Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari,R1, Kumaran.G2
1- Assistant Professor, 2- Professor
Department of Civil and Structural Engineering, Annamalai University, Annamalai nagar, 600 002, Tamilnadu, India
siva_1667@yahoo.com

ABSTRACT

Non-metallic reinforcements (Glass Fibre Reinforced Polymer reinforcements - GFRP) are viable alternate to the conventional steel reinforcements owing to their excellent properties such as non-corrosive, nonconductive and nonmagnetic properties. This study focuses on the performance of GFRP reinforced concrete one way slabs under constant and variable amplitude fatigue and it is compared with conventionally reinforced concrete one way slabs. A total number of thirty nine one way concrete slabs, out of which eleven are reinforced with conventional steel reinforcements and twenty eight are reinforced with Glass Fibre Reinforced Polymer (GFRP) reinforcements. Among the thirty nine slabs, sixteen are subjected to static loading, sixteen are subjected to constant amplitude fatigue loading and seven are subjected to variable amplitude fatigue loading. Finite element analysis is also carried out to study the effect of different parameters on the flexural capacity of one way slabs. Different parameters like thickness of slabs, reinforcement ratios, types of reinforcements and grades of concrete are considered. Based on this study, static load carrying capacities and fatigue performance of the conventional and GFRP reinforced concrete one way slabs are compared. A good agreement exists between the analytical and experimental results.

Keywords: One way slabs, Glass Fibre reinforced Polymer reinforcements (GFRP), Static loading and Fatigue Loading.

1. Introduction

The deterioration of Reinforced Concrete (RC) structures has been a perennial problem due to the corrosive nature of reinforcements embedded in the concrete. Though several recommendations like the use of water proofing admixtures in concrete, impermeable membranes, epoxy coated reinforcements are tried for preventing the corrosion of steel reinforcement, all the attempts are not commercially much viable. The use of non-corrosive reinforcements in the place of steel reinforcements has therefore been focused as an alternative to improve the life span of the concrete structures. Fibre Reinforced Polymer (FRP) reinforcements offer many advantages over steel reinforcements including resistance to electrochemical corrosion, high strength to weight ratio and easy in fabrication and electromagnetic insulating properties. Further more, FRPs are available commercially in the form of sheets or reinforcements. FRP reinforcements are made of two components namely, fibres and matrix. The matrix is usually a thermoset resin such as vinyl ester or epoxy, while the fibres are carbon, aramid or glass fibres. The use of GFRP reinforcements, in lieu of conventional steel reinforcements requires better understanding under different parametric
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R, Kumaran. G

conditions. So far, studies are largely confined to cyclic test on FRP reinforcements alone. Considerable research has also been carried out mainly on FRP reinforced concrete specimens under monotonically increasing load (Nawy 1977, Benmokrane 1995, ACI -440, Michaluk 1998, Theriault 1998, Ombres 2000, Sobhy Masoud 2001, Ganesh Thiagrajan 2003 ). Only a limited research has been carried out on FRP reinforced concrete specimens under pulsating or repeated loading conditions (Ragaby 2007, Sivagamasundari 2007). Therefore the present study deals mainly with the behaviour of Reinforced Concrete (RC) one way slabs reinforced internally with Glass Fibre Reinforced Polymer (GFRP) reinforcements under repeated loading conditions. Based on rigorous modelling and experimental analysis, improved recommendations are proposed for Indian Standard (IS) codes.

2. Behaviour of Concrete under Fatigue Loading

Fatigue is a permanent internal structural (micro cracking) change in a material subjected to fluctuating stresses or strains, if the loading exceeds a certain limit. Fatigue failure of materials normally occurs at a stress level much lower than the static stress because of repeated stress or deformation, and in most cases it appears in an abrupt brittle fracture pattern. Pavements, bridges and other structures supporting oscillating machinery are included in this category. Fatigue fracture of concrete is characterized by considerably large micro cracking and strains when compared to fracture of concrete under static loading. The degree of fatigue damage can be measured by the magnitude of elastic and residual (plastic) deflection, crack widths and strains at various levels along the thickness of the specimen. In fatigue test, the number of cycles applied on the slabs up to their failure is noted and a graph is drawn between stresses versus numbers of cycles applied (S-N curve). In the present study, two types of repeated loading schemes such as constant amplitude fatigue loading (scheme I) and accelerated fatigue loading with variable amplitude (scheme II) are adopted. Generally, bridge structures are seldom subjected to constant amplitude repeated loading during their life time, but considering the variability in the load amplitudes, constant load amplitude is being normally considered (Ferreira 2001, Kae-Hwan Kwak 2001, Benmokrane 2007).

