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Performance of CFRP-confined concrete cylinder specimens - laboratory study

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Research Paper

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Performance of CFRP-confined concrete cylinder specimens - laboratory study

The research presented in this paper focuses on the application of innovative materials for the repair and strengthening of RC columns of buildings in seismically active regions. The analytical and laboratory research for defining the compressive strength and elastic modulus of concrete cylinders confined with CFRP (Fibre Reinforced Polymers) was carried out at the Skopje-based Institute of Earthquake Engineering and Engineering Seismology – IZIIS in order to present the possibilities and benefits of using these materials. Selected results from laboratory testing of built-in materials, and some analytical results from the designed CFRP-confined RC columns for quasi static tests, are presented in this paper.

Key words:
innovative materials, CFRP, laboratory tests, compressive strength, confined, ductility

Prethodno priopćenje

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Ponašanje valjkastih uzoraka betona ovijenih CFRP-om - laboratorijska studija

U ovom se radu istražuje primjena inovativnih materijala za potrebe sanacije i pojačanja AB stupova građevina smještenih u seizmički aktivnim područjima. U Institutu za potresno inženjerstvo i inženjersku seizmologiju (IZIIS, Skoplje) provedena su analitička i laboratorijska ispitivanja tlačne čvrstoće i modula elastičnosti betonskih valjaka ovijenih CFRP-om (polimerom armiranim vlaknima) kako bi se odredile mogućnosti i koristi od upotrebe tih materijala. U radu su prikazani odabrani rezultati laboratorijskih ispitivanja ugrađenih materijala kao i djelomični analitički rezultati kvazistatičkih ispitivanja projektiranih AB stupova ovijenih CFRP-om.

Ključne riječi:
inovativni materijali, CFRP, laboratorijska ispitivanja, tlačna čvrstoća, ovijenost, duktilnost

1. Introduction

Figure 1. Photos taken during casting of models

Structural behaviour of the existing reinforced-concrete buildings throughout their service life, as well as during earthquakes, depends on many factors. On the one hand, there are external factors, i.e., loads acting upon the structures (in addition to main loads, there are also additional loads as well as the effects of possible explosions, fires, earthquakes, etc.). On the other hand, there are factors that directly depend on the very structure of the buildings (structural system, type, quality and quantity of materials used for building the structure, number of storeys, type of foundations, etc.). All these factors directly affect the strength and deformation capacity of individual structural elements and of the structural system as a whole.

The seismic strengthening of reinforced concrete structural elements is one of the methods that are used for increasing the earthquake resistance of damaged or undamaged buildings. The strength of the structures can thus be moderately or significantly increased and their ductility can be improved. In other words, it can be said that the concept of strengthening involves a) increase in strength; b) increase in strength and ductility; and c) increase in ductility.

It has been a usual practice to perform the repair, strengthening, and rehabilitation of the existing RC building structures by applying traditional methods (most frequently, jacketing of elements) but, lately, new innovative materials, and a special construction and repair technology, have increasingly been applied [1-3]. The application of these materials is still the subject of many investigations worldwide, particularly as to the application of these materials in seismically active regions.

In order to make a contribution towards the development and application of new innovative materials in engineering practice, appropriate experimental quasi-static tests were carried out in the Dynamic Testing Laboratory at UKIM-IZIIS – Skopje, R.N. Macedonia, and laboratory tests on materials were conducted at the Institute for Material Testing – ZIM, AD Skopje, R.N. Macedonia [4].

Selected laboratory test results for built-in materials, a part of analytical results, and a part of quasi-static experimental investigations of models designed and constructed using FRP-materials, are presented in this paper.

2. Laboratory testing of built-in material models for experimental research carried out at UKIM-IZIIS

2.1. Preparation of trial concrete cylinders for testing

To realize the experimental quasi-static tests, two models were designed and constructed, namely Model M1 and Model M2. The models exhibited identical proportions (i.e., 50/50/116 cm for the supporting beam and 30/30/200 cm for the column), constructed on a scale of 1:1. The concrete class was the same as the models were concreted simultaneously. The FRP placement mode and technology were also the same, while the percentage of vertical and transverse reinforcement in the models were varied, at the constant vertical axial force in the columns. Since a relatively small amount of concrete was necessary, Sintek-Specific decided to use the self-compacting concrete "SIBET". To enable easier incorporation of FRP materials, the decision was made to build the models in vertical position.

