Experimental Investigation of Continuous Shear Bonding Field in Ferrocement-Aluminium Composite Elements

Prof. Dr. Sa'ad Fahad Resan[*1] , Prof. Dr. Nabeel A. Jasim[2]

[1] *Civil Engineering Department, Engineering College, University of   Misan, Amarah, Iraq.*
[2] *Civil Engineering Department, Engineering College, University of   Basrah, Basrah, Iraq.*
[*]*Corresponding author; E-mail:* <u>sadresan@uomisan.edu.iq</u>

Abstract: Bonding between various construction materials is the key to developing smart composite action within structural elements, likewise beams, slabs, columns, etc. The push-out test is best to determine shear bonding strength and related slip and uplift response in composite components. Push-out test almost could be considered a smart, efficient technique to predict the shear bonding strength between various construction materials in the laboratory. There is no code specification related to the push-out test for adhesive shear bonding. This study introduces a suggested mode regarding continuous shear bonding field in concrete-metal composite elements, which adopts the most common configuration considered in investigating the mechanical fastener's shear resistance. An experimental program is considered. The results depict that the failure loads are changed from (55.7 kN) to (58.01 kN) as the thickness of the adhesive epoxy layer increased from 3 mm to 6 mm, and the results related to the behaviour of load - slip an exponential equation normalizes response of adhesive epoxy layer. Generally, the obtained results confirmed that the introduced continuous shear bonding field could be considered a more proper technique than the mechanical technique. The slip remains very small during the test.

Keywords: Push-out test, load-slip response, load-uplift response, composite beam, shear bonding mechanism, and epoxy adhesive layer.

1. Introduction

The composite action between concrete and metal, likewise steel or aluminium, makes using composite beams in buildings more economical than typical standard section beams. This can be attributed to the reduction of section depth, which reduces the overall section weight. Composite elements can be constructed by tightening two different materials; the designer should consider the shear bonding strength between them as an important tip. Since the early fifties of the previous century, many theoretical and experimental programs have been achieved to investigate the response of composite structures. Developing composite action between various construction materials like steel-concrete composite structure, being among the faster, economical and eco-friendly methods, has been extensively used in high rise buildings and medium span bridge decks; many specifications covered the design aspects of such structures [1-4]. Traditionally, these structures' proposed shear connection mechanism assessment is based on push-out tests [5,6]. Besides, investigating the efficiency of the provided shear connector within developed composite members requires conducting a push-out test to get the necessary information regarding the set composite action [7-10].

Various bonding techniques are used; the more common one is mechanical shear studs; with the significant development of adhesive bonding material, the epoxy resin has become an economical option. A suggested model is presented in this study because no code specification is concerned with a push-out test for adhesive shear bonding. The introduced model adopted the common push-out test configuration to investigate mechanical studs' shear strength. The adopted model is considered to investigate shear bonding strength and response using a continuous field of adhesive epoxy material instead of mechanical shear studs to tie various materials to develop composite actions.

2. Experimental Program
2.1 Materials

The common configuration of a push-out test is used, which consists of two solid blocks made from ferrocement, which is a specific type of concrete, tightened to an aluminium element using a continuous field of adhesive epoxy resin denoted as Sikadur 31 [11].

Structural aluminium alloy sections produced by the Jordanian aluminium industry has been used in this investigation as metal part. At the same time, the ferrocement is considered the solid block, a form of thin reinforced concrete in which a brittle cement-sand mortar matrix is reinforced with closely spaced multiple layers of light wire mesh [12].

Sikadur-31 thixotropic epoxy resin adhesive is used as a continuous shear bonding field in the proposed concrete-metal composite model. It is a solvent-free, thixotropic, two-component adhesive mortar. It complies with ASTM C-881 [13]. The mechanical strengths of solid concrete block and Sikadur 31 epoxy are listed in Table 1.

