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EFFECTIVE BOND LENGTH OF MODIFIED CEMENT-BASED ADHESIVE FOR FRP-NSM STRENGTHENING SYSTEM

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ABSTRACT

Concrete strength for flexure, shear and torsion has been improved using near-surface mounted (NSM) strengthening technology with epoxy adhesives. Due to the hazards from toxic fumes and to enhance the performance of structures in high-temperature environments, a new cement-based adhesive has been used as an alternative to epoxy in several studies. The application of cement-based adhesive has been studied for externally-bonded reinforcement (EBR) and the critical failure was debonding between fibre and adhesive. To make the cementitous adhesive meet the requirements of the NSM technique, a new modification of cement-based adhesive has been accomplished. The aim of this paper is to find the critical bond length of the modified cement-based adhesive with the NSM technique using FRP laminate. To determine the effective bond length of this adhesive, an experimental program of pull-out testing using a single-lap shear test set-up was undertaken with different bond lengths. Three prisms were tested for each bond length in this investigation. The results show the effective bond length for the modified cement adhesive. The experimental results also indicate that the adhesive is efficient with the NSM technique. Finite element analysis was carried out using the ATENA 3-D computer program to shed further light on the performance and the properties of this cementitous adhesive. The results confirm the experimental analyses, and good agreement was found between the experimental results and finite element analysis.

KEYWORDS

FRP laminate, strengthening, effective bond length, NSM, concrete prisms, ATENA 3-D.

INTRODUCTION

Fibre reinforced polymer (FRP) is an advanced composite material consisting of two key elements, FRP and adhesive. Rehabilitation and strengthening techniques using epoxy and cement-based adhesive as bonding agent have been applied to many structural elements worldwide (Pham and Al-Mahaidi 2004; Al-Mahaidi and Hii 2007). The sensitivity of epoxy to temperature is considered a serious problem for FRP application (Barnes and Fidell 2006). Other problems include hazardous toxic fumes, moisture impermeability and flammability, and the deterioration of strength with temperatures higher than the glass transition (Tg) of 60-70 °C (fib-bulletin 14 2001; Gamage et al. 2005). Because of the problems of epoxy at elevated temperatures, an alternative bond material to epoxy has become important for strengthening. The work of Wiberg (2003) was one of the first attempts to use cement-based adhesive for EBR FPR beams with cementitous mortar by applying the morter to the concrete surface after adequate surface preparation. Recently, good bond properties have been achieved for the EBR FRP strengthening technique using a new cement-based adhesive developed by Hashimi and Al-Mahaidi (2010; 2012). Hashemi and Al Mahaidi (2010) examined the bond strength of FRP concrete specimens by single-lap shear testing and FRP beam flexural behaviour, and their study includes an experimental study and finite element analysis. Their new mortar includes ordinary Portland cement and micro-cement at a mixing ratio of 1:4 by weight, in addition to silica fume to improve the mechanical properties of the mortar, filler to reduce cement dosage, and super-plasticiser to achieve the required workability. Two main sections were included in this study. The first part was a single-lap shear test of a concrete prism to investigate the bond properties of carbon FRP material (fabric and textile). The second experimental study focused on the flexural properties of RC beams with the same materials, and the software ATENA was used to execute non-linear finite element analysis. The researchers found that the failure mode of all samples in a single-lap shear test was debonding cracking at the CFRP-mortar interface.

Early de-bonding has become the major issue in the EBR FRP strengthening technique. To reduce these problems, the near-surface mounted (NSM) technique (Nanni et al. 2004) provides greater resistance to de-bonding. The NSM technique has been used extensively with epoxy resin. The cement paste has not been used with (NSM) technique due to its low viscosity which causes flow it away from the groove and makes it difficult to apply in practice. In recent times, the use of cement-based adhesive with the NSM technique has been reported by Ahmed and Al-Mahaidi (2012). The improvement of a new cement-based adhesive achieved by Hashimi and Al-Mahaidi (2010) is therefore necessary for NSM application. In this investigation, the researchers achieved excellent bond properties by adding polymer to the adhesive mortar, which increases the viscosity of the adhesive, and significant ductile behaviour was observed for all specimens. The modification of the adhesive obviates dropping away and it works more functionally in practical applications. It is recommended to use the modified mortar with 30 minutes of pot-life. The results of the strengthening with NSM using modified cement adhesive were compared with the corresponding ERB test results of Hashimi and Al-Mahaidi (2010). This comparison showed that NSM was 2.5 times more effective than EBR.

