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Quasi-static tests on RC building columns strengthened with CFRP

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Research Paper

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Quasi-static tests on RC building columns strengthened with CFRP

To explore the possibilities and benefits of using CFRP (Carbon Fibre Reinforced Polymers) in strengthening RC building columns, quasi-static tests (compression and bending) were carried out at the Institute of Earthquake Engineering and Engineering Seismology - IZIIS, Skopje by variation of concrete class, reinforcement percentage and by using various strengthening technologies. Some recommendations and outcomes regarding the approach, technology and conclusions drawn from practical application of these materials, are given. Based on the analysis of values obtained from nonlinear static and nonlinear time history analyses, it can be concluded that the ductility capacity for displacement of model strengthened with CFRP is greater by 60 %, while its strength capacity is greater by 7.7 % when compared to the values obtained for the model without CFRP. It can generally be concluded that CFRP systems are a very practical tool for strengthening and retrofitting concrete structures, as they can extensively improve flexural strengthening, shear strengthening, column confinement, and ductility.

Key words:

RC building columns, quasi-static tests, innovative materials, CFRP, strength, ductility

Prethodno priopćenje

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Kvazistatička ispitivanja CFRP-om pojačanih stupova AB građevina

Kako bi se istražile mogućnosti i prednosti primjene CFRP-a (ugljičnim vlaknima armiranih polimera) za pojačavanje AB stupova građevina, u Institutu za potresno inženjerstvo i inženjersku seizmologiju u Skoplju (IZIIS) provedena su kvazistatička ispitivanja (na tlak i savijanje) variranjem razreda betona i koeficijenata armiranja, te primjenom raznih tehnologija pojačanja. U radu se daju preporuke i rezultati u pogledu korištenog pristupa i tehnologije te zaključci koji su doneseni kao rezultat praktične primjene tih materijala. Na temelju analize vrijednosti dobivenih pomoću nelinearnih statičkih analiza i nelinearnih vremenskih proračuna može se zaključiti da je duktilnost na pomak modela pojačanog s CFRP-om veća za 60 % u odnosu na model bez CFRP-a, a čvrstoća mu je veća za 7,7 %. Općenito se može zaključiti da su sustavi CFRP izuzetno praktična sredstva za pojačavanje i obnovu betonskih konstrukcija jer mogu znatno poboljšati savojnu nosivost, posmičnu nosivost, ovijanje stupova i njihovu duktilnost.

Ključne riječi:

AB stupovi građevina, kvazistatička ispitivanja, inovativni materijali, CFRP, nosivost, duktilnost

1. Introduction

Despite great advances in this field regarding definition of the technology of construction, control of built-in materials (type of cement, filler, water), transport and layering of concrete, both in the R. N. Macedonia and in the wider region, it often happens that the built-in concrete does not reach the designed concrete class. Sometimes, this deviation is of a larger scale making it necessary to anticipate and take appropriate repair and strengthening measures involving a smaller or greater number of structural elements and even integral structures. The same problem can also occur during construction of additional storeys and enlargements, in which case the existing structural system cannot meet relevant strength, stiffness, and deformability requirements.

It is a usual practice in the R. N. Macedonia and the wider region to use traditional methods with traditional materials (most frequently jacketing of elements) for the repair and strengthening of structures. However, lately, and more frequently over the last two decades, new construction materials have been developed for the strengthening and design of structures. They are referred to as composites strengthened by polymer fibres (FRP). These materials have some special characteristics, especially with regard to mechanical properties. The application of these materials is still the subject of extensive investigations worldwide, particularly in the field of application of these materials in seismically active regions.

Investigations performed worldwide in the scope of many research studies [1-5] have shown that the strengthening of buildings involving the use of traditional construction materials (concrete and reinforcement) enables an increase in the strength, stiffness and ductility of buildings, while also revealing that this procedure is quite complex and time consuming. Strengthening by FRP composite materials not only ensures great ductility, but also has other advantages like short time needed for the performance of works. Advanced technologies for the production of FRP composite materials based on sophisticated production techniques are evolving at a steady pace. In addition, polymer composite materials enable production of higher quality laminates with minimal voids and precise alignment of fibres at acceptable cost (in the beginning, the prices of these materials were much higher).

The results and comparisons made during realization of a comprehensive experimental research program on samples of plain concrete and concrete strengthened by FRP can be found in [6].

Strengthening with carbon fibre-reinforced polymers was investigated by Wang Lu Liu et al. [7], who experimentally investigated and compared the response, failure mode, and energy absorption of foam concrete with and without CFRP confinement, when subjected to quasi-static and dynamic loading. Several important outcomes were achieved in this study:

- The response and failure modes of foam concrete varied from shear and splitting (without CFRP) to crushing (with CFRP confinement);
- The resistance and energy absorption capacity improved with an increase in load, regardless of whether the foam concrete was confined with CFRP or not;
- The confining effect induced by the CFRP–foam concrete interaction significantly improved the compression resistance and energy absorption capacity; the compression resistance increased by approximately ten times, and the specific energy absorption within a strain of 0.5 also increased by approximately tenfold.
- The compression resistance and the energy absorption capacity of CFRP-confined foam concrete were by approximately 300 % higher in quasi-static loading and 150 % higher in dynamic loading than those of standalone CFRP and foam concrete combined.

The concept of repair and strengthening involving the use of composite materials was investigated in the past through a number of research projects including shaking table and quasi static tests at the Institute of Earthquake Engineering and Engineering Seismology – IZIIS, Skopje, [8-10]. The principles of the repair and strengthening methodology focus on increasing the displacement capacity and ductility of structures as stated in a number of standards and publications [11-24].

The results obtained through specimen testing have shown that the proposed retrofit techniques can improve behaviour of this kind of structures by increasing their capacity and ductility. Experimental investigations have greatly contributed to the field of strengthening of buildings by CFRP strips.

