COMPORTAREA ZONEI DE INTERFAȚĂ DINTRE PLATBANDELE COMPOZITE POLIMERICE ARMATE CU FIBRE ŞI BETON
THE BEHAVIOUR OF THE INTERFACE BETWEEN CARBON FIBRE REINFORCED POLYMER COMPOSITE PLATES AND CONCRETE

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The interface behaviour of fibre reinforced polymer carbon plates bonded to concrete represents a key issue in the efficiency of the strengthening solutions based on externally bonded composite plates.

An extensive research program was developed at the Faculty of Civil Engineering and Building Services from Iasi, to study the interfacial behaviour between carbon fibre reinforced polymeric composite (CFRP) plates and concrete. The study includes nine strengthened concrete elements which were tested under double shear pull testing set up. On the basis of the performed tests the recorded failure mode was the same for all tested specimens namely the interfacial failure. It essentially occurs in concrete close to the FRP plate-concrete interface.

The recorded data have been used to plot the load-slip curves and strains distributions along the composite bonded plates. Together, they served later on to calibrate the finite element method (FEM) based modelling accompanying the laboratory tests.

Comportarea zonei de interfață dintre platbandele din compozite polimerice armate cu fibre din carbon şi suprafața betonului reprezintă o problemă-cheie în asigurarea eficienței soluțiilor de consolidare prin placare exterioară cu elemente compozite.

La Facultatea de Construcții şi Instalații din Iaşi, s-a realizat un program complex de cercetare pentru studierea comportării regiunii de interfață dintre platbandele compozite armate cu fibre din carbon (CPAFC) şi beton, corespunzătoare soluțiilor de consolidare. Studiul include nouă elemente din beton consolidate cu fâşii compozite, testate la forfecare dublă. Având la bază testările realizate, modul de cedare înregistrat a fost acelaşi pentru toate probele încercate, şi anume cedarea interfeței. Aceasta are loc, în principal, în beton, în apropierea interfeței platbandă CPAFC-beton.

Rezultatele înregistrate au fost folosite pentru a reprezenta curbele încărcare-lunecare şi distribuția deformațiilor specifice de-a lungul platbandelor compozite aplicate. Rezultatele obținute au fost utilizate la calibrarea modelării pe baza metodei cu elemente finite (MEF) care au completat încercările experimentale.

Keywords: *externally bonded strips, carbon FRP plates, interface behaviour, finite element analysis*

1. Introduction

The use of fibre reinforced polymeric (FRP) composites to strengthen reinforced concrete (RC) elements has been the subject of many experimental, analytical and numerical studies available in literature [1-9], nevertheless some issues are still under discussion in the research communities. One of them, seriously affecting the efficiency of FRP plate bonding systems is the premature debonding of the reinforcement from the substrate. Thus, an accurate estimation of the bond strength between FRP and concrete substrate represents a key issue for the proper use of externally bonded reinforcement (EBR).

With a tradition of over four decades in the field of fibre reinforced polymer (FRP) composites in constructions, the Faculty of Civil Engineering and Building Services of Iasi is continuously engaged in promoting these materials for structural applications in civil engineering. Within these applications, hybrid systems associating externally applied FRP composite materials and concrete have been shown to fail in efficiently transferring stresses between the two components. As main contributor to this, the complex phenomena occurring at the concrete – FRP interface which involves a large number of variables is studied under bond related problems.

As found within previously completed research programs and the consulted literature, bond related problems require different approaches when studied.

The two general types of applications of externally bonded FRP hybrid systems for concrete structures are known as contact-critical and bond-critical. In contact-critical applications, load is transferred between FRP and concrete by contact stress (pressure) across the interface, as in passive column confinement. In bond-critical applications, load is transferred by shear stress as well as peeling-stress, as in flexural and shear

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reinforcements for beams.

High strength epoxies are required to transmit substantial shear and peeling stresses in bond-critical applications, whereas either epoxies or non-shrink cementitious grouts are suitable to ensure the intimate interfacial contact required for contact-critical applications. Proper initial bond quality is critical to the long-term durability of external reinforcements for concrete structures. Therefore, proper procedures for preparing the concrete and installing the FRP material should be followed [10].

