- *Technical Paper* -

EVALUATION OF PULL-OUT BEHAVIOR OF TEXTILE REINFORCED CONCRETE

Bui Si MUOI[*1] and Minoru KUNIEDA[*2]

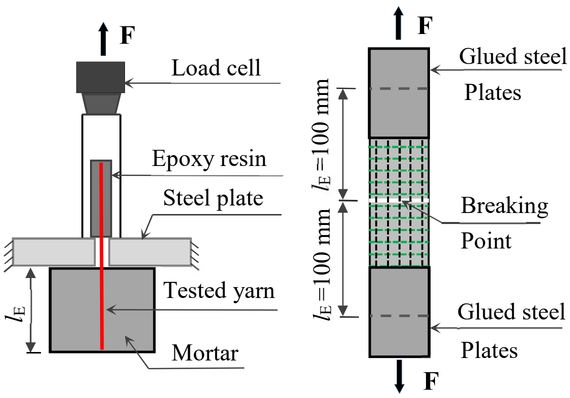
ABSTRACT
The extensive utilization of Textile Reinforced Concrete (TRC) in modern days demands to standardize the test methods for determining mechanical properties, particularly bond behavior between textile reinforcement and mortar. Pull-out test is a typical method utilized to obtain bond behavior. The aim of this study is to propose a pull-out test for evaluating the bond behavior of textile reinforcement and cement matrix in TRC. Tests with different embedded lengths were conducted in order to characterize failure modes of textile roving as well as obtain a representative trend of pull-out behavior. The proposed test method gave stable load – displacement relationship and seems to be possible to provide reasonable and reliable results on the bond characteristic in TRC.
Keywords: Textile reinforced concrete, TRC, pull-out test, bond behavior

1. INTRODUCTION

Reinforced concrete is considered as one of the most important construction materials. However, in addition to the advantage of high load capacity, this material has historically shown disadvantages in term of durability including corrosion of re-bars. In the modern era, materials providing sustainability are becoming a major driving force for innovation in construction industry. Textile Reinforced Concrete (TRC) has emerged in recent years as a new, valuable and alternative construction material [1]. TRC is a concrete or mortar matrix reinforced by multi-axial noncorrosive textile fabrics. The sustainability attributes offered by TRC spans over a wide range, including favorable mechanical performance, high corrosion resistance, and longer life service as well as thinner and light-weight structures [2]. Therefore, TRC is very suitable for production of structural and non-structural elements, such as road, pedestrian bridges and silos as well as façades and/or sandwich panels. Furthermore, a thin layer of TRC with very high tensile strength is possible for repairing or strengthening existing structures [3].

In fiber composite materials, such as TRC, bond behavior between the textile yarns and the cementitious matrix is a principal factor influencing the global structural behavior [4]. For that reason, the determination of bond behavior is essential for properly understanding the behavior of TRC and providing input data for numerical models. The so-called pull-out test was widely accepted experimental technique to determine the bond behavior between textile reinforcement and surrounding mortar. Depending on the failure mechanism and the sample geometry, the experimental setups described in the literature could be simplified into one-sided and two-sided pull-out tests.

For one-sided pull-out tests, as shown in Fig.1a, proposed by Banholzer [5] as well as by Peled & Bentur [6], the investigated yarns were embedded on one side in the concrete matrix. At the opposite end, the anchorage was done by means of special mechanical clamping devices or by pouring the filament yarn into an epoxy resin block. A disadvantage of this method was the capillary phenomenon which may induce the penetration of epoxy resin into the interior of embedded length and led to an adverse effect on the result of test.



a) Test setup by Banholzer b) Test setup by Butler

Fig.1 Setups of pull-out test proposed by Banholzer [5] and Butler [7]