The RC columns retrofit technique involving CFRP was explored in a number of paper such as in [25, 26]. The results of the studies showed that wrapping reinforced concrete columns with FRP increased ductility and compressive strength of RC columns. FRP strengthened RC columns feature 3 different behaviour stages, namely,

- elastic behaviour
- inelastic hardening
- inelastic degradation, followed by return to the response traced by the as-built behaviour.

A test on CFRP retrofitting was conducted at ITU University – Turkey by Prof. Dr. Alper ILKI from ITU University and his team within the project entitled "Efficiency of Seismic Retrofit with CFRPS through Full Scale Site Testing of Substandard RC Structures" (2016) [27]. After experimental investigations, it was concluded that the building that was not retrofitted collapsed at a 0.0135 drift ratio, while the retrofitted building did not collapse even after the drift ratio of 0.15.

Ample laboratory research for defining characteristics of these materials, and experimental investigations of RC columns strengthened by FRP (Fibre Reinforced Polymers) materials, were carried out [28-34] to provide an original contribution to the possibilities and benefits of the use of these innovative construction materials in strengthening structural elements of buildings and integral building structures. Important aspects of these experimental investigations are presented in this paper.

An original research program involving experimental investigations on a series of two elements-models (columns) was defined to contribute to the definition of 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. The main objective of the research programme was to define the strength and deformability of the elements made 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 in the scope 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 visual monitoring of the occurrence of cracks and development of failure mechanism.

2. Design of column models

Two column elements were designed for the needs of experimental investigations. The column models were designed as fixed cantilever girders 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, the percentage of longitudinal and transverse reinforcement and axial forces were taken as variable parameters. The concrete class, i.e., the compressive strength of concrete and the type of CFRP, were the same for both models. The elements were designed to the geometrical scale of 1:1. The axial force for the simulation of gravity load was 500 kN for Model M1, while it was 300 kN for Model M2. In designing the column models, the mode of simulation of the fixation of column elements was also designed. The fixation of the models was conducted in an identical way. An RC column with proportions b/h equal to 50/50 cm and length of 116 cm was designed. It was reinforced in such a way to provide for complete fixation of the model. The main longitudinal reinforcement of the column model was anchored to the column in such a way to avoid loss of adhesion in the course of the experiment. The column models were screwed, through the fixation column, to a steel support by means of eight prestressed steel screws (four on each side). The total weight of the entire composition (column + column for fixation of the model) amounted to 1.2 tons (Figure 1 and Figure 2).

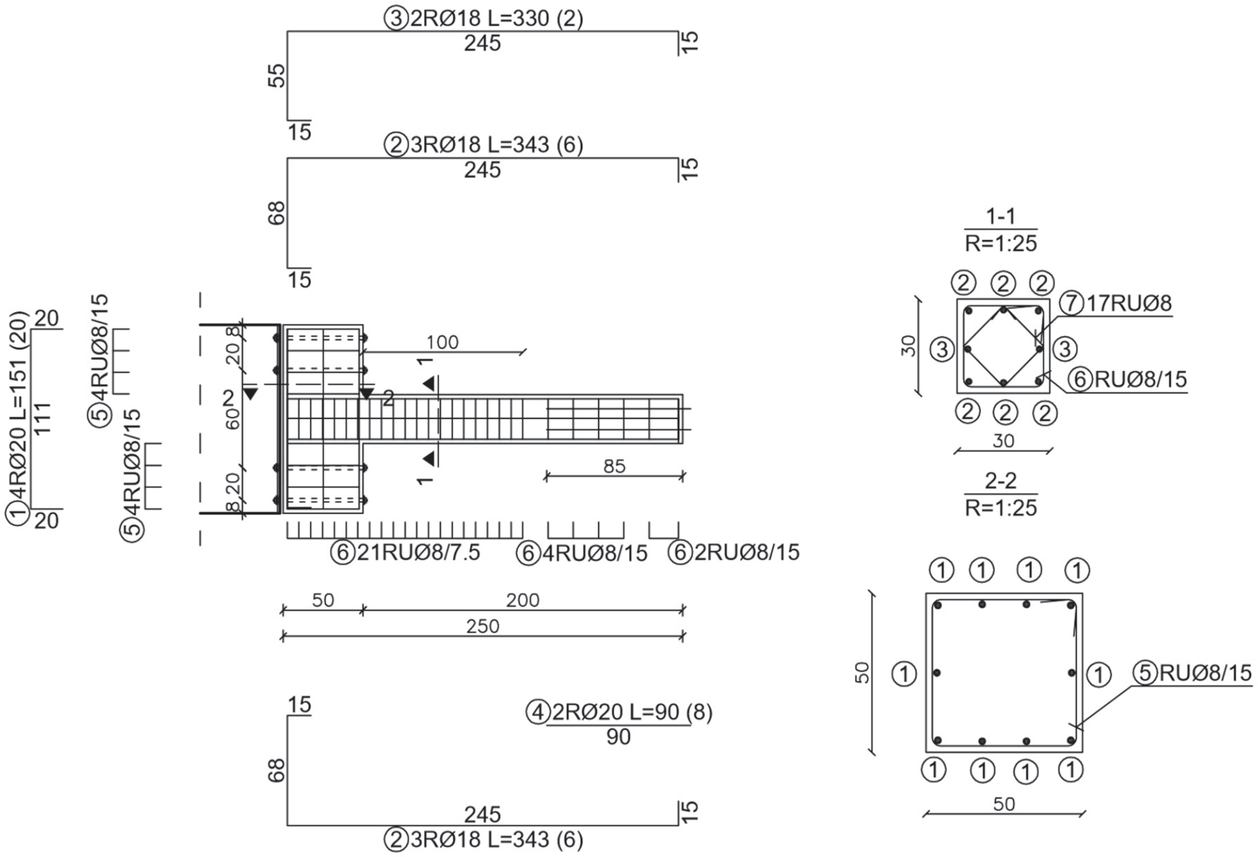

Figure 1. Detail of geometry and reinforcement of column models (Model M1)

