State of the Art Review on Fatigue Behaviour of Reinforced Concrete Beams with Mineral Admixtures

R Dineshkumar
PG Student,
Kongu Engineering College,
Erode, Tamil Nadu, India.

Dr P Srinivasan
Senior Principal Scientist,
CSIR-SERC,
Chennai, India.

Dr S Suchithra
Assistant Professor (Sr.G),
Kongu Engineering College,
Erode, Tamil Nadu, India

Abstract— **Fatigue is a progressive brittle failure of a structural element under repeated, cyclic or fluctuating loads. Due to the effect of fatigue load on bridge girders, marine structures and tall structures, the structure life is reduced. This paper gives a comprehensive information about the fatigue behavior of reinforced concrete beam with mineral admixtures. Fly ash, GGBS, Silica Fume, Bottom ash are some of the mineral admixtures which can be used in concrete. Bottom ash is a non-combustible residue obtained from furnace or incinerator, which can be used either as a pozzolana in cement after grinding or partially replaced for fine aggregate. The fatigue behaviour of reinforced concrete beam depends on the size of the beams, support conditions, number of fatigue cycles, loading limits, frequency and amplitude of loading applied. An overview is given about the influence of mineral admixtures on the mechanical behavior of concrete and the state of damage of the beam due to fatigue. The method of application of fatigue loading on the beam and the parameters to be determined from the test are explained. The influence of mineral admixtures in the propagation of crack and final crack width observed in concrete and steel in the beam after fatigue loading is explained from the literatures. The fatigue life is determined from the relationship between the number of fatigue cycles and the stress developed in the beam due to fatigue loading.**

Keywords— RC beam, Mineral admixtures, Fatigue behaviour, Cyclic loading, Fatigue life.

I. INTRODUCTION

Fatigue failure is defined as the tendency of a material to fracture by means of progressive brittle cracking under repeated alternating or cyclic stresses of an intensity considerably below the normal strength.

The reinforced concrete structures were designed to take the static loads. But in nature, floors subjected to crowd, vehicle vibration in road pavements, traffic load in bridges, wind and wave action in marine structures gives cyclic or fatigue load to the structure. Fatigue is generally effect of degradation, which reduces the structural service life. The service life of reinforced concrete structure directly depends on the stress level, stress range and number of the loading cycles during the cyclic loading [12].

The addition of mineral admixtures such as Fly ash, GGBS, Silica Fume, Bottom ash in concrete may improves the mechanical behaviour of concrete. The mineral admixtures can either be added as pozzolona to cement in powdered form or as partial replacement for fine aggregate with respective to their physical properties. These mineral admixtures were industrial wastes and by using them as partial replacement for fine aggregate may help in reduction of ecological degradation by conserving river sand.

The application of industrial by products as mineral admixtures help in waste utilization. Waste usage helps in reduction of environmental degradation by preserving natural river sand, if partially used as replacement for sand. Bottom ash can be success fully used as a partial replacement for fine aggregate up to optimum value [23].

Due to the increase in the traffic growth and widespread overload of freight, the repeated fatigue loading of vehicle will leads to brittle fatigue failure without any warning. When RC bridge structures are under corrosive environment and repeated vehicle load affects the steel reinforcement under the coupling effects of corrosion and fatigue, performance of RC bridge structures will deteriorate rapidly. The flexural behavior of RC beams and mechanical properties of steel reinforcing bars plays a crucial role in the structural serviceability and safety of RC bridge structures [16].

Fatigue loading is divided into two types as Low cycle fatigue and High cycle fatigue. Low cycle fatigue refers to lesser cycles at high stress values, whereas High cycle fatigue refers to high load cycles at lower stress values. Structures subjected to earthquake comes under low cycle fatigue. Airport pavements, Highway and Railway bridges, Road pavements are subjected to High cycle fatigue [22].

The reinforced concrete structures were designed for the load bearing capacity. Due to the fatigue loading, the repeated application of stresses causes the structure fail to before reaching the ultimate load carrying capacity under static loading. Structures subjected to cyclic loads failed in the positive moment region due to high-cycle fatigue fracture of the main steel reinforcement [6].

II. MATERIAL PROPERTIES

A. Concrete

Concrete is assumed as a homogenous material, constitutes of cement, fine aggregate, coarse aggregate, water and admixtures. The strength of the concrete depends upon the proportion of the constituents added. The mineral admixtures when added to concrete may change the mechanical properties of the concrete. The fatigue failure of concrete may be as the failure of bond between the cement mortar, failure of bond between cement and aggregate, breaking of aggregate or combination of above [20]. The addition of mineral admixtures can improve the bond between the composites of concrete.