Bonding between carbon fibre reinforced polymer (CFRP) laminates and concrete substrates have been discussed in a number of researches. The results of shear tests performed on CFRP – concrete hybrid systems have been described [11-19]. Important bending tests on half – scale RC beams reinforced by means of CFRP sheets and statically tested to failure in three-point bending have been reported in [20]. The genuine interfacial stress in FRP strengthened RC beams is best reproduced by bending tests, but the simplicity of the shear setup makes them popular for laboratory investigations of FRP to concrete bond behaviour. Nevertheless, comparisons made on different set-ups shown that, in general, shear tests offer lower bond strength than bending tests [21-23]. This reduction of bond strength in case of flexural elements can be caused by the peeling stresses that also develop along the FRP-concrete interface and their interaction with shear stresses [24].

This paper describes both experimental and numerical investigations performed at the Faculty of Civil Engineering and Building Services.

The study included nine twin-prisms with externally applied FRP carbon plates adhesively bonded. The double shear pull test set-up has been performed utilising a specially designed device to convert the compressive loading delivered by the universal testing machine into tension loading conditions. The recorded failure modes were similar for all tested specimens and were classified as mixed peel-off/ rip-off mode. This mixed mode typically occurs in concrete close to the FRP plate-concrete interface, indicating that the bond strength between FRP and concrete is mainly dependent on the tensile strength of concrete.

Proven as a practical method for investigating the bond behaviour between FRP plates and concrete, a FEM based numerical study was performed using the ANSYS software package. Three-dimensional models of the experimentally studied specimens were analysed. The FEM analysis revealed the capabilities of this specialized software to describe the FRP-to-concrete bond behaviour with reasonable accuracy.

2. Experimental program

The experimental program consists in a series of tests performed on 2 concrete blocks (150x150x400mm) separated in the middle by a thin steel plate and strengthened on two opposite sides with EBR CFRP laminates (Fig. 1) and subjected to tension. A total of 9 specimens were tested, which were divided in 3 categories, depending on the used strengthening system, having the properties listed in Table 1 [25].

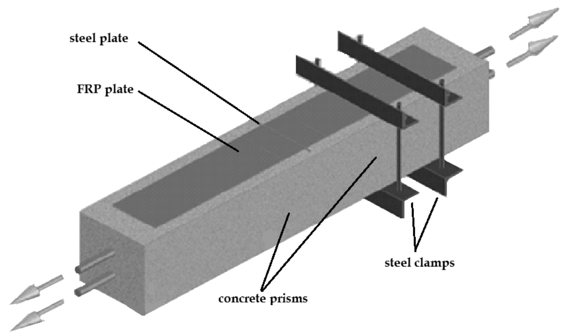


Fig. 1 - The test specimen / *Probă experimentală.*

2.1. Materials used and specimens manufacturing

The concrete mix was designed to have a minimum strength on cylinders $f_{c,cyl}$ = 30 N/mm^2. The properties of the hardened concrete used for manufacturing the specimens were determined by testing the compressive strength on cubes with 150 mm side length and on cylinders with 150mm diameter and 300 mm length [26] and presented in Table 2. The concrete was poured in specially fabricated steel moulds so that the two concrete prisms will be held together and prevent any relative movement during transportation and mounting into the testing device. Special screw bolts have been provided on the side with no strengthening plate, so that the prisms will remain fixed during curing and handling, (Fig. 2).

The laminates used for the tests were 700 mm in length, 100mm in width and with thicknesses equal to 1.2 mm and 1.4 mm. According to the technical specifications provided by the suppliers the CFRP reinforcements have a minimum fibre volume fraction equal to 68%; other material properties are given in Table 1.

