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Flexural fatigue strength of steel fibrous concrete containing mixed steel fibres*

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Abstract: This paper reports investigation conducted to study the fatigue performance of steel fibre reinforced concrete (SFRC) containing fibres of mixed aspect ratio. An extensive experimental program was conducted in which 90 flexural fatigue tests were carried out at different stress levels on size 500 mm×100 mm×100 mm SFRC specimens respectively containing 1.0%, 1.5% and 2.0% volume fraction of fibres. About 36 static flexural tests were also conducted to determine the static flexural strength prior to fatigue testing. Each volume fraction of fibres incorporated corrugated mixed steel fibres of size 0.6 mm×2.0 mm×25 mm and 0.6 mm×2.0 mm×50 mm in ratio 50:50 by weight. The results are presented both as *S-N* relationships, with the maximum fatigue stress expressed as a percentage of the strength under static loading, and as relationships between actually applied fatigue stress and number of loading cycles to failure. Two-million-cycle fatigue strengths of SFRC containing different volume fractions of mixed fibres were obtained and compared with plain concrete.

Key words: Fatigue strength, Static flexural strength, Stress level, Stress ratio, Steel fibre reinforced concrete (SFRC)
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INTRODUCTION

A number of experimental fatigue studies were conducted on plain concrete as well as on steel fibre reinforced concrete (SFRC) beams of different sizes under different loading conditions. Murdock and Kesler (1958) investigated the effect of stress ratio on the fatigue strength of plain concrete. Batson *et al*.(1972) reported fatigue strength of 74% and 83% of the first crack static flexural strength at 2 million cycles of complete reversed and not-reversed loads respectively for a steel fibre content of 2.98% by volume. Ramakrishnan *et al*.(1987) studied the flexural fatigue performance of concrete reinforced with collated hooked-end steel fibres of size 50 mm×0.50 mm and 60 mm×0.80 mm. Two different fibre volume fractions of 0.50% and 0.75% were tested. After addition of these fibres to the concrete, the ductility and post-crack energy absorption capacity were greatly increased. Tatro (1987) investigated the performance of SFRC mixes under flexural fatigue loading and containing large aggregates with a maximum size of 40 mm. The tests on large aggregates mixes showed a relatively small effect of fibres on the fatigue properties of fibre reinforced concrete. Ramakrishnan (1989) reported the results of an investigation on the fatigue performance of steel fibre reinforced refractory concrete (SFRRC). Refractory concrete incorporating melt-extract stainless steel fibres of size 25 mm×0.46 mm and in three concentrations of 0.5%, 1.0% and 1.5% were tested under flexural fatigue loading. The endurance limits expressed as a percentage of its own modulus of rupture were 44%, 51% and 40% for fibre volume fractions of 0.5%, 1.0% and 1.5%, respectively. Two-million-

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cycle fatigue strengths of 1.61, 2.60, 4.19 and 4.82 MPa were obtained for plain refractory concrete, concrete reinforced with 0.5%, 1.0% and 1.5% volume fractions of steel fibres, respectively. Ramakrishnan *et al*.(1989) investigated the performance characteristics of fibre reinforced concretes subjected to flexural fatigue loading. A comparative evaluation of the fatigue properties was reported for concretes without and with four types of fibres (hooked-end, straight, corrugated, and polypropylene) at two different volume fractions of 0.5% and 1.0% using the same mix proportions for all the concretes. It was observed that the addition of all the four types of fibres caused considerable increase in the flexural fatigue strength and endurance limit, with the hooked-end steel fibres providing the highest improvement (143%) and that the straight and the polypropylene fibres providing the least. Johnston and Zemp (1991) examined the performance of SFRC under flexural fatigue loading in terms of fibre volume fractions (0.5%, 1.0% and 1.5%), fibre aspect ratio (47:100) and fibre type (smooth wire, surface-deformed wire, melt-extract and slit sheet). In all, nine mixtures were tested including one without fibres. The test results were presented as *S*-*N* relationships with the maximum stress expressed as a percentage of the static flexural strength, as well as relationships between actually applied stress and number of cycles to failure. It was observed that the *S*-*N* relationships depend primarily on fibre content and aspect ratio, whereas the fibre type is secondary in importance. Shi *et al*.(1993) showed that the probabilistic distribution of fatigue life of plain concrete can be modelled by two-parameter Weibull distribution.

