Comparative study on calculation methods for local buckling critical stress of rectangular section FRP members

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Abstract. The prediction accuracy of the local buckling critical stress calculation formula of the existing FRP members is analyzed by the experimental data of the local buckling critical stress of the fiber reinforced polymer (FRP) members. Verification of the validity of the finite element model based on experimental data. The comparison results between the numerical simulation critical stress and the predicted value of the calculation formula after adjusting the size of the FRP member are obtained. The variation of the prediction accuracy of the existing calculation formula is studied. The research shows that the predictive value of the calculation method proposed by Strongwell in 1998 underestimated the database test data by 45.4%, and underestimated the finite element simulation result by 46.3%. It is the equation closest to the actual local buckling critical force of the PFRP member. As a general formula, predicting the local buckling critical stress of the PFRP member can improve the material utilization rate. After the research, it was found that the calculation formula proposed by Strongwell Company had a large error with the database test data, and there is still room for improvement.

1. Introduction

Since the advent of Fiber-Reinforced Polymer (FRP) materials in the 1940s, it has been first used in aerospace, military and other fields. It was first used in civil buildings in the 1960s, but it was not until the 1990s that with the rise of FRP-reinforced reinforced concrete structures, the engineering community gradually recognized this new material and extended it to the reinforcement of building structures [1]. FRP material has the advantages of light weight, high strength, convenient construction, good moldability and strong corrosion resistance, so it has become an ideal material for building structures [2].

Compared with traditional structural materials, FRP profiles are a new type of material. Studying and mastering the critical force of new materials is the necessary basis for studying the new structure composed of this new material. At present, one of the main reasons for the slow application and research development of FRP structure is the lack of research on the critical force formula of FRP profiles and comparative analysis. In order to study the basic properties of FRP structures composed of FRP profiles, it is necessary to master the performance of FRP profiles (rods) [3].

In summary, it is necessary to give an accurate formula for calculating the critical force. The finite element model is established and validated by limited experimental data. Establish a database of local buckling critical force of full-size rectangular section FRP members. Using the experimental data and numerical simulation, the accuracy of the formula for calculating the local buckling critical stress of FRP members is studied. The formula for calculating the local buckling critical force of the rectangular
section FRP member with the highest accuracy is proposed, which is of great significance for studying the basic mechanical properties of FRP members.

2. Calculation method for local buckling critical stress of FRP members

The existing calculation method for predicting the local buckling critical stress of FRP members will be described below:

2.1. Bleich suggested method [4]

In 1952, Bleich proposed a full-section buckling analysis method that considers a plate as a single unit constrained by the rotation of adjacent plates. Calculate the equation for the local buckling critical stress of axially compressed long plates made of materials with the same elasticity:

$$F_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \left( \frac{t}{b} \right)^2 \left[ p + 2\sqrt{q} \right]$$

(1)

Where b is the plate width; t is the plate thickness; p and q is the long axis constraint condition.

2.2. ASCE recommended method [5]

The American Society of Civil Engineers (ASCE) gave a local buckling critical stress for predicting isotropic materials in 1984:

$$\sigma_{cr,iso,L} = k_{iso} \frac{\pi^2 E}{12(1-\nu^2)} \left( \frac{t_f}{b_f} \right)^2$$

(2)

$$k_{iso} = 0.45 + \left( \frac{b_f}{a} \right)^2$$

(3)

The equation for predicting the local buckling critical stress of anisotropic materials is also given:

$$\sigma_{cr,ortho,L} = \left[ \frac{\pi^2 E_L}{12(1-\nu_{LT}\nu_{TL})} \left( \frac{b_f}{a} \right)^2 + G_{LT} \right] \left( \frac{t_f}{b_f} \right)^2$$

(4)

where $\sigma_{cr,ortho,L}$ is local buckling critical stress of anisotropic materials; $\sigma_{cr,iso,L}$ is local buckling critical stress of isotropic material; $\nu_{LT}$ is main Poisson's ratio; $\nu_{TL}$ is secondary Poisson's ratio; $t_f$ is flange thickness; $b_f$ is flange width.

This equation can be used to predict $P_L$. If the half wavelength is very large, and $b_f/a$ is very small and the formula can be simplified to:

$$\sigma_{cr,ortho,L} = G_{LT} \left( \frac{t_f}{b_f} \right)^2$$

(5)

Planar shear modulus is not available when FRP material performance parameters are inaccurate or missing. Through the isotropic equation, an estimate of the effect of different stiffnesses on the buckling stress can be obtained.

