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BEHAVIOR OF FULLY ENCASED STEEL-CONCRETE COMPOSITE COLUMNS SUBJECTED TO MONOTONIC AND CYCLIC LOADING

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The paper presents a numerical model developed for fully encased steel-concrete composite columns under monotonic and cyclic loading. The numerical model was realized with the FineLg program, developed at ArGenCo department, University of Liège. The numerical model was validated using five experimental tests taken from the international literature: two realised at Technical University of Cluj-Napoca and the others in Taiwan, USA and China. The experimental tests used for validation of the numerical model dealt with both normal and high strength concrete. Different parameters were compared in the paper: partial and full ductility, energy dissipation, resistance and rigidity ratio.
Key words: Fully encased composite columns, Numerical model

INTRODUCTION

Aside the experimental research on fully encased steel-concrete composite columns, another very important side is the analytical research, the mathematical modeling of the member behavior, under monotonic and cyclic loading. Computer simulation of the behavior of elements is a much cheaper, rapid and efficient method of research, but it cannot exclude and reduce the importance of experimental research. The calibration of proposed numerical model was based on five experimental programs taken from the international literature.

EXPERIMENTAL PROGRAMS USED FOR VALIDATION OF THE NUMERICAL MODEL

The first two experimental programs used for validation were developed in the Structures Department, at Faculty of Civil Engineering, Technical University of Cluj-Napoca, Romania, year 2000 and 2011.The third program was developed at National Central University in Taiwan, year 2008. The forth experimental research was developed at California University in San Diego, USA in 1992 and the fifth at Chiao Tung University, Hsinchu, China, in 2008. The first four experimental programs used I type steel profiles and the last used cross steel profiles fully embedded in concrete. All columns were subjected to compressive axial loading and bending moment (induced by horizontal lateral forces), except the fourth program where the columns were additionally subjected to shear too. The mechanical model and test up procedure for all experimental programs are presented in Figure 1.

EXPERIMENTAL PROGRAM DEVELOPED AT UTC-N, ROMANIA, 2000

The experimental program realized by Cristina Campian, 2000, at Technical University of Cluj-Napoca, Romania, included 12 tests (3 mono-

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tonic and 9 cyclic) on fully encased steel-concrete composite columns. All columns had the same cross-section and were grouped according to their length. The elements were made with a Romanian steel section I12 (which is quasi similar to IPE 120 section) fully covered with reinforced concrete including 4 ф 10 longitudinal bars as shown in Figure 2. In Table 1 are presented some characteristics of the tested specimens.

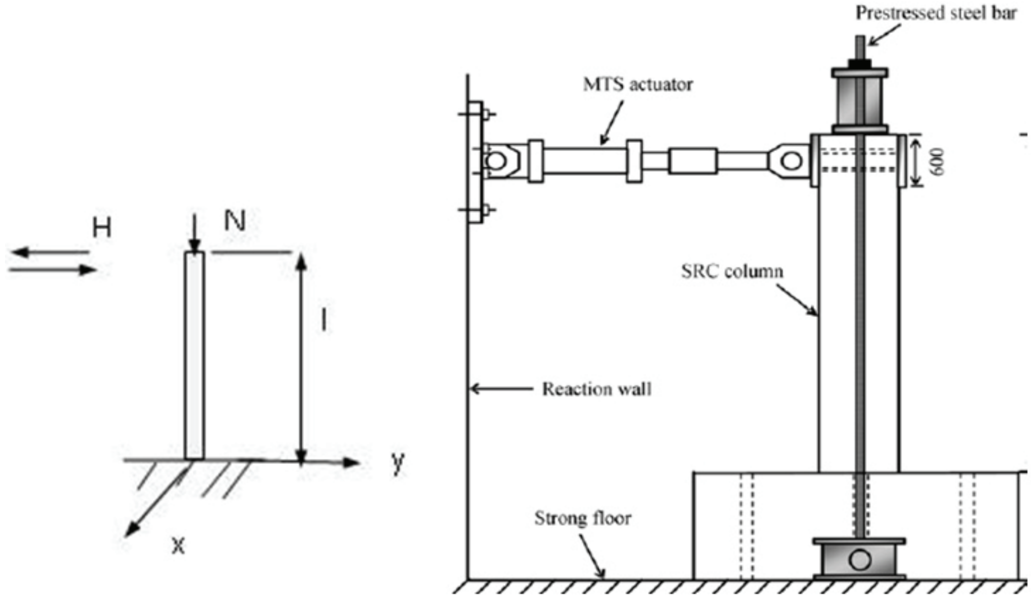


Figure 1: Mechanical model and test up procedure for experimentally tested columns

