SHEAR CONNECTIONS BETWEEN GFRP PULTRUDED PROFILES AND CONCRETE: A COMPARISON BETWEEN BOLTING AND BONDING

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Abstract

GFRP–concrete hybrid structural elements present a remarkable structural capacity, not only for rehabilitation purposes but also in construction, mainly in sandwich systems and lightweight bridge decks. In the literature, static, dynamic and creep experiments were performed on medium-scale structures. The connection between GFRP and concrete has been shown to be a shear connection since the friction is practically zero. Two techniques are usually adopted: mechanical bolting and adhesive bonding. In this paper, push out tests are conducted to examine the mechanical behavior of both connection types. GFRP pultruded profiles are connected to ordinary concrete with steel bolts in the first set and with epoxy in the second set. The experiments are monitored and digital image correlation (DIC) is used to evaluate the load slip behaviour at the interface. DIC allows a close examination of the deformations. Stiffness of the connections is measured and may be used to develop a mechanical model that will enable the simulation of GFRP–concrete elements on a larger scale.

1. Introduction

GFRP-concrete hybrid structural elements, consisting of GFRP pultruded profiles connected to concrete slab(s), show a remarkable structural capacity not only for rehabilitation purposes, but also in the construction of lightweight bridge decks or footbridges. In fact, GFRP profiles have interesting mechanical and environmental properties such as high strength to self-weight ratio and good resistance to chemical agents. These properties make these elements suitable for structural applications for both building and bridges [1]. Moreover, the association of these profiles with concrete compression elements makes a better use of both GFRP profile and concrete. Indeed, concrete elements increase the bending stiffness and the structural strength, reduce the deformations of GFRP profiles, and prevent the lateral buckling phenomenon.

GFRP–concrete hybrid structural elements have been studied in the literature. Static, dynamic [2-4] and creep experiments [5] were performed on medium-scale structures. In [6], Correia et al. investigated the connection between GFRP and concrete at the specimen scale. This connection has been shown to be a shear connection since the friction between GFRP and concrete is practically zero. Therefore, the push-out test (figure 1), similar to the standard push test in [7], is conducted in this study in order to characterize and compare bolted and bonded connections.

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Data inferred from the force/displacement meausurements on the test machine and by full-field digital image correlation (DIC) are used to accurately determine the stiffnessess of both bolted and bonded connections. In future studies, results will be used to predict the mechanical behaviour of GFRP–concrete hybrid structural elements.

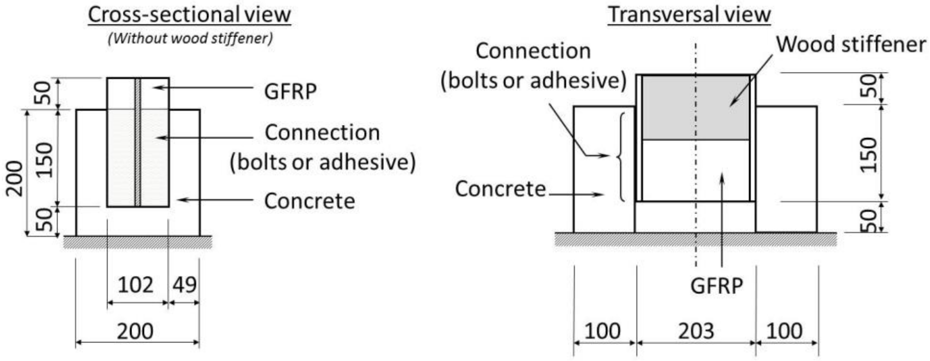

Figure 1. Dimensions of push-out test specimens (units are in mm)

2. Shear connection test

2.1. Test Setup

Push out test specimens are fabricated according to the dimensions indicated in figure 1. In this study, two sets of 5 specimens are built. The first, POPB2 is connected by bonding while the second POPB3, is bolted. The concrete composition of the concrete substrates was formulated in previous internal works. Compression tests done on 100 mm cubic specimens on the same day as push out tests gave in case of bonding 48.4 MPa (± 3.7 MPa) and bolting 51.4 MPa (± 0.6 MPa),.

