A comprehensive methodology for the design of fibre-reinforced concrete pavements

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Abstract

Use of fibre-reinforced concrete for pavements, though widely established, lacks comprehensive standardization with respect to both design as well as implementation. Most widely used design methods have adopted the established techniques used for slab-on-grade, mostly due to lack of studies specific to pavements. This is a major drawback since the failure of slabs-on-grade is predominantly caused by static loading whereas the failure of pavements, more often than not, occurs at much lower stresses due to fatigue. In this context, a comprehensive design methodology exclusively for FRC pavements is proposed here including the effect of fatigue in conjunction with inelastic analysis. The static load design equation is based on Meyerhof's ultimate load (yield line) analysis. The material capacity is estimated using the flexural capacity factored by a stress reduction factor for FRC in the cracked and the uncracked state obtained from suitable S-N relations to account for the fatigue stresses. The material parameters incorporated in the design equations include the flexural strength and the equivalent flexural strength of FRC obtained using the unnotched prisms as per Japanese standards (JSCE-SF4).

Keywords

Fibre-reinforced concrete, pavement design, yield line analysis, fatigue.

1 Introduction

Improving the performance of rigid pavements requires that the material used has sufficient resistance against cracking, which is the most critical mode of failure. Use of pseudo-ductile concrete prepared by incorporating fibres seems to be ideally suited to satisfy the performance requirements of the rigid pavement. However, the use of fibre-reinforced concrete (FRC) for pavements, though widely established, lacks universal acceptance with respect to both design as well as implementation. In order to make this technology more easily adoptable, a comprehensive design methodology specific for FRC pavement applications, including critical stress conditions, arising from fatigue, in addition to the tyre loads, is proposed in this study.

2 Design philosophies

In the context of using FRC for pavement applications, most design techniques advocate inelastic techniques for static loading design (Gettu et al. 2000, DRAMIX Manual 2001, TR34: 2003, Elsaigh et al. 2005, Altoubat et al. 2008, Meda 2003, Roesler et al. 2008, ACI 360 R 2010, TR34 2013). Such inelastic techniques assume the concrete to be in a cracked condition at collapse so as to extend the design beyond the elastic regime. Methods like yield-line analysis and elasto-plastic techniques have been widely employed for this purpose. The design for the ultimate collapse load condition, as adopted in inelastic methods, becomes economically advantageous since it results in lower pavement thickness in comparison to equivalent plain concrete pavements, where the design is usually done by elastic analysis (IRC 58:2010, MEPDG 2004, Roesler et al. 2008, AASHTO 1993). Along the same lines, comparative experimental studies of plain and fibre-reinforced concrete slabs have yielded relations such as (Elsaigh et al. 2005):

$$h_f = \frac{h_p}{\sqrt{\left(1 + R_{e,3}\right)}} \tag{1}$$

where h_p is the thickness of the reference plain concrete slab, h_f is the thickness of the SFRC slab with same load-carrying capacity, and $R_{e,3}$ is the equivalent flexural strength ratio, as defined in JSCE-SF4 and ASTM 1609 (IRC SP:46 1997, Elsaigh et al. 2005). In tests on steel fibre-reinforced concrete (SFRC) slabs designed using this equation, a reduction of about 20% of thickness was obtained with 30 kg/m^3 of fibres by Elsaigh et al. (2005).

The use of ($1+R_{e,3}$) as the strength enhancement factor so as to define a design flexural strength using the toughness parameter is commonly adopted to represent the contribution of fibres to the flexural behaviour of concrete (IRC SP:46 1997, Elsaigh et al. 2005, Altoubat et al. 2008, Roesler et al. 2008, ACI 360R 2010). However, the term design flexural strength of FRC can be misleading as it is well established that the addition of fibres does not significantly enhance the flexural strength of concrete, at least for the commonly used fibres and dosages. It has to be emphasised that the increase in moment carrying capacity is not due to an increase in flexural strength but due to the increase in the post-cracking moment carrying capacity of the SFRC slab. Therefore, the use of the term "design flexural strength of SFRC" should be avoided since it could be wrongly extended beyond the failure typology considered here.