Table 1 Mechanical Strengths [13-15]

Mat.	f''_c,MPa	f_r,MPa	E_e,MPa
Epoxy	31.2	37.9	4.3
Ferrocement	40	5.5	28

2.2. Test Specimens

The specimens consist of two precast ferrocement segments attached to the aluminium section from two sides. Precast ferrocement segments are made with five wire mesh layers. The ferrocement segments were used 28 days after casting. The specimens were made by bonding ferrocement to aluminium by adhesive epoxy layer, and after initial hardening of the adhesive layer (about 1 hour), the second segment bonded. The specimens   (P1, P2 and P3) were tested; the first specimen was with one day of applying the adhesion epoxy layer and 3mm epoxy layer thickness and the other two specimens were with three days of using the adhesion epoxy layer, P2 with 3mm and P3 with 6 mm epoxy layer thickness. Table .2 shows push-out specimens' details, while Figs. (1-3) show the model and specimen configuration.

2.3. Test Procedure

The Testing Machine of 20 Ton capacity was used, Fig. 4. The load was applied in equal increments and maintained constant at each load level (rate of loading = 10 kg/sec). At the same time, the vertical slip between the ferrocement blocks and the aluminium segment was determined. The mechanical dial gauges were used to measure the vertical slip at the interface of aluminium and ferrocement blocks. The specimens were loaded to ultimate load without unloading.

Table 2 Details of push-out test specimens

Specimens	Epoxy layer thickness (mm)	Epoxy hardening time to test (days)	Compressive strength of ferr. matrix, $f_{c'}$ (MPa)	Flexural strength of ferr. matrix, f_r (MPa)
P1	3	1	40.1	6.15
P2	3	3	40.1	6.15
P3	6	3	40.1	6.15

a.Front view b. Side view c. Top view

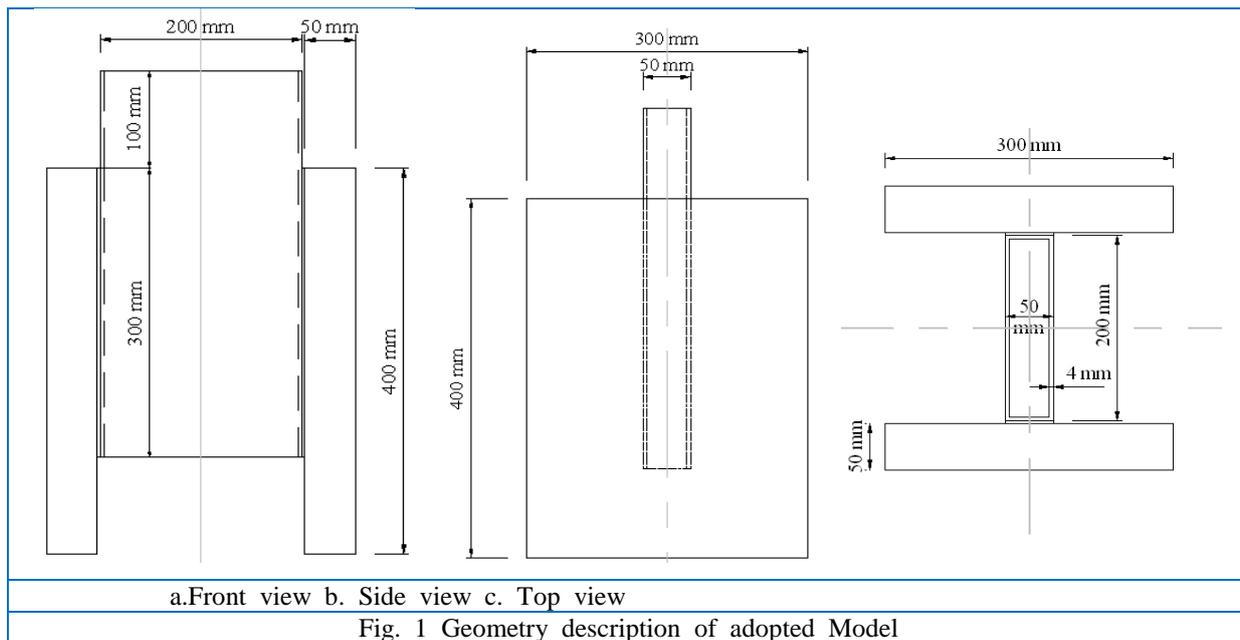Fig. 1 Geometry description of adopted Model

Fig. 2 Push out specimens components

Fig. 3 Push out specimen

Fig. 4 Push-out test arrangement

3. Results and Discussion
3.1. Load-slip response

Tests were conducted on the adopted push-out specimens 28 days after casting ferrocement segments. The details and results of tested push-out specimens are summarized in Table .3. The variation of measured slip with the total load is plotted in Fig. 5. The response shows that the epoxy has good resistance to the applied shear; however, when the ultimate load is reached, sudden separation of ferrocement block occurs. The figure illustrates that the failure loads for P2 and P3 specimens are (55.7 kN) for P2 and (58.01 kN) for P3. This is found although the thickness of the adhesive epoxy layer is changed from 3 mm for P2 to 6 mm for P3. So the test depicts that the layer thickness is not an effective parameter.

