The Interfacial Bond Stresses in Concrete Filled FRP Tubes

Ali Alinejad, Pedram Sadeghian, and Amir Fam

Abstract Composite structures have gained more attention these days due to their advantages, such as high strength (because of complementary performance of core concrete and FRP tube), excellent durability, light weight, and fast erection. One of the composite structures is concrete filled fiber-reinforced polymer (FRP) tubes (CFFTs). The technology has been investigated in the past, but more attention should be paid to some specific problems, such as quantifying an adequate bond between the tube and the concrete core to act as a full-composite structure, which is an important issue, especially in flexural member. This study proposes a new and simple analytical method calculating the bond stress in flexural members. The equilibrium between the tension and the compression forces is used to develop a MATLAB code to calculate the bond stress. The section is divided into some fibers. The force in each fiber is calculated according to the stress distribution. The total tension and compression forces are calculated by the sum of fibers' forces. The bond stress is the total tension or compression force divided by the interface between the concrete core and the FRP tube. However, the ultimate moment capacities given from tests are used in the simplified method to calculate the bond stress. The tension and the compression forces are calculated based on the arm between them. Finally, the bond stress is determined. Furthermore, a comparison between the bond stress calculated according to two methods and the bond strength data derived from push-off tests is made. The results show that although the bond stresses are a bit more than the bond strength at the ultimate condition, there is an adequate bond between the concrete and the FRP tube before reaching the ultimate condition as the differences are not too much.

Keywords Concrete filled FRP tubes (CFFTs) · CFFT flexural members · Interfacial bond stresses

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1 Introduction

The strengthening of concrete members by bonding and wrapping of fiber-reinforced polymer (FRP) straps, sheets, and shells around the concrete members has increased in recent years. FRP is one of the several choices due to its advantages, such as its high strength, lightweight, lower need for maintenance, and resistance against corrosion. Concrete filled FRP tubes (CFFTs) also are known as composite structures. Using FRPs shows a significant increase in strength and ductility of concrete members. However, the exact behavior of composite structures had to be examined. In this regard, experimental and analytical studies have been started since about 1990. As some of the early attempts to evaluate the behavior of composite structures, Mirmiran and Shahawy [11] and Fam and Rizkalla 4 tested many concrete columns confined by fiber composite. The results show that the use of fiber composites is an effective means of confinement. In addition, Fam and Rizkalla [5] and Samaan et al. [10] presented analytical models for confined concrete by fiber composite, which can precisely predict these types of structures' behavior. Composite tubes were examined experimentally and numerically in recent years [1, 8, 14] as well as FRP tubes with fibers in declined direction, which showed a great nonlinear with high ductility behavior. According to some experimental studies, FRP tube with fibers in $\pm$ 55° direction was considered one of the best choices for composite structures [2, 3, 6, 13].

The problem that should be solved is finding an adequate bond between FRP tube and concrete. The bond should be assessed to understand the exact process between the FRP tube and the concrete. This problem has been addressed in concrete filled steel tubes (CFSTs) by considering effective parameters on the bond strength during many push-off tests, and some equations are defined to calculate the bond strength in different codes. However, this problem remains unsolved in CFFTs. In this study, a detailed method using fiber analysis is developed in MATLAB software to calculate the exact bond stress between the FRP tube and concrete, and a simplified method for two extreme hypothetical cases is presented to calculate the approximate bond stress. Also, several push-off tests data, which have been done to calculate the bond strength in CFFTs, have been collected to compare with bond stresses driven from the presented methods.

2 Basic Assumptions

The equilibrium between the tension and the compression forces is used in the detailed method to develop a MATLAB code to calculate the bond stress. The section is divided into some fibers, and the force in each fiber is calculated by multiplying the area of the fiber to the stress distribution. The total tension and compression forces are calculated by the sum of fibers' forces in tension and compression zones. The bond stress is the total tension or compression force divided by the interface between the concrete core and the FRP tube. However, the ultimate moment capacities given from tests are used in the simplified method to calculate the bond stress. The tension and the compression forces are calculated by dividing the moment capacity to the arm between the tension and the compression forces (fiber analysis is used to find the arm). Finally, the bond stress is determined using the same approach used in the detailed method.

