Examination at a Material and Structural Level of the Fatigue Life of Beams Strengthened with Mineral or Epoxy Bonded FRPs: The State of the Art

M. Mahal, T. Blanksvärd* and B. Täljsten

Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Luleå SE-971 87, Sweden

(Received: 9 September 2012; Received revised form: 13 May 2013; Accepted: 11 June 2013)

Abstract: This paper presents a state of the art review of different material combinations and applications of mineral-based and epoxy-based bonded Fiber Reinforced Polymers (FRP), used for the strengthening of concrete structures subjected to fatigue loading. In this review, models of the fatigue life at the material and structural level are presented. This study examines the mechanical behavior of the FRP-material, surface bonding behavior and concrete beams strengthened under fatigue loading with different types of FRP-systems. The parameters that are investigated are applied load value, time dependent effects, type of strengthened structures (shear, flexural or combined) and the configuration of sheets or plates. The building codes and researchers' recommendations are also discussed. As a result of this review, the reader will obtains an overview of suitable materials and methods for strengthening structures subjected to fatigue loading by referring to the estimated fatigue life of material and strengthening structures at various applied stress levels.

Key words: fatigue, reinforced concrete, bonding, fiber reinforced polymer, textile, mineral-based composites.

1. INTRODUCTION

With increased loads and traffic flows on highways and across bridges, it is not only the load carrying capacity that is of real concern but also the fatigue life of the structures. Fatigue can be defined as irreversible internal structural changes to a material when exposed to repeated loading. These changes occur due to initial microcracks that grow to macroscopic size and finally result in failure of the material. Two examples of systems for prolonging the fatigue life of concrete structures are: 1) mineral-based bonding system, where a fiber component is embedded into a mineral-based binder and then bonded to strengthen an existing concrete structure (Täljsten 2006) and 2) epoxy-based bonding systems, where an epoxy is used as an adhesive to bond a fiber component to an existing concrete structure. Previous literature reviews (Harries 2005; Diab and Wu 2008; Kim and Heffernan 2008) focused on the effectiveness of the epoxy-based method in enhancing the fatigue life of structures. The first section of this state-of-the-art paper describes the definition and behavior of both mineral-based and epoxy-based strengthening systems under fatigue loading, at the material, bonding surface and structural levels (see Figure 1). At the material level, the models and behavior of raw materials used in the strengthening of structures such as FRP reinforcement (textile, grids, dry fibers), matrices and bonding agents are also discussed. At the structural level, anchorage tests to concrete prisms and concrete beams strengthened with different strengthening configurations from various researchers are presented.

The second section of this paper includes the description of the behavior of common FRP-materials that have been used to strengthen concrete structures. In section three, the fatigue life models for these materials

*Corresponding author. Email address: thomas.blanksvard@ltu.se; Fax: 0920-491399; Tel: +46920-491642.
Associate Editor: J.G. Dai.

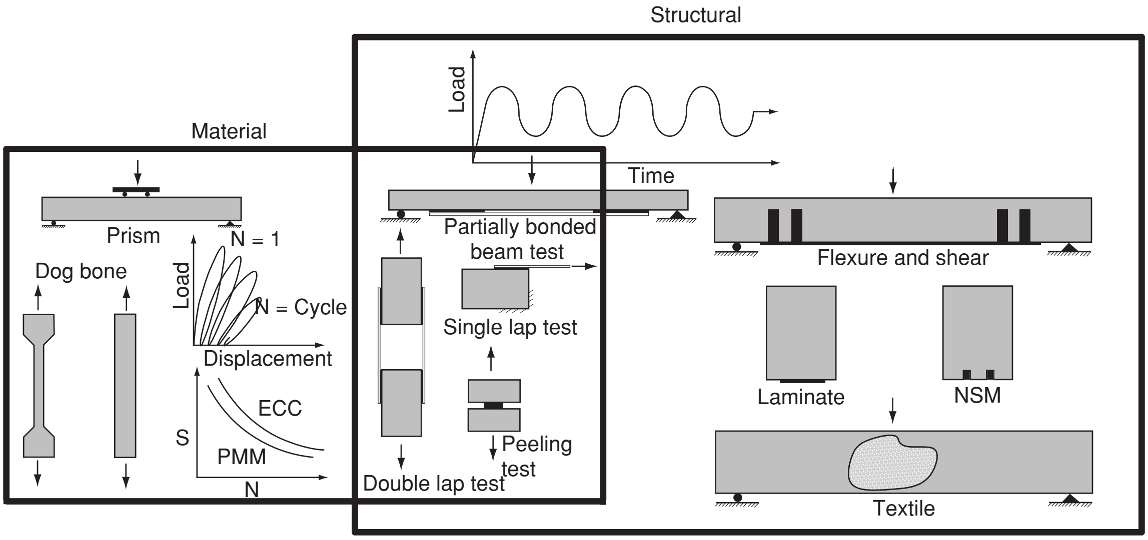

Figure 1. From the material to the structural level

either based on the regression analysis of the available data or taken from literature are presented. The fatigue life model is used mainly to predict the life of a material or structural component at specific fatigue stresses. The bond behavior and model of both the epoxy-based and the mineral-based methods are presented in section four. In section five, the description of fatigue behavior and models moves from the materials level to the structural level. Finally, the building codes and other researchers' recommendations related to strengthening structures are presented in section six.

This state-of-the-art review contributes to the selection of the most suitable materials and methods for strengthening concrete structures under fatigue loading and to identify the current research and building codes needs that are required in this field.

2. MATERIAL BEHAVIOR UNDER FATIGUE LOADING

2.1. Fiber Reinforced Polymer

Fiber Reinforced Polymer (FRP) is defined as a linear elastic composite material that consists of a fiber reinforced polymer matrix. The three common types of fibers used are aramid, glass and carbon, all of which have a higher ultimate strength than normal reinforcing steel. Polyesters and epoxies are often used as the matrix material because they have a higher strain to fracture than the fibers and because they bind to the fibers thus transferring the stresses between them. In addition, the matrix material protects the fibers from mechanical and environmental damage (Jones 1999). FRP has several different configurations including 1) rods that are used as internal reinforcement or for near-surface mounted reinforcement (NSM); 2) composite plates and sheets; 3) FRP grid, which is typically a multidirectional prefabricated composite and 4) impregnated textiles, which provide a variety of textile structures that are used as reinforcement. 1) and 2) are often associated with epoxy-based bonding agents; 3) and 4) are often used together with mineral-based bonding agents. FRP normally has a better fatigue resistance than that of reinforcing steel, in particular when high modulus fibers such as carbon are used; but the fatigue strength of glass fiber composites is lower than steel with a low stress ratio (Badawi 2007). The fatigue failure mechanism of FRP composites is more complex than the failure of plain concrete or steel. Composite materials often show a much greater fatigue life than other homogenous materials (Papakonstantinou *et al.* 2001), where cracks, due to fatigue, format a weak point and continue to grow with each load cycle. Conversely, if the individual fibers within FRP composites develop a defect, this defect does not propagate across the other fibers; thus, the undamaged fibers reduce the number of cracks that grow. Once the FRP composite has been damaged, the damage propagates along the matrix between unidirectional fibers and does not pass through adjacent fibers (Kim and Heffernan 2008). A failure in an FRP composite is a combination of different degradation mechanisms such as matrix cracking, fiber breakage, fiber-matrix debonding and delamination (Adimi *et al.* 2000). When the surface fibers fail under a repeated load, the remaining fibers hold the redistributed load and this behavior repeats until total failure occurs. There are four stages that the FRP composites go through before failure due to fatigue (Ramakrishnan and Jayaraman 1993; Curtis 1989; Newaz 1985; Salvia *et al.* 1997). The first and second stages are matrix cracking combined with interfacial debonding.

The third stage is a delamination between the matrix and the fibers. The final stage is the failure of the remainder of the fibers due to tensile stress. An important behavior of FRP composites is their ineffectiveness under a compression load. The compression load leads to local layer instability and layer buckling that causes failure, perhaps even before resin and interfacial damage within the layers occurs. Because of that, the reversed axial fatigue, or tension-compression loading, is considered the worst type of loading for the FRP composite. For this reason, the most suitable use for FRP composites is to strengthen structures subjected to tension-tension fatigue load. Gorty (1994) showed that the modulus of elasticity of a CFRP rod did not change when the material was subjected to high cyclic loading. Badawi (2007) found that CFRP tendons exhibited good fatigue resistance in the tension-tension fatigue test. Demers (1998) investigated GFRP bars that were subjected to repeated cyclic loading with different stress ratio and frequency; it was found that GFRP bars can withstand a large amount of cyclic loading, exceeding 2 million cycles with maximum-ultimate stress ratio less than 0.5. Aramid fibers, under tension-tension fatigue loading, exhibit excellent behavior more than 2 million cycles in the range of 54 to 73 % of the ultimate tensile strength (Odagiri *et al.* 1997).