B. Bottom Ash

Bottom ash is a granular incombustible residue obtained from the furnace, boilers, and chimneys. Bottom ash is having similar properties of sand and it can be partially replaced with sand. The increase in the percentage of bottom ash for partial replacement sand reduces the workability of concrete. The compressive strength of the concrete containing 30% and 40% bottom ash was found to be 108% and 105% at 90 days was more than that of normal concrete. The flexural strength was in the range of 113-118% at 90 days when compared to that of normal concrete at 28 days [9].

C. Fly Ash

Fly ash is a finely powdered coal combustible material collected from the boilers, chimneys. Fly ash is a mineral admixture which is having high pozzolonic properties which can be used in the manufacturing of PPC. Fly ash can be used as mineral admixture in concrete which improves the mechanical properties of concrete. Naik and Singh tested flexural and fatigue strength of beams with C type fly ash shows that increasing the fly ash content from 15% to 50% causes reduction in fatigue strength of the beam [1].

D. GGBS

Ground Granulated Blast furnace Slag (GGBS) is one of the mineral admixture which cis having pozzolonic property. GGBS can be either used as an ingredient in cement manufacturing or in concrete. Babu and Kumar studied the efficiency of GGBS in concrete shows that increase of 8.6% for 50% and 19.5% for 65% replacement in total cementitious material for achieveing the strength at 28 days for nominal concrete [4].

E. Steel

The tensile load in the structure is withstand by the steel embedded in the concrete in RC members. The reversal load may affect the mechanical response of the steel [2]. The strain hardening and strain softening action due to the repeated loads may affect the tensile strength of steel and brittle cracks will be formed. The sudden loss in the bond strength between the concrete and steel causes brittle failure. The fatigue load may also affects the fatigue bond behaviour between steel and concrete [10].

III. EXPERIMENTAL SETUP

A. Loading Arrangement

The beam specimens were tested for four point bending at one third of the span from either side of the support or three point bending in the mid span. The fatigue loading was given to the beam by actuator using a computer controlled system. The frequency of the loading is adopted with respect to the actuator capacity. The upper and lower load limits were set according to the ultimate load carrying capacity of the beam determined from static load test. Before applying the fatigue loading, 5 -10 kN static load was loaded and reduced repeatedly to improve the bearing contact. Testing and checking were simultaneously done to see if the data of each channel was normal. The loading arrangement used by Al-Rousan and Issa is shown in Fig. 1 [16].

Then, beam specimen was adjusted to the average fatigue force, fatigue loading started. The fatigue test was paused and actuator is unloaded after the completion of 0, 1, 1 X 10^4, 2 X 10^4, 5 X 10^4, 10X 10^4, 20 X 10^4, 50 X 10^4, 100 X 10^4, 150 X 10^4 and 200 X 10^4, fatigue cycles. After the residual deformation was stable, the beam n was monotonically loaded to the upper limit value of fatigue load under step loading of 10 kN and the deflection data was collected at each step of monotonic loading. When fatigue fracture of any one of the tensile reinforcing bars occurred, the actuator immediately unloaded for protection to prevent the beam specimens from being secondary loaded after fatigue failure. The fatigue loading test ended [28].

B. Deflection Measurement

The deflection in the beams due to the fatigue loading can be measured using mechanical or digital instruments. Usually deflection was measured at mid span and at quarter span of the beam. Dial gauges or Linearly Variable Differential Transformers (LVDT) can be used to measure the deflection.

To measure deflection of the beams during testing, three numbers of Linear Variable Differential Transformers (LVDT) were placed; one at the centre of the beams and other two at middle third points of the effective span of the beams on each size [17].

C. Strain Measurement in Concrete

Strain measurement in concrete due to the fatigue loading gives the variation of material deformation. The fatigue life of the beam is determined using the relationship between the strain and number of fatigue cycles. Strain gauges were used to measure the strain in concrete at the top and bottom fiber and at mid height of the beam at mid span.

For all the concrete beams, three strain gauges were fixed on the surface of concrete beams in tension zone and one strain gauge in compression zone of gauge length 60 mm to measure the variation of strain during static/fatigue loading [19].