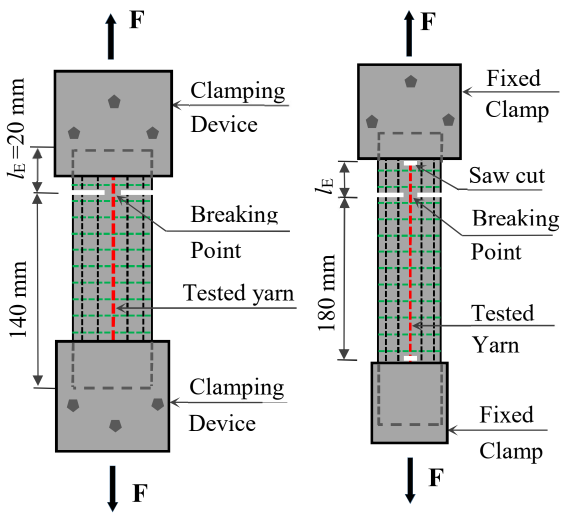
In contrast, in two-sided pull-out tests by Butler [7], Kang & Brameshuber [8] and Krüger [9], the tested yarns were completely embedded into the surrounding fine concrete and the force was transmitted to the yarn through the bond with the matrix. During the pull-out test, the tensile force F and the associated crack opening w were measured in the area of predetermined breaking point. In symmetrical two-sided pull-out tests (Fig.1b) described by Butler [7], the anchorage lengths of both sides of specimen got the same value of 100 mm, which

*1 Graduate School of Engineering, Gifu University, JCI Student Member
*2 Prof., Dept. of Civil Engineering, Gifu University, JCI Member

led to a simply assuming that the slip of yarns at one side equaled half of crack opening w at predetermined breaking point. Whereas, numerous investigations showed that the sufficient embedded length should be smaller than 100 mm. Generally, when the end anchorage length is greater 100 mm, the fracture failure of tested yarn occurs rather than pull-out failure, particularly secondary coated textile reinforcement. By contrast, the two-sided test mentioned by Krüger [9] had asymmetrical anchorage lengths, see Fig.2a. On one side of specimen, the selection of a short end anchoring length l_E of 20 mm ensured the pull-out failure of investigated yarn. On the opposite side, the anchoring of the tested yarn in the fine concrete matrix could be ensured by a final anchoring length of 140 mm. As a result of the complete embedding in the surrounding fine concrete, a direct introduction of force into the multifilament yarn was possible via the bond with the matrix. However, the drawback of the test was the clamping devices which induced directly lateral pressure onto the surrounding mortar of examined yarn.

For a systematic and reliable testing of randomly configured textile reinforcement structure as well as for an improved and correct evaluation of the pull-out test, a further development of the experimental setup is necessary. Based on the test of Krüger, Lorenz and Ortlepp [10, 11] developed a new technique to gain understanding of bond behavior between textile reinforcement and mortar. For eliminating effect of clamping devices, saw cuts were created to separate the testing area from clamping areas. Therefore, the anchorage lengths were limited by distance between breaking point and saw cut. Accordingly, in the literature, numerous researches proved the accuracy and validity of this configuration [10, 11, 12, 13].

The setup of pull-out test in this publication referred to principle approaches of the test proposed by Lorenz and Ortlepp [10].



a) Test setup by Krüger b) Test setup by Lorenz

Fig.2 Setups of pull-out test proposed by Krüger [5], and Lorenz [6]

2. TEST PROGRAMS

2.1 Materials description

(1) Mortar

The pull-out test specimens were fabricated of mortar according the mix composition described in Table 1. The mechanical characteristics of mortar are compiled in Table 2.