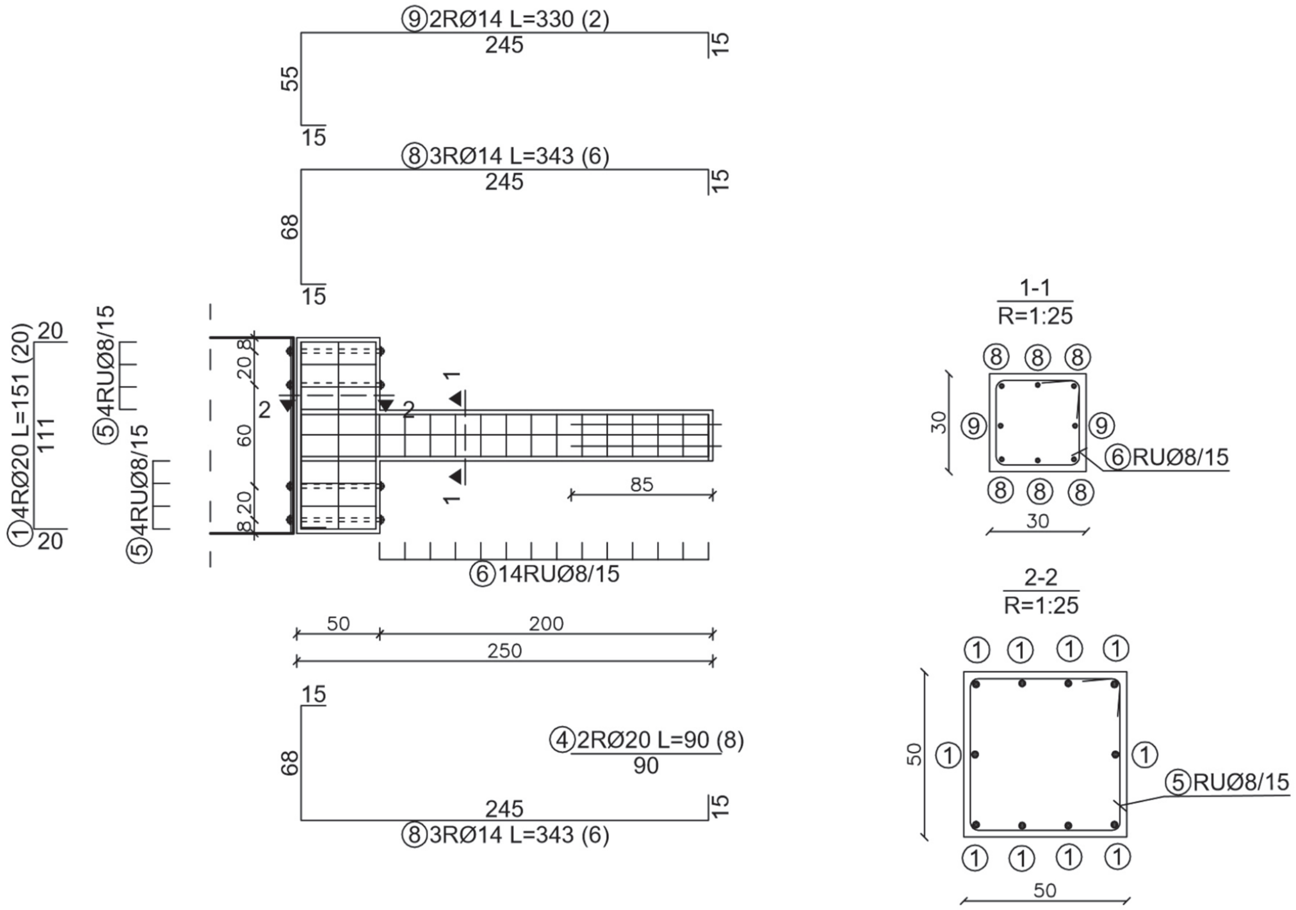

Figure 2. Detail of geometry and reinforcement of column models (Model M2)

When concreting the models, nine trial cylinders measuring 15/30cm and three trial cubes measuring 15/15/15cm were made. Using the trial concrete specimens – cylinders, three series of compressive strength tests and tests for defining the modulus of elasticity of the built-in concrete were carried out 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.

Characteristics of the materials (concrete, reinforcement, and type of CFRP) used in the design and construction of models,

Table 1. Characteristics of materials used for designed column models

Specimen	f_c [MPa]	b/h [cm]	Longitudinal reinforcement		Transverse reinforcement	
			Type of steel	A_{vlak} [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-Sheet 240, 300 g/m^2					

Table 2. Characteristics of materials used for designed column models

Specimen	f_c [MPa]	b/h [cm]	Longitudinal reinforcement		Transverse reinforcement	
			Type of steel	A_{vlak} [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 3. Compressive strength of three series of concrete cylinders

Date of concreting: 4.10.2019.; Date of testing: 15.11.2019.; Concrete cylinders CC (3 series) 15/30 cm						
Series			**Proportions D/H** [cm]	**Weight** [g]	**Failure force** [t]	**Compressive strength** [MPa]
Specimens	0	Cylinders without CFRP	15/30	12200	29.6	16.8
	1	Cylinders with one CFRP layer	15/30	12700	67	37.9
	2	Cylinders with two CFRP layers	15/30	12800	95.5	54.1

and the reinforcement percentages, are shown in Table 1, Table 2 and Table 3.

Based on laboratory tests, it was concluded that the achieved concrete class was 16/20 instead of 25/30. For these trial cylinders, it was concluded that the failure force and compressive strength values in the case of series 1 (cylinder wrapped with 1 CFRP layer) and series 2 (cylinder wrapped with 2 CFRP layers) were by 2.26 and 3.23 times greater than the failure force in the case of the cylinder without FRP. The elasticity modulus of the cylinders wrapped with one CFRP layer and two CFRP layers was by 17 % and 61 % greater than that of the cylinder without CFRP.