Using the NSM technique with carbon fibre-reinforced polymer (CFRP) laminates and modified cement-based adhesive is one suggested method for the rehabilitation of concrete structures and stopping cracking. For this repair method, it is important to find the effective bond length for CFRP laminates. The work reported in this paper is an investigation into the properties of this modified cement paste and aims to determine the effective bond length by performing single-lap shear tests using CFRP laminate material applied to the concrete prisms.

TEST SET-UP AND MATERIAL PROPERTIES

Experimental tests using the modified cement-based adhesive with CFRP laminates are reported in this paper for several different bond lengths. For these materials, the minimum bond length that is required to achieve the maximum was determined. The experimental work included testing fifteen concrete prisms measuring 250 × 75 × 75 mm consisting of a concrete mix of 1.0 Ordinary Portland cement, 2.24 sand, 4.17 coarse aggregate of 10 mm maximum size, and a water-cement ratio of 0.58. The concrete prisms were designed to fit the set-up for single-lap shear testing. The cement paste involved Ordinary Portland cement, micro-cement, silica fume, filler, super-plasticiser and primer. The compressive strength, Brazilian or splitting tensile strength and elastic modulus of the concrete and mortar specimens (cylinders of 100 mm diameter and 200 mm length for concrete, and 50 mm diameter and 100 mm length for mortar) were determined in the laboratory on the same day as the prism testing, and the results are shown in Table 1. The mechanical properties of the FRP laminate used in this study are also presented in Table 1.

Table 1. Mechanical properties of concrete, mortar and FRP

Material	FRP laminate	Concrete	Mortar
Compressive strength (MPa)	-	45	65
Tensile strength (MPa)	3550	3.9	5.1

After 14 days of curing, grooves were made in the longitudinal direction of the concrete prisms. The minimum depth of the grooves must be at least 1.5 times the depth of the FRP laminate strip, and the minimum width of the groove must be at least 5 times the thickness of the FRP laminate strip (ACI 2002). Therefore, the groove size was 5 mm wide and 18 mm deep. The grooves were then cleaned and filled with cement mortar using a steel blade and thin layers of the mortar were applied to the faces of the CFRP laminates. The CFRP laminate strips (10×1.4 mm) were introduced to the required depth, and the excess mortar was removed. The specimen details and groove dimensions are shown in Figure 1.

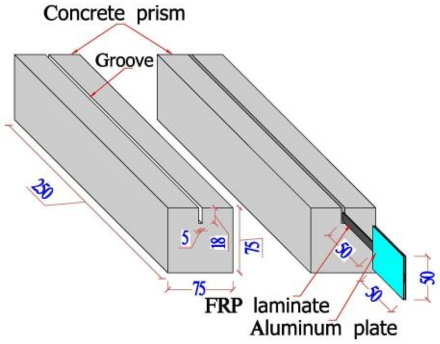

Figure 1. Specimen details and groove dimensions

The laminate was extended to around 100 mm out of each prism. The aluminum plates were fixed for gripping after 14 days of mortar curing using Araldite epoxy adhesive, which has been used successfully with FRP. The effective bond length of the cement mortar was investigated by using different CFRP bond lengths. Three specimens of 100, 125, 150, 175 and 200 mm bond lengths were used to fix the laminates. To avoid concentration of stresses and premature edge failure, the bonding started from the edge of the prism, as shown in Figure 2. Table 2 presents the variables in the samples.

