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ÚSTAV BETONOVÝCH A ZDĚNÝCH KONSTRUKCÍ

STRENGTHENING OF CIRCULAR COLUMN SUBJECTED TO LATERAL CYCLIC LOADING

ZESÍLENÍ KRUHOVÉHO SLOUPU NAMÁHÁNÉHO LATERÁLNÍM CYKLICKÝM ZATÍŽENÍM

DOCTORAL THESIS SUMMARY
TEZE DISERTAČNÍ PRÁCE

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ABSTRACT

The presented doctoral thesis deals with the strengthening of circular concrete columns by Fibre Reinforced Polymers (FRP) wraps subjected to lateral cyclic loadings. This research study focuses on examining the use of FRP for retrofitting, improving the performance of circular reinforced concrete columns and developing a design algorithm for circular column strengthening by FRP composite materials based on the analytical study, numerical simulations and the experimental results. Therefore, a design process of strengthening and confinement was presented to predict the behaviour of the concrete columns subjected to lateral cyclic loadings. Simultaneously with the axial force application, the lateral cyclic load was provided in two different ways; first, it was applied under force control test (i.e. same lateral cyclic force for 1 million cycles), second, it was applied under displacement control - reversed cyclic loading test based on a pattern of progressively increasing displacements. The dissertation also presents a literature review of research studies on the FRP confined concrete, design methodology of FRP jackets in seismic zones and code provisions of Eurocode and ACI. The experimental program was considered to verify the behaviour of confined circular column subjected to lateral cyclic loading. In the conclusions, the behaviour of a cantilever concrete column confined by FRP wraps was investigated and an empirical model for FRP confined concrete subjected to high and low cyclic loadings was proposed and some information on possible future research were provided.

ABSTRAKT

Předložená disertační práce se zabývá zesílením kruhových železobetonových sloupů pomocí vlákny vyztužených polymerů (FRP) namáhaných laterálním cyklickým zatížením. Tato výzkumná studie se zabývá popisem chování ovinutých sloupů a odvozením návrhového algoritmu pro zesílení kruhového sloupu pomocí kompozitních FRP materiálů. Návrhový algoritmus byl odvozen na základě analytické studie, numerických simulací a výsledků experimentální činnosti. Při experimentální práci byly zkušební vzorky zatíženy současně axiální sílou a příčným cyklickým zatížením. Toto bylo provedeno dvěma různými způsoby. První způsob zatěžování byl proveden konstantní velikostí laterální síly po daný počet cyklů (1 milion) se sledováním změny deformace. A druhý způsob provedení spočíval v zatížení konstantní deformací se sledováním úbytku síly během zatěžovací zkoušky. Dizertační práce rovněž předkládá přehled současného stavu poznání zesílení železobetonových kruhových sloupů ovinutím FRP tkaninou vystavených působení seismického zatížení. Dále uvádí přehled návrhových metodik a normová ustanovení Eurokódu a ACI. Experimentální program byl proveden za účelem ověření chování ovinutých kruhových sloupů při působení laterálního cyklického zatížení. Závěr práce sumarizuje poznatky o chování sloupů zesílených ovinutím FRP tkaninou při působení laterálního cyklického zatížení a představuje empirický model pro návrh zesílení ovinutím při vysokém a nízkém cyklickém zatížení.

KEYWORDS/KLÍČOVÁ SLOVA

Fibre Reinforced Polymer composite materials, strengthening of circular column subjected to cyclic load.

Vlákny vyztužený polymer, kompozitní material, zesílení kruhového sloupu cyklickým zatížením.

CONTENTS

1. INTRODUCTION

Columns are ones of the most important structural elements in buildings and bridges. A significant number of structural failures are attributed to column failure, especially those constructed under-designed according to load demands or seismic design provisions. Improving ductility, compressive strength and durability of concrete structures, which are affected by the environmental degradation, corrosion of steel and which are required for upgrading of structures to current seismic codes, can be achieved by lateral confinement. The conventional methods of confinement (concrete, steel) may not always be adequate to provide the desired levels of ductility. FRP confinement can provide significantly higher confining pressure than conventional methods and it can enhances its performance potential in seismic design of existing and new structures. Recent cost reductions have allowed FRP composites to become a feasible option for structural applications, which results in an increase in research on this topic. FRPs have been widely applied in construction and structural rehabilitation due to their high strength, stiffness-to-weight ratio, high-corrosion resistance, minimal thickness, ease and speed of application, and ability to fit to any structural shape.

2. RESEARCH OBJECTIVES

This present study is part of a comprehensive research program, which has been carried out at Brno University of Technology in the Institute of Concrete and Masonry Structures.

The research objectives are:

1. To investigate the behavior of cantilever circular concrete columns transversally confined by CFRP wrap
2. To propose design algorithm to strengthen circular concrete columns with CFRP wraps subjected to axial load and cyclic lateral load
3. To propose an empirical model for FRP confined concrete subjected to cyclic loading.

The procedures carried out in this research are as follows:

1. **Experimental test:** Four specimens of cantilever circular concrete columns have been selected to provide experimental test; one specimen as control specimen subjected to high and low cycle loading and two specimens confined with six layers of CFRP wrap at plastic hinge length subjected to the same load configuration as control specimen and one unconfined specimen subjected to low cycle loading only. Columns were subjected to axial force and lateral cyclic load in two different ways. Firstly, under force control; i.e. same lateral cyclic force pulling in one direction for certain number of cycles (approximately 1 million cycles), secondly under displacement control; i.e. reversed cyclic lateral load based on a pattern of progressively increasing displacements.
2. **Analysis:** Numerical study consists of mathematical model based on finite element method, was created by ATENA 3D software to simulate the behavior of unconfined and confined circular columns subjected to static axial and cyclic lateral load.
3. **Design:** Design Algorithm introduces the considerations of the design of circular column confined with FRP subjected to cyclic loading (Empirical Model), and the procedures to

improve flexural hinge ductility, and lap splice clamp developed by C# programming language.

3. OVERVIEW OF THE COMPOSITE MATERIAL AND CONFINEMENT

3.1 COMPOSITE MATERIAL

Composite materials are materials formed from two or more materials with significantly different physical or chemical properties, that when combined, produce a material with characteristics different from the individual components. Composite materials have the advantages of being stronger and lighter or less expensive when compared to traditional materials. Fiber Reinforced Polymer (FRP) is a composite material consisting of polymer matrix reinforced with fibers. The fibers are stronger than the matrix. There are many types of fiber, usually are glass (G), carbon (C) and aramid (A). The polymer matrix is usually an epoxy, vinyl ester or polyester thermosetting plastic, and phenol formaldehyde resins are still in use. The mechanical properties of FRP depend on many factors; fiber quality, form, direction, volumetric ratio, adhesion to the matrix, and the manufacturing process. The stress-strain relationships for fibers, matrix, and the resulting FRP material are illustrated in *Figure 1*.

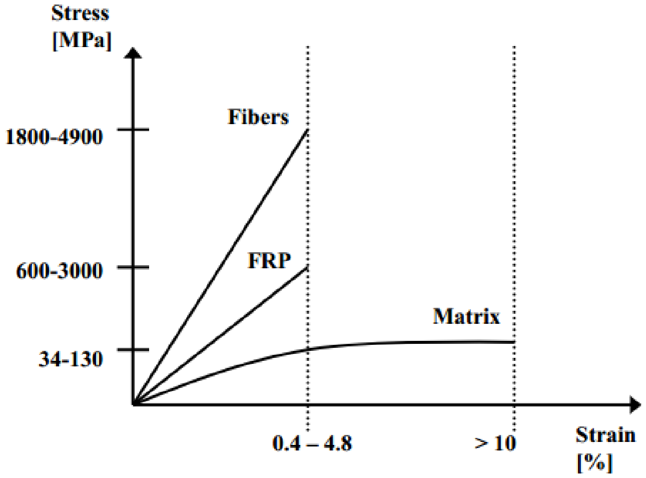


Figure 1 *- Stress-strain relationship of fiber, matrix and FRP [14]*

Table 1 *- Typical properties of fibers (Feldman 1989, Kim 1995) [4]*

Fiber Type		Tensile Strength [MPa]	Elastic Modulus [GPa]	Ultimate Tensile Strain [%]
Carbon	High Strength	3500-4800	215-235	1.4-2.0
	Ultra High Strength	3500-6000	215-235	1.5-2.3
	High Modulus	2500-3100	350-500	0.5-0.9
	Ultra High Modulus	2100-2400	500-700	0.2-0.4
Glass	E-Glass	1900-300	70	3.0-4.5
	S-Glass	3500-4800	85-90	4.5-5.5
Aramid	Low Modulus	3500-4100	70-80	4.3-5.0
	High Modulus	3500-4000	115-130	2.5-3.5

Figure 2 shows typical stress-strain diagrams for common materials. FRP has elastic behavior up to failure contrary than steel, which applies a constant confining pressure after yield. Therefore, FRP exhibits its confining action on concrete under axial load in a different way than steel.

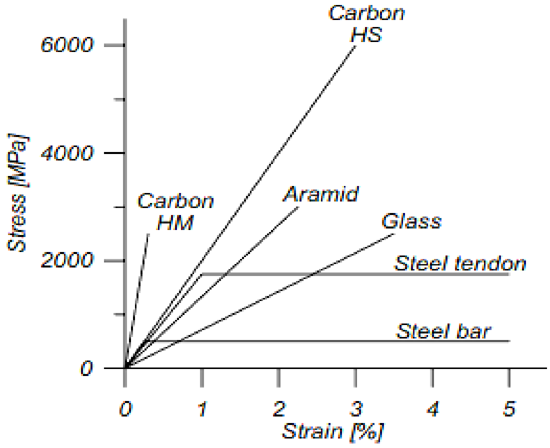


***Figure 2** - Stress-strain diagram for fibers & reinforcement steel [2]*

3.2 METHODS OF RETROFITTING OR JACKETING

Retrofitting method is the modification of existing structures to make them more resistant to lateral excitation, increasing in load demands, and failure due to environmental degradation. Three common methods of jacketing are available for retrofitting/strengthening existing structures; reinforced concrete jackets, steel jackets and composite materials FRP jackets. Compared to concrete and steel jacketing, FRP wrapping has several advantages (high-corrosion resistance, minimal thickness, ease and fast application, ability to fit to any structural shape, etc.). Composite jacket reinforcement acts in most cases in passive way to increase confinement, which leads to significant increase in strength and ductility [4], [6]. These systems are mainly divided into three types [4]:

1) Wet lay-up systems
2) Pre-fabricated systems and
3) Special systems e.g. automated wrapping, pre-stressing etc.

Surface preparation of existing column is very important. FRP wrapping is vulnerable to stress concentration. The prepared column surface should be roughened to ensure proper bonding of FRP wrap with the existing column.

3.3 CONFINEMENT ACTION

The main purpose of confinement is to provide lateral support to the vertical reinforcement, to improve the compressive strain and the deformation capacity of the concrete columns. The benefits of using FRP jackets and the differences of the behavior of the concrete confined with FRP, compared to steel, attract the attention of civil and construction industry to work on developing more accurate models for FRP-confined concrete. The differences originate from the elastic behavior of FRP jackets that supply increasing pressure on the concrete with lateral expansion. On the contrary, a steel jacket applies constant pressure after yielding. Two different types of confinement can be recognized: passive and active confinement.

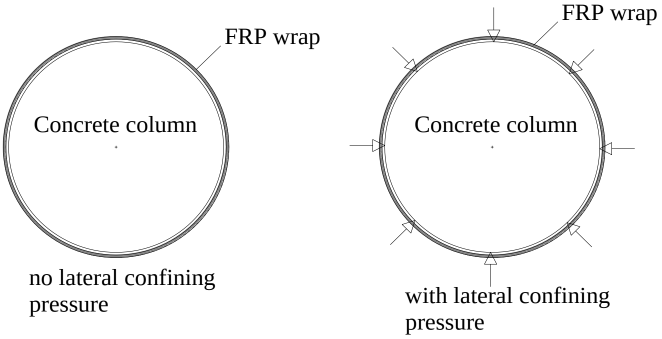


Figure 3 *- Passive and active confinement of column cross-section*

3.3.1 PASSIVE CONFINEMENT

Passive confinement controls the lateral expansion of concrete, and it is achieved by wrapping the concrete with FRP wraps. When the concrete is loaded axially, a lateral expansion of the concrete occurred, which is restrained by the confining, which produces a lateral pressure at the interface. As the axial load increases, the tendency for lateral expansion increases and therefore the confining pressure increases. Mander et al. (1988) [11] model was formulated using the tri-axial test data which is characterized by a constant confining pressure unlike the constantly increasing confining pressure applied by the FRP wraps. In addition, the Mander et al. model [11] adopted the stress-strain curve proposed by Popovics (1973), which was inappropriate for describing the bilinear behavior of concrete confined by FRPs.

