**Short term Crack width Prediction of CFRP Bars reinforced Coral Concrete**

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**ABSTRACT** In order to study the crack development of CFRP reinforced coral concrete under different bending conditions, experimental study and numerical investigation of crack width of steel and CFRP reinforced coral concrete beams were performed. A comparative study of cracking rate, maximum crack height and crack patterns in CFRP bars reinforced coral concrete beams at different stages is made with ordinary steel reinforced coral concrete beams. The results show that under similar reinforcement ratio, the crack width and crack spacing of CFRP reinforced coral concrete beams are larger than that of steel reinforced concrete beams, increasing the reinforcement ratio of test beams can effectively reduce the crack width. The current deign formula from existing design codes overestimates the value of the relative bond characteristic coefficient () and the strain inhomogeneity coefficient (). Therefore, in this paper, the formula for maximum crack width of the beams is developed based on the experimental data, the relative bond characteristic coefficient, the strain inhomogeneity coefficient of the longitudinal reinforcement, the ratio of the maximum crack width to the average crack width () are included in the formula. The formula is validated with test results, the calculated value agrees well with the experimental results. Therefore, can be used for the future design.

**Keywords：**Coral concrete beams; lightweight aggregate concrete; CFRP bars; crack width; average crack spacing; relative slip

**1. Introduction**

Fiber Reinforced Polymer Bar (FRP) has excellent tensile strength, corrosion resistance and electromagnetic resistance. It is an ideal alternative to steel reinforcement in an erosive environment (coral concrete buildings, seaports, islands and reefs, etc.) [1-3]. However, compared to normal steel rebars, the elastic modulus of FRP bars is low, and the bonding performance is poor, which results in large crack width and deflection of FRP reinforced concrete beams under bending, and there are few studies on FRP bar reinforced coral concrete beams. The Lack of sufficient understanding of its structural performance affects the design and use of this new type of structures [4-7].

The existing research is primarily focused on the bond slip of FRP bars and concrete and the influence related parameters on FRP reinforced concrete. Masmoudi and Thriault and other research [8-9]; show that the maximum crack width of FRP reinforced concrete beams is 3~5 times of the crack width of steel reinforced concrete beams under the same conditions Adam and Aiello [10-11] found that the FRP bars with low elastic modulus causing large deflection and cracks will affect the use of the member under normal conditions. The design of the member should be controlled by the deflection. Zeng et al. [12] believes that the formula for the deflection and crack width of the steel reinforced concrete member can be used for FRP bar reinforced cone as long as the influence of the elastic modulus of the FRP bar is considered. RJ Gravina and ST Smith [13] suggest that when calculating the crack width and crack spacing of the flexural members, the bond performance of the FRP bars should be considered. Toutanji et al. [14]; pointed out that the crack formula of ACI 440.1-R can accurately calculate the maximum crack width of single-row FRP bars reinforced beams, but the calculation results of double-row bars are conservative Dias-da-Costa D, Ahmed E et al. [15-16] found that the Eurocode 2 specification overestimates the crack width of lightweight aggregate concrete beams, and the crack development speed varies under different loads. It is recommended to conservatively estimate the deflection

Due to the lack of systematic research on the crack width of FRP reinforced concrete beams, there is no separate formula for calculating the crack width. In current FRP design specifications [17, 22, 23, 24], the calculation [18] for the crack width are still using the same calculation form [19-20] for steel reinforced concrete. There is a lack of experimental data to support the selection of correlation coefficient ( E.g. relative bond characteristic coefficient and the strain inhomogeneity coefficient ,etc.). It needs to pay more attention to the entire process of crack development, especially the development rate at the initial stage of the crack, which is a key stage to affect the crack width. In summary, there are obvious limitations and shortcomings to simply apply current design theory of FRP reinforced concrete structures to FRP reinforced coral concrete structures. To fill this gap, in this paper, the crack development rate, height and crack patterns of CFRP reinforced coral concrete beams are studied by comparison with steel reinforced coral concrete beams. In addition, the formula for crack width from existing FRP concrete design code is modified, new formula for CFRP reinforced coral concrete is developed, which would provide some suggestions for the future CFRP reinforced coral concrete design.

**2. Test program**

2.1 *Test specimens*

In this paper, CFRP bars produced by Zhejiang Haining Anjie Composite Material Co., and their surface finish and basic mechanical properties are shown in Fig. 1 and Table 1. The mix ratio of coral concrete is designed in accordance with "lightweight aggregate concrete technical regulations" JGJ 51-2002. P.042.5 ordinary Portland cement (545kg/m3) produced in Xing'an, Guangxi are used. The coarse aggregate (716kg/m3) is natural continuous graded coral debris from North Harbor of China South Sea. The fine aggregate (830kg/m3) is made of ordinary natural river sand. The water is artificial seawater (153kg/m3) and polycarboxylic acid superplasticizer (1.64kg/m3) is added. At the same time, six cubic (150mm×150mm×150mm) and six prism (150mm×150mm×300mm) concrete specimens were casted and tested after 28 days of curing(In standard curing room, the temperature is 20±2 ℃) under the same conditions as the test beams. The axial compressive strength, tensile spitting strength and elastic modulus of coral concrete were measured. The basic mechanical parameters of coral concrete were shown in Table 2, and the values presented in this table represent the average results.