The constant amplitude loading has been actuated between a minimum load and a peak load i.e. 10% and 80% of the nominal ultimate static strength of the control slab at a rate of 4 Hz to acquire the load cycles of constant amplitude. The minimum load level is set to prevent any impact during cyclic loading and the maximum load is fixed so as to accelerate the speed of testing. The loading range is same for all the specimens and it is chosen to be approximately symmetrical around the service load and to enable the slab specimen failure within the reasonable time. The accelerated fatigue loading with variable amplitude (scheme II) is done to assess the effect of cyclic loading at lower peak load levels. The minimum load is fixed as 2 kN and different percentages (20%, 40%, 60% and 80%) of the peak loads of the corresponding slabs are selected as variable maximum loads. For all the specimens, 10,000 number of cycles is applied for each and every percentage of load at a frequency of 4 Hz. and is continued till the slab completely fails.

3. Experimental Program

3.1 Concrete

The concrete mix is designed for relatively higher strength due to the high strength possessed by fibre reinforcements. All the slab specimens are cast using normal weight concrete of
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings
Sivagamasundari. R, Kumaran. G

grade 20MPa and 30MPa. After casting the specimens, they are allowed curing in real environmental conditions for about 28 days. The properties of concrete mix are given in Table 1.

Table 1: Mix proportions of concrete

| Material            | M20 grade of concrete | M30 grade of concrete |
|---------------------|-----------------------|-----------------------|
| Cement              | 62 kg                 | 77 kg                 |
| Fine aggregate      | 80 kg                 | 84.7 kg               |
| Coarse aggregate    | 183 kg                | 204.82 kg             |
| water               | 28 litres             | 31 litres             |

3.2 GFRP reinforcements

GFRP reinforcements used in this study are manufactured by pultruded composites Ltd (Dextra industries Ltd, India; Ercon industries Ltd, India; Hydro S&S industry Ltd, India). All the GFRP reinforcements supplied by these industries are manufactured by pultrusion process with the glass fibre volume approximately 61%. Three different types of GFRP reinforcements with different surface indentations (Grooved or threaded-G1 and sand blasted-G2 and Plain –G3) are tried. The mechanical properties of all types of GFRP reinforcements are obtained from appropriate standard tests. Table 2 summarizes the mechanical properties of all GFRP and conventional steel reinforcements. Basic tests such as; tensile strength, thermal coefficient of expansion and bond tests have already been carried out by the authors and reported (Bank 1998, Amnon Katz 1999, Nanni 2000, Amnon Katz 2000, Roman Okelo 2005, Benmokrane 2000).

Table 2: Mechanical properties of reinforcements

| Sl.No | Specification of Reinforcements | f (Mpa) | E, (Gpa) | d, mm | Strain, ε |
|-------|---------------------------------|---------|----------|-------|-----------|
| 1.    | G1                              | 600     | 60       | 10    | 0.01      |
| 2.    | G2                              | 690     | 68       | 10    | 0.01      |
| 3.    | G3                              | 525     | 47       | 10    | 0.011     |
| 4.    | S                               | 415     | 200      | 10    | 0.002     |

\[ f = \text{tensile strength of reinforcements}; \ E = \text{modulus of elasticity of reinforcements}; \ d = \text{diameter of reinforcements}; \ \varepsilon = \text{Strain of reinforcements at ultimate load} = f / E ; \ G_1, G_2, G_3 \text{ and S=Grooved, Sand Sprinkled and Plain GFRP and Steel reinforcements respectively} \]

3.3 Testing programme

The Testing programme is classified into three categories: 1. Sixteen slabs are subjected to static or monotonic type of loading; 2. Sixteen slabs are subjected to constant amplitude of fatigue loading; 3. Seven slabs are subjected to variable amplitude of fatigue loading scheme.
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings
Sivagamasundari. R, Kumaran. G

Figure 1: Model of one way slab with loading arrangement (All dimensions are in mm)

3.4 Experimental set up for Static loading condition

The length and width of all slabs are 2400 mm and 600 mm respectively. The clear span of 2200 mm is kept constant for all the specimens. A clear concrete cover of 20 mm is adopted for the longitudinal reinforcements. Load frame of capacity 50 tonnes is used for testing all slab specimens. All slabs are instrumented with a Linear Variable Differential Transformer (LVDT range 0-100mm) at mid span and at one-third points to monitor vertical deflections. The static load on the slabs is applied with the help of hydraulic jack having 25 tones capacity and measured with a proving ring. Demec gauge pellets are pasted at the topmost compression fibre, at the middle of the slab and at the level of reinforcements of slab to observe the displacements. The load is applied at an increment of 2 kN. The crack widths are measured using crack width detection microscope. The static test results are presented in Table 3. The experimental test set up for static loading is shown in figures 2 and 3.
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings
Sivagamasundari. R, Kumaran. G

