A Review on Fatigue Life Prediction of Plain Concrete

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Abstract. Fatigue analysis of concrete structures is important since it is the limiting factor to service life of many infrastructures. The heterogeneity in concrete and its complex behaviour upon repetitive loading makes the fatigue life prediction of concrete erratic. This paper presents a review on the fatigue life prediction models of plain concrete. Review includes the deterministic and probabilistic approach for the prediction of fatigue life of concrete. It has been observed that deterministic approach depends on certain parameters and initial conditions and is not reliable for the prediction of fatigue life of concrete. So there is a demand for a more generalised model based on probabilistic approach which includes randomness in the fatigue failure of concrete. Recent studies show utilisation of artificial neural network, a computational tool based on this approach can be utilised to predict the fatigue behaviour of concrete.

1. Introduction

The phenomenon of gradual microstructural changes that occurs permanently in a material due to cyclic loading is known as fatigue. In many infrastructures such as highway and airfield pavements, railway sleeper, bridge decks supporting structure of offshore windmills, concrete has to resist large number of cycles of varying amplitude. Basically concrete consists of three components: the cement matrix, the aggregate and matrix-aggregate interface. The heterogeneous nature of concrete result in the formation of numerous internal flaws which triggers crack initiation. These flaws are the region of high stress concentration and upon fatigue loading cracks will start to propagate and continue until the failure. Crack growth due to fatigue is classified into three different zones namely crack initiation zone, crack propagation zone and unstable crack growth. The crack propagation will be through the weakest path in the concrete matrix. Several experimental, numerical and analytical investigation were conducted based on different approaches to understand the mechanism of fatigue failure of concrete and to develop a fatigue model.

There are basically three approaches to assess the fatigue life of a structural element viz. the S-N curve method, fracture mechanics method and continuum damage mechanics method. In the first approach, fatigue stress life data of concrete at varying stress levels from many fatigue tests are analysed and a typical empirical formula is generated using regression analysis based on S-N curve [1]. But this approach only considers overall fatigue life and suffers from heterogeneity of concrete. The approach based on fracture mechanics considers the failure condition of the material by crack initiation and propagation. It depends on the stress intensity factor which is a function of stress state and crack length [1]. To investigate fatigue damage mechanics, there are two approaches including continuum damage method and the energy dissipation method. In the former, the fatigue life of concrete is predicted using damage evolution equation which is based on certain damage variables representing the damage of material. The variation in the energy dissipation during fatigue loading is analysed in energy method.
and the mode of energy dissipation is utilised to predict the fatigue failure of concrete [3], [4]. In this method stress level is not taken into account and is concerned only with the strength. Moreover, it is only applicable to viscoelastic concrete. This is the limitation of fatigue damage method since it depends highly on stress level for fatigue life prediction of concrete.

The deterministic model does not include elements of randomness and so the models that account for it with as many variables is too cumbersome to work with it. It depends upon certain mathematical model and conditions will give a simple solution but will not be consistent. Probabilistic (stochastic) model uses distribution instead of fixed values which include variation and uncertainty. All the three approaches stated above gives a deterministic model based on parameter values and initial conditions which is not a dependable one for fatigue life of concrete since it consists of uncertainty.

Thus there is a demand for stochastic approach which can include the randomness in the fatigue of concrete. It can also incorporate the varying parameter involved in the fatigue life prediction of concrete. Artificial neural network (ANN), an effective computational tool is gaining wide acceptance for its application to engineering problems [5]. All the approaches to analyse the fatigue life of concrete is based on deterministic approach and suffers from randomness in fatigue testing and variable properties of concrete. ANN which is based on probabilistic approach may be more suitable for fatigue prediction models by which randomness in fatigue failure of concrete can be included.

2. Models based on S-N curves

The approach based on fatigue stress-life relationship (S-N curve) is known as Palmgren-Miner hypothesis and it states that damage accumulates linearly with number of cycles applied at a particular stress level. The failure criterion is given by

\[ \sum_{i=1}^{k} \frac{n_i}{N_i} = 1 \]

where \( n_i \) is the number of cycles at stress level \( i \), \( N_i \) is the number of cycles to failure at stress level \( i \), and \( k \) is the number of stress levels [1]. The applicability of Miner hypothesis of cumulative fatigue damage which assumes that fatigue damage is accumulated linearly was studied and it did not work well for concrete. Also it was concluded that by introducing rest periods into loading spectrum, there occurred a reduction in the failure probability corresponding to a specific number of load cycles and stress levels [6]. In 1958 by analysing the data from fatigue test on plain concrete, a relationship between applied stress level and cycles to failure is established [7].