For the bolted specimens, GFRP profiles are prepared (cleaned, degreased), then the concrete blocks are cast in place successively (Figure 2). The two blocks of each push-out specimen are therefore not from the same mix (7 days apart). For bonded specimens, all concrete blocks are cast in one batch, then the bonding is carried out after sandblasting and dusting down the surface to be bonded (Figure 2). The adhesive used is an epoxy bi-component Sikadur 31 CF. The thickness of the adhesive joint is not controlled, but estimated to be less than a millimeter. For bolting, 80 mm long M10 galvanized bolts with a class resistance of 6.8 are used. Four bolts are used for a specimen (two bolts per block).

Figure 2. Specimen preparation (left) Casting of bolted specimens (right) Bonding between GFRP and concrete

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2.2. Primary test results

Shear connection tests are performed on a Wolpert compression press under increasing monotonic loading until failure. The crosshead speed is 0.6 mm / min. The effort and crosshead displacement are recorded. Force-displacement curves for all the specimens are given figure 3.

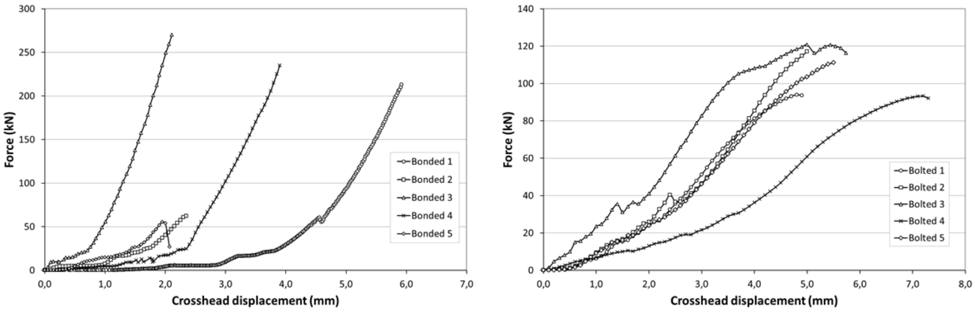

Figure 3. Force versus crosshead displacement of (left) Bonded specimens (right) Bolted specimens

Excluding specimens with premature failure, bonded specimens show similar behaviors. After a loading phase while contacts are rearranged between the specimen and the testing machine, the force-displacement curve is almost linear up to failure. Among 5 specimens, two of them showed premature failure, probably due to mishandling or improper positioning of the specimen on the testing machine. Rupture occurs abruptly–by shearing in the concrete near the interface and parallel to its plane (cohesive failure in the concrete). Before failure, no deformation is visible to the naked eye. Considering only the samples 1, 3 and 4, the average stress at failure is 7.95 MPa (± 0.9 MPa).

Bolted specimens also exhibit similar behavior. At failure, the bolts are severly inclined, the slip between concrete and GFRP is visible. Failure comes after yelding then rupture of the bolts by bending. The average failure load is 26.3 kN (± 3.5 kN) per bolt.

Table 1. Properties of the optical sensor and the video lens

mvBlueFOX 224G CCD		**FUJINON 1 :1.4/16mm HF16SA-1**	
Model	CCD, gray scale	Focus	Manual
Resolution	1600 x 1200 Px	Iris	Manual
Max. frame rate	16 Hz	Focal length	16 mm
Sensor size	7.18 x 5.32 mm (1/1.8 ‘’)	Iris range	F1.4 – F22
Pixel size	4.4 x 4.4 µm	Focusing range	0.1 m - …
Exposure time	30 µs – 10s		

2.3. Measurements with DIC

The DIC software Icasoft is used in this study to measure the displacement fields at the GFRP-concrete interface. Optical equipment specifications are given in Table 1. The specimens are prepared for the DIC; a black and white speckle pattern is applied to the zone of interest (ZOI). The optical sensor is placed at 45 ° with respect to the specimen at a distance of about 0.60 m as shown in figure 4. Thus, the visible faces of the profile and the concrete block are not in the same plane, this is taken into account when operating the results. By default, the following values are used for calculation (i) Pattern size, min = 25, max = 32 (ii) Grid step = 9 (iii) Precision = 1/100 pixel.