Table 1

Main characteristics of CFRP laminates / *Caracteristici principale ale stratificatelor CPAFC*

Sample *Probă*	Thickness *Grosime* [mm]	Width x length *Lățime x lungime* [mm]	Elastic modulus *Modul de elasticitate* [GPa]	Tensile strength *Rezistență la tracțiune* [MPa]	Ultimate strain *Deformație specifică ultimă* [%]
C1	1.2	100 x 700	165	3100	>1.7
C2	1.4	100 x 700	210	3200	>1.35
C3	1.2	100 x 700	165	1000	>0.6

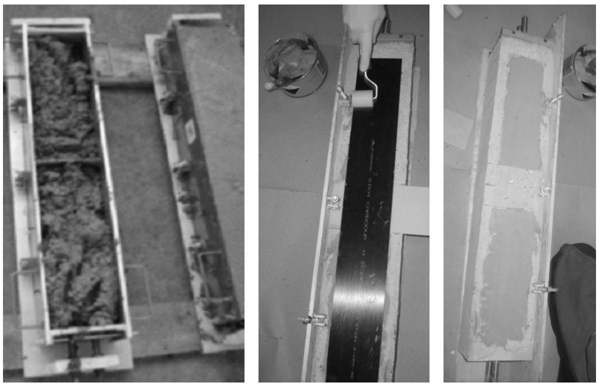


Fig. 2 - The specimen manufacturing / *Confecționarea probei.*

Table 2

The concrete mix / *Rețeta de beton*

Concrete mix for 1 m^3 *Rețeta de beton pentru 1 m^3*		
Sand / *Nisip* 0/3 [kg/m^3]	561.7	
Sand / *Nisip* 3/7 [kg/m^3]	321.1	
Gravel / *Pietriş* 7/16 [kg/m^3]	715.2	
Cement / *Ciment* CEM II 42.5 R [kg/m^3]	413.9	
Water / *Apă* [l]	141.2	
Fresh concrete properties *Proprietățile betonului proaspăt*		
Batch / *Lot*	Density / *Densitate* [kg/m^3]	Slump / *Tasare* [mm]
Batch 1 / *Lot 1*	2350	120
Hardened concrete properties (at 28 days) *Proprietățile betonului întărit (28 zile)*		
Batch / *Lot*	$f_{c,cube}$ [N/mm^2]	$f_{c,cyl}$ [N/mm^2]
Batch 1 / *Lot 1*	34.68	31.37

The laminates used for the tests were 700 mm in length, 100 mm in width and with thicknesses equal to 1.2 mm and 1.4 mm. According to the technical specifications provided by the suppliers the CFRP reinforcements have a minimum fibre volume fraction equal to 68%; other material properties are given in Table 1.

Prior to CFRP bonding, the concrete surface was abraded and the grinding dust was removed until the cement paste was detached (Fig. 3), and the CFRP plates were cleaned of grease and impurities with an organic solvent [27].

The CFRP plate was bonded on two opposite sides of the concrete specimens. Over a central zone of 100 mm, where the two concrete prisms connect to one another, the bonding was prevented. The desired bonded length of the CFRP plates was of 300 mm for each prism, greater that the bond length according to *fib* Bulletin 14 [28].

The adhesive used for bonding the CFRP plates was of epoxy type (Table 3), [29], applied with a constant thickness of 3 mm. Initially, a thin layer of approximately 1 mm was applied on the concrete surface, after which a layer of 2 mm was applied on the CFRP plates. The evenness of the adhesive layer was ensured by rolling and applying an appropriately uniform contact pressure on the strip to provide a proper adherence [30].

Table 3

The main characteristics of the epoxy adhesive [29]
Caracteristicile principale ale adezivului epoxidic

Property *Proprietate*	C1, C2, C3
Mixing ratio *Raport de amestecare*	1:3
Density / *Densitate* [kg/m^3]	1650
Elastic modulus / *Modul de elasticitate* [MPa]	12800
Compressive strength / *Rezistență la compresiune* [MPa]	85 – 95 (at / *la* +35ºC)
Shear strength / *Rezistență la forfecare* [MPa]	17 – 20 (at / *la* +35ºC)
Tensile strength / *Rezistență la tracțiune* [MPa]	27 – 32 (at / *la* +35ºC)

2.2. Instrumentation and loading procedure

The specimens loading was applied using a specially designed steel device, which was conceived so that the universal testing machine of 3000 KN by applying compression to the steel device will load the specimens in tension (Fig. 4). The force controlled loading rate was set for 6KN/min. A load cell with a maximum capacity of 1000 KN was used to monitor the applied load.