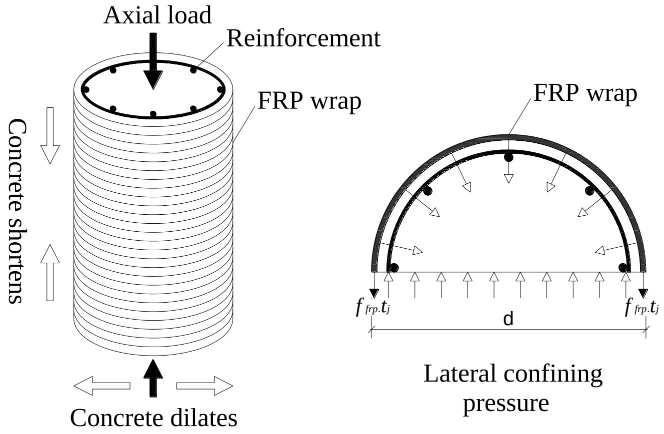


Figure 4 *- Confining action of FRP*

The bilinear behavior of the confined concrete was exhibited and confirmed experimentally by many studies. The lateral confining pressure can be derived using the stress equilibrium and radial displacement compatibility considerations between the concrete core and the jacket as shown in *Figure 4*.

The lateral pressure can be computed [14]

$$\sigma_l = \frac{2 f_{frp} t_j}{d} = \frac{2E_{frp} \varepsilon_{frp} t_j}{d}, \tag{1}$$

where $f_{frp} = E_{frp} \varepsilon_{frp}$; the tensile strength of FRP in the hoop direction, $t_j =$ total thickness of the FRP jacket, $d =$ diameter of the confined concrete core. The effectiveness of FRP confined members only depends on a fraction of the confinement lateral pressure exerted by the system, namely effective confinement lateral pressure $\sigma_{l,eff}$. The effective confinement lateral pressure is a function of member cross-section and FRP configuration as indicated in the following equations

$$\sigma_{l,eff} = k_{eff} \sigma_l, \tag{2}$$

where k_{eff} is the coefficient of efficiency ($k_{eff} = 1$ for circular cross section), which will be discussed in details in the next paragraph (Factors influencing the confinement performances).

3.3.2 ACTIVE CONFINEMENT

Active confinement, which can be achieved by pre-stressing the confinement material before applying axial load to the concrete, is independent on the lateral expansion of concrete and the lateral stiffness of confining material. Richart et al. (1928) [15] was one of the pioneers who worked in the field of concrete confinement, especially under tri-axial stress state. The authors used a tri-axial pressure vessel to exert active confining pressure on concrete cylinders. Lateral confining pressure was widely varied from 7% to 57% of the compressive strength of unconfined concrete. The superiority of active confinement compared to passive confinement encouraged some researchers to investigate the feasibility of applying active confinement in the field of seismic retrofit.

3.4 PROPOSED MODELS FOR CONFINEMENT

The existing models are classified into two categories Lam & Teng (2003) [9]:

1) Numerical or analysis-oriented models and

2) Empirical or design-oriented models.

For the first category, constitutive models were improved using incremental procedure to plot the entire stress-strain response. Such models need special computer programs (non-linear finite element analysis). For the second category, the models are mainly based on test results with regression analysis methods in order to calibrate those results.

The typical form of design-oriented expressions for the prediction of axial strength is as follows:

$$\frac{f_{cc}}{f_{co}} = k_1 + \frac{k_2 \sigma_l^{k_3}}{f_{co}}, \tag{3}$$

where k_1, k_2, k_3 are constants, the value of k_1 is usually 1, the values of k_2 and k_3 are different for each model.

The analysis-oriented models are based on the tri-axial concrete material models with strain and stress compatibility between the concrete and the FRP. Several models are based on non-linear elastic material law. In this case there is a direct relationship between stresses and strains

$$\sigma = \left[D\right]\varepsilon\,, \tag{4}$$

where the stress σ and the strain ε are represented by vectors of six components for a three dimensional approximation and $\left[D\right]$ is the elasticity matrix is defined in terms of the material properties. The elements $\left[D\right]$ depend on the current level of stresses. In uniaxial loading with monotonic axial strain the elastic modulus of concrete decreases, meanwhile the Poisson's ratio increases.

***Table 2** - Design-oriented models for confined concrete*

Models	Ultimate compressive strength	Ultimate strain
Fardis & Khalili 1982	$\frac{f_{cc}}{f_{co}} = 1 + 3{,}7\left(\frac{\sigma_l}{f_{co}}\right)^{0{,}86}$ by Richart et al. $\frac{f_{cc}}{f_{co}} = 1 + 4{,}1\left(\frac{\sigma_l}{f_{co}}\right)$ by Newman et al.	$\varepsilon_{cc} = \varepsilon_{co} + 0{,}001\left(\frac{E_f t_f}{D f_{co}}\right)$
Spoelstra & Monti 1999	$\frac{f_{cc}}{f_{co}} = 0{,}2 + 3{,}0\sqrt{\frac{\sigma_l}{f_{co}}}$	$\varepsilon_{cc} = \varepsilon_{co}\left[2 + 1{,}25\frac{E_c}{f_{co}}\varepsilon_f\left(\frac{\sigma_l}{f_{co}}\right)^{0{,}5}\right]$ where $\varepsilon_{co} = 0{,}002$
Ilki et al. 2002	$\frac{f_{cc}}{f_{co}} = 1 + 2{,}227\left(\frac{\sigma_l}{f_{co}}\right)$ for CFRP wraps	$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 15{,}156\left(\frac{\sigma_l}{f_{co}}\right)^{0{,}735}\right]$
Lam and Teng 2003	$\frac{f_{cc}}{f_{co}} = 1 + 3{,}5\frac{\sigma_l}{f_{co}}$	$\varepsilon_{cc} = \varepsilon_{co}\left(1{,}75 + 12\left(\frac{\sigma_l}{f_{co}}\right)\left(\frac{\varepsilon_{h,rup}}{\varepsilon_{co}}\right)^{0{,}45}\right)$
Bisby et al. 2005	$\frac{f_{cc}}{f_{co}} = 1 + 2{,}425\frac{\sigma_l}{f_{co}}$ $\frac{f_{cc}}{f_{co}} = 1 + 2{,}217\left(\frac{\sigma_l}{f_{co}}\right)^{0{,}911}$ $\frac{f_{cc}}{f_{co}} = 1 + 3{,}587\frac{{\sigma_l}^{0{,}84}}{f_{co}}$	$\varepsilon_{cc} = \varepsilon_{co} + k_2\left(\frac{\sigma_l}{f_{co}}\right)$ $K_2 = 0{,}0240$ for CFRP-confined concrete $K_2 = 0{,}0137$ for GFRP-confined concrete $K_2 = 0{,}0536$ for AFRP-confined concrete
Youssef et al. 2007	$\frac{f_{cc}}{f_{co}} = 1 + 2{,}25\left(\frac{\sigma_l}{f_{co}}\right)^{\frac{5}{4}}$	$\varepsilon_{cc} = 0{,}003368 + 0{,}259\left(\frac{\sigma_l}{f_{co}}\right)\left(\frac{f_{frp}}{E_{frp}}\right)^{0{,}5}$
Wu et al. 2009	$\frac{f_{cc}}{f_{co}} = 1 + 3{,}2\frac{\sigma_l}{f_{co}}$	$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 9{,}5\left(\frac{\sigma_l}{f_{co}}\right)\right]$
Benzaid et al. 2010	$\frac{f_{cc}}{f_{co}} = 1 + 2{,}2\frac{\sigma_l}{f_{co}}$	$\varepsilon_{cc} = \varepsilon_{co}\left[2 + 7{,}6\left(\frac{\sigma_l}{f_{co}}\right)\right]$

***Table 3** - Analysis-oriented models for confined concrete*

Models	Ultimate compressive strength	Ultimate strain
Mander et al. 1988	$\frac{f_{cc}}{f_{co}} = 2{,}254\sqrt{1 + \frac{7{,}94\sigma_l}{f_{co}}} - 2\frac{\sigma_l}{f_{co}} - 1{,}254$	$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 5\left(\frac{f_{cc}}{f_{co}} - 1\right)\right]$
Marques et al. 2004	$\frac{f_{cc}}{f_{co}} = 1 + 6{,}7\frac{{\sigma_l}^{0{,}83}}{f_{co}}$	$\varepsilon_{cc} = \varepsilon_{co}\left(1 + 33{,}5k_3\frac{{\sigma_l}^{0{,}83}}{f_{co}}\right)$ $k_3 = \frac{40}{f_{co}} \leq 1$
Binici et al. 2005	$\frac{f_{cc}}{f_{co}} = \sqrt{1 + \frac{9{,}9\sigma_l}{f_{co}}} + \frac{\sigma_l}{f_{co}}$	$\varepsilon_{cc} = 5\varepsilon_{co}\left(\frac{f_{cc}}{f_{co}} - 0{,}8\right)$
Albanesi et al. 2007	$\frac{f_{cc}}{f_{co}} = 1 + 3{,}609\left(\frac{\sigma_l}{f_{co}}\right)$	$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 18{,}045\left(\frac{\sigma_l}{f_{co}}\right)\right]$
Teng et al. 2007	$\frac{f_{cc}}{f_{co}} = 1 + 3{,}5\frac{\sigma_l}{f_{co}}$	$\varepsilon_{cc} = 5\varepsilon_{co}\left(\frac{f_{cc}}{f_{co}} - 0{,}8\right)$
Xiao et al. 2010	$\frac{f_{cc}}{f_{co}} = 1 + 3{,}24\left(\frac{\sigma_l}{f_{co}}\right)^{0{,}80}$	$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 17{,}4\left(\frac{\sigma_l}{f_{co}}\right)^{1{,}06}\right]$

4. THEORETICAL PART

4.1 ANALYTICAL PART- CROSS-SECTION ANALYSIS OF CIRCULAR COLUMNS

The analytical example is provided to show the influence of confinement action of unidirectional (transverse direction) and multi-layers of carbon fibre reinforced polymers (CFRP) wrap on the interaction diagram of circular reinforced concrete columns. The axial and flexural resistance of unconfined and confined reinforced concrete column are expressed by a column interaction diagrams as shown in *Figure 5* and *Figure 6* respectively. The theory adopted was based on the Eurocode provisions and design-oriented models for confinement concrete predicted by some authors as mentioned in *Table 3***.** In addition, the effect of numbers of FRP layers on the interaction diagram using the confinement action in Eurocode provisions was provided.

Figure 5 shows the comparison of interaction diagrams between unconfined and CFRP-confined circular reinforced. The axial capacity of the selected unconfined concrete column is 2398 kN, and the range of the enhancement on the axial capacity provided by CFRP in hoop direction is 2600 to 2981 kN which present 1.08 % to 1.25 %.

Figure 6 shows the influence of multi-layers CFRP wrap (1x, 2x, 4x and 6x) on the interaction diagram of reinforced concrete columns adopting the Eurocode provisions for confinement, a substantial gain in both axial compression and flexural capacity can be expected. The axial capacity of the circular concrete column is 1.20, 1.29, 1.50, and 1.70 % for the 1x layer, 2x layers, 4x layers and 6x layers respectively.

