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Friction coefficient between FRP pultruded profiles and concrete

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Abstract This paper presents the experimental results of a direct shear test to determine the friction coefficient between fibre reinforced polymer (FRP) pultruded profiles and concrete. The FRP pultruded profile used in this study was glass fibre reinforced polymer (GFRP) I-section. The specimens were composed of a concrete block and a coupon of the GFRP pultruded profile. The experiment was conducted by using the direct shear test method. The parameters investigated included the type of concrete (self-compacting concrete and normal concrete) and the compressive strength of the concrete, as well as the different components (web and flange) of the I-section. The test results verify that the bond behaviour between the concrete and the GFRP pultruded profiles mainly depends on two factors, the friction stress and the adhesion stress. The friction coefficient between the FRP pultruded profiles and the concrete was between 0.5 and 0.6 when the normal stress fluctuated between 0.5 MPa and 2 MPa, and the adhesion stress was about 0.2 MPa. The compressive strength of the concrete and the different components of the I-section have little effect on the friction coefficient, however, the type of the concrete significantly affects this coefficient.

Key words Friction coefficient · Concrete · GFRP pultruded profiles · I-section

1 Introduction

Fibre reinforced polymer (FRP) pultruded profiles are being increasingly investigated in recent years due to their well-known advantages such as superior corrosion resistance, high strength-to-weight ratio and easy installation. Besides using FRP pultruded profiles solely for all FRP structures, several studies have been conducted to explore the application of FRP pultruded profiles in the hybrid structures [1-4]. The performance of the hybrid structure is mainly dependent upon the properties of concrete and FRP pultruded profiles, as well as the bond properties of the interface between the two components [5]. Therefore, it is essential to investigate the bond properties at the interface between the FRP pultruded profiles and the concrete to ascertain the composite action of the hybrid structures.

Pull-out [6] or Push-out [7, 8] tests are traditional methods to investigate the bond stress-slip relationship of FRP (or steel) reinforcement to concrete. Using this technique, the mechanics of the stress transferred by the bond between the FRP reinforcement and concrete were studied. Three factors affected the results: friction due to the roughness of FRP reinforcement, the mechanical interlock of FRP reinforcement against the concrete and the chemical adhesion [6, 9, 10]. For the bond behaviour of FRP pultruded profiles to concrete, the mechanical interlock effect could be ignored since the surface of the FRP profiles is traditionally smooth without any ribs. Therefore, the bond behaviour between the concrete and the FRP pultruded profiles is usually considered to depend on two factors, the friction behaviour and the chemical adhesion. However, the existing analysis about these two factors was only qualitative analysis, and no further studies were conducted to investigate the accurate value of the friction stress and the adhesion stress.

The friction coefficient is a significant parameter to evaluate the friction stress. This parameter is usually required in the finite element (FE) analysis to simulate the contact of two interfaces by using the theory of Coulomb friction [11]. For example, when simulating the contact between the steel and the concrete by using ABAQUS, the friction coefficient 0.57 is used and was tested by Rabbat and

Russell in 1985 [12]. However, the friction coefficient between the FRP pultruded profiles and the concrete has not been given enough attention. Due to the lack of this parameter, the contact at the interface between the concrete and the FRP pultruded profile in the composite structures is usually simplified as a rigid connection in the FE model [13,14]. However, this simplification may not be accurate due to the slip that occurs between the concrete and the FRP pultruded profile in the hybrid beams. For example, when the GFRP rectangular tubes are filled with concrete to form a type of composite beam [15], the flexural test results show that the slip between the filled concrete and the FRP tube was apparent. Therefore, the rigid connection between the two components in the FE model is inaccurate unreasonable. As a result, it is essential to determine the friction coefficient between the FRP pultruded profiles and the concrete, thus developing a more accurate FE model for the hybrid structures reinforced by the FRP pultruded profiles.

In this experimental study, the direct shear test method was employed to determine the friction coefficient between the FRP pultruded profiles and concrete. The FRP pultruded profiles used were GFRP I-section. The specimens were divided into five groups based on the different configurations. The four specimens in each group were tested under different normal stress levels of 0.5 MPa, 1 MPa, 1.5 MPa and 2 MPa. The experimental results discussed herein include the failure mode of the specimen, shear stress-displacement curves and the relationship between the ultimate shear stress and the normal stress.

