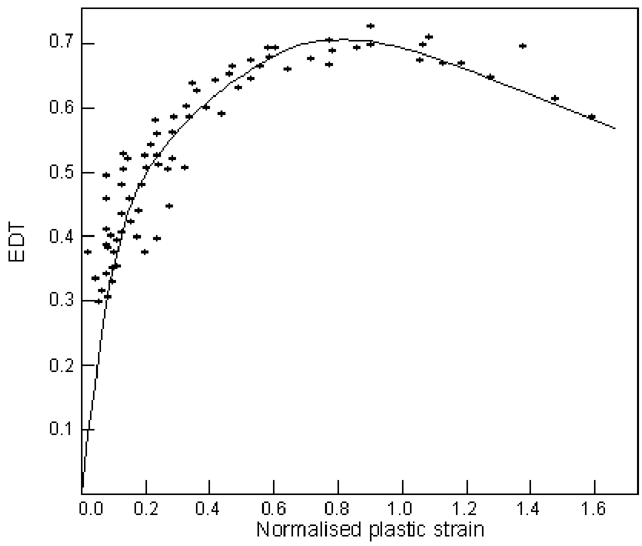


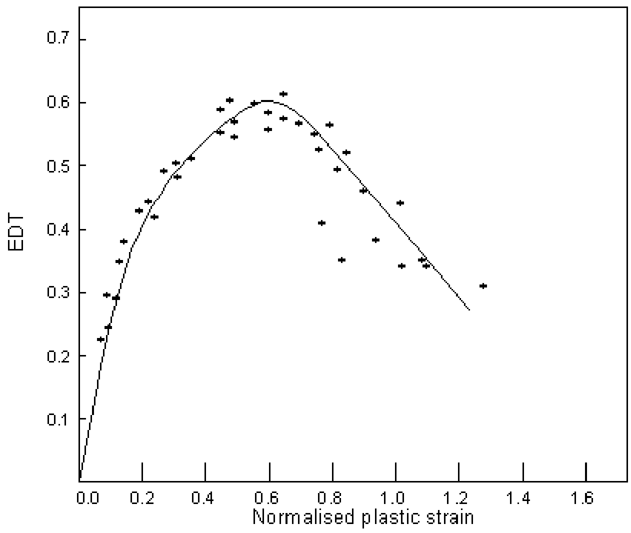
Fig.9 Comparison of EDT Versus Envelope Strain Curves



(a) One Percent SFRC



(b) Two Percent SFRC



(c) Plain Concrete

Fig.10 EDT Versus Plastic Strain Curve

Fig.11 Comparison Of EDT Versus Plastic Strain Curves

CONCLUSIONS:

(i) The energy dissipation characteristics of SFRC were studied using the experimental cyclic stress-strain curves and compared with that of plain concrete. Energy dissipation curves were presented in forms of the EDT ratio versus the envelope strain and the EDT ratio versus the plastic strain at unloading. These curves were initially approximately linear with high rate of increase of the EDT ratio followed by a nonlinear in nature with relatively lesser rate of increase of EDT ratio.

(ii) The energy dissipation ratio, EDT, is used in the present study to express the energy dissipated per cycle of loading/unloading. Curves of EDT versus envelope point strain and EDT versus plastic strain for SFRC and plain concrete show that EDT values for SFRC and plain concrete specimens increases up to envelope strain ratio of approximately 1.2. At this point EDT values for one percent and two percent SFRC specimens are about 8.1% and 17.5% higher than that for plain concrete specimens. After this point EDT values decreases. Slope of descending portion of curves of SFRC specimens are less steeper than that of plain concrete specimens. This indicates that SFRC specimens possess more energy dissipation capacities than that of plain concrete specimens.

(iii) From the energy dissipation characteristics, it can be hypothesized that a stress of 0.53 σ_m and 0.51σ_m can be used as the elastic limit for two percent and one percent SFRC specimens respectively. Stress ratios of 0.75 σ_m and 0.74 σ_m can be used as damage indicator of the material for two percent and one percent SFRC specimens respectively from energy dissipation characteristics. These stress ratios are also in close proximity with the peak stress ratios predicted by the stability point curves for both types of SFRC specimens.