The assumptions for two analytical methods are as below:

1. Plane sections remain plane
2. There is no slip between the concrete and the FRP tube
3. There is no local buckling in FRP tube
4. Concrete tensile strength is neglected
5. Strain compatibility is used to determine the stress distribution.

2.1 Geometry of the Problem and Stress Distribution

Figure 1 shows the cross section and the geometry defined for the problem. D_0 and t are the total diameter and thickness of tube, respectively. D is the average diameter of the tube, and n is the number of fibers by which the section is divided. hi is the thickness of each fiber. The depth of the center of each fiber is shown by $h(i)$. The length of the perimeter of the tube within the fiber on one side is shown by $L(i)$. $\varphi_1(i)$ and $\varphi_2(i)$ are the angles in radians between the vertical center line of the section and the two radiuses bounding the length of the arc $L(i)$, and $\varphi(i)$ is the angle between the vertical center line of the section and the radius reaching to the perimeter at the level of the mid thickness of the fiber. $B(i)$ is half of the width of the fiber. $A_f(i)$ and $A_c(i)$ are the area of the tube and the area of the concrete core at each fiber, respectively. All the parameters are defined as below:

$$D = D_0 - t \tag{1}$$

$$hi = \frac{D}{n} \tag{2}$$

$$h(i) = hi(i - 0.5) \tag{3}$$

$$\varphi_1(i) = \cos^{-1}\left[\frac{0.5D - h(i) + 0.5hi}{0.5D}\right] \tag{4}$$

$$\varphi_2(i) = \cos^{-1}\left[\frac{0.5D - h(i) - 0.5hi}{0.5D}\right] \tag{5}$$

$$\varphi(i) = \cos^{-1}\left[\frac{0.5D - h(i)}{0.5D}\right] \tag{6}$$

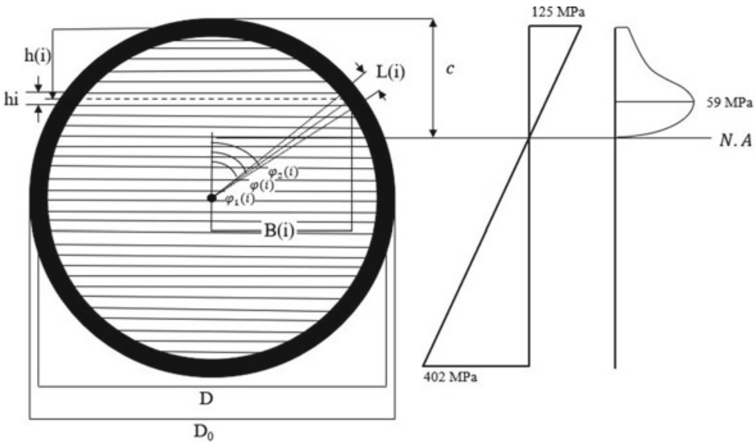

Fig. 1 Geometries and stresses distributions

$$L(i) = 0.5D(\varphi_2(i) - \varphi_1(i)) \tag{7}$$

$$B(i) = 0.5D \sin \varphi(i) \tag{8}$$

$$A_f(i) = 2L(i)t \tag{9}$$

$$A_c(i) = 2B(i)hi - 0.5A_f(i) \tag{10}$$

The centers of gravity for tension and compression zones are determined according to the stress distribution along the section depth.

To calculate the center of gravity, each fiber is considered a cube. The center of gravity for the compression zone is defined as a weighted mean of the center of gravity of the concrete and the center of gravity of the FRP tube in compression. However, the center of gravity in the tension zone is just the center of gravity of the FRP tube. Finally, the center of gravity of each zone is calculated as below.

For compression zone:

$$\mathrm{COG_c} = \left(\sum (0.5D - h(i))A_c(i)\varepsilon(i)\right) / \left(\sum A_c(i)\varepsilon(i)\right) \tag{11}$$

$$\mathrm{COG_f} = \left(\sum (0.5D - h(i))A_f(i)\varepsilon(i)\right) / \left(\sum A_f(i)\varepsilon(i)\right) \tag{12}$$

$$\mathrm{COG_{com}} = (\mathrm{CFF} \times \mathrm{COG_f} + \mathrm{CCC} \times \mathrm{COG_c}) / (\mathrm{CFF} + \mathrm{CCC}) \tag{13}$$