To understand the hypothesis of fatigue failure of concrete, further experimental studies were conducted varying the parameters and criteria of failure. The studies included the deterioration of bond between aggregate and mortar mix, influence of material properties, difference in loading pattern, effect of stress ratio etc. The conventional S-N equation was further modified to consider the influence of frequency of loading. Two different models were developed to anticipate the fatigue strength of concrete, one for high cycle fatigue (\( 10^5 < N < 10^7 \)) and other for low cycle fatigue (\( N < 10^5 \)) [8].

Due to high variability in fatigue test data, probability theories were introduced to estimate fatigue life of concrete and concluded that conventional S-N curves are valid for prediction for fatigue stress level from 65 to 85 % [9]. Through the studies conducted on plain concrete under constant and variable amplitude fatigue loading, it was observed that Palmgren-Miner hypothesis is not reliable to evaluate the fatigue fracture of concrete [10].

3. Models based on fracture mechanics

The fracture mechanics method considers the condition around the crack tip and the crack growth due to fatigue as the failure criterion. In Paris formula, the crack propagation associated with variation of stress state is the basis for identifying the fatigue fracture. Several researchers extended the fatigue damage study on metals to concrete and found some of them working for concrete. Paris law turned into the first proposed model based on this approach and many researchers used these models directly to observe the crack growth behaviour of concrete. Paris law gives the relationship between crack length increment per cycle and the amplitude of stress intensity factor. The proposed law is based on fatigue crack propagation and is given by
Where \( N \) is the corresponding load cycle, \( a \) is the crack length, \( \Delta K \) is the amplitude of stress intensity factor and \( C \) and \( m \) are material constants [11]. Paris law is only applicable to macroscopic cracks, that is only for very large specimens and was found to be incompatible with the heterogeneous nature of concrete and it requires some modifications.

Since Paris law is applicable only for large sized specimen, it was adjusted to apply for small sized concrete specimens and evolved size effect law. Paris law was adjusted to include the size-effect and the crack length increment depends on size adjusted stress intensity factors. A new parameter called brittleness number (ratio of structure size \( D \) to transitional size \( d_0 \)) was introduced for size adjustment which distinguishes the responses governed by stress intensity factor and nominal stress according to the transitional size of specimen. The size-adjusted Paris law is given by

\[
\frac{da}{dN} = C \left( \frac{\Delta K}{K_{IC}} \right)^m
\]

(3)

where \( K_{IC} \) is the fracture toughness and \( \beta \) is the brittleness number \((D/d_0)\). The advantage of size-effect method is that one can obtain size independent fracture parameters by measuring the maximum load values of geometrically similar specimen of different sizes. Experiments show that \( d_0 \) for monotonic loading is much less than \( d_0 \) for cyclic loading, which means that the brittleness number for monotonic loading is much greater than the brittleness number for cyclic loading [12]. The fatigue tests conducted on single edged notched beam specimens inferred that Paris law can be applied for crack growth in plain concrete with \( C \) rely on the stress cycle ratio \( R \) and \( m \) as a constant [13].

The concrete beams tested under three point bending subjected to flexural fatigue loading was carried out. Specimens were subjected to quasi-static cyclic and constant amplitude fatigue loading and was concluded that the critical value of mode I stress intensity factor is constant along the post-peak part of quasi-static envelope and can be predicted using the following condition: \( K_i = \text{critical value of } K_i = K_{IC}. \)

It was shown that the crack growth in the acceleration stage could be accurately modelled using the Paris law. The Paris coefficients were considered to be material constants for low cycle, high amplitude fatigue loading. The crack growth in the deceleration stage was modelled using an analytical expression which is derived from the concepts of \( R \)-curve and is given as

\[
\frac{\Delta a}{\Delta N} = C_1 (D_a)^{n_1}
\]

(4)

where \( C_1 \) and \( n_1 \) are constant and exponent respectively and \( D_a \) is the total increase in crack length [14]. Based on the concepts of fracture mechanics which considers the effect of the loading pattern, size effect parameters and loading frequency a fatigue crack propagation model was proposed for concrete and was used to predict the residual strength of plain and reinforced concrete beams. An increase in brittleness is noticed as the size of plain concrete beam increases with the fatigue crack propagation. In the case of reinforced concrete (RC) beams, the stability of fracture process can be accomplished only when the beam has sufficient reinforcement [15]. The prediction of crack growth rate and fatigue life of concrete was achieved through the fatigue crack propagation law. However the varying parameters make it more complex and not dependable.

4. Model based on fatigue damage mechanics

4.1. Continuum damage models

The destruction of bond between the cement matrix and aggregate, damage of material grains themselves affects the elastic properties of concrete and the material becomes anisotropic. The progression of microcracks and voids is the reason for this destruction and thus the nonlinearity in concrete. The
damage due to this anisotropy which occurs in an initially isotropic material is utilised for the development of Continuum damage models (CDM) [16].