2 Experimental Program

2.1 Test specimens

The specimens were composed of a concrete block (100 mm × 100 mm × 100 mm) and a coupon cut from the GFRP I-section. The dimension of the I-section was 10 mm in thickness (both in the flange and web), 100 mm in width and 200 mm in height. The coupons from the different components (flange and web) of the I-section were investigated. One type of the coupon was cut from the flange

and the other one type from the web as shown in Fig. 1. Coupon A was taken from the flange and had a T section with a flange width of 100 mm and web length of 50 mm. Coupon B was taken from the web and had the dimensions of 100 × 100 mm. Due to the different shapes of the coupons, two types of specimens (Type A and Type B) were cast as shown in Fig. 2. Type A refers to the concrete block with a coupon from the flange of the GFRP I-section. Type B refers to the concrete block and a coupon from the web of the GFRP I-section.

The label of the specimens consists of three parts. The first part is the number 30 or 40, which indicates the nominal compressive strength of the concrete, followed by a letter F or W indicating the coupons taken from the flange (F) or the web (W); this is then followed by a number to represent the normal stress loaded in the specimen; the letter S in Group 30FS means that self-compacting concrete was used, and the letter N in Group 40WN indicates that the effect of the adhesion is eliminated.

A total of 20 specimens were cast and tested, and the specimens were divided into five groups. The configurations of the specimens are shown in Table 1. In Group 30FS, the specimens were tested to determine the friction coefficient between the self-compacting concrete and the I-section, and the nominal compressive strength of the self-compacting concrete was 30 MPa. The influence of the type of the concrete was investigated by using traditional concrete with a nominal compressive strength of 30 MPa in Group 30F. For Group 40F, the concrete with a nominal compressive strength of 40 MPa was employed to estimate the influence of the compressive strength of the concrete on the friction coefficient. The coupons in Group 40W were taken from the web of the I-section, aiming to study the influence of the coupons from the different locations of the I-section on the friction coefficient. Group 40WN is a reference group, in which the specimens had the same configurations and curing condition as the specimens in Group 40W. Nevertheless, the coupon and the concrete block for these specimens were separated before the test commenced. In this manner, the effect of chemical adhesion at the interface of the specimens in Group 40WN was eliminated, and only the friction effect was left. One

specimen in each group was tested under a normal stress of 0.5 MPa, one at 1 MPa, one at 1.5 MPa and the final one at 2 MPa.

2.2 Determination of normal stress

The direct shear test requires the specimens to be tested under different normal stresses. The normal stress in the direct shear test should be close to the actual normal stress for the FRP pultruded profiles, to determine the friction coefficient as accurately as possible. If the normal stress in the test significantly deviates from the actual normal stress, the test results will probably be affected. For example, the actual normal stress probably fluctuates between 0 MPa and 10 MPa, if a normal stress of 100 MPa is loaded on the specimens, the test results will be unreliable. However, it is traditionally difficult to achieve the actual range of the normal stress at the interface of the FRP pultruded profiles due to the technical issue. Therefore, the FRP-confined concrete method was used to indirectly estimate the general range of the normal stress on the FRP profiles due to the similar material properties, for example, both FRP wraps and FRP pultruded tubes could be used to reinforce the concrete columns. Hence, the normal stress in this direct shear test was determined as below. It should be noted that the theory of FRP-confined concrete is only an approximate approach to evaluate the order of magnitude of the normal stress, and the accuracy of this method may need to be improved if a more comprehensive theory is available.

Over the last few years, a significant number of experimental and theoretical studies have been conducted about FRP-confined circular concrete specimens [16-19]. The literature shows that when an FRP-confined circular concrete specimen is tested under axial compression, the concrete expands and this expansion causes the lateral confinement pressure (i.e. normal pressure) on the FRP jackets as shown in Fig. 3. The lateral confinement pressure can be calculated by:

$$f_l = \frac{2f_{FRP}t}{d} \quad (\text{Eq. 1})$$

where f_l is the lateral confinement pressure, f_{FRP} is the tensile strength of the FRP in the hoop direction, t is the total thickness of the FRP wrapped at the specimen, and d is the diameter of the column specimens. Most of the confinement pressures were found not more than 10 MPa in accordance with the existing studies [20-22]; additionally, when testing the friction coefficient between the concrete and the steel [12], the normal pressure was recommended to be about 1 MPa. Taking all the above-mentioned factors into consideration, the four normal pressures in this direct shear test were determined to be 0.5 MPa, 1 MPa, 1.5 MPa and 2 MPa.