Use $E_T$ to get equation (2)(2) $\sigma_{cr, iso, L}$:

$$\sigma_{cr,ortho,L} = \sigma_{cr, iso,L} \sqrt{\frac{E_L}{E_T}}$$

Substituting the formula into equation (2) yields a new formula:

$$\sigma_{cr,ortho,L} = k_{iso} \frac{\pi^2 \sqrt{E_L E_T}}{12(1-\nu^2)} \left( \frac{t_f}{b_f} \right)^2$$

After finishing:
2.3 Creative company suggested method [6]

In 2001, Creative used experimental data to present a semi-empirical design equation for the calculation of the local buckling critical stress:

$$\sigma_{cr, ortho,L} = k_{Yuan} \phi \left( \frac{\pi^2 E_L}{12(1-\nu^2)} \left( \frac{t_f}{b_f} \right)^2 \right)$$  \hspace{1cm} (6)

For orthotropic materials, coefficient $\phi$ is 0.8, the buckling coefficient $k_{Yuan}$ is 0.5.

2.4 The method recommended by Strongwell [7]

Strongwell’s 1998 design specification proposed a local buckling critical stress calculation method:

$$\sigma_{cr, ortho,L} = kE_L \left( \frac{2b_f}{t_f} \right)^{1.5}$$  \hspace{1cm} (8)

When the rod size is $203\,mm \times 203\,mm \times 9.53\,mm$, $k$ take 0.5.

3. Test Data

The calculation method of studying the local buckling critical stress of FRP members has certain complexity, and it requires a large amount of data to test the accuracy of the calculation formula. At present, scholars from various countries have studied the critical force of FRP rods through a large number of experiments. Although there are many experimental data, there are not many data on rectangular section FRP rods. The finite element model is established by the existing experimental data, and the numerical simulation is used to increase the accuracy of the verification formula.

The test data is from Cardoso [8], as shown in Table 1, contains: (1) FRP rod fiber and resin type; (2) cross-sectional shape; (3) rod size, effective length $L$ and cross-sectional area $A$; (4) material properties such as half-wave length $a$, Poisson’s ratio $\nu$, longitudinal compressive modulus $E_L$, transverse compressive modulus $E_T$, shear modulus $G_{LT}$, and longitudinal compressive strength $F_{LC}$; (5) Test critical stress $\sigma_{cr}$ and critical load $P_{EXP}$. All test pieces in the database are fixed by bolt joints in the steel frame, applying uniform axial compressive stress to the bars until the bars are damaged.

4. Numerical simulation

In order to study the accuracy of the empirical formula of the local buckling critical stress of the existing FRP members, the experimental data was used for verification. However, due to the lack of experimental data, the finite element model was established using ANSYS software, and the numerical simulation results were used to compare the results with the formula prediction results. In the finite element model, the FRP rods are assumed to be linear elastic and orthotropic, and the relevant geometric and mechanical properties are shown in Table 1. In the structural design, the FRP member is usually not considered for its anisotropy, and it is regarded as a transversely isotropic material, that is, it is regarded as an isotropic material in a macroscopic manner [9], so the model adopts a shell unit (SHELL63). The unit consists of four nodes, each with six degrees of freedom, which can be used to simulate the linear elastic response of a thin-walled section. The finite element mesh selection divides the finite element model into 16 small units.

The local buckling failure mode of the rectangular section bar is shown in Figure 2. The local buckling critical stress predicted by numerical simulation is close to the experimental evidence observed by other researchers. AAE (average value of absolute error) and SD (standard deviation)
were 1.4% and 1.6%, respectively, and the arithmetic mean of the numerical simulation results (Mean) was overestimated by 1.7%. The numerical results were in good agreement with the experimental results. The validity of the finite element model and the reliability of the corresponding numerical results.