Eight beams were fabricated with the length of 2400 mm. Their net span is 2100 mm. The sectional dimension is 120mm×250mm, the cover of the concrete is 25 mm, and the diameters of the longitudinal bars are 8 mm, 10 mm and 12 mm, respectively. The diameters of the steel rebars of the comparative study were 14 mm and 16 mm, respectively. The parameters such as size and reinforcement ratio are shown in Table. 3 .

 

（a）（b）

**Fig. 1**. CFRP bars and coral debris.（a）CFRP bars. （b）Coral debris.

**Table 1** Surface finish and mechanical properties of CFRP bars.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Type of bar | Diameter（mm） | Rib height (mm)  /mm | Rib spacing  (mm) | Tensile strength *fcu*（MPa） | Elastic modulus (GPa) |
| CFRP bar | 8 | 0.44 | 8.65 | 1628.3 | 106.4 |
| CFRP bar | 10 | 0.18 | 8.78 | 1515.9 | 108.6 |
| CFRP bar | 12 | 0.53 | 8.93 | 1910.8 | 111 |

**Table 2** mechanical properties of coral concrete.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Concrete strength | water-cement ratio | Cubic compression strength (MPa） | Cylindric compressive strength (MPa) | Tensile splitting strength (MPa) | Young’s Modula (GPa) |
| C45 | 0.28 | 46.4 | 42.6 | 2.56 | 31.6 |

**Table 3 T**ested beams reinforcement details.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Beam | Longitudinal bars | Diameter (mm) | Erection bar | Stirrup | Stirrup spacing (mm) | Reinforcement ratio |
| CRL8-1 | CFRP bar | 8 | Φ6 CFRP bar | CFRP bar | 100 | 0.37% |
| CRL8-2 | CFRP bar | 8 | Φ6 CFRP bar | CFRP bar | 100 | 0.37% |
| CRL10-1 | CFRP bar | 10 | Φ6 CFRP bar | CFRP bar | 100 | 0.58% |
| CRL10-2 | CFRP bar | 10 | Φ6 CFRP bar | CFRP bar | 100 | 0.58% |
| CRL12-1 | CFRP bar | 12 | Φ6 CFRP bar | CFRP bar | 100 | 0.84% |
| CRL12-2 | CFRP bar | 12 | Φ6 CFRP bar | CFRP bar | 100 | 0.84% |
| GJL14-1 | Rebar | 14 | Φ6 CFRP bar | Rebar | 100 | 1.14% |
| GJL16-1 | Rebar | 16 | Φ6 CFRP bar | Rebar | 100 | 1.49% |



NB: Numbers 1-11 indicate the measuring points of the strain gauge.

**Fig. 2** Test rigs and dimension, RC detail of test beams.



**Fig. 3** Test beam loading condition.

2.2 *Instrumentation and loading process*

The test is carried out according to Chinese design code "Standard for Testing Methods of Concrete Structures" (GB50152-2012). The Four-point bending method is adopted. The loading is controlled by load, and the load control system includes the hydraulic jack with a load cell. The load increment is 3kN at each step and using a loading rate of 0.3 kN/s. Each loading step is lasted for 5 minutes. The electronic crack monitor device is used to measure the crack width of the concrete at the height of the longitudinal rebars, and the crack development height and crack development speed are measured and recorded. The interval between each measurement is 9kN. Five dial gauges were installed at mid span, loading point and support to measure the deformation of the test beam under different load conditions. The amount of deformation at the mid-span and loading point minus the amount of bearing settlement, and the maximum deformation is taken as the deflection of the test beam. Dial gauges were also placed at both ends of the test beam at the location of the extended CFRP rebars. Another two dial gauges were placed set on the concrete surface. These four gauges were used to measure the relative slip between the CFRP rebar and the concrete. Because coral concrete is different from ordinary concrete, placing five strain gauges on the concrete is to verify the assumption of a flat section, measure the surface strain change of the concrete, and judge the height change of the compressed area. The test loading device and instrumentation arrangement are shown in Fig 2, and the loading condition of the test beam is shown in Fig. 3.

**3. Test result**

## 3.1 Crack development process

It can be seen from Fig. 4, the cracks can be divided into three types: vertical cracks in the pure bending zone, diagonal cracks in the shear bending zone, and the longitudinal cracks along the direction of the longitudinal reinforcement. For steel reinforced coral concrete beam, cracks were noticed at the load of 15kN in the pure bending zone, and the average crack height is 4.5cm. A diagonal crack was observed at about 26% Pu, and the crack width and crack height development is very slow throughout the loading process. The crack development is slow with the increase of the load.

While for CFRP reinforced coral concrete beams, cracks were first noticed at 9kN, the average crack height reaches 14cm, the initial crack development speed is relatively fast. The reason for the different cracking load is that the elastic modulus of CFRP bars is smaller than that of steel bars, which makes the axial stiffness of CFRP bars test beams smaller than that of steel bars. After 30% Pu (Pu is the ultimate bearing capacity), the vertical cracks in the pure bending zone were not developed further. At this time, the average crack height has reached 80% of the beam height. The first diagonal crack was observed at 23% Pu, and it quickly extends to the loading point with the increase of the load. At this time, the development speed of the diagonal crack is much higher than that of the vertical crack in the pure bending zone. For the longitudinal crack, the CFRP bars reinforced beam has obvious large-area longitudinal cracks in the compression zone when it approaches the ultimate load. The concrete surface at the same height as the longitudinal bars has more transverse cracks and they are connected to each other, and there is a large area of concrete spalling observed.