All further analyses of the referent model were performed with the designed concrete class values for concrete strengths CC 25/30 and CC16/20, reinforcement and CFRP.

3. Construction of models for experimental investigations

The construction of models (Model M1 and Model M2), as well as placement of CFRP (placement technology) were done by the construction firm SINTEK-SPECIFIC DOO based in Skopje. The entire process of preparation and construction of models for experimental investigations was realized in the Laboratory of UKIM-ZIIS. Since the construction and curing of models took place at the same laboratory, additional risks pertaining to transport of models from another place were avoided.

During concreting of models, concrete trial specimens were realized in the form of nine cylinders measuring 15/30 cm and three cubes measuring 15/15/15 cm, which were then used to define characteristics of the built-in concrete. Tests on trial cubes as well as definition of characteristics of the built-in reinforcement were done at the Civil Engineering Institute – Macedonia, stock holding company (AD GIM Skopje), while the cylinders were tested at ZIM-Skopje AD. All results obtained by testing built-in materials (concrete, reinforcement, and CFRP materials) are presented in Section 5 of this paper.

Preparations for construction of the models, and preparation of reinforcement for both models, started on 23 September 2019. The models were placed vertically to enable easier placement of CFRP materials. Model concreting activity was conducted in two phases. First of all, concreting of foundations (column supports) of both models was conducted and, in the second phase, columns of both models were concreted. The self-compacting concrete – SIBET - was used in concreting operations. Concreting of the supports – foundations - was performed on 25 September 2019 and, in the second phase, concreting of columns was performed on 4 October 2019 when concrete trial specimens were taken (9 cylinders and 3 cubes). Photos taken during construction of models – Model M1 and Model M2 are shown in Figure 3.

3.1. Placement of CFRP on models

Once the models were concreted, the carbon fabric S&P C-Sheet 240, 300 gr/m^2 was applied on 25 October 2019 using the following procedure:

- Removal of cement slurry by a diamond grinding machine on 25 October 2019
- Shaping rounded edges of the column and connection with support – foundation on 25 October 2019
- Application of base made of epoxy composite Sikacarbon H on 25 October 2019
- Application of glue on the carbon fabric by a spiral roller on 28 October 2019
- After 24 hours, a new Sikacarbon B layer was applied on 29 October 2019.

Figure 3. Construction of column models (Model M1 and Model M2) for experimental test

Figure 4. Photos taken during application of CFRP on models and concrete cylinders

Figure 5. Photos taken during application of CFRP on models and concrete cylinders

In parallel with the process of applying carbon fabric on the models, the same procedure was also used for wrapping trial concrete specimens – cylinders 15/30. It should be mentioned that, prior to the application of the epoxy composite base, strain gauges were glued onto both models and concrete specimens – cylinders. These were necessary for further laboratory and quasi-static tests of both the cylinders and the models. Some photos of the entire carbon fabric application process are given below (Figure 4 and Figure 5).

4. Quasi-static tests – equipment, instrumentation and course of experiments

4.1. Equipment, disposition and instrumentation of models

The quasi-static cyclic load testing was conducted in the Dynamic Testing Laboratory of UKIM-IZIIS. The equipment for the performance of such experimental investigations consists of:

- Equipment for application of force or displacement
- Instruments for measuring force and deformation
- Equipment for automatic control of experiments
- Data acquisition system.

The equipment for the application and transfer of forces and/or displacements consists of three hydraulic actuators and three steel supports. The actuators and the supports are connected to the RC floor slab via prestressed bolts. Figure 6 shows the disposition of column models during the tests. The column model was connected through the fixation column (by 8 prestressed bolts) to a steel support. Since a complex stress state consisting of compression and bending was tested, two actuators were used for the application of load. The first actuator has a capacity of 100 tons and serves for the transfer of constant axial force to the front side of the column of the size of 500 kN (for Model M1) and 300 kN (for Model M2), while the second actuator with a capacity of 50 tons serves for the transfer of cyclic shear force to the free end of the element. The connection between the tested element and both actuators was realized via steel reducers.

The instrumentation of the columns was defined so as to obtain necessary information on the deformation and behaviour of the models at various loading phases. The accuracy of the measured quantities and their further usability depended on the mode of instrumentation of the position where measuring devices were placed. Two types of instrumentation, namely, internal and external instrumentation, were used for the purposes of these experimental investigations.

The internal instrumentation of the models consisted of strain gauges placed on the longitudinal reinforcement. The strain gauges were installed at places where maximum elongations of reinforcement were expected. The gauges were glued to the reinforcement and protected in laboratory conditions. Strain gauges were glued onto the concrete surface of the columns, on both sides, for the purpose of measuring strains in concrete. These gauges can be considered as inner instrumentation because the CFRP material was placed over them. The external instrumentation was installed in such a way to obtain information on forces and lateral displacements in the direction of application of the force (at the free end of the model). LCs for force measurements (LC 1 and LC 2) (Figure 7) and LVDTs (with a base of 3 inches, 1 inch = 2.54 cm) for displacement measurements were used for that purpose. These devices serve for the control and application of displacement at the free end of the model. The strain in concrete and reinforcement was measured in the zone of expected occurrence of plastic hinge. It should be mentioned that 4 strain gauges were placed on the longitudinal reinforcement of each model (two on each side), and additional two strain gauges were placed on concrete, on both sides of the columns.

Figure 6. Disposition of column model elements and equipment during experiment

Figure 7. Disposition of measurement positions

An integral system for automatic control, measurement and acquisition, with conversion of signals from analogue to digital (A/D convertors), was developed for the acquisition of instrument quantities. The system consists of three control units for hydraulic actuators, one control unit for automatic control, a digital indicator of measured quantities that can be monitored continuously on a computer, including also graphic presentation of all results (Figure 8).

The horizontal cyclic force and displacement at the free end of the model were monitored during the entire testing by means of digital indicators.