In spite of the availability of these equations, there is always a concern about their acceptability for pavement design since the general failure patterns of actual pavements rarely resemble the yield-lines and failure is more likely to occur due to fatigue. In addition, the current codes for pavement design, including IRC 58:2010, FHWA method of FRC overlays (Roesler et al. 2008), MEPDG (2004), recommend the design to be elaborately done as per the Cumulative Fatigue Damage (CFD) limit. Therefore, it is understood that a separate serviceability condition under fatigue loading has to be devised for the design to be comprehensive (Cachim 1999).

3 Fatigue design

As mentioned earlier, it is inadequate that a design method addresses only the tyre (static) loading conditions as it is well established that, in general, the failure of pavements occurs due to fatigue as the pavement ages (MEPDG 2004, Fwa 2006, Huang 2008). Many design techniques try to address the issue of fatigue loading through the consideration of a dynamic factor converting the dynamic/cyclic load to an equivalent static load (TR34 2003, TR34 2013, Dramix Manual 2001, di Prisco and Mauri 2004, ACI 360R 2010). However, such an approximation, though widely accepted, has its drawbacks in that it is not possible to alter the design criterion to accommodate any benefits in the performance characteristics of the material since the factor is common and not specific to the material. This becomes a significant drawback as it is evident that FRC has better fatigue response than plain concrete. Though extensive studies have been done on fatigue behaviour of both plain and fibre-reinforced concrete, the understanding is not very comprehensive in comparison to metals. A detail overview of the existing studies on fatigue testing is given by Lee and Barr (2004), with a model proposed for fatigue life prediction. The current paper discusses the possible application of the available results and models to pavement design and, consequently, the proposal of a design methodology.

Various studies have been done on plain and fibre-reinforced concrete to obtain the fatigue characteristics, which mostly consist of fatigue life predictions, fatigue creep rate values, etc. Both empirical and analytical fatigue models are reported in literature for plain and fibre-reinforced concrete. The experimental models have the drawback that the testing methods vary significantly due to the lack of standardized testing procedures for fatigue testing and so a comparison may not be always appropriate. However, these models are more easily adoptable than the numerical models due to their simplicity. The major differences in the testing configurations in the literature are in the type of loading, test control parameters (load/displacement), specimen shape and size, loading frequency, loading range, definition of endurance limit and the type of concrete itself (i.e., high strength, normal strength, fibre type and dosage, etc.) (Reinhardt and Cornelissen 1984, Oh 1991, Batson et al. 1972, Johnston and Zemp 1991, Chang and Chai 1995, Wei et al. 1996, Naaman and Hammoud 1998, Germano and Plizzari 2012, Singh et al. 2004, Singh and Kaushik 2003, Pasakova and Meyer 1997).

In spite of the differences, a few definite conclusions regarding the performance of FRC with reference to plain concrete can be drawn:

- The fatigue performance of FRC is better with longer or more slender fibres (i.e., with higher aspect ratio), though a definite relation with the shape of fibres could not be drawn. The improvement in fatigue performance, especially in bending, is related to the fibre volume, with more significance for low cycle loading (Batson et al. 1972, Chang and Chai 1995, Wei et al. 1996, Naaman and Hammoud 1998, Zhang et al. 1999, Lee and Barr 2004);
- The effect of the fibre addition is most significant in the second stage of crack growth during fatigue cracking (Chang and Chai 1995, Lee and Barr 2004);
- The endurance limit of FRC is in the range of 65 - 85% of the static first-crack strength in comparison to 50 - 60% for plain concrete (with the endurance limit being defined at 2–10 million cycles) (Batson et al. 1972, Johnston and Zemp 1991, Chan and Chai 1995, Wei et al. 1996, Naaman and Hammoud 1998, Cachim 1999, Germano and Plizzari 2012);

- The incorporation of fibres results in a substantial increase in deformation (crack opening) at failure, reflecting the increase in toughness (Cachim 1999). Consequently, FRC has higher energy dissipation capacity than plain concrete, which is also indicated by the higher residual toughness values (in both uncracked and pre-cracked/notched specimens) (Pasakova and Meyer 1997, Lee and Barr 2004, Germano and Plizzari 2012);
- At higher fibre content and aspect ratio, the stiffness of SFRC under cyclic loading increases (Chang and Chai 1995).