Table 1 Composition of the mortar

Composition	Mass rate (-)	Quantity (kg/m^3)
High early strength cement	0.375	518
Fly ash	0.125	173
Sand	1.000	1380
Water	0.125	173
Super plasticizer	0.005	7

Table 2 Mechanical properties of the mortar

Characteristics	Unit	Value
Density	kg/m^3	2335
Compressive strength	N/mm^2	75.3
Tensile strength	N/mm^2	7.83
Elastic modulus	N/mm^2	36500

(2) Textile reinforcement

The textile reinforcement mesh in this study was stitch-bonded biaxial fabric with equal quantity of fiber rovings in two orthogonal directions [0°/90°] (Fig. 3). The textile consisted of two carbon filament yarns, the longitudinal yarn (warp yarn) and the transverse yarn (weft yarn). The mesh size was 10 mm and 8.5 mm in warp and weft directions, respectively. At the joint point, knitting threads were used to hold the rovings together in a stable manner. For improving adhesion at interphase layer of roving and mortar as well as enhancing the uniform stress distribution between individual filaments, a secondary coating layer – Styrene butadiene – was utilized to coat textile reinforcement. Other properties of roving including cross sectional area of individual roving, distance between two adjacent rovings and mechanical properties are shown in Table 3.

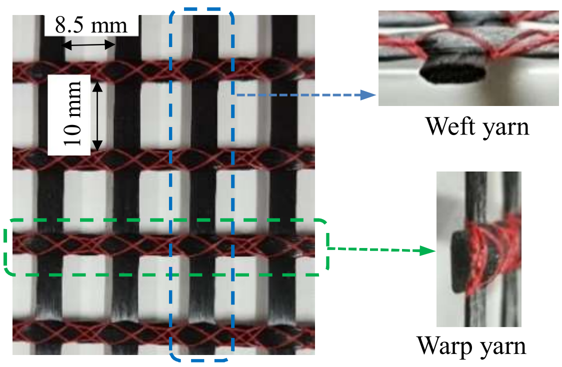


Fig.3 Textile fabric used

Table 3 Properties of roving

Type of yarn	Cross-sectional area (mm^2)	Roving distance (mm)	Tensile strength (MPa)	Elastic modulus (GPa)
Warp/weft	1.91	12.5	1700	140-200

2.2 Specimens

The TRC specimens were produced by hand lamination process in steel formworks resulting in large-format textile reinforced concrete slabs with dimension of 1000 x 1000 x 15 mm. The slabs contained only one layer of textile reinforcement. The textile layer and mortar layers were placed in the formwork alternately with a mortar layer in its bottom and top. The reinforcement layers were arranged symmetrically to the thickness and set parallel to slab surface. After curing period, the slabs were cut into small rectangular specimens with proper dimensions (see Table 4). With this configuration, the all investigated specimens in the test came from one and the same batch of mortar. As a result, the comparability of the individual tests as well as reducing scattering of the quality of concrete and composite properties could be ensured.

During the pull-out test, only one individual yarn (warp yarn) of the specimens was tested. Each specimen might be divided into 3 parts: the upper part and the lowest part were used for clamping; the mid part was the tested area where the pull-out failure of yarn carried out (see Fig.4). The parts of specimen were separated by two holes with diameter of 10 mm. At the position of the holes, the tested yarn also was cut to ensure that the pressure from clamp devices did not affect the result of test. In the tested area, there were two different types of embedded length of warp yarn: the short and long anchorage length that were split up by the saw cuts on the both sides of specimen. These saw cuts with width of 24 mm were created and controlled by wet saw cutter. They not only played the role of isolating tested yarn but also created the predetermined breaking point of specimen. The short anchorage length, l_{E1}, limited by the upper hole and the predetermined breaking point. The length l_{E1} should not be smaller than 14 mm in order to ensure safe handling of specimen. If the distance of the transverse yarn is smaller than that, l_{E1} should be chosen as a multiple of this distance [10]. In this research, four different values of embedment length were chosen, the detail of dimension of each type shown in Table 4. In contrast, the long anchorage length, l_{E2} was defined by saw cuts and the second hole. This length must be sufficiently long to prevent the slippage at the free unloaded endpoint.