Figure 2: Experimental Test setup

Figure 3: Photograph of Test Set up for Static loading

Table 3: Static Test Results of slabs

| Sl no | Designation of slabs | Theoretical Values | Experimental Values | $w_{cr}$ mm (exp) | Ultimate Deflection, mm (exp) |
|-------|----------------------|--------------------|---------------------|------------------|-----------------------------|
|       |                      | $\rho_U$ kN        | $\rho_{fr}$ kN      | $\rho_U$ kN      |                             |
| 1     | $M_2G_1\rho_1D_1$   | 33                 | 11.4                | 40               | 1.2                         | 70.2                        |
| 2     | $M_2G_1\rho_2D_1$   | 38.9               | 11.6                | 45.6             | 1                           | 72                          |
| 3     | $M_2G_1\rho_3D_1$   | 42.4               | 11.8                | 49.2             | 0.9                         | 71.6                        |
| 4     | $M_2G_2\rho_1D_1$   | 43.6               | 11.5                | 55.2             | 0.9                         | 59.2                        |
| 5     | $M_2G_2\rho_2D_1$   | 52                 | 11.6                | 58.6             | 0.74                        | 56.2                        |
| 6     | $M_2G_2\rho_3D_1$   | 56.2               | 12.0                | 65.4             | 0.7                         | 52.4                        |
| 7     | $M_2G_3\rho_1D_1$   | 20                 | 10.5                | 22.6             | 1.8                         | 105.2                       |
| 8     | $M_2G_3\rho_2D_1$   | 24.3               | 10.7                | 28               | 1.6                         | 99.6                        |
| 9     | $M_2G_3\rho_3D_1$   | 33.4               | 10.9                | 38.2             | 1.4                         | 95.2                        |
| 10    | $M_2S\rho_1D_1$     | 30.4               | 11                  | 40               | 0.36                        | 40.8                        |
| 11    | $M_2S\rho_2D_1$     | 33.6               | 11.2                | 46.2             | 0.34                        | 42                          |
| 12    | $M_2S\rho_3D_1$     | 35.7               | 11.5                | 48.5             | 0.3                         | 41.6                        |
| 13    | $M_2G_2\rho_1D_1$   | 49.2               | 11.6                | 60.2             | 0.6                         | 54.6                        |
| 14    | $M_2S\rho_1D_1$     | 45.6               | 12.4                | 50               | 0.32                        | 35.6                        |
| 15    | $M_2G_2\rho_2D_2$   | 62.5               | 19                  | 73.5             | 0.42                        | 45.6                        |
| 16    | $M_2S\rho_2D_2$     | 58.2               | 18.2                | 62.5             | 0.24                        | 28.6                        |

$M_2, M_3$ = Grades of concrete $M_{20}, M_{30}$ respectively; $G_1, G_2, G_3, S$ = Grooved, Sand coated, plain GFRP and Steel reinforcements; $\rho_1, \rho_2, \rho_3$ = Different reinforcement ratios 0.65%, 0.82% and
1.15% respectively; $d_e$ = Effective depth of slab; $P_u$ = static ultimate load in kN; $P_{fc}$ = first flexural crack load in kN; $w_{cr(fat)}$ = crack width in mm under fatigue load

3.5 Experimental set up for constant amplitude of fatigue loading condition

To simulate the traffic loading, two types of repeated loading have been tried in this study. First set of slabs (sixteen in numbers) are subjected to constant amplitude of fatigue loading scheme. Slabs are kept on the loading frame. A 20mm thick neoprene sheet is used between the steel plate and the concrete surface to avoid local effect. A clear span of 2200mm is adopted between the supports. A 50 kN capacity with 250mm stroke actuator monitored by computer is programmed to apply fatigue loads on the slab. A data acquisition system is used to monitor and acquire all strain readings with the help of strain gauges and LVDTs for both the static and repeated loadings. Demec gauges are also used to observe the displacements on a pre defined positions i.e on the brass pellets. The minimum load level is set at 2 kN to prevent any impact due to repeated loading and also to represent the effect of superimposed loads on a bridge like pavement and insulation (Kumaran 2002, Kumaran, 2003 Viyaprakash 2004, Rashid 2005). The maximum load level is set at 80% of ultimate static load of $M_2S_PD_1$ (i.e., conventional reinforced slab) and is applied uniformly at a rate of 4 Hz till the failure of the slab and is followed for all the slabs (Benmokrane 2007, Sivagamasundari 2007). The fatigue loading range is chosen to be approximately symmetrical around the service load so that the upper limit simulates some kind of overloading on the specimen; and enables the failure of the slab within a reasonable time. The results of slabs under constant amplitude of fatigue loading scheme are presented in Table 4. Figure 4 shows the test set up for the same.