Figure 2: Cross-section of the tested specimens and failure mode

Table 1: Characteristics of tested specimens

Column type	Length [m]	Compressive concrete strength [N/mm²]	Concrete Young modulus [N/mm²]	Yield strength of longitudinal reinforcement [N/mm²]	Longitudinal reinforcement Young modulus [N/mm²]	Yield strength of embedded profile [N/mm²]	Embedded profile Young modulus [N/mm]
SI	2.00	30.5	-				
SII	2.50	27.0	-	559	207000	302	207000
SIII	3.00	29.5	37373.33				

The failure of all tested columns was governed by the plastic hinge formation at column base (see Figure 2)

EXPERIMENTAL PROGRAM DEVELOPED AT UTC-N, ROMANIA, 2011

The two types of composite columns tested by Vlăduț Sav, 2011, were similar to the ones tested at Technical University of Cluj-Napoca in 2000. The main difference between the experimental programs was the type of concrete used. The author of the experimental program use high strength concrete, class C70/85. The tested columns had 2 different lengths: 3.00 m (columns S1, S2, S3 and S4) and 2.00 m (columns S5, S6, S7 and S8). The cross-section of the composite column was the same for all tested specimens, of 170x220 mm (see figure 3), with an IPN120 embedded profile and 4 Ø10 bars as longitudinal reinforcement.

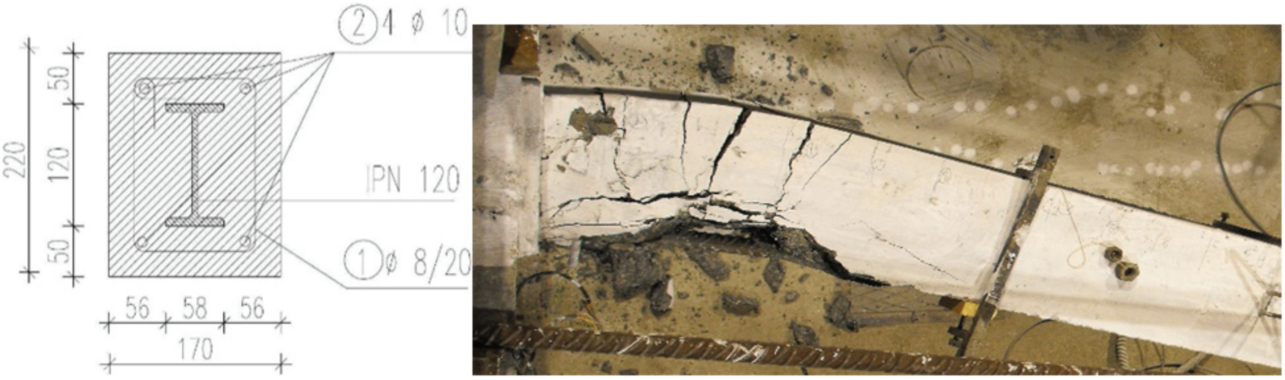


Figure 3: Cross-section of the tested specimens and failure mode

In Table 2 are presented a few characteristics of the tested specimens. The author performed first monotonic tests on both type of columns and after, three cyclic tests for each type of column.

Table 2. Characteristics of tested specimens

Compressive concrete strength [N/mm^2]	Concrete Young modulus [N/mm^2]	Yield strength of steel [N/mm^2]
92,3	43634,65	380.20

The failure mode was similar for all tested specimens. In comparison with the columns made with normal concrete and presented at 2.1, the failure of the columns made with high strength concrete was violent and brittle.

EXPERIMENTAL PROGRAM DEVELOPED AT NCU, CHUNG-LI, TAIWAN, 2008

The experimental study made by H. L. Hsu, F. J. Jan and J. L. Juang, 2008, was developed at the Department of Civil Engineering, National Central University, Chung-Li, Taiwan. All tested columns had the same cross-section, 370 mm x 370 mm (see Figure 4), with six different embedded profiles (Table 3). The type of loading and direction are presented also in Table 3.

Identical reinforcement were used in all specimens, 4Φ20 as longitudinal reinforcement and Φ 9.525 stirrups. The stirrup spacing was 100 mm within the confined zones and 150 mm in the non-confined zones. Yield strength for the structural steel, longitudinal bars and stirrups were 314 MPa, 543 MPa and 586 MPa respectively. The concrete compressive strength, determined from cylinder tests was 38 MPa.

The member performances were governed by plastic hinge formation, as shown in Figure 4.