Displacements have been measured with LVDTs installed at the location of the transition between the central un-bonded and the bonded

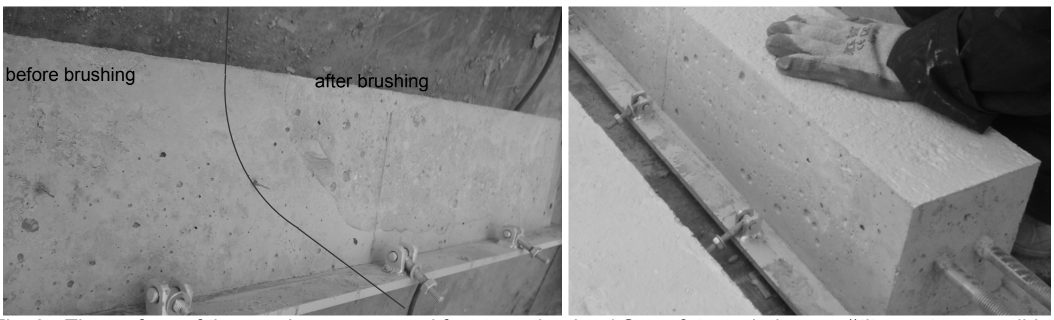


Fig. 3 - The surface of the specimens prepared for strengthening / *Suprafața probelor pregătite pentru consolidare.*

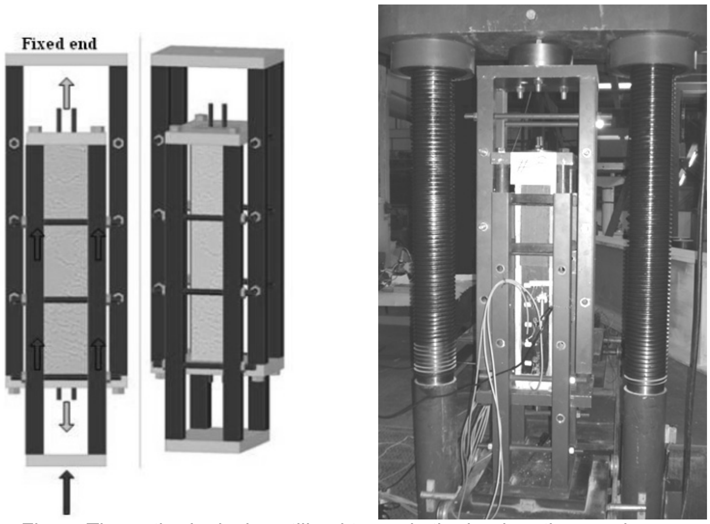


Fig. 4. The author's device utilized to apply the load on the specimens
Dispozitivul conceput de autori pentru încărcarea probelor.

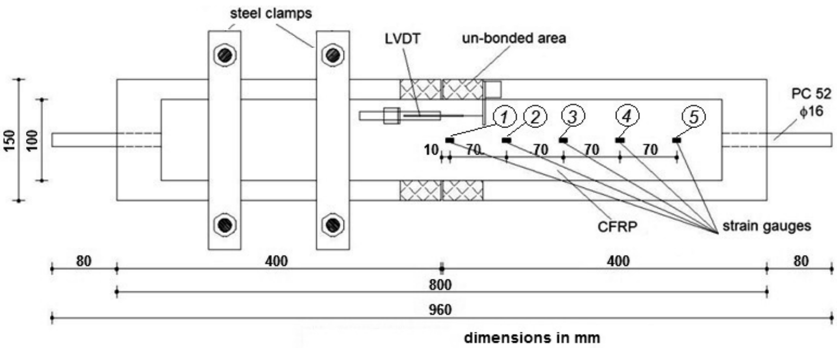


Fig. 5. Specimen instrumentation with LVDTs and strain gauges / *Instrumentarea probelor cu traductori de deplasare şi rezistivi.*

zone, fixed to the concrete and directly connected to the FRP reinforcement at the loaded end; the strains on the CFRP plate are recorded with strain gauges installed as presented in Figure 5. During testing, steel clamps were used on the un-instrumented prism leading the failure to occur on the instrumented side.