Yin and Hsu (1995) studied the fatigue behaviour of SFRC under uniaxial and biaxial compression and observed that the *S*-*N* curves can be approximated by two straight lines connected by a curved knee instead of a single straight line. Wei *et al*.(1996) studied the effect of fibre volume fraction, amount of silica fumes and their composite action on fatigue performance of SFRC. Ong *et al*.(1997) investigated the behaviour of steel fibre mortar overlayed concrete beams under cyclic loading whereas the behaviour of composite concrete sections reinforced with conventional steel bars and steel fibres, and subjected to flexural cyclic loading was analysed by Spadea and Bencardino (1997) by means of a mechanical model. Jun and Stang (1998) reported that the accumulated damage level in fibre reinforced concrete in fatigue loading was 1~2 order of magnitude higher than the level recorded in static testing of the same materials. Effects of fly ash on fatigue properties of hardened cement mortar were studied by Taylor and Tait (1999), whereas Daniel and Loukili (2002) investigated the behaviour of high strength fibre reinforced concrete under cyclic loading. SFRC with two types of hooked end steel fibres was tested by Cachim *et al*.(2002) in an experimental study to evaluate the performance of plain and fibre reinforced concrete under compressive fatigue loading. In a review paper, Lee and Barr (2003) provided a general overview of recent developments in the study of the fatigue behaviour of plain and fibre reinforced concrete.

RESEARCH SIGNIFICANCE

Examination of earlier investigations conducted on SFRC revealed that there is no information available on the performance of SFRC containing fibres of mixed aspect ratio. Therefore, the present investigation was planned to study the performance of SFRC beams containing mixed fibres subjected to flexural fatigue loading. Concrete containing three volume fractions of steel fibres of 1.0%, 1.5% and 2.0% was tested at different stress levels. The specimen incorporated two different sizes of the steel fibres in 50:50 ratio by weight. The two-million-cycle fatigue strengths of SFRC were determined for different volume fractions of steel fibres and compared with that of plain concrete.

EXPERIMENTAL PROGRAM

Concrete mix used for casting the test specimens, its 28 days compressive strength and static flexural strength are listed in Table 1. Ordinary Portland Cement, crushed stone coarse aggregates with maximum size 12.5 mm and river sand were used. The materials used conformed to relevant Indian Standard specifications. The specimen incorporated two different aspect ratios of Xerox type steel fibres namely 20 (fibre size 2.0 mm×0.6 mm×25 mm) and 40 (fibre size 2.0 mm×0.6 mm×50 mm) by weight of the shorter and longer fibres in the proportions of 50%-50%. The specimens used for flexural fatigue tests and static flexural tests were fibre concrete beams of size 500 mm×100 mm×100 mm. The specimens were cast in 9 batches, each batch consisting of 14 fibre concrete beams, of which 4 were tested in static flexural condition to obtain the flexural strength of the batch and the remaining 10 were tested in flexural fatigue condition at different loading conditions to obtain the fatigue lives of SFRC. The quality of each batch of SFRC was checked by obtaining its 28 days compressive strength. The average 28 days compressive strength of SFRC with 1.0%, 1.5% and 2.0% fibre content is presented in Table 2.