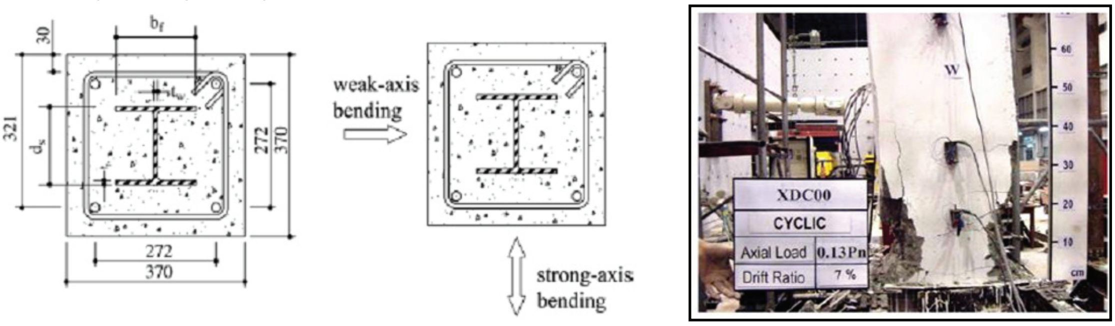


Figure 4: Cross-section of the tested specimens and failure mode

Table 3: Characteristics of tested specimens

Column type	Embedded profile	Loading direction	Loading type
YAM	H100x100x6x8		
YBM	H150x100x6x9		
YDM	H200x100x5.5x8		
YCM	H150x150x7x10		
YEM	H200x150x6x9		
YFM	H200x200x8x12	Weak-axis bending	monotonic
XAC00	H100x100x6x8		
XBC00	H150x100x6x9		
XDC00	H200x100x5.5x8		
XCC00	H150x150x7x10		
XEC00	H200x150x6x9	Axial loading + strong-axis bending	
XFC00	H200x200x8x12		cyclic

EXPERIMENTAL PROGRAM DEVELOPED AT UC, SAN DIEGO, CALIFORNIA, SUA, 1992

The experimental program realized by James M. Ricles and Shannon Paboojian, 1992, was performed on fully encased steel-concrete composite columns, subjected to compressive axial load, bending moment and shear. The tests were developed at California University in San Diego, USA. The composite columns analyzed consisted of a W8x40 steel profile encased in a 406x406 mm reinforced concrete section. The two chosen sections used for validation of the numerical model had the same length, the same embedded profile and the same longitudinal and transversal reinforcement, but different concrete class.

Table 4: Characteristics of tested specimens

Specimen no.	db [mm]	s [mm]	Length [mm]	Concrete compressive strength [N/mm^2]	Yield strength steel profile [N/mm^2]	Yield strength reinforcement [N/mm2]
3	22.2	95.3	1930	30.9	373	479.2
7	22.2	95.3	1930	62.9		

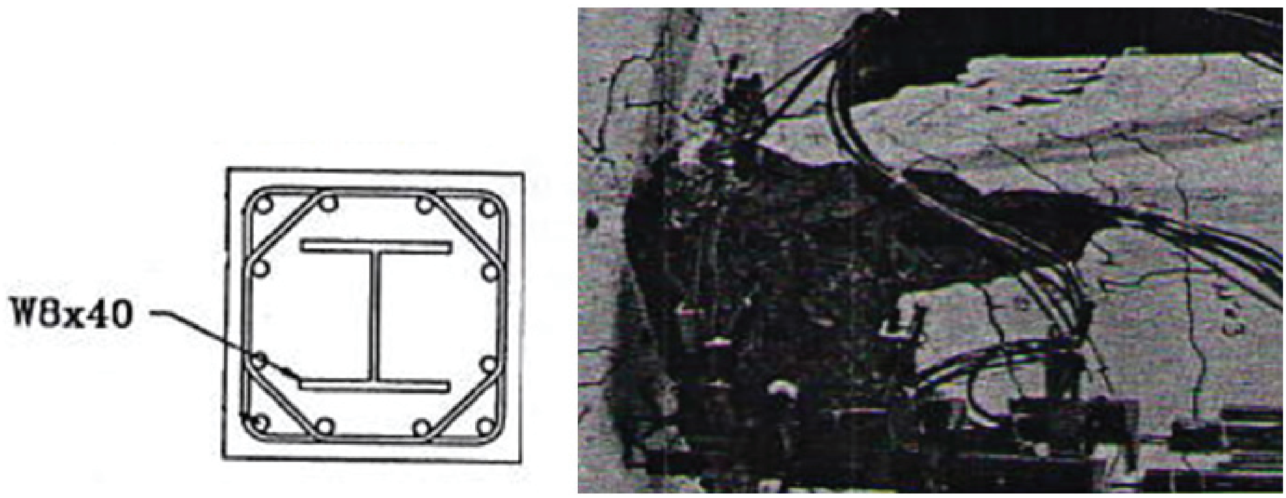


Figure 5: Cross-section of the tested specimens and failure mode

Specimen 3 was made with normal concrete and specimen 7 with high strength con-cre¬te (the compressive resistance is larger than 60 MPa). The cross-section of the tested co-lumns is presented in figure 5 and some characteristics regarding the specimens in Table 4.

The authors of the experimental tests performed only cyclic tests on the studied specimens. The failure of the tested specimens was similar to the other experimental studies presented (see Figure 5).