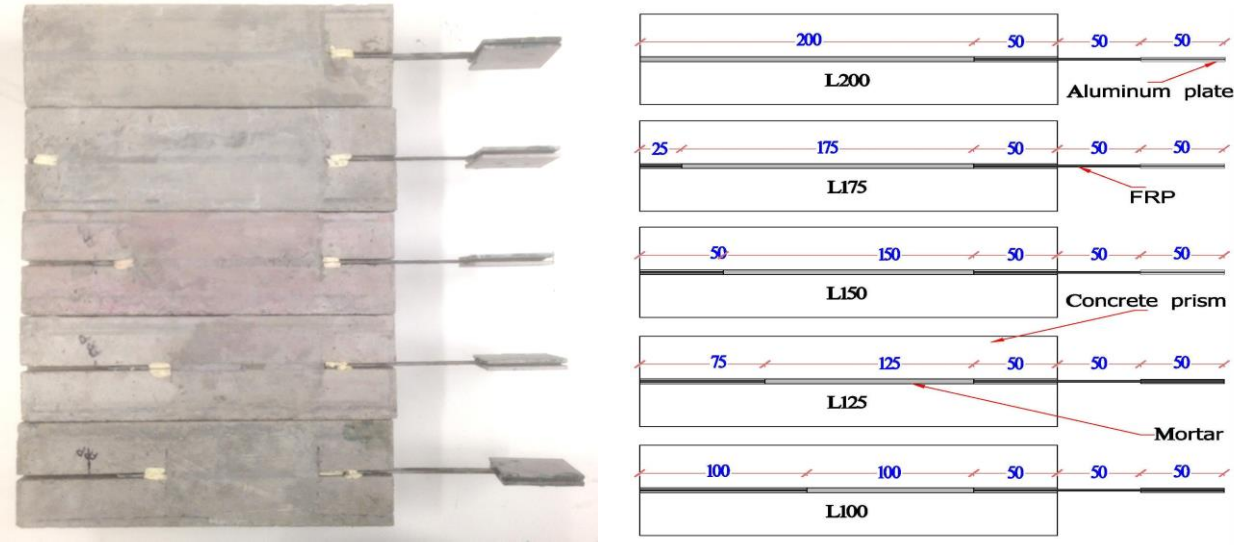

Figure 2. Dimensions of the bond applications

Table 2. Details of prisms

Prism lab symbol	No. of prisms	FRP area (mm2)	Bond length (mm)
L100	3	1.4×10	100
L125	3	1.4×10	125
L150	3	1.4×10	150
L175	3	1.4×10	175
L200	3	1.4×10	200

Single-lap shear testing was carried out on an Instron machine as presented in Figure 3 with a displacement-controlled rate of 0.1 mm/minute.

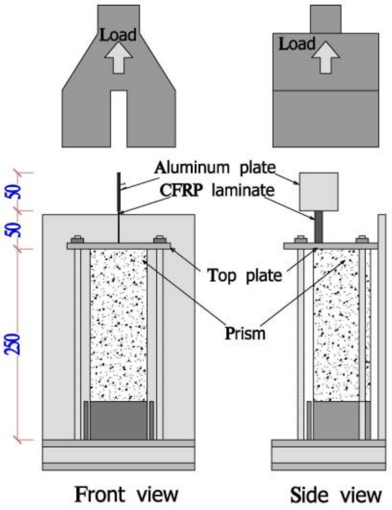

Figure 3. The set-up of the single-lap shear test

TEST RESULTS

After 14 curing days for the mortar, one sample from each series was tested, and two samples were tested after 21 curing days in order to examine the effect of the curing time for the mortar.