2.2. Textile Reinforced Matrix

A textile is anything that is made up of fibers, yarns or fabric. There are mainly two kinds of textile fibers: short chopped fibers and long continuous fibers. Textiles can take several forms such as plates, mats and woven or non-woven fabrics (Brand 2009). The most common form used for strengthening concrete structures is woven textile fiber, which consists of three components: longitudinal strands (warp), transverse strands (fill) and a pure matrix area of fine grain concrete or polymer modified mortar (Harris 2003). The main three types of yarns used in textile are AR (alkali resistant) glass, carbon and aramid. These fibers can be made into filaments or twisted yarns, with the filament yarns being the best for reinforcing since they have little in the way of elongation to their structure (Brameshuber 2006). When strengthening concrete, the textile used must have a stable open structure with a small displacement, a higher modulus of elasticity than the mortar matrix and good adhesion to the mortar (Brameshuber 2006). The density and separation distance of the yarns as well as the angle of wefts in textile reinforcement structures are placed according to the stress acting on the structure and the degree of bonding that is planned with the matrix. Textile Reinforced Matrixes (TRM) are inhomogeneous, anisotropic and their behavior is more complex than FRP composites under fatigue loading. The main reason behind this is that the different types of fatigue damages that can occur are related to the microstructural damage within the impregnated strands and the macroscopic damage within the textile fabric composite, as described by Fuji *et al.* (1993), Takemuraand and Fujii (1994), Hansen (1999), Harris (2003), Cuypers (2001) and Zhu *et al.* (2011). Microcracking in the matrix, fiber-matrix interface debonding and fiber fracture are considered to be part of the microstructural damage mechanism. The macroscopic damage mechanisms are understood to be transverse cracking of the fill, shear failure in the warp, cracking of the pure matrix area, delamination between longitudinal and transverse strands, delamination between adjacent layers and finally tensile failure of the strands. All of these possible damages are shown in Figure 2. Depending on how the above two mechanisms of damage play out, the fatigue damage process can be divided into the following stages. The first stage is the characteristic damage state, where the microstructural damages and transverse cracks in the fill are formed and continue until the cracks have stabilized; the second stage of damage is as hear failure in the warp, with cracking in the pure matrix areas and the start of the delamination and propagation between the fill and the warp and between the layers. In the final stage, all the damage types develop rapidly and, because of the complex nature of woven fabric composites, although damage development is potentially slower, the fibers finally fracture and there is a complete failure. Fujii *et al.* (1993) showed that specimens, consisting of polyester resin forming the matrix and a plain weave glass cloth as reinforcement, under fatigue loading experience a rapid modulus decay at the beginning of the fracture process and then have a gradual modulus decay in the middle stages. Van Paepegem and Degrieck (2001) investigated the fatigue behavior of plain woven glass/epoxy composites and found a gradual stiffness degradation with fatigue. Zhu *et al.* (2011) tested cement-based composites reinforced with three types of fabric [carbon, ARglass and polyethylene (PE)] under high-rate loading conditions. The tests showed that the highest load carrying capacity was achieved by the carbon composite followed by the

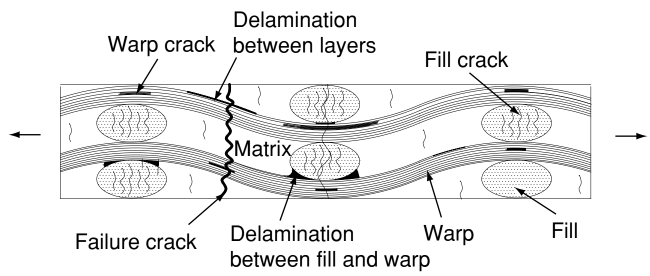

Figure 2. Schematic illustration of various types of fatigue damage in TRM

AR glass composite and lastly, the PE composite. Cuypers (2001) evaluated cyclic stiffness and residual strain of a textile-reinforced matrix consisting of inorganic phosphate cement with E-glass fiber. The results showed that there was a clear loss of stiffness and accumulation of residual strain with extra deflection during the first stage of repeated loading.

2.3. Polymer Modified Mortar

Polymer Modified Mortar (PMM) can be defined as a mortar where the admixture modifies or improves the properties of the mortar, proper ties such as strength, bond strength, adhesion, damage-absorbing deformation nor resistance to environmental effects (Ohama 1998). The polymer modified mortar plays a major part when used as the matrix with grid or textile fibers to strengthen structures (Blanksvärd *et al.* 2009). Different types of polymer modified mortars are available, such as latex-redispersible polymer powder, liquid resin, water-soluble polymer and monomer (Ohama1995). When any of these types are used, it is most important that both the hydrated cement and polymer thoroughly mix to produce a monolithic matrix. Under fatigue loading, the way in which PMM fails can be split into three phases (Suthiwarapirak *et al.* 2002). First, after the initial few applications of the cyclic load, numerous microcracks on the tension surface start that lead to significantly increased damage. Second, microcracks gradually start without forming a macroscopic crack; no visible crack is observed at this stage. It is difficult to see when the first stage of damage moves to the second stage. The microcracks in stage two lead to an almost steady state in the progression of the damage. Finally, large localized cracks appear that rapidly grow until failure occurs. The second stage resists the effects of fatigue loading longer than the first stage. Suthiwarapirak *et al.* (2002) found from their study that the PMM exhibited very brittle behavior under fatigue loading.

2.4. Engineered Cementitious Composite

Engineered Cementitious Composite (ECC) is one of a number of high performance fiber-reinforced cementitious composites (HPFRCC), optimizes the quantity and the properties of the fibers in it and exhibits strain-hardening behavior after yielding (Chun and Matsumoto 2011; Chun and Ohga 2012). The optimization can be achieved through designing the micromechanical interactions between fibers in the cementitious matrix and the interfacial bond between the fibers and the cementitious matrix. ECC is part of a family of materials with adjustable ductility and tensile strength to best match the structures they are used in (Li 2003). Both polyvinyl alcohol fibers (PVA) and the high modulus polyethylene fibers (PE) are used in ECC (Li 2008). In general, ECC exhibits high ductility under fatigue loading and its general behavior shows three phases similar to the previous material (Suthiwarapirak *et al.* 2002; Xu and Liu 2011). However, its behavior under fatigue loading is different from the previously mentioned materials. The first stage starts with a few visible cracks appearing after the first cyclic loading followed by a rapid increase in damage. As the fatigue loading increases, new cracks start that join with existing cracks, leading to a gradual increase in damage and energy dissipation of the fatigue loading. The second stage sees the amount of damage stabilize before the last stage where one crack expands leading to failure of the material.

3. MODELS OF THE FATIGUELIFE OF MATERIALS

The most common way of modeling the effect of applied stress on the fatigue life of a material is the stress-life (*S-N*) approach, also known as Wöhler curves, where *S* is the stress range. These empirical curves give a graphical representation of the fatigue performance under a certain load. Fatigue life models do not take into account the actual degradation mechanisms though, such as matrix cracks, fiber ruptures, delamination and damage progress, but use *S-N* curve diagrams to infer some sort of fatigue failure criteria. In this paper, fatigue models for fiber, textile, polymer modified mortar and epoxy resin are presented. The mathematical symbols used in the models have not been changed from those used in the literature to avoid any confusion. An extensive summary of the fatigue life model and behavior of plain concrete and steel bars can be found in ACI 215-74 (ACI 1997).

3.1. Fiber Reinforced Polymer

A review of the research to date shows that, by considering different factors that affect the fatigue life of FRP composites under fatigue loading, different models for fatigue life result. Some of these models include:

- Stress ratio: several researchers, such as Elkadi and Ellyin (1994), Hwang and Su (2006), Reis *et al.* (2009), Toutanji *et al.* (2006) and Kawai and Suda (2004), have tested the effect of stress ratio (ratio of the minimum stress to the maximum stress) on the fatigue strength of FRP composites. In general, test data showed an increase in fatigue life with increased stress ratios, where the stress amplitude decrease as the stress ratio increased, which cause an increase in the fatigue life. Toutanji *et al.* (2006) defined the relationship between the applied cyclic stress level (*S*), the number of cycles to failure (N) and the stress ratio (R) for carbon fiber sheet as follows:

$$S = \frac{\sigma_{\max}}{f_{fu}} = 1 - \alpha(1 - R)\log(N) \quad (1)$$

where $\sigma_{\max}$ is the maximum applied stress, f_{fu} is the ultimate strength and α is a constant determined experimentally.

- Stress frequency: the fatigue life increases as the stress frequency increases (Hwang and Su 2006). The reason of this behavior, that the maximum strain for the same maximum applied stress is reduced with increased frequency. Where, the time of the strain to reach the maximum strain at lower frequency is decreased due to viscoelastic behaviors of polymer matrix composite. Epaarachchi and Clausen (2003) proposed a model of the relationship between stress ratio, stress frequency, the number of cycles to failure and applied maximum stress:

$$\sigma_u - \sigma_{\max} = \alpha \sigma_u^{1-\gamma} \sigma_{\max}^{\gamma} (1 - R)^{y} \frac{1}{f^{\beta}} (N^{\beta} - 1) \quad (2)$$

where γ and β are material constants and f is frequency (Hz), $\sigma_{\max}$ is the maximum applied stress, σ_u is the ultimate static stress and R is the stress ratio.

- Temperature: polymer matrix composites of viscoelastic materials and their mechanical properties are significantly influenced by temperature. Kawai and Taniguchi (2006) and Jen *et al.* (2008) found the fatigue life deceased with increased temperature. Increasing the temperature change the matrix composite status due to caused reductions in both modulus of elasticity and ultimate strength of matrix, thereby weaken the bond performance of FRPs. Mivehchi and Varvani-Farahani (2010) proposed a model that showed the relationship between S-N and temperature as follows:

$$\sigma_{\max} = A(T_0)\left[1 - \frac{\left(\frac{A(0)}{A(T_0)} - 1\right)}{\text{In}\left(1 - \frac{T_0}{T_m}\right)} \text{In}\left(\frac{\left(1 - \frac{T}{T_m}\right)}{\left(1 - \frac{T_o}{T_m}\right)}\right)\right] (N_f(T))^{m(To)\left[\frac{\text{In}\left(1 - \frac{T}{T_m}\right)}{\text{In}\left(1 - \frac{T_o}{T_m}\right)}\right]} \quad (3)$$

where $\sigma_{\max}$ is the maximum applied stress, $A(T)$ and $m(T)$ are the curve characteristics, T_o is room temperature and T_m is the polymer melting temperature of the composites. T, T_o, and T_m are all in Kelvin.