EXPERIMENTAL PROGRAM DEVELOPED AT CTU, HSINCHU, CHINA, 2008

The experimental program developed by Weng ChengChiang, Yin YenLiang, Wang JuiChen and Liang ChingYu, 2008, aimed the use of a multi-spiral cage of five interconnected spirals, named "5-spirals" as transversal reinforcement for rectangular columns. The tests were performed at the Department of Civil Engineering from Chiao Tung University, Hsinchu, China. All tested columns had the same cross-section, of 600 mm x 600 mm and the same height of 3250 mm. The columns had a cross steel profile 2H350x175x6x9 fully embedded in concrete (see Figure 6). The longitudinal reinforcement was the same, 16 Ø 25+4 Ø 13. The diameter of the perimetral spiral was Ø 13 and for the four corner spirals Ø 10. The distances between the spirals were different, 95 mm for C-SRC1 column and 115 mm for the C-SRC2 column. The resistance of the materials were determined experimentally and are presented in Table 5.

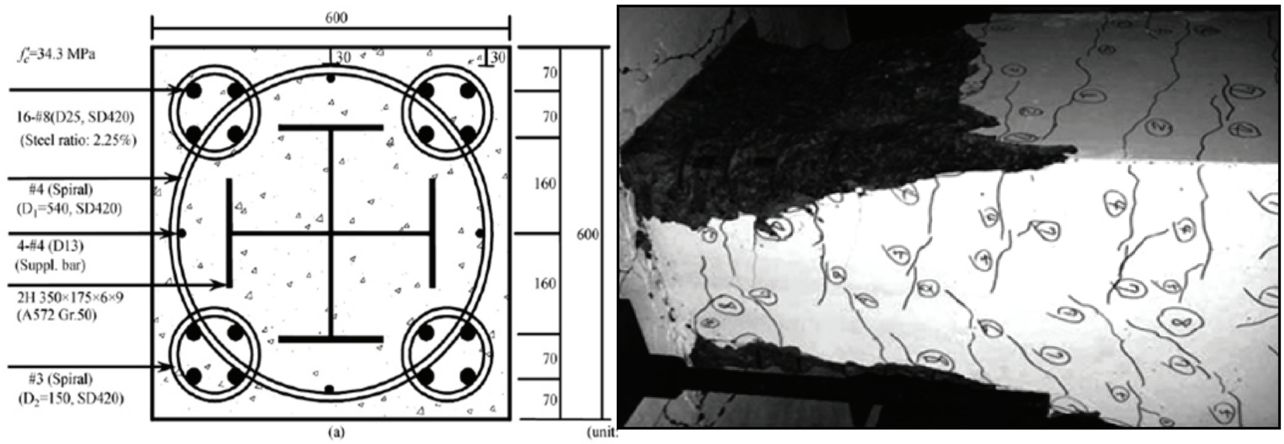


Figure 6: Cross-section of the tested specimens and failure mode

Table 5: Characteristics of tested specimens

Concrete compressive strength [N/mm²]	Yield strength steel profile [N/mm²]	Yield strength reinforcement [N/mm²]
37.3	435.3	437

The tests ended when the drift angle of the composite column reached 6.0% radians. The concrete cover near the column base was tangibly flaked off, but the concrete confined by the 5-spirals remain intact, the longitudinal reinforcement did not buckle, nor did the spirals break, as shown in figure 6.

NUMERICAL MODEL FOR STEEL-CONCRETE COMPOSITE COLUMNS

Calibration and material laws

The numerical model was developed in FineLg, a finite element program developed at ArGenCo department, University of Liège, Belgium. The proposed numerical model was calibrated against the five test results presented previously. The columns were considered as plane bars with 3 nodes (see figure 7). Node 1 and 3 has three degrees of freedom (m, u, q). Node 2 has only one degree of freedom, which permits taken into account an eventual displacement between steel and concrete. In the analysis is considered a perfect connection between steel and concrete. The model uses multi-fibers beam elements with mono-axial nonlinear material laws for concrete, embedded steel and reinforcement steel (see figure 9). Because the validation of the numerical model was performed using experimental data, for the resistance of materials the safety coefficients were considered equal to 1.

The steel elements (embedded profile and longitudinal reinforcement) are defined using a bilinear law, presented in Figure 8a. The local and general bucking effects are not considered in the model. The buckling of the longitudinal reinforcement is prevented by the transversal confining reinforcement. A parabolic-rectangle law is used for concrete in compression (see figure 8c). The law takes into account the tension resistance of the concrete, which is evaluated with the SR EN 1992-1-1 formula.