Fig. 6. Typical failure mode with a separation of a thin concrete layer
Cedare tipică cu separarea unui strat subțire de beton.

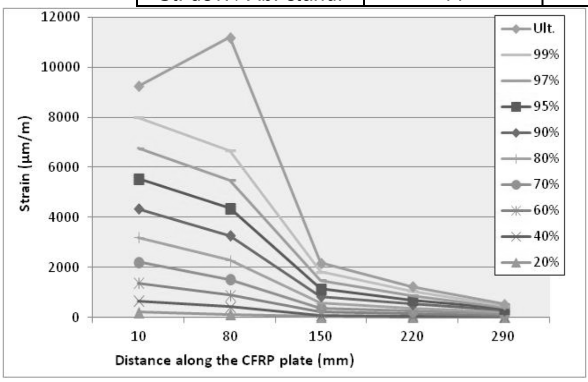
3. Experimental results

On the basis of the performed tests the recorded failure mode was the same for all tested specimens namely debonding of the CFRP plate from concrete surface. Firstly, the cracks were initiated in the concrete, in the central area, where the two prisms are connected; secondly, the final failure, of the concrete – CFRP bond, occurred only on one side, in a brittle manner and accompanied by a large release of energy. Fragments of concrete from the prism, crashed when the strengthening system failed. It has been noticed that the specimens, after failure, had attached to the CFRP plate a thin concrete layer as illustrated in Figure 6. The test specimens were grouped in 3 series of samples (C1, C2 and C3). For each specimen the experimental results are reported, with respect to half of the load given by the load cell, in terms of the load corresponding to each bond interface. The results for all tested specimens are summarised in Table 4.

Table 4

The main experimental results for the tested specimens
Rezultatele experimentale principale pe epruvetele testate

Specimen / *Probă*	$N_{fa,max}$ [kN]	σ_u [MPa]	ε_u [%]	τ_m [MPa]	s_{LVDT} [mm]
C1_1	45.2	376.67	0.116	1.51	0.17
C1_2	52.55	437.917	0.132	1.75	0.16
C1_3	40.92	341	0.125	1.36	0.15
Mean / *Medie*	46.223	385.196	0.124	1.54	0.16
St. dev. / *Ab. stand.*	5.882	49.02	0.008	0.197	0.01
C2_1	61.65	440.36	0.14	2.06	0.35
C2_2	50.45	360.36	0.09	1.68	0.14
C2_3	61.3	437.86	0.11	2.04	0.23
Mean / *Medie*	57.8	412.86	0.12	1.93	0.24
St. dev. / *Ab. stand.*	6.37	45.48	0.03	0.21	0.11
C3_1	60.2	501.67	0.154	2.01	0.65
C3_2	44.95	374.58	0.110	1.5	0.3
C3_3	66.3	552.50	0.165	2.21	0.51
Mean / *Medie*	57.15	476.25	0.138	1.91	0.49
St. dev. / *Ab. stand.*	11	91.64	0.037	0.37	0.18



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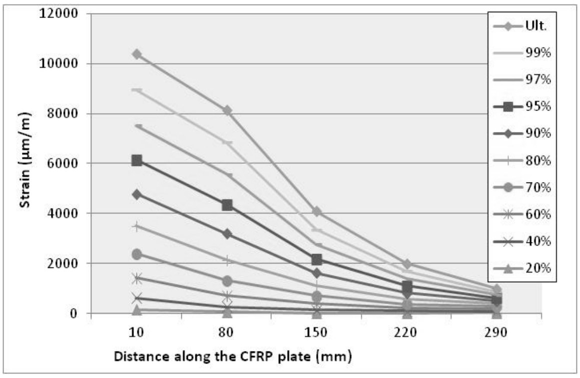

