A Review on Residual Life Assessment of Plain and Reinforced Concrete Members

Ajimi S[1], Keerthy M Simon[2], Bharati Raj[2]

[1] Student, Department of Civil Engineering, NSS College of Engineering, Palakkad, India
[2] Assistant Professor, Department of Civil Engineering, NSS College of Engineering, Palakkad, India

*Corresponding author: ajimi1234@gmail.com

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ABSTRACT

Under fatigue loading, concrete like quasi-brittle materials exhibit softening behaviour since an inelastic zone will be formed in front of the crack tip called the fracture process zone (FPZ). There are various toughening mechanisms that exhibiting in this region. Current design practices for reinforced concrete assumes a zero tensile strength for concrete which is actually overly conservative. In fact, concrete can bear significant tensile stress and strain. Therefore, the tension softening response of RC member should consider in the study. Under fatigue loading, strength and stiffness decrease progressively according to the maximum amplitude and the number of cycles of loading. Fracture plays an important role in failure of normally and lightly reinforced beam. Since FPZ mechanisms and fibre bridging action resist crack propagation, we have to consider these mechanisms while assessing remaining life of RC member. Fatigue failure occurs when applied load is much less than the moment capacity. Such structures susceptible to fatigue load need to be monitored and residual life is to be predicted. This paper is presenting a review on the residual strength assessment on plain and reinforced concrete. The review includes the influence of various tension-softening models in predicting the residual life of plain and reinforced concrete. A comparative study is also conducted in order to assess the residual life by considering various tension softening laws.

Keywords: Fracture Process Zone (FPZ), Residual life, Tension softening

1 Introduction

Many concrete structures like bridges, pavements, highways, airports, flyovers and other infrastructural engineering structures undergo repeated loading. Therefore, a structural fatigue failure may occur because of this cyclic loading and significant changes on the characteristics of materials such as stiffness, toughness and durability etc may occur which will in turn affect residual life of concrete member. Fatigue is a phenomenon that is taken place in a material in a gradual, permanent, micro-structural way due to the application of repeated loading. Under cyclic loading, the stresses near the crack tip are high enough to lead to failure even if, the nominal stresses are well below the yield limit of the material, even though concrete is a heterogeneous material, it is treated as homogeneous material from design perspectives. But under fatigue loading, concrete may exhibit a softening response due to the existance of heterogeneities when it is tested under displacement control. Quasi-brittle materials like concrete will show a strain-softening behaviour. This softening behaviour is due to the formation Fracture Process Zone (FPZ) ahead of the crack tip.

Fracture Process Zone (FPZ) is dominated by various toughening mechanisms. Out of these toughening mechanisms, micro cracking and aggregate bridging are the major mechanisms that are responsible for the softening behaviour. Fatigue failure will occur even when the applied load is much lower than the yield value

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(ie, the tensile strength for concrete). So, it is necessary to assess remaining life of existing structure to prevent catastrophic failure. As the crack within the concrete member after initiation, propagate continuously under fatigue loading, its strength and stiffness decreases progressively. Hence residual strength assessment of members are also an important issue that has to be looked upon. Due to the presence of FPZ in front of crack tip, post peak softening response acutely influence crack propagation and therefore it is appropriate to consider FPZ mechanisms while assessing residual strength of concrete. There are various tension softening models to mathematically represent the post peak softening mechanisms of concrete. FPZ in ductile and brittle materials are shown in figure 1.

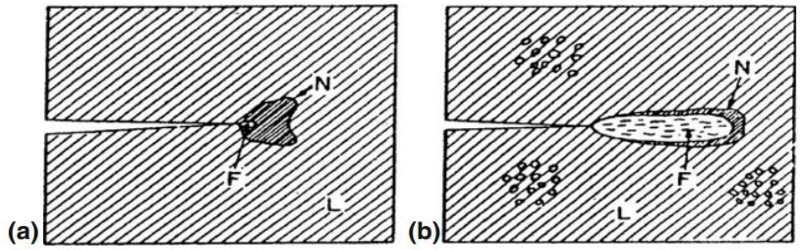


Figure 1. FPZ in ductile and brittle materials. (a) Ductile-brittle (metals). (b) Quasi-brittle (concrete).