REFERENCES:

1. Johnston, C.D. (1974), *International Symposium on Fibre Reinforced Concrete* SP –44, *ACI Detroit*127-142.
2. Williamson, G.R. (1974), *International Symposium on Fiber Reinforced Concrete*, SP-44, *ACIDetroit*,195-207.
3. Saluja, S.K., Sharma, M.S., Singh, A.P.and Kumar, S.(1992) , *Indian Conc.J.*, 66;99-102.
4. Fanella, D.A. and Naaman, A.E. (1985), *ACI J. Proc.*, 82;475-488.
5. Otter, D.E.,and Naaman, A.E. (1986), *Proc. 3rd RIL. Symp. on Development in Fiber Reinforced Cement and Concrete*, University of Sheffield,.
6. Sabapati, P. and Achyutha, H. (1989), *J.ofInst.of Eng.*,69; 257-261.
7. Otter, D.E. and Naaman A.E. (1987), *Proc., Int. Symp. on Fibre Reinforced Concrete,* Madras, December, 2.225-2.235.
8.Sinha, B.P., Gerstle, K.H., and Tulin, L.G(1964),*ACI J Proc.*, 61No.2;195-211.
9.Karsan, I.D., and Jirsa, J.O. (1965), *J. of Struct. Eng., ASCE*, 952543-2563.
10.Karsan, I.D. (1986), *Behaviour of Plain Concrete Under Variable Load Histories* Ph.D. Thesis, Rice University Houston, Texas.
11.Yankelevsky, D.Z. and Reinhardt, H.W. (1987), *J. of Struc. Eng., ASCE,* 113,No.2; 228-240.
12.Bahn, B.Y., and Hsu, C.T. (1998), *ACI Mat. J.,* 95 No. ;2178-193.
13. Alshebani, M.M. and Sinha, S.N. (1999) , *J. of Str. Eng., ASCE*, 125 No.; 6600-604.
14. Alshebani, M.M. and Sinha, S.N. (2000),*Str. Eng. and Mech.*, 9, No.; 4 375-382.
15. Naranie, K.S., and Sinha, S.N., *J. of Str.Divi., ASCE*, 115, No.21432-1445.
16. Naraine, K.S., and Sinha, S.N. (1989) , *J. of Str. Divi., ASCE*, Oct.; 2631-2644.
17. Choubey, U.B., and Sinha, S.N. (1991), *J. of Mas. Int.*4,No.; 394-98.
18. Romualdi, J.P., and Batson, G.B. (1963), *J. of Eng. Mech. Division, Proc., ASCE*, 89;147-168.
19. Fanella, D.A. and Naaman, A.E. (1985), *J. of ACI, Proc.*, 82;475-488.
20. Bayasi, Z. and Soroushian, P. (1991), *Mag. of Concre. Res.*,43, No. 157; 243-248.
21. Johnston, C.D., *Int. Symp. on Fibrous Concrete (CI-80)* Construction Press, Lancaster, 29-47.
22. Otter, D.E. and Naaman, A.E. (1988), *ACI Mat. J.*, July-Aug. 254-261.

23. Otter, D.E.,and Naaman (1986), A.E., *Proc. 3rd RILEM Symposium* on Development in Fiber Reinforced Cement and Concrete, University of Sheffield.
24.Paskova, T., and Meyer, C. (1997), *ACI Mat. J.* July-Aug.; 273-285.
25.Brown, R.H., and Jirsa, J.O.,*ACI J*. (1971), May ;380-390.
26.Gosain, N.K., Brown, R.H., and Jirsa, J.O. (1977), *J. of Str. Divi.,* ASCE, July ;1461-1473.
27.Hwang, T., and Scribner, C.F., *J. of Str. Eng.*, ASCE, March (1984) 477-489.
28.Naranie, K.S., and Sinha, S.N. (1989) , *J. of Str. Divi.*, ASCE, 115, No.2;1432-1445.
29.Choubey, U.B. and Sinha, S.N. (1994), *J. of Str. Eng*., Oct.; 203-211.
30. Shukla M. (2003),*Investigations on the Behaviour of Steel Fibre Reinforced Concrete Beams Under Cyclic Loading,* Ph.D. Thesis, RGPV Bhopal.