In contrast, there is no obvious longitudinal crack in the steel reinforced beam and along the direction of the longitudinal rebars. Under the condition of similar reinforcement ratio, the crack development height of CFRP test beam is obviously larger than that of steel reinforced beam, and there are many crack branches. The reinforcement ratio has no obvious influence on the development height of crack. The average crack height at failure is about 90% of the beam height. While, the average crack height at the time of failure of the steel reinforced beam is about 70% of the beam height.

The main reasons for the large deformation and obvious failure patterns of the test beam are as follows: Firstly, after the cracking, the tensile stress at the crack is mainly borne by the longitudinal rebars. The elastic modulus of the CFRP rebar is about 1/2 of the steel rebar, and the bond performance with the coral concrete is weaker compared to normal concrete. Secondly, the CFRP stirrup has poor restraining ability on the coral concrete, which makes the diagonal crack in the bending and shear zone develop rapidly; Thirdly, for FRP rebar, the stress difference between the crack and uncracked zone is larger than that of steel rebar. The radial stress from the bond causes larger longitudinal cracks. In addition, the coral concrete is more brittle than ordinary concrete. Because the coral concrete is a lightweight aggregate concrete.When the concrete is cracked, the crack runs through the coarse aggregate and the section is relatively flat, and the frictional force and mechanical occlusion force between the cracks are lower than that of the ordinary concrete, which causes larger crack height and crack width.



(a)



(b)



(c)



(d)



(e)

**Fig. 4** Crack distribution and development of the test beams: (a) GJL14-1; (b) GJL16-1; (c) CRL8-1; (d) CRL10-1; (e) CRL12-1.

From the comparison of Fig. 4 and Fig. 5, it can be seen that, under the same load conditions, with the increase of the reinforcement ratio of CFRP bars, the crack development speed is slowed down, the average crack width and maximum crack width are also significantly reduced, but their influence on the spacing is not obvious. The number of major cracks in each test beam at the bottom of the beam is between 13-16. As can be seen from figure 5, when the steel reinforced concrete beams GJL14-1 and GJL16-1 are cracked, the average crack width is 0.05mm, the average crack width at failure is 0.55mm and 0.27mm, the maximum crack width is 1.1mm and 0.5mm, respectively, and correspondent crack spacing is 121mm and 120mm. While the average crack width of the CFRP bar reinforced beams is 0.13mm for the first crack, the average crack width is between 0.89~1.33mm, the maximum crack width is between 1.16~2.45mm, and the crack spacing is between 123mm~142mm. In addition, as the reinforcement ratio of CFRP bars increases, the amount of slip in the test beam decreases. The maximum slip of the test beam is 2.45mm, and the minimum slip is 0.59mm. However, no slippage of the reinforced beam occurred.

The main reason is that the elastic modulus of CFRP rebars is low, and the bonding performance with coral concrete is poor, and it is easy to produce relative slip, which makes the crack width relatively large. At the same time, the longitudinal cracks and relative slips of the CFRP rebar under high stress state are the important reasons for the large crack width and spacing in Fig. 5(b). The relative bonding performance of steel bars reinforced coral concrete is better, and the modulus of elasticity is higher, so that the crack width and spacing are relatively small.

 

(a) (b)

**Fig. 5** crack width and slip of for each test beams: (a) Average crack width and slip for each test beams (1 and 2 represent the first and second test beams, respectively); (b) Maximum crack width for each test beams.

## 3.2 Effect of CFRP bar slip on crack width

It should be pointed out that, almost all CFRP bars in test beams have different degrees of slip. Under the condition of the same diameter, the greater the relative slip between the CFRP bars and the coral concrete, the larger of the average crack width, but this law has certain contingency on the maximum crack width, especially under high stress state. The crack width and slip of the test beam are shown in Fig. 5. The slip between CFRP bars and coral concrete has great influence on the ultimate flexural capacity and deflection of the beam, and it is shown in Fig. 6. The structural design should consider the influence of bond slip on the working performance of the flexural members, especially the difference in mechanical properties of the members.



**Fig. 6** Load-deflection curve of test beam.

**4. Existing formula for Short term Crack width**

## 4.1 Existing design formula from the code

In general, the calculation method of the crack width of the flexural members is mostly a linear function of the cover thickness C, the rebar spacing S, the rebar diameter d, the effective reinforcement ratio [21]. In this paper, the maximum crack width, average crack spacing are calculated from the existing formula from FRP design specification and modified based on the experimental results.

### 4.1.1 ACI 440.1R-06

In 2015, the US ACI 440.1R-15 modified the calculation formula of the maximum FRP spacing, and limit the maximum crack width by limiting the maximum FRP spacing. When calculating the maximum crack width, the calculation forms of US ACI 440.1R-15 and ACI 440.1R-06 are consistent. There is no crack spacing calculation, and the crack width is calculated as:

 （1）

Where:  is the tensile stress of the FRP rebar;  is the elastic modulus of the FRP rebar;  represents the ratio of the distance from the neutral axis to the bottom edge of the tension zone and the distance from the neutral axis to the center of the longitudinal bar;  is bond characteristic coefficient, take 0.6<<1.72, take 1.4 when the experimental data is missing;  is the distance from the bottom of beam to the gravity center of the longitudinal bar; is the spacing of the longitudinal bar.