Table 1 Concrete mix proportions, compressive and static flexural strengths of plain concrete

Parameter	Value
Water-Cement ratio	0.35
Sand-Cement ratio	1.35
Coarse aggregate-Cement ratio	2.12
28 d compressive strength (MPa)	57.82*
Static flexural strength (MPa)	5.35**

* Average of 10 tests; ** Average of 12 tests

Table 2 Compressive and static flexural strengths of steel fibrous concrete (50% 50 mm+ 50% 25 mm long fibres)

Fibre volume fraction (%)	28 d average compressive strength (MPa)	Average static flexural strength (MPa)
1.0	62.89	7.45
1.5	65.85	8.44
2.0	65.42	8.92

Static tests were conducted on a 100 kN INSTRON^{TM} universal testing machine to determine the mean static flexural strength (f_r). The beams were simply supported on a span of 450 mm and subjected to four point bend tests. The average static flexural strength of various mixes is shown in Table 2. Experimental set-up for static flexural tests is shown in Fig.1a. The fatigue tests were conducted on a 100 kN MTS^{TM} electrohydraulic universal testing machine. The span/points of loading in the fatigue tests were kept the same as those for the static tests. Flexural fatigue tests were conducted at different stress levels. Constant-amplitude sinusoidal loads were applied at a frequency of 20 Hz. For each volume fraction of fibres and mix type, the number of cycles to failure of the specimen under different load conditions were noted as fatigue-life *N*. The test was terminated as and when the specimen failure occurred. Experimental set-up for flexural fatigue tests is shown in Fig.1b. The fatigue life data of SFRC with different fibre contents containing fibres of mixed aspect ratio are listed in ascending order in Table 3.

(a)

(b)

Fig.1 Experimental setup for (a) static flexural tests and (b) flexural fatigue tests

RESULTS AND DISCUSSION

Performance under static flexural loading

The average static flexural strengths of SFRC with 1.0%, 1.5% and 2.0% fibre volume fractions were obtained as 7.45, 8.44 and 8.92 MPa, respectively. The static flexural strength of plain concrete was 5.35 MPa. Increasing the fibre content from 1.0% to 2.0% had significant beneficial effect on the static flexural strength of concrete. There was an increase of 39%, 58% and 67% in the static flexural strength of SFRC over the plain concrete with the addition of

Table 3 Laboratory fatigue-life data (number of cycles to failure, *N*, in ascending order) for SFRC containing mixed fibres (50% 50 mm + 50% 25 mm long fibres). Fibre volume fraction: V_f; Stress level: *S*

V_f=1.0%			V_f=1.5%			V_f=2.0%		
S=0.90	*S*=0.85	*S*=0.80	*S*=0.85	*S*=0.80	*S*=0.70	*S*=0.85	*S*=0.80	*S*=0.70
929	5267	36622	390	576*	1918*	140	845	32683
1306	6281	46803	531	3095	96180	174	937	36347
1458	9283	50810	800	3778	170168	203	1258	58703
1867	9320	84871	900	6409	182933	345	1596	83573
2577	9946	92033	1037	7015	297931	403	2080	92561
3295	16387	106169	1503	9200	318835	403	2361	123188
3564	21273	130139	1956	11334	395384	494	4395	146041
3657	24494	204223	2697	14468	608535	624	5103	206339
5450	27488	231996	3225	24319	745099	781	6977	236496
25449*	37321	317929	−	30028	1154990	832	−	430098
−	−	−	−	−	−	1439	−	1194268*

* Rejected as outlier by Chauvenet's Criterion, not included in analysis

1.0%, 1.5% and 2.0% volume fractions of fibres to concrete respectively.

To study the flexural fatigue performance of SFRC containing fibres of mixed aspect ratio was the main objective of this investigation.

Performance under flexural fatigue loading

As the fatigue test data of SFRC show considerable scatter because of the random orientation of fibres, some data points may deserve consideration for rejection as outliers. So, Chauvenet's Criterion (Kennedy and Neville, 1986) was applied to the data points at each stress level and points meeting this criterion for rejection were identified, and were not included in further analysis. Factors such as non-uniform distribution of fibres in the matrix may probably be the reason for this scatter in the fatigue test data. Batson *et al.*(1972) and Johnston and Zemp (1991) used the same criterion for rejection of outliers in their investigations to study the flexural fatigue behaviour of SFRC.