![Figure 4: Photograph of Test Setup for repeated loading (Constant and Variable amplitudes)](image)

| Sl no | Designation of slabs | Number of load cycles | $w_{cr(fat)}$ | Residual deflection, mm |
|-------|----------------------|-----------------------|---------------|------------------------|
| 1     | $M_2G_1 \rho_1 D_1$ | 65,120                | 1.8           | 52                     |
| 2     | $M_2G_1 \rho_2 D_1$ | 78,603                | 1.3           | 50.2                   |

*International Journal of Civil and Structural Engineering*
*Volume 2 Issue 2 2011*
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari, R; Kumaran, G

International Journal of Civil and Structural Engineering
Volume 2 Issue 2 2011

| Sl No | Designation of slabs | Crack widths at various load levels, mm | $w_{cr (fat)}$ at Service load mm |
|-------|-----------------------|----------------------------------------|----------------------------------|
| 1     | $M_2 G_1 \rho_1 D_1$  | 0.24 0.5 2 -                        | 0.52                             |
| 2     | $M_2 G_2 \rho_1 D_1$  | 0.18 0.36 1.02 1.6                 | 0.42                             |
| 3     | $M_2 G_3 \rho_2 D_1$  | 0.16 0.32 1.0 1                     | 0.36                             |
| 4     | $M_2 G_4 \rho_1 D_1$  | 0.12 0.28 0.8 0.8                  | 0.32                             |
| 5     | $M_2 G_5 \rho_1 D_1$  | 0.15 0.32 1.2 1.56                 | 0.4                              |
| 6     | $M_2 G_6 \rho_1 D_2$  | 0.08 0.26 0.5 0.84                 | 0.26                             |

3.6 Experimental set up for variable amplitude of fatigue loading condition

The second set of slabs (sixteen numbers) are subjected to constant amplitude of fatigue loading scheme. The experimental set up for variable amplitude of fatigue loading condition is similar to constant amplitude of fatigue loading condition. The variable loading scheme is applied by selecting 2 kN as minimum load for all the slabs and different percentages of their ultimate loads (i.e. 20%, 40%, 60%, and 80%) as maximum loads to assess the effect of cycling at lower peak load levels (Sobhy Masoud 2001). Each and every fatigue loading steps is applied for 10,000 cycles at a frequency of 4 Hz till the failure of the slabs. The degree of fatigue damage can be evaluated by the magnitudes of strains in reinforcement, crack width, elastic deflection and residual (plastic) deflection. The magnitude of residual deflections is the energy dissipation of the slab which is considered as a proper measure to estimate the degree of damage. The deflections, crack widths, crack propagation, crack patterns, modes of failure and number of cycles up to failure are measured at the end of each repeated loading step. The results of slabs under variable amplitude of fatigue loading scheme are presented in Table 5 and 6.

Table 5: Fatigue test results of the slabs (Variable amplitude repeated loading)
Table 6: Fatigue test results of the slabs (Variable amplitude repeated loading)

| Sl No | Designation of slabs | Deflections at various load levels, mm |
|-------|----------------------|----------------------------------------|
|       |                      | 0.2P | 0.4P | 0.6P | 0.8P |
| 1     | $M_2 S \rho_1 D_1$   | 15.2 | 41.2 | 75.6 | -    |
| 2     | $M_2 G_1 \rho_1 D_1$ | 11.2 | 34.2 | 54.2 | 66.5 |
| 3     | $M_2 G_2 \rho_1 D_1$ | 10.6 | 32   | 52.6 | 64.2 |
| 4     | $M_2 G_1 \rho_2 D_1$ | 9.5  | 30.8 | 50.3 | 63.6 |
| 5     | $M_2 G_2 \rho_2 D_1$ | 10.5 | 32.4 | 52.6 | 62.4 |
| 6     | $M_2 G_2 \rho_1 D_2$ | 5.2  | 20.3 | 29.2 | 46   |
| 7     | $M_2 S \rho_1 D_1$   | 10.4 | 26   | 45.8 | -    |

4. Analytical Study

In this study, a non-linear finite element model consisting of full size one-way concrete slab is considered. Material modelling for concrete is done based on the compressive and tensile behaviour and the degradation properties of concrete due to cracking and crushing using shell elements. GFRP reinforcements are modelled as layers which exhibits uni-axial response. A perfect plastic and strain hardening plastic approaches are used to model the compressive and tensile behaviours of concrete. Figure 5 shows the finite element representation of full size RC one way slab. The effect of finite element mesh is also considered in this study and the results are compared.