2 Residual Life Using LEFM Principle

Linear Elastic Fracture Mechanics (LEFM) is a method to study the crack growth rate and the mechanism of crack growth in different components of a structure. This method is originally developed by Griffith and is modified by Irwin. LEFM is applicable to almost every material but it should satisfy certain criteria such as material should be elastic except at some infinitesimally small area near the crack tip.

LEFM is based on the stress intensity factor K, which can be determined by using stress analysis. When the stress intensity at the crack tip (K_C) reaches a critical value K_{IC}, the crack starts to propagate. In this principle, it is assumed that when a major fatigue crack is formed, the bridging behaviour within that region will govern the rate of fracture crack propagation.

2.1 Residual Life Assessment for Plain Concrete Member

According to classical theory, when a structural component is subjected to high amplitude cyclic loading, the bottom of the members will experience an in-plane loading. But the current design practices for reinforced concrete assumes a zero tensile strength for concrete which is actually overly conservative. . In fact, concrete can bear significant tensile stress and strain. Ramachandramoorthy et al. [3] established a procedure to determine the residual moment carrying capacity of a pre-notched beam by considering the crack effect. The residual life of a pre-notched beam is determined in terms of moment carrying capacity as a function of increasing crack length under cyclic loading. The stress at initial notch, a_0 is assumed to be zero. The stress and strain distribution corresponding to (a_0 +Δ_a) is shown in figure 2. The moment of resistance M_R can be is found out by using equations of equilibrium and is given by,

$$M_R = Tx\ (lever\ arm) = T\frac{2}{3}(h - a_0) \tag{1}$$

Where, *h* and *B* are depth and width of the beam and T is total tension.

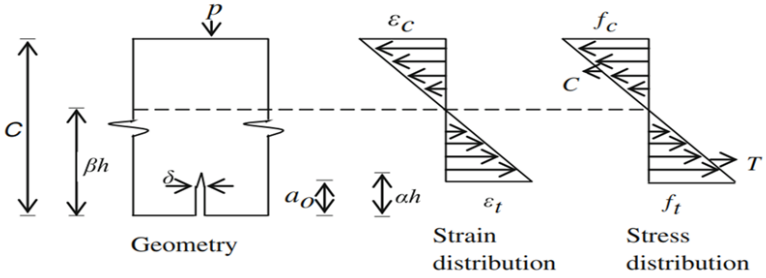


Figure 2. Bending stress and strain distribution [3]

2.2 Residual Life Assessment for Reinforced Concrete Member

The fatigue behaviour of RC beams were studied by Sain and Kishen [2] using the LEFM based fatigue law after suitable modifications to incorporate the various applied load frequencies and the effect of reinforcement. A closing force is used at the level of steel to account for the presence of reinforcement.

The residual life of the reinforced members subjected to fatigue loading is a function of increasing crack length for assuring safety. The residual strength is expressed in terms of ultimate moment carrying capacity and is given as,

$$M_F = \frac{K_{IC} B D^{\frac{3}{2}}}{Y_M(\alpha)} + \frac{F_P D}{Y_M(\alpha)}\left[F_1\left(\frac{x}{a},\alpha\right) + Y_M(\alpha)\left(\frac{1}{2}-\frac{C_S}{D}\right)\right] \qquad (2)$$

Where, Y_M is the geometric factor, $C_S$is the Clear cover, F1 is the geometry factor, $F_P$is the steel force in post tension regime and $K_{IC}$is the fracture toughness.

It is concluded from their study that the capacity of the structural member has overestimated the assumption of steel yielding throughout the propagation stage.