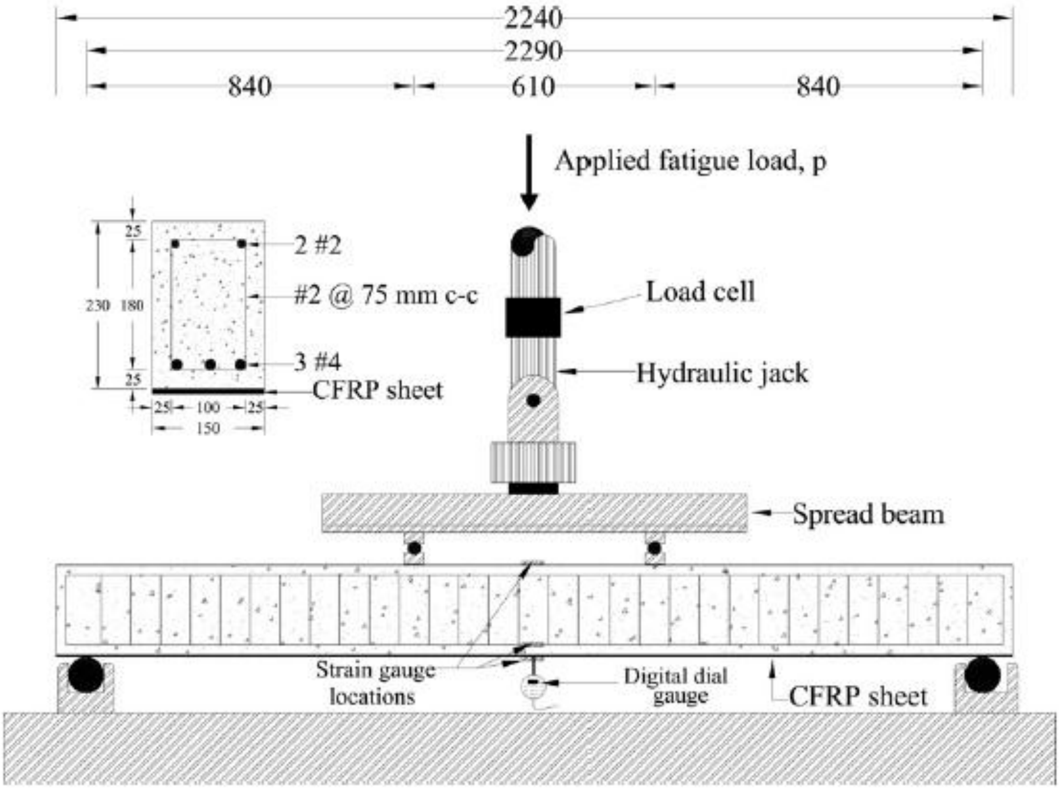

Fig. 1 Loading arrangement [16].

D. Strain Measurement in Steel

Due to the cyclic loading in the beam, reversal stresses was produced in the reinforcement steel. The reversal stresses cause strain hardening and strain softening in steel. The beam under fatigue loading may fail by the rupture of tension reinforcement. Therefore, it is important to measure the strain in the reinforcement steel due to the application of fatigue loading. Strain gauges are placed in the tension reinforcement in mid span and at top reinforcement near the support. [32].

E. Maximum and Minimum Loading

For fatigue loading the maximum and minimum limits have to be set with respect to the ultimate load carrying capacity of the beam. The maximum and minimum values can be provided either with the stress limits or load limits. Generally, the minimum load is taken in the 10% - 20% of the ultimate load carrying capacity of the beam or of the maximum fatigue load and the maximum load is taken in the range of 50% - 85% of the ultimate load carrying capacity of the beam. The ultimate load carrying capacity is determined either by the monotonic loading on the beam or by theoretical methods.

Sun and Huang uses the actual stress level of simply supported RC girder bridge in service, by means of analysis and calculation, the upper limit value of fatigue load was taking as 70 kN, which was 47.3% of static failure load of the girder. The lower limit value of fatigue load was taking as 30 kN, which was equivalent to the effect of bridge dead load. The corresponding upper limit value of fatigue stress for the tensile reinforcement was 221.9 MPa, lower limit value of fatigue stress was 95.1 MPa, and stress range was 126.8 MPa [16].

F. Rate of Loading

The variation in the loading frequency may affect the fatigue behaviour of the beam. High stress range with decreasing frequency causes reduction in the fatigue strength. Lower frequency loading results in least fatigue cycles when compared to high frequency loading. The fatigue crack growth for constant amplitude loading differs from variable amplitude.