![Finite Element Modelling of Slab](image)

Figure 5: Finite Element Modelling of Slab
Behaviour of steel/GFRP reinforcements

Steel reinforcements have an elasto-plastic behaviour and is defined by its yield strength, with a typical elastic modulus of 210 GPa whereas GFRP reinforcements are made from unidirectional polyester-glass materials having a modulus of elasticity 60, 68 and 47 Gpa and ultimate stress of 600, 690 and 525 Mpa for the grooved, sand coated and plain GFRP reinforcements respectively. In this study, all the GFRP reinforcements are modelled as layers of equivalent thickness. Each reinforcing layer exhibits a uniaxial response, having strength and stiffness characteristics in the longitudinal direction of the reinforcement only.

Compressive behaviour of concrete

The non linear behaviour of concrete is inelastic. A perfect plastic and strain hardening plasticity approaches are used to model the compression behaviour of concrete. A dual criterion for yielding and crushing in terms of stresses and strains is considered (Ferreira 2001).

Tensile behaviour of concrete

The response of concrete under tensile stresses is assumed to be linear elastic until the fracture surface is reached. This type of fracture or cracking is governed by a maximum tensile stress criterion. Cracks are expected to form in planes perpendicular to the direction of maximum tensile stress, as soon as it reaches a specified concrete tensile strength. In this study, concrete is assumed to be an isotropic material before cracking and the concrete becomes orthotropic after cracking, with a material axis oriented along the directions of cracking.

4.1 Finite Element Implementation

Figure 2 shows the finite element representation of full size RC one way slab simply supported along two opposite edges and free along other two. The slabs are rectangular in plan and spanned 2400mm with two variable thicknesses of 100mm and 120 mm. They are reinforced with mesh type of reinforcements with three different types of steel/ GFRP ratios of 0.65%, 0.82% and 1.15% in longitudinal directions. Concentrated loading is applied at one third points. The entire thickness of slab is divided into ten concrete layers of equal thickness, out of which one layer is steel/GFRP. In each layer, 144 slab elements are considered in the basic analysis and totally 1440 elements in the entire slab. In order to investigate the effect of finite elements mesh size on the results a 144 and a 288 elements are considered in each layer in the finite element modelling of the slab and the results are compared. The material properties of the specimen are summarized in Table 2.

5. Interpretation of the Results

The results of the experimental study are depicted in the form of graphs as shown in Figures 6-23.

5.1 Static loading results
From the static test, it is observed that the increase in reinforcement ratios, grade of concrete and thickness of slab exhibited greater strengths, lesser deflections and reduced crack widths than those of identical slabs (Vijayakraksh 2004, Rashid 2005, Amir 2007, Sivagamasundari 2007). The slabs reinforced with sand coated reinforcements show better performance than the slabs reinforced with the other types of reinforcements. $M_2G_2\rho_1D_1$ slab shows 14% higher strength than $M_2G_1\rho_1D_1$, 75% than $M_2G_1\rho_1D_1$ and 15% than $M_2S\rho_1D_1$. The ultimate deflection in the mid span of $M_2G_2\rho_1D_1$ slab is 0.84 times and 0.56 times lesser than that of $M_2G_1\rho_1D_1$ and $M_2G_2\rho_1D_1$ respectively. At the same time, the ultimate mid span deflection of $M_2G_2\rho_1D_1$ is 1.45 times higher than that of $M_2S\rho_1D_1$ slab. The crack width of $M_2G_2\rho_1D_1$ slab has been reduced by 25% and 50% of the crack width of slabs $M_2G_1\rho_1D_1$ and $M_2G_2\rho_1D_1$ respectively. By increasing the grade of concrete from 20 N/mm$^2$ to 30 N/mm$^2$ for the identical slabs, the flexural strength is promoted from 10 to 17%. The load carrying capacity of $M_2G_2\rho_1D_1$ slab increases by 35%, by increasing the thickness of slab to 20 mm. Owing to it, the ultimate deflection and the crack width also reduce substantially.