4.2. Load programme and course of experiments

The loading programme had to be defined in order to realize experimental tests on the models. Based on the adopted geometry of the models and the quality and quantity of the built-in material (concrete and reinforcement), preliminary analytical computations of the bearing and deformability capacity of the models were carried out for different stress-strain states. The obtained parameters further represented referent values for definition of the loading programme for experimental investigations. It should be mentioned that approximate quantities from experimental and analytical investigations given in international literature were taken as ultimate values of strain for the elements constructed with CFRP materials.

The loading programme consisted of cycles of displacement or force that was iterated twice or three times for the same level of magnitude. By gradually increasing the amplitude of the applied force, the element was brought from elastic to yielding state, i.e., to the ultimate state of bearing and loading and, finally, to failure. The level of applied force for which the element reached the characteristic stress-strain states varied and was changed depending on the defined bearing and deformability capacity of the designed models.

Figure 8. Equipment for automatic control of the experiment

Figure 9. Assembly of supports and model in UKIM-IZIIS' laboratory

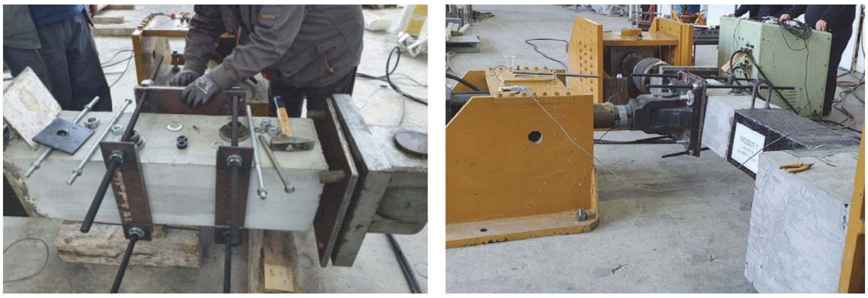

Figure 10. Assembly of steel joints for application of forces and equipment for experimental tests

4.3. Preparation of models for experimental tests

After the mounting and instrumentation of the model, the testing procedure started with the control of the functioning of the entire system for the performance of quasi-static tests and then the loading programme.

Some photos taken during assembly of supports and models, and during placement of steel joints for the transfer of cyclic and axial forces to the models, including photos of the equipment for quasi-static testing, are presented below (Figure 9 and Figure 10).

5. Experimental investigation results

The experimental investigations involved quasi-static tests on a series of two models of columns (Model M1 and Model M2).

Such course of the experiments was conditioned by the geometry of the models so that there was no change of disposition of the models and the equipment. Two different models of columns were exposed to cyclic horizontal forces with an increasing intensity and constant axial force (N = 500 kN for Model M1 and N=300 kN for Model M2) was applied to the front side of the column. The experiments were conducted by applying load onto the free end of the models.

Experimental test results are presented in the form of hysteretic relationships between force-displacement, force-deformation (in the concrete or the reinforcement in selected channels) and history of displacement at the free end of the model. Some photos (taken during the tests) that provide a visual presentation of the occurrence and extent of damage are also presented. It should be mentioned that the loading process was not interrupted during the experiments in order to mark the cracks in the carbon fabric, since these were negligible and could not be seen with a naked eye. Prior to the total failure and cracking of carbon, a pretty loud snapping noise could be heard. The snapping was the result of failure of the CFRP carbon fibres. This was followed by explosive failure in the zone of occurrence of plastic hinges, which was accompanied by tearing of the carbon fabric and complete crushing of concrete below the carbon fabric. This manifestation was identical in both models.

Some photos taken during the tests are presented so as to provide a visual representation of the occurrence and extent of damage. Some results obtained from the experimental tests on both models (Model M1 and Model M2) are also presented.

5.1. Model of RC column – Model M1

Model M1 (Figure 6) was exposed to cyclic horizontal forces with increasing intensity, and the constant axial force of N=500kN was applied onto the front part of the column. The experiment was conducted through control of displacement, while at the same time the level of horizontal force applied on the free end of the model through steel plates, at distance of 158 cm from the column support, was controlled. Prior to the beginning of the experiment, the programme was defined for monitoring the behaviour of the model in the linear phase up to the state of deep nonlinearity. The experiment started with the application of vertical force on the column, starting from 0.0 to 500 kN. When the value of 500 kN was reached, strain values in concrete and reinforcement were read from the strain gauges. In the beginning, it was established that one strain gauge in reinforcement SG_4 was not functional as the values could not be read from it. The values measured by strain gauges in concrete SG_1 and SG_2 under force of Nv = 500 kN amounted to $\varepsilon_{c}1$ = 0.809 ‰, ε_{c2} = 0.336 ‰, while those measured with strain gauges in reinforcement SG_3 and SG_6, amounted to ε_{s3} = 0.765 ‰ and ε_{s6} = 0.367 ‰ (Figure 11). Once these initial values were read from the strain gauges in concrete and reinforcement, the horizontal force was applied, with simultaneous control of displacement values. The procedure started with the application of three 2 mm displacement cycles at the free end of the column, while further on in the experiment, the applied displacement values were increased.

Time histories of strain gauges (SG_1, SG-2, SG_3, SG_5, and SG_6), horizontal force, the corresponding displacement and the force – displacement relationship referring to Model M1, are given in Figure 11 and Figure 12, respectively.