- Matrix type: the matrix type of FRP has a significant effect on the fatigue life of FRP composites. Where the matrix type affect the ability of composite to resist crack and fiber-matrix debonding Newaz (1985) carried out fatigue tests on two types of composite fiber consisting of the same E-glass fiber with different matrix materials: epoxy matrix [Dow Epoxy Resin (DER) 331] and vinyl ester matrix (Derakane411 – 45) Using this data, the fatigue life models, respectively, are as follows:

$$\frac{S_{\max}}{S_{\text{ult}}} = 0.7557 - 0.10626 \text{ Log } N \quad (4)$$

$$\frac{S_{\max}}{S_{\text{ult}}} = 0.68 - 0.106 \text{ Log } N \quad (5)$$

Papakonstantinou and Balaguru (2007) also showed the effect that the type of matrix has on the fatigue behavior by comparing the results of their tests on carbon fiber with a geopolymer resin matrix (Eqn 6 below) to the results of tests collected by Demers (1998) on anepoxy matrix (Eqn 7 below). Geopolymer resin was prepared by mixing an aqueous solution containing silica and potassium oxide with silica powder. The S-N models were:

$$\frac{S_{\max}}{S_{\text{ult}}} = 1.1055 - 0.046903 \text{ Log } N \quad (6)$$

$$\frac{S_{\max}}{S_{\text{ult}}} = 0.8227 - 0.0519 \, Log N \quad (7)$$

where $S_{\max}$ and S_{ult} are the maximum applied fatigue stress and ultimate static stress respectively.

- Fiber Type: Wu *et al.* (2010) evaluated the effect of fiber type on the fatigue behavior of FRP composite sheets. Experiments were conducted on various types of FRP [carbon(CFRP), E-glass (GFRP) and basalt (BFRP) fibers] and hybrid FRP sheets [carbon/E-glass (C1G1)] with the same epoxy matrix. The results showed that the carbon and polyparaphenylene FRP sheets exhibited, which they have higher tensile modulus of elasticity, superior fatigue resistance, whereas the E-glass and basalt FRP sheets showed similar fatigue behavior. In addition, it was found that the hybrid FRP sheet (C1G1) had slightly improved fatigue behavior, where the fatigue behavior of hybrid FRP depended mainly on the interaction surface of different fibers .The *S-N* relationship for four types was modeled as follows:

$$\frac{P_{max}}{P_{av}} = A - \alpha \text{ Log } N \tag{8}$$

where P_{max} and P_{av} are the maximum applied load and the average of the monotonic load-carrying capacity, respectively. A and α are constants as shown in Table 1.

- Fiber load angle: Hashin and Rotem (1973) and Awerbuch and Hahn (1981) carried out an investigation to evaluate the effect of loading on the fatigue strength of FRP composites using GFRP and CFRP respectively. In these investigations, different loading angles were used. The results indicated that the fatigue life was strongly dependent upon the fiber load angle, where the wider angle gives a lower fatigue life. Based on their data, the fatigue life model for CFRP and GFRP is as follows:

$$S_{max} = A - \alpha \text{ Log } N \tag{9}$$

where S_{max} is the maximum applied stress (MPa). A and α are constants as shown in Table 2 and Table 3.

Table 1. Fatigue constants for the *S-N* model of fiber types and material constants

Fiber type	*A*	α	Tensile modulus (GPa)	Tensile strength (MPa)	Ultimate strain (%)
CFRP	1.001	0.020	230	3400	1.48
GFRP	1.004	0.062	73	1500	2.05
C1G1	1.015	0.069	152	2242	1.48
BFRP	0.997	0.071	91	2100	2.31

Table 2. Fatigue constants for the *S-N* model for CFRP load angle

Fiber angle (Degree)	*A*	α
10^0	427.9	40.1
20^0	191.4	13.2
45^0	89.5	7.3
60^0	57.1	1.4

Table 3. Fatigue constants for the *S-N* model for GFRP load angle

Fiber angle (Degree)	*A*	α
10^0	151.4	9.7
20^0	95.9	9.1
30^0	73.4	7.3
60^0	29.8	1.1

3.2. Textile Reinforced Matrix

Several investigations of the fatigue life of textile fiber, impregnated with epoxy or polyester to act as a matrix, have been carried out (Harris 2003; Curtis and Moore 1987; Van Paepegem and Degrieck 2001). Textile fiber is considered to be part of the FRP family. To date, a model of textile fiber impregnated with cement mortar has not been developed. Cuypers (2001) presented the results from tests of a textile reinforced matrix, consisting of inorganic phosphate cement with E-glass fiber, under fatigue loading, as shown in Figure 3. A horizontal arrow extending from a data point in the plot indicates the specimen had not failed at the indicated number of fatigue cycles. The S-N relationship was modeled as follows:

$$S_{max} = 37.029 - 3.231 \text{ Log } N \tag{10}$$

where S_{max} is the maximum applied stress of the fatigue load.

3.3. Polymer Modified Mortar

The fatigue life models for two types of polymer modified mortar were described by Suthiwarapirak *et al.* (2002). They used a low ratio of fibers (less than 0.5%) which did not improve the tensile properties of the mortar. The first type, which consisted of cement, fine aggregate, lightweight aggregate and a low ratio of acrylic polymer fibers, was modeled as follows:

$$\frac{S_{max}}{S_{ult}} = 1.001 - 0.067 \text{ Log } N \tag{11}$$

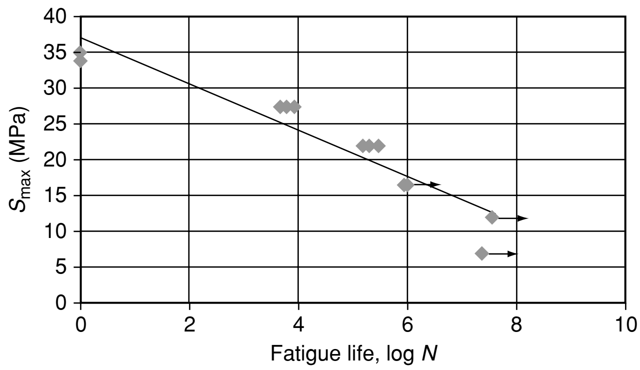

Figure 3. *S-N* curve for the textile reinforced matrix

The second type of polymer modified mortar consisted of cement, fine aggregate, SBR polymer and also a small amount of polyvinyl alcohol fibers; it was modeled as follows:

$$\frac{S_{max}}{S_{ult}} = 0.928 - 0.0808 \text{ Log } N \qquad (12)$$

where S_{max} and S_{ult} represent the maximum applied fatigue stress and average ultimate static stress respectively. From the models we can see that the type one have higher fatigue life than the second type due to presence light weight aggregates which make it behave more ductile under fatigue load.

3.4. Engineering Cementitious Material

The models of the *S-N* relationships for two types of ECCs containing polyvinyl alcohol (PVA) and polyethylene (PE) fibers were proposed by Suthiwarapirak *et al.* (2004); the models describe a bilinear fatigue stress-life line as follows:

- ECC with polyvinyl alcohol

$$\frac{S_{max}}{S_{ult}} = 1.00 - 0.0226 \text{ Log } N \quad 1 \le N \le 1 \times 10^4 \qquad (13)$$

$$\frac{S_{max}}{S_{ult}} = 1.595 - 0.1750 \text{ Log } N \quad 1 \times 10^4 \le N < 2 \times 10^6 \qquad (14)$$

- ECC with polyethylene

$$\frac{S_{max}}{S_{ult}} = 1.00 - 0.032 \text{ Log } N \quad 1 \le N < 3 \times 10^2 \qquad (15)$$

$$\frac{S_{max}}{S_{ult}} = 1.157 - 0.0903 \text{ Log } N \quad 3 \times 10^2 \le N < 2 \times 10^6 \qquad (16)$$

where S_{max} and S_{ult} represent the maximum applied fatigue stress and average ultimate static stress respectively. The reason behind that the ECC with polyvinyl alcohol have higher fatigue life than ECC with polyethylene is the behavior of fibre in post cracking stage.

3.5. Epoxy Resin

The literature study identified different types of fatigue test in epoxy resin: cyclic bending fatigue (Nagasawa *et al.*1995), uniaxial cyclic fatigue (Tao and Xia 2007) and shear cyclic fatigue (Tao and Xia 2008). Tao and Xia (2007) proposed that the relationship between stress amplitude and fatigue life using a uniaxial cyclic fatigue test for epoxy resin with a modulus of elasticity 2900 MPa was as follows:

$$S_{max} = 192.6\, N^{-0.362} + 35 \qquad (17)$$

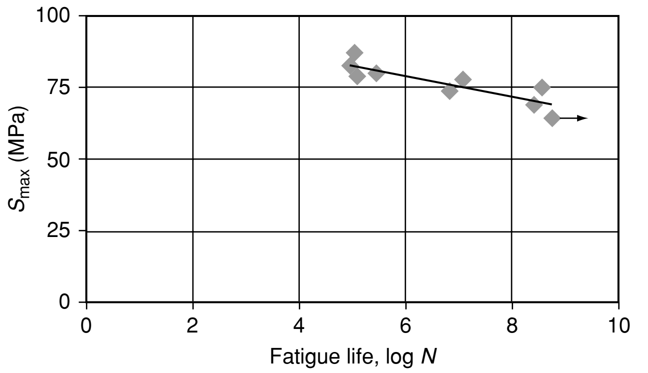

Figure 4. *S-N* curve for epoxy resin material

The model proposed from the cyclic bending fatigue test data with tensile strength (82.1 MPa), presented by Nagasawa *et al.* (1995), as shown in Figure 4 is as follows:

$$S_{max} = 100.54 - 3.6228 \text{ Log } N \qquad (18)$$

where S_{max} is the maximum applied fatigue stress .We can see that the epoxy resin have very high fatigue stress which make it more suitable as bonding material for different strengthening purposes under different load values.

4. BOND

The most significant effect on the behavior of a strengthened structure is the bond between that structure and the strengthening material. The bond determines the failure behavior of the structure: a strong bond can lead to the brittle failure of the structure whereas a weak bond can lead to ductile failure. The bond performance is determined by the strength of the adhesives used and the tensile strength of concrete. The bonding can be classified as an epoxy-based method, which uses epoxy resin as a binder and a mineral-based method, which uses fine grade mineral as a binder.

