Construction and Building Materials 127 (2016) 383–393

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Modelling of near-surface mounted carbon fibre reinforced polymer strips embedded in concrete with cement-based adhesive

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HIGHLIGHTS

- NSM CFRP strip was modelled efficiently as embedded reinforcement in cement adhesive.
- Developed FE models are able to simulate the experimental aspects accurately.
- Developed FE models can be used in the design of NSM CFRP-strengthened RC members.

ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form 21 September 2016
Accepted 26 September 2016

Keywords:
Bond
Near-surface mounted (NSM)
Carbon fibre reinforced polymer (CFRP)
Strips
Concrete
Cement-based adhesive

ABSTRACT

The use of near-surface mounted (NSM) carbon fibre reinforced polymer (CFRP) is a promising technique for strengthening deficient reinforced concrete members. In order to shed further light on this technique, the finite element method (FEM) was used to simulate the bond behaviour between NSM CFRP strips and concrete substrate with cement-based adhesive in single-lap shear tests. Non-linear FEM software ATENA 3-D was used in this study. The developed numerical models can predict the experimental aspects reasonably well and can be used in the design of reinforced concrete members strengthened with NSM CFRP strips.

1. Introduction

In recent years, the near-surface mounted (NSM) carbon fibre reinforced polymer (CFRP) technique has been used as a strengthening method to increase or restore the flexural and shear capacity of deficient reinforced concrete (RC) members [2,9,10,7]. The term NSM is used to differentiate it from the externally-bonded (EB) technique. Early de-bonding of FRP from the concrete substrate in the EB FRP strengthening method has led to the use of the NSM FRP strengthening method [18,14,15,16]. The NSM FRP method provides greater resistance to de-bonding than the EB FRP method [9]. In the NSM FRP technique, the FRP is placed into slots in the cover of the concrete [6]. The NSM FRP method has been used widely with organic resins (epoxy resins). However, organic resins have serious issues, including the emission of toxic fumes and flammability [20]. In addition, these resins are unsafe when exposed to high temperature or fire conditions [11]. Therefore, the need for alternative bonding adhesives to epoxy resins has become necessary for NSM FRP applications. Mineral-based materials may be an alternative adhesive material, since they are safe in high temperature or fire conditions. There is also no emission of toxic fumes and they are non-flammable. Recently, significant composite action has been achieved using cement-based adhesives in the FRP strengthening technique [1,12]. The bond between the NSM FRP and the concrete substrate is the key to the NSM FRP strengthening method. Consequently, the bond of CFRP material to concrete using the NSM method must be assessed. For this purpose, single-lap shear tests (direct pull-out tests) were carried out [1], measuring the monotonic pull-out force at the CFRP strips and the loaded-ends slip. The influence of CFRP strips with two different dimensions (1.4×10 mm, 1.4×20 mm) and surface types (smooth, rough) on the bond behaviour between NSM CFRP strips and concrete substrate using cement-based adhesive was analysed.

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http://dx.doi.org/10.1016/j.conbuildmat.2016.09.109
0950-0618/

Fig. 1. Pull-out test set-up.

Table 1
Monotonic pull-out test results.

Specimen ID	$F_{s,max}$ (kN)	S (mm)	$\mathbf{T}_{max}$ (MPa)	σ_{max} (MPa)
MR20C-1	24.52	2.13	3.18	876.0
MR20C-2	23.94	2.76	3.10	855.0
MR20C-3	18.29	1.99	2.37	653.3
MR10C-1	11.60	1.32	2.83	829.0
MR10C-2	10.82	1.08	2.64	773.2
MR10C-3	10.39	1.11	2.53	742.5
MS20C-1	7.44	0.59	0.96	265.7
MS20C-2	6.90	0.38	0.89	246.5
MS20C-3	9.14	0.61	1.18	326.5
MS10C-1	5.44	1.31	1.33	388.6
MS10C-2	6.05	0.77	1.47	432.5
MS10C-3	5.38	0.88	1.31	384.2