5.2 Repeated loading results

The degree of fatigue damage is determined by the magnitudes of strains in reinforcement, crack widths, elastic deflections and plastic (residual) deflections (Kae-Hwan Kwak 2001, Yost 2001). The magnitude of residual deflections is related to the energy dissipation of the slab and the same is considered in this study as an accurate measure to estimate the degree of damage. Based on this study, it is observed that with the increase in the number of load cycles, the corresponding ultimate deflection, number of cracks and the width of the cracks increase. These measurements differ considerably according to the types of reinforcements used in this study. $M_2G_1\rho_2D_1$ and $M_2G_1\rho_2D_1$ slabs experience 1.21 times and 1.46 times greater fatigue performance than $M_2G_1\rho_1D_1$ type slab. $M_2G_2\rho_1D_1$ slab shows 1.43 times and 1.85 times greater fatigue performance than $M_2G_1\rho_1D_1$ and $M_2G_3\rho_1D_1$ slabs. The fatigue performance of $M_2G_2\rho_1D_2$ slab is found to be 1.85 times higher than $M_2G_2\rho_1D_1$ slab. Also, by increasing the grade of concrete from 20 N/mm$^2$ to 30 N/mm$^2$, the fatigue performance of similar type of slabs increases by 1.33 times. It is also noted that the magnitude of damage accumulated to the slab reinforced with steel reinforcements is higher than GFRP reinforced ones. Among all the GFRP reinforced slabs, sand coated GFRP reinforced slabs exhibits the lowest residual deflection and the greatest stiffness. Sand coated GFRP reinforced slabs proved its excellent fatigue performance over the slabs reinforced with other types of reinforcements. Under the variable amplitude scheme of loading, the load was applied at different loading steps by choosing a constant minimum and varying maximum loads and each load steps are repeatedly applied for about ten thousand times. It is observed that most of the slabs exhibited equal or nearer values of ultimate deflection and crack width that have been experienced in the slabs subjected to static loading. The test results (residual and ultimate deflections and crack widths) are lesser than the results obtained from the constant amplitude scheme of loading. The experimental results of the constant and variable amplitude repeated loadings are shown in Table. 4, 5 and 6. S-N curves are drawn for constant amplitude loadings and are depicted in Figure 16. From the fatigue test results, it is found that GFRP reinforced concrete slabs have failed at 60-75% of the static ultimate load. The equation regarding the relation between the operational stresses and the number of cycles is shown as follows.
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings
Sivagamasundari. R, Kumaran. G

\[ Y = B \cdot \ln N + A \] (1)

where, A and B are experimental constants derived from the test values, \( Y \) operational stress applied, \( N \) is the fatigue life of slabs in terms of number of load cycles. From the above study, the relation between fatigue strength (which is the percentage ratio of fatigue loading and static ultimate loading) and fatigue life are depicted in Fig. 7. Eqn. 2 is obtained from the regression analysis.

\[ S = -15.788 \ln(N_f) + 246.13 \] (2)

where (\( R^2 = 0.783 \))

5.3 Crack growths and modes of failure

Cracks appear at the bottom surfaces of concrete slabs whenever the tensile stresses exceed the modulus of rupture of concrete. The first crack appears at the middle of the slab and develops slowly across the width of the slab. The second crack forms at the right support of the slab and subsequently at the left support of the slab. Further development of cracks occurs, on increasing the application of load under static type of loading and on increasing the number of load cycles under the fatigue type of loading at constant amplitude and variable amplitude. All the slabs experience flexural type of failure. At ultimate load GFRP reinforced slabs experience concrete crushing followed by the rupture of GFRP reinforcements. Steel reinforced slabs show the flexural type of failure by the yielding of steel which is then followed by crushing of concrete. The ultimate load carrying capacity of GFRP reinforced slabs is increased and the corresponding deflections, strains and crack width are reduced by increasing the thickness, grade of concrete, reinforcement ratio of the slabs. GFRP reinforced concrete slabs experience better performance and longer fatigue life when compared with those slabs reinforced with steel. This is mainly attributed due to the equal values of the modulus of elasticity for GFRP reinforcements and concrete in addition to the linear-elastic behaviour of GFRP reinforcements. From the experimental results it is observed that sand coated GFRP reinforced slabs have showed better fatigue performance than the other reinforced slabs.

5.4 Finite element analysis observations

Based on Finite Element Analytical study, it is observed that the effect of tension stiffening and mesh size of the element are almost identical and agreeable very well with the experimental results. But in contrast, the solution without the effect of mesh size of the element significantly overestimates the slab deflection.
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R, Kumaran. G

The results of the latter case reveal that the crack band width extends over the entire element and model becomes much more flexible than the real structure. In order to improve the accuracy of the results, a much finer mesh is tried out. It has also been observed that neglect of the effect of strain softening of concrete results in lesser deflection consequently higher stiffness than the actual slab. Figure 19 compares the analytical load-deflection relation with the experimental data. It is found that the predictions of the proposed model are in good accordance with the experimental data.