2.3 Material test

The GFRP I-section investigated was made from vinyl ester resin with E-glass fiber and manufactured by using the pultrusion process. The mass density of the pultruded profile is 1950 kg/mm³. The stacking sequence of the plies is the form of $[0^\circ / +45^\circ / 0^\circ / -45^\circ / 0^\circ / -45^\circ / 0^\circ / +45^\circ / 0^\circ]$, and the fibers in 0° direction coincided with the longitudinal axis of the GFRP I-section. The properties of the I-section were determined in the longitudinal direction, since the majority of the GFRP fiber is traditionally laid out in this direction. The coupons were cut from the flange and web. The tensile test was conducted by using ISO 527 and the dimension of the coupons was 25 mm $\times$ 250 mm. The compressive strength was determined by using ASTM D695 [24], and the dimension of the coupons was 12.7 mm $\times$ 38.1 mm. Five coupons were tested to determine the average tensile or compressive strength, and the test results are shown in Table 2. It should be noted that the different standards (ISO and ASTM) were used to determine the material properties of the GFRP pultruded profiles. This is because the tensile test method provided by ISO standard, and the compressive strength method provided by the ASTM standard, had been proved to be more effective approaches by several studies [25,26] to determine the materials properties of the GFRP pultruded profiles.

The compressive strength of each batch of concrete was determined by three cylinders with 100 mm diameter and 200 mm height by using AS 1012 [27]. The mean compressive strength of the concrete was 32.8 MPa in Group 30FS, 33.4 MPa in Group 30F and 42.3 MPa in Groups 40F, 40W and 40WN. It should be mentioned that the size of the specimens was small in this experimental study, which were cast with the other large specimens of the authors together by using the self-compacting concrete provided by a local supplier to ensure the quality. The maximum aggregate size of the self-compacting concrete was 10 mm. The workability of the fresh concrete was examined by using slump flow tests [27], and the slump flow was found to be 512 mm.

2.4 Fabrication of specimens

The first step of the fabrication of specimens was to cast the concrete block. The coupons were cut from the flange and web of the GFRP I-section as shown in Fig. 1, and all the surfaces were carefully cleaned by using the acetone to ensure the smooth surfaces. The concrete was manually cast with the coupons together. The specimens were demolded after seven days (Fig. 2) and then cured in a moist environment to the age of 28 days.

The dimension of the cross-section of the shear box is 120 mm × 120 mm, which is larger than that of the concrete block as shown in Fig. 2. Therefore, the high strength plaster was filled into the gap between the concrete and the shear box to fix the specimen in the shear box. The preparation process included three steps: (1) the concrete block was placed into a customized plastic formwork which has the same dimension as the shear box; (2) the high strength plaster was then poured into the formwork as shown in Fig. 4, and the interface between the coupons and the concrete block was ensured to be level during the casting of the plaster; (3) after 40 minutes, the specimen encased by the plaster was demolded and cured in ambient environment. After seven days, the specimens were tested by using the direct shear test.

2.5 Test setup and failure mode

Direct shear test is a laboratory or field test used by geotechnical engineers to measure the shear strength properties of soil or rock material. Several direct shear tests have been conducted by using the modified apparatus to obtain the friction coefficient between the steel and the asphalt [28], or the friction coefficient between sand and steel [29]. Therefore, the direct shear test has been demonstrated to be an effective approach to determine the friction coefficient. The TREADWELL [30] test apparatus, shown in Fig. 5(a) was used in this experimental study.

Figure 5 (b) shows the test setup of this direct shear test for specimens in Type A. The specimens were fixed in the top shear box, and one steel plate was placed below the bottom shear box to adjust the location of the shear interface. The shear interface should be within the gap between the top shear box and bottom shear box. When the specimens in Type B were tested, the height of the steel plate was adjusted due to the differing height of the specimen. In this case, a thin layer of kaolin was placed between the steel plate and the specimen to eliminate the effect of any gap at the interface. When the setup was finished, the specified normal pressure was loaded at the top shear box. Then, the shear force controlled by displacement was applied on the bottom shear box at a rate of 0.1 mm/min. The test was terminated when the ultimate shear load was reached.

Among the 20 specimens tested in this experimental study, one specimen failed due to the operation error, and the tests of the other 19 specimens were successful. All the specimens showed similar failure mode. The coupons and the concrete block were separated totally at the interface after the peak load. Both the surfaces of the concrete and the GFRP profiles were smooth, which means that the failure of the samples occurred at the interface. If the failure had been found at the concrete block or the GFRP profiles, rather than the interface, the test results would not allow evaluation of friction and adhesion.