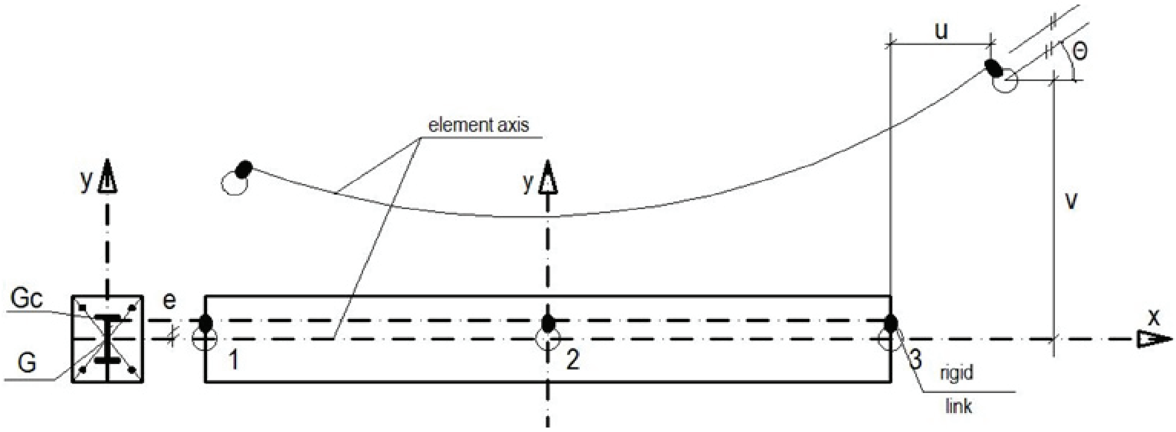


Figure 7: Finite element

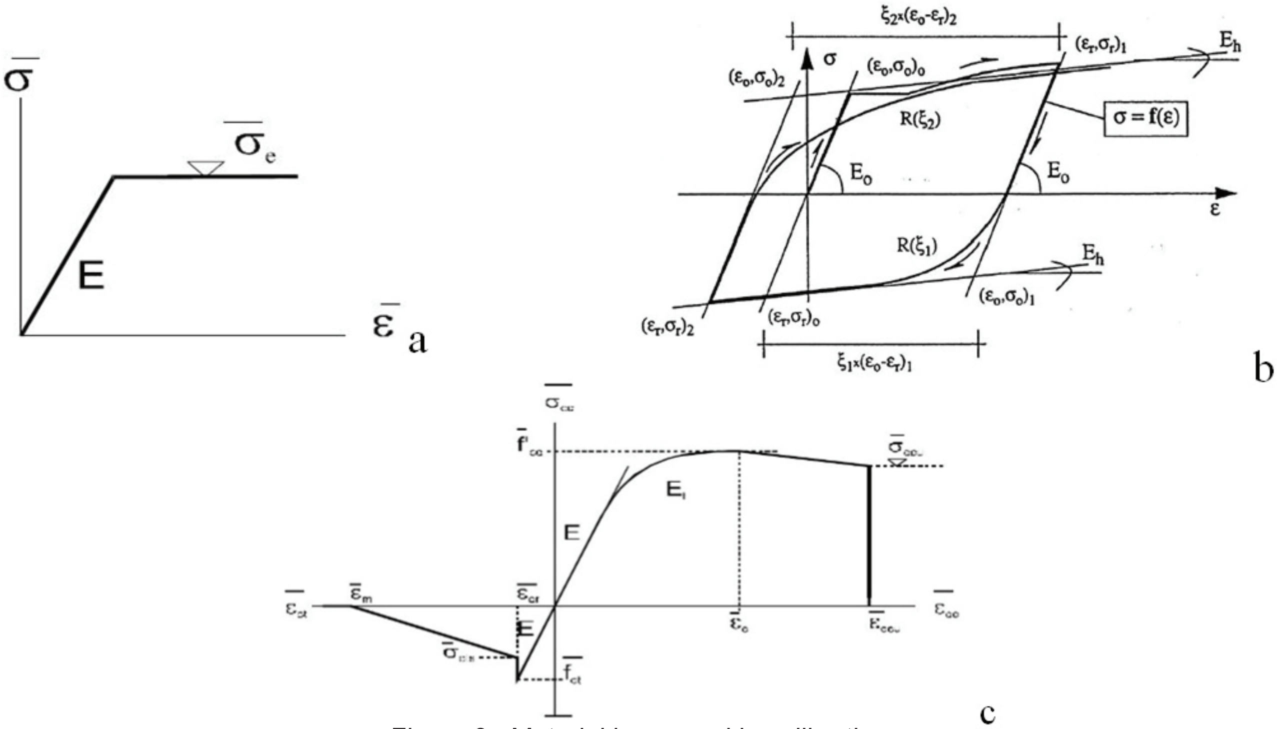


Figure 8: Material laws used in calibration

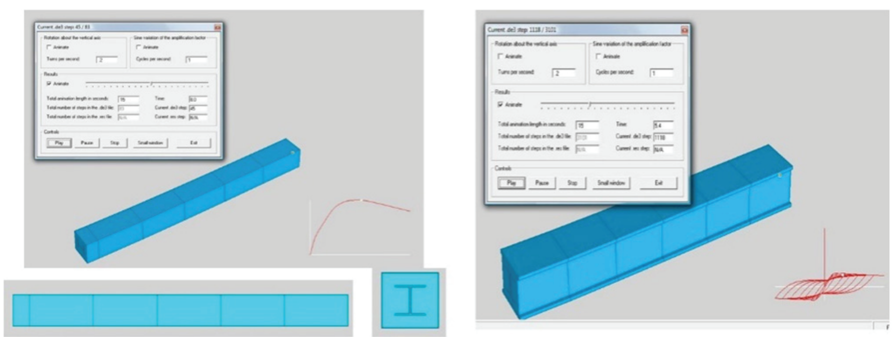
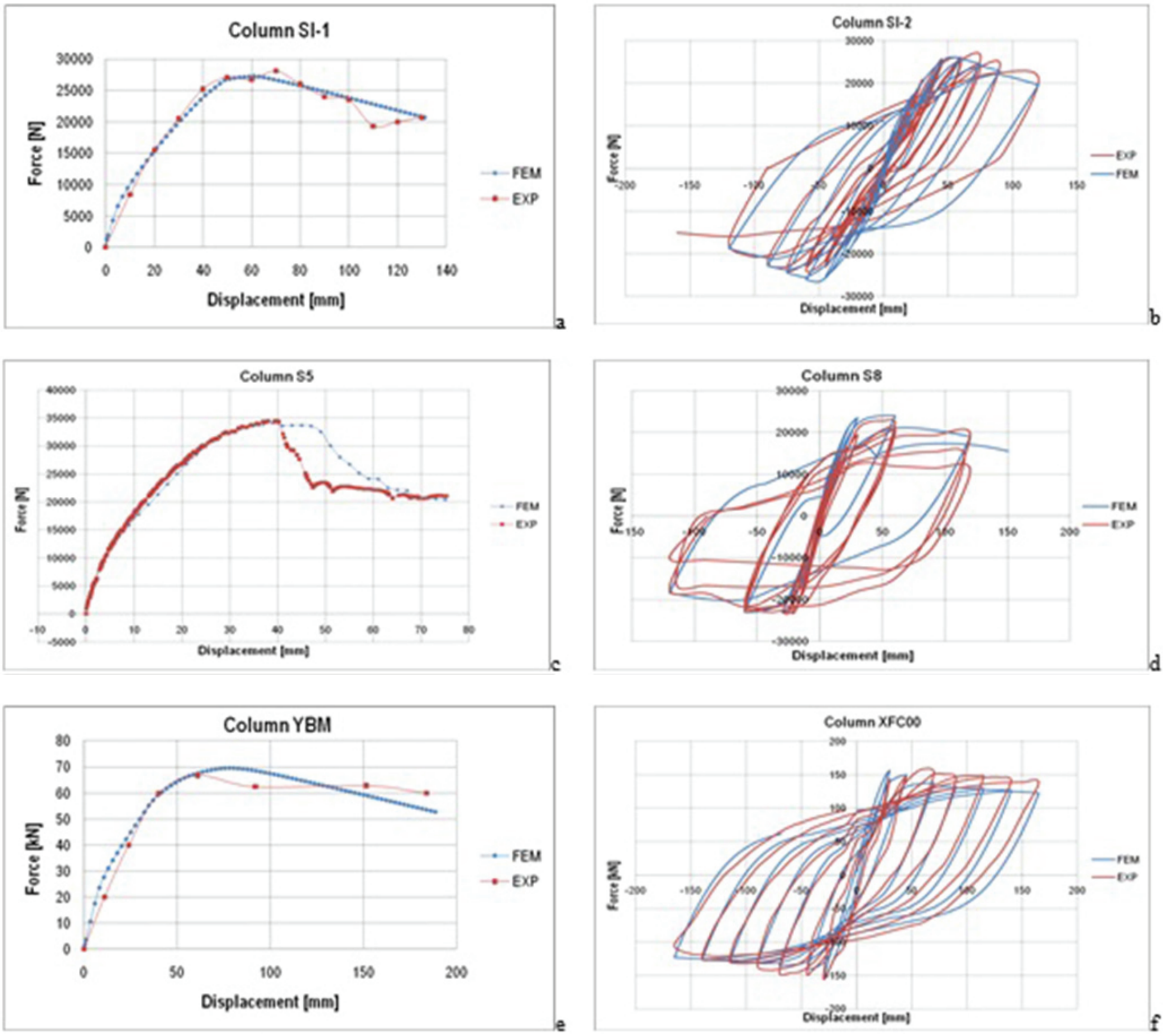


Figure 9: Calibration of monotonically and cyclically tested column

The creep and shrinkage effects were not taken into consideration. In the model were used the confined values of the concrete. For normal concrete was used the SR EN 1992-1-1 law and for high strength concrete the Cusson-Paultre law. For simplicity the section was considered divided into two zones, confined (the zone between the transversal reinforcement) and unconfined (at the exterior of the transversal reinforcement). For the cyclic loading the Menegotto-Pinto law was used (see Figure 8b).