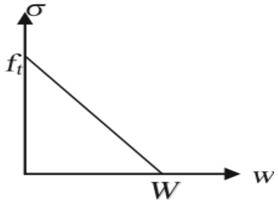
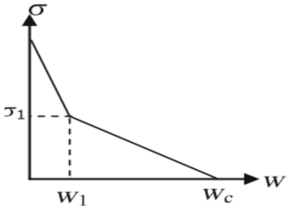
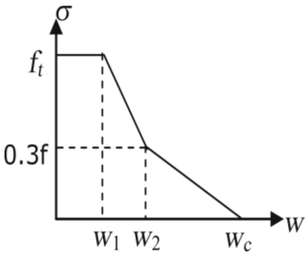
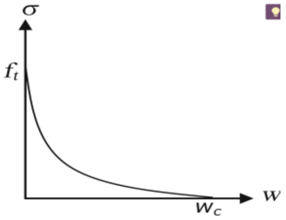
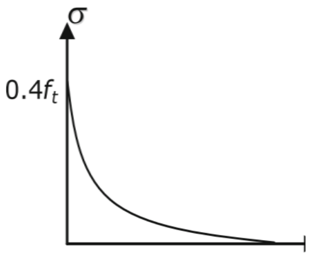
3 Mathematical Modelling of FPZ

The heterogeneities in the concrete will lead to the formation of an inelastic zone ahead of the crack tip called Fracture Process Zone (FPZ). Due to this FPZ, concrete will exhibit a softening behaviour. This post peak softening response acutely influence the crack propagation and it is necessary to consider the FPZ mechanisms while determining residual life. There are various toughening mechanisms like crack shielding, crack deflection, aggregate bridging and micro cracking are experienced in fracture process zone. Out of these, micro cracking and aggregate bridging are the major mechanisms that are responsible for softening behaviour. This FPZ mechanisms can be can be mathematically modelled and are discussed below.

3.1 Tension Softening Models

Once the crack start to propagate, aggregate in concrete will provide a bridging resistance along the cracked surface. At the beginning, this resistance to crack propagation will increase according to the crack length. So an additional force or moment is essential to get over this bridging resistance. The bridging force development can mathematically be represented using tension softening laws. The tension softening models are obtained by defining the stress as a function of crack opening displacement w. Since tensile strain cannot be directly measured, crack opening displacement is measured and it is converted to equivalent strain. The different tension softening laws represented as linear, bilinear, trilinear, exponential and power curves and their corresponding mathematical representations are given in Table 1.

Table 1. Different types of bridging force along the cracked surface

Type	Expression	Shape
Linear curve	$\sigma = f_t(1 - \frac{w}{w_c})$	
Bilinear curve	$\sigma = \begin{cases} f_t - \frac{(f_t - \sigma_t)w}{w_c} & for\ w \le w_1 \\ \sigma_1 - \frac{\sigma_1(w - w_1)}{w_c - w_1} & for\ w_1 > w \end{cases}$	
Trilinear curve	$\sigma = \begin{cases} f_t & for\ w \le w_1 \\ f_t - 0.7\, f_t(w - w_1)(w_2 - w_1) & \\ & for\ w_1 < w < w_2 \\ \frac{0.3 f_t(w_c - w)}{w_c - w_2} & for\ \ w_2 < w < w_c \end{cases}$	
Exponential curve	$\sigma = \left(1 - \frac{w}{w_c}\right)^n$ Where *n* is the fitting parameter	
Power curve	$\sigma = f_t\left(1 - \frac{w}{w_c}\right)^n$ Where,0<n<1 is a fitting parameter $\sigma = f_t\, exp(kw^{e})$, where *k* and λ are material parameters *k*= -0.06163 and λ=1.01 for concrete with *f'c* values of 33-47 MPa σ= 0.4 $f_t\left(1 - \frac{w}{w_c}\right)$1.5	

3.2 Cyclic Aggregate Bridging Model

Simon and Kishen[5] studied the fatigue behaviour of concrete by considering the resistance given by the aggregate bridging force in FPZ. Bridging resistance offered at the crack tip is found out by connecting mesoscale properties with the macroscale such as fracture toughness and elastic modulus at interface. The mesoscale and macroscale properties can be equated as,

$$\frac{4a(\sigma_a-\sigma_b)}{E} g_2\left(\frac{a}{D}\right) g_3\left(\frac{x}{a},\frac{a}{D}\right)=\frac{G_F^{Interface}}{\sigma_b}$$

Where, σ_b is the bridging stress, σ_a is the stress due to the applied load, $G_F^{Interface}$ is the size dependent fracture energy of the interface. Therefore, the bridging stress is given by,

$$\sigma_b = \frac{\left(1 - dlog(N)\sigma_t w_0^p\right)}{w_0^p + w^p}$$

Where, N is the number of cycles, w_0 corresponds to the crack opening when the stress has dropped to half of σ_t and p is the shape factor and d is the degradation factor.