3 Experimental results and Analysis

3.1 Shear stress – displacement curves

Figure 6 shows the shear stress-displacement curves of the Group 30FS, and similar curves were revealed for the other three Groups (30F, 40F and 40W). After some fluctuations in the initial stage, the shear stress experienced an almost linear increase until the failure of the specimen. The ultimate shear stress and the corresponding normal stress are summarized in Table 3. Although the specimens were tested under a constant normal load, it should be noted that the actual normal load was slightly fluctuated because of the shear dilatancy. As such, Table 3 reports the nominal normal stress and the actual normal stress.

The shear stress-displacement curves of Group 40WN (Fig. 7) are different with the other four groups. When the test began, the shear stress was linearly increased to the ultimate stress, and then was kept constant. The sudden descending stage after the ultimate load in the other four Groups (30FS, 30F, 40F and 40W) was not observed. Based on the difference of the shear stress-displacement curves between Group 40WN and Group 40W, it is confirmed that the sudden drop of shear stress in Groups (30FS, 30F, 40F and 40W) were caused by the loss of the chemical adhesion.

3.3 Ultimate shear stress – normal stress curves

Figure 8 shows the curving fitting results of the ultimate shear stress and the corresponding normal stress in the Group 30FS. The other three Groups (30F, 40F and 40W) demonstrated similar fitting results. The fitting result of Group 40WN is shown in Fig. 9. Based on the fitting results, the linear relationship between the ultimate shear stress and the normal stress is revealed and the relationship is shown as below:

$$\tau = \rho\sigma + c \quad \text{Eq. 2}$$

where τ is the shear stress at the interface, μ is the friction coefficient, σ is the normal stress and c is a constant.

The fitting results confirmed that the shear stress (τ) at the interface mainly depends on two factors; (1) the friction stress ($\mu\sigma$) in which the friction coefficient (μ) is a constant and is increased with the increase of the normal stress (σ); (2) the adhesion stress (c), which is a constant and does not change with the increase of the normal stress. Therefore, when the effect of the adhesion stress was eliminated in Group 40WN, only the friction stress was kept but the adhesion stress was decreased to 0.04 MPa (almost 0 MPa) as shown in Fig. 9. The above-mentioned fitting results and the existing analysis show the same conclusion: that the bond between the concrete and the GFRP pultruded profiles is composed of two factors, friction stress and adhesion stress. More importantly, this study provides the accurate value of the friction coefficient and the adhesion stress. Table 4 summarizes the friction coefficient and the adhesion stress determined in this research study.

The influence of the type of concrete on the friction coefficient was investigated through the comparison between Group 30FS and Group 30F. The concrete in the two groups had similar compressive strength, but the concrete used in Group 30FS was self-compacting concrete and it was normal concrete in Group 30F. The friction coefficient in Group 30FS was 0.51, which is smaller than that (0.62) in Group 30F. This may be because the high deformability of self-compacting concrete caused a smoother interface of the concrete block, leading to a smaller friction coefficient.

The compressive strength of concrete had little effect on the friction coefficient based on the comparison between Group 30F (0.62) and Group 40F (0.58). The effect of the different parts of the I-section (web and flange) on the friction coefficient was investigated through the comparison in Group

40F and Group 40W. No obvious difference was found for the friction coefficient between these two groups. Therefore, the different parts of the I-section have little effect on the friction coefficient.

It should be noted that the above-mentioned analysis, including the friction coefficient and the adhesion stress, was objective and reliable when the normal stress was within 0.5 MPa to 2 MPa. However, the friction behaviour and the friction coefficient out of this range (0.5 MPa to 2 MPa) still needs to be further confirmed due to the limitation of the test apparatus and lack of references in this aspect. More attention should be paid to these details and further experimental studies are essential to involve more variables, thus developing a comprehensive theoretical model.

4 Conclusions

The friction coefficient between GFRP pultruded profiles and concrete was investigated in this paper, and a total of 20 specimens were tested by using a direct shear test method. The parameters involved in this study included the type of concrete, the compressive strength of concrete and the different components of the I-section. Conclusions as below could be drawn based on the experimental results.

1. Direct shear tests verify that the bond behavior between the concrete and the FRP pultruded profiles mainly depends on two factors, friction stress and adhesion stress.

2. When the normal stress varies between 0.5 MPa and 2 MPa, the value of the friction coefficient is between 0.5 and 0.6, and the adhesion stress is about 0.2 MPa.