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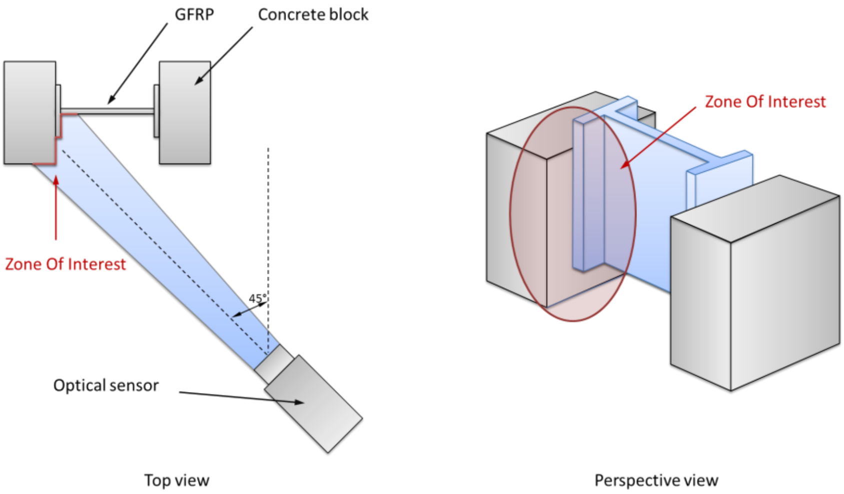

Figure 4. Position of the ZOI for DIC

3. DIC results

3.1. Bonded connections

Out of the 5 specimens of POPB2 set, two tests are put aside due to premature rupture. A third test (bonded specimen 1) is also not exploitable with the DIC due to synchronization problems between the picture acquisition and the crosshead displacement values. Then, only bonded specimens 3 and 4 will be discussed in the following.

Vertical displacement fields for bonded specimen 3, for different loading values, are shown in figure 5. There is no clear discontinuity in the displacement field. The vertical displacements measured for the concrete block and the profile are not homogeneous. The displacement that is measured depends on the distance to the optical sensor. The further the point, the lower the measured displacement is. This observation is consistent, it indicates that the 2D field measurement is disturbed when the object is not included in a plane perpendicular to the optical axis.

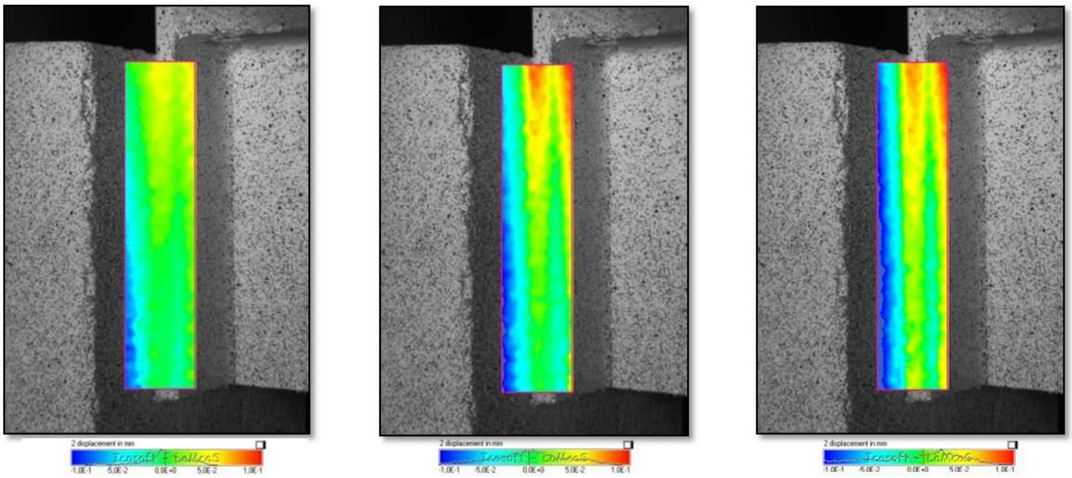

Figure 5. Bonded specimen 3, vertical displacements field for three loading values (left) 13,0 kN (center) 136,8 kN (right) 269,3 kN

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However, this aspect does not completely discredit the measurements. Here the measured displacements, rigid body displacements excluded, are comprised between -100 and 100 microns, while the size of a pixel is estimated to be 165 microns. The slip between concrete and GFRP, if there is any, is less than 200 microns at failure, and is not properly captured by the optical equipment available. The same observations are made for the bonded specimen 4.