3.3 Cohesive Crack Model (CCM)

Apart from the tension softening models, the FPZ can be mathematically modelled using Cohesive Crack Model. Generally, in fracture mechanics based models, a smooth stress-strain curve is considered. But actually, there will be an influence of the formation of micro cracks near the vicinity of macro crack as the macro crack continue to develop. Due to the interference of this micro crack to macro crack, the crack opening will not be smooth. Alam and Loukili [6] presented a new cohesive stress – crack opening relation by introducing the effect of micro-macro crack interactions. The study reveals a transient behaviour of macro crack opening as the micro crack is formed in the surrounding. A new crack opening function ξ is introduced to incorporate the micro-macro crack interaction. They developed a new stress-crack opening response curve which is shown in figure 3. When loading increases, crack opening function ξ shows a transient behaviour. Then steady state is achieved when critical crack opening is reached.

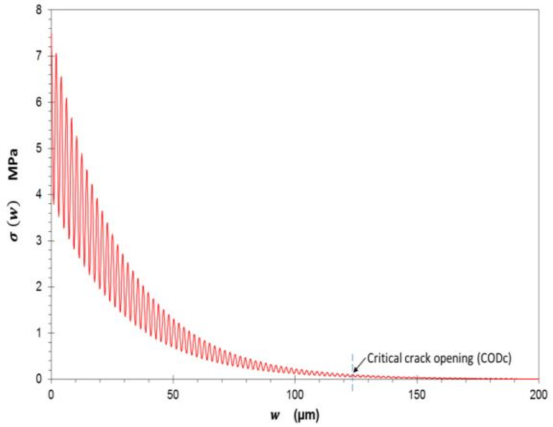


Figure 3. Stress – crack opening curve obtained using cohesive crack model with micro-macro crack interaction [10]

They also developed a modified cohesive crack model which includes the effect of micro-macro crack interaction. In the modified CCM, a damping transitory stress σ_ξ due to micro macro crack interaction is added to the cohesive stress σ_c.

$$\sigma(w) = \sigma_c(w) + \sigma_\xi(w) = [f_t + \cos(2\pi f w)]e^{\lambda w} \quad (3)$$

Where the parameter f_t is to be determined from experiment. In order to determine the parameters f and λ can be determined from regression analysis. Now the parameter can be easily determined using the boundary condition σ (CODc) = 0.

4 Residual Strength Assessment Using Non Linear Fracture Mechanics (NLFM)

Since LEFM principles is not suitable for describing fracture in concrete due to the formation of large process zone, nonlinear fracture mechanics theory is used to predict the residual life accurately. Here, the existence of an inelastic zone called fracture process zone is considered. And also secondary crack formation is considered. Also LEFM principles are suitable for metals where the size of inelastic zone is considerably small. For quasi brittle materials like concrete, residual moment can be calculated more accurately using nonlinear fracture mechanics principles. Many researchers have adopted this method to determine the moment carrying capacity of concrete structures.

4.1 Residual Strength Assessment for Plain Concrete

4.1.1 Fictitious Crack Model (FCM)

Ramachandramoorthy et al [3] has been employed fictitious crack model to study tensile cracking behaviour of plain concrete member under bending. It assumed that a long and infinitesimally narrow fracture process zone is existing at the crack tip. A rectangular simply supported beam is considered which is subjected to an external load P. The normal stress distribution in the cracked section of beam for fictitious crack developing stage is shown in figure 4. The residual moment can be estimated by the equation:

$$M = \int_0^{\propto h} \sigma_1(x)(h-x)Bdx + \int_{\propto h}^{h} \sigma_{11}(x)(h-x)Bdx \quad (5)$$