4.1. Epoxy Bonded System

The properties of epoxy resin are mainly dependent on the hardener used, the choice of which depends on the properties required for the specific application (Täljsten 2006). The mechanical behavior of epoxy material is analogous to brittle material under cyclic loading and passes through three stages (Nagasawa *et al.* 1995; Tao and Xia 2007). The first stage sees the start of microcracking, which continues through the whole of the low stress amplitude fatigue life cycle, causing no damage to the material itself until a fracture is imminent. Throughout this stage, there is a linear relationship between stress and strain. The strength of bonded joints not only depends on the cohesive strength of the adhesive (Neil *et al*. 2007) but also on the degree of adhesion to the bonding surface (Täljsten 2006) and the type of FRP being used (Ko and Sato 2007). For these reasons, the fatigue life of epoxy material is not representative of the fatigue life of the whole epoxy bond system even if the failure is only in the epoxy layer. The different test methods used to evaluate the bond behavior of externally-bonded FRP composite sheets and plates under fatigue loading include the single shear (single lap joint) test (Bizindavyi *et al*. 2003; Mazzotti and Savoia 2009), the double lap joint test (Ferrier *et al*. 2005), the pull-out specimen method for measuring peeling stresses (Khan *et al*. 2011) and the partially bonded beam test (Gheorghiu *et al*. 2004) as shown schematically in Figure 1. The single lap joint test gives inaccurate results because it creates undesirable flexural loading. From experiments conducted (Dai *et al*. 2005; Bizindavyi *et al*. 2003; Yun *et al*. 2008; Nigro *et al*. 2011; Diab *et al*. 2007; Ko and Sato 2007), it can be seen that the local slip of FRP-concrete joints increases gradually with cyclic loading. The general behavior is similar to monotonic load behavior except for the rate of change of debonding propagation. The rate of change of slip slope increased with increasing stress amplitude (Dai *et al*. 2005; Bizindavyi *et al*. 2003; Yun *et al*. 2008).There are different types of failure caused by debonding: debonding between the epoxy resin and the epoxy primer, debonding into the coarse aggregate (split of concrete cover) and debonding between the plies for joints with more than one plies (Bizindavyi *et al*. 2003). Ferrier *et al*. (2005) showed that the lap joint that used the epoxy with a higher glass transition temperature behaved the best under fatigue loading. In their tests, Ferrier *et al*. (2005) used three types of epoxy with different glass transition temperatures: type A (46 °C), type B (55 °C) and type C (80°C). Dai *et al*. (2005) and Bizindavyi *et al*. (2003) showed that an increase in bond length under cyclic fatigue loading led to an increase in fatigue life unlike under static loading, where an increase of length beyond the effective length made no difference. Nigro *et al*. (2011) found that under cyclic loading with 70% of the maximum debonding static load, the fatigue loading was negligible even when the bond length was less than the effective bond length by 50% for carbon sheet and plates. Diab *et al*. (2007) showed that the fatigue endurance limit (2 million cycles) is reached when the stress level is below 30% of the maximum debonding static load.

CFRP and GFRP are well-known types of fiber used for strengthening concrete structures. In order to produce fatigue life models for bonding FRP-concrete joints only showing the effect of fiber type, data have been collected from existing literature as shown in Table 4 and Figure 5 [carbon fibers (marked with filled shapes) and glass fibers (marked with unfilled shapes)]. The fatigue life models of CFRP and GFRP can be estimated from this data and can be predicted from the following equations respectively:

$$S_{max} = 1.4926 - 0.1428 \text{ Log } N \quad (19)$$

$$S_{max} = 1.9321 - 0.212 \text{ Log } N \quad (20)$$

where S_{max} is the maximum applied average bond stress.

Table 4. Summary of available material data and test setup

Reference	Lap type test	Compressive concrete strength (MPa)	FRP Modulus of elasticity (GPa)	FRP Tensile strength (MPa)
Diab et al. (2009)	Double	32	240	3500
Bizindavyi *et al*. (2003) - CFRP	Single	42.5	75.7	1014
GFRP	Single		29.2	472
Ferrier *et al*. (2005) Type A	Double	NA	70	340
Type B	Single and double		75	885
Type C	Double		88	1000
Diab *et al*. (2007)	Double	32	240	3500

NA = not available

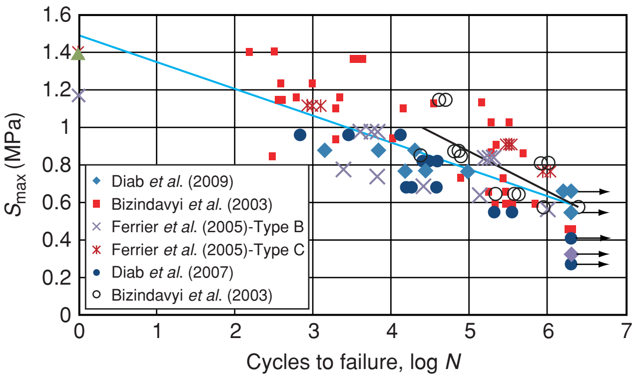

Figure 5. *S-N* curve for bonds of CFRP and GFRP to concrete

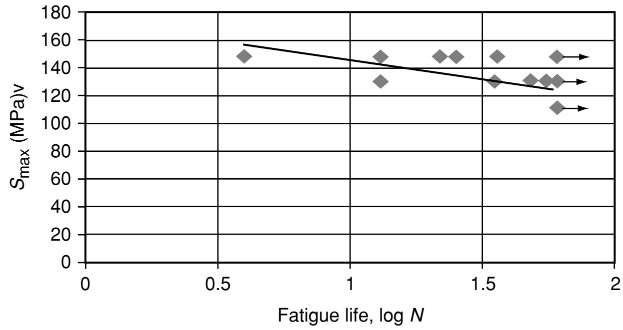

Figure 7. *S-N* curve of alkali-resistant glass reinforced matrix

It can be seen in Figure 5 that the CFRP results show improved *S-N* behavior when compared to GFRP. This improvement is represented by a reduction in the slope of the *S-N* curve. The shallow slope means that a small reduction in stress gives a greater increase in fatigue life.

4.2. Mineral Bonded System

There are two types of strengthening systems using mineral-based bonding agents: the ECC overlay system and the mortar impregnated with textile fibers or grid fibers system. There have been few studies investigating bonding using the mineral-based method under fatigue loading. Zhang and Li (2002) investigated the effect of surface bonding on the fatigue performance of the ECC overlay system using a flexural test. The result showed that the layer–based interface characteristics, rough or smooth, do not influence the fatigue life. The *S-N* model of the results as shown in Figure 6 is as follows:

$$S_{max} = 12.251 - 0.6202 \text{ Log } N \tag{21}$$

where S_{max} is the maximum flexural stress applied.

In the second system, the bonding failure can theoretically be classified as either being a micro or macro level failure. Besides the debonding between the yarns and mortar, the debonding between the outer and inner filaments of the yarns, which form the main components of textile fabrics (Brameshuber 2006), can be considered to be a micro level debonding failure. There are different types of macro level bonding failure: debonding between composites of the textile and the matrix with the concrete substrate, delamination of the matrix at the textile layer, delamination between the layers of textile if more than one layer is used in the matrix, delamination in the concrete substrate and finally fiber-pullout in the mortar matrix layer (Brameshuber 2006).

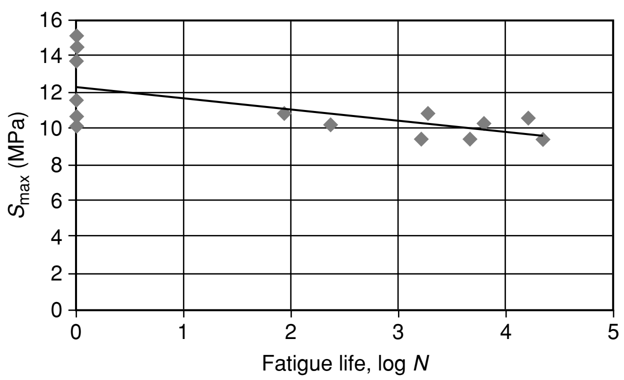

Figure 6. *S-N* curve for bonds using the ECC overlay system

At the micro level, Kang and Brameshuber (2006) investigated the bond behavior under a cyclic load at three different stress levels. The textile reinforcement was made of alkali-resistant glass embedded in a fine-grained concrete matrix, which consisted of two symmetric parts separated by a very thin baffle. Further details about the test and materials data can be found in Kang and Brameshuber (2006). The results showed that the stress levels produced by the cyclic load were indicative of the rate of damage accumulation and the failure of the specimens. The *S-N* relationships from these tests are shown in the Figure 7; the model is:

$$S_{max} = 172.98 - 27.431 \text{ Log } N \tag{22}$$

where S_{max} is the maximum applied stress of the fatigue load.

To date, to the author's knowledge, there has been no study that investigates the behavior of macro level bonding under fatigue loading.