### 4.1.2 JSCE(1997)[23]

In Japanese Design Guide JSCE(1997)[23], the maximum crack width and average spacing are calculated as follows:

 （2）

 （3）

Where:  is the bond characteristic coefficient, usually take 1.0~1.3, but the specification considers that the FRP bars are similar to steel bars, often taking 1.0; *c* is the thickness of the concrete protective layer;*cf* is the spacing of the longitudinal bars; φ is the diameter of longitudinal FRP, reinforcement;  is the tensile stress of the longitudinal FRP, reinforcement;  is the elastic modulus of the FRP;  is the strain used to evaluate the crack width increment caused by the shrinkage and creep of the concrete, generally 150 × 10-6.

### 4.1.3 CNR-DT 203/2006[24]

In Italian Design Guide CNR-DT 203/2006[24], the maximum crack width and average spacing are calculated as follows:

 （4）

 （5）

Where: *β* is a coefficient relating average crack width to the characteristic value, to be set equal to: 1.7 for cracking due to loads.  is the average strain accounting for tension stiffening, shrinkage, etc.; *k1* is a coefficient accounting for the bond properties of the FRP bars, to be set equal to 1.6; *k2* is a coefficient depending upon the strain diagram (0.5 for flexure, 1.0 for pure tension); *db* is the equivalent diameter of the FRP bars, in mm; if bars of different diameter are used, their average value can be considered; is the effective reinforcement ratio, equal to *Af* / *Ac,eff* .

### 4.1.4 GB 50608-2010[17]

Chinese design code "Technical Specifications for the Application of Fiber Reinforced Composites Construction"2010 [17] gave the calculation formula for the crack width and average crack spacing of the FRP bars:

 （6）

 （7）

 （8）

Where: ψ is the strain unevenness coefficient of the longitudinal reinforcement;  is the tensile stress of the longitudinal reinforcement;  is the elastic modulus of the FRP rebars; c is the thickness of the concrete cover;  is the equivalent diameter of the FRP bars in tension zone;  is the Effective reinforcement ratio of FRP bars;  is the bond coefficient of FRP bars in the tension zone,  ,0.7 is taken when the data is lacking;*ni* is the number of FRP bars of the ith type in the tension zone; *di* is the i-type FRP bars of the tension zone diameter.

### 4.1.5 Formula of Dong et al. [18]

Dong et al. [18] studied the bond characteristic coefficient of FRP bars, the force characteristic coefficient of the member and the value of the relevant parameters. The crack width of the FRP reinforced concrete beam is calculated as follows:

 （9）

 （10）

 （11）

Where: take1.0, the remaining symbols is same as formula (6).

4.2 Comparison of formula of different specifications

It can be seen from Fig. 7 that under the normal design load (*w*max=0.5mm), the existing calculation formulas significantly underestimate the crack width of the CFRP reinforced coral concrete beam. The difference significantly increased when load increases, and the average crack width calculation also has a large error. Among them, the crack calculation formulas of the United States, Italy and Japan consider the factors of bond characteristic coefficient, cover thickness, longitudinal bars spacing and rebar diameter. therefore, they can accurately predict the initial crack width. The crack width is similar in the initial stage of cracking, but as the load increases, the prediction difference increases. In the crack calculation formula of China FRP specification and that proposed by Dong et al. [18], longitudinal strain non-uniformity coefficient and effective reinforcement ratio are considered, which reduce the prediction error under normal design load as well as the average crack width. But the calculation formula underestimates the crack width of the CFRP reinforced coral concrete beam before it achieves the maximum crack width allowed (0.5 mm).

There are two main reasons for this kind of calculation error: Firstly, most of the formulas does not pay enough attention to the elastic modulus of FRP bars and the concrete bond performance of different reinforcement. The calculation of overestimate the bond characteristic coefficient and strain non-uniformity coefficient; Secondly, the bond performance of CFRP bar reinforced coral concrete is relatively poor, relatively large slip results larger crack widths, therefore, causing large differences of crack width between the different beams. However, the reasons for the poor bonding performance between CFRP bars and coral concrete are as follows: first, the low rib height of CFRP bars makes the mechanical bite force and friction force between CFRP bars and coral concrete lower. Second, the strength of coral aggregate is lower, and the intercostal concrete is easier to be cut and broken.

 

(a) (b)

 

(c) (d)

**Fig. 7** comparison of crack widths calculated from existing codes with test results: (a) CRL8; (b) CRL10; (c) CRL12; (d) Comparison of crack spacing.

**5. Modified formula for short term crack width**

Considering the factors discussed in section 4, in this section, the existing crack width formula is further modified based the findings from the test results.