For series L100, the corresponding forces of the 21 days curing samples were 8.1 and 8.6 kN, with an average force of 8.35 kN. However, the ultimate force of the 14 days of curing sample was 7.1, slightly less than the average of the samples with 21 curing days. The load-displacement curves are presented in Figure 4. The deformability of all three samples is about the same, with more rigidity for the 21 curing days samples. The average ultimate force was 10.2 kN for the 21 day samples in the L125 series, and the corresponding ultimate forces were 8.8 and 11.6 kN. The difference slightly exceeds the maximum difference resulting from the pot life of the mortar (between 5-30 minutes), whereas a reduction in the ultimate load can be expected up to 20%, depending on the age of the mortar (Ahmed and Al-Mahaidi 2012). The ultimate load after 14 days of curing was 9.4 kN, which is still lower than the average of the 21 curing days samples. Figure 5 presents the load-displacement curves. For the L150 series, only two samples were considered as the third sample was canceled because of an error in the machine during the test. The ultimate force of the 14 days sample was 11.3 kN, and that of the 21 days sample was 12.7 kN. The ultimate force of the 21 days sample was higher than the force of the 14 days sample by 11%.The load-displacement curves are shown in Figure 6. The L175 series had an average ultimate force of 14.95 kN for twenty one days samples. The corresponding ultimate force of the 21 and 14 days samples were 15.1, 14.8, and 13.1 kN respectively, as shown in the load-displacement curves in Figure 7. There are small differences between the ultimate loads and the performance of the samples with 14 and 21 curing days. An average ultimate force of 14.5 kN was achieved for the 21 days samples in the L200 series, and that of the 14 days sample was 13.3 kN. Figure 8 presents the load-displacement curves for the three samples, and shows that more rigid behaviour was achieved by the 21 curing day’s samples.

Table 3 shows the values of the ultimate loads achieved by all tested samples and the averages for 21 curing days samples are presented. It can be concluded that the effective bond length is almost 175 mm for this cement paste. The results show that the mortar has similar behaviour for the samples with 21 curing days, while the ultimate load changes depending on the bond length in each series. The load–displacement curve for the samples with 14 curing days presents a lower stiffness and a lower peak load in all series. The failure was in general interface cracking and FRP bold slip for all specimens.

Table 3. The values, mean, and standard deviation for the ultimate loads

	Load (kN)			Mean of 21 days
Age Bond L	14 days	21 days no 1	21 days no 2	
100 mm	7.1	8.1	8.6	8.35
125 mm	9.4	8.8	11.6	10.2
150 mm	11.3	-	12.7	12.7
175 mm	13.1	14.8	15.1	14.95
200 mm	13.3	15.7	13.3	14.5

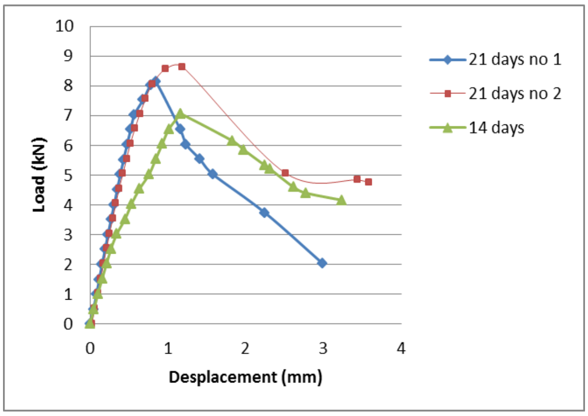

Figure 4. Load-displacement curves for L100 series

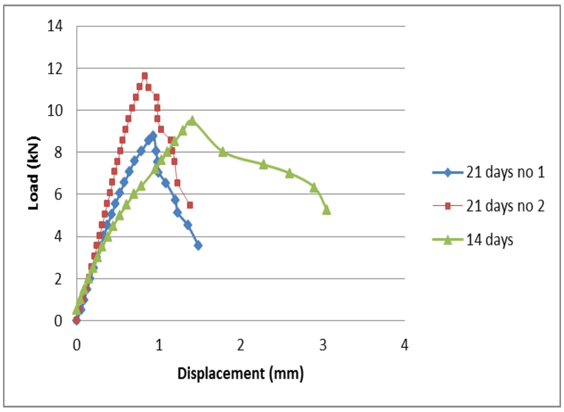

Figure 5. Load-displacement curves for L125 series

NUMERICAL ANALYSIS

In order to shed further light on the performance of the mortar and the behaviour of prisms with the NSM near technique, non-linear finite element (FE) analysis was carried out using the software ATENA 3-D (Cervenka and Cervenka 2010).