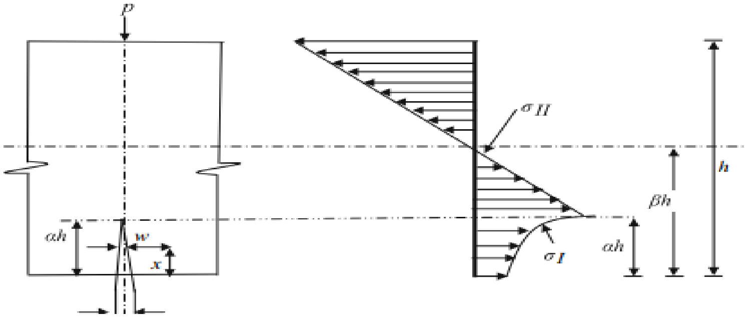


Figure 4. Distribution of normal stress in the cracked section [3]

Where $\sigma_1(x)$ and $\sigma_{11}(x)$ are normal stress functions in cracked and uncracked sections respectively.

Different numerical studies are also conducted to determine the remaining life. Different tension softening models are validated by using experimental values. From the observations it is concluded that, power model and bilinear model shows good result in remaining life prediction. Also the residual moment prediction using these tension softening models are in good agreement with the analytical values. The predicted residual moment and assumed tension softening model follows the similar trend as in the case of predicted remaining life.

4.1.2 Cyclic Aggregate Bridging Model

The residual strength of damaged plain concrete beam in terms of moment carrying capacity is computed by considering the aggregate bridging action by Simon and Kishen [5]. The stress-strain distribution along the crack profile is assumed to be linear as depicted in Figure 5. The moment carrying capacity of the damaged specimen is computed by making use of fundamental concepts of equilibrium.

$$M = M_1 + M_2 + M_3 \tag{6}$$

Where M_1, M_2 &M_3 are the moment of resistance provided by regions R_1, R_2 & R_3

$$M_1 = T_1 * l_1 = T_1\left[D - \frac{kD}{3} - \propto D - l_p - \frac{y_1}{3}\right]$$

$$M_2 = T_2 * l_2 = T_2\left[D - \frac{kD}{3} - \propto D - da - y_1 - x_g\right]$$

$$M_3 = T_3 * l_3 = T_3\left[D - \frac{kD}{3} - \propto D - \frac{2da}{3}\right]$$

Where kD is the depth of neutral axis, l_p length of process zone, $\propto$ crack length to depth ratio, x_g is the centroidal distance

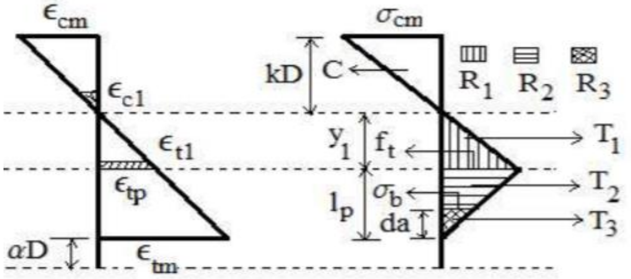


Figure 5. Bending stress-strain distribution for the proposed linear model [6]

In order to study the influence of aggregate bridging action on the residual strength, the moment carrying capacity is defined in function of crack size. The moment carrying capacity determined by with and without the effect of the bridging action. From the study, it is observed that the moment carrying capacity is significantly enhanced when bridging resistance is considered.

4.2 Residual Strength Assessment- Reinforced Concrete

Sain and Kishen [1] examined the effect of tension-softening on the moment carrying capacity of reinforced concrete beam. The moment or load carrying capacity of reinforced concrete beams with a given crack size (or tensile strain or crack opening at the tip of crack) is determined using an inverse method. By assuming a linear crack opening profile, the ultimate moment capacity is determined using the crack tip opening displacement w_c criteria. The moment of resistance can be computed as

$$M_R = M_{UT} + M_{soft} + M_{st} \tag{7}$$

Where M_{soft} is the moment of resistance provided by the softening zone, M_{Ut} is the moment of resistance provided by the uncracked tension concrete and M_{st} is the moment of resistance due to the reinforcement.