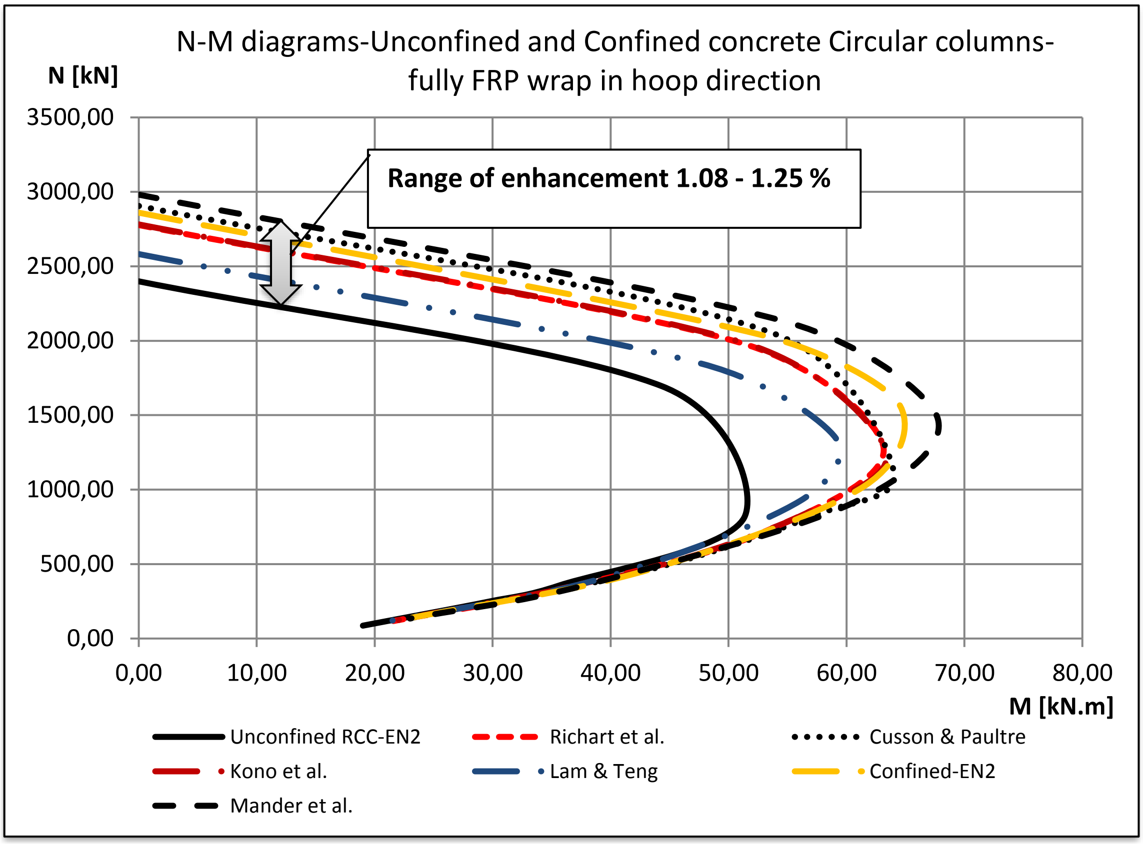


Figure 5 *- N-M diagram of RC circular column wrapped with FRP in hoop direction*

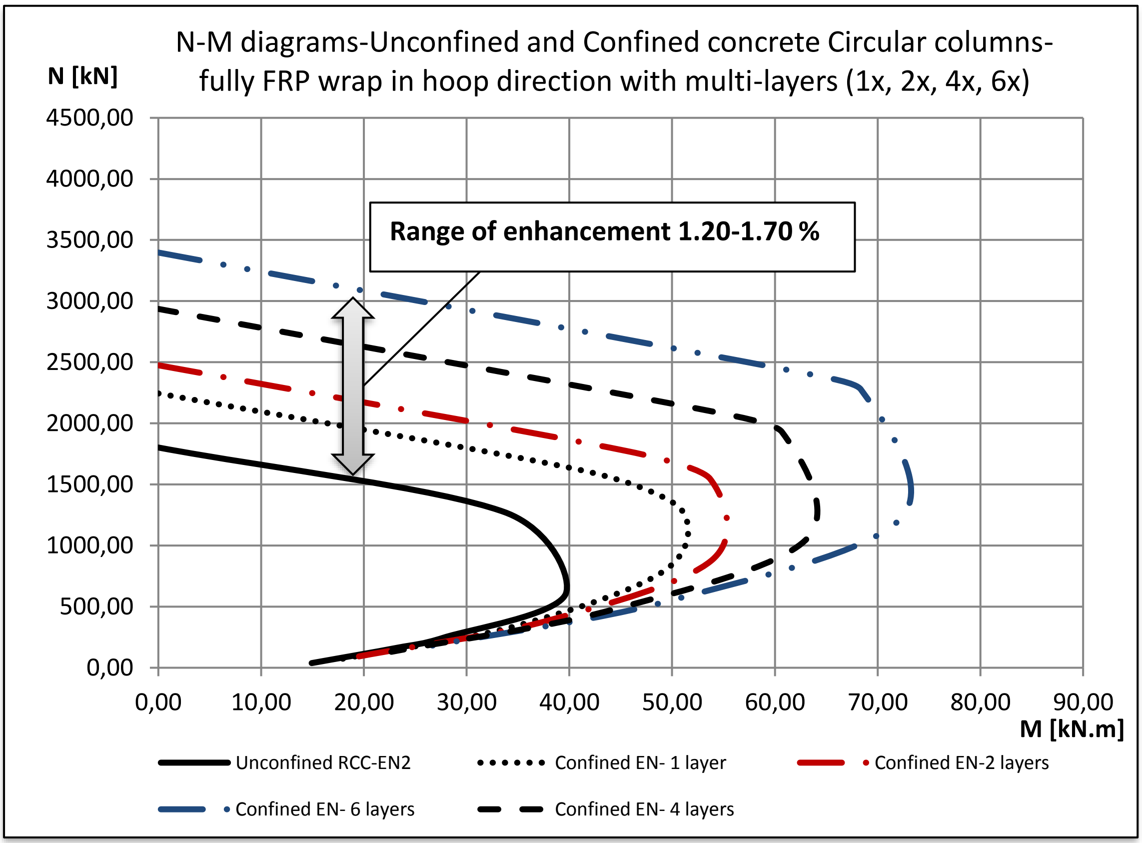


Figure 6*- N-M diagram of RC column wrapped with multi-layers of FRP based on Eurocode*

4.2 MOMENT CURVATURE ANALYSIS OF TEST SPECIMENS

Moment curvature diagram is a graphical representative of moment of resistance variation at a section with respect to curvature. Moment curvature relation is helpful to understand the ductility of reinforced concrete elements. Section analysis conducted by Sap2000 software is performed in moment curvature response using a fibre section decomposition approach, which shows that the diagrams for test specimen C1 with various configurations; unconfined, confined with spiral reinforcement, and confined with spiral and wraps.

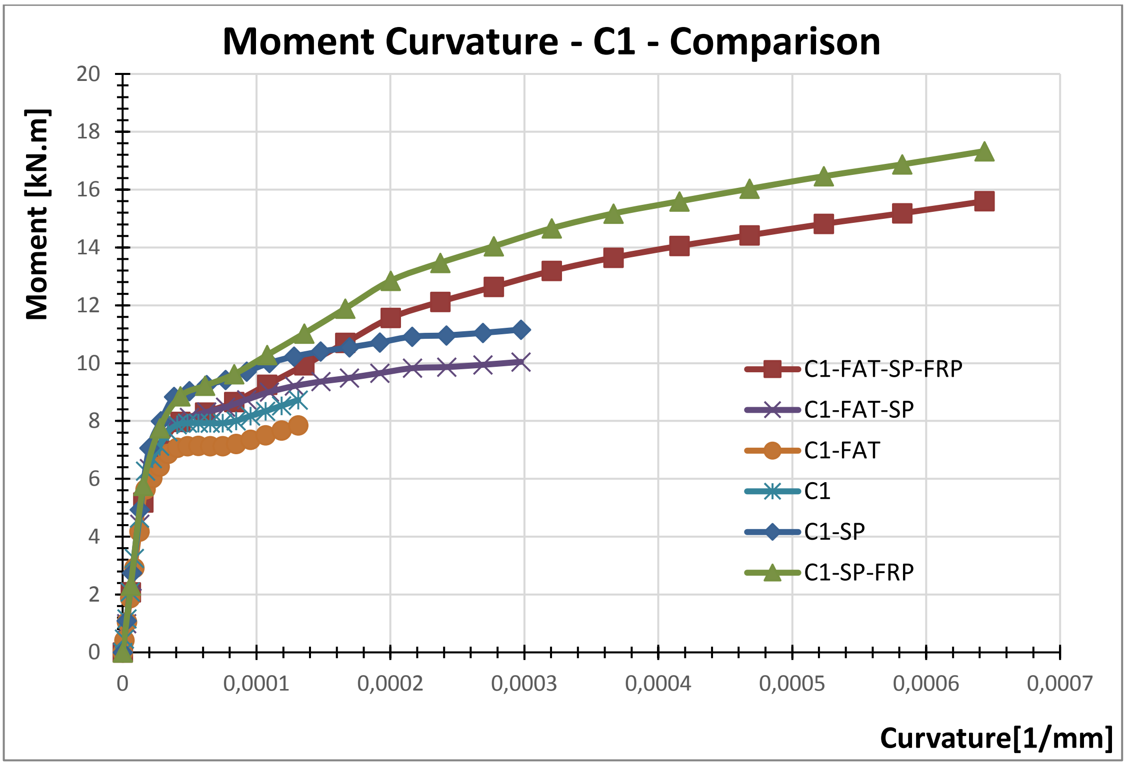


Figure 7 *- Comparison of Moment vs. Curvature diagrams for test specimen C1*

The fatigue of the material can affect the behavior of the moment curvature diagram, the performance of the initial yield curvature and moment are reduced approximately by 3 and 11% respectively.

Notation of symbols in the graphs and tables:

- C1-Unconfined: represents the unconfined concrete circular column type C1;
- C1-SP: represents the column type C1 confined by spiral;
- C1-SP-WRAP: represents the column type C1 confined by spiral and wrap;
- C1-FAT: represents the unconfined column type C1 considering the degradation of strength of concrete and steel due to fatigue;
- C1-FAT-SP: represents the column type C1 confined by spiral and considering the degradation of strength of concrete and steel due to fatigue;
- C1-FAT-SP-WRAP: represents the column type C1 confined by spiral and wraps considering the degradation of strength of concrete and steel due to fatigue.

5. EXPERIMENTAL PART

5.1 TEST SPECIMENS PARAMETERS

Four specimens of circular reinforced concrete columns were tested under axial compressive and lateral cyclic loads applied at the top free-end of the columns. Two columns were confined by CFRP in hoop direction with six layers up to 600 mm from the column base and two columns were unconfined (one considered as control specimen, and another has different load configuration). Simultaneously with the axial force application, the lateral cyclic load was provided in two different ways; first, it was applied under force control test (i.e. same lateral cyclic force pulling in one direction for certain number of cycle's~ 1 million cycles), second, it was applied under displacement control - reversed cyclic load based on a pattern of progressively increasing displacements. The diameter of all test specimens is 200 mm with total height of 2440 mm. The effective height is 2090 mm measured from the column base to the position of lateral load application and the part of column embedded in steel footing is 350 mm.

A summary of test specimen's configuration is given in *Table 4*.

Table 4 *- Configuration of test specimens*

Experimental test configuration		
Type of column	**Confinement**	**Loading**
C1	Unconfined	Both loading (high and low cycle fatigue load) are applied
C2	Confined	Both loading (high and low cycle fatigue load) are applied
C3	Confined	Both loading (high and low cycle fatigue load) are applied
C4	Unconfined	Only high cycle fatigue load is applied

Table 5 shows the properties of Sikawrap®-600C/120 and Sikadur ®-300. A gap of 5 mm was maintained between the footing top and CFRP wrap to avoid the strength contribution in the longitudinal direction.