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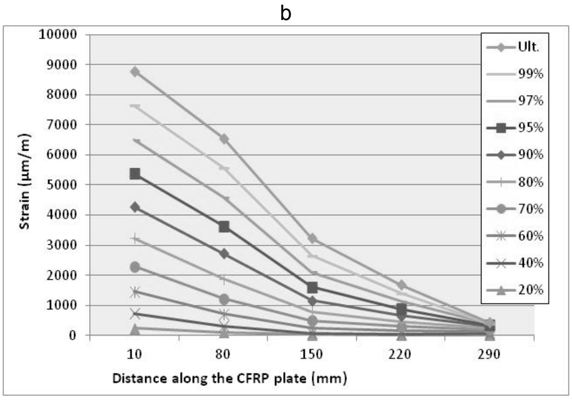


c

Fig. 7. The strain distribution along the CFRP plate / *Distribuția deformației specifice în lungul platbandei CPFAC*:
(a) C1 series / *seria* ; (b) C2 series / *seria*; (c) C3 series / *seria*

Figure 7 indicates that, as the load started to be applied on the specimens, the strains on the CFRP plate near the end of the concrete prism increased progressively until the bond failure was initiated.

The load level corresponding to starting of debonding can be associated to the change in the strain profile (Fig. 7 a, b, c). The strains started developing gradually from one gauge to another along the bonded length, beginning from the end of the CFRP plate, and propagate as the crack spread until a complete debonding failure occurred. The small variation in the strain of the gauge located near the junction (at 10 mm) between the two concrete prisms demonstrates that there was no bond damage at this position before the failure of the tested specimen.

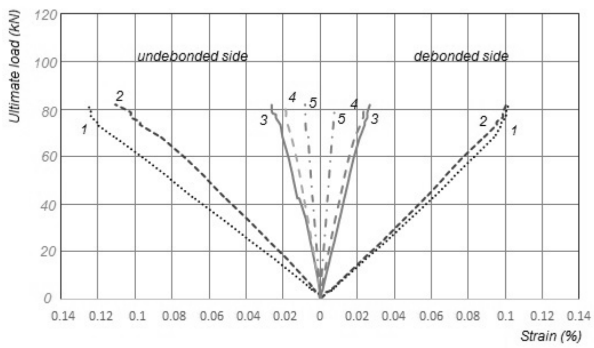


Fig. 8. The load strain curves for C1_3 specimen
Curbele încărcare – deformație specifică pentru probele C1_3.

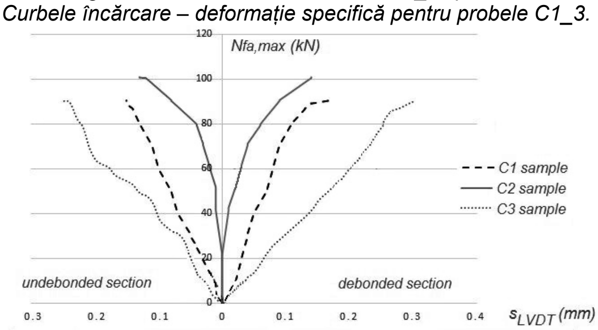


Fig. 9. The load slip curves
Curbele încărcare – alunecare.

The comparative results for the strains recorded on the opposite sides of the specimens can be observed in Figure 8.

The slip was measured directly by the linear voltage displacement transducers (LVDTs) and their variation is shown in Figure 9. Debonding failure is believed to result from a condition where in the remaining bonded length is insufficient to transfer stresses between the CFRP and the concrete substrate. As previous experimental studies have shown [24], the higher extensional stiffness of the external FRP reinforcement influences the tension stiffening of cracked concrete, engaging the latter in undertaking tension stresses between cracks. This is valid for the C2 specimen where an overall better tensile behaviour, accompanied by a smaller slip (Fig. 9) may be observed.