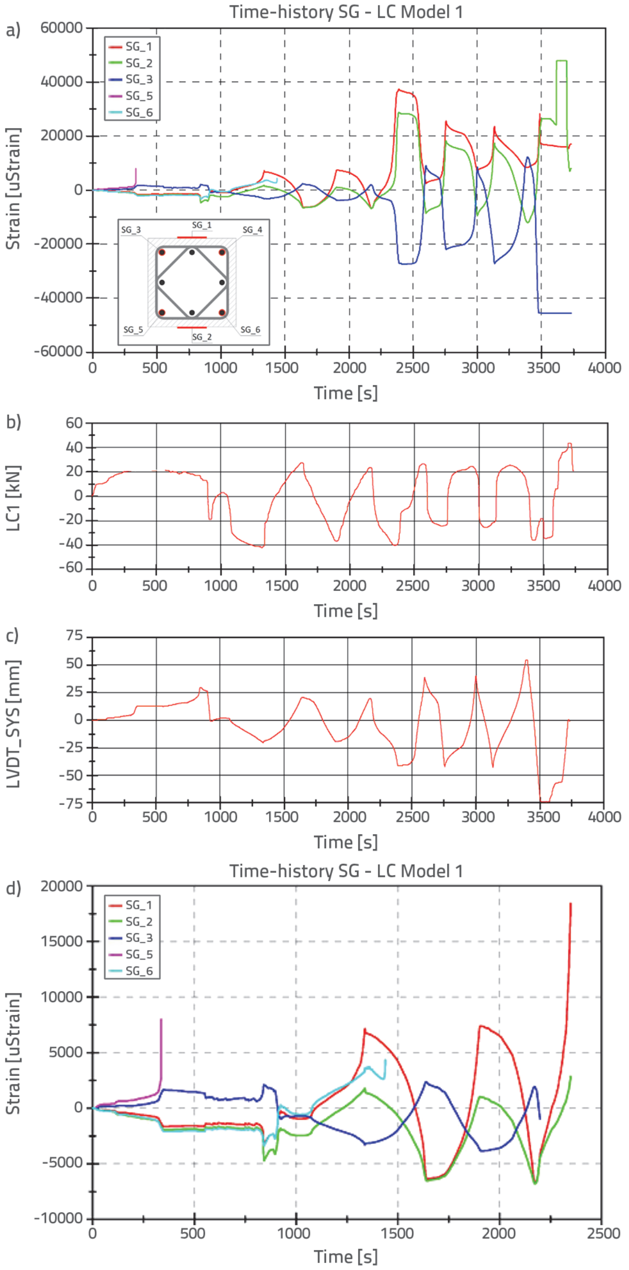

Figure 11. Model M1: a) Time histories of strains up to 4000 sec.; b) horizontal force; c) corresponding displacement during the test; d) time histories of strains up to 2500 sec. Slika 12. LC1-SG_1, Odnos sile i pomaka, model M1

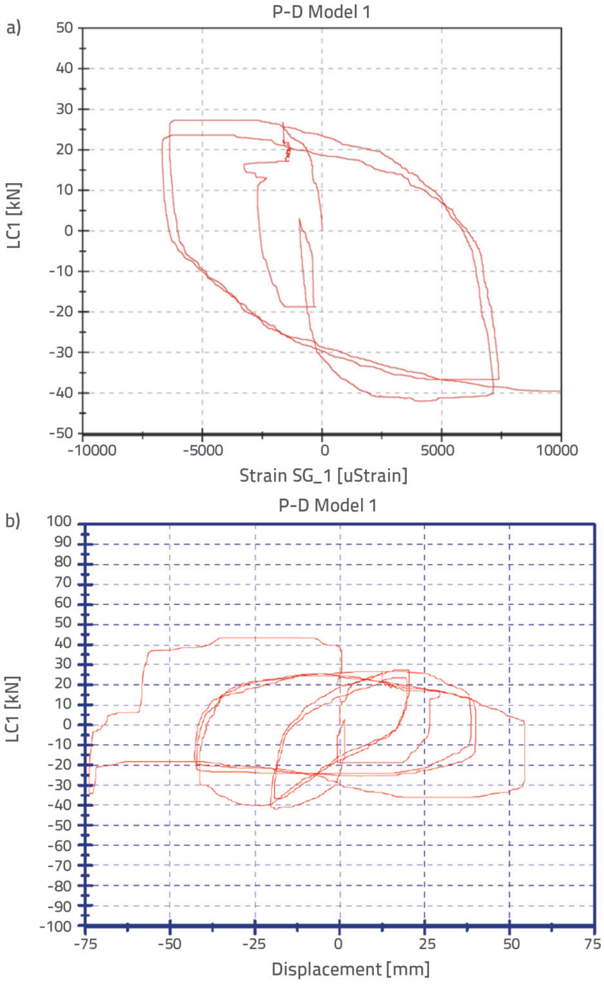

Figure 12. LC1-SG_1, Force – displacement relationship, model M1

Photos taken during quasi-static tests on Model M1, and photos of characteristic damage, are presented below (Figure 13 and Figure 14).

Figure 13. Photos taken during quasi static testing of column model – Model M1

Figure 14. Photos taken during quasi static testing of column model – model M1

5.2 Model of RC Column – Model M2

Time histories of strain, horizontal force, the corresponding displacement and the force – displacement relationship referring to Model M2, are given in Figure 15 and Figure 16.

The extensive crushing of concrete below the carbon fabric during collapse of Model M1 confirmed that the quality of the built-in concrete was very low and that it corresponded to the values obtained from ZIM "Skopje", Skopje. The decision was therefore made to reduce the vertical axial force in the column. Hence, a force of max. 300 kN was applied on Model M2. At that force, the values of the ε concrete and ε steel were ε_{c1} = 0.553 ‰ and ε_{c2} = 0.293 ‰, respectively. In the case of this model, no damage occurred on strain gauges in the concrete and reinforcement. In other words, all 6 strain gauges were operational, i.e. sg-1 and sg-2 for concrete and sg3, sg4, sg5, and sg6 for reinforcement. The loading programme was the same as that applied for Model M1. During the experiment, all data were recorded at 4500 points. The maximum displacement attained amounted to 69.28mm, when complete tearing of the carbon fabric and crushing of concrete took place. Extensive bending of reinforcement was also observed. In addition, results regarding hysteresis relationships are given for force LC1-with SG_1 and SG_3, including also force displacement relationships. Photos taken during the quasi-static tests on Model M2 and photos of characteristic damage are presented below (Figure 17 and Figure 18).