Several fatigue models, in terms of stress ratio-fatigue life (S-N curves), have been proposed for FRC, and a comparison of some of these models is given in Figure 1 for flexural fatigue of unnotched specimens with fibre volume fractions of 0.5%; the fatigue model used in IRC 58:2010 for plain concrete (PCC) has also been shown for the purpose of comparison. From Figure 1 it can be understood that the shift of the curves towards the right for the FRC indicates a higher value of allowable load repetitions for the same stress level in comparison to PCC. Though the comparison is done only with respect to a single model for PCC, similar trends are seen in other models (e.g., Cachim 1999, Lee and Barr 2004).

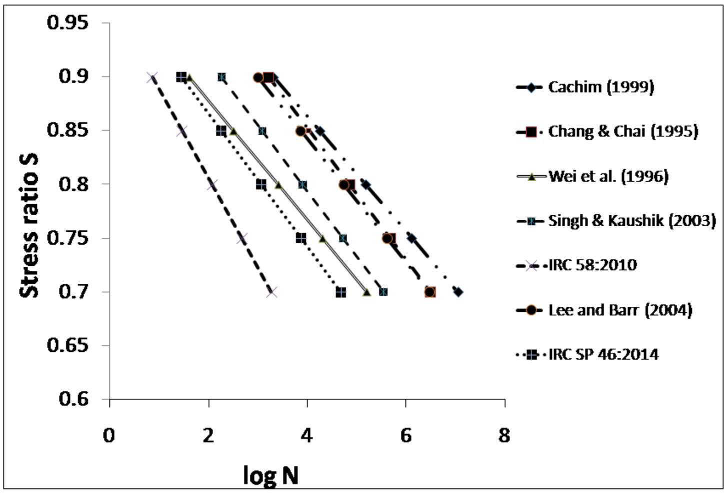

Figure 1: Fatigue models for uncracked SFRC compared with that for plain concrete (IRC 58: 2010).

Since the fibres mainly influence of the response in the fracture process zone, a study on the effect of load cycling on the uncracked specimen may be insufficient to draw significant conclusions regarding the effect of fatigue loading on the toughness. Therefore, data from models based on the performance of pre-cracked specimen have also been presented in Figure 2 (Naaman and Hammoud 1998, Germano and Plizzari 2012), which is more representative of the response of cracked FRC, as considered in inelastic design. Since the specimens in these tests are pre-cracked, the fatigue behaviour corresponds to the crack initiation and propagation stages and can be taken to be governed by the toughness of the FRC. It is seen that, even in comparison to the model for uncracked PCC, the FRC specimens show high fatigue resistance. Note that the study by Naaman and Hammoud (1998) is on high early strength concrete with high dosages of fibres (above 1%) resulting in a strain hardening type of response, which is not directly comparable to the applications being discussed here.

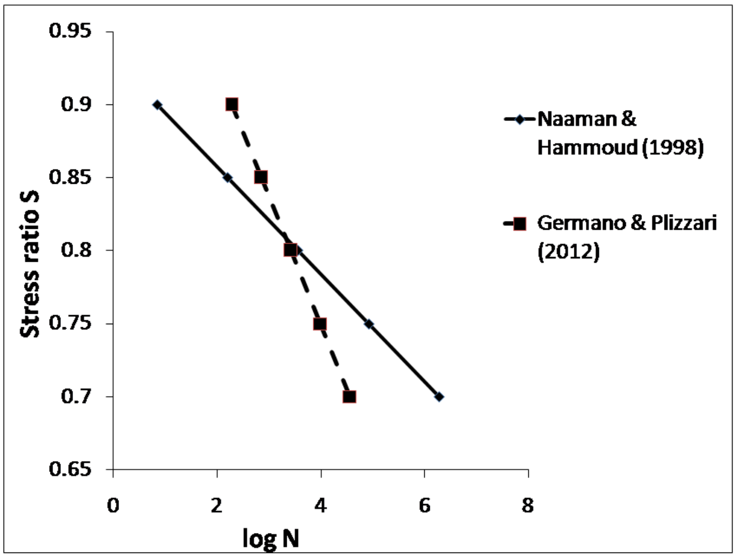

Figure 2: Fatigue response of pre-cracked FRC specimens under flexure compared with a model for plain concrete.