VALIDATION OF THE NUMERICAL MODEL

The validation of the numerical model is presented in figure 10, by comparing the force-displacement curves obtained experimentally and numerically. Figures 10a and 10b present the results for the SIII column from the program presented at 2.1., tested monotonically and cyclically. Figures 10c and 10d present the results for the 2.00 m column made with high strength concrete from the Cluj-Napoca experimental program. Figures 10e and 10f present the comparison for YDM monotonically tested column and for XFC00 cyclically tested column from the experimental program developed in Taiwan. The experimental program developed in San Diego included only cyclic tests on columns made with both normal (see figure 10g for specimen 3) and high strength concrete (see figure 10h for specimen 7). The validation of the numerical model for columns with cross profiles fully embedded in concrete is presented in figures 10i and 10j. Until reaching the peak load the numerical model is quite accurate, the differences between the experimental and numerical values being under 5%. After the peak load the numerical model doesn't offer such accurate results as before, the differences being about 15%.



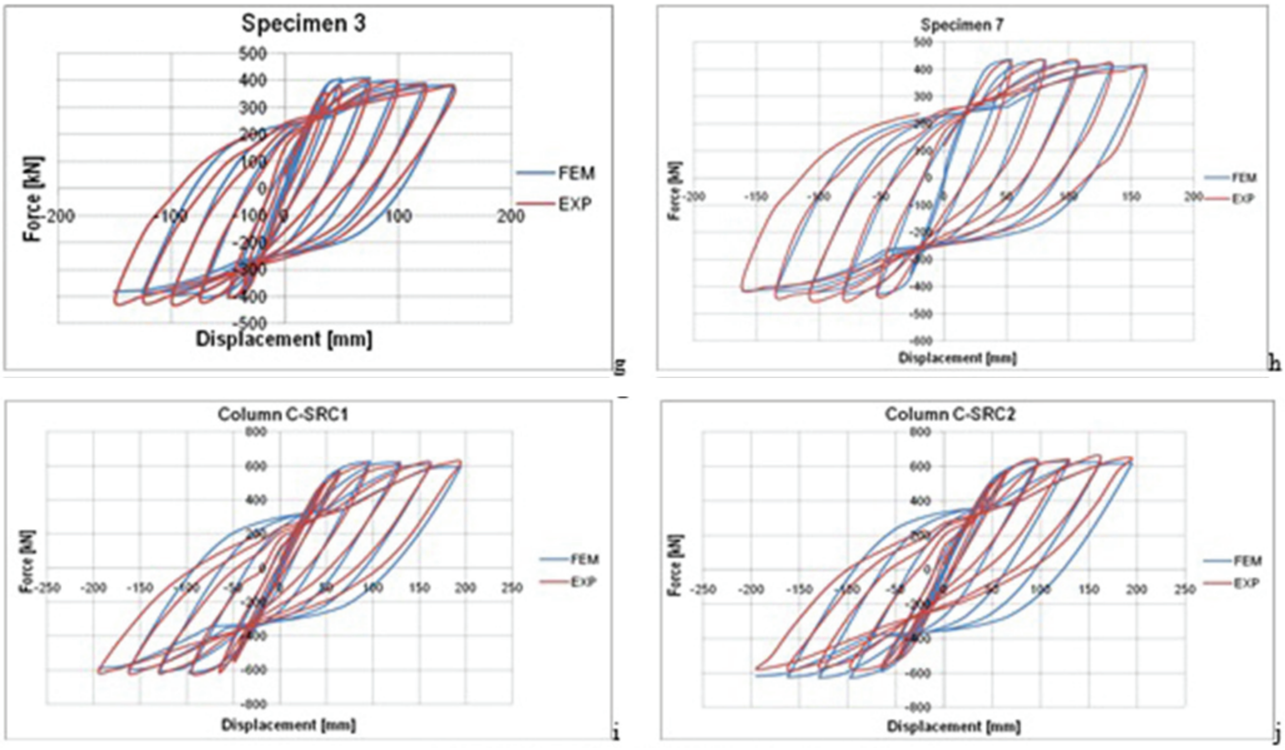


Figure 10: Validation of the numerical model

CONCLUSION

The solution of fully encased composite column is a competitive solution for seismic and non-seismic zones, due to the excellent seismic performances (resulted from the presented experimental tests) and also because of improved fire protection. The numerical modeling is a very efficient and economic investigation method for the behavior of fully encased steel-concrete composite columns, especially for sections that are not covered by the current provisions of the SR EN 1994-1-1, but cannot exclude experimental research. The results obtained on the columns made with high strength concrete showed improved performances, especially resistance. Due to the brittle fracture of the high strength concrete more experimental and numerical research must still be made.