To arrive at conclusions on the comparative relationships between number of cycles to failure and stress level, a linear regression was carried out on each set of data based on the least squares technique and plotted on semilogarithmic format. Figs.2 and 3 present the *S*-*N* relationships for SFRC with different volume fractions of fibres. In Fig.2 the ordinate represents the maximum fatigue stress expressed as percentage of the corresponding static flexural stress whereas in Fig.3 the ordinate represents the actually applied maximum fatigue stress.

The influence of increasing fibre content can be seen from Fig.2 wherein the ordinate represents applied fatigue stress as percentage of the corresponding static strength. Increasing the fibre content from 0.0% to at least up to 1.0% improves the fatigue performance significantly, but with further addition of fibres the performance drops. For example, the two-million-cycle fatigue strengths are 58.30%, 72.10%, 65.40% and 62.00% of the corresponding static flexural strengths for fibre contents of 0.0%, 1.0%, 1.5% and 2.0%, respectively. Evidently, the best performance is given by SFRC containing 1.0% fibre content followed by SFRC with 1.5% and 2.0% fibre content when the comparison is made in terms of applied stress expressed as percentage of the corresponding static flexural stress of SFRC. The two-million-cycle fatigue strengths for SFRC containing different volume fractions of mixed steel fibres are listed in Table 4 along with corresponding fatigue strength of plain concrete. It can be seen that there is an increase of 24% in the two-million-cycle fatigue strength of

Table 4 Two-million-cycle fatigue strengths for plain concrete and SFRC

Fibre volume fraction (%)	*A* and *B* in the fatigue equation $S=A+B\times\lg N$		Two-million-cycle fatigue strength* (%)
	A	*B*	
0.0	1.1303	−0.0868	58.30
1.0	1.1029	−0.0606	72.10
1.5	1.0396	−0.0612	65.40
2.0	1.0103	−0.0619	62.00

* Expressed as percentage of corresponding static flexural stress

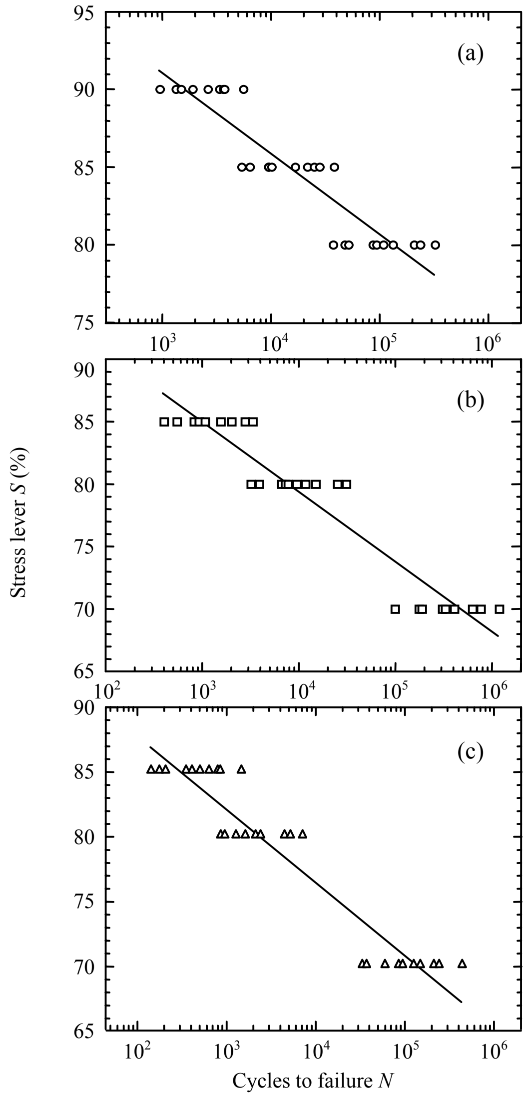


Fig.2 ***S-N*** **relationships for steel fibre reinforced concrete 50% 50 mm+50% 25 mm long fibres based on applied fatigue stress as percentage of static flexural stress. (a)** V_f**=1.0%; (b)** V_f**=1.5%; (c)** V_f**= 2.0%**