Figure 1 shows photos taken during casting of the foundation-beam and columns for both models. The casting of the supports – foundations was conducted in the first phase, and both columns were cast in the second phase.

During casting of the models, three test specimens - concrete cubes measuring 15/15/15 - were taken from the supports – beams, and three test cubes measuring 15/15/15 were taken from the columns, as well as nine (9) cylinders measuring 15/30 cm (Figure 2). Laboratory tests for defining the compressive strength and concrete class were performed at the stock holding company GIM - Skopje (for the cubes) and ZIM – Skopje (for the cylinders), while the tests for defining the modulus of elasticity of the built-in concrete were conducted at ZIM – Skopje.

Figure 2. Photos of concrete test specimens (cubes and cylinders)

Using the concrete test specimens – cylinders, three series of compressive strength and elastic modulus tests were conducted for the built-in concrete as follows:

- Series 0: concrete cylinders without FRP- plain concrete
- Series 1: concrete cylinders wrapped with 1 (one) FRP layer
- Series 2: concrete cylinders wrapped with 2 (two) FRP layers

Some of the photos taken during preparation of concrete cylinders for further tests are presented below (Figure 3 and Figure 4).

Figure 3. Placing strain gauges on concrete cylinders

Figure 4. Wrapping concrete cylinders with CFRP for laboratory tests at ZIM - Skopje

2.2. Test results for built-in concrete classes

The compressive strength and elasticity moduli of the concrete models were tested in laboratory for all three series of concrete test specimens – cylinders. The laboratory tests were realized by the Institute for Testing Materials and Development of New Technologies ", ZIM "Skopje" AD Skopje. Results obtained by testing the three series of concrete test cylinders are presented.

2.2.1. Compressive strength of concrete cylinders

The compressive strength of concrete was defined by exposing 15/30 cm test specimens – cylinders to a monotonously increasing compressive force up to failure. The specimen sampling was conducted on 4 October 2019, and laboratory tests on 6 (six) cylinders were performed on 15 November 2019. The remaining three cylinders were tested on 29 November 2019. The tests at the ZIM laboratory in Skopje were done after more than 28 days (on the 43rd and the 57th day) because we wanted to obtain these results closer to the day of the quasi-static testing of models at UKIM-IZIIS, which were realized on 20 and 22 November 2019 (i.e., 48 and 50 days after the casting).

Photos taken during laboratory tests for defining the compressive strength of concrete for the three series are shown in figures 5÷11. It must be pointed out that the collapse of the models belonging to the first and the second series was explosive, with big crushing of concrete wrapped with CFRP. This was particularly pronounced in Series 2 where concrete was wrapped with two CFRP layers. Therefore, while applying the force, the part with the cylinder had to be protected by a steel plate in order to prevent unwanted effects.

Figure 5. Testing compressive strength of plain concrete (Series 0 - without CFRP)

Figure 6. Testing compressive strength of plain concrete (Series 0 - without CFRP)

Figure 7. Testing compressive strength of concrete wrapped with a single CFRP layer – Series 1

Figure 8. Testing compressive strength of concrete wrapped with a single CFRP layer, Series 1

Figure 9. Testing compressive strength of concrete wrapped with two CFRP layers, Series 2

Figure 11. Photos of test cylinders for the three series

2.2.2. Compressive strength test results for concrete cylinders

In parallel with the testing performed for the three series, the results obtained by testing failure force and compressive strength of all three series of concrete cylinders were recorded and presented in appropriate tables (Table 1).

The results show that the force inducing failure of concrete cylinders without CFRP amounts to 296.0 kN. For the cylinder with one CFRP layer, it amounts to 670.0 kN, while it amounts to 955.0 kN for the cylinder with two CFRP layers. The compressive strength for all three series amounts to 16.8 MPa, 37.0 MPa, and 54.1 MPa, respectively.

The results obtained are presented graphically in Figure 12 and Figure 13.