It can be seen from formula (6) that the calculation of the maximum crack width in Chinese code is based on the average crack width, considering the strain unevenness and the force characteristic coefficient of the longitudinal bars. The basic calculation form is as follows. Show:

**** （12）

 （13）

Where: is the maximum crack width;  is the force characteristic coefficient of the crack width of the member;  is the strain non-uniformity coefficient of the longitudinal reinforcement between the concrete cracks;  is the strain of the longitudinal reinforcement;  the average crack spacing;  is the coefficient of increase of crack width under long term load; is the ratio of the maximum crack width to the average crack width under short-term load; the influence coefficient of concrete elongation between cracks on crack width.

The values of the coefficients of the above formula are obtained by reference to the reinforced concrete specification. Therefore, it is necessary to correct and check the values of the coefficients.

## 5.1 Recommended value for Relative bond characteristic coefficient

In Chinese code GB50608-2010, the Relative bond characteristic coefficient is defined as the ratio of the bond strength of the FRP bars and ribbed steel rebars obtained by the bonding test under the same conditions , and 0.7 when the data is lacking. It can be seen from Fig. 7 (d) that when the value of is taken as 0.7, the crack spacing is overestimated. When the value is taken as 1.0 by JSCE (2007) [23] and Dong et al [18], the average crack width is underestimated. The average crack prediction is more inaccurate in CRN-203 [23], as a bond characteristic coefficient K1 of 1.6 is used. At present, many studies have shown that [8-12], the bond strength between FRP bars and concrete is slightly weaker than that of ribbed steel bars under the same conditions. Achillides et al [25]. carried out pull out tests on 131 FRP bars and steel bars, they found that the bond strength of CFRP bars or GFRP(Glass Fiber Reinforced Polymer) bars is about 72% of that of the steel bars. The bond strength of AFRP (Aramid Fiber Reinforced Polymer) bars and HFRP (Hybird Fiber Reinforced Polymer) bars is about 85%~90% of that of steel bars [25], as shown in Fig. 8 ; Zhang et al. [26] carried out the pull-out test on 84 FRP reinforced concrete specimens. The results show that the bond strength between CFRP bars and concrete is 13% to 19% lower than that of AFRP bars and HFRP. In addition, it is found from Fig.9 that the bonding performance between CFRP bars and coral concrete is not good, which makes the strain on the surface of CFRP bars larger.

Due to the few researches on the bond performance between FRP bars and coral concrete, the data of bond strength is lacking. Under the same conditions, the bond strength of FRP bars and concrete is not significantly different from that of FRP bars and coral concrete. Therefore, the calculation result of the bond strength between FRP bars and coral concrete uses the calculation results of the bond strength between FRP bars and concrete. In this paper, the relative bond characteristic coefficient is evaluated according to Chinese code GB50608-2010[17], . However, according to the references [25-27], the relative bond characteristic coefficient of FRP bars basically varies between 0.7 and 1.0. Based on the surface condition of CFRP bars in this paper and the rib parameters in table 1, the relative bond characteristic coefficient takes the median value of 0.85, which is relatively consistent with the actual situation.



**Fig.8** Bond strength between FRP bars or steel bars with concrete (data from reference [25])

 

(a) (b)



(c)

**Fig.9** Strain at each point on the surface of CFRP bar (a) CRL8; (b) CRL10; (c) CRL12.

## 5.2 Calculation of strain non-uniformity coefficient of longitudinally FRP bars

It can be known from equation (6) that the calculation of the unevenness coefficient of the longitudinal bars between the cracks will directly affect the accuracy of the crack width. However, the relevant Chinese design code use the same calculation formula for calculating the strain non-uniformity coefficient of the longitudinal bars between cracks:

 （14）

It has been shown that the bond strength is almost proportional to the tensile strength of concrete. The tensile strength and actual reinforcement ratio of concrete have an important influence on the non-uniformity coefficient. Obviously, the surface hardness and shear strength of steel bars are much larger than ordinary concrete. Therefore, the slip is mainly caused by the shear failure of concrete. When the reinforcement ratio and the steel bar stress are constant, formula (14) is in line with the actual situation that the strain non-uniformity coefficient of the rebar decreases with the increase of the tensile strength of the concrete. However, the mechanism of bond-slip failure between FRP bars and concrete is more complicated, and the relationship between the tensile strength and bond strength are not linear. When the concrete strength is 15 MPa, the bond-slip failure is characterized by crash of the concrete. As the strength of concrete increases, it gradually changes into shear failure of epoxy resin on the surface of FRP bars [25-27]. The relationship between bond strength and tensile strength of concrete is shown in Fig. 10. Therefore, the strain non-uniformity coefficient of FRP bars in the flexural members changes nonlinearly with the increase of bond strength, and the influence of bond-slip failure on the coefficient may be greater than the increase of bond strength.