5. STRENTHENED BEAM BEHAVIOR UNDER FATIGUE LOADING

5.1. Epoxy Bonded System

Several studies have been carried out on the effects of fatigue on structures strengthened with FRP bonded using the epoxy-based method. These studies investigated fatigue using different material types (e.g. fibers), different applied load values, time dependent effects (e.g. temperature, relative humidity, freeze and thaw), different types of strengthened structures (shear, flexural or combined) and different configurations of sheet or plate. In order to evaluate the fatigue performance of beams strengthened with externally bonded FRP laminate, this section presents the test results of beams subjected to fatigue loading under different conditions, drawn from the literature. Among them, Yu *et al.* (2011) carried out fatigue testing of RC beams strengthened with GFRP sheet and this study showed that GFRP sheets reduce the stress in reinforcing steel and increase the fatigue life of a strengthened beam under fatigue loading. IN addition, the fatigue failure of strengthened beams with GFRP are similar to the beams strengthened with CFRP. The fatigue behavior of flexurally strengthened concrete beams with near surface mounted (NSM) CFRP was investigated by Yost *et al.* (2007). The results appeared to show that the bond action between NSM CFRP and the concrete was not affected by fatigue loading. The response of CFRP-strengthened beams under fatigue loading with different load amplitudes were studied by Gheorghiu *et al.* (2007). The results showed that the higher fatigue amplitude significantly increased the cracking strain of the CFRP-concrete joint. The fatigue performance of RC beams shear strengthened with CFRP fabrics was investigated by Chaallal *et al.* (2010), who discovered that the fatigue life of two layers of CFRP was lower than that of one layer, where the greater rigidity of FRP (two layer) changed the stress distribution in concrete causing crush of concrete rather than yielding of steel stirrups. Ekenel and Myers (2009) exposed test beams to severe environments and defects caused by delamination in order to study the durability of RC beams strengthened with CFRP. By using cycles of continuous freeze and thaw, prolonged exposure to extreme temperatures, continuous relative humidity cycles and ultraviolet light, they showed that fatigue loads combined with harsh environmental conditions significantly affected the flexural stiffness of the beams as a result of environmental effect on bond strength of the adhesive. Gussenhoven and Breña (2005) discovered that wider laminates are more effective than narrower laminates atincreasing the fatigue life of strengthened beams, due to that the wider laminates reduce shear lag effects and are also able to restrain crack opening more than narrower laminates. Al-Rousan and Issa (2011) studied the effect of using different CFRP sheet configurations, different numbers of CFRP layers, a differing CFRP contact area with the concrete, a variety of frequencies and number of fatigue cycles, varying stress ranges and severe salt-water exposure on flexural beams strengthened with CFRP. The results showed that the stress ranges have a noticeable effect on fatigue life. Furthermore, the frequency of the fatigue loading did not significantly affect the strengthened beam in the range of 1 – 4 Hz. This conclusion help to accelerate the fatigue test by increase the frequency within this limit, whilst the fatigue life increased with increasing numbers of CFRP layers and greater contact area due to more release of the stresses in the tension steel bar. Barnes and Mays (1999) carried out experimental work to study the effects of different types of load on fatigue behavior. When they applied the same stress range in the rebar for both the strengthened and the unstrengthened beams, they found that the fatigue life of the strengthened beams was higher than that of the unstrengthened beams. Conversely, they found that when applying an equal percentage of the ultimate static load capacity to each beam, the fatigue life of the plated beam was shorter than that of the unplated beam. The reason for this is that, the ultimate load for strengthened beam was much higher than from unplated beam and thereby the same percentage of ultimate load gave a high stress range in tension steel bars of plated beam. Masoud *et al.* (2001) showed that the fatigue life of a corroded beam improved using transverse CFRP wrapping and flexural sheet causing reduction of stress level in the corroded tension steel bars. Khan *et al.* (2011) found from their study that shear end anchorages enhanced the fatigue performance of flexurally strengthened RC beams. The arguments for this behavior is that the end anchorage reduce the high interfacial shear and peeling stresses at the point of plate cut-off, which cause debonding of CFRP laminate. Huang *et al.* (2011) studied the effect of temperature on the fatigue behavior of strengthened beams. The results showed that the fatigue life decreased with increased temperature, where the failure modes of strengthened beams changed from steel yielding to interface debonding of laminate. Senthilnath *et al.* (2001) showed that when the delamination exceeded the worst case delamination as recommended by ACI, there was minimal effect on the fatigue performance of the CFRP strengthened RC beams. Minnaugh and Harries (2009) discussed the fatigue behavior of RC beams strengthened with steel fiber reinforced polymer (SFRP) and CFRP and suggested that SFRP largely improved the fatigue behavior of RC beams and superior compared with CFRP, where no evidence of debonding for the (relatively high) stress ranges. Derkowski (2006) tested beams under fatigue loading with two flexural strengthening systems on the bottom of the beam, with the system consisting of one or two CFRP strips. The results showed that the fatigue life of beams strengthened with two strips was greater than when using one strip because two strip have more efficient to restrain cracks opening. Wang *et al.* (2007) discovered that an FRP strengthened T-beam exhibited excellent behavior under fatigue loading when using hybrid FRP, consisting of CFRP plates for flexure and a GFRP U-strip for shear. Harries *et al.* (2007) studied the effect of adhesive stiffness; the results showed that the generated stress in tensile steel under fatigue loading was greater with more flexible adhesive due to reduce ability of the adhesive to transfer stress to the strengthening material.

From most of the studies (Harries *et al.* 2007; Toutanji *et al.* 2006; Barnes and Mays 1999; Shahawy and Beitelman 1999; Papakonstantinou *et al.* 2001; Aidoo *et al.* 2004; Masoud *et al.* 2001; Dong *et al.* 2011), the general behavior of beams strengthened with FRP is that there is an initial change in stiffness and increase of deflection due to a redistribution of the cracks in the beams. This is then followed by unchanging stiffness with increasing deflection due to the cyclic creep, the time evolution of the plastic strain under cyclic load, of the concrete as explained by Papakonstantinou *et al.* (2001). Finally, there is a sudden increase of deflection just before the failure. The behavior of strengthened beams under fatigue loading depends mainly on the maximum stress generated in the main tension reinforcement, the bond strength between the FRP and the concrete as well as the configuration of the FRP. If the bonding strength between the concrete and the FRP is sufficient, the initial failure will be due to steel rupture, followed by rupture of the FRP or debonding from the concrete substrate or delamination of the concrete cover caused by flexural-shear cracking. FRP debonding rarely occurs because both the tensile strength and the shear strength of epoxy adhesive are twice as great as those of the concrete cover (Derkowski 2006). If the bonding of the FRP with the concrete substrate is defective, either because of sub-standard workmanship or design problems with the anchorage, any failure due to the debonding of the FRP will, for most cases, cause a steel rebar rupture; the fatigue life will obviously be impaired. Figure 8 shows the *S-N* data for sheet, laminate FRP strengthened beams and NSM strengthened beams from the literature (Barnes and Mays 1999; Breña *et al.* 2005; Dong *et al.* 2011; Heffernan and Eriki 2004; Papakonstantinou *et al.* 2001; Yu *et al.* 2011; Quattlebaum *et al.* 2005; Badawi 2007 and Abdel Wahab 2011). This figure only includes data for rectangular beams to avoid any effects due to beam shape on the *S-N* model. The stress range (S_r) reported is the stress range in the internal reinforcing tension steel at the first cycle. Regression curves for CFRP, GFRP and NSM strengthened beams are also shown in Figure 8 and are

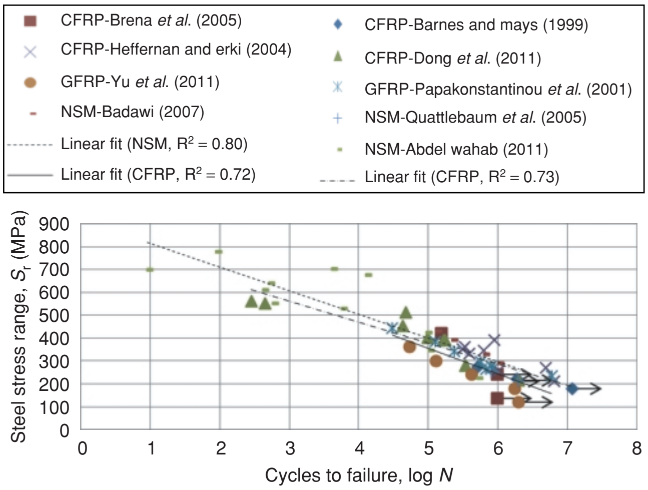

Figure 8. *S-N* curves for FRP laminates, sheets and NSM

modeled with the following equations respectively:

$$S_r = 834.31 - 91.329 \text{ Log } N \tag{23}$$

$$S_r = 913.19 - 111.52 \text{ Log } N \tag{24}$$

$$S_r = 917.81 - 103.64 \text{ Log } N \tag{25}$$

where S_r is the steel stress range in steel.

It can be seen in Figure 8 that the near surface mounted applications have an improved fatigue performance over both the CFRP and the GFRP laminate For a given steel stress range, the NSM strengthened beams appear to have the longest fatigue life with GFRP having the shortest. The strength of FRP and bond of the FRP bar to the concrete plays a major role in the improved fatigue behavior. The bond is responsible for transferring the forces between FRP bar and the surrounding concrete, so that the section acts as one unite with NSM.

5.2. Mineral-Based Method

Mineral-based method is used to avoid some of epoxy adhesive drawbacks like working environment, minimum application temperature, often above 10 °C, and epoxy creating diffusion-closed surfaces which may imply moisture and freeze/thaw problems for concrete structures (Blanksvärd *et al.* 2009). Very little research had been conducted on beams strengthened with mineral material as an adhesive under fatigue loading. Papanicolau *et al.* (2006) experimentally compared the fatigue behavior of beams strengthened with one layer of textile reinforcement with a cementitious binder to beams strengthened with one layer of textile reinforcement with a resin-based matrix. Although the cementitious bonding proved less effective than the resin bonding, if given sufficient shear resistance under fatigue loading, the effectiveness of the cementitious bonding increased with increased numbers of textile layers. The main feature of fatigue behavior of beams strengthened with a textile cementitious matrix compared with an epoxy-based system was the increase in the beam ductility under fatigue loading due to clearly visible cracks in the cementitious mortar matrix. The results of the research by Leung *et al.* (2007) showed that the ECC layer significantly improved the fatigue life of the plain concrete beam, handling large deflection without failure because the ECC controls the growth of fatigue cracks. An inorganic matrix consisting of an aluminosilicate powder blended with a water-based activator was used by Toutanji *et al.* (2006) as a matrix to bond unidirectional carbon fiber fabric to reinforced concrete beams, which were subjected to fatigue loading. The result showed that the fatigue life increased and the behavior of failure was analogous to epoxy-based methods using for strengthening. Steel-reinforced inorganic polymer tapes consisting of steel fiber tapes with a modulus of elasticity of 210 MPa and an inorganic matrix, Geopolymer, were used as flexural strengthening for beams by Katakalos and Papakonstantinou (2009). The results showed that the fatigue life increased and failure was determined by the main steel tension reinforcement and the steel-reinforced inorganic polymer system. The fatigue life model for beams strengthened with steel-reinforced inorganic polymer system was proposed to be:

$$S_r = 624 - 67 \text{ Log } N \tag{26}$$

where S_r is the stress range in steel.