For tension zone:

$$\mathrm{COG_{ten}} = \left(\sum (0.5D - h(i))A_f(i)\varepsilon(i)\right) / \left(\sum A_f(i)\varepsilon(i)\right) \tag{14}$$

2.2 Stress Distribution

The properties of the beam BC given from Helmi et al. study [7] are used for calculations. The model presented by Mander et al. [9] has been selected for the concrete core due to its accurate representation of the material's non-linearity as shown in Fig. 1, while the linear stress–strain relationship is considered for the FRP tube. The stress distributions are defined as below, in which E_{FRP} is the modulus of elasticity of the FRP tube, $\varepsilon(i)$ is the strain at each fiber, f_c' is the compressive strength of unconfined concrete, E_c and E_{sec} are tangent and secant modulus of elasticity of concrete.

FRP in tension:

$$f_t(i) = E_{\mathrm{FRP}}\varepsilon(i) \tag{15}$$

FRP in compression:

$$f_f(i) = E_{\mathrm{FRP}}\varepsilon(i) \tag{16}$$

Concrete in compression:

$$f_c(i) = \frac{f_c' x(i) r}{r - 1 + x(i)^r} \tag{17}$$

$$x(i) = \frac{\varepsilon(i)}{\varepsilon_c'} \tag{18}$$

$$r = \frac{E_c}{E_c - E_{\mathrm{sec}}} \tag{19}$$

$$E_c = 4700\sqrt{f_c'} \tag{20}$$

$$E_{\mathrm{sec}} = \frac{f_c'}{\varepsilon_c'} \tag{21}$$

3 Proposed Methods

Two methods are presented in this section. The sample calculations have been done for the beam given from Helmi et al. study [7] (beam with identification BC) using both detailed and simplified methods, and the results for the other beams are presented in the result section.

3.1 Detailed Method

The equilibrium between the tension and the compression forces is used to develop a MATLAB code to calculate the bond stress. The beam section is divided into some fibers. The force in each fiber is calculated according to the stress distribution. The total tension and compression forces are calculated by the sum of fibers' forces, and the depth of the neutral axis is determined using the equilibrium between total tension and total compression forces. The bond stress is the total tension or compression force divided by the interface between the concrete core and the FRP tube. The equilibrium equation used in this method is shown below, and the neutral axis depth is equal to 0.239 D according to the equilibrium.

$$\sum \mathrm{Eft}\varepsilon_{\mathrm{ft}}(i)\mathrm{Aft}(i) = \sum \mathrm{Efc}\varepsilon_{\mathrm{fc}}(i)\mathrm{Afc}(i) + \sum A_c(i) f_c(i) \rightarrow c = 0.239\,\mathrm{D} \quad (22)$$

Then, the arcs and the bond stresses between the concrete and the FRP tube are calculated in the tension and the compression zones. The location of the neutral axis and the arm is shown in Fig. 2. The 3D schematic of the parameters used in the detailed method is presented in Fig. 3.

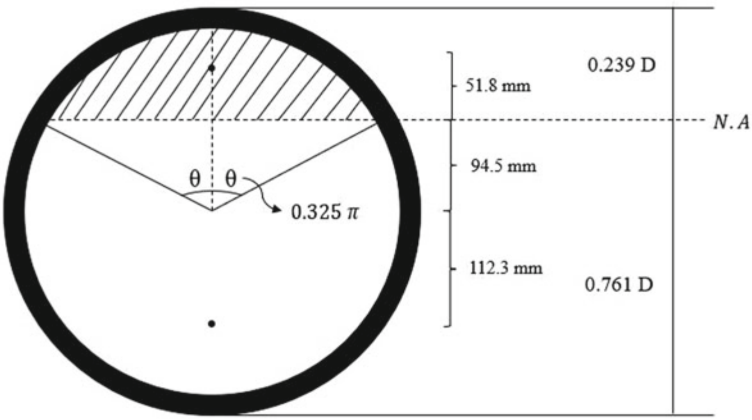

Fig. 2 Cross section of beam based on the equilibrium of the tension and compression forces