Figure 10. Testing compressive strength of concrete wrapped with two CFRP layers, Series 2

Table 1. Compressive strength of three series of concrete cylinders

Date of casting: 4.10.2019 Date of testing: 15.11.2019 Concrete cylinders CC (3 series) 15/30 cm						
Series			**Dimensions H/D** [cm]	**Weight** [g]	**Failure force** [kN]	**Compressive strength** [MPa]
Specimens	0	Cylinders without CFRP	30/15	12200	296.0	16.8
	1	Cylinders with one CFRP layer	30/15	12700	670.0	37.9
	2	Cylinders with two CFRP layers	30/15	12800	955.0	54.1

Table 2. Modulus of elasticity of three series of concrete cylinders

Date of casting: 4.10.2019 Date of testing: 15.11.2019 Concrete cylinders CC (3 series) 15/30 cm						
Series			**Dimensions H/D** [cm]	**Weight** [g]	**Failure force** [kN]	**Elastic modulus** [MPa]
Specimens	0	Cylinders without FRP	30/15	12200	296.0	28200.0
	1	Cylinders with one FRP layer	30/15	12700	670.0	33000.0
	2	Cylinders with two FRP layers	30/15	12800	955.0	43500.0

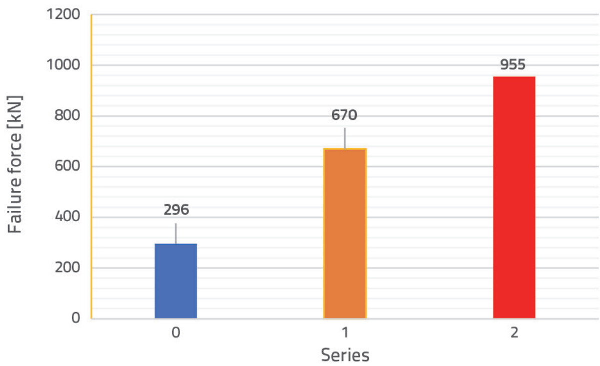


Figure 12. Diagram of failure forces for each series

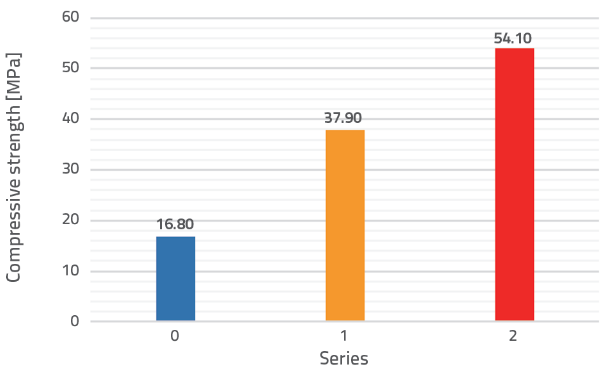


Figure 13. Diagram of compressive strength for each series

Figure 14. Testing static modulus of elasticity for all three series

2.2.3. Elastic modulus test results

The static modulus of elasticity for each series (0, 1, 2) of built-in concrete was also tested in the laboratory of the Institute for Testing Materials – ZIM – Skopje AD. The tests for obtaining the static modulus of elasticity under pressure were performed according to MKS U.M1.025. The mean value of the recorded entries of the strain gages, after dissolution in the last cycle, was the most relevant for estimating the static modulus of elasticity. Some of the photos taken while testing the three series of concrete cylinders are presented in Figure 14. Results obtained for all three series of concrete cylinders are presented in Table 2. In general, it can be concluded that the modulus of elasticity increases with an increase in the number of FRP layers. Elastic modulus values obtained by laboratory testing are graphically presented in Figure 15.

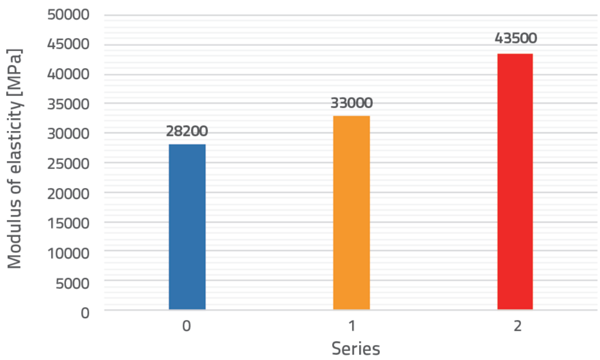


Figure 15. Diagram of elastic moduli for all three series

It can generally be concluded that the values obtained for concrete cylinders with one and two CFRP layers are higher than the values obtained for concrete cylinders without CFRP.