As a consequence, the behavior at the interface between concrete and GFRP pultruded profile connected by bonding is regarded as infinitely stiff. Thus, we can make the assumption of no slip at the interface until failure.

3.2. Bolted connections

The 5 specimens of POPB3 set are workable from the perspective of the DIC. For example, the ZOI of the bolted specimen 5 at the beginning and end of the test (last picture before failure) is given in figure 6. The deformation of the bolt is visible to the naked eye, it is strongly tilting downward.

The slip measurement is done by comparing the vertical displacements between the points P1,P2 and P3 (situated on the profile) on one hand and B1,B2 and B3 (situated on the substrate) on other hand (figure 6).

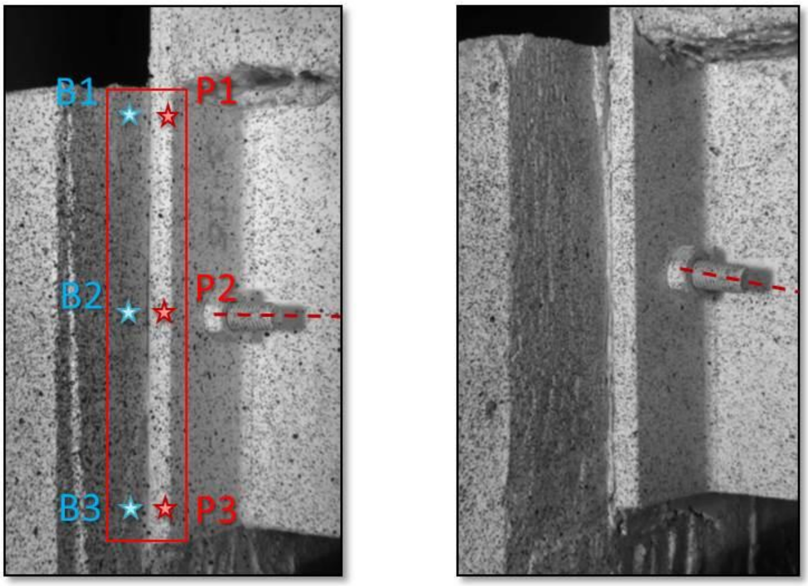

Figure 6. Bolted specimen 5, ZOI (left) before test (right) end of the test

The slip measurements between profile and concrete block for the bolted specimen 5 are given in figure 7. The measured slip are significant. After a low rise, until a machine load of about 18 kN, slip increases almost linearly with the loading. Slip measured at points 1, 2 and 3 are very close, there is a rigid body motion between GFRP and concrete block. Thereby, the average slip (mean value of points 1, 2 and 3) will be used hereinafter.

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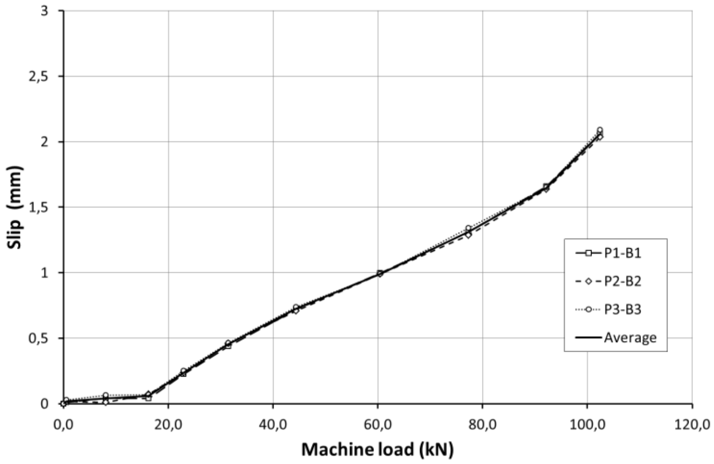

Figure 7. Bolted specimen 5, slip as a function of machine load

Vertical displacements fields for the bolted specimen 5, at different load levels, are shown in figure 8. We can observe the rigid body motion of the GFRP profile and the concrete block. The deformation of the specimen predominantly occurs at the junction, by deformation of the bolt.