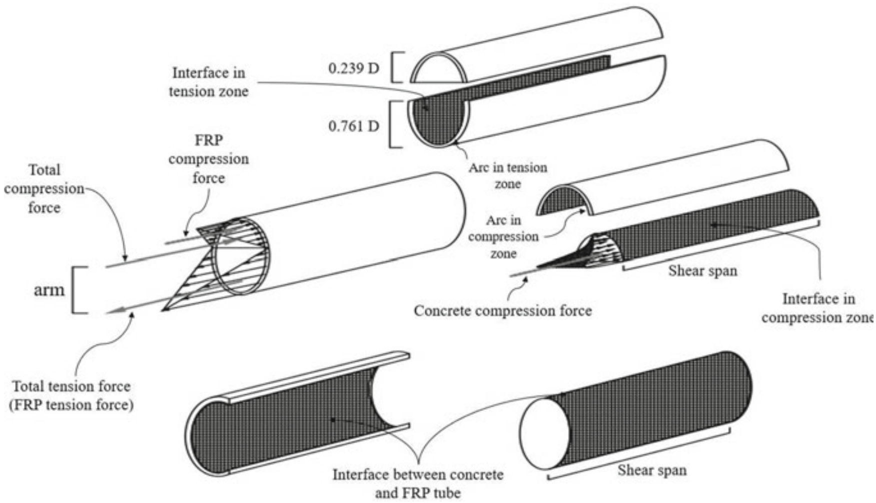

Fig. 3 3D schematic of the parameters used in the detailed method

The calculation for one beam given from Helmi et al. study [7] is presented in this section as an example. The beam ID is BC according to the study. The dimensions and mechanical properties of the beam is presented in Table 1.

The calculations for beam BC (the dimensions are given from Helmi et al. study [7]) in compression zone are as follows:

$$C_c = 759\,\text{kN (according to the fiber analysis have been done in MATLAB)}$$

$$\text{arc}_c = r \times 2 \times \theta = 181.1 \times 2 \times 0.325\pi = 369.8\,\text{mm}$$

$$\tau_c = \frac{C_c}{\text{arc}_\text{c} \times \text{Shear span}} = \frac{759 \times 10^3}{369.8 \times 2000} = 1.026\,\text{MPa}$$

The same calculations have been done for the tension zone as follows:

Table 1 Dimensions and mechanical properties of beam BC [7]

Outer diameter (mm)	Total wall thickness (mm)	Structural wall thickness (mm)	Longitudinal modulus (GPa)	Longitudinal tensile strength (MPa)	Length of the beam (m)	Shear span (m)	Ultimate moment capacity (kN m)	Bond Strength due to push-off test (MPa)
367	5.7	4.8	23.1	402	5	2	200	0.664

$T = 837\,\text{kN}$ (according to the fiber analysis have been done in MATLAB)

$$\text{arc}_\text{T} = r \times 2 \times (\pi - \theta) = 181.1 \times 2 \times 0.675\pi = 768.1\ \text{mm}$$

$$\tau_t = \frac{T}{\text{arc}_\text{t} \times \text{Shear span}} = \frac{837 \times 10^3}{768.1 \times 2000} = 0.545\ \text{MPa}$$

3.2 *Simplified Method*

This section considers two extreme cases for the depth of the neutral axis (c). The first case is the least depth of neutral axis, which can happen in tests, and the second one is the most depth of neutral axis. c is equal to 0.2 and 0.45 D for the first and second cases, respectively.

The ultimate capacities of beams are given from experimental studies [7, 12]. The arm between compression and tension forces is calculated according to fiber analysis. Also, the compression force of FRP tube is calculated. The total compression and tension forces are calculated $\left(C = T = \frac{M}{\text{arm}}\right)$. For calculating the bond stress between the FRP tube and the concrete core, the FRP tube force is deducted from the total force (C) to calculate the concrete force (C_c) in compression zone, while the total force (T) is considered for the tension zone. The interface between concrete and FRP tube in compression and tension zones is calculated (arc $\times$ L). Eventually, the bond stresses in compression and tension zones are calculated $\left(\tau = \frac{\text{Force}}{\text{interface}}\right)$.

The equilibrium of tension and compression forces is neglected in this section, and the arm is calculated as the distance between the compression and tension force according to the fiber analysis.

3.2.1 $C = 0.2$ D

The neutral axis and the centers of gravity of tension and compression zones are shown in Fig. 4 when c is equal to 0.2 D.