Figure 6: Load Vs Deflection for 100mm thick slab reinforced with different types of Reinforcements

Figure 7: Load Vs Deflection for 100mm thick slabs reinforced with g2 type of GFRP reinforcements having three different reinforcement ratios
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R, Kumaran. G

Figure 8: Comparison of slabs reinforced with g2 type of reinforcements having different parameters like grade of concrete and depth of slab

Figure 9: Comparison of moment and curvature values of 100mm and 120 mm thick g1 and Fe 415 (S) reinforced slabs
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R, Kumaran. G

Figure 10: Comparison of experimental and theoretical load and deflection values of 100 mm thick g1 and Fe 415(S) reinforced slabs

Figure 11: Comparison of experimental and theoretical load and deflection values of 120mm thick g1 and Fe 415(S) reinforced slabs
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R, Kumaran. G

Figure 12: Comparison of the effect of moment (static loading) on crack width for 100mm and 120mm thick slabs

Figure 13: Constant amplitude fatigue loading pattern
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R, Kumaran. G

Figure 14: Deflection of slabs due to constant amplitude repeated loading

Figure 15: Deflection of slabs due to constant amplitude repeated loading
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R, Kumaran. G

Figure 16: Deflection of slabs due to constant amplitude repeated loading

Figure 17: Development of crack width with the number of load cycles on various parametric slabs
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari, R, Kumaran, G

Figure 18: Graph showing the strains at different levels while loading statically for 100 mm thick g1 and Fe415(S) reinforced slabs

Figure 19: Graph showing the strains at different levels while loading statically for 120mm thick g1 and Fe415 (S) reinforced slabs
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R, Kumaran. G

**Figure 20:** Bar chart showing the Comparison of 100mm thick slabs having different parameters when subjected to repeated loading

**Figure 21:** S-N curve (A Regression Analysis)
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings
Sivagamasundari, R, Kumaran, G

5.5 Conclusions

A total number of thirty eight one-way concrete slabs, (out of which eleven are reinforced with conventional steel reinforcements and twenty nine are reinforced with Glass Fibre Reinforced Polymer (GFRP) reinforcements) are studied. A rigorous analytical and experimental studies on the behaviour of conventional and GFRP reinforced concrete one way slab under static and repeated loading are investigated by considering reinforcement
ratios, grade of concrete, thickness of slab and type of GFRP reinforcements. GFRP slabs are investigated for static and repeated loading (with constant and viable amplitude loading). Finite element analysis is also performed to study the effect of different parameters on the flexural capacity of slabs. All the slabs experience flexural type of failure. At ultimate load, GFRP reinforced slabs experience concrete crushing followed by the rupture of GFRP reinforcements. As the ultimate load carrying capacity of GFRP reinforced slabs is increased, the corresponding deflections, strains and crack width are reduced by increasing the thickness, grade of concrete, reinforcement ratio of the slabs. GFRP reinforced concrete slabs experiences better performance under repeated loading than those slabs reinforced with steel. It is due to the fact that the onset of permanent deformations is delayed due to the higher strains in the GFRP specimens than the conventionally reinforced slabs. This is mainly attributed due to the equal values of the modulus of elasticity for GFRP reinforcements and concrete in addition to the linear-elastic behaviour of GFRP reinforcements. From the experimental results it is observed that sand coated GFRP reinforced slabs have shown better fatigue performance than the other reinforced slabs. Based on this study, it is found that a good agreement exists between the analytical and experimental results.

6. References

1. Edward G.Nawy., and Gary, E.Neuwerth (1977), ‘Fibre glass Reinforced Concrete Slabs and Beams’, Journal of Structural Division, 103, pp 421-439.

2. Benmokrane, B. Challal, O and Masmoudi, R (1995), ‘Flexural response of concrete beams reinforced with FRP reinforcing bars’, ACI Materials Journals, 91(2), pp 345-355.

3. ACI Committee 440, (1996), State-Of-The-Art Report on Fiber Reinforced Plastic (FRP) reinforcements for concrete structures.

4. Craig R.Michaluk., Sami H.Rizkalla., Gamil Tadros and Brahim Benmokrane (1998), ‘Flexural behavior of one-way concrete slabs reinforced by Fibre reinforced plastic reinforcements’, ACI Structural Journals, 95(3), pp 353-364.

5. Michale Theriault and Brahim Benmokrane (1998), ‘Effects of FRP reinforcement ratio and concrete strength on flexural behavior of concrete beams’, Journal of composites for construction, 2(1), pp 7-16.