To define the structural geometry for the specimens using ATENA 3-D, basic steps taken during pre-processing should include: material properties, geometrical model, supports and actions, finite element mesh, and solution procedure. 3-D Nonlinear Cementitous is a fracture plastic model in ATENA 3-D used for brittle materials such as concrete and mortar. The 3-D elastic isotropic model is suitable for aluminium plates. FRP can be modelled as discrete bars near the concrete surface with the area corresponding to the total FRP cross section, and the FRP material properties can be defined using reinforcement material. The 3-D interface material was used to define the contacts between the mortar and the concrete. Three-dimensional solid regions called macro-elements and the reinforcement pars elements were used in ATENA 3-D to model the geometry of the specimens. Brick elements were created and a suitable mesh size was selected to make the analysis satisfactory. The Newton-Raphson method provided in ATENA 3-D was used as the non-linear finite element solution method. Figure 9 presents the complete uniaxial stress-strain results for concrete and mortar and the numbers 1-4 in this diagram are used in the results of the analysis for denoting the case of damage. The stress-strain law for the reinforcement material that was used to model the CFRP laminate as a discrete bar was assumed to be linear, as shown in Figure 10.The numerical model in Figure 11 was adopted for all tested specimens. Non-linear finite element (FE) analysis was carried out using the ATENA 3-D computer program. The results of the numerical runs were extracted and compared with the experimental results. The load-displacement curves of the models for all prisms are shown in Figure 12. From the experimental and FE results, it is evident that the stiffness and ultimate loads are predicted with reasonable accuracy, and there is a good correlation between the experimental and numerical results. The ultimate loads for each bond length are consistent with the ultimate loads obtained by experiment. Comparisons of ultimate loads can be found in Figure 13.