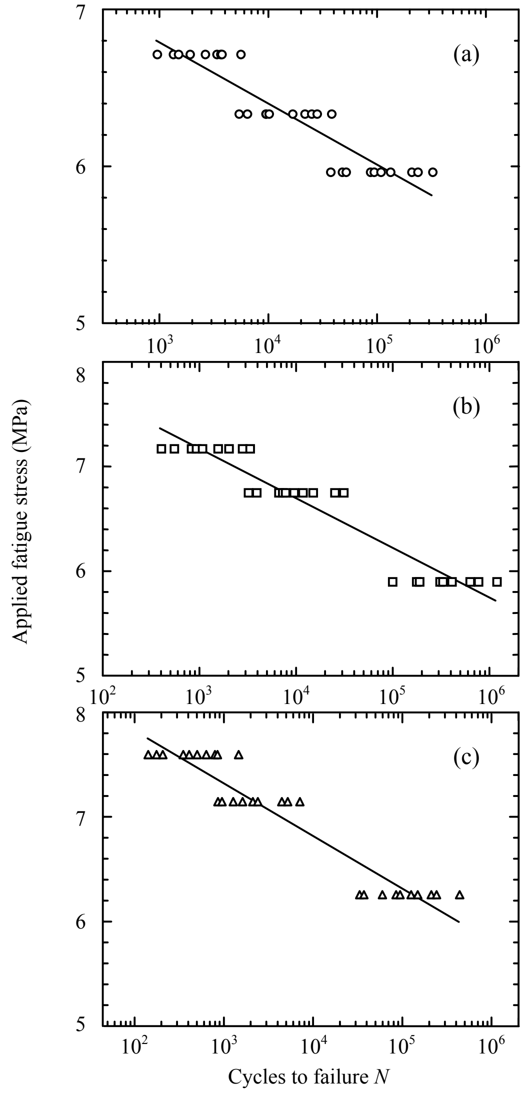
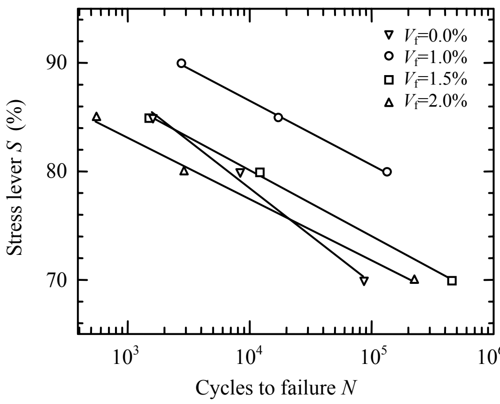


Fig.3 ***S-N*** **relationships for steel fibre reinforced concrete 50% 50 mm+50% 25 mm long fibres based on actually applied maximum fatigue stress. (a)** V_f**=1.0%; (b)** V_f**=1.5%; (c)** V_f**= 2.0%**

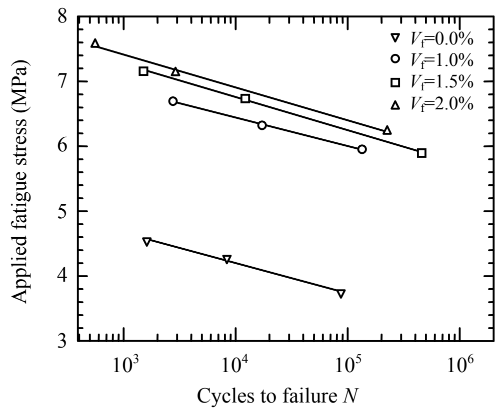
SFRC with the addition of 1.0% steel fibres to plain concrete. The corresponding increase in the two-million-cycle fatigue strength of SFRC over plain concrete is 12% and 6% with the addition of 1.5% and 2.0% steel fibres respectively. The corresponding fatigue equations as obtained in this investigation by linear regression are also listed in Table 4. These fatigue equations can be used to predict the flexural fatigue strength of SFRC.