Table 5 *- Properties of Sikawrap and Sikadur [16] & [17]*

Sikawrap® -600C/120		
Density of Sikawrap-600C/120	1,81	g/cm³
Tensile strength	3800	N/mm²
Tensile modulus of elasticity of wrap	242000	N/mm²
Strain at rupture	1,55	%
Thickness of wrap	0,337	mm
Thickness of laminate(impregnated Sikadur 300)	1,3	mm
Tensile modulus of elasticity of laminate	50000	N/mm²

Sikadur® -300		
Density of Sikadur-300 (component A+B)	1,16	kg/l
Tensile strength	45	N/mm²
Tensile modulus of elasticity of Sikadur-300	3500	N/mm²
Strain at rupture	1,5	%

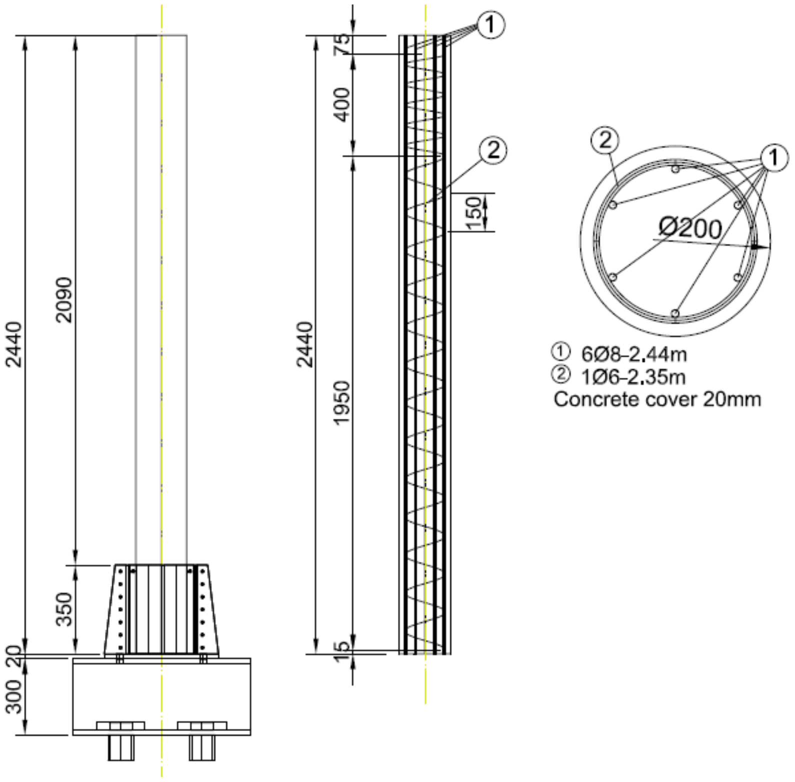


Figure 8 *- The geometry of circular columns*

5.2 EXPERIMENTAL TEST RESULTS

The experimental results are introduced in form of hysteresis force-displacement envelope diagrams, energy dissipation-displacement diagrams, energy dissipation-drift, and lateral force-drift. The test results are compared to quantify the improvement in column behavior provided by the FRP wraps and the effect of high and low cycle loading.

5.2.1 FORCE DISPLAEMENT ENVELOPE DIAGRAMS

Figure 9 illustrates the comparison between unconfined specimen C1 and confined specimens C2 and C3 subjected to high and low-cycle loading, and unconfined specimen C4 subjected to low-cycle loading only. It shows that column type C4 has higher ductility than C1. The fatigue occurs in the specimen C1 due to high-cycle (one million cycles) and low-cycle; and a progressive structural damage occurs when a material is subjected to both cyclic loadings (high and low). Same configuration has been implemented for columns type C2 and C3, and even though a small difference in the results occurred due to the difference in the mechanical properties of the concrete (material characteristics). The comparison between unconfined specimen C1 and confined specimens C2 and C3 subjected to high and low-cycle loadings shows that FRP wraps in hoop direction provide an improvement in the ductility, i.e. means adding of FRP wraps to columns changes the mechanical properties of materials which improves the fatigue resistant and the life of columns. The initial slope of the load vs. displacement response curves for the unconfined specimen C1 and confined specimens C2 and C3 is not similar, i.e. that the FRP wraps have an influence on the stiffness of the columns. The hysteresis curve of the columns shows that the ultimate force of the unconfined column C1 reached about 40 kN for displacement of 23 mm and for the confined column C2 and C3 47 kN and 49 kN respectively for the same displacement in the push direction (positive zone).

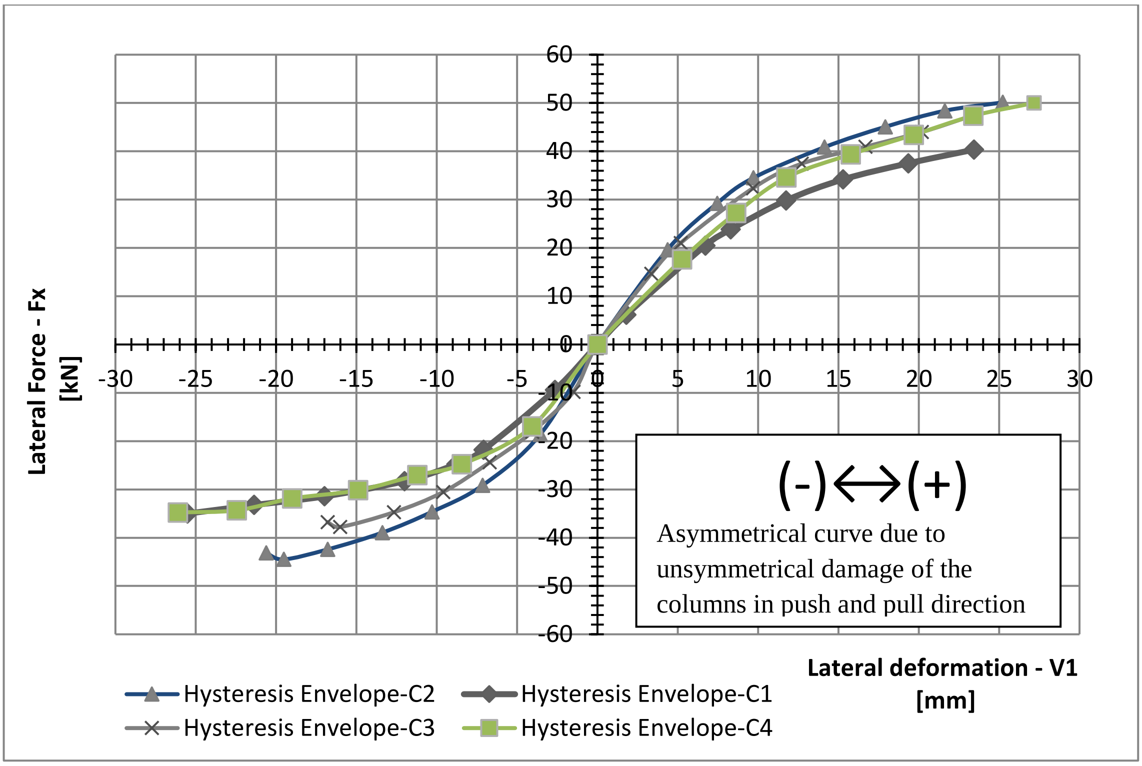


Figure 9 *- Force-Displacement Envelope Diagrams for all specimens-Experimental*

It means that FRP wraps enhance the capacity of the unconfined column C1 approximately by 20% (considering the average of confined columns C2 and C3). The ultimate lateral forces in the push and pull directions are not matching. The asymmetrical of the curve in the positive (push direction) and negative zone (pull direction) may be probably caused by unsymmetrical damage of the columns during the test in push and pull directions and to the effect of inhomogeneity of concrete.

5.2.2 ENERGY DISSIPATION -DISPLACEMENT ENVELOPE DIAGRAMS

Energy dissipation is a fundamental structural property of structural elements subjected to cyclic loading. The failure mechanism of reinforced concrete columns is dependent on the load path history and affects the ductility and energy dissipation capacity of the columns. The energy dissipation of the column is derived from the work done in deforming the column. The energy released due to change in displacement caused by a lateral force in an interval time $E_{si}(t)$ and the total energy E_{si} are defined by

$$E_{si}(t)=\frac{1}{2}\frac{\Delta X_i}{\Delta t}\left[F_i(t)+F_{i+1}(t)\right] \qquad (5)$$

$$E_{si}=\int_{t=0}^{n}E_{si}(t).\Delta t \qquad (6)$$

Specimen type C1 subjected to high and low-cycle loading dissipates less than the specimen C4, which is subjected to low-cycle loading only. The total energy dissipated by the specimen C1 and C4 are 616,314 KN.mm and 881,540 KN.mm respectively, which is 43% higher. Additionally, the confined specimens with FRP wraps C2 and C3 subjected to high and low-cycle loading have higher dissipated energy level than specimen type C1. The total average energy dissipated by the specimens C2 and C3 is 798,321 KN.mm, which is higher 29,50 % than the total energy dissipated by the specimen C1. The difference in the energy dissipation between columns type C2 and C3 is due to the variance in the material properties. It can be concluded that the ductility and energy dissipating capacity increase when the confinement is presented. Additionally, the low-cycle loading decreases the ductility and the energy dissipating capacity of the columns. It can be concluded that the high-cycle loading and the FRP wraps have a significant effect of the behavior of the concrete columns.

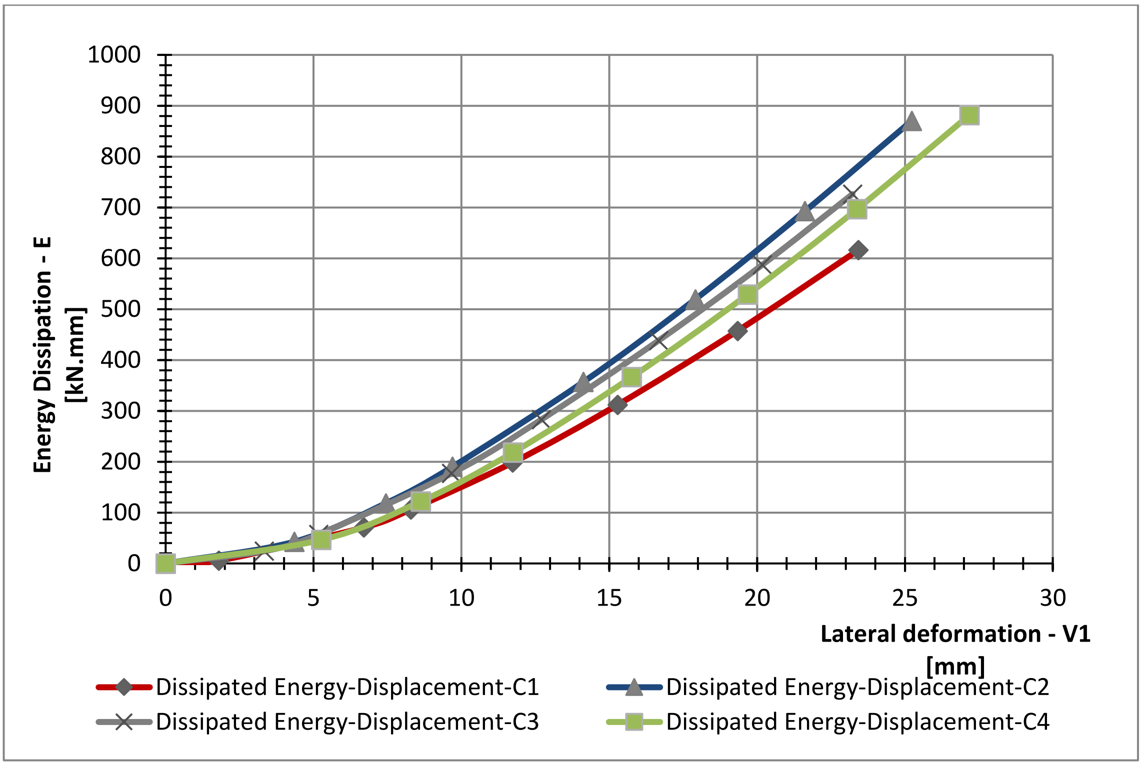


***Figure 10** - Energy Dissipation-Displacement Envelope Diagrams for all Specimens-Experimental*

5.2.3 LATERAL FORCE-DRIFT DIAGRAMS

The lateral drift ratio of the cantilever column is defined as the ratio of maximum lateral displacement ($\Delta_{\max}$) deriving from lateral force to total height (L) of the specimen.

$$Drift = \mu = \frac{\Delta_{\max}}{L} \tag{7}$$

Figure below illustrates the comparison of the lateral force-drift of the unconfined columns C1 and C4, and the confined columns with FRP wraps C2 and C3. The test data and figure above indicate that the drift capacity of unconfined column type C1 subjected to high and low-cycle loading is lower than the drift of unconfined column type C4 subjected to low-cycle loading only. Additionally, the drift capacity increases when the confinement is presented as shown in the comparison between columns C1 and confined columns C2 and C3. The difference in drift between columns type C2 and C3 is due to the variance in the material properties.