Based on the literature review and model comparisons, it is inferred that the incorporation of fibres results in the enhancement of fatigue life of concrete by about 20–25% in the pre-cracked stage. After cracking, the PCC is not expected to have any further life as failure will occur almost simultaneously with the first crack appearance, whereas FRC can endure cyclic loading at least at low stress levels for an appreciable number of cycles and this phenomenon can be related to the toughening due to the fibres. However, a conclusive quantitative estimate of the relationship between the fatigue life and toughness of FRC could not be obtained.

4 Proposed design method for FRC pavements

The use of toughness parameters for representing the enhanced post-cracking capacity of FRC is common in the techniques found in design codes and recommendations for slabs-on-grade/pavements, e.g., Concrete Society Guidelines TR34, DBV Recommendations, FHWA Recommendations (TR34 2003, Gettu et al. 2000, Roesler et al. 2008). On similar lines, a design methodology is proposed here, where the toughness parameter adopted in the design is the equivalent flexural strength, $f_{e,n}$, defined as per the JSCE-SF4. The design equation is a modified form of that proposed in TR34:2003, based on the collapse condition taken as the appearance of cracking at the top of the slab. At this condition, the plastic moment capacity due to the FRC is fully mobilized at the bottom of the slab since the crack is open and the negative moment capacity corresponds to the flexural strength of concrete since the crack has initiated, as shown in Figure 3 (TR34:2003, Elsaigh et al. 2005, Meda 2003, Meyerhof 1962). Thus, the limiting moment is the sum of the positive plastic and the negative moments (Meda 2003, Losberg 1961, Meyerhoff 1962, Baumann 1983, Rao and Singh 1986):

$$M_o = M_n + M_p \tag{2}$$

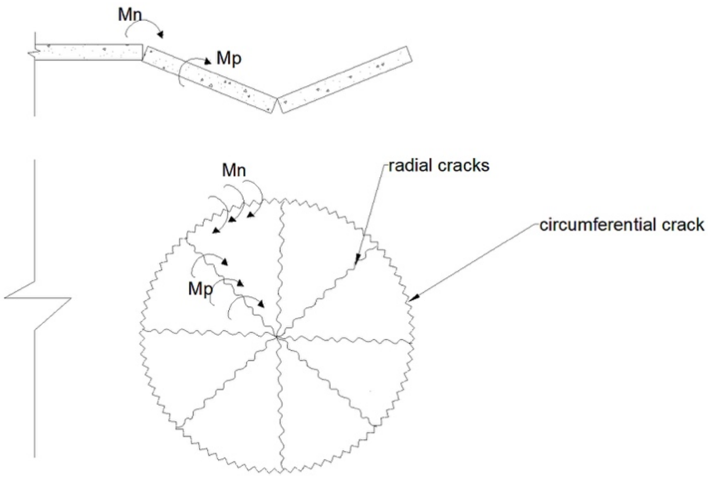

Figure 3: Cracked state of slab at collapse or at the failure condition.

The plastic moment capacity in the FRC slab is taken as the post-cracking moment carrying capacity, which is a function of post-cracking flexural strength, such as the equivalent flexural strength as specified in JSCE SF4 (1984). Consequently, the plastic moment capacity per unit length of the slab is estimated as:

$$M_P = f_{e,150k}\frac{h^2}{6}$$

where $f_{e,150k}$ is the characteristic equivalent flexural strength of concrete (obtained from the flexural test of an unnotched prism) until a deflection of span/150, and h is the thickness of the slab. The equivalent flexural strength is used here since the term represents an average response over a range of crack widths.

The negative moment capacity is a function of the flexural strength (or modulus of rupture) of the concrete (obtained from the same flexural test):

$$M_n = f_{ct,k}\frac{h^2}{6}$$

where $f_{ct,k}$ is the characteristic value of the flexural strength of the concrete. As per the stress condition, the design equation for the section capacity in terms of the allowable moment per m of the slab is

$$M_{all} = \left(f_{ctk} + f_{e150,k}\right)\frac{h^2}{6} \tag{3}$$

In the case of FRC pavements, the section capacity will be affected by fatigue loading. The challenge is to estimate material response parameters, such as flexural strength, endurance limit and toughness, for incorporation in the inelastic methodologies.