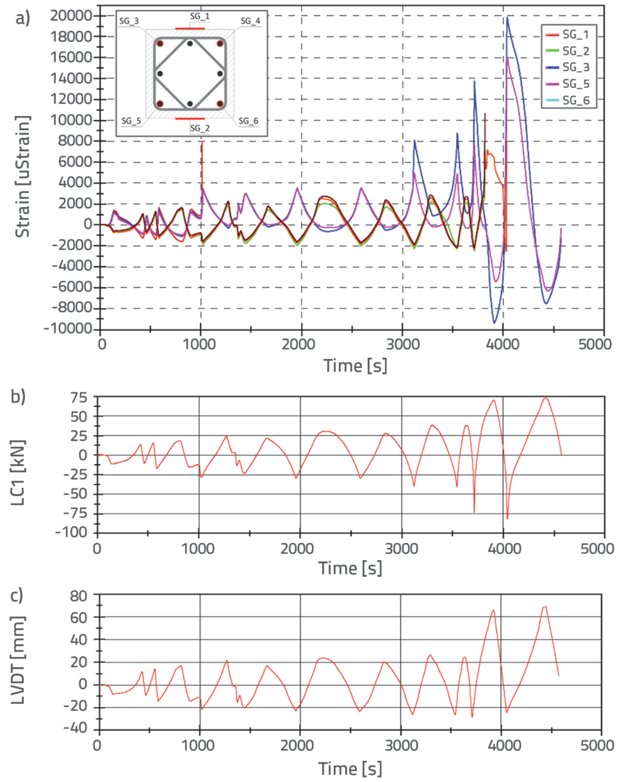

Figure 15. Time histories of strain, horizontal force, and corresponding displacement during the test, Model M2

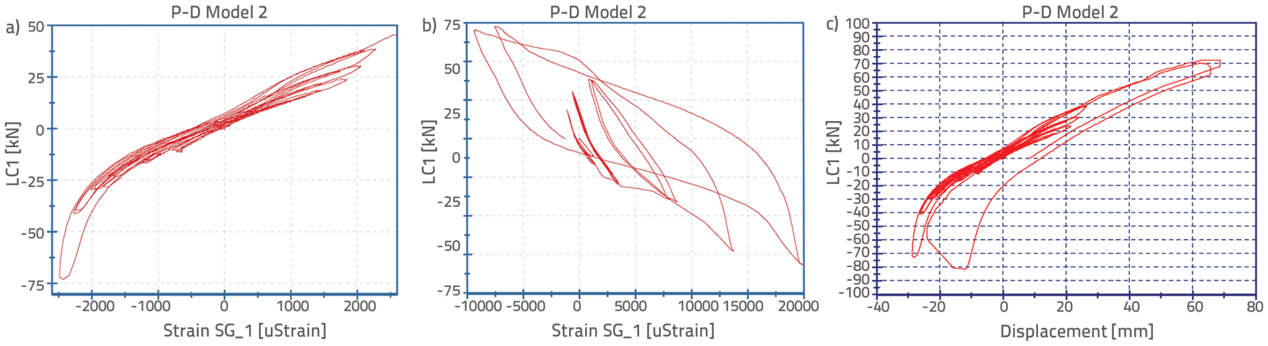

Figure 16. LC1-SG_2,LC1_SG_3, Force – displacement relationship, Model M2

Figure 17. Photos taken during quasi static testing of column model – Model M2

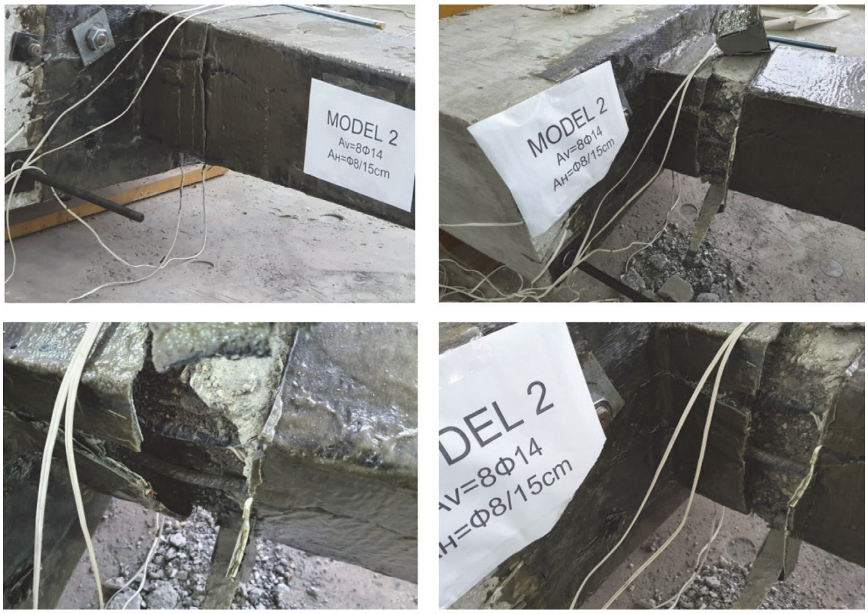

Figure 18. Photos taken during quasi static testing of column model – Model M2

6. Analysis of analytical and experimental results

Extensive analytical research was conducted using the SAP2000 computer package. The methodology developed by „Park & Paulay" (1975) was first used. This was followed by nonlinear analyses, static "pushover" and dynamic "time-history" analyses. Figure 19 shows the moment curvature up to ε_b =10 ‰ and M-N for Model 1 along with comparison with the referent model without CFRP.

Table 4 shows the summary of displacement and ductility values obtained by analytical and experimental investigations of Model 1 and Model 2. Graphical comparison between displacement and ductility investigations are presented in Figure 20.