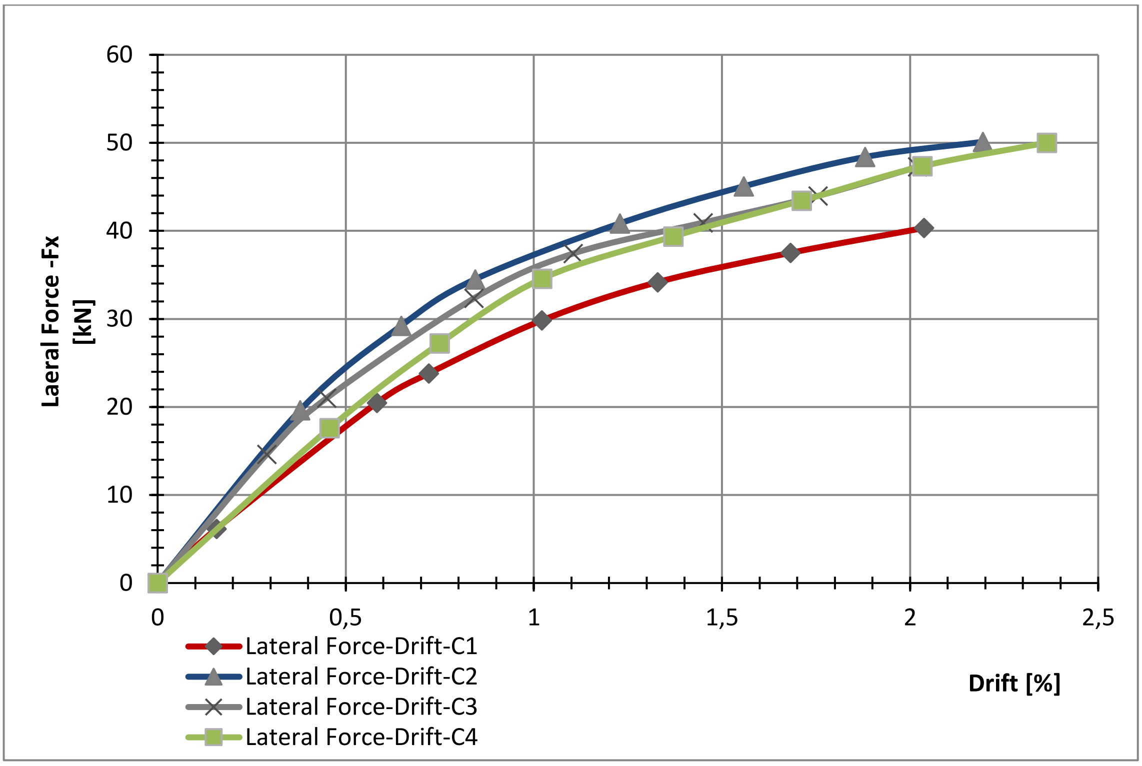


Figure 11 *- Lateral Force-Drift Ratio for all Specimens-Experimental*

5.2.4 EMPERICAL MODEL FOR FRP CONFINED CONCRETE SUBJECTED TO CYCLIC LOADING

One of the main objectives of this dissertation work is to develop an empirical model (design-oriented model) of the confined concrete subjected to cyclic loading and to predict the confined compressive strength of concrete wrapped with CFRP. The typical form of design-oriented expressions is

$$\frac{f_{cc}}{f_{co}} = k_1 + k_2 \left(\frac{\sigma_{l,eff}}{f_{co}} \right)^{k_3}, \tag{8}$$

where k_1, k_2, k_3 are constants, the value of k_1 is usually 1, the values of k_2 and k_3 are unknown parameters based on the results of loading test and the various compressive strength of the concrete. f_{cc}, f_{co}, *and* $\sigma_{l,eff}$ are the predicted confined compressive strength of the concrete, the compressive strength of the unconfined concrete and the effective lateral pressure contributed by the FRP wraps respectively. For the compressive strength subjected to cyclic loading a similar expression will be adopted within consideration the FRP wraps contribution on the enhancement of the unconfined concrete. The relationship mentioned above is describing the development of the strength of the confined concrete which depending on the amount of the lateral pressure contributed by the FRP warps.

Based on the results obtained from the experimental study among specimens C1, C2 and C3, the enhancement of the FRP wraps on the behavior of the unconfined concrete is approximately 20 % (taken the average between of C2 and C3). A calibration was conducted due to the properties of concrete variations of the test specimens. After performing the calibration the enhancement of the FRP wraps on the unconfined column increased approximately 10 %. The unknown parameters k_2 and k_3 were determined based on the results and the behavior of the unconfined and confined concrete columns subjected to cyclic loading by defining one unknown and finding the second unknown using the logarithm functions . For k_2 = 1.5, respectively k_3 = 1.30. The design oriented expression to predict the strength of the confined concrete can be written in the following form

$$\frac{f_{cc}}{f_{co}} = 1 + 1.5\left(\frac{\sigma_{l,eff}}{f_{co}}\right)^{1.30} . \quad (9)$$

Various models for confinement of concrete with FRP have been developed. The majority of these models were performed on plain concrete specimens' tests. Most of the existing strength models for FRP confined concrete adopted the concept of Richart et al. (1929), in which the strength at failure for concrete confined by hydrostatic fluid pressure. In addition, limited models have been conducted on confined concrete subjected to high cycle loading.

To validate the proposed model, the compressive strength of FRP confined columns of various models proposed by other authors was compared with the compressive strength of the proposed model. The compressive strength of columns type C2 and C3 was adopted and the fatigue compressive strength of concrete was computed according to EN 1992-1-1. The lateral confining pressure provided by 6 layers of CFRP wraps was evaluated. A comparison of strengthening ratio versus confinement ratio of various proposed models is presented in *Figure 12***Chyba! Nenalezen zdroj odkazů.**. The confinement lateral pressure was calculated for confined concrete column with CFRP wraps by 1x till 6x layers.

Table 6 – C*omparison of the strengthening ratio of various proposed models*

	Lam & Teng (2003)	**Cusson & Paultre (1995)**	**Richart et al. (1928)**	**Mander et al. (1988)**	**Eurocode 2 (1992)**	**Mansour (2018)**
Confinement ratio	**Strengthening ratio**					
$\sigma_l/f_{co,fat}$	$f_{cc,fat}/f_{co,fat}$	$f_{cc,fat}/f_{co,fat}$	$f_{cc,fat}/f_{co,fat}$	$f_{cc,fat}/f_{co,fat}$	$f_{cc,fat}/f_{co,fat}$	$f_{cc,fat}/f_{co,fat}$
0,08	1,28	1,37	1,34	1,49	1,42	1,54
0,17	1,55	1,60	1,69	1,85	1,54	1,60
0,25	1,83	1,80	2,03	2,15	1,75	1,67
0,34	2,11	1,98	2,38	2,39	1,96	1,74
0,42	2,38	2,14	2,72	2,60	2,17	1,82
0,50	2,66	2,30	3,06	2,78	2,38	1,91

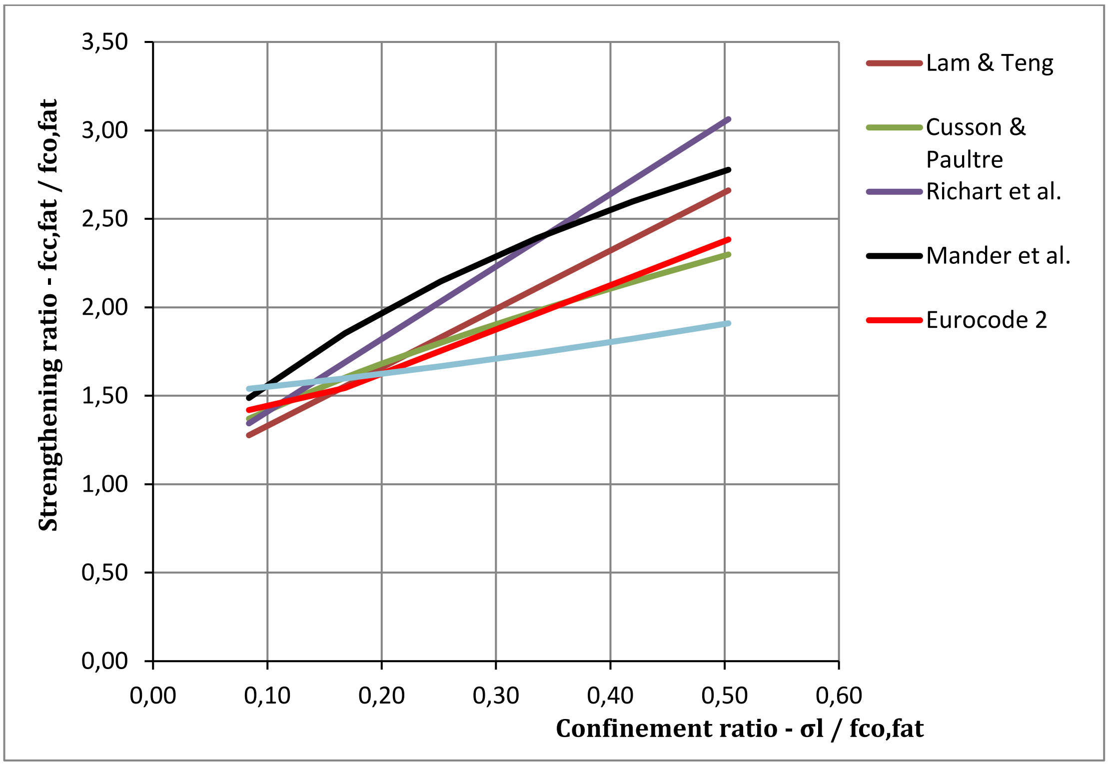
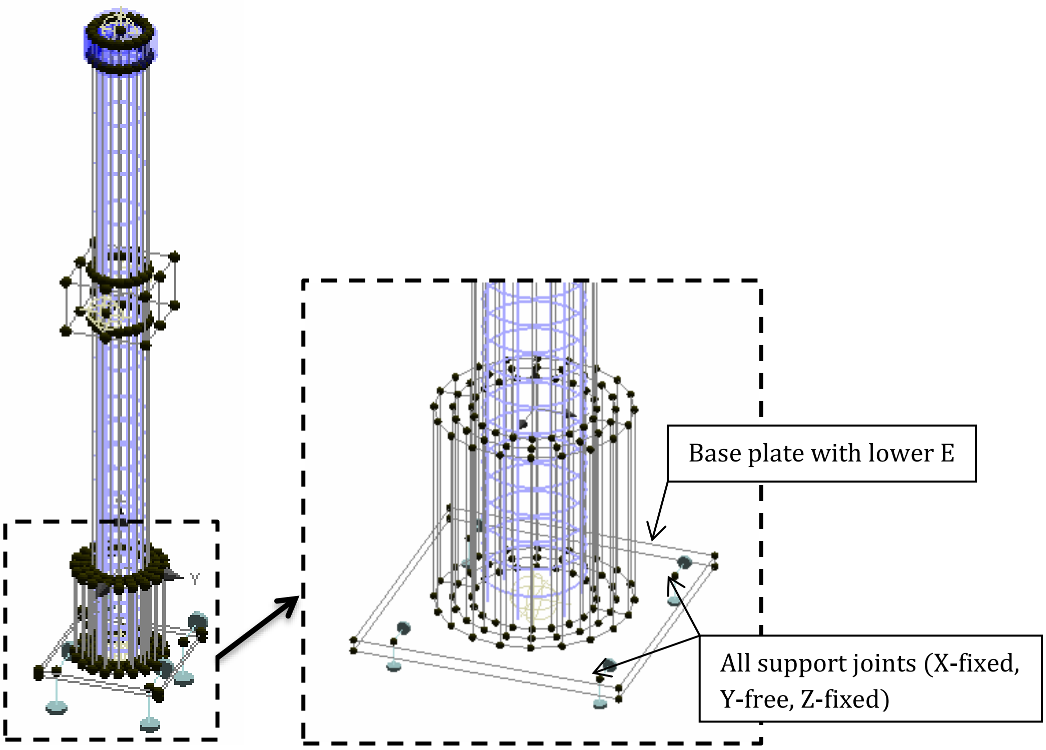


***Figure 12** – Strengthening ratio vs Confinement ratio comparison of various proposed models*

6. NUMERICAL ANALYSIS

Parallel to the experimental investigations, finite element method was used to understand and to simulate the behaviour of circular reinforced concrete columns under monotonic and quasi-static cyclic loading. The numerical analysis was conducted by ATENA 3D software. The model was developed from 3D macro-elements and reflects the actual geometry of the column, its material composition and boundary conditions. The concrete was modelled as quasi-brittle material, which considers the formation and development of cracks; it was defined as 3D nonlinear Cementitious. The longitudinal and transverse reinforcements were modelling as elastic-plastic material. Two load cases are defined, supporting and loading. First contains the supports; the support at the bottom end is provided as fixed end support to prevent movement in three directions, and the top end is free. Second contains the axial compressive force at the top end in Z (-) direction and lateral cyclic load in X direction. The loading history consists of load steps. Each load step is defined as a combination of load cases as defined previously (supporting and loading).