3.2. Load uplift response

In the push-out test, and because of the absence of any standard test for uplift, a dial gauge was used to measure the separation between the aluminium and ferrocement components at the mid-length of the specimen. The variation of measured separation with the total load is plotted in Fig. 6. From the figure, two stages can be distinguished. The first stage starts by applying the load up to approximately 7.5 % of the ultimate load for specimens P1 and P2, with 3 mm layer thickness, and 14 % of the ultimate load for specimen P3 with 6 mm epoxy layer. The separation in this stage is positive (separation) and may has the same concept of uplift mechanism between composite beam components. With increasing the load, the separation changes to become negative (compression) indicating the beginning of the second stage up to failure load.

Table 3   Ultimate values of load and slip in push-out test

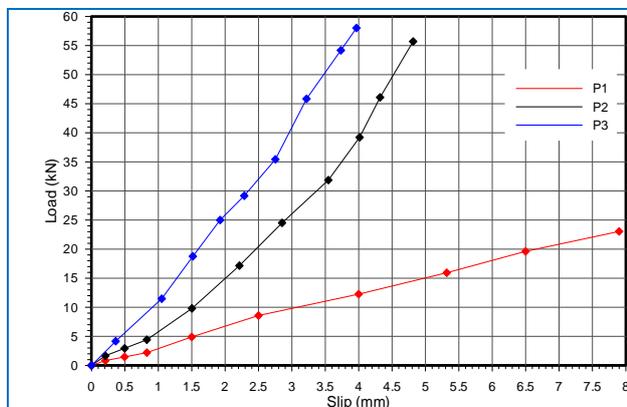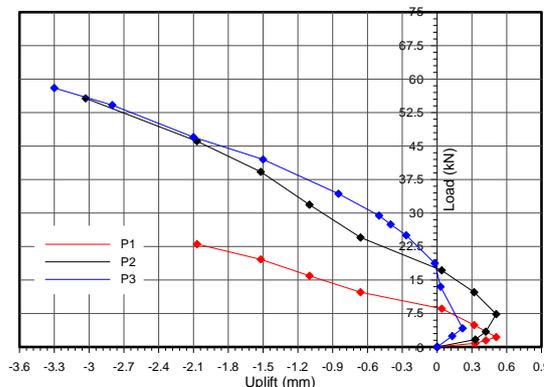| No.	Specimens designation	Epoxy layer thickness	Period of hardening of epoxy layer	Failure mode	Total ultimate load (kN)	Ultimate shear stress	Extrapolated slip at ultimate load (mm)
1	P1	3	1	Debonding of adhesive epoxy layer	23.04	0.77	7.9
2	P2	3	3	Ferrocement splitting at adhesive region	55.70	1.86	4.8
3	P3	6	3	Ferrocement splitting at adhesive region	58.01	1.94	3.4

Fig. 5 Load–slip relationships

Fig. 6 Load–uplift relationships

3.3. Failure Modes

Two modes characterize the failure of specimens. In the first, deboning occurred between ferrocement blocks and aluminium segment, as shown in Fig. 7.a. This failure mode was observed in specimens (P1), tested after only one day of hardening of the adhesive epoxy layer. In the second mode observed in specimens P2 and P3, a thin shell of ferrocement split and separated from ferrocement block in the interface region because of stress concentration in this region, Fig. 7.b and Fig. 7.c. This indicates that the weak components in the system are the solid concrete block and the epoxy layer. The time for hardening of three days is sufficient to give full bond strength.

a. Specimen (P1)

b. Specimen (P2)

c. Specimen (P3)