Al-Rousan and Issa tested with two point loading. Constant amplitude sinusoidal loading is applied in fatigue testing. Two fatigue-loading frequencies of 1 Hz and 4 Hz were used to demonstrate the difference in the responses of two identical beams under different fatigue loading rates [11].

Stroeven uses lower frequency case which results in lower number of cycles to fracture. For minimum amplitude the distance between both curves is about 100 cycles and at maximum amplitude is about 10 cycles. Thus, time to fracture is similar for the two frequency cases at minimum amplitude; however, the life span difference between the two frequency cases amounts to a factor of 10 at highest amplitude. So, larger amplitudes in the high frequency case lead to a dramatic reduction in the number of cycles to fracture [14].

IV. DISCUSSION ON EXPERIMENTAL RESULTS

A. Fatigue Failure

The RC beams subjected to fatigue loading fails by the yielding of reinforcement in tension zone followed by the crushing of concrete in the compression zone. The number of fatigue cycles the beam withstands determines the fatigue strength of beam. Most of the tests were stopped after 2,000,000 cycles if the beam resists in order to save energy and time.

Sun and Huang tested reinforced beam under fatigue in both controlled beam and beams with corroded reinforcements. Control beams resists fatigue failure up to 2 million cycles and after that static load is applied up to failure. The control beams also shows ductile failure in static loading. The static failure load applied after 2 million cycles were same as that of the actual static failure load 148 kN. It was showed that fatigue effect had no substantial influence on the static performance of RC beams without corrosion [27].

Harwalker and Awanthi studied the flexural fatigue behaviour in high volume fly ash concrete beams of size 500mm X 75mm X 100mm under two point loading. Constant amplitude sinusoidal wave loading was applied with frequency of 4Hz having maximum stress value as 0.8fck and minimum loading as 10% of maximum load. The failure was found to be brittle in nature. The fatigue strength for high volume fly ash concrete was higher when compared to conventional concrete [22].

B. Effect of Load Range

The variation in the load range may affect the fatigue behaviour of the beam irrespective of its dimensions, support conditions, etc. Rietl, et al tested the fatigue behaviour of reinforced beams with various load range. It is found that increase in load range results in reduction of fatigue life. These beams shows that the fatigue strength at one million cycles reaches 50% of static load. The test results were shown in Table 1 [4].

C. Crack Propagation

Concrete failure may be possible due to the presence of air voids, honey combs due to improper compaction, voids due to shrinkage. These voids may be prone to development of cracks due to the cyclic loading. The fatigue cracks were flexural in nature as they occurs in pure bending region. The crack width increases with increase in the number of fatigue cycles. A few cracks were found outside the pure bending section due to the progression of fatigue cycles.

TABLE 1 Fatigue test results with different load ranges [4].

S. No	Reference	Length mm	Width mm	Depth mm	Frequency Hz	Pmax kN	Pmin kN	Load Range	Fatigue Cycles @ failure	Static Failure kN
1	Rteil, et al (2007)	1800	150	250	1.5					
	Using 20mm dia bars									100
i	F 75 - 20					85	10	75	130	
ii	F 65 - 20					75	10	65	3080	
iii	F 60 - 20					70	10	60	1750	
iv	F 55 - 20					65	10	55	34202	
v	F 53 - 20					63	10	53	53969	
vi	F 50 - 20					60	10	50	1000000	
vii	F 40 - 20					50	10	40	1000000	
	Using 25mm dia bars									120
i	F 75 - 25					96	12	84	820	
ii	F 65 - 25					90	12	78	27688	
iii	F 60 - 25					84	12	72	41102	
iv	F 55 - 25					78	12	66	606847	
v	F 53 - 25					76	12	64	278173	
vi	F 50 - 25					72	12	60	1000000	

Hong-Bing tested T beams under fatigue loading, within the constant-amplitude fatigue test, the cracks in the beam included normal cracks located in the pure-bending segment and bending shear oblique cracks. The crack depth reached to the half-height of the beam at the first loading and the cracks were distributed symmetrically along the span direction on both sides of the cross section. The width, depth, and numbers of cracks that developed during the fatigue test are grouped into the rapid development stage, stable development stage, and failure stage [13].