The bond mechanism between NSM FRP and concrete substrate is relatively complex and can be affected by many variables, such as FRP (rods/strips) properties and dimensions, adhesive properties, and concrete properties and dimensions. It is impossible to study each factor in laboratory investigations. Therefore, accurate numerical modelling may be an alternative research tool. The finite element analysis (FEA) of concrete structures with the power of computer simulation has become a novel design tool in structural engineering. In this paper, non-linear FEA using ATENA 3-D software from Červenka Consulting Ltd., is used in the simulation of the single-lap shear tests that were carried out. This software is specially designed for the analysis of RC members [3]. All material properties and parameters used in this software were taken from the experimental work, and the performance of the developed numerical models was analysed.

2. Experimental study

Direct pull-out tests (single-lap shear tests) were used in the experimental programs reported here. The concrete prism sizes were 75 × 75 × 250 mm. The prisms were held down using a steel cage (see Fig. 1).

The average values of concrete compressive and tensile strength at testing age were 41.13 MPa and 4.28 MPa, respectively. CFRP strips with two different dimensions (1.4 × 10 mm, 1.4 × 20 mm) and two surface types (smooth, supplied by S & P Laminates, and rough supplied by MBrace) were used. The elastic modulus of the S & P CFRP laminate was 210 GPa, while for the MBrace CFRP laminate it was 212 GPa, based on laboratory tests. Cement-based adhesive was used to bond the NSM CFRP strips to the concrete prisms. The bonding length was 180 mm and the curing period was 21 days. For more information, see Al-Saadi et al. [1]. Table 1 lists the monotonic pull-out test results.

The first letter of the specimen ID "M" refers to monotonic test; the next letter "R" means rough CFRP strips and "S" means smooth CFRP strips; the number "20" means 1.4 × 20 mm CFRP strips and "10" means 1.4 × 10 mm CFRP strips; "C" means cement-based adhesive; and the final number "1,2,3" refers to specimen number.

where:

$F_{s,max}$: is the maximum pull-out force (kN) during the test.

S: is the slip (mm) at the loaded end, at maximum pull-out force ($F_{s,max}$).

$\mathbf{T}_{max}$: is the maximum bond strength (MPa), calculated by dividing the maximum pull-out force by the contact area between the adhesive material and CFRP strips.

$\mathbf{T}_{max} = F_{s,max}/[2 \cdot (T_f + W_f) \cdot L_b]$, where T_f and W_f is the thickness and width of the CFRP strip, respectively and L_b is the bond length.

σ_{max}: is the axial stress in CFRP strips (MPa) at maximum pull-out force.

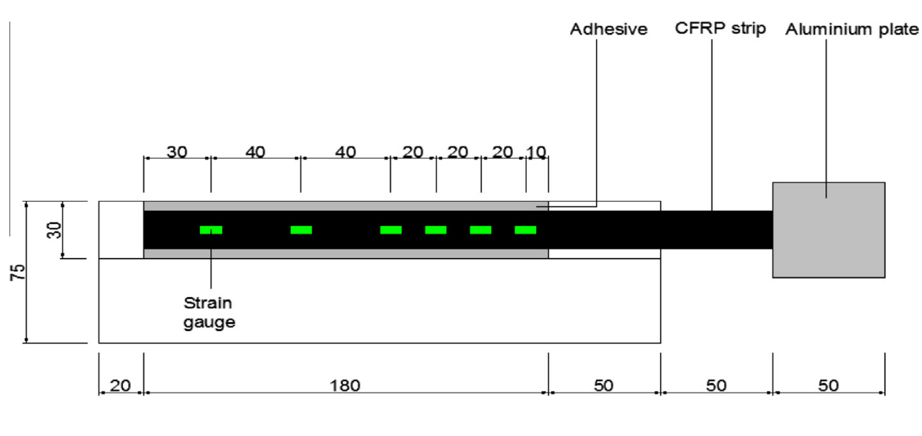

Fig. 2. Strain gauge layout of specimen MR20C-SG.