Research On Safety Level Of Crack Control For FRP Strengthened Concrete Members

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Abstract: According to the crack-width formula in FRP strengthened concrete structure design codes, the relationship between flexural crack-width formula’s calculation guarantee rate and load combination was studied. A new concept named as “equivalent guarantee rate” was created to evaluate the safety level of flexural crack-width calculation under frequent combination and quasi-permanent combination. With this new concept the safety level of flexural crack-width formula in GB 50608-2010 were evaluated. In the end two revised suggestion about present flexural crack-width formula in GB 50608-2010 were presented: the flexural crack-width formula’s calculation guarantee rate should be lowered from 95% to 85% under characteristic combination, correspondingly the value of characteristic coefficient in flexural crack-width formula should be lowered from 2.1 to 1.8; Alternatively, the flexural crack-width should be calculated under frequent combination in place of characteristic combination.

1 . Introduction

Some experts and scholars at home and abroad have done a lot of research on the crack control of FRP reinforced concrete members. The countries around the world have also specified the crack width calculation and control standards for FRP reinforced concrete members, which also provided the necessary basis for related designs with them [1, 2]. At the same time, some scholars have done a great deal of work on the reliability research of the ultimate state of the ultimate bearing capacity of FRP reinforced concrete structures [3, 4]. However, there are relatively few researches on the control of cracks in concrete structures with FRP reinforcements, especially the level of safety setting around the crack control standards. Based on this, the concept of equivalent guarantee rate was put forward for the relevant provisions of China's current GB 50608-2010 "Fiber Reinforced Composite Materials Construction Engineering Application Technical Specifications" [5] crack control, and the corresponding safety crack setting control level was set. Analytical research provides a reference for the revision of relevant regulations in China.

2 . The concept of equivalent guarantee rate

2.1. Probability significance of equivalent guaranteed rate. GB 50608-2010 gives the formula for crack width of FRP reinforced concrete beam members as follows:
The general form of the crack width calculation formula is as follows:

\[ w = W(F_k, r_s, a_1, a_2, \ldots, a_n). \]  

(2)

In the formula, \( r_s \) is the short-term crack width expansion factor; \( r \) is the crack width expansion factor that reflects the long-term effect, and \( a_1, a_2, \ldots, a_n \) are the component parameters.

When the \( a_1, a_2, \ldots, a_n \) and load combinations are all given, the calculated crack width calculated by using the standard combination (the load effect value under the standard combination is \( F_k \)) according to formula (2) is \( w_{ck} \). Then, in the case where the actual component parameter conditions including the load effect are exactly the same as those in equation (2), if the real component maximum crack width value is \( w_{s} \), the probability that \( w_{ck} \) exceeds \( w_{s} \) is \( P_k = P(w_{ck} > w_{s}) \). Corresponding to the guarantee rate of the calculated value of the crack width under the standard combination, this guarantee rate can also be regarded as the guarantee rate under the action of short-term load, which can be obtained through a large number of tests.

Let quasi-permanent combinations (calculate the value of the crack width calculated by the quasi-permanent combination load effect value \( F_q \) in place of \( F_k \) in equation (2)): \( w_{eq} \); use frequent combination (in equation (2)) The crack width calculated by the load effect \( F_l \) instead of \( F_k \) is calculated as \( w_{ef} \). The probability that \( w_{eq} \) exceeds \( w_{s} \) is \( P_q = P(w_{eq} > w_{s}) \), and the probability that \( w_{ef} \) exceeds \( w_{s} \) is \( P_k = P(w_{ef} > w_{s}) \). In this case, \( P_q \) and \( P_k \) are defined as the equivalent guaranteed rate of the calculated crack width when quasi-permanent combination or frequent combination is used in formula (2). \( P_q \) and \( P_k \) can also be regarded as the probability that the calculated crack width \( w_{eq} \) and \( w_{ef} \) calculated by formula (2) using quasi-permanent combination or frequent combination is not exceeded by actual value \( w_{s} \) in the design reference period. It can clearly be seen that the concept of equivalent guarantee rate proposed in this paper is essentially the extension of the guarantee rate of the original short-term crack width calculation value to the guarantee rate of the calculated crack width during the design reference period.