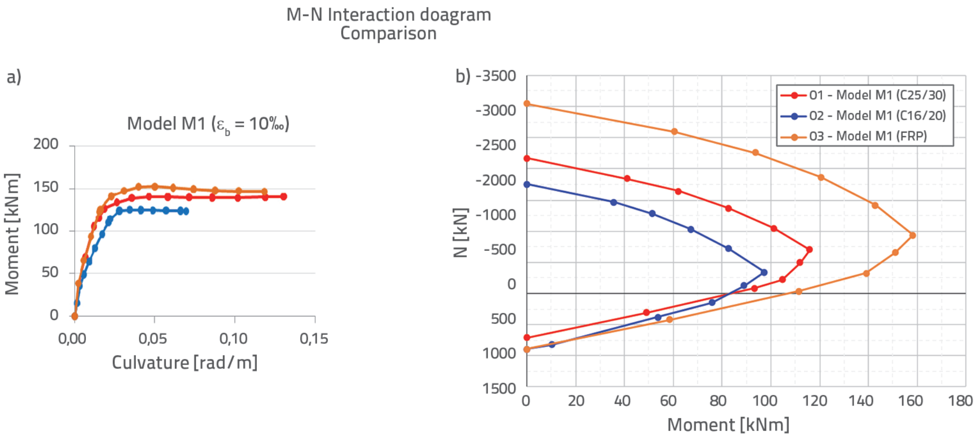

Figure 19. a) Moment-curvature and b) M-N diagramfor Model 1 (analytical results)

Table 4. Summary of displacement and ductility values based on analytical and experimental results

	Park & Paulay (1975) [35]		**Pushover and time history analysis with SAP2000 [36. 37]**		**Experiment**	
Specimen	**dy** [mm]	**du** [mm]	**dy** [mm]	**du** [mm]	**dy** [mm]	**du** [mm]
Model M1-03	12.81	56.31	8.55	45.06	10.065	55.30
Ductility		**4.39**		**5.27**		**5.49**
Model M2-03	19.22	67.02	9.04	48.03	10.73	69.28
Ductility		**3.49**		**5.31**		**6.45**

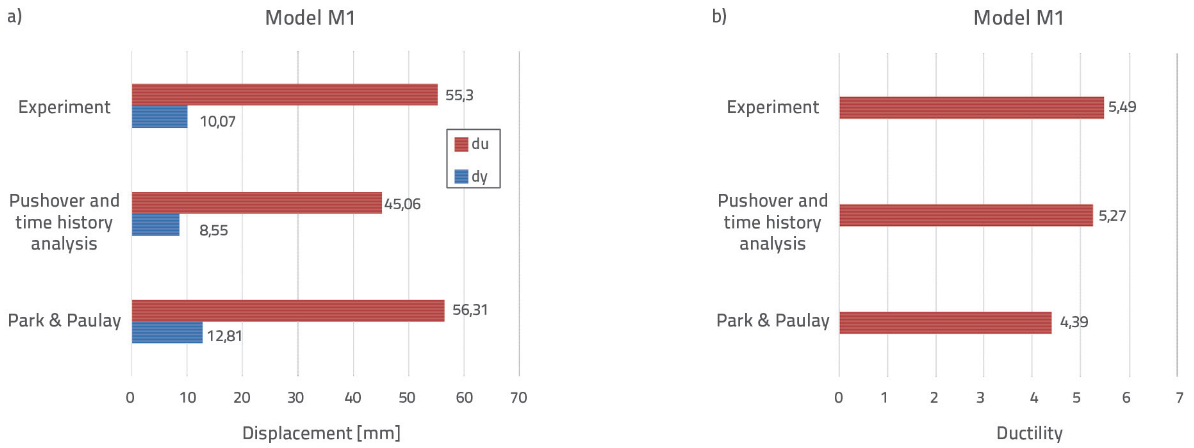

Figure 20. Comparison of displacements and ductility, Model M1- obtained by use of three methods

7. Conclusions

The following can be concluded from the results obtained for MODEL M1:

- The maximum displacement measured at the free end of the model in positive direction was 55.3 mm.
- The values registered by strain gauges were maximum ones that could be measured, namely displacement of around 40 mm and horizontal force of about 38kN.
- Within the displacement interval (0-35.3 mm) for which real records of cyclic force and displacement were obtained, the model exhibited a ductile hysteretic behaviour and energy dissipation with a wide hysteretic loop.
- The model exhibited nonlinear behaviour with the occurrence of cracks near the fixation. It must be emphasized that tearing of the carbon fabric was explosive, with extensive crushing of concrete at that point, as can be seen in enclosed photos.
- Based on the analysis of values obtained by nonlinear static and nonlinear time history analyses, it can be concluded that, compared to the model without CFRP, the ductility capacity for displacement of Model M1 strengthened with CFRP is greater by 64.6 %, while its strength capacity is greater by 21.1 %.

The following can be concluded from the results obtained for MODEL M2:

- The maximum displacement measured at the free end of the model in positive direction was 69.28 mm.
- The values registered on strain gauges reached the maximum ones that could be measured, namely displacement of about 37 mm and horizontal force of about 45kN.
- Within the displacement interval (0-37.5 mm) for which real records of cyclic force and displacement were obtained, the model exhibited a ductile hysteretic behaviour and energy dissipation with a wide hysteretic loop.
- The model exhibited nonlinear behaviour with the occurrence of cracks near the fixation. It must be emphasized that tearing of the carbon fabric was explosive, with extensive crushing of concrete at that point, as can be seen in enclosed photos.
- Based on the analysis of values obtained from nonlinear static and nonlinear time history analyses, it can be concluded that the ductility capacity for displacement of Model M2 strengthened with CFRP is greater by 60 %, while its strength capacity is greater by 7.7 % when compared to the values obtained for the model without CFRP.

The displacement and ductility values obtained during quasi-static experimental investigations at the yielding point and the ultimate point, compared to the displacements obtained in accordance with the Park and Pauley's methodology and the static nonlinear pushover and nonlinear time history analysis, are very close. In deep nonlinearity, the difference ranges from 2.3 % to 20 %. Good quasi-static test results were obtained with regard to these values. It can generally be concluded that CFRP systems are a highly practical tool for the strengthening and retrofitting of concrete structures, and that they are appropriate for flexural strengthening, shear strengthening, column confinement, and ductility improvement.

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