Table 4 Dimension of specimens

Series	l_{E1} (mm)	l_{E2} (mm)	Width (mm)	Length (mm)
Series 1	25	220	60	310
Series 2	50	220	60	330
Series 3	100	340	60	500
Series 4	200	740	60	1000

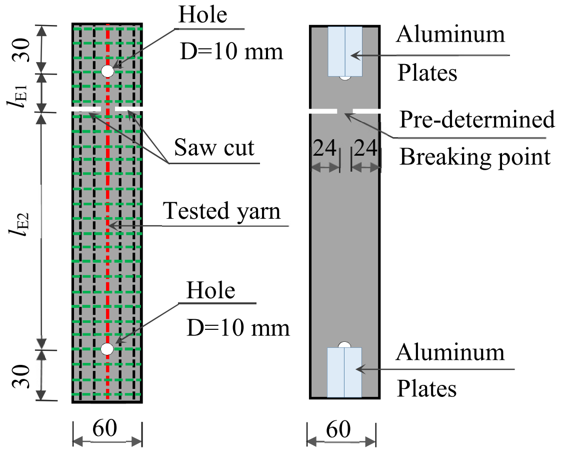
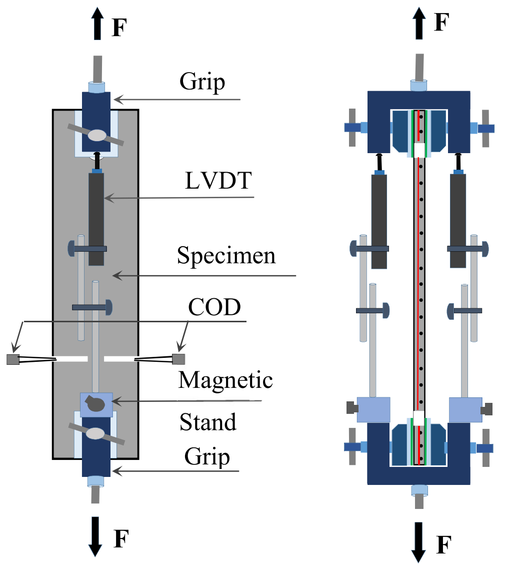


Fig.4 Sketch of specimen used for pull-out test

2.3 Test setup

The test setup is shown in Fig. 5, 6. Before testing, aluminum plates were attached to both sides of the ends of specimens by glue. These plates prevented the damage of concrete under the consequence of direct lateral pressure of grips. The tensile load was applied via clamping devices on the upper and lower ends of the specimen. The type of used clamping device was flat chuck tensile grip that had flexible connection to testing machine. The contact pressure was set in such a way that the slippage between clamp and specimen prevented and the compressive strength of mortar was not exceeded. On top of the upper grip, a load cell with proper capacity was placed in order to measure the value of tensile force. The total deformation of the specimen measured by using two LVDT deformation transducers placed on either side of the specimen. At the position of pre-determined breaking point, two Clip-on Displacement (COD) transducers were arranged to determine crack-opening.