6. Lawrence C.Bank, Moshe Puterman and Amnon katz (1998), ‘The effect of material degradation on bond properties of Fibre reinforced plastic reinforcing bars in concrete’,ACI Material Journal, 95(3), pp 232-242.

7. Amnon Katz, Neta Berman and Lawrence C. Bank (1999), ‘Effect of High Temperature on Bond strength of FRP Rebars’, Journal of composites for construction, 3(2), pp 73-81.

8. Francesco Focacci, Antonio Nanni and Charles E. Bakis (2000), ‘Local Bond –Slip Relationship for FRP reinforcement in concrete’, Journal of composites for construction, 4(1), pp.24-31.
Experimental study on the behaviour of concrete one way slabs reinforced with GFRP reinforcements under constant and variable amplitude repeated loadings

Sivagamasundari. R., Kumaran. G

9. Amnon Katz (2000), ‘Bond to concrete of FRP Rebars after Cyclic loading’, Journal of composites for construction, 4(3), pp 137-144.

10. Roman Okelo. A.M, and Robert L.Yuan, P.E (2005), ‘Bond strength of Fibre reinforced polymer rebars in normal strength concrete’, Journal of composites for construction, 9(3), pp 203-213.

11. Reda Adimi, A.Habib Rahman and Brahim Benmokrane (2000), ‘New method for testing Fibre reinforced Polymer Rods under fatigue’, Journal of composites for construction, 4(4), pp 206-213.

12. Ombres.L.T., Alkhrdaji, and A.Nanni (2000), ‘Flexural analysis of one way concrete slabs reinforced with GFRP rebars’, International conference on composite materials, Proceedings of Int. Conference on Advancing with composites 2000, Italy, pp 243-250.

13. Sobhy Masoud, Khaled Soudki and Tim Topper (2001), ‘CFRP strengthened and corroded RC beams under Monotonic and Fatigue Loads’, Journal of composites for construction, 5(4) , pp 228-235.

14. Ganesh Thiagrajan. A.M, (2003), ‘Experimental and analytical behaviour of carbon fiber based rods as flexural reinforcement’, Journal of composites for construction, ASCE, 7(1), pp 64-72.

15. A.J.M.Ferreira, P.P.camacho, Marques, A.T. Fenandes, A.A (2001), ‘Modelling of concrete beams reinforce with FRP rebars’, Journal of composite structures, 53, pp 107-116.

16. Kae-Hwan Kwak and Jong-Gun Park (2001), ‘Shear-fatigue behavior of high-strength reinforced concrete beams under repeated loading’, Journal of Structural engineering and Mechanics, 2(3), pp 213-231.

17. Joseph R.Yost, Shawn P.Gross, and David W.Dinehar (2001), ‘Shear strength of normal strength concrete beams reinforced with deformed GFRP bars’, Journal of composites for construction, 5(4), pp 268-275.

18. G.Kumaran, D. Menon, and K. Krishnan Nair (2002), ‘Evaluation of dynamic load on railtrack sleepers based on vehicle-track modelling and analysis’, International Journal of Structural Stability & Dynamics, 2(3), pp 355-374.

19. G.Kumaran, D. Menon, and K. Krishnan Nair (2003), ‘Dynamic Studies of Railtrack Sleepers in a Track Structure’, Journal of Sound and Vibration, 268, pp 485-501.

20. G.N.Vijayaprakash, R.Sivagamasundari, and G.Kumaran (2004), ‘Flexural Behaviour of one-way Concrete slabs Reinforced with Non-metallic Fibre based Reinforcement’, M.E thesis, Department of Civil & Structural Engineering, Annamalai university, India.

21. M.A.Rashid, M.A. Mansor and P.Paramasivam (2005), ‘Behaviour of Aramid Fiber Reinforced polymer reinforced high strength concrete beams under bending’, Journal of composites for construction, 9(2), pp117-127.

International Journal of Civil and Structural Engineering
Volume 2 Issue 2 2011
22. Amir El-Ragaby, Ehab El-Salkawy and Brahim Benmokrane (2007), ‘Fatigue analysis of Concrete Bridge Deck Slabs reinforced with E-Glass/Vinyl Ester FRP Reinforcing bars,’ Journal of composite structures, 11(3), pp 258-268.

23. R.Sivagamasundari and G.Kumaran (2007), ‘A critical study on the suitability of glass fibre reinforced polymer reinforcements for concrete one way slabs’, Proceedings of International conference on Recent Developments in Structural Engineering-RDSE, pp 117-124, India.