2.2. Effect of equivalent guarantee rate. At present, it is recognized in the civil engineering world that the index used to measure the structural bearing capacity or the level of safety of the normal use limit state is a reliable index reflecting the failure probability [6]. Under the condition that the current limit state reliability of normal FRP reinforced concrete structures is not sufficiently studied, the equivalent assurance rate index is a reasonable attempt to avoid the calculation of more tedious reliability indexes, and the calculation of crack width for different load combinations is needed. At the time of the crack control standard safety level setting level provides a means for quantitative comparison, can provide a reference and reference for people engaged in related research at home and abroad.

3. GB 50608-2010 Theoretic derivation of the equivalent guaranteed rate of crack width calculation
Based on the calculation values of fracture width in GB 50608-2010 specifications, the formula for calculating the equivalent guaranteed rate of the calculated crack width of the flexural members under different load combinations is deduced. Combining with the commonly encountered dead load plus a simple combination of live load and the corresponding load effect ratio, the equivalent guaranteed rate of calculated crack width of the flexural member in the GB 50608-2010 specification is calculated.

Since the equivalent guarantee rate is derived on basis of the short-term crack width calculation rate assumption, according to the definition of the existing traditional crack width calculation rate guarantee rate, the calculation rate of the short-term crack width calculated value of the bending member is given below. Formula, used for deriving the formula for calculating the equivalent guaranteed rate $P_w$ below:

$$P_w = \Phi\left[\left(\frac{\tau_{sw} - \tau_{sm}}{\delta_w}\right)\right]. \quad (3)$$

In the formula, $\Phi[\ ]$ is the standard normal distribution function; $\tau_{sw}$ is the short-term crack width enlargement coefficient of the flexural member; $\tau_{sm}$ and $\delta_w$ are the average and standard deviation of the flexure member $\tau_{si}$, respectively, and $\tau_{si}$ is the ratio of the $i$ crack width $w_{si}$ on each bent or axial tension member to the average crack width $w_{m}$ on the same element bending or axial tension.

For existing reinforced concrete members, existing experimental studies have shown that $\tau_{sm}=1.0$ and $\delta_w=0.398\approx0.4[7]$. And for FRP reinforced concrete members, the above coefficients are not yet clear. The existing fracture test observations for 24 GFRP reinforced concrete members show that $[2,8]$: the maximum crack width (pitch) at the height position of the GFRP tendon in the uniformly bent section, and the crack width (The ratio of the average value of the spacing) is 1.34, and the ratio of the maximum crack width to the average crack width in the reinforced concrete beam member test conducted as a comparison under the same conditions is 1.42, and the difference between the two is about 6%. It can clearly be seen that although there is a certain difference between the bonding effect of FRP tendons and concrete compared with the bond effect between steel bars and concrete, the FRP tendons reinforced concrete members can be seen from the distribution law of the maximum crack width and average crack width of the same component. There is no significant difference from reinforced concrete components. Based on this, it is considered that for the FRP reinforcement concrete member, the corresponding $\tau_{sm}=1.0$, $\delta_w=0.398\approx0.4$.

Taking the quasi-permanent combination as an example, the calculation formula of the equivalent guarantee rate is given. For the flexural member, the standard combination and the quasi-permanent combination, the tensile stress calculation formula of FRP tendons can be seen in (4) and (5) respectively.

$$\sigma_{k} = \frac{M_{k} + M_{q}}{0.87 A h_0}. \quad (4)$$

$$\sigma_{q} = \frac{M_{k} + \psi_{q} M_{q}}{0.87 A h_0}. \quad (5)$$

In the formula, $M_{k}$ is the permanent load standard value/N; $\sigma_{k}$, $\sigma_{q}$ are FRP tendon tensile stress/(N/mm²) calculated according to the standard combination and quasi-permanent combination; $\psi_{q}$ is the quasi-permanent value coefficient.