3. Design of models for experimental quasi static tests of RC

An original research program involving experimental investigations on a series of two elements-models (columns) was defined for the needs of this investigations in order to contribute to the definition of the joint behaviour of concrete, reinforcement, and CFRP materials in the nonlinear range, and to develop a methodology and criteria for the application of these materials in seismically active regions, [32]. The main objective of the research programme was to define the strength and deformability of the elements constructed of innovative materials, as a function of a number of selected parameters that were varied in the course of the experiments. The percentage of longitudinal and transverse reinforcement was varied within the frame of the experimental programme realized at UKIM-IZIIS. The concrete class and the CFRP type were the same for both models. The behaviour of the models exposed to cyclic loads (quasi-static tests) up to failure was investigated by visually monitoring the occurrence of cracks and development of failure mechanism.

Two column elements were designed for the needs of the experimental investigations. The column models were designed as fixed cantilever girders measuring 200 cm in constant length (the column was treated only up to the inflection point, i.e., up to a half of the total height) and 30/30 cm in cross section. In both models, variable parameters were the percentage of longitudinal and transverse reinforcement, and axial forces. The concrete class, i.e., the compressive strength of concrete and the type of CFRP, was the same for both models. The elements were designed to a geometrical scale of 1:1. The axial force for simulating gravity load amounted to 500 kN and 300 kN for models M1 and M2, respectively.

The mode of simulation of the fixation of the column elements was also defined during the design of column models. The fixation of the models was done in an identical way. An RC support measuring 50/50 cm in width and height, and 116 cm in length, reinforced in such a way to provide complete fixation of the model, was designed for this purpose. The main longitudinal reinforcement of the column model was anchored to the support in such a way to avoid the loss of adhesion in the course of the experiment. The column models were screwed, through the fixation support, to a steel support by means of eight prestressed steel screws (four on each side). The total weight of the entire composition (column + support for fixation of the model) amounted to 1.2 tons (Figure 16). Characteristics of the materials (concrete, reinforcement, and type of CFRP) used in design and construction of the models, and the reinforcement percentages, are shown in Table 3 and Table 4.

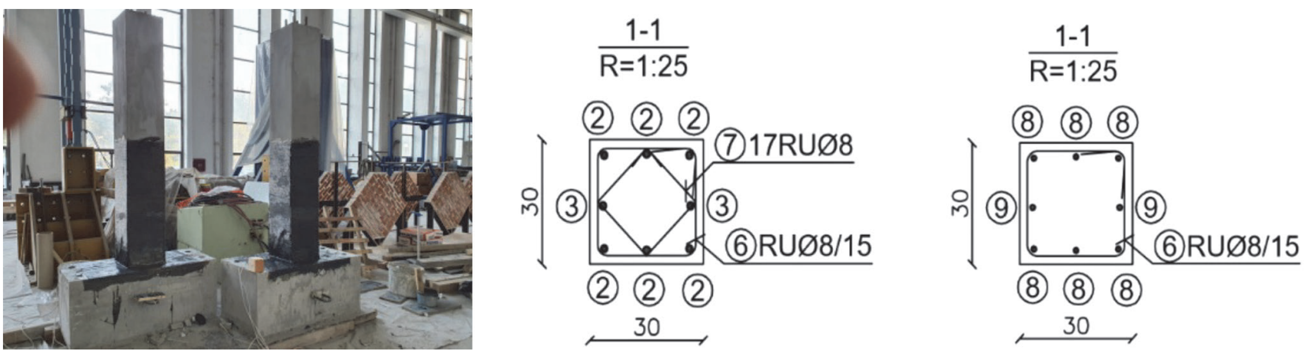


Figure 16. Design of column models and cross section (Model M1 - left, Model M2 - right)

Table 3. Characteristics of materials used for designed column models

Specimen	CC [MPa]	b/h [cm]	Longitudinal reinforcement		Transverse reinforcement	
			Type of steel	$A_{tension}$ [cm^2]	Type of steel	s [cm]
Model M1	25/30	30/30	RA 400/500	7.63	RA 400/500	7.5
Model M2	25/30	30/30	RA 400/500	4.62	RA 400/500	15.0