D. Deflection under Fatigue

The cracks were formed and closes after completion one cycle of fatigue loading and the deflection at the mid span and quarter span due to crack formation were recorded in the LVDT's. The flexural stiffness of the beam reduces due to the rapid change in the mid span deflection. The concrete in tension zone cracks and becomes ineffective after fatigue loading for the first time, thus the neutral axis is shifted up thereby changing the flexural moment of inertia of the beam [16].

E. Strain

The stiffness of the beam reduces due to the application of load. Cyclic load on the beam causes an initial deformation in the beam which causes strain in steel. The strain in concrete and steel were obtained from the strain gauges fixed in compression zone, mid half side of the beam and in mid span of tension reinforcement and near the support at compression reinforcement respectively. The strain value in steel increases with the variation in the mid span deflection due to fatigue loading. Gandhi underwent investigation on comparing the fatigue behaviour of GFRP bars with TMT bars shows that with increase in the load range may increase the strain in steel [32].

F. Flexural Behaviour of concrete

The addition of mineral admixture in concrete may influence the flexural property. Nikbin, et al studied the mechanical properties of the concrete with waste bottom ash as replacement for natural aggregate using M40 grade of concrete. The results shows that increase in the percentage of replacement may reduce the flexural strength of the concrete when compared to conventional concrete. For 100% replacement of bottom ash for sand reduces 27% of flexural strength. Optimum results were found for 20% replacement of bottom ash for fine aggregate [23].

Guo, et al studied the flexural fatigue strength of the concrete with Fly ash and GGBS as additives with cement and crushed Basalt aggregate for different mixes. Two point fatigue loading is provided with two maximum stresses as 0.7 and 0.5 of compressive strength of concrete and 15% maximum load as minimum load. The results shows that the optimum addition of fly ash and GGBS increases the mechanical properties of concrete [13].

G. Fatigue Life

The fatigue life is the number of cycles the beam can sustain before the rupture of reinforcement steel. The fatigue life can be calculated from S-N curve. S-N curve gives the relation between the stress amplitude and the No of fatigue cycles.

Kaur, et al studied the flexural fatigue behaviour of concrete with steel fibres and additives like Lime powder (LP), Fly ash (FA), Silica Fume (SF) and Metakaolin (MK) with cement. Control mixe contain 100% OPC, CF mix contains 70% OPC + 30% FA, CFM mix contains 70% OPS + 20% FA + 10% MK and CFS mix contains 70% OPC + 20% FA + 10% SF. Frequency of fatigue loading was kept as 10Hz having four stress ranges 75%, 80%, 85% and 90% for static failure loads. Test was carried out up to 2 million cycles. The S-N curve shows that the fatigue life of additive concrete shows higher values when compared with conventional concrete. Fig. 2 shows the fatigue curves for different mixes [18].

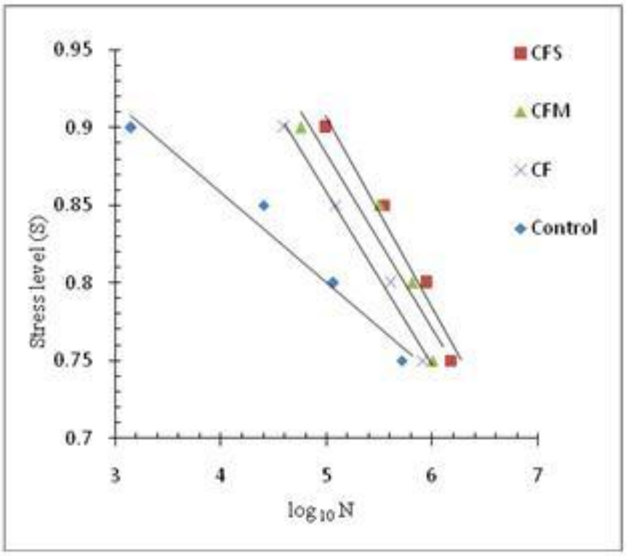

Fig. 2 Fatigue curve for different mixes [18].

V. CONCLUSION

- The fatigue behaviour of the reinforced concrete beams with addition of mineral admixture was studied.
- The addition of mineral admixtures up to an optimum extend increases the mechanical properties of the concrete.
- The fatigue strength of the beam is determined from the number of fatigue cycles the beam can withstand up to failure due to the application of fatigue loading.
- The deflection of the beam under the fatigue loading was determined using LVDT or dial gauge.

- The strain in the concrete and steel was measured using the strain gauges.
- The addition of mineral admixture in an optimum percentage will improve the flexural fatigue strength of the concrete.

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