At the beginning of the test, displacement is different from the upper section to the bottom of the concrete block. Figure 8.a, the difference is of the order of 0.3 mm, while the measured slip at the interface is 0.05 mm. This small difference is visible up to a load of 15.5 kN. Then from 15.5 to 18.6 kN, a vertical displacement jump appears between profile and concrete block. This corresponds to the end of the first part of the curve (figure 7), the measured slip is then 0.1 mm. Subsequently, the slip is clearly observed between the two parts. Picture 3 (figure 8.c) is the last for which the image correlation can be made using a single ZOI. Over 48 kN, vertical slip strongly disturb the DIC measurement. It is then necessary to use two ZOI (Figure 8.d to 8.f).

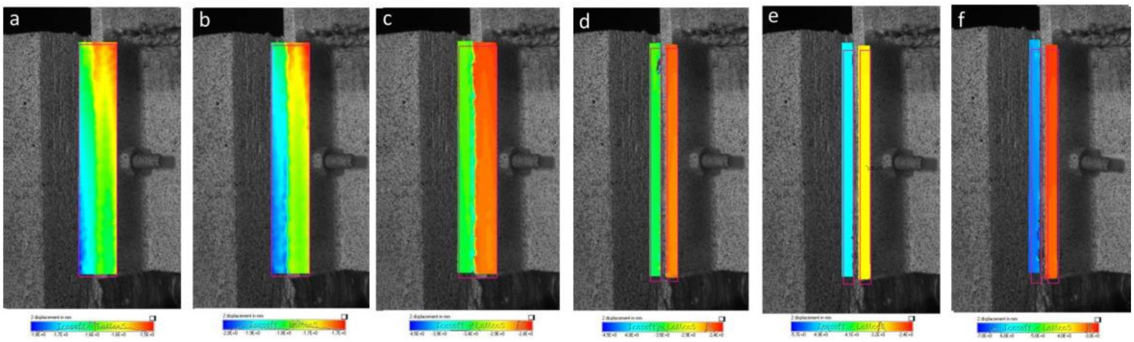

Figure 8. Bolted connection 5, vertical displacement fields for different loading values (a) 15,5 kN (b) 18,6 kN (c) 46,1 kN (d) 49,3 kN (e) 88,0 kN (f) 111,1 kN

A similar slipping behavior is observed for all 5 specimens. Average slip as a function of force per bolt are shown in figure 9. The maximum slip is approximately 2.5 to 3.0 mm before failure, for a maximum load included between 23 and 30 kN per bolt. The slip curve can be split into three parts. Initially the slip is negligible, to a average threshold of 1.8 kN (± 38.4%) by bolt. The concrete block and GFRP-profile remain attached. There is no localized deformation. Then in the second part, concrete block and GFRP-profile start to separate. A vertical slip arises, it increases almost linearly

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with the applied force (see figure 9). This slip results from the bending deformation of the bolt. At the end of the test, slip accelerates. It is reasonable to state that the bolts are yelding, slip increases rapidly until total failure. These three slip phases are visible for all the tests performed, with slightly varying loading levels.