4. Numerical modelling

4.1 Geometry of the FE models

In addition to the experimental research presented previously in this paper, 3D finite element (FE) models were built to analyse the bonding behaviour using ANSYS software package [31]. The models have the same geometry, material properties and boundary conditions as the RC specimens tested in the experimental program, thus three models were developed in correspondence with the 3 series of tested specimens, namely C1, C2 and C3.

In order to reduce the solving time and to increase the precision the geometrical model was simplified using the symmetry of the elements, thus the simplified model is actually a quarter of the benchmark specimen. The chosen approach considered the external reinforcement to be perfectly adherent to the adhesive layer, which was modelled as an individual layer.

The FE modelling of all components was performed using 3D solid elements (Fig. 10). Namely, the specimens were modelled using 20 nodes solid elements, Solid 186, while for the interface area CONTA 174 were employed; these types of FE elements are currently used by ANSYS in modelling the contact and slip between two surfaces. As an initial step, a fine FE mesh was employed especially in the area of CFRP bonding to the concrete substrate. In other words, the model was divided into a number of small elements, and after loading, stresses and strains are calculated at integration points of these small elements.

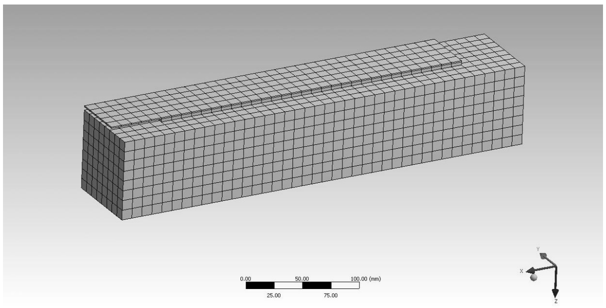


Fig. 10 - The finite element mesh / *Rețeaua de elemente finite.*

4.2 Numerical results

The results of the numerical simulations have been compared with those obtained experimentally, in order to validate the developed FE models. Thus, after performing a considerable number of iterations, the numerical model describes, in an acceptable manner, the general behaviour of the interface region, in terms of the maximum normal stresses and the ultimate loads (Fig. 11 a, b).

The obtained models present in a reliable manner the chart of the relative displacement, presented in Figure 12 for the C2 series.

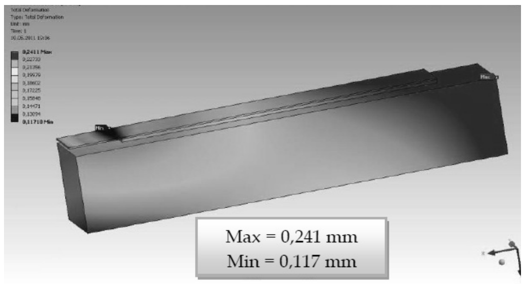
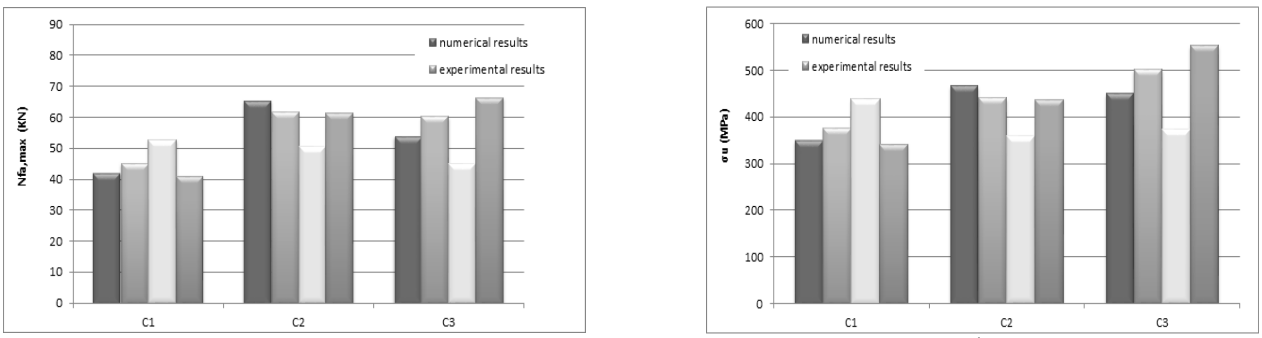