Figure 1 Cross sections of Rectangular FRP member

Figure 2 Local buckling failure mode of the members
5. Comparative analysis of calculation results of buckling load

5.1 Comparison of the predicted values of the equation with the experimental results

In order to obtain the high-precision calculation method of local buckling critical stress of FRP members, the experimental results in the database are compared with the predicted values of equations (4)-(8). The deviations between various rod dimensions and equations are shown in Table 3 and Figure 3 (a). It can be seen intuitively that with the $\eta = b_f / l_f$ increase of the value, the local buckling critical stress of the FRP member is also gradually reduced. The mean and standard deviation of the absolute value of the error of equation (8) are 5.8% and 6.2%, respectively, and the critical load prediction value underestimates the database test data 45.4%, the curve of equation (8) and the equations (4)-(7). The curve comparison is the closest to the test results. Equation (4) predicts that the critical load of the FRP member underestimates the actual average carrying capacity of the FRP member over 51.4%, and the prediction accuracy is second only to equation (8). Equation (5) is a reduced version of equation (4). When $b_f / a$ is very small, equation (4) can be reduced to equation (5). The comparative analysis does not pay attention to the ratio of the sum, which may cause the error of equation (5) to be too large.

By comparison, it is found that equation (5) underestimates the local buckling critical load of FRP members, exceeding 90%. Equation (5) predicts that the critical stress of the member is the most conservative, as shown in Figure 3(a), and other test results. Far from deviation. Equations (6) and (7) underestimate the local buckling critical loads of FRP members by 67.6% and 71.1%, respectively. The curves overlap slightly and the prediction results are close. It is a conservative empirical formula for predicting the local buckling critical load of FRP members.

5.2 Comparison of the predicted values of the equation with the finite element simulation results

The finite element simulation results are compared with the experimental results. As shown in Table 1, the mean and standard deviation of the absolute values of the errors are 1.4% and 1.6%, respectively, and the arithmetic mean is overestimated by 1.7%. The numerical results agree well with the experimental results. Comparing the simulation results with the existing equation prediction results, as shown in Figure 3(b) and Table 4, the equations in Figure 3(a) and (b) are similar, with no major deviations. The finite element simulation results are reasonable. Compared with other equations,
equation (8) is closest to the finite element simulation results. The mean and standard deviation of the absolute value of the error are 6.6% and 7.1%, respectively, and the critical load prediction value underestimates the finite element simulation result by 46.3%. The prediction accuracy of equation (4) is second only to equation (8), and the simulation result is underestimated by 51.6%. Followed by equations (6) and (7), respectively, the simulation results are underestimated by 67.5% and 71.2%, respectively, and the curves are close to each other, as shown in curve (6) and curve (7) in Figure 3(b). The most biased prediction result is equation (5), and the arithmetic mean is underestimated by 93.0%, which is too conservative. Equation (8) has the highest prediction accuracy and is very close to the comparison of the previous test data. It can be used as a general formula.

![Figure 3 Comparison of equation prediction critical load and (a) test data and (b) finite element simulation results](image1)

Table 3 Statistics of predictions of the proposed and existing closed-form equations

| Equation | AAE(%) | Mean(%) | SD(%) |
|----------|--------|---------|-------|
| (4)      | 19.2   | -151.4  | 19.6  |
| (5)      | 1.1    | -193.1  | 1.1   |
| (6)      | 6.7    | -167.6  | 7.0   |
| (7)      | 3.1    | -171.1  | 3.4   |
| (8)      | 5.8    | -145.4  | 6.2   |

Table 4 Statistics of predictions of the proposed and the finite element simulation results

| Equation | AAE(%) | Mean(%) | SD(%) |
|----------|--------|---------|-------|
| (4)      | 18.7   | -151.6  | 19.1  |
| (5)      | 1.1    | -193.0  | 1.2   |
| (6)      | 6.3    | -167.5  | 6.7   |
| (7)      | 3.5    | -171.2  | 3.9   |
| (8)      | 6.6    | -146.3  | 7.1   |

6. Conclusion

In order to study the calculation method of local buckling critical stress of rectangular section FRP members, the finite element model is established by the existing experimental data to verify the accuracy of the equation:

1) The equations (4)–(7) proposed by the American Society of Civil Engineers and Creative Pultrusions are relatively conservative, which tends to lead to material waste in structural design.

2) The equation (8) and the equations (4)–(7) proposed by Strongwell are close to the experimental data, which reduces material waste and improves material utilization. It can be used as a general formula to predict the local buckling critical stress of FRP members. Since the predicted value underestimates the database test data by 45.4%, there is room for improvement in the predicted critical stress of equation (8).
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