Fig. 7 Failure Modes of tested specimens

4. Theoretical Normalization

The first specimen is considered to investigate the hardening time. It is not considered theoretical normalization because the result confirms that the adopted curing time is insufficient for structural adhesive bonding. The load–slip relationships of the specimens of full bonding are nonlinear and deviate from the standard exponential equations suggested by Yam and Chapman [16] for a shear connector in steel – concrete composite beams, which has the form;

$$Q = a \ (1 - e^{-bS}) \tag{1}$$

where,
Q = load on one connector (kN)
S = slip (mm)
a and b = constants

Based on the experimental results of P2 and P3, an exponential equation is suggested, which has the following form:

$$P = a \ (e^{bS} - 1) \tag{2}$$

where,
P = Total applied load (kN)
S = slip (mm)
a and b = constants

The values of the constants a and b in Eq. (2) are chosen to obtain as good as possible results. The equations below (Equations 3 and 4) are adopted for the two specimens P2 and P3, respectively. The results are shown in Figs. 8 and 9.

$$Q = 11.22 \ (e^{0.37S} - 1) \tag{3}$$
$$Q = 12.97 \ (e^{0.5S} - 1) \tag{4}$$

Generally, equations Eqs. (3) and (4) normalized the current results, and more tests are recommended for generation purposes.
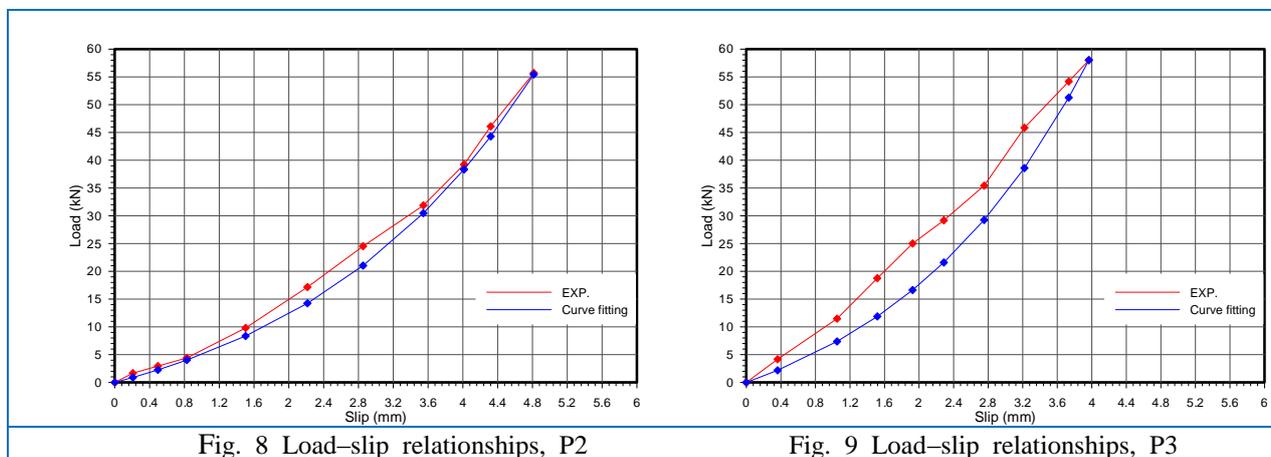

Fig. 8 Load–slip relationships, P2   Fig. 9 Load–slip relationships, P3

Conclusions

1. The ferrocement block with a full continuous connection to the metal segment provided sufficient constrain for the thin metal flange and eliminated the local buckling problem, a characteristic problem in the thin metal section.
2. The adopted push-out model may be considered the standard test for continuous shear bonding field in concrete-metal composite elements
3. An exponential equation may represent the load-slip relationship of adhesive bonding field within specimens of completed curing (full band) $P = a \ (e^{bS} - 1)$. This relationship differs from the suggested standard exponential equation for steel-concrete composite beams $Q = a \ (1 - e^{-bS})$ [16].

4. As depicted by the push-out test, the adhesive epoxy layer thickness is not an effective parameter. The failure loads are changed from (55.7 kN) to (58.01 kN) as the thickness of the adhesive epoxy layer increases from 3 mm to 6 mm.

5. It can be observed that using Sikadur 31 as an adhesive epoxy layer provides adequate bond shear strength between the two layers. The connection of continuous shear bonding field in concrete-metal composite elements could be considered a more proper technique than the mechanical technique as the slip remains very small during the test.

6. The hardening time for an adhesive epoxy layer is a very effective parameter. The full capacity of beams was attained after three days of epoxy layering.

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