In order to verify the influence of concrete strength on the non-uniformity coefficient of the longitudinal reinforcement, 60 data of simply supported CFRP, BFRP and GFRP reinforced concrete beams with different strengths of rebars were collected in this paper [28-38]. 30% and 40 % of the ultimate load is used to work out the strain non-uniformity coefficient is calculated in Table 4, and the effect of the concrete tensile strength on the value is shown in Fig. 11. It is found that the strain non-uniformity coefficient of FRP bars increases with the increase of concrete strength. When a certain strength is reached, the strain non-uniformity coefficient no longer changes with the further increase of concrete strength. In addition, the strain distribution of the longitudinal bars under stress is not uniform. The strain unevenness coefficient of longitudinal bars varies within a certain range. Eq. (15) reflects the common trend of FRP bars, so the Eq. (15) is applicable to all FRP bars without special treatment. The coefficient is further derived by fitting these data as following formula:

 （15）



**Fig. 10** Relationship between bond strength and concrete strength. (reference [25])

|  |
| --- |
|  |

**Fig. 11** Relationship between strain non-uniformity coefficient and concrete tensile strength.

**Table 4** The value of the non-uniformity coefficient from different document and test result of this paper.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Literature | Strength of Concrete | FRP | *w*\**h*\**l* (mm) | Af（mm2） | Ef（GPa） | *ftk*（MPa） | （0.3*Mu*） | （0.4*Mu*） |
| [24] | C20 | CFRP | 180\*250\*1800 | 27.68 | 111 | 1.54 | 0.490 | 0.576 |
|  | C25 | CFRP | 180\*250\*1800 | 37.68 | 111 | 1.78 | 0.480 | 0.608 |
| [25] | C25 | CFRP | 150\*350\*2400 | 121.58 | 70.1 | 1.78 | 0.162 | 0.184 |
|  | C25 | CFRP | 150\*300\*2400 | 207.6 | 70.1 | 1.78 | 0.171 | 0.197 |
|  | C25 | GFRP | 150\*300\*2400 | 357.97 | 30.2 | 1.78 | 0.299 | 0.479 |
|  | C25 | GFRP | 150\*250\*2400 | 572.75 | 30.2 | 1.78 | 2.91 | 0.4 |
|  | C35 | GFRP | 150\*150\*2400 | 922 | 49 | 2.20 | 0.868 | -- |
| [26] | C45 | GFRP | 180\*200\*1800 | 157 | 47.3 | 2.51 | 0.408 | 0.689 |
|  | C45 | GFRP | 180\*200\*1800 | 235.5 | 47.3 | 2.51 | 0.556 | 0.856 |
| [27] | C50 | GFRP | 120\*200\*1200 | 151 | 59.7 | 2.64 | 0.659 | 0.833 |
|  | C50 | BFRP | 120\*200\*1200 | 151 | 60.2 | 2.64 | 0.780 | 0.994 |
| [28] | C60 | GFRP | 140\*190\*1800 | 402 | 64.2 | 2.85 | 0.878 | 1.012 |
|  | C60 | GFRP | 160\*190\*1800 | 402 | 64.2 | 2.85 | 0.931 | 0.967 |
| [29] | C30 | BFRP | 200\*300\*1800 | 402 | 60 | 2.01 | -- | 0.465 |
|  | C30 | BFRP | 200\*300\*1800 | 603 | 60 | 2.01 | 0.306 | 0.486 |
| [30] | C30 | BFRP | 180\*250\*1800 | 402 | 49.7 | 2.20 | 0.738 | 0.903 |
|  | C50 | BFRP | 180\*250\*1800 | 401.92 | 49.7 | 2.64 | 0.713 | 0.834 |
|  | C70 | BFRP | 180\*250\*1800 | 602.88 | 49.7 | 2.99 | 0.931 | 1.030 |
| [31] | C35 | BFRP | 100\*200\*13000 | 100.48 | 49 | 2.20 | 0.478 | 0.694 |
|  | C85 | BFRP | 100\*200\*13000 | 100.48 | 49 | 3.10 | 1.000 | 1.050 |
|  | C35 | CFRP | 100\*200\*13000 | 56.52 | 130 | 2.20 | 0.654 | 0.762 |
|  | C35 | CFRP | 100\*200\*13000 | 100.48 | 130 | 2.20 | 0.796 | 0.854 |
| [32] | C45 | BFRP | 180\*250\*2100 | 804.25 | 55 | 2.60 | 0.649 | 0.686 |
| [33] | C30 | CFRP | 200\*400\*3600 | 226.08 | 49.8 | 2.01 | 0.352 | 0.743 |
| [34] | C20 | CFRP | 100\*150\*900 | 100.48 | 111 | 1.54 | 0.187 | 0.454 |
| This paper | C45 | CFRP | 120\*250\*2100 | 100.48 | 106.4 | 2.56 | 0.669 | 0.783 |
|  | C45 | CFRP | 120\*250\*2100 | 10048 | 106.4 | 2.56 | 0.644 | 0.743 |
|  | C45 | CFRP | 120\*250\*2100 | 157 | 108.6 | 2.56 | 0.935 | 0.999 |
|  | C45 | CFRP | 120\*250\*2100 | 157 | 108.6 | 2.56 | 1.040 | 1.086 |
|  | C45 | CFRP | 120\*250\*2100 | 226 | 111 | 2.56 | 0.904 | 0.953 |
|  | C45 | CFRP | 120\*250\*2100 | 226 | 111 | 2.56 | 0.845 | 0.946 |

NB: When ****, ****is 0.2 ;

，is1.0 .

5.3 *ratio of the maximum crack width to the average crack width under short-term load *

The average crack width can reflect the overall cracking and the maximum crack width. The European Committee for Standardization (CEN) considers that the maximum crack width of a flexural member is 1.7 times the average crack width, and the value of this value in the Chinese reinforced concrete specification is 1.66. Yuan [29] compares 435 cracks of GFRP reinforced concrete beams under different loads. It is recommended that the value of the GFRP specimen beam be 1.645. At the same time, 310 cracks of CFRP reinforced concrete beams under different loads are compared. It is recommended the value is 1.398.