Fig. 12 - The relative displacement for C2 series *Deplasarea relativă pentru seria de probe C2.*



a b

Fig. 11 - Experimental versus numerical results in term of a) ultimate load; b) maximum direct stress / *Comparații între rezultatele experimentale şi cele numerice a) încărcarea ultimă; b) tensiunea normală maximă.*

5. Conclusions

The interface between the CFRP plates and the concrete prisms has been evaluated using experimental tests and numerical modelling. All specimens tested as part of the experimental program failed primarily due to the debonding by the shear induced peel-off. A very thin layer of concrete, or mostly cement paste, remained attached to the CFRP strip after failure. Debonding initiated at the loaded end and rapidly propagated towards the free end. A special experimental device has been conceived and constructed to enable an adequate transfer of the loading from the universal testing machine to the experimental samples.

The numerical method offers convenient versatility and acceptable precision, making possible the numerical analysis using different elements with complex geometry, various loading schemes and boundary conditions. Analysing the numerical results by comparing them to the experimental ones revealed a good correlation between the simulated structural behaviour and the test results. The FE analysis utilized in case of externally bonded FRP composites proved to be a powerful instrument in determining the general behaviour of the considered element especially when the adhesive layer is included in the model.

The results confirm that increasing the FRP plate stiffness parameters the overall tensile behaviour of the strengthened element is enhanced. This is mainly attributed to the internal concrete micro-cracking phenomenon governing the debonding behaviour.

Debonding initiates from the propagation of a dominant crack nearby the concrete – FRP interface. Thus, it can be concluded that the specimens failed due to shear stresses that occurred within the concrete substrate, adjacent to the concrete – FRP interface, and a very thin layer of concrete remained bound to the FRP composite strip after bonding failure.

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MANIFESTĂRI ŞTIINȚIFICE / SCIENTIFIC EVENTS

Call for papers

The 7th International Symposium on Refractories (ISR2016), Sept. 20-22, 2016, Xi'an, China

The Seventh International Symposium on Refractories (ISR 2016), organized by the Chinese Society for Metals, the Chinese Ceramic Society and Sinosteel Luoyang Institute of Refractories Research Co., Ltd., will be held in Xi'an, China on Sept. 20-22, 2016.

International Symposium on Refractories (ISR) is a regular international conference held in China every 3-5 years. ISR 2016 will provide a good opportunity for researchers, manufacturers, suppliers and users in refractory industry around the world to review the progress and achievements made in recent years, to assess new developments in refractories research, production and application to meet new challenges, and to promote further international exchange and cooperation.

Theme

More advanced refractories, greener high temperature industries

Topics

- Refractory raw materials
- Refractories for iron and steel industry
- Refractories for nonferrous, cement, glass and other industries
- Safety, environmental issues & recycling solutions for refractories
- Advanced techniques & equipment for production, testing, evaluation & installation of refractories
- Fundamentals, education, standardization, patent on refractories

Abstracts and Papers

Welcome authors worldwide to submit an abstract before Nov. 30, 2015 to the symposium secretariat by www.isr2016.com or by Email to isr2016@csmorg.cn. Only 2500 characters will be accepted at maximum. Abstracts will be reviewed by Academic Committee. Authors will be notified the review results with an instruction for preparing the manuscripts by Dec. 31, 2015. The complete camera-ready manuscripts in PDF form as well as word edition are requested to be submitted by May 31, 2016.

Language

The working language of the symposium is English.

Deadlines

Submission of abstract	*Nov. 30, 2015*
Notification of acceptance	Dec. 31, 2015
Submission of manuscript	May 31, 2016

Conference Secretariat

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