Each load step contains also a definition of solution parameters, which define solution methods that are to be used during the load steps; in our case Newton-Raphson, method was considered. Monitoring is useful during nonlinear analysis, to monitor forces, deformations or stresses in the model. Four monitoring points are placed on each column at the ends of column to monitor deformation and applied forces and to be able to define the load curve.



Base plate with lower E

All support joints (X-fixed, Y-free, Z-fixed)

Figure 13 - *Boundary Conditions*

7. COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

The following figures illustrate the comparison between the experimental and numerical results provided by ATENA.

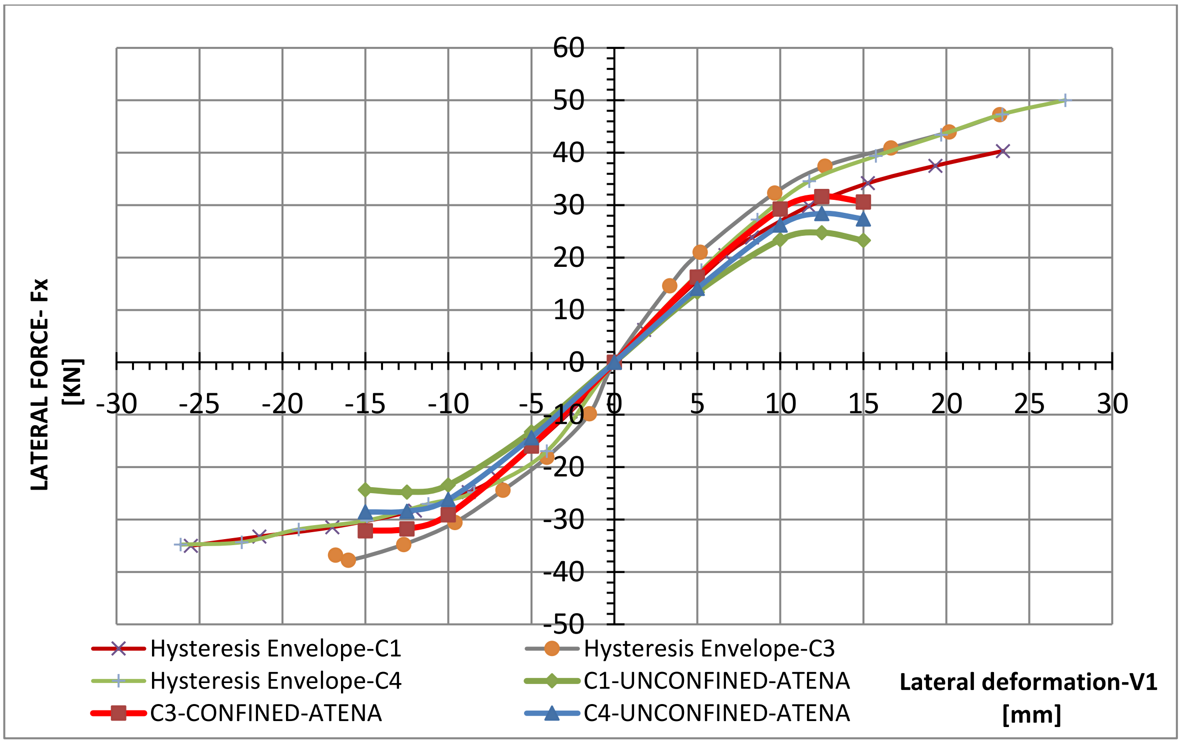


Figure 14 - *Envelope line - Experimental vs. Atena*

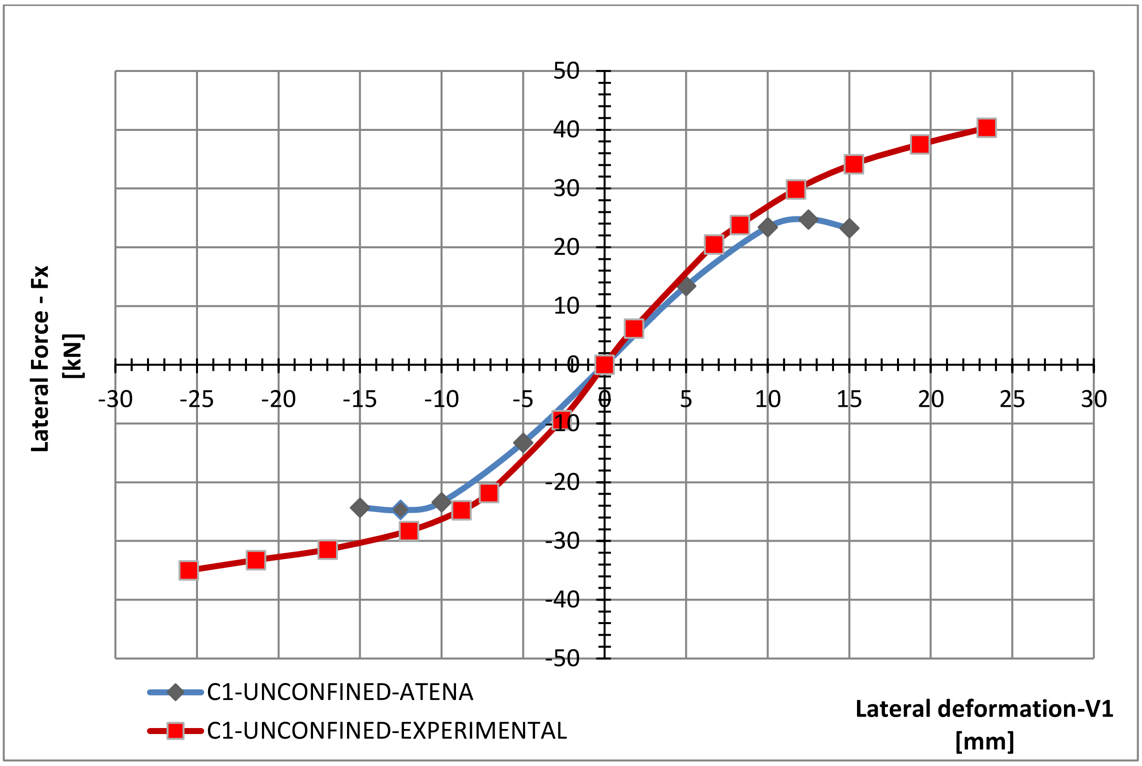


Figure 15 *- Envelope line for Columns C1 - Experimental vs. Atena*

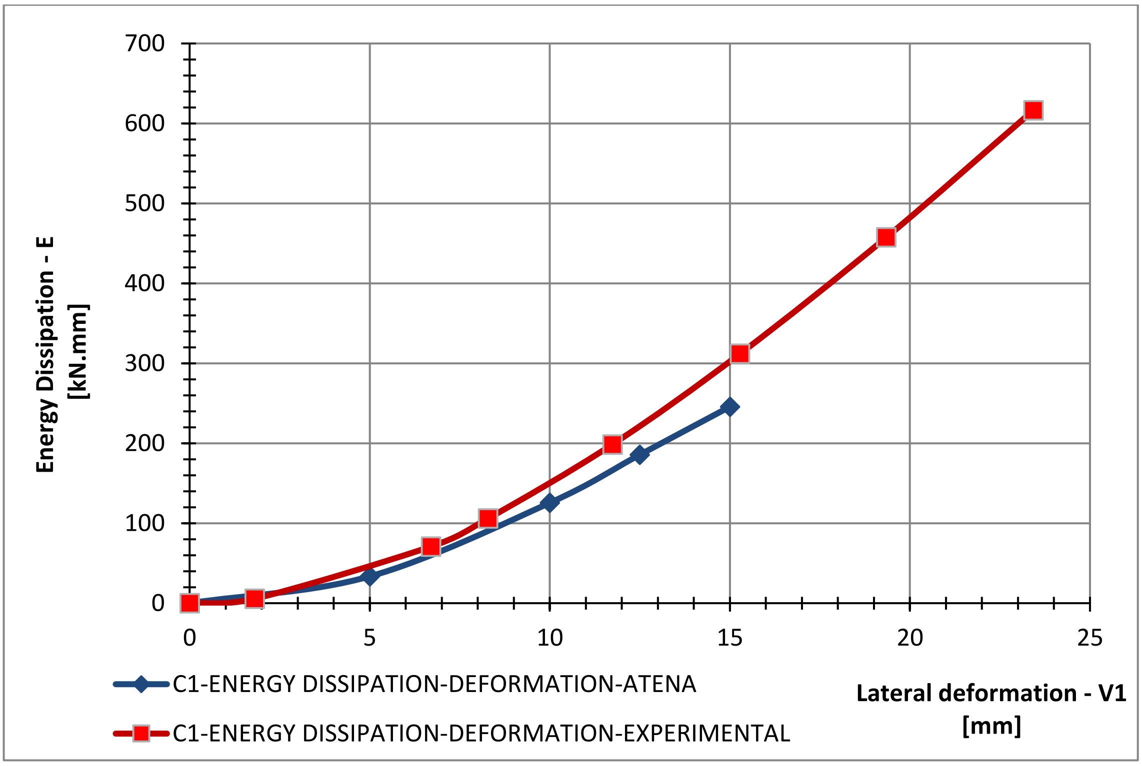


Figure 16 *- Energy dissipation - deformation for Columns C1- Experimental vs. Atena*