The arm and arcs in tension and compression zones, the total tension and compression forces, the concrete force in compression, and the bond stress between the concrete and the FRP tube in tension and compression zones can be determined as follows:

$$\text{arm} = 43.2 + 108.7 + 108.1 = 260\,\text{mm},\ \ M_\text{BC} = 200\,\text{kN m},$$
$$C = T = \frac{M_\text{BC}}{\text{arm}} = \frac{200 \times 10^3}{260} = 769.2\,\text{kN}$$

$$C_\text{FRP} = 82\,\text{kN (according to the fiber analysis)} \rightarrow C_c = 769.2 - 82 = 687.2\,\text{kN}$$

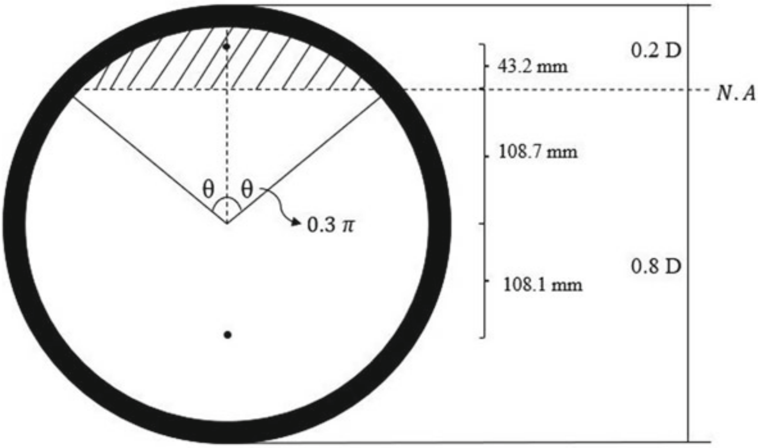

Fig. 4 Cross section of beam when $c = 0.2$ D

$$\mathrm{arc_c} = 181.1 \times 2 \times 0.3\pi = 341.4\,\mathrm{mm}, \quad \mathrm{arc_t} = 181.1 \times 2 \times 0.7\pi = 796.5\,\mathrm{mm}$$

$$\tau_c = \frac{C_c}{\mathrm{arc_c} \times \text{Shear span}} = \frac{687.2 \times 10^3}{341.4 \times 2000} = 1.006\,\mathrm{MPa},$$
$$\tau_t = \frac{T}{\mathrm{arc_t} \times \text{Shear span}} = \frac{769.2 \times 10^3}{796.5 \times 2000} = 0.483\,\mathrm{MPa}$$

3.2.2 $C = 0.45$ D

The neutral axis and the centers of gravity of tension and compression zones are shown in Fig. 5 when c is equal to 0.45 D.

The same calculations are done when c is equal to 0.45 D.

$$\tau_c = 0.313\,\mathrm{MPa}, \quad \tau_t = 0.655\,\mathrm{MPa}$$

4 Verification of the Detailed Method

The ultimate moment capacities calculated by MATLAB software are compared with the ultimate moment capacities given from tests to determine the accuracy of the detailed method.

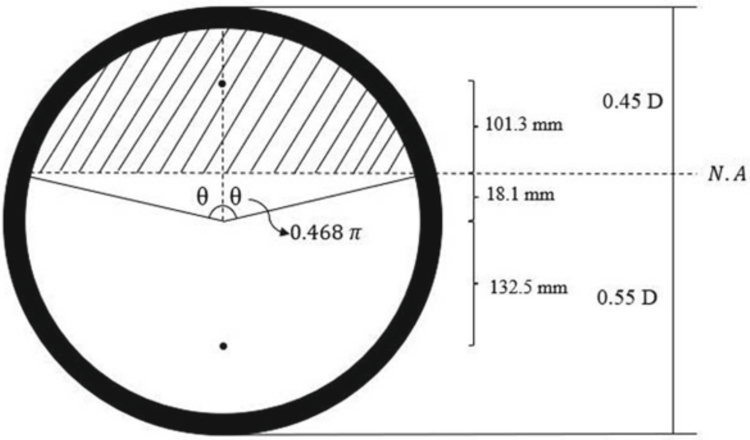

Fig. 5 Cross section of beam when $c = 0.45$ D

Table 2 Comparison between ultimate moment capacities given from tests and MATLAB software

	Specimen ID	Moment capacity (kN m) using MATLAB code	Moment capacity (kN m) given from tests	Difference between moment capacities (%)
Helmi et al. [7]	BC	217.7	200.0	8.1
	BPL	217.7	195.0	10.4
	BPU	217.7	189.0	13.2
Qasrawi and Fam [12]	Beam 10	162.8	155.0	4.8

The differences between the moment capacities driven from tests and the moment capacities calculated using MATLAB software are presented in Table 2.