a) Front view b) Cross section

Fig.5 Sketch of Setup for pull-out test

a) Before fixing LVDT b) After fixing LVDT

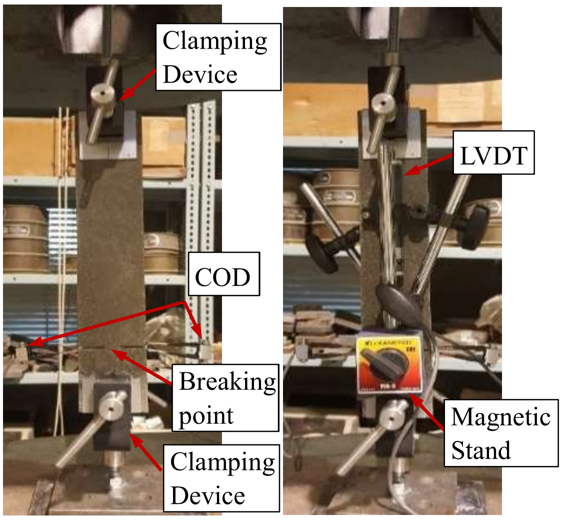


Fig.6 Setup of pull-out test

3. RESULT AND DISCUSSION

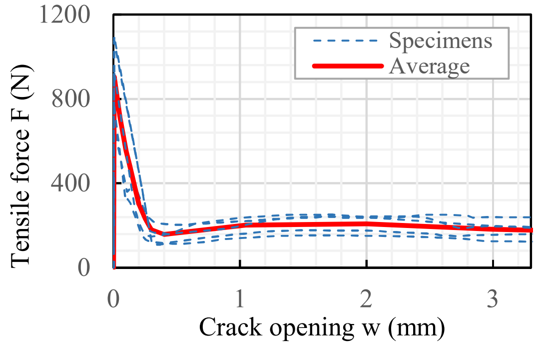
The result of textile pullout test was force – crack opening and force – total displacement relationship shown in Fig.7 and 8 respectively. The increase of the pull-out force together with a larger displacement were observed when the embedded length increased. In addition, the dominant failure mode was pullout of multi-filament yarn in surrounding mortar (Fig.11) when 19 out of total 20 specimens occurred this failure mode.

Table 5 showed dispersion of maximum loads and correlative crack opening that obtained from pull-out test of four series. The range of scatter was not too wide. The standard deviations (SD.) were only about 10-23% of mean value, demonstrating the reasonableness and suitability of test method.

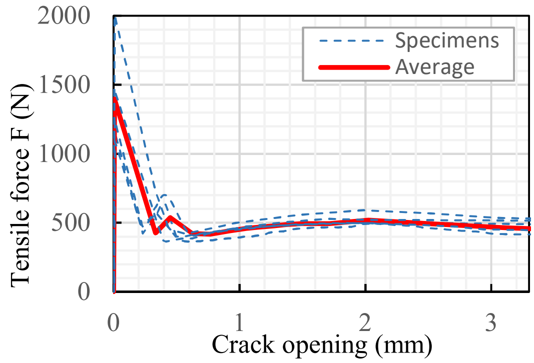
Table 5 Standard deviation of maximum pull-out load and corresponding displacement

Series	Series 1	Series 2	Series 3	Series 4
Avg. of bond strength (N)	160	537	1103	3277
SD. of bond strength (N)	38	148	201.6	281.4
Avg. of crack opening (mm)	0.368	0.452	0.740	3.378
SD. of crack opening (mm)	0.029	0.087	0.102	0.274

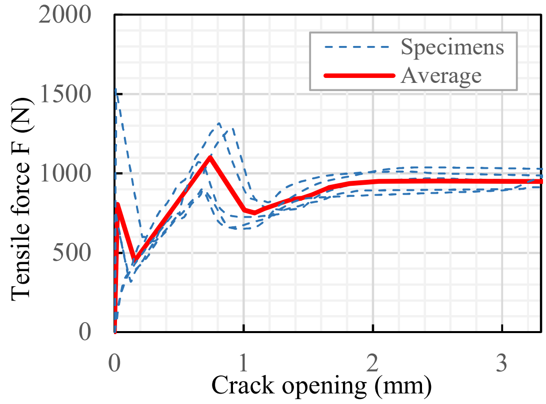
As shown in Fig.8 and 9, the characteristic of bond behavior in four series was slightly different. For the specimens with embedded length greater than 25 mm (series 2, 3 and 4), the force – crack opening curve showed a double peak. The first peak might be attributed to crack of mortar at the pre-determined breaking point. As the matrix lost the load bearing capacity, the adhesive bond between reinforcement and