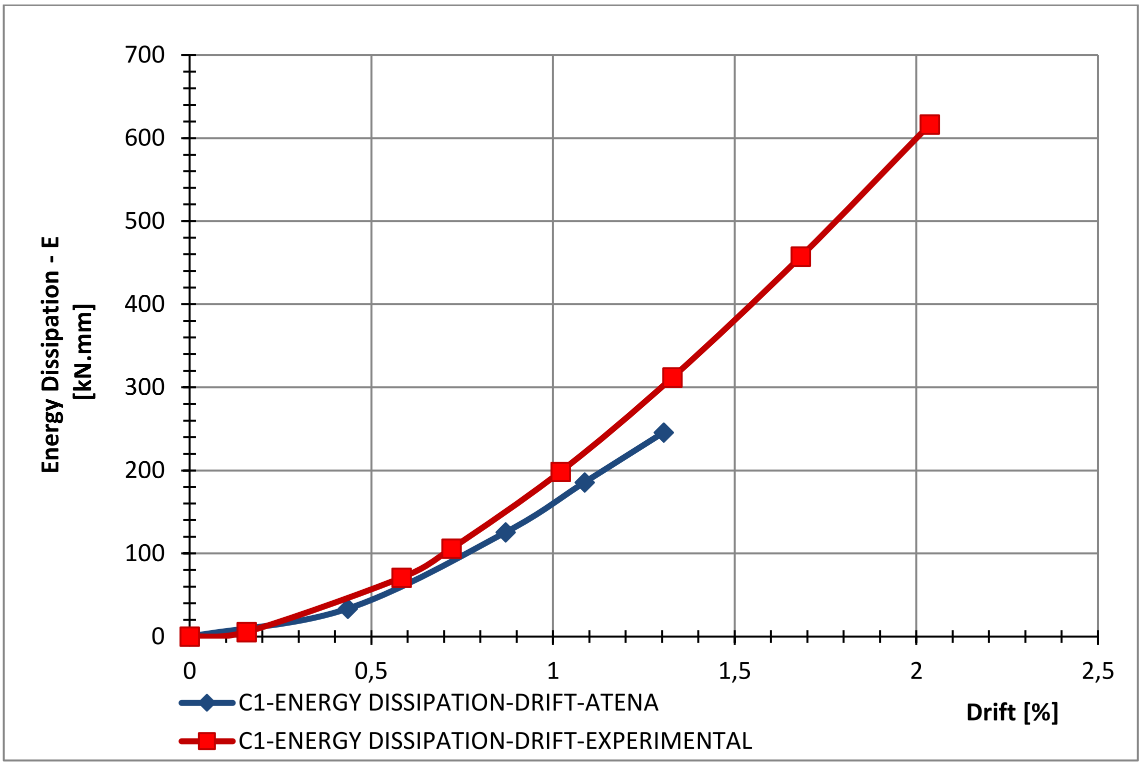


Figure 17 *- Energy dissipation - drift for Columns C1- Experimental vs. Atena*

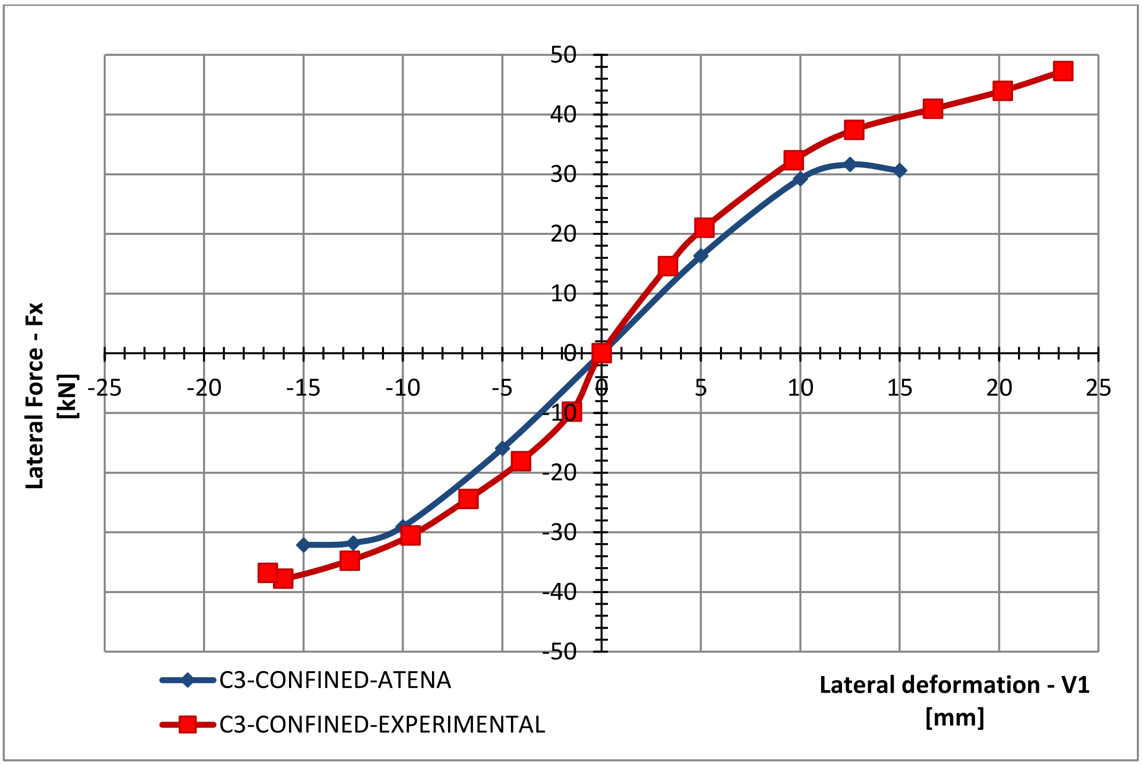


Figure 18 *- Envelope line for Columns C3 - Experimental vs. Atena*

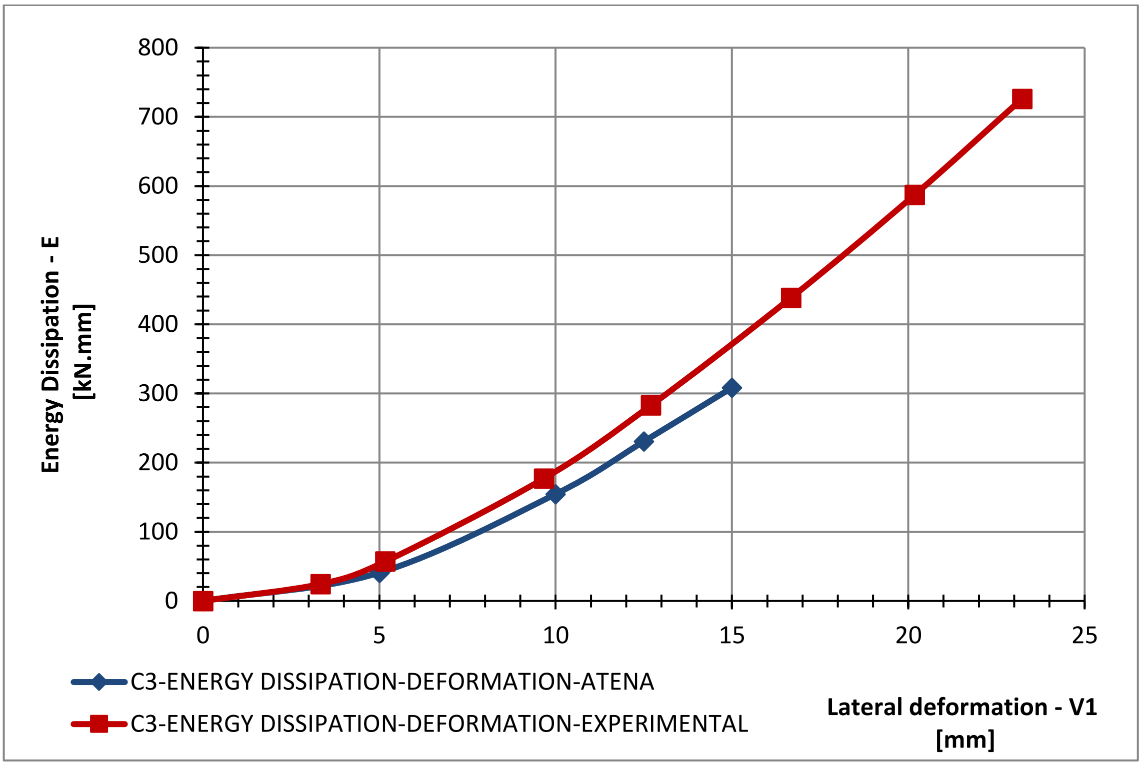


Figure 19 *- Energy dissipation - deformation for Columns C3- Experimental vs. Atena*