By substituting the values of FRP tendons stress calculated from equations (4) and (5) into equation (1), the calculated values $w_{km}$ and $w_{qm}$ of the crack width under standard combination and quasi-permanent combination can be obtained respectively. By substituting different load effect ratio $\rho=M_{k}/M_{q}$, the ratio $w_{qm}/w_{km}$ between the calculated value of the crack width under quasi-permanent combination and the calculated value of the crack width under the standard combination is deduced, as shown in equation (6):

$$\frac{w_{qm}}{w_{km}} = \frac{1 + \psi_{q} \rho}{1 + \rho}. \quad (6)$$
The calculation of the equivalent guarantee rate shall be based on the principle that the calculated value of the crack width under the quasi-permanent combination is equal to the calculated value of the crack width obtained by adjusting the short-term crack width expansion factor under the standard combination:

$$w_{q_{\text{max}}} = t_s^{q} \sigma_n \alpha \tau \psi \frac{1}{E_s} (1.9c + 0.08 \frac{d}{\rho})$$  \hspace{1cm} (7)

In the formula, $t_s^{q}$ is the short-term crack width enlargement coefficient that reflects the equivalent guarantee rate under the quasi-permanent combination, and let $t_s^{k}$ be the short-term crack width enlargement coefficient that reflects the equivalent guarantee ratio under the standard combination, and then the relation formula between $t_s^{q}$ and $t_s^{k}$ can be obtained:

$$\frac{t_s^{q}}{t_s^{k}} = \frac{w_{q_{\text{max}}}}{w_{k_{\text{max}}}} = \frac{1 + \psi_{q} \rho}{1 + \rho}$$  \hspace{1cm} (8)

According to the definition of the equivalent guaranteed rate under the standard combination of this paper, it can be known that $t_s^{k} = \tau_{sw} = 1.66$, according to which, the expression of $t_s^{q}$ is obtained by transposition of equation (8) and is substituted into equation (3).

$$P_{wq} = \Phi \left[ \frac{1 + \psi_{q} \rho}{1 + \rho} - \tau_{s,m} \right]$$  \hspace{1cm} (9)

In the formula, $P_{wq}$ is the quasi-permanent combination of the equivalent guaranteed rate of the calculated crack width of the flexural member.

In the same way, the equivalent guaranteed rate $P_{wf}$ calculation formula for the frequent combination can be obtained, and only the $\psi_{q}$ in the equation (9) can be replaced by the frequency coefficient $\psi_f$.

4. Calculation Results and Analysis of Equivalent Guaranteed Rate

Permanent load combined with civil building floor variable load (abbreviated as $G + L_1$) is selected to calculate the equivalent guaranteed rate of the calculated value of the crack width of the flexural member for each combination of quasi-permanent combinations and frequency combinations. Combining with the current GB 50009-2012 “Load Codes for Building Structures” \cite{9}, corresponding quasi-permanent value coefficients and frequent-value coefficients are taken for different variable load types. The effects of common load effect ratios are considered in the calculation. The calculation results are shown in Figs. 1 to 2.
According to the calculation results shown in Figs. 1 to 2, it can be seen that:

Taking into account the load effect ratio, the mean value of the equivalent guaranteed rate of the calculated crack width for the $G+L_1$ combination is 82.4% under the quasi-permanent combination and 87.7% under the frequency combination. In foreign countries, the guaranteed rate of the calculated value of short-term crack width of concrete structures is generally taken as 80%–95%[10]. According to the practice of ACI 440.1R-15 and the research results of Beeby et al., for the calculation of the crack width of ordinary reinforced concrete members, it is basically appropriate to take the equivalent equivalence rate of more than 80%[11]. For FRP reinforced concrete structures, FRP tendons can avoid the risk of corrosion, such as steel reinforcement, and the corresponding crack width calculation guarantee rate can be more relaxed. Therefore, it is recommended that the corresponding assurance rate be adjusted to about 85% in terms of the calculation of the crack width of the FRP reinforced concrete structure.