5 Result and Discussion

The comparison between bond stress calculated according to the detailed method and bond strength given from push-off tests is shown in Table 3. The results show that the bond stresses in the compression zone are greater than the bond strengths, while they are less than bond strengths in the tension zone.

Also, it should be noted that the bond strength given from Qasrawi and Fam's study [12] is related to the hollow section. So, the bond strength is much lower than the bond strength given from another study.

In addition, the comparison between bond stress calculated according to the two hypothesis cases and bond strength given from push-off tests is shown in Table 4.

Table 3 Comparison between bond stress calculated according to the detailed method and bond strength given from push-off tests

	Specimen ID	Moment capacity (kN m) (based on equilibrium)	Bond strength due to push-off test (MPa)	Shear span (m)	Bond stress according to equilibrium According to concrete force in compression	Bond stress according to equilibrium According to GFRP force in tension
Helmi et al. [7]	BC	217.7	0.664	2	1.025	0.538
	BPL	217.7	0.825	2	1.025	0.538
	BPU	217.7	0.538	2	1.025	0.538
Qasrawi and Fam [12]	Beam 10	162.8	0.2	2	0.984	0.563

The bond stresses calculated according to the concrete force in the compression zone are more than bond strengths when c equals 0.2 D, while bond stresses in the tension zone are less than bond strength. However, when c is equal to 0.45 D, bond stresses in the compression zone are less than bond strengths, and bond stresses in the tension zone have different situations.

Generally, the decision can be made that there is an adequate bond between the concrete core and the FRP tube as the bond stresses are calculated according to the ultimate moment capacities, which means that there is not enough bond at the ultimate capacities. However, an adequate bond is provided between the concrete core and the FRP tube before reaching the ultimate capacities.

6 Conclusions

This paper has presented two detailed and simplified analytical methods. The equilibrium between the tension and the compression forces is used for the detailed method to calculate the bond stress. The bond stress is the total tension or compression force divided by the interface between the concrete and the FRP tube, while moment capacities given from tests are used for calculating the bond stress between the concrete and the FRP tube in the simplified method. The exact tension and compression forces are used in the detailed method while they were assumed in the simplified method.

Comparisons between the predicted moment capacities of CFFRs according to the detailed method using fiber analysis and experimental results available in the literature show good agreement.

Although the detailed method shows a good agreement with the test results for moment capacities, it is not completed as the bond stress distribution is not uniform

Table 4 Comparison between bond stresses calculated according to the two hypothesis cases and bond strength given from push-off tests

	Specimen ID	Moment capacity (kN m)	Bond strength due to push-off test (MPa)	Shear span (m)	Bond stress (MPa) N.A = 0.2 D According to concrete force in compression	Bond stress (MPa) N.A = 0.2 D According to GFRP force in tension	Bond stress (MPa) N.A = 0.45 D According to concrete force in compression	Bond stress (MPa) N.A = 0.45 D According to GFRP force in tension
Helmi et al. [7]	BC	200	0.664	2	1.006	0.483	0.313	0.655
	BPL	195	0.825	2	0.978	0.471	0.295	0.639
	BPU	189	0.538	2	0.945	0.456	0.272	0.619
Qasrawi and Fam [12]	Beam 10	155	0.2	2	1.022	0.484	0.344	0.657

through the section. As a result, a new method should be described which is more accurate to find the bond stress distribution through the section.

The results given from the detailed method reveal that the tension zone is the safe zone as the bond strength is more than the bond stress in that zone while the bond strength is less than bond stress in the compression zone according to the ultimate condition. Although the bond stresses between the concrete core and the FRP tube in the compression zone are more than the bond strength when the ultimate condition is considered, there is almost enough bond strength in tension and compression zones before reaching the ultimate condition. However, the simplified method's results show that the bond stresses between the concrete core and the FRP tube are more than the bond strength in ultimate conditions.

This research is not completed, and more exact results will be presented at the conference.

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