$$M_{soft} = T_s x \; lever \; arm = T_s\left[\left(1 - \propto - \frac{k}{3}\right)D - \frac{2}{3}l_p\right]$$

$$M_{UT} = T_{Ut}\left[\left(1 - \propto - \frac{k}{3}\right)D - \frac{xx}{3}l_p\right]$$

$$M_{st} = T_{st}\left[\left(1 - \frac{k}{3}\right)d\right]$$

Where, T_s is the tensile force in softening zone, T_{Ut} is he tensile force provided by uncracked concrete, T_{St} is the Tensile force provided by reinforcement $\propto$ is the relative crack depth, l_p is the fracture process zone length and k is the Neutral axis depth factor

Normalised moments are plotted against crack opening displacements. At the initial stage ie, upto the steel yielding, the moment carrying capacity is steadily increasing as the crack length increases. But after that, the moment starts to decrease, which is reasonable in the case of RC specimen. So, the conclusion from the study is that the assumption of steel yielding throughout the crack propagation regime is obviously overestimates the capacity of the member during the initial crack propagation stage and can be avoided.

5 Conclusions

This paper reviews the various methods used to asses the residual life of plain and reinforced concrete. Also, this review paper analyses various models that are used to mathematically represent the FPZ. Also, it can be concluded that ignoring the FPZ mechanisms under predicts the residual life of concrete members.

- Quasi- brittle materials like concrete will show a strain-softening behaviour. This softening behaviour is due to the formation of an inelastic zone called Fracture Process Zone (FPZ) ahead the crack tip. Fracture process zone (FPZ) is dominated by various toughening mechanisms. Out of these toughening mechanisms, micro cracking and aggregate bridging are the major mechanisms that are responsible for the softening behaviour
- The life of concrete structures can be determined using LEFM principles. But LEFM over predicts the life of concrete like quasi brittle material. . LEFM approach ignores the fracture process zone mechanisms. So Remaining life of concrete structures can be predicted accurately by considering FPZ mechanism.
- The post-peak softening behaviour has been mathematically modelled by using different tension softening laws. Out of the various tension softening models, bilinear law predicts fatigue behaviour accurately for plain concrete members.
- When the crack advances beyond an aggregate that continues to transmit stresses across the crack, there occurs a bridging of coarse aggregate until it ruptures or is pulled out. It therefore becomes necessary to include these effects for predicting the mechanical behaviour reasonably well and estimating the residual strength of existing cracked and damaged structures. The bridging resistance offered by the coarse aggregate is seen decrease with crack length and the rate of decrease is large during the initial stages of crack growth. The moment carrying capacity of beams get significantly enhanced when the bridging resistance is considered in the analysis.
- For reinforced concrete, the FPZ is modelled using linear law. It is observed that the capacity of member increases along the crack length when the reinforcement is within the elastic regime, whereas after steel yielding the value reduces with further propagation of crack.

After considering all the models it can be concluded that LEFM approach cannot predict a reliable result due to FPZ in concrete and therefore it is better to adopt nonlinear approach. The residual life can be predicted accurately by considering the FPZ mechanisms. The residual life predicted without considering the FPZ mechanism results in an overly conservative design.

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References

[1] Trisha Sain and J M Chandra kishen (2007), *Residual strength assessment of concrete considering tension softening behaviour*, International Journal for fatigue, 29, 2138-2148

[2] Trisha Sain and J M Chandra kishen (2008), *Fracture stability and residual strength assessment of reinforced concrete beams*, Materials and Structures ,41, 1451-1463

[3] A Rama Chandra Murthy, G S Palani, Nagesh R Iyer, Smitha Gopinath and B K Raghu Prasad (2012),*Residual strength evaluation of concrete structural components under fatigue loading*, Sadhana, 37(1), 133-147

[4] Sonalisa Ray and J M Chandra Kishen (2014) *Analysis of Fatigue crack growth in Reinforced Concrete Beams* , Materials and Structures, 47, 183-198

[5] Keerthy M Simon and J M Chandra Kishen (2016). *Influence of aggregate bridging on the fatigue behavior of concrete.* International Journal of Fatigue, *90*, 200-209.

[6] Syed Yasir Alam and Ahmed Loukili (2020), *Effect of micro-macro crack interaction on softening behaviour of concrete fracture*, International Journal of Solids and Structures, 34-45