Table 4. Characteristics of materials used for constructed column models

Specimen	CC [MPa]	b/h [cm]	Longitudinal reinforcement		Transverse reinforcement	
			Type of steel	$A_{tension}$ [cm^2]	Type of steel	s [cm]
Model M1	16/20	30/30	RA 504/642	7.63	RA 595/696	7.5
Model M2	16/20	30/30	RA 513/637	4.62	RA 595/696	15.0
CFRP	S&P C-folija 240. 300 g/m^2					

4. Analysis of results obtained during analytical investigations

Several mathematical models were developed using the CSI software SAP2000, module Section Designer [18, 31, 33], for analysing the capacity of the designed columns. The columns were modelled with material properties corresponding to test results. The section capacity calculation was realised using the fibre analysis of column sections, taking into account geometric properties, reinforcement details, and different values of axial forces. The commonly used confined concrete model proposed by Mander et al. [34] was implemented along with the elastic perfectly plastic model with strain hardening for the steel reinforcement. The ideal axial stress-strain diagram according to Olivova, K et al. [8] was used for the reinforced concrete wrapped with CFRP sheet.

4.1. Definition of real strength and deformability of column models

The values concerning the quality of built-in concrete and reinforcement obtained for both vertical and transverse reinforcement, and the type of CFRP applied (presented in Table 4), were used to define the real bearing and deformability capacity of the built column models. In the first phase, the real M-Φ (moment – curvature) relationships of the column cross-sections were computed by applying axial force, the real M-N diagrams, and then the strength and deformability capacity of each model was defined based on the obtained M-Φ diagrams. The strength and deformability characteristics (M-N) and (M-Φ) at the cross-section level were analytically defined using the SAP2000 computer software. The following analyses were carried out:

- For Model M1, definition of the M-Φ diagram for Nv = 500 kN (Figure 20) and M-N diagram (Figure 19) for the following values:
  - For the designed concrete class (DC) (EC-25/30) with the quality and quantity of reinforcement shown in Table 3, Series 01.
  - For the built-in concrete class (CC) (EC-16/20) with the quantity and quality of reinforcement shown in Table 4, Series 02.
  - For the built-in concrete class with one layer of CFRP (CC-FRP) (38/46) with the quantity and quality of reinforcement shown in Table 4, Series 03.

- For Model M2, definition of the M-Φ diagram for Nv = 300 kN (Figure 22) and M-N diagram (Figure 21) for the following values:
  - For the designed concrete class (DC) (EC-25/30) with the quality and quantity of reinforcement shown in Table 3, Series 01.
  - For the built-in concrete class (CC) (EC-16/20) with the quantity and quality of reinforcement shown in Table 4, Series 02.
  - For the built-in concrete class with one layer of CFRP (CC-FRP) (38/46) with the quantity and quality of reinforcement shown in Table 4, Series 03.
  - The working diagrams (s-e) for concrete and the working diagram of steel shown in Figure 17 were used for all analyses of RC cross-sections without CFRP. All analyses were conducted by taking into consideration confinement of the cross-section of transverse reinforcement.

The working diagram shown in Figure 18 was used for concrete wrapped with CFRP [8]. The results obtained during these analyses are presented as follows.

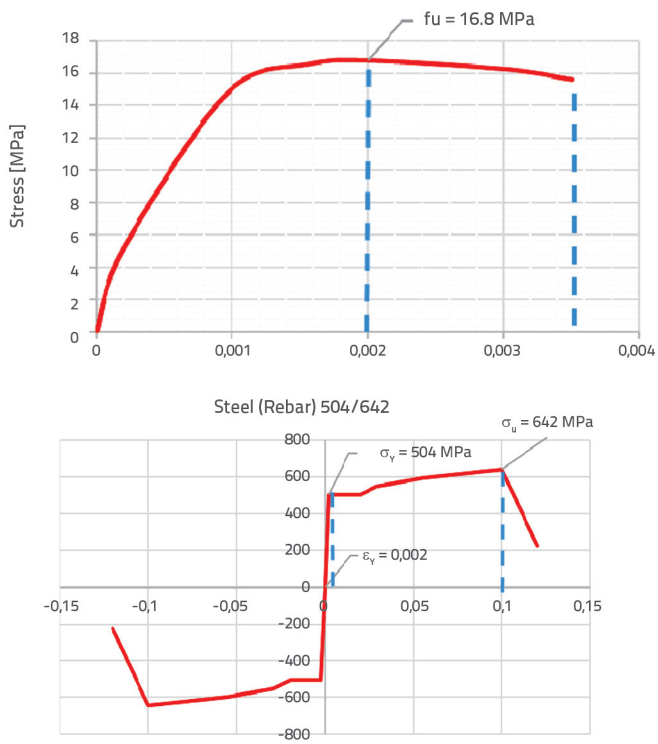


Figure 17. Stress-strain relation for non-linear structural analysis of concrete C16/20 and rebar RA 504/642