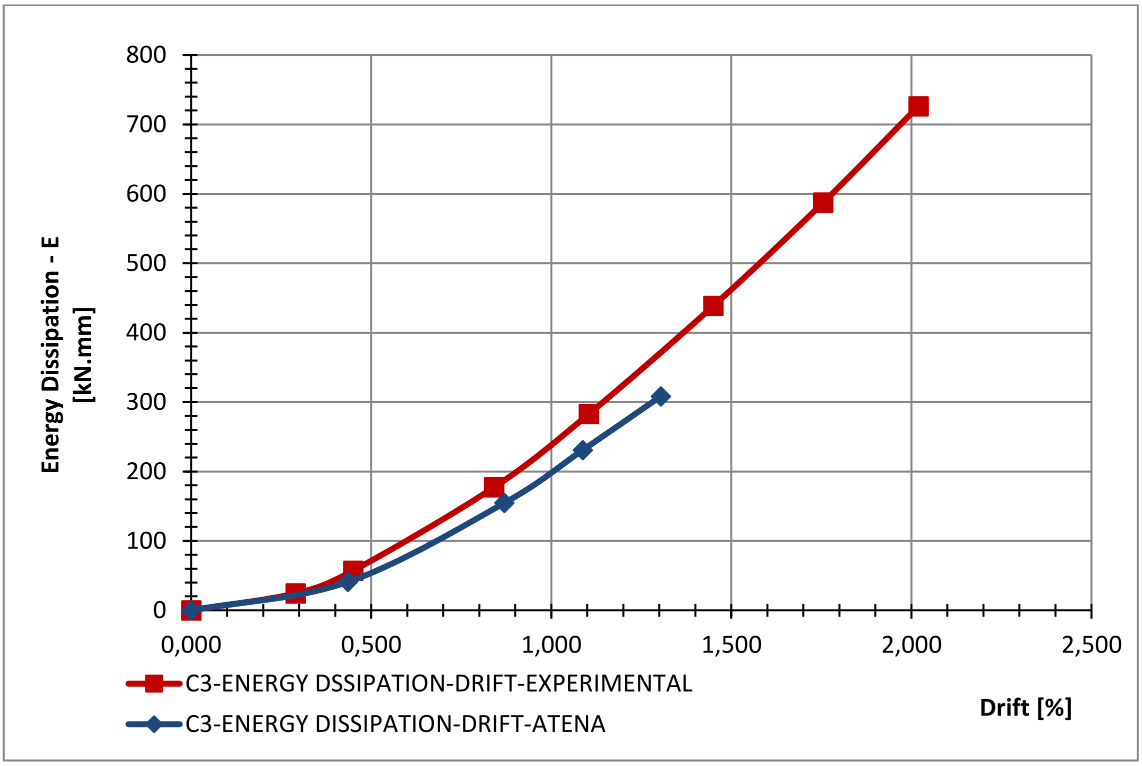


Figure 20 *- Energy dissipation - drift for Columns C3- Experimental vs. Atena*

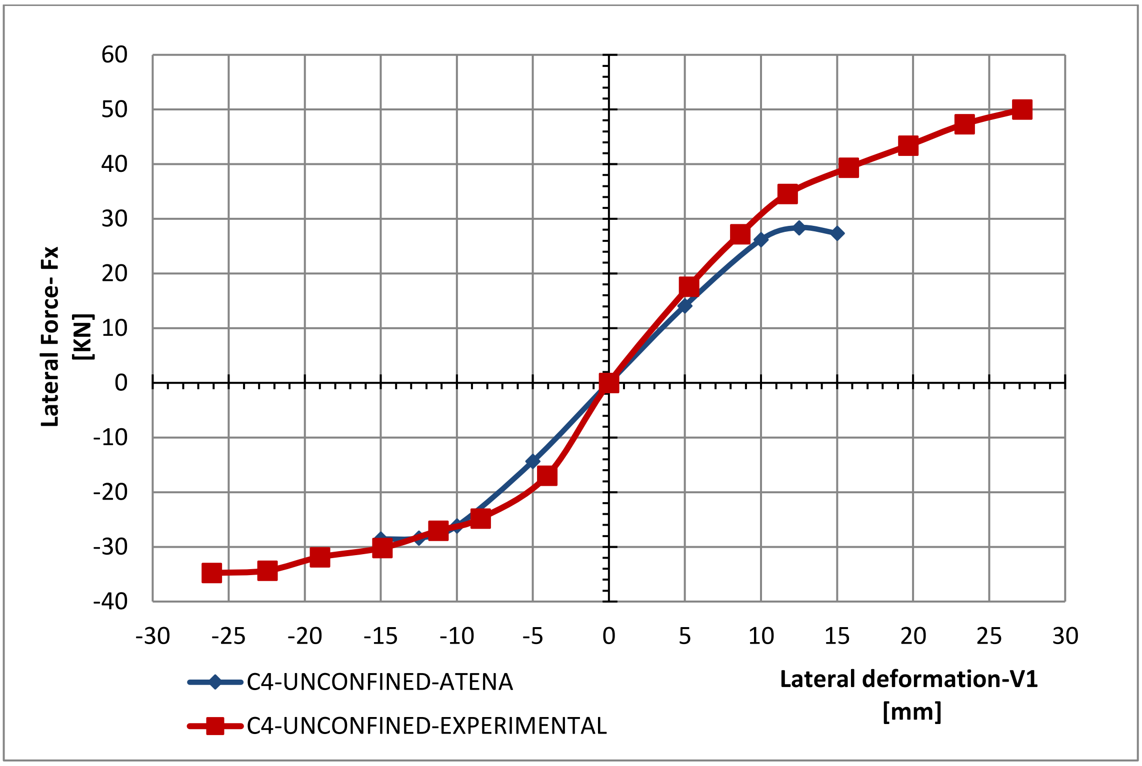


Figure 21 *- Envelope line for Columns C4 - Experimental vs. Atena*

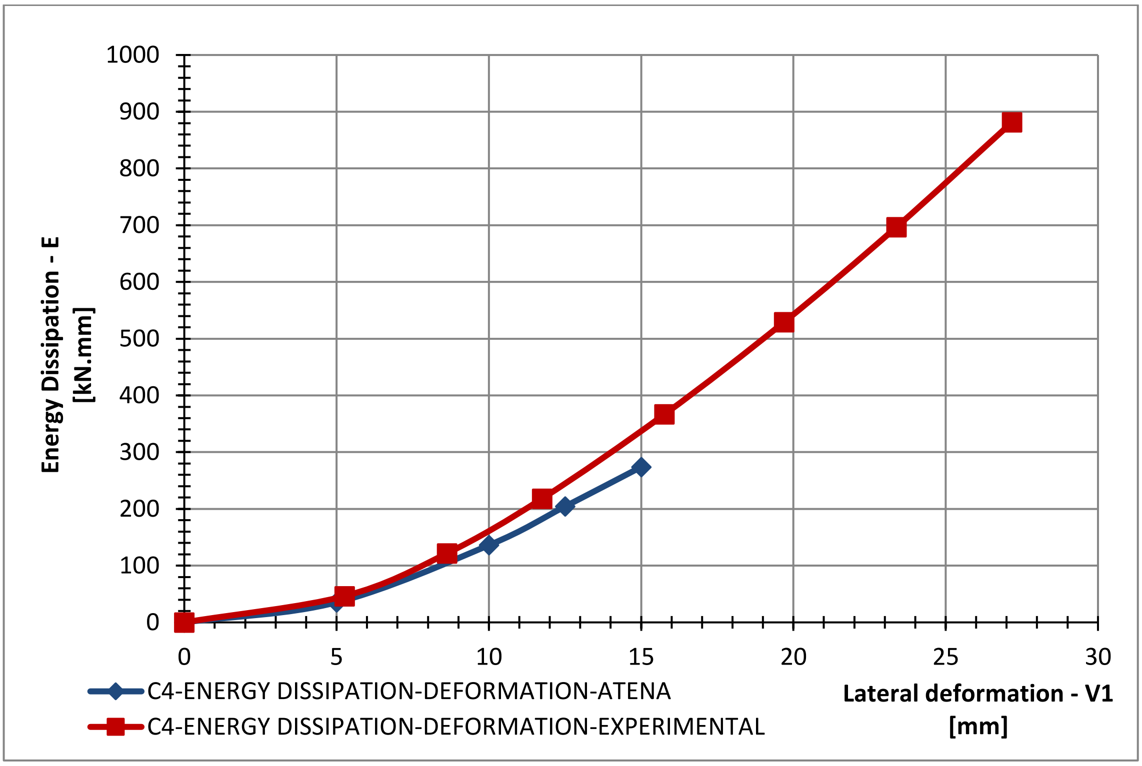


Figure 22 *– Energy dissipation- deformation for Columns C4 - Experimental vs. Atena*

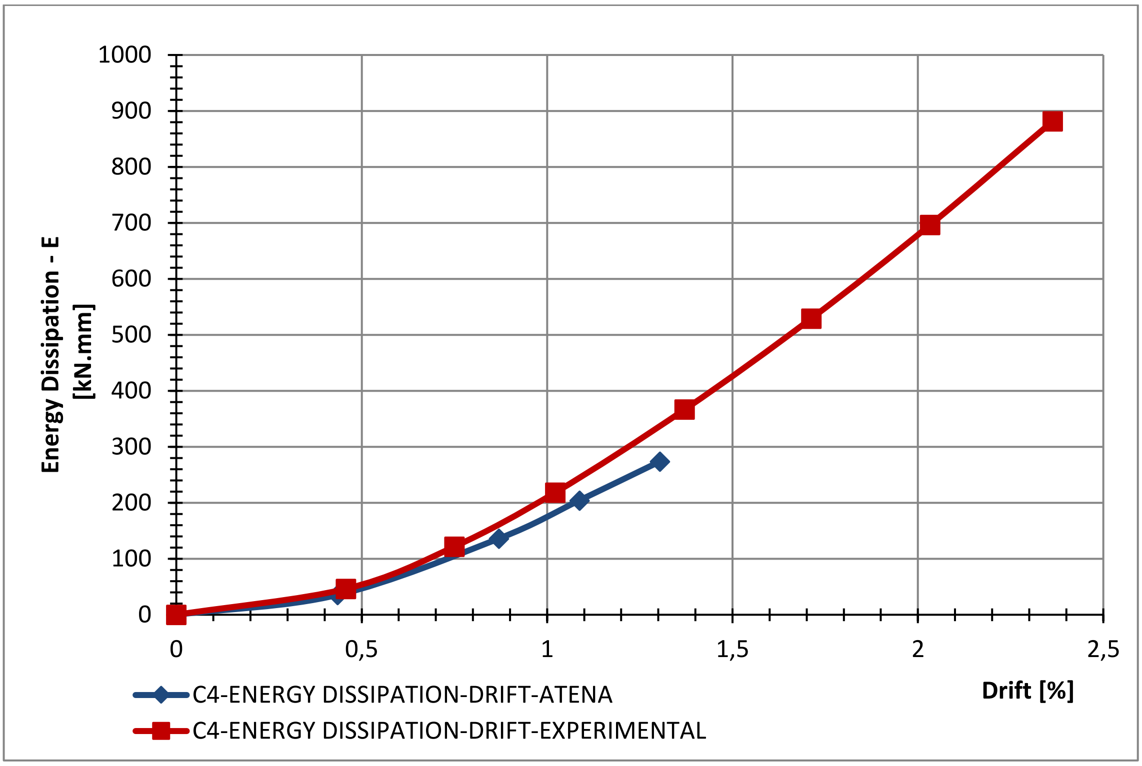


Figure 23 *- Energy dissipation - drift for Columns C4- Experimental vs. Atena*

As shown in the envelope line diagram obtained from the experimental and numerical results, the behaviour of the unconfined column type C1 and C4, and confined column type C3 subjected to constant axial force, lateral cyclic force is similar, and the energy dissipation versus lateral deformation and drift are coincident. During the experiment, the columns continued to deform until stopping the test. In the numerical simulation, the columns stopped deformation while large cracks appeared at the bottom zone of the column. The ultimate lateral forces in the push and pull directions are not matching as shown in *Figure 9* and *Figure 14* of the experimental results. The asymmetrical of the curve in the positive (push direction) and negative zone (pull direction) was probably caused by unsymmetrical damage of the columns during the test in push and pull directions and due to the effect of inhomogeneity of concrete. Additionally, the reason of the symmetrical envelope line in the numerical simulation and not in the experiment is the loose fitting of the connection between the stroke of the electrical hydraulic actuator and the concrete columns which it was not faced in the numerical simulation.

8. SUMMARY AND CONCLUSION OF THE INVESTIGATION

The dissertation work is dealing with the behaviour of unconfined and confined circular concrete columns subjected to axial static load and lateral cyclic load (high and low-cyclic loadings). Based on the overall results, FRP wraps provide additional strength capacity, which reduces the risk of a brittle failure, and increases the strain capacity of concrete in compression, leading to enhancing the member ductility. The majority of standards and codes provide numerical equations to predict the confinement lateral pressure contributed by wrapping. These standards do not consider the degradation of concrete compressive strength due to preloading and especially cyclic load (high cyclic loading). Thereby, the degradation of the concrete compressive strength of the existing structures has to be considered due to the material fatigue by finding out the actual concrete compressive strength of the existing structures and by verifying the results with the theoretical value predicted by the codes and standards.

Conclusions of the dissertation work

The aim of this work was to predict the enhancement of the FRP wraps on the behaviour of the circular concrete columns subjected to lateral cyclic loading (predicting of design-oriented model) and to introduce the strengthening procedure of a circular column by FRP wraps.

Based on the experimental results and research of the theoretical study, the following outlines were obtained:

- The enhancement contributed by FRP jackets on the section analysis of circular reinforced concrete columns by using the interaction diagrams was verified, and the ultimate compressive strength and bending moment enhancement of a concrete section depends on the number of FRP layers provided.
- The ductility enhancement of unconfined and confined columns, moment-curvature analysis of test specimens conducted by software SAP2000 was evaluated and it shows that the ductility performance of the unconfined columns can be improved by the confinement of concrete conducted by FRP wraps and spiral reinforcement.
- The plastic hinge length is a significant factor between the displacement, rotation, and curvature ductility factors of the cantilever column.
- The use of FRP jackets for the ductility and load capacity enhancement in unconfined reinforced concrete columns subjected to axial load and lateral cyclic loading was verified experimentally, based on the comparison between unconfined specimen C1 and confined specimens C2 and C3.
- There is a difference in the behaviour of reinforced concrete columns subjected to low and high-cycle fatigue loadings. The unconfined column C1 subjected to high-cycle loading (approximately 1 million cycles) before exposing to low-cycle loading can dissipate lower energy than the column C4 exposed to low-cycle loading only due to the fatigue of materials. Additionally, providing FRP wraps to columns exposed to high-cycle loading improve their energy dissipation and ductility as shown in the comparison between unconfined column C1 and confined columns C2 and C3.
- During high-cycle loading (in the experiment, a lateral force of a minimum of 2.0 kN and a maximum of 8.0 kN was selected) of 1 million cycles, specimens C1, C2, and C3 do not display any sign of failure. The performing of a fatigue life assessment of the column based on a pattern of progressively increasing displacements, few cycles are enough for the strength degradation and failure of the specimens.
- Prediction of a new empirical model for FRP confined concrete circular column subjected to axial static loading and lateral cyclic loadings (high and low- cyclic loading) is presented.
- The mathematical model based on FEM conducted by ATENA 3D software, which simulates the behaviour of unconfined and confined reinforced concrete columns subjected to axial static load and reversed cycle lateral load was evaluated by the line envelope and

energy dissipation versus lateral displacement and compared to the experimental results, which provide a good agreement with the experimental results.

- The strength degradation due to the high-cycle loading (comparison between unconfined specimens C1 and C4) should be taken into consideration while the strengthening of existing concrete column is carried out.
- The energy dissipation of the test specimens increased with providing the FRP wraps. The energy dissipation of the FRP confined columns is between 17% and 28% larger than the unconfined column subjected to high and cycle loadings, and 13% larger for the unconfined column subjected to low-cycle loading only.
- The required amount of transverse confinement of columns should be provided to achieve certain level of ductility and strength of concrete columns.
- The displacement ductility capacity of the concrete columns was significantly improved by the contribution of the FRP wraps at the plastic hinge location of the columns, and the ductility was controlled by the strength of the FRP wraps.

9. FUTURE RESEARCH AND RECOMMENDATIONS

Due to complexity of operation to perform such tests under realistic loads in large quantities especially on large-scale concrete columns, the available investigations and researches are still limited. Therefore, it is recommended to enlarge researches and investigations and to describe relevant parameters to seismic behaviour of concrete columns. Based on the experimental results and complication faced during the testing, hereby the following recommendations:

1. To have statistically significant results, a larger number of columns with the same configuration to be tested and to be able to quantify the shear strength degradation of the concrete columns subjected to cyclic loading.
2. The selection of the geometry and the size of the specimens to be based on the available equipment in the laboratory.
3. To study larger number of parameters in the experimental study affecting the columns subjected to cyclic loading such as frequency, number of layers of the FRP, the magnitude of the lateral force, the number of cycles and the fatigue of FRP wraps.

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