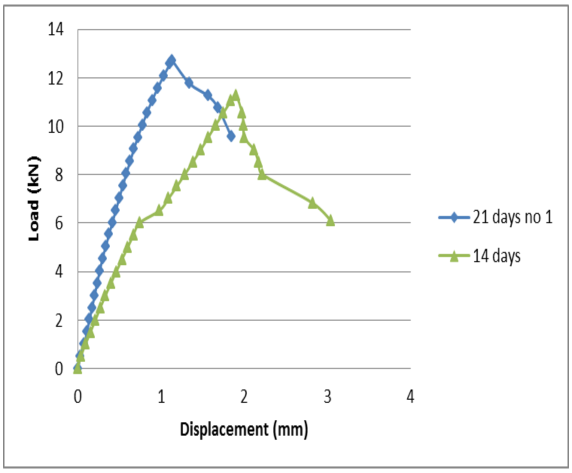

Figure 6. Load-displacement curves for L150 series

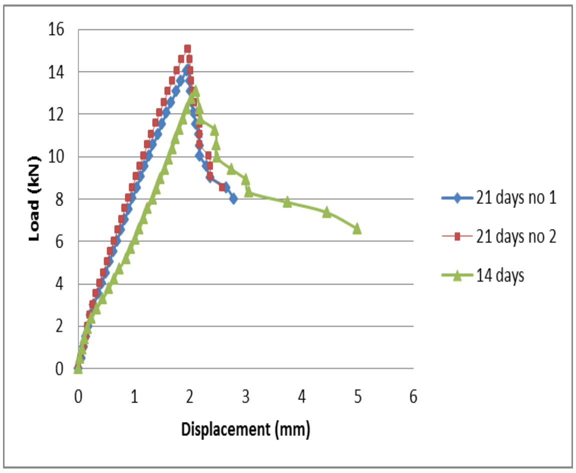

Figure 7. Load-displacement curves for L175 series

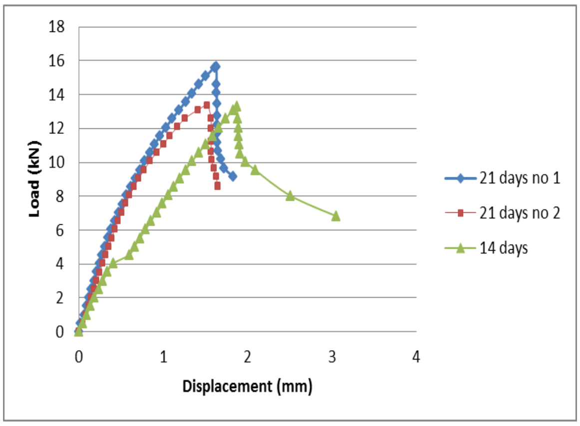

Figure 8. Load-displacement curves for L200 series

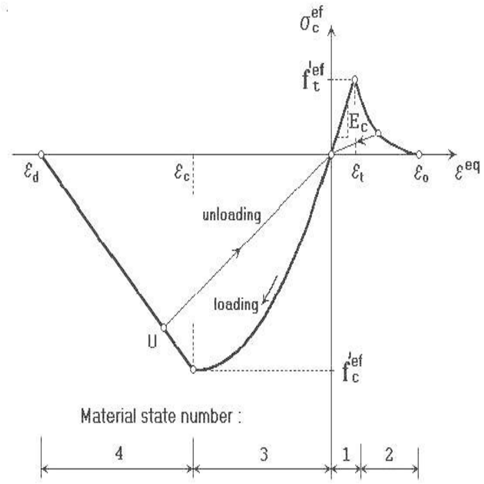

Figure 9. Uniaxial stress-strain for concrete and mortar (Cervenka et al 2005)

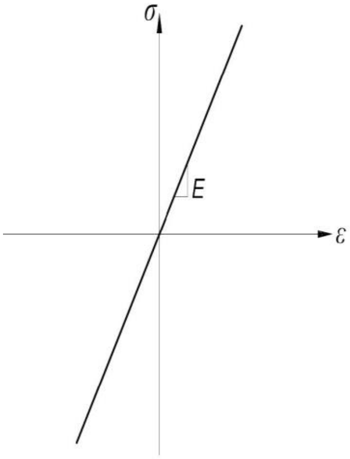

Figure 10. Stress-strain law for the CFRP laminate (Hashemi 2011)