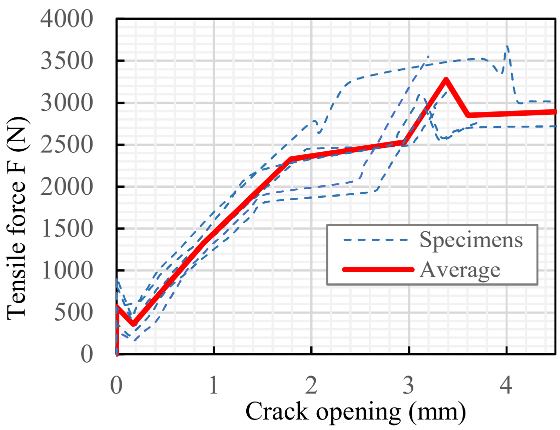
a) Anchorage length l_{E1} = 25 mm (series 1)



b) Anchorage length l_{E1} = 50 mm (series 2)



c) Anchorage length l_{E1} = 100 mm (series 3)



d) Anchorage length l_{E1} = 200 mm (series 4)

Fig.7 Tensile force – crack opening relationship matrix was activated that was depicted by an ascending branch of the curve. The inclination of this branch correlates closely to stiffness of bond layer. After reaching the bond strength, the destruction of the adhesive bond occurred due to debonding of the yarn from matrix. As a result, the force transmission fell dramatically. Simultaneously, there was a significantly increase of the relative displacement between textile reinforcement and mortar. Lastly, the remaining pull-out force was based on friction, which was identified by a considerable plateau. When the relative displacement increased, the friction reduced regularly due to the decrease of embedded length (see Fig. 8, 9). In addition, it was shown that the average value of friction approximately equals bond strength. This feature might be one of the reasons suggesting the explanation for the characteristic of series 1 which had unique peak. As for short embedment length of 25 mm, due to the insignificant effect of the mechanical adhesion, bond strength identified by friction and there was not the existence of second peak, which represented for effect of adhesive bond (see Fig.7a).

For long embedment length (200 mm), as the result of the increasing tensile force, the load was gradually transferred from reinforcing yarn to the matrix. There was a buildup of stress in the matrix until tensile strength of matrix was exceeded. Therefore, in some specimens, additional cracks were formed (Fig.7d). In particular, the 5^{th} specimen of series 4 occurred fracture of tested yarn at load of 3450 N and crack opening of 3.2 mm. This might provide useful suggestion on determining anchorage length of textile reinforcement in subsequent experiments.

The significantly difference between crack opening and total displacement, measured by COD and LVDT respectively, might be clearly observed in series 1 and 2 (see Fig.10). Before the crack of mortar occurred, with the same tensile force level, the total displacement of specimen was always greater than value of crack opening. This deviation was due to the elastic elongation of specimen under the impact of tensile force. The deviation tended to steadily decrease together with the increase of crack opening and the transmission of tensile force to roving. In activated state of adhesive bond and friction bond, both COD and LVDT gave the approximately equal value.

In order to evaluate the influence of embedment length on bond strength, the results of the textile pull-out tests were described as bond flow – crack opening relationship. The bond flow T in N/mm was calculated by relating the pull-out force F to the anchorage length l_{E1} of roving (equation (1)) [11].

$$T=F_G/l_{E1} \quad (1)$$

where,

T : bond flow (N/mm)

l_{E1} : embedded length of tested yarn (mm)

$F_G=F-F_W$

F : pull-out force obtained from test (N)

F_W : dead weight of the test setup's upper section

The values of T corresponding to pull-out resistance of series from 1 to 4 were 6.2, 10.6, 10.9 and 16.3 N/mm respectively. Obviously, T varied in a wide range and T increased along with the rise of embedded length. Reason of the variability in the results was presumed to be the uneven and irregular geometry of multifilament yarn that induced potential bond along anchorage length [12].