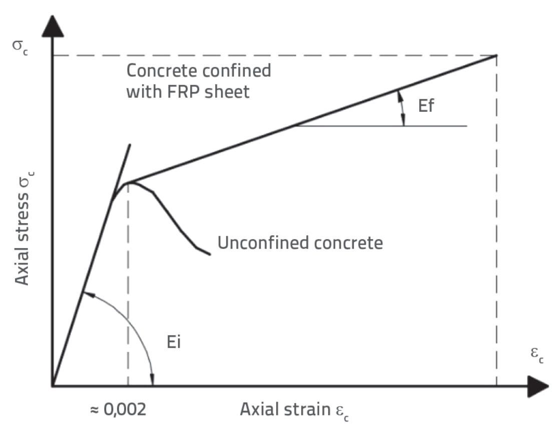
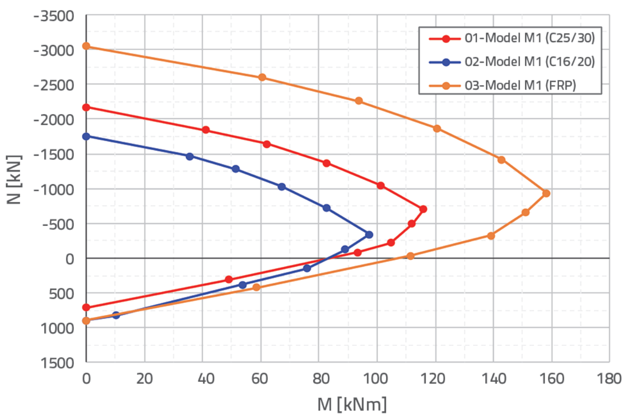


Figure 18. Ideal axial stress-strain diagram σ_c-σ for concrete confined with CFRP sheet

4.2. M-N and M-Φ relationship for Model M1

The results from three series of analyses (0.1, 0.2, 0.3 series) performed for the definition of M-N, and three series for M-Φ diagrams, are presented for Model M1. All presented diagrams were obtained using the SAP2000 program [18, 31, 33]. The M-N interaction diagrams shown in Figure 19 clearly point to the difference between the three series of analyses. The M-N and M-Φ comparative diagrams for Model M1 are presented below.

Based on the results obtained, the following conclusions can be made: From the comparative analysis of the three curves – series 01, 02, and 03, as presented in Figure 19 and Figure 20, it can be concluded that the ductility of the cross-section with CFRP exceeds that of the cross-section without CFRP by 39.9 %



if the achieved strain in concrete amounts to ε_c = 10 ‰.