In contrast, when the fatigue performance is examined in terms of actually applied fatigue stress as shown in Fig.3, the ranking differs greatly. Increasing fibre content from 0.0% to 2.0% seems to improve the performance in terms of the actually applied maximum fatigue stress. For example, the two-million-cycle fatigue strengths are 3.12, 5.28, 5.51 and 5.53 MPa for fibre contents of 0.0%, 1.0%, 1.5% and 2.0%, respectively. It may be noted that the performance of SFRC containing 1.5% and 2.0% fibres is almost the same in this case. Ramakrishnan (1989) and Johnston and Zemp (1991) obtained similar trends of two-million-cycle fatigue strengths in terms of fibre content for both applied maximum fatigue stress expressed as percentage of static flexural strength and actually applied maximum fatigue stress.

Fig.4 presents comparison of the *S*-*N* relationships of SFRC containing mixed steel fibres of different volume fractions of fibres. In Fig.4a, the ordinate represents actually applied maximum fatigue stress as percentage of corresponding static flexural stress whereas in Fig.4b the ordinate represents actually applied maximum fatigue stress. The *S*-*N* curve for plain concrete is also plotted in these figures for comparison.



(a)



(b)

Fig.4 Comparison of *S*-*N* relationships for steel fibrous concrete based on (a) stress as percentage of static flexural stress and (b) actually applied fatigue stress

Above all, the accuracy with which the fatigue strengths have been established is determined by the accuracy with which the static ultimate flexural strength of the specimens was approximated. However, the trend of the data in this investigation is well defined, and it is considered that the curves established from these data are representative of the fatigue behaviour of SFRC.

Mode of failure

The failure of almost all the specimens of SFRC under fatigue loading was due to the initiation of a single crack in the middle third of the specimen. With an increase in the number of cycles, the crack propagated and widened leading to the complete failure of the specimen. At higher stress levels, the failure was almost immediate after the initiation of first visible crack. However, at lower stress levels, the fibre concrete specimens withstood sufficient number of load cycles even after initiation of first visible crack. This indicates the crack arrest characteristics and increased bond properties of fibres, used in this investigation, due to their deformed surface. The failure of the SFRC specimens containing 1.0%, 1.5% and 2.0% volume fraction of mixed fibres was partly due to pull-out and partly due to fracture of some fibres. The fibre failure mode was fracture at 2.0% and pull-out at 1.0%. The failure of specimens under static flexural load was almost the same as under flexural fatigue load. In most of the cases the crack was initiated in the middle third span of the specimen and widened further leading to failure of the specimen.

CONCLUSION

Flexural fatigue strengths for two million cycles of load application for SFRC with fibre content of 1.0%, 1.5% and 2.0% were determined in this investigation. Each volume fraction contained two types of steel fibres, i.e., 50 mm long and 25 mm long mixed in the proportion of 50:50 by weight. The fatigue test data thus obtained were used to plot *S*-*N* diagrams and derive fatigue equations for predicting SFRC flexural strength. The two-million-cycle fatigue strengths for SFRC containing fibres of mixed aspect ratio are 72.10%, 65.40% and 62.00% of the corresponding static flexural strength for 1.0%, 1.5% and 2.0% volume fraction of fibres respectively whereas the two-million-cycle fatigue strength for plain concrete is 58.30% of the corresponding static flexural strength. The best performance is given by SFRC containing 1.0% fibre content. Comparison of performance based on percentage *S*-*N* relationships gives trends that differ significantly from the trends obtained when comparisons are made based on actually applied fatigue stress. The two-million-cycle fatigue strengths in terms of actually applied fatigue stress are 5.28, 5.51 and 5.53 MPa for fibre contents of 0.0%, 1.0%, 1.5% and 2.0% respectively, whereas it is 3.12 MPa for plain concrete. Further, fatigue equations for different fibre volume fractions have been proposed which can be used to predict the flexural fatigue strength of SFRC containing such fibres.

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