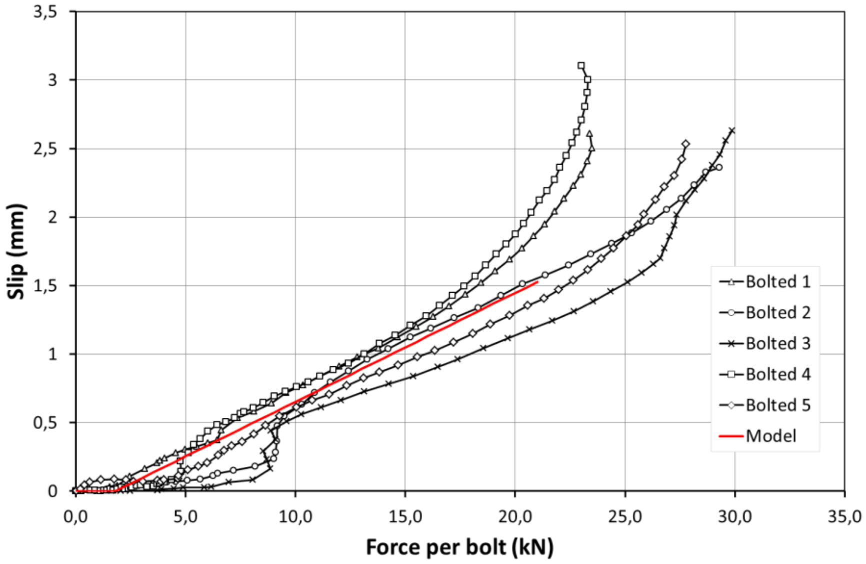

Figure 9. Slip as a function of force per bolt for bolted specimens

The second part of the curves (quasi-linear phase) can be used to determine the stiffness (flexibility) of the connection. Threshold 1 is the beginning of the linear phase, determined graphically. Threshold 2 represents the end of the linear phase, it corresponds to the force per bolt for a 1.5 mm slip. The flexibility is determined using a linear regression between thresholds 1 and 2. The numerical values are given in Table 2. An average flexibility of 0.0795 mm/kN (± 12.3%) is determined, i.e an average of stiffness of 12.75 kN/mm (± 13.4%). The third part of the curve (failure behavior) is not treated here.

Thus, the behavior at the interface between GFRP pultruded profile and concrete block bolted together is modeled by a bilinear constitutive law. This law can be used to predict the mechanical behaviour of GFRP–concrete hybrid structural elements.

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Table 2: Parameters definition for the constitutive law of bolted connections

Specimen	Threshold 1 (kN)	Flexibility (mm/kN)	Stiffness (kN/mm)	Threshold 2 (kN)
Bolted 1	1.52	0.0877	11.40	18.5
Bolted 2	1.21	0.0784	12.76	20.3
Bolted 3	1.97	0.0644	15.53	25.1
Bolted 4	1.36	0.0888	11.26	17.7
Bolted 5	2.92	0.0781	12.80	22.7
Average	1.80 (±38.4%)	0.0795 (±12.3%)	12.75 (±13.4%)	20.86 (±14.6%)
Commentary		*Linear phase*		*Δy=1.5 mm*

4. Conclusion

Two test series, 5 specimens per each, were tested by push out and the results were exploited to compare both types of GFRP-concrete connection : bolting ans bonding. The experimental approach using DIC to measure the relative displacement between the assembled elements shows promising results, with some limitations.

The study shows that the bonded connection demonstrates a very stiff behavior with very little relative displacement recorded before failure. An average stress of 7.95 MPa (± 0.9 MPa) was measured at failure, without being able to accurately determine the corresponding slip. The DIC equipment used in this study indicates a relative displacement lower than ± 100 microns, but does not allow to define the slip more accurately. Further efforts are needed to investigate this point. In a first approach, the behavior at the interface between concrete and GFRP pultruded profile connected by bonding is regarded as infinitely stiff. We can make the assumption that no slip occures at the interface.

Bolted connections show a significant slip at the interface mainly due to bending of the bolts. The DIC technique allows to measure an homogeneous slip at the interface, which can be divided in three parts. A first part with zero slip, a second with slip increasing proportionaly with the load (average stiffness of 12.75 kN/mm (± 13.4%)) and a third part with a strong slip increase before failure. In addition, the reproducibility of measurements on bolted specimens is satisfaying. The behavior at the interface between GFRP pultruded profile and concrete bolted together is therefore modeled by a bilinear constitutive law. This model can be used in interface modelling of GFRP-concrete hybrid structural elements.

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