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POSSIBILITIES OF USE OF PRODUCTS FROM WASTE TYRE RECYCLING IN CONCRETE INDUSTRY

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Paper presents the effect of products obtained during recycling of waste tyres on properties of concrete. Only by taking into account specific properties of each product obtained by recycling, it is possible to apply them in concrete industry for preparation of concrete products with special properties. Products incorporating waste tyres can then be ecologically, technically and economically competitive alternative to products traditionally used in engineering practice.
Key words: Waste tyres, Recycled rubber, Recycled steel fibres, Recycled textile fibres

INTRODUCTION

Extensive use of tyres in car industry has resulted in accumulation of large quantities of used tyres that have to be disposed of at the end of their useful life. As many as 1.5 billon of tyres for the automobile industry are produced worldwide each year, and almost 3.5 million tons of waste tyres are generated in the EU countries alone [01]. According to the Directive 1999/31/EC [02], any form of disposal of used tyres in natural environment has been completely banned since 2006 and, following this decision, the quantity of available used tyres has grown considerably. Recent data show that the quantity of waste tyres disposed in an uncontrolled manner has reduced considerably in Europe over the past decade, and that it now amounts to no more than 4% of the total quantity of waste tyres. At the same time, it is estimated that 29% of waste tyres (about 450,000 t or about 42.5 millions of tyres) are disposed of in an uncontrolled manner in new EU member countries. Tyre recycling belongs to the field of sustainable development as the recycling of used products results in valuable raw materials that can be used for manufacturing products with a new value. Three raw materials can be obtained by waste tyre recycling: a) rubber granules, b) steel fibres, and c) textile fibres (Figure 1).

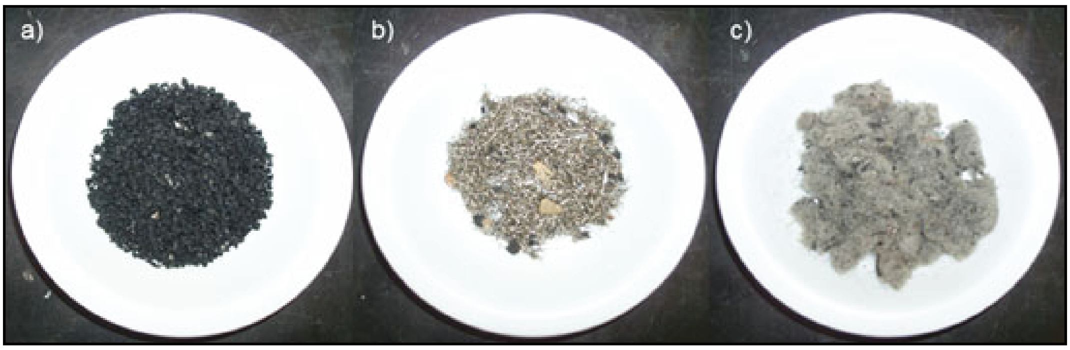

Figure 1: Products obtained by the automobile tyre recycling: a) rubber granules, b) steel fibres, and c) textile fibres [03]

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Only 5% of recycled waste tyres are currently used in construction industry, although the possibilities for such use are much greater in this field. In recent times, rubber has found its use in cement industry, in the production of surfaces for playfields and sports terrains, and as a component of various lining and covering products. In addition, one of new directions that has been studied over the past several years is the use of waste tyres and their components in the concrete manufacturing technology, since concrete technology is trying to reduce environmental impact of production, and at the same time contribute to the preservation of natural resources [04].

USE OF RUBBER GRANULATES

One of advantages of the use of rubber as a replacement for some of the aggregate is the reduction in the density of concrete mix. Furthermore, the nonpolarity of rubber, and roughness of its surface, result in introduction of an additional quantity of air [03, 05]. The addition of rubber to the fresh concrete mixture also results in a reduced workability, especially when greater proportions are added (>30% of the total volume of aggregate) [05]. The replacement of aggregate with rubber reduces the compressive strength and stiffness in the composite, which could have been expected considering the physical and mechanical properties of rubber compared to stone aggregate. The capability of rubber to reject water, due to hydrophobicity of its surface, and consequent introduction of an additional quantity of air into the mixture, ensures a greater quantity of closed pores in the composite structure that are not available to water [06]. This is why these composites have a lower capability to absorb water by capillary absorption. Despite a lower capillary absorption, the presence of rubber particles causes higher penetration of water under pressure, due to the poor quality of the rubber to cement matrix interface, but also to physical properties of rubber which “shrinks” when subjected to high water pressure [07]. Furthermore, physical properties of rubber enable this material to behave as an absorber of internal stress due to hydrostatic pressure of water during the freezing and thawing cycle [05, 08].