A damage model based on both monotonic and cyclic behaviour of concrete was developed. Based on continuum damage theory, certain damage variables are selected to characterise the material damage and then an equation for damage evolution was established. By applying thermodynamics theory, using dissipation function, growth rate of damage is evaluated and the damage evolution model was developed with respect to thermodynamic force conjugates of the damage variables [17]. The theory was based on certain assumptions and cannot be generalised. A nonlinear damage model which is able for predicting the fatigue life under compression for a range of concrete strength was developed. The fatigue behaviour for both high-cycle and low-cycle fatigue induced by varying cyclic stress ratios can be predicted using this model. Also a damage evolution model for concrete was developed applicable for proportionate monotonic loading conditions and uniaxial compression [18].

4.2. Energy method
In concrete, there will be an exchange of energy with the surrounding environment throughout the loading process. The total energy dissipated from the system can be divide into two, heat energy and the dissipated energy due to material damage. Plastic strain energy, the energy required during crack propagation and defect formation etc. are the usual energy dissipation due to material damage. The degree of material damage is characterised by corresponding physical quantities and is taken as governing damage variable. Then the damage evolution law of materials and its fatigue life prediction is obtained based on the energy dissipation trends [19]. An equation was proposed to determine the fatigue failure of concrete based on the stability of the single-cycle energy dissipation and uniformity of the critical energy dissipation and is validated with experimental data. However, this method is only applicable for viscoelastic concrete material and is unfit for ordinary concrete material which is quasi-brittle [20].

5. Model based on neural network
Artificial neural networks, or neural networks (NNs) are a class of computational tools developed inspiring the biological nervous system. Neurons are the basic components of ANN and is divided into three layers viz. input, hidden and output layers. The neurons in one layer is connected to the previous layers by weights and a computational model is used by these neurons for information processing. Using ANN, complex relationships between inputs and outputs can be modeled and can find the patterns of data. ANNs are able to learn from the predefined samples without possessing any prior understanding to the complex formula[21].

The compressive strength of concrete was predicted using ANN model and it shows better performance than traditional methods. Also it considers sufficient factors which influence the concrete strength development [22]. The number of reversals to fatigue failure of steel reinforcing bars was predicted using ANN and it gives better prediction results than nonlinear regression analysis with improved accuracy [23]. This enlightens the possibilities of using ANN for the fatigue life prediction of concrete which may provide a model considering the discreteness of concrete property and randomness in fatigue testing.

Very few researches were done using ANN for the prediction of fatigue life of concrete. A prediction model was created to predict the fatigue endurance limit of conventional asphalt concrete pavements utilising ANN. Also by using ANN extraction rules, a standalone equation was derived which is capable to predict the strain values with good prediction accuracy [24]. Fatigue cracking (FC) is a significant problem in asphalt pavements and is related with transfer function which is an empirical mathematical model based on critical mechanical responses. Utilising the similarity between FC transfer function and neural network, accuracy of FC prediction was improved considering all variables which is otherwise difficult and not reliable[25]. However, a generalised model for prediction of fatigue life of concrete is not yet established and is a scope to find it with ANN.

6. Conclusions
In this paper a review of literature on fatigue life prediction models of plain concrete is carried out. Review mainly includes the evolution of models developed using three basic approaches of fatigue life
assessment of structural element and the possibilities of using artificial neural network in predicting the fatigue life of concrete. At first prediction of fatigue life of concrete was based on S-N curves. Various fatigue tests were conducted and analysed to obtain the number of cycles at different stress level, which helped in developing a failure criterion. Later further investigations showed that this approach is not sufficient for inculcating the variability in fatigue tests. Fracture mechanics based approach gained more acceptance in which Paris law was the first model proposed based on this approach. Later, certain modifications were brought by researchers and the size effect law was the major one among them. In model based on fatigue damage approach, results were predicted based on the damage of material which is associated with a non-local approach, where fracture mechanics is related to local stress intensity range at the crack tip. Damage approach produce a rational generalised behaviour but based on non-realistic behaviour of material.

All these were based on deterministic approaches and it is subjective because of the following reasons

- The fatigue life of structural elements is influenced by the uncertainties in the lifetime of structures
- Randomness in fatigue test and discreteness in concrete property upon fatigue loading
- Approaches is based on certain failure criteria and cannot be generalised

Considering all these, a conclusion can be drawn that there is necessity for a probabilistic approach to overcome the limitations of deterministic approach. ANN, a nonlinear statistical data modelling tools which can be used to model complex relationships between the inputs and outputs based on a probabilistic approach. So far it is used to predict fatigue lives of pavements and found it as a reliable approach with better prediction accuracy. This can be extended to establish a generalised model for predicting the fatigue life of concrete.

7. References

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