6. BUILDING CODES AND RESEARCHERS RECOMMENDATIONS

Presently, there are no recommendations in the building codes for strengthening structures under fatigue loading using mineral-based methods. Extracted from the different building codes and research literature, the following recommendations deal with epoxy-based methods:

(1) The ACI 440.2R-08 (2008) recommendation to prevent fatigue and creep failure for GFRP, AFRP and CFRP material is to have a total stress to FRP ultimate strength ratio below of 0.2, 0.3 and 0.55 respectively. Diab and Wu (2008), Breña *et al.* (2005) and Harries and Aidoo (2006) considered this recommendation to be inadequate and impossible to achieve. The author's consider this recommendation to be good in order to ensure that the FRP itself does not fail under fatigue load.

(2) The JSCE recommendations (JSCE 2001) recommended a reduction factor of $\mu = 0.7$ on the interfacial fracture energy relatingto the bonding of fiber reinforced polymer sheets to concrete under fatigue loading. Harries and Aidoo (2006) considered this reduction factor too small when compared to the recommended reduction factor for a monotonic load to prevent debonding. In the author's opinion, this recommendation is suitable for high cyclic fatigue, where the load is less than the yield static load of beam.

(3) The Italian design guide CNR-DT200 (NRC 2004) recommended a long-term conversion factor, $\eta = 0.5$, multiplied by a property of FRP composites to prevent possible fatigue failure. However, this does not take into account the stress range of the fatigue loading and the properties of the concrete.

(4) ISIS Canada design manual (ISIS Canada 2008) only recommended a reduction factor to account for the effect of creep on FRP composites without fatigue load.

(5) The model code 2010 (draft) indicated different values of stress range for different types of FRP bar which can be used as reinforcement bars in concrete. These values are unsuitable for NSM application due to a difference in bonding systems.

Kim and Heffernan (2008), as well as Barnes and Mays (1999), recommended, good recommendation, that the conventional method of using unstrengthened reinforced concrete to prevent fatigue failure can be used for FRP-strengthened structures. Ferrier *et al.* (2011) did not take into account the stress range in steel and limited the shear stress between the concrete and CFRP to 0.8 MPa to prevent fatigue failure over 1×10^6 cycles. Yao *et al.* (2006) proposed, to prevent fatigue failure of CFRP, that the ultimate fatigue strength of a carbon fiber laminate strengthened reinforced concrete beam is 0.58 times of its ultimate static loading. Bren˜ a *et al.* (2005) indicated that the maximum composite stress in CFRP laminates is 15 to 25% of the ultimate strength lower than the ACI 440.2R-08 (2008) recommendation. Senthilnath *et al.* (2001) performed fatigue tests on beams with different sizes of delamination and got important results that the maximum delamination area of 16000 mm^2, as recommended by ACI 440.2R-08 (2008), has little effect on the fatigue behavior of strengthened flexural beams.They also considered the lap length of 50 mm to be insufficient for CFRP sheets under fatigue loading as currently recommended for the MBrace composite strengthening system (2002) under a static load. Yang

Table 5. Summary of available material data and test setup

Reference	Tested beam numbers	Beam dimensions (mm)	Load configuration	Compressive concrete strength (MPa)	Steel yield stress (MPa)	FRP Modulus of elasticity (GPa)	FRP Tensile strength (MPa)
arnes and Mays (1999)	3	125 × 230 × 2300	Four-point bending	50	NA	135	1226
Dong *et al*. (2011)	10	152.4 × 304.8 × 2896	Four-point bending	38.2	414	731	960
Brena *et al*. (2005)	3	203 × 356 × 2692	Four-point bending	40	434	227.7	3800
Heffernan and Erki (2004)	6	150 × 300 × 2850	Four-point bending	37	511	233	NA
	3	300 × 574 × 4800		32.9	479	325	NA
Papakonstantinou *et al*. (2001)	8	152.4 × 152.4 × 1220	Third-point bending	39.3	427	72.4	1730
Yu *et al*. (2011)	5	150 × 250 × 2300	Four-point bending	20	335	30.2	643
Quattlebaum *et al*. (2005)	2	152 × 254 × 4572	Third-point bending	29.5	446	154.2	2785
Badawi (2007)	4	152 × 254 × 3300	Four-point bending	40	440	136	1970
Abdel Wahab (2011)	7	150 × 250 × 2000	Four-point bending	60	510	136	1970
	4					130	2166

and Nanni (2002) recommended a lap splice length of 101.6 mm, if the maximum applied stress does not exceed 40% of the ultimate static strength. Diab *et al.* (2007) recommended that the FRP fatigue stress for FRP-strengthened beams should not exceed 30% of the static bond capacity of the FRP-concrete interface. Gunes *et al.* (2006) recommended that a minimum bond anchorage be provided on the end regions of the FRP flexural reinforcement, at a distance equal to the beam depth to ensure improved cyclic load performance. From the above recommendations, we can find complete criteria to design strengthening of beams under fatigue load include important parts, such as bond, FRP and steel.

7. CONCLUSION

This paper has provided an inclusive review of available studies of the fatigue behavior of materials used in external strengthening of concrete structures with FRP; it has also considered beam strengthening using epoxy-based methods or mineral-based methods. The damage to the FRP-concrete interface under fatigue loading was discussed. The existing building codes and recommendations from other researchers, related to the fatigue behavior of FRP-strengthened structures, were also reviewed. From this state of the art review, it is interesting to note that the effectiveness of strengthening material on the fatigue life of beams depended on the bond behavior between the strengthening material and the concrete substrate. Where, enough bond strength between strengthening system and substrate helps to distribute the stress in the member and reduce the stress level generated in the steel reinforcement. Various environmental conditions affected the behavior of FRPs at the material and structural level by affecting the durability of the strengthening material. The mineral-based strengthening method appeared more ductile than the epoxy-based strengthening method under fatigue loading. The epoxy-based FRP NSM technique demonstrated superior fatigue life compared to using plate or sheet bonded strengthening. Most composite materials under fatigue loading went through three different stages: an initial matrix cracking stage, a steady state damage stage and finally a failure stage where the fibers broke. The duration of each stage depended on the matrix and the types of fibers. However, this is different for TRM, where the matrix cracking occurs at the second stage of damage after initial transverse cracks in the fill have appeared. Testing double lap joint under fatigue loading produced more accurate results compared with single lap joint testing, where there was undesirable flexural loading. As ECC exhibits excellent behavior under fatigue loading, it is assumed that ECC, when combined with grid stows of fibers, would be able to be more effective at enhancing the fatigue life of strengthened structures. This study also showed that bonded CFRP joints have better *S-N* behavior than GFRP. Further research should be carried out into the influence of bonding, both between the base concrete and binder along with the transition zone and between binder and fiber composites under fatigue loading. More studies on the effect of FRP laminate thickness and modulus of elasticity on the fatigue behavior of strengthening beam are needed. Further research should also be carried out into the fatigue life of beams strengthened using mineral–based and epoxy-based FRP NSM techniques under different environmental conditions, in order to produce fatigue life models and to find the best conditions in which to use mineral-based strengthening and NSM techniques under fatigue loading. Lap joint tests are needed to construct the fatigue life model of bonding using the mineral-based system at a macro level. Furthermore, fatigue testing is needed to optimize the properties of the mortar, which is used as the binder and matrix in mineral-based strengthening systems. Further studies are needed to find the recommendations to prevent fatigue failure of mineral-based method (maximum stress or strain to FRP ultimate ratio, FRP material properties and properties of bond to the concrete substrate) for both flexural and shear strengthening. Studying the effect of mechanical fasteners of FRP grid in fatigue behavior of mineral-based method are needed together with the suitable lap length of FRP used with mineral materials. More studies are also needed to find fatigue models of textile fiber and FRP grid impregnated with polymer-modified mortar. In addition, comparison studies of different strengthening material (FRP laminates, FRP grid or textile fiber with polymer modified material, ECC) under fatigue load are also needed. The effect of number of layers for FRP grid with mineral based bonding material on the behavior of strengthening beam under fatigue load are also needed.

REFERENCES

Abdel Wahab, N. (2011). *Bond Behaviour of Beams Reinforced with Near Surface Mounted Carbon Fibre Reinforced Polymer Rods under Fatigue Loading*, PhD Thesis, University of Waterloo, Waterloo, Canada.

ACI 215R-74 (1997). *Considerations for Design of Concrete Structures Subjected to Fatigue Loading (ACI 215R-74)*, American Concrete Institute, Farmington Hills, Michigan, USA.

ACI440.2R (2008). *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI440.2R)*, American Concrete Institute, Farmington Hills, Michigan, USA.

Adimi, M.R., Rahman, A.H. and Benmokrane, B. (2000). "New method for testing fiber-reinforced polymer rods under fatigue", *Journal of Composites for Construction,* ASCE, Vol. 4, No. 4, pp. 206–213.

Aidoo, J., Harries, K. and Petrou, M. (2004). "Fatigue behavior of carbon fiber reinforced polymer strengthened reinforced concrete bridge girders", *Journal of Composites for Construction*, ASCE, Vol. 8, No. 6, pp. 501–509.

Al-Rousan, R. and Issa, M. (2011). "Fatigue performance of reinforced concrete beams strengthened with CFRP sheets", *Construction and Building Materials*, Vol. 25, No. 8, pp. 3520–3529.

Awerbuch, J. and Hahn, H. (1981). "Off-axis fatigue of graphite/epoxy composite", *Fatigue of Fibrous Composite Materials,* ASTM STP 723, American Society for Testing and Materials, Philadelphia, USA, pp. 243–273.

Badawi, M. (2007). *Monotonic and Fatigue Flexural Behavior of RC Beams Strengthened with Prestressed NSM CFRP Rods,* PhD Thesis, University of Waterloo, Canada.

Barnes, R. and Mays, G. (1999). "Fatigue performance of concrete beams strengthened with CFRP plates", *Journal of Composites for Construction*, ASCE, Vol. 3, No. 2, pp. 63–72.