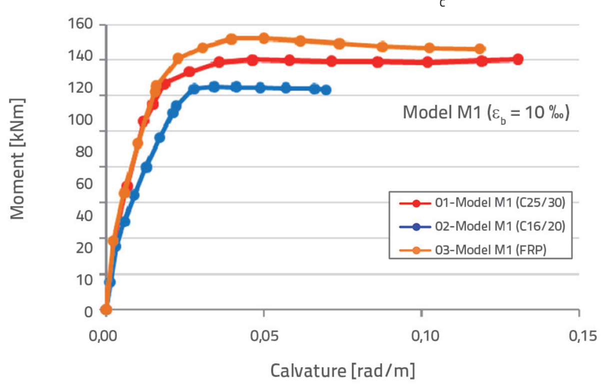


Figure 19. M-N Interaction Diagram for Model M1 - Comparison

Figure 20. M-Φ Interaction Diagram for Model M1 – Comparison

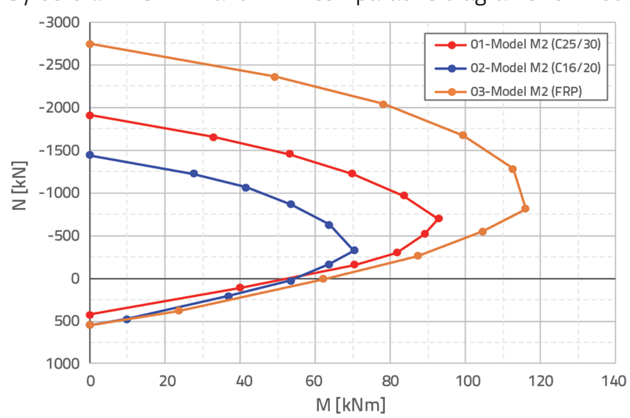
Considering the results regarding achievement of ε_c = 20 ‰, it can be concluded that strains in the reinforcement are very high, reaching the value of up to 53.50 and 38.5 ‰ (for the cross-section with CFRP). In addition, there is a deep nonlinearity as manifested by buckling of the reinforcement, so that further analyses of the cross-section with CFRP were conducted by using the values for achievement of 15 ‰. In this case, the ductility capacity for Model M1 with CFRP exceeds that of the cross-section without CFRP by 98 %.

The moment capacity obtained for series 03 (cross-section with CFRP) exceeds by 68 % that of cross-section 0.2 (series with built-in concrete class of 16/20).

The capacity of axial forces obtained for series 03 (cross-section with CFRP) exceeds by 71 % that of cross-section 0.2 (series with built-in concrete class of 16/20).

4.3. M-N and M-Φ relationship for Model M2

The results for three series of analyses (series 01, 02, and 03) for the definition of M-N and M-Φ diagrams are presented for Model M2. All presented diagrams were obtained by means of the SAP2000 program [18, 31, 33]. The interaction diagrams (Figure 21 and Figure 22) clearly show the difference between all series of analyses. The moment capacity for series 03 (cross-section with CFRP) exceeds by 63 % that of cross-section 02 (series with built-in concrete class of 16/20). The capacity of axial forces for series 03 (cross-section with CFRP) exceeds that of cross-section 02 (series with built-in concrete class of 16/20) by 59.5 %. The M-N and M-Φ comparative diagrams for Model



M2 are presented below.

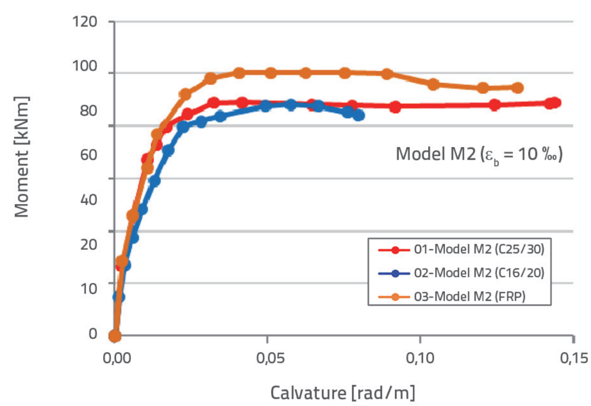


Figure 21. M-N Interaction Diagram for Model M2 - Comparison

Figure 22. M-Φ Interaction Diagram for Model M2 – Comparison

Based on the results obtained, the following conclusions can be made: Comparative analysis of the three curves – series

Table 5. Rotation and displacement capacity for Model M1 and Model M2

Specimen	Rotation		Ductility	Displacement		Ductility
	Φy [rad/m]	Φu [rad/m]	DΦ	dy [cm]	du [cm]	Dd
Model M1-02	0.0127	0.0696	5.48	1.056	2.626	2.487
Model M1-03	0.0154	0.1730	11.23	1.281	5.631	4.306
Model M2-02	0.0128	0.0663	5.18	1.065	2.542	2.387
Model M2-03	0.0231	0.1963	8.50	1.922	6.702	3.487

Table 6. Shear and bending moment capacity for Model M1 and Model M2

Specimen	Moment		Length	Shear force	
	My [kNm]	Mu [kNm]	L [m]	Qy [kN]	Qu [kN]
Model M1-02	80.00	123.39	1.58	50.02	78.09
Model M1-03	122.00	149.27	1.58	77.20	94.47
Model M2-02	59.25	87.50	1.58	37.50	55.38
Model M2-03	92.00	94.26	1.58	57.20	59.65