3. Compared with the self-compacting concrete, the friction coefficient between the normal concrete and the FRP pultruded profiles is approximately 20% larger.

4. The compressive strength of concrete and the different parts of the I-section (web and flange) have little effect on the friction coefficient.

This experimental study fulfils the research gap regarding the determination of the friction coefficient between the GFRP pultruded profiles and concrete. The friction coefficient is significant to warrant investigation of the application of GFRP pultruded profiles in the composite structures, and it also contributes to developing a more accurate FE model for the composite structures reinforced by the FRP pultruded profiles. More variables should be taken into the consideration in the next step to improve the accuracy of this friction coefficient, for example, the concrete mix design as well as the surface condition of the FRP pultruded profiles.

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Compliance with Ethical Standards

- The authors declare that they have no conflict of interest.
- This study was not funded by any company.
- Research did not involve Human Participants and Animals
- Both authors conducted this study and they prepared this manuscript.

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Table 1 Test matrix

Group	Specimen	Concrete (MPa)	Position of coupon	Normal pressure (MPa)	Type of specimens
A	30F0.5S	32.8 (Self-compacting)	Flange	0.5	Type 1
	30F1S	32.8 (Self-compacting)	Flange	1	Type 1
	30F1.5S	32.8 (Self-compacting)	Flange	1.5	Type 1
	30F2S	32.8 (Self-compacting)	Flange	2	Type 1
B	30F0.5	33.4	Flange	0.5	Type 1
	30F1	33.4	Flange	1	Type 1
	30F1.5	33.4	Flange	1.5	Type 1
	30F2	33.4	Flange	2	Type 1
C	40F0.5	42.3	Flange	0.5	Type 1
	40F1	42.3	Flange	1	Type 1
	40F1.5	42.3	Flange	1.5	Type 1
	40F2	42.3	Flange	2	Type 1
D	40W0.5	42.3	Web	0.5	Type 2
	40W1	42.3	Web	1	Type 2
	40W1.5	42.3	Web	1.5	Type 2
	40W2	42.3	Web	2	Type 2
E	40W0.5N	42.3	Web	0.5	Type 2
	40W1N	42.3	Web	1	Type 2
	40W1.5N	42.3	Web	1.5	Type 2
	40W2N	42.3	Web	2	Type 2

Table 2 Material Properties of GFRP I-section

Position of coupon	Dimensions of coupon (mm)	Property	Averages and Sample Standard Deviations
Flange	25 ×250	Tensile strength (MPa)	381.5 ± 8.1
	12.7 ×37.1	Compressive strength (MPa)	214.2± 17.4
Web	25 ×250	Tensile strength (MPa)	353 ± 30
	12.7 ×37.1	Compressive strength (MPa)	233.8 ± 18.4

Table 3 Test results

Normal pressure	Group A		Group B		Group C		Group D		Group E	
	Normal	Shear	Normal	Shear	Normal	Shear	Normal	Shear	Normal	Shear
	stress (MPa)	stress (MPa)	stress (MPa)	stress (MPa)	stress (MPa)	stress (MPa)	stress (MPa)	stress (MPa)	stress (MPa)	stress (MPa)
0.5 MPa	0.53	0.496	-	-	0.57	0.51	0.5	0.53	0.52	0.34
1MPa	1.07	0.71	0.96	0.74	1.04	0.90	1.04	0.79	1.016	0.598
1.5 MPa	1.34	0.88	1.54	1016	1.46	0.96	1.494	1.098	1.432	0.748
2 MPa	1.948	1.212	2.01	1.39	2	1.39	2.01	1.409	2.132	1.216

Table 4. Friction coefficient and adhesion stress

	Group 30FS	Group 30F	Group 40F	Group 40W	Group 40WN
Friction coefficient	0.51	0.62	0.58	0.60	0.54
Adhesion stress (MPa)	0.20	0.16	0.21	0.2	0.04

Fig. 1. Types of coupons (mm)

Fig. 2. Types of specimens

Fig. 3. Confinement of FRP composite

Fig. 4. Casting the plaster

(a) Test apparatus

(b) Shear box

Fig. 5. Shear box and test apparatus

Fig. 6. Shear stress – displacement curves of Group 30FS

Fig. 7. Shear stress – displacement curves of Group 40WN

Fig. 8. Shear stress – normal stress relationship of Group 30FS

Fig. 9. Shear stress – normal stress relationship of Group 40WN