Bizindavyi, L., Neale, K. and Erki, M. (2003). "Experimental investigation of bonded fiber reinforced polymer-concrete joints under cyclic loading", *Journal of Composites for Construction*, ASCE, Vol. 7, No. 2, pp. 127–134.

Blanksvärd, T., Täljsten, B. and Carolin, A. (2009). "Shear strengthening of concrete structures with the use of mineral-based composites (MBC)", *Journal of Composites for Construction*, ASCE, Vol. 13, No. 1, pp. 25–34.

Brameshuber, W. (2006). *State-of-the-Art Report of RILEM Technical Committee 201-TRC: Textile Reinforced Concrete*, RILEM Publications S.A.R.L., Bagneux, France.

Brand, A.M. (2009). *Cement-Based Composites. Materials, Mechanical Properties and Performance*, 2nd Edition, Taylor & Francis, London, UK.

Breña, S., Kreger, M. and Wood, S. (2005). "Fatigue tests of reinforced concrete beams strengthened using carbon fiber reinforced polymer composites", *ACI Structural Journal,* Vol. 102, No. 2, pp. 305–313.

Chaallal, O., Boussaha, F. and Bousselham, A. (2010). "Fatigue performance of RC beams strengthened in shear with CFRP fabrics", *Journal of Composites for Construction*, ASCE, Vol. 14, No. 4, pp. 415–423.

Chun, P. and Matsumoto, T. (2011). "Optimal design of DFRCC subjected to fatigue loading", *Advanced Materials Research,* Vol. 250–253, pp. 430–433.

Chun, P. and Ohga, M. (2012). "Effect of fiber diameter on fatigue strength of fiber reinforced concrete and its design", *Applied Mechanics and Materials*, Vol. 138–139, pp. 810–815.

Curtis, P. (1989). "The fatigue behaviour of fibrous composite materials", *Journal of Strain Analysis*, Vol. 24, No. 4, pp. 235–244.

Curtis, P. and Moore, B. (1987). "A comparison of the fatigue performance of woven and non-woven CFRP laminates in reversed axial loading", *International Journal of Fatigue*, Vol. 9, No. 2, pp. 67–78.

Cuypers, H. (2001). *Analysis and Design of Sandwich Panels with Brittle Matrix Composite Faces for Building Applications*, PhD Thesis, Vrije Universiteit Brussel, Brussels, Belgium.

Dai, J.G., Sato, Y., Ueda, T. and Sato, Y. (2005). "Static and fatigue bond characteristics of interfaces between CFRP sheets and frost damage experienced concrete", *Proceedings of Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures (FRPRCS-4),* Kansas City, USA, pp. 1515–1530.

Demers, C. (1998). "Fatigue strength degradation of E-glass FRP composites and carbon FRP composites", *Construction and Building Materials*, Vol. 12, No. 5, pp. 311–318.

Derkowski, W. (2006). "Fatigue life of reinforced concrete beams under bending strengthened with composite materials", *Archives of Civil and Mechanical Engineering*, Vol. 6, No. 4, pp. 33–47.

Diab, H., Wu, Z. and Iwashita, K. (2007). "Experimental and numerical investigation of fatigue behavior of FRP-concrete interface", *Proceedings of the 8th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures* (FRPRCS-8), Patras, Greece.

Diab, H. and Wu, Z.S. (2008). "Review of existing fatigue results of beams externally strengthened with FRP laminates", *Proceedings of the 4th International Conference on FRP Composites in Civil Engineering (CICE2008),* Zurich, Switzerland.

Dong, Y., Ansari, F. and Karbhari , V. (2011). "Fatigue performance of reinforced concrete beams with externally bonded CFRP reinforcement", *Journal of Structure and Infrastructure Engineering*, Vol. 7, No. 3, pp. 229–241.

Ekenel, M. and Myers, J. (2009). "Fatigue performance of CFRP strengthened RC beams under environmental conditioning and sustained load", *Journal of Composites for Construction*, ASCE, Vol. 13, No. 2, pp. 93–102.

El Kadi, H. and Ellyin, F. (1994). "Effect of stress ratio on the fatigue of unidirectional Glass fibre/epoxy composite laminae", *Composites*, Vol. 25, No. 10, pp. 917–924.

Epaarachchi, J. and Clausen, P. (2003). "An Empirical model for fatigue behavior prediction of glass fiber-reinforced plastic composites for various stress ratios and test frequencies", *Composites: Part A*, Vol. 34, No. 4, pp. 313–326.

Ferrier, E., Bigaud, D., Clément, J. and Hamelin, P. (2011). "Fatigue-loading effect on RC beams strengthened with externally bonded FRP", *Construction and Building Materials*, Vol. 25, No. 2, pp. 539–546.

Ferrier, E., Bigaud, D., Hamelin, P., Bizindavyi, L. and Neale, K. (2005). "Fatigue of CFRPs externally bonded to concrete", *Materials and Structures*, Vol. 38, No. 1, pp. 39–46.

Fujii, T., Amijima, S. and Okubo, K. (1993). "Microscopic fatigue processes in a plain-weave glass-fibre composite", *Composites Science and Technology*, Vol. 49, No. 4, pp. 327–333.

Gheorghiu, C., Labossiere, P. and Proulx, J. (2007). "Response of CFRP-strengthened beams under fatigue with different load amplitudes", *Construction and Building Materials*, Vol. 21, pp. 756–763.

Gheorghiu, C., Labossiere, P. and Raihe, A. (2004). "Environmental fatigue and static behavior of RC beams strengthened with carbon fiber-reinforced polymer", *Journal of Composites for Construction*, ASCE, Vol. 8, No. 3, pp. 211–218.

Gorty, S.S. (1994). *Mechanical Properties of Composite Cables*, Master Thesis, South Dakota School of Mines and Technology, South Dakota.

Gunes, O., Karaca, E. and Gunes, B. (2006). "Design of FRP retrofitted flexural members against debonding failures", *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, San Francisco, California, USA.

Gussenhoven, R. and Breña, S.F. (2005). "Fatigue behaviour of reinforced concrete beams strengthened with different FRP laminate configurations", *Proceedings of the Seventh Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS7) Conference*, New Orleans, USA.

Hansen, U. (1999). "Damage development in woven fabric composites during tension–tension fatigue", *Journal of Composite Materials*, Vol. 33, No. 7, pp. 614–639.

Harries, K.A., Reeve, B. and Zorn, A. (2007). "Experimental evaluation of factors affecting monotonic and fatigue behavior of fiber-reinforced polymer-to-concrete bond in reinforced concrete beams", *ACI Structural Journal*, Vol. 104, No. 6, pp. 667–674.

Harries, K. and Aidoo, J. (2006). "Debonding- and fatigue-related strain limits for externally bonded FRP", *Journal of Composites for Construction*, ASCE, Vol. 10, No. 1, pp. 87–90.

Harris, B. (2003). *Fatigue in Composites*, Woodhead Publishing Ltd, Cambridge, UK.

Harris, K. (2005). "Fatigue behaviour of bonded FRP used for flexural retrofit", *Proceedings of International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005)*, International Institute for FRP in Construction, Hong Kong, China, pp. 547–552.

Hashin, Z. and Rotem, A. (1973). "A fatigue failure criterion for fiber reinforced materials", *Journal of Composite Materials*, Vol. 7, No. 4, pp. 448–464.

Huang, P., Zhou, H., Wang, H. and Guo, X. (2011). "Fatigue lives of RC beams strengthened with CFRP at different temperatures under cyclic bending loads", *Fatigue & Fracture of Engineering Materials & Structures*, Vol. 34, No. 9, pp. 708–716.

Hwang, S.F. and Su, Y.D. (2006). "Effects of stress frequency and stress ratio on the fatigue of glass/epoxy composite materials", *Key Engineering Materials*, Vol. 326–328, pp. 1031–1034.

ISIS Canada (2008). *FRP Rehabilitation of Reinforced Concrete Structures*, ISIS Canada Research Network, Canada.

JSCE (2001). *Recommendations for Upgrading of Concrete Structures with Use of Continuous Fiber Sheets*, Japanese Society of Civil Engineering, Tokyo, Japan.

Jen, M., Tseng, Y., Kung, H. and Huang, J. (2008). "Fatigue response of APC-2 composite laminates at elevated temperatures", *Composites: Part B*, Vol. 39, No. 7, pp. 1142–1146.

Jones, R. (1999). *Mechanics of Composite Materials*, 2nd Edition, Taylor & Francis, PA, USA.

Kang, B.G. and Brameshuber, W. (2006). "Bond behaviour of textile reinforcement made of AR-glass under cyclic loading", *Proceedings of the 1st International RILEM Symposium, RILEM Proceedings PRO 50*, RILEM Publications S.A.R.L., Bagneux, France, pp. 111–119.

Katakalos, K. and Papakonstantinou, C. (2009). "Fatigue of reinforced concrete beams strengthened with steel-reinforced inorganic polymers", *Journal of Composites for Constructions*, ASCE, Vol. 13, No. 2, pp. 103–112.

Kawai, M. and Suda, H. (2004). "Effects of non-negative mean stress on the off-axis fatigue behavior of unidirectional carbon/epoxy composites at room temperature", *Journal of Composite Materials*, Vol. 38, No. 10, pp. 833–854.

Kawai, M. and Taniguchi, T. (2006). "Off-axis fatigue behaviour of plain weave carbon/epoxy fabric laminates at room and high temperatures and its mechanical modeling", *Composites: Part A*, Vol. 37, No. 2, pp. 243–256.

Khan, A., Al-Gadhib, A. and Baluch, M. (2011). "Experimental and computational modeling of low cycle fatigue damage of CFRP strengthened reinforced concrete beams", *International Journal of Damage Mechanics*, Vol. 20, No. 2, pp. 211–243.

Kim, Y. and Heffernan, P. (2008). "Fatigue behavior of externally strengthened concrete beams with fiber reinforced polymers: state of the art", *Journal of Composites for Construction,* ASCE, Vol. 12, No. 3, pp. 246–256.