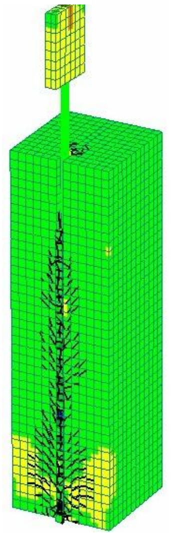

Figure 11. ATENA 3-D modelling for the concrete prisms

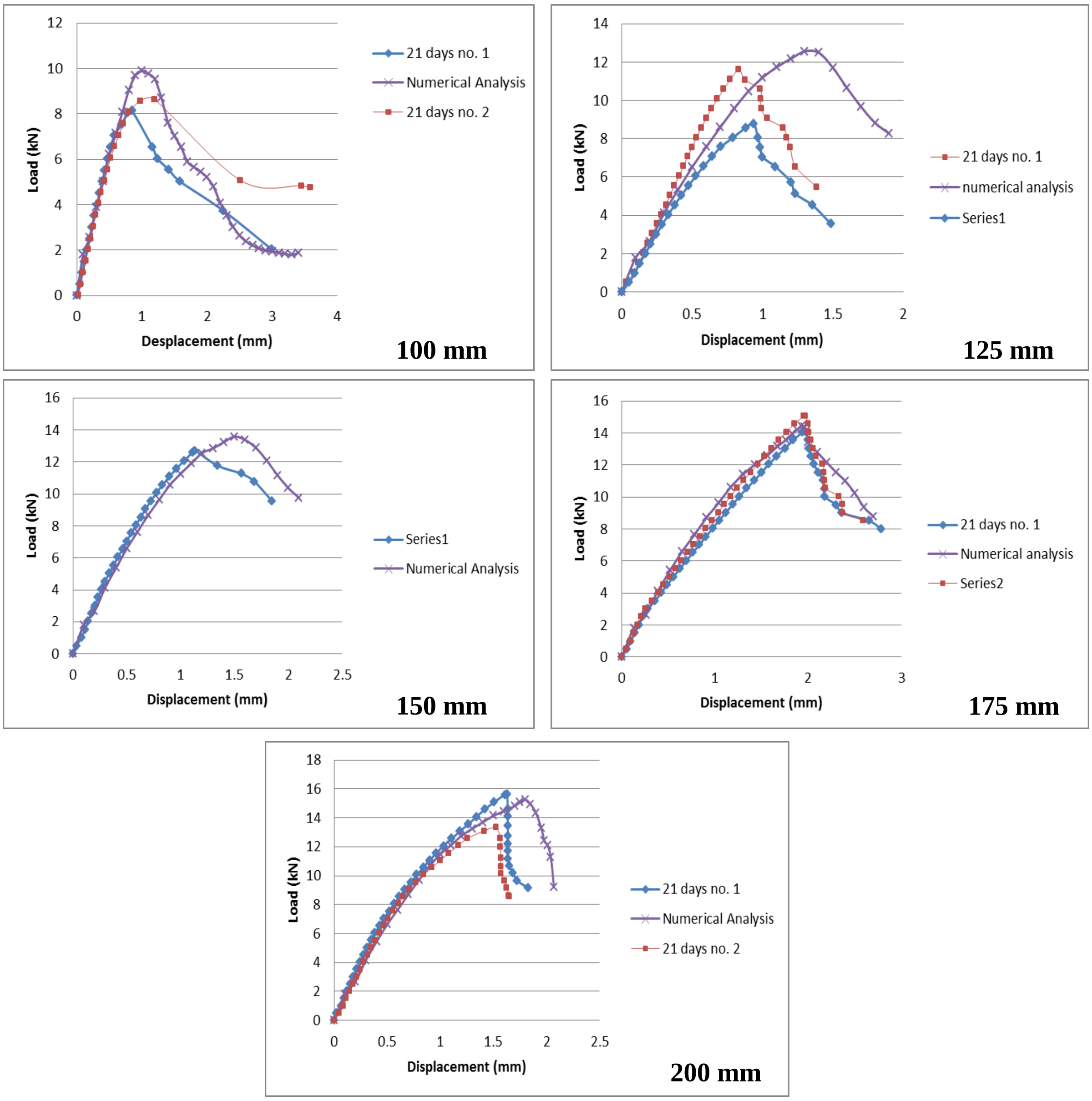

Figure 12. Numerical and experimental analysis results

CONCLUSIONS

Fifteen prisms were strengthened using the NSM technique and modified cement-based adhesive, and single-lap shear test was carried out to test these prisms. FE analysis was adopted using the ATENA 3-D computer software to assess the accuracy of the experimental results. From the results, it can be concluded that

(1) Good properties and considerable composite actions can be achieved when using this modified mortar as an adhesive.
(2) The 175 mm bond length is the most effective bond length for this new cementitious mortar with CFRP laminate.
(3) 14 days of curing time for the mortar is insufficient. The samples displayed less stiffness and ultimate loads when compared with the 21 curing day's samples, and this is considered adequate curing time for the mortar.
(4) The failure mode was interface failure between the mortar and the concrete with longitudinal cracks in the adhesive and some slip in the FRP laminate.
(5) Good agreement was achieved between the numerical analysis and the experimental work in terms of the ultimate loads and the initial stiffness.

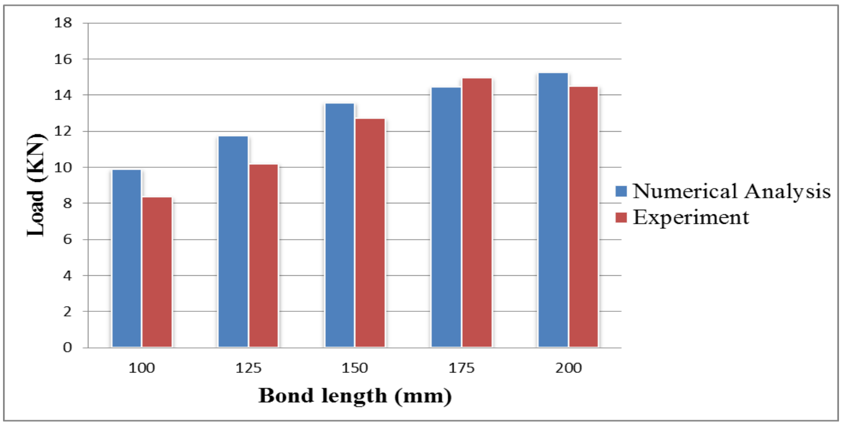

Figure 13. Average ultimate load for each bond length

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