To sum up, if the safety standard setting level of the crack control standard under the standard combination of the existing standard FRP reinforcing bar concrete members of the current standard is properly adjusted, it is suggested that the guarantee rate of the crack width formula can be reduced to 85%, and the combined formula (4) is available. Corresponding $\tau_s = 1.414$, in combination with other known data, the characteristic coefficient of the bending member in GB 50608-2010 can be reduced from 2.1 to 1.8.

In addition, the use of quasi-permanent combinations or frequent combinations to calculate the crack width instead of the standard combination can also achieve the purpose of indirectly reducing the level of crack control safety settings. Considering that the quasi-permanent combination coefficient of some variable loads is significantly smaller, the corresponding equivalent guarantee rate is reduced too much. It is suggested that for cracked concrete structures with FRP tendons, crack width calculations can also be performed with frequent combinations.

5. Conclusions
1) Generally speaking the crack control standard specified in GB 50608-2010 is higher than the safety control reserve specified in ACI 400R-15.

2) The concept of "equivalent guarantee rate" was put forward, which was used as a criterion to describe the safety degree of the crack width calculation formula of FRP reinforced concrete members under frequent combination or quasi-permanent combination.
3) Two sets of proposals for revision of the crack width calculation formula are proposed: (1) In the standard combination of the original specification, the calculation rate of the crack width is taken as 85%, and the corresponding force coefficient of the flexural member is reduced from 2.1 to 1.8; (2) Calculation of crack width using frequent combinations instead of standard combinations.

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References
[1] Baena M, Torres L1, Turon A, Mias C. Analysis of cracking behavior and tension stiffening in FRP reinforced concrete tensile elements[J]. Composites: Part B. 2013, 45(1): 1360-1367.
[2] Barris C, Torres L, Vilanova I, Miàs C, Llorens M. Experimental study on crack width and crack spacing for Glass-FRP reinforced concrete beams[J]. Engineering Structures, 2017(131): 231-242.
[3] Ye Lieping, Feng Peng, Lin Xuchuan, et al. Analysis of safety margin indices for structural members with FRP[J]. China Civil Engineering Journal, 2009, 42(9): 21-31. (in Chinese)
[4] He Zheng, Li Xiaoming. Reliability-based design for FRP-reinforced concrete members[J]. Journal of Harbin Institute of Technology, 2008, 40(8): 1177-1183. (in Chinese)
[5] GB 50608-2010. Technical code for infrastructure application of FRP composites[S]. Beijing: China Construction Industry Press, 2010. (in Chinese)
[6] Yao Jitao, Song Can, Liu Wei. Reliability analysis on crack control of concrete flexural members[J]. China Civil Engineering Journal, 2017, 50(03): 28-34. (in Chinese)
[7] Li Yang, Hou Jianguo. Comparison analysis of reliability of crack control criteria for Chinese and foreign concrete design specifications[J]. Journal of Central South University (Science and Technology), 2013, 44(9): 3786-3792. (in Chinese)
[8] Barris C, Torres L, Comas J, Miàs C. Cracking and deflections in GFRP RC beams: An experimental study[J]. Composites: Part B, 2013, 55:580–590.
[9] GB 50009-2012. Load code for the design of building structures[S]. Beijing: China Construction Industry Press, 2012. (in Chinese)
[10] ACI 224R-01. Control of Cracking in Concrete Structures[S]. American Concrete Institute, Farmington Hills, Mich., 2001.
[11] Beeby A W. The Prediction of Crack Widths in Hardened Concrete[J]. The Structural Engineer, 1979, 57A (1): 9-17.