Ko, H. and Sato, Y. (2007). "Bond stress–slip relationship between FRP sheet and concrete under cyclic load", *Journal of Composites for Construction*, ASCE, Vol. 11, No. 4, pp. 419–426.

Leung, C., Cheung, Y. and Zhang, J. (2007). "Fatigue enhancement of concrete beam with ECC layer", *Journal of Cement and Concrete Research,* Vol. 37, No. 5, pp. 743–750.

Li, V.C. (2003). "On engineered cementitious composites (ECC)—a review of the material and its applications", *Journal of Advanced Concrete Technology*, Vol. 1, No. 3, pp. 215–230

Li, V.C. (2008). "Chapter 24: Engineered cementitious composites (ECC)–material, structural, and durability performance", *Concrete Construction Engineering Handbook*, CRC Press, USA.

Masoud, S., Soudki, K. and Topper, T. (2001). "CFRP-strengthened and corroded RC beams under monotonic and fatigue loads", *Journal of Composites for Construction*, ASCE, Vol. 5, No. 4, pp. 228–236.

Mazzotti, C. and Savoia, M. (2009). "FRP-concrete bond behaviour under cyclic debonding force", *Advances in Structural Engineering*, Vol. 12, No. 6, pp. 771–780.

M-Brace (2002). *MBrace Composite Strengthening System-Engineering Design Guidelines*, 3rd Edition, Watson Bowman Acme Corp., New York, USA.

Minnaugh, P. and Harries, K. (2009). "Fatigue behavior of externally bonded steel fiber reinforced polymer (SFRP) for retrofit of reinforced concrete", *Materials and Structures*, Vol. 42, No. 2, pp. 271–278.

Mivehchi, H. and Varvani-Farahani, A. (2010). "The effect of temperature on fatigue strength and cumulative fatigue damage of FRP composites", *Procedia Engineering*, Vol. 2, No. 1, pp. 2011–2020.

Nagasawa, M., Kinuhata, H., Koizuka, H., Miyamoto, K., Tanaka, T., Kishimoto, H. and Koike, T. (1995). "Mechanical fatigue of epoxy resin", *Journal of Materials Science*, Vol. 30, No. 5, pp. 1266–1272.

NRC (2004). *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures*, National Research Council, Rome, Italy.

Newaz, G. (1985). "Influence of matrix material on flexural fatigue behavior of unidirectional composites", *Composites Science and Technology,* Vol. 24, No. 3, pp. 199–214.

Nigro, E., Di Ludovico, M. and Bilotta, A. (2011). "Experimental investigation on FRP – concrete debonding under cyclic actions", *Journal of Materials in Civil Engineering*, ASCE, Vol. 23, No. 4, pp. 360–371.

O'Neill, A., Harries, K.A. and Minnaugh, P. (2007). "Fatigue behavior of adhesive systems used for externally-bonded FRP applications", *Proceedings of the Third International Conference on Durability and Field Applications of Fiber Reinforced Polymer (FRP) Composites for Construction (CDCC 2007),* Quebec City, Canada, pp. 41–48.

Odagiri, T., Matsumoto, K. and Nakai, H. (1997). "Fatigue and relaxation characteristics of continuous aramid fiber reinforced plastic rods", *Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3)*, Tokyo, Japan, pp. 227–234.

Ohama, Y. (1995). *Handbook of Polymer-Modified Concrete and Mortars, Properties and Process Technology*, Noyes Publications, Park Ridge, New Jersey, USA.

Ohama, Y. (1998). "Polymer-based admixtures", *Cement and Concrete Composites*, Vol. 20, No. 2–3, pp. 189–212.

Papakonstantinou, C. and Balaguru, P. (2007). "Fatigue behavior of high temperature inorganic matrix composites", *Journal of Materials in Civil Engineering*, ASCE, Vol. 19, No. 4, pp. 321–328.

Papakonstantinou, C.G., Petrou, M.F. and Harries, K.A. (2001). "Fatigue of reinforced concrete beams strengthened with GFRP sheets", *Journal of Composites for Construction,* ASCE, Vol. 5, No. 4, pp. 246–253.

Papanicolau, C., Triantafillou, T., Bournas, D. and Lontou, P. (2006). "TRM as strengthening and seismic retrofitting material of concrete structures", *Textile Reinforced Concrete. Proceedings of the 1st International RILEM Symposium, RILEM Proceedings PRO 50,* RILEM Publications S.A.R.L., Bagneux, France, pp. 331–340.

Quattlebaum, J., Harries, K.A. and Petrou, M.F. (2005). "Comparison of three CFRP flexural retrofit systems under monotonic and fatigue loads", *Journal of Bridge Engineering,* ASCE, Vol. 10, No. 6, pp. 731–740.

Ramakrishnan, V. and Jayaraman, N. (1993). "Mechanistically based fatigue-damage evolution model for brittle matrix fibre-reinforced composites", *Journal of Material Science*, Vol. 28, No. 20, pp. 5592–5602.

Reis, P., Ferreira, J., Costa, J. and Richardson, M. (2009). "Fatigue life evaluation for carbon/epoxy laminate composites under constant and variable block loading", *Composites Science and Technology,* Vol. 69, No. 2, pp. 154–160.

Salvia, M., Fiore, L. and Fournier, P. (1997). "Flexural fatigue behaviour of UDGFRP experimental approach", *International Journal of Fatigue*, Vol. 19, No. 3, pp. 253–262.

Senthilnath, P., Belarbi, A. and Myers, J. (2001). "Performance of CFRP strengthened reinforced concrete (RC) beams in the presence of delaminations and lap splices under fatigue loading", *Proceeding of the International Conference in Construction,* Porto, Portugal, pp. 323–328.

Shahawy, M. and Beitelman, T.E. (1999). "Static and fatigue performance of RC beams strengthened with CFRP laminates", *Journal of Structural Engineering*, ASCE, Vol. 125, No. 6, pp. 613–621.

Suthiwarapirak, P., Matsumoto, T. and Kanda, T. (2004). "Multiple cracking and fiber bridging characteristics of engineered cementitious composites under fatigue flexure", *Journal of Materials in Civil Engineering*, ASCE, Vol. 16, No. 5, pp. 433–443.

Suthiwarapirak, P., Matsumoto, T. and Kanda, T. (2002). "Flexural fatigue failure characteristics of an engineered cementitious composite and polymer cement mortar", *Journal of Materials, Concrete Structures and Pavements,* Vol. 718, No. 57, pp. 121–134.

Takemura, K. and Fujii, T. (1994). "Fatigue damage and fracture of carbon fabric/epoxy composites under tension–tension loading", *JSME International Journal, Series A*, Vol. 37, No. 4, pp. 472–480.

Täljsten, B. (2006). "The Important of bonding - a historic overview and future possibilities", *Advances in Structural Engineering,* Vol. 9, No. 6, pp. 721–736.

Tao, G. and Xia, Z. (2007). "An experimental study of uniaxial fatigue behavior of an epoxy resin by a new non-contact real-time strain measurement and control system", *Polymer Engineering and Science*, Vol. 47, No. 6, pp. 780–788.

Tao, G. and Xia, Z. (2008). "Fatigue behavior of an epoxy polymer subjected to cyclic shear loading", *Materials Science and Engineering: A* , Vol. 486, No. 1–2, pp. 38–44.

Toutanji, H., Zhao, L., Deng, Y., Zhang, Y. and Balaguru, P. (2006). "Cyclic behavior of RC beams strengthened with carbon fiber sheets bonded by inorganic matrix", *Journal of Materials in Civil Engineering*, ASCE, Vol. 18, No. 1, pp. 28–35.

Van Paepegem, W. and Degrieck, J. (2001). "Fatigue degradation modelling of plain woven glass/epoxy composites", *Composites: Part A*, Vol. 32, No. 10, pp. 1433–1441.

Wang ,Y., Lee, M. and Chen, B. (2007). "Experimental study of FRP-strengthened RC bridge girders subjected to fatigue loading", *Composite Structures*, Vol. 81, No. 4, pp. 491–498.

Wu, Z., Wang, X., Iwashita, K., Sasaki, T. and Hamaguchi, Y. (2010). "Tensile fatigue behavior of FRP and hybrid FRP sheets", *Composites: Part B*, Vol. 41, No. 5, pp. 396–402.

Xu, S. and Liu, W. (2011). "Experimental study on flexural fatigue property of ultra-high toughness cementitious composites", *Advanced Materials Research*, Vol. 150–151, pp. 1369–1378.

Yang, X. and Nanni, A. (2002). "Lap splice length and fatigue performance of fiber-reinforced polymer laminates", *ACI Materials Journal*, Vol. 99, No. 4, pp. 386–392.

Yao, G., Huang, P. and Zhao, C. (2006). "Flexural fracture and fatigue behavior of RC beams strengthened with CFRP laminates under constant amplitude loading", *Key Engineering Materials*, Vol. 306–308, pp. 1343–1348.

Yost, J.R., Gross, S.P. and Deitch, M.J. (2007). "Fatigue behavior of concrete beams strengthened in flexure with near surface mounted CFRP", *Proceedings of the 8th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures (FRPRCS-8)*, Patras, Greece.

Yu, T., Li, C., Lei, J. and Zhang, H. (2011). "Fatigue of concrete beams strengthened with glass-fiber composite under flexure", *Journal of Composites for Construction*, ASCE, Vol. 15, No. 4, pp. 557–564.

Yun, Y., Wu, Y. and Tang, W. (2008). "Performance of FRP bonding systems under fatigue loading", *Engineering Structures*, Vol. 30, No. 11, pp. 3129– 3140.

Zhang, J. and Li, V.C. (2002). "Monotonic and fatigue performance in bending of fiber reinforced engineered cementitious composite in overlay system", *Cement and Concrete Research*, Vol. 32, No. 3, pp. 415–423.

Zhu, D., Peled, A. and Mobasher, B. (2011). "Dynamic tensile testing of fabric-cement composites", *Construction and Building Materials*, Vol. 25, No. 1, pp. 385–395.