In the present approach, reduction factors based on the fatigue models from literature are applied to the strength parameters used in the design of the section. Equation 3 is then modified for the moment carrying capacity under fatigue loading, as

$$M_{all} = \left(Xf_{ctk,k} + Yf_{e,150k}\right)\frac{h^2}{6} \tag{4}$$

where X and Y are the reduction factors for the negative moment carrying capacity (i.e., at crack initiation) and the positive moment carrying capacity (i.e., post-cracking regime, with an open crack), respectively. The values of X and Y are to be obtained from suitable fatigue models (e.g., S-N curves) considering the fibre type and dosage used, and the specified grade of concrete.

4.1 Determination of fatigue reduction factors

In the case of pavement design, the starting point of the design should be the axle load spectrum from the traffic data. From the design traffic data, the expected number of repetitions for each axle load class has to be obtained, as in typical rigid pavement design. For each load class, the corresponding expected number of load repetition N has to be used when determining the reduction factor from the fatigue model. Appropriate fatigue models have to be chosen for both uncracked and post-cracked stages of the FRC and the safe stress ratio corresponding to the N value has to be determined. This is illustrated in Figure 4 where S-N curves for uncracked and pre-cracked concrete are used to obtain the reduction factors; e.g., for a required N = 1000 (i.e., *log N* = 3), the safe stress ratio limits for FRC are, in the uncracked state, X = 0.92 from curve 1, and for the cracked state, Y = 0.84 from curve 2.

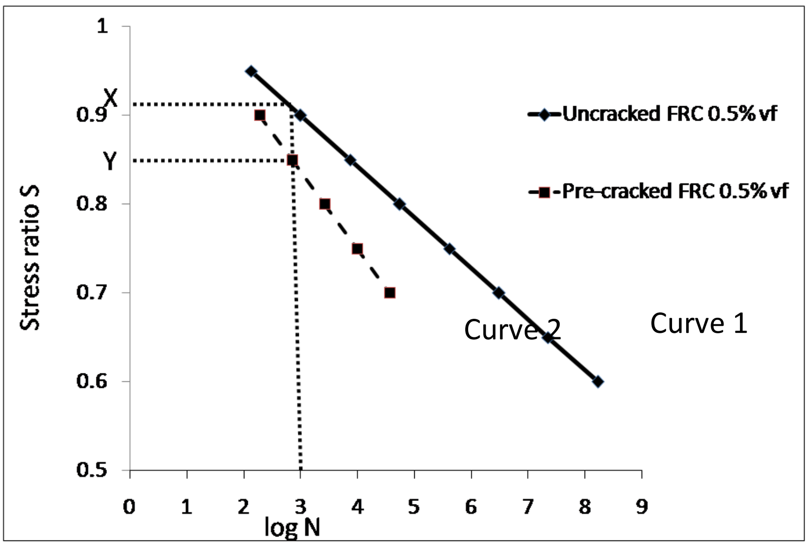

Figure 4: Fatigue reduction factors from S-N curves.

5 Conclusions

The paper discusses a design procedure for fibre-reinforced concrete pavements incorporating inelastic design for the load carrying capacity, a reduction factor for fatigue loading specific to the material toughness, and estimates of thermal and shrinkage stresses. The methodology has the following features:

- The design stress for static loading is calculated using inelastic design techniques as per Meyerhof's ultimate load analysis;
- The limiting moment is obtained assuming the failure condition to be the initiation of cracking at the top of the slab thus making the limiting moment to be the sum of the positive moment at the bottom cracked part of the slab and negative moment at the top of the slab;
- The design method incorporates a relevant material parameter of FRC, that is, the equivalent flexural strength in the evaluation of the moment carrying capacity;
- Fatigue failure criteria are incorporated in the design by assigning reduction factors to the flexural and equivalent flexural strengths in the section capacity calculations.

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