01, 02 and 03 presented in Figure 21 and Figure 22 - clearly shows that the M-Φ diagram for the cross-section with CFRP is characterized by the highest strength and deformation characteristics compared to other diagrams. When comparing the results, it can be concluded that the ductility of the cross-section with CFRP exceeds that of the cross-section without CFRP by 83.7 %, for the achieved strain in concrete of 10 ‰. When the results regarding achievement of ε_c = 20‰ are analysed, it can be concluded that strains in the reinforcement are very high, reaching the value of up to 55.0 and 41.2 ‰ (in the case of cross-section with CFRP). These results point to deep nonlinearity and are not realistic, which is why the values for reaching 15 ‰ in concrete were used in further analyses. In this case, the ductility capacity for Model M2 with CFRP exceeds that of the cross-section without CFRP by 64.0 %.
The moment capacity for series 03 (cross-section with CFRP) exceeds by 63 % that of cross-section 02 (series with built-in concrete class of 16/20). The capacity of axial forces for series 03 (cross-section with CFRP) exceeds by 59.5 % that of cross-section 02 (series with built-in concrete class of 16/20). All results are presented in Table 5 and Table 6. Based on the analyses of results shown in Table 5, it can be concluded that the ductility to rotation for Model M1 is by 2.049 greater for the model with CFRP, while the ductility to displacement exceeds that of Model M1 without CFRP by 76.7 %. In the case of Model M2, the ductility to rotation is higher by 64 % in the case of the Model with CFRP, while the ductility to displacement exceeds that of the Model M2 without CFRP by 46.1 %.

5. Conclusions

As a result of comprehensive laboratory tests conducted on concrete cylinders for: Series 0 - concrete cylinders without CFRP - plain concrete; Series 1 - concrete cylinders wrapped with 1 (one) CFRP layer; Series 2 - concrete cylinders wrapped with 2 (two) CFRP layers, It can be concluded that the force inducing failure of concrete cylinders without CFRP amounts to 29.6 t, i.e., 296 kN. For the cylinder with one CFRP layer, it amounts to 67.0 t, i.e., 670 kN, while for the cylinder with two CFRP layers, it amounts to 95.5 t, i.e., 955 kN. The compressive strength for all three series amounts to 16.8 MPa, 37.0 MPa, and 54.1 MPa, respectively. It can be concluded that the failure force and compressive strength in the case of series 1 and 2 is 2.26 and 3.23 times greater compared to the failure force for the cylinder without FRP.
The results obtained reveal that the elastic modulus of concrete cylinders without CFRP amounts to 28200 MPa. For the cylinder with one CFRP layer, the elastic modulus amounts to 33000. MPa, while it amounts to 43500 MPa for the cylinder with two CFRP layers. It can be concluded that the elastic modulus of the cylinder wrapped with one CFRP layer is higher by 17 % and the elastic modulus for the cylinder with two CFRP layers is higher by 61 %, compared to that of the cylinder without CFRP.
Analytical analyses of samples were carried out to define the strength and deformability capacity (M-N) and (M-Φ) at cross-section level using the SAP2000 computer programme [18, 31, 33]. The strength and ductility capacity of each model was defined based on the obtained M-Φ diagrams.
The moment capacity obtained for cross-section of Model M1 with CFRP exceeds by 21.07 % that of the cross-section without CFRP. The moment capacity obtained for cross-section of Model M2 with CFRP exceeds by 7.7 % that of the cross-section without CFRP.
In the case of model M1, the ductility to rotation is higher by 98 % in the case of the model with CFRP, while the ductility to displacement according to Park & Poulay [15] is higher by 76.7 % compared to the ductility of the model M2 without CFRP.
In the case of model M2, the ductility to rotation is higher by 64 % in the case of the model with CFRP, while the ductility to

displacement according to Park & Poulay [15] is higher by 46.1 % compared to the ductility of model M2 without CFRP.
It can generally be concluded that FRP systems represent a very practical tool for the strengthening and retrofitting of concrete structures and are appropriate for the flexural strengthening, shear strengthening, column confinement, and ductility improvement. Laboratory and experimental investigations carried out in the scope of this doctoral dissertation provide an original scientific contribution to the field of repair and strengthening of RC columns by innovative materials, while at the same time the investigation results can largely be applied in practical construction and earthquake engineering applications.

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