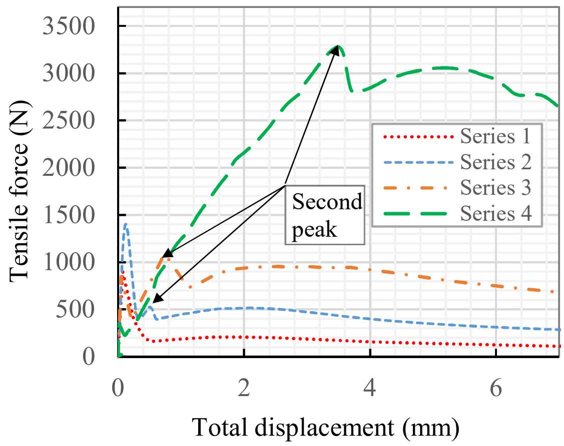


Fig.8 Tensile force – total displacement relationship of four series

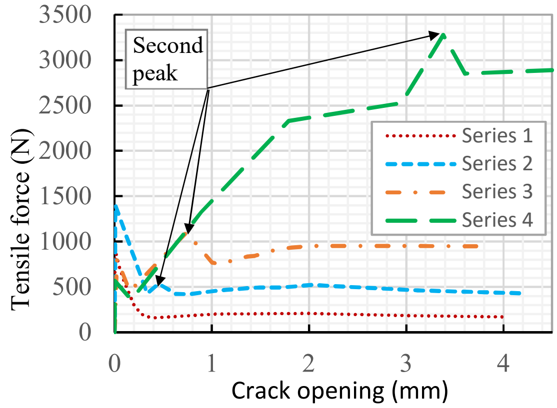


Fig.9 Tensile force – crack opening relationship of four series

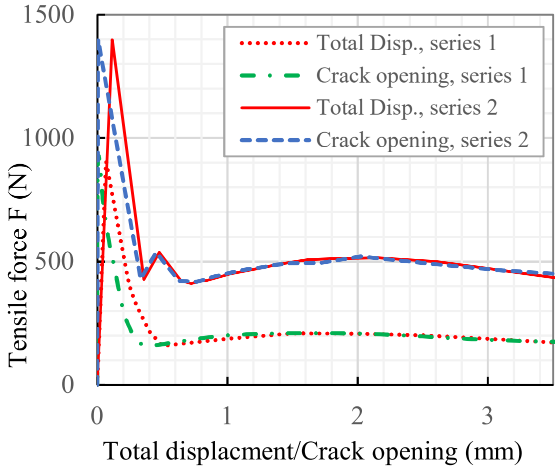
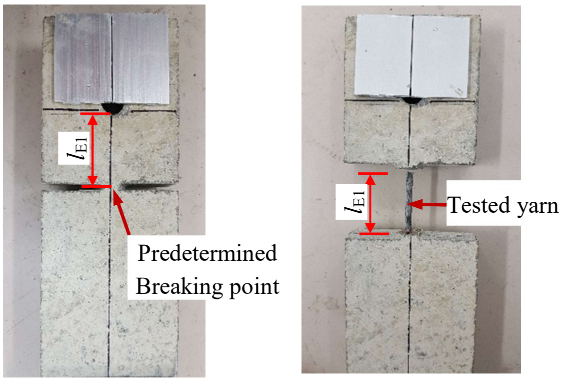


Fig.10 Correlation between total displacement and crack opening of series 1 and series 2



a) Before pull-out test b) After pull-out test

Fig.11 Pull-out failure of warp yarn

4. CONCLUSIONS

The increasing application of TRC in construction field claims the formalization of experimental method and design standards. This publication provided an overview of pull-out tests to determine bond law between textile reinforcement and mortar. The strengths and the weaknesses of each experiment were analyzed and evaluated, therefore, the most suitable and reliable pull-out test was proposed. The real tests were conducted that give insightful understanding on bond behavior of examined mortar and textile fabric. Additionally, result from experiments gave hints on choosing anchorage length of TRC.

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