In order to obtain the crack ratio t of the CFRP bars reinforced coral concrete beam more accurately, the cracks of 83 CFRP reinforced beam and 29 steel reinforced beam are compared as it shown in Fig 12. Based on these data the ratio  is recommended as 1.4.

The main reasons affecting the difference of the coefficient are as follows: Firstly, the tensile strength of the longitudinal reinforcement is different, and the longitudinal reinforcement of the FRP with high tensile strength can withstand large tensile stress, and the tensile stress of the longitudinal reinforcement is greater than that at the late loading stage. When the maximum bond stress of concrete is used, FRP bars are more likely to produce relative slip in concrete, so that the growth trend of each crack is more consistent; while the tensile strength of rebars (FRP or steel) with lower tensile strength, the failure of beams occurred before yielding of the rebars or the slip of the rebar, so the crack width ratio is generally large. Secondly, the surface hardness and shear strength of the steel bar are greater than that of the FRP bar to the concrete, so that the crack width ratio coefficient of the steel reinforced beam is greater than that of the CFRP bar reinforced beam.



**Fig. 12** ratio of maximum crack width to average crack width.

5.4 *Modified formula*

The value of the force characteristic coefficient under the long-term load is related to the value of each coefficient in the formula (13), such as the influence of the concrete elongation between the cracks, the section size, shape, and thickness of the concrete cover. At present, there is no relevant experimental study on the value of FRP reinforced concrete. The value of crack width increase coefficient under long-term load is the result of different factors such as test environment and load lasting time. At present, only a few long-term experimental tests have been done [4, 39-42]. Therefore, based on current research results, it is difficult to accurately determine the value of the coefficient. At the same time, there are many uncertain factors in the calculation of crack width [43-44].

Therefore, new formula for calculating the maximum crack is developed with consideration of the correlation coefficient under short-term load. According to the above experimental data and theoretical analysis, the stress coefficient  is only considered. The safety factor is taken as 1.2, the value of  is 1.68, and the maximum crack width under short-term load can be calculated as follows:

 （16）

 （17）

 （18）

Where：when<0.01, it is taken as 0.01.

5.5 *Validation of proposed modified formula*

Fig 13 is a comparison of the maximum crack width of CFRP reinforced coral concrete beams calculated by the modified formula of this paper and the measured value from the tests, and the comparison are also shown in Table 5. Since the cracks collected are the width of the crack at the bottom of the beam and the thickness of the concrete cover is inconsistent, the modified formula calculates the crack width at the longitudinal FRP bars. Therefore, according to the research of [8], the crack at the bottom of the beam is converted according to formula (19). The analytical and experimental result of the width of the crack at the FRP rebar is compared. It can be seen that, within the normal design load, the proposed formula can better predict the maximum crack width of the test beam. The calculated value is in good agreement with the experimental value and is generally safe.

 （19）

Where: *w* is the maximum crack width after conversion; *w*max is the measured maximum crack width at the bottom of the beam; *af* is the distance from the center of gravity of the longitudinal rib to the bottom edge of the member; *h0* is the distance from the center of gravity of the longitudinal rib to the top edge of the member.

It should be pointed out that the crack development has a certain randomness, and the relative slip between the CFRP bar and the coral concrete has a great influence on the crack development, which is an important reason discrepancy in Fig 13 (a). In addition, the development rate and crack pattern at the initial stage of crack development is an important stage which controls the maximum crack width.

 

（a） （b）

 

（c） （d）

**Fig. 13** comparison of the maximum crack width of the modified formula and test results (a) CRL8; (b) CRL10; (c) CRL12; (d) The crack width calculated by the modified formula is compared with the test crack width.

**Table 5** Maximum crack width and crack enlargement coefficient.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Reference | | Beam | Test data | | | | | | | | | |  | Modified formula crack width | |
| w (mm) h (mm) d (mm) *Ef* (GPa) c (mm) ftk (MPa) Af (mm2) *Mk* (kN/m) *wmax*(mm) *w* (mm) *wmax* | | | | | | | | | | | | |
| [4] | N-L1-G12a | | 140 | 190 | 12 | 64.5 | 20 | 2.01 | 226 | 3.50 | 0.10 | 0.08 | | | 0.11 |
|  | N-L1-G12b | | 140 | 190 | 12 | 64.5 | 20 | 2.01 | 226 | 3.50 | 0.11 | 0.08 | | | 0.11 |
|  | N-L2-G12a | | 140 | 190 | 12 | 64.5 | 20 | 2.01 | 226 | 4.90 | 0.21 | 0.18 | | | 0.24 |
|  | N-L2-G12b | | 140 | 190 | 12 | 64.5 | 20 | 2.01 | 226 | 4.90 | 0.20 | 0.17 | | | 0.24 |
|  | N-L1-G16a | | 140 | 190 | 16 | 63.4 | 20 | 2.01 | 402 | 3.50 | 0.05 | 0.04 | | | 0.05 |
|  | N-L1-G16b | | 140 | 190 | 16 | 63.4 | 20 | 2.01 | 402 | 4.55 | 0.10 | 0.08 | | | 0.06 |
|  | N-L2-G16a | | 140 | 190 | 16 | 63.4 | 20 | 2.01 | 402 | 5.60 | 0.13 | 0.11 | | | 0.09 |
|  | N-L2-G16b | | 140 | 190 | 16 | 63.4 | 20 | 2.01 | 402 | 5.60 | 0.16 | 0.14 | | | 0.09 |
| [39] | B1-F1 | | 100 | 150 | 9.5 | 46.9 | 25 | 1.78 | 142 | 1.89 | 0.36 | 0.28 | | | 0.29 |
|  | B2-F1 | | 100 | 150 | 9.5 | 46.9 | 25 | 1.78 | 142 | 1.89 | 0.28 | 0.24 | | | 0.29 |
|  | B1-F2 | | 100 | 150 | 9.5 | 46.9 | 25 | 1.78 | 142 | 1.89 | 0.28 | 0.24 | | | 0.29 |
|  | B2-F2 | | 100 | 150 | 9.5 | 46.9 | 25 | 1.78 | 142 | 1.89 | 0.35 | 0.30 | | | 0.29 |
|  | B1-F3 | | 100 | 150 | 9.5 | 44.8 | 25 | 2.01 | 142 | 2.01 | 0.29 | 0.25 | | | 0.31 |
|  | B2-F3 | | 100 | 150 | 9.5 | 44.8 | 25 | 2.01 | 142 | 2.01 | 0.26 | 0.22 | | | 0.31 |
|  | B1-F4 | | 100 | 150 | 12.7 | 49.9 | 25 | 2.01 | 253 | 2.54 | 0.25 | 0.19 | | | 0.12 |
|  | B2-F4 | | 100 | 150 | 12.7 | 49.9 | 25 | 2.01 | 253 | 2.54 | 0.20 | 0.17 | | | 0.12 |
|  | B1-F5 | | 100 | 150 | 12.0 | 66.5 | 25 | 1.78 | 226 | 2.50 | 0.25 | 0.19 | | | 0.15 |
|  | B2-F5 | | 100 | 150 | 12.0 | 66.5 | 25 | 1.78 | 226 | 2.50 | 0.25 | 0.19 | | | 0.15 |
|  | B1-F6 | | 100 | 150 | 15.9 | 42.5 | 25 | 1.78 | 397 | 2.53 | 0.22 | 0.17 | | | 0.10 |
|  | B2-F6 | | 100 | 150 | 15.9 | 42.5 | 25 | 1.78 | 397 | 2.53 | 0.22 | 0.17 | | | 0.10 |
|  | B1-F7 | | 100 | 150 | 15.9 | 41.0 | 25 | 1.78 | 397 | 2.50 | 0.26 | 0.20 | | | 0.11 |
|  | B2-F7 | | 100 | 150 | 15.9 | 41.0 | 25 | 1.78 | 397 | 2.50 | 0.21 | 0.18 | | | 0.11 |
|  | B1-F8 | | 100 | 150 | 9.5 | 120.7 | 25 | 1.78 | 142 | 2.66 | 0.28 | 0.24 | | | 0.22 |
|  | B2-F8 | | 100 | 150 | 9.5 | 120.7 | 25 | 1.78 | 142 | 2.66 | 0.27 | 0.21 | | | 0.22 |
|  | B1-F9 | | 100 | 150 | 9.5 | 152.7 | 25 | 1.78 | 142 | 2.78 | 0.27 | 0.21 | | | 0.18 |
|  | B2-F9 | | 100 | 150 | 9.5 | 152.7 | 25 | 1.78 | 142 | 2.78 | 0.23 | 0.18 | | | 0.18 |
| [45] | 5#15G2 | | 200 | 400 | 15 | 69.3 | 40 | 2.50 | 995 | 38.79 | 0.30 | 0.25 | | | 0.31 |
|  | 2#25G3 | | 200 | 400 | 25 | 60.3 | 40 | 3.10 | 1020 | 34.77 | 0.53 | 0.45 | | | 0.46 |

*w*: According to formula (19), converted maximum crack width at FRP bar from test results;

*wmax* : Predicted using modified formula.

**6. Conclusion**

(1) CFRP reinforced coral concrete beam shows similar response to FRP reinforced concrete beam. When cracking, large crack width and spacing than steel reinforced concrete is noticed. The crack height is about 0.63h0 of the beam; the maximum crack width is more than 1.5mm at failure. The height is about 90% of the beam height.

(2) Increasing the reinforcement ratio of CFRP bars within a certain range can effectively reduce the maximum crack width and average crack width of the beam, and the average crack spacing first increases and then decreases, but when the maximum crack width limit(0.5mm) specified in the design specification is reached, The load is only 23.5% to 38.5% of its ultimate bearing capacity.

(3) The bond performance of FRP bars and coral concrete has an important influence on the development of crack width. The value of the bond characteristic coefficient () is recommended to be 0.85.

(4) A New modified short-term calculation formula of crack width is developed which consider the new suggested value of strain non-uniformity coefficient () , the ratio of the maximum crack width to the average crack width () and the force characteristic coefficient () derived based on the test result. The modified short-term crack width formula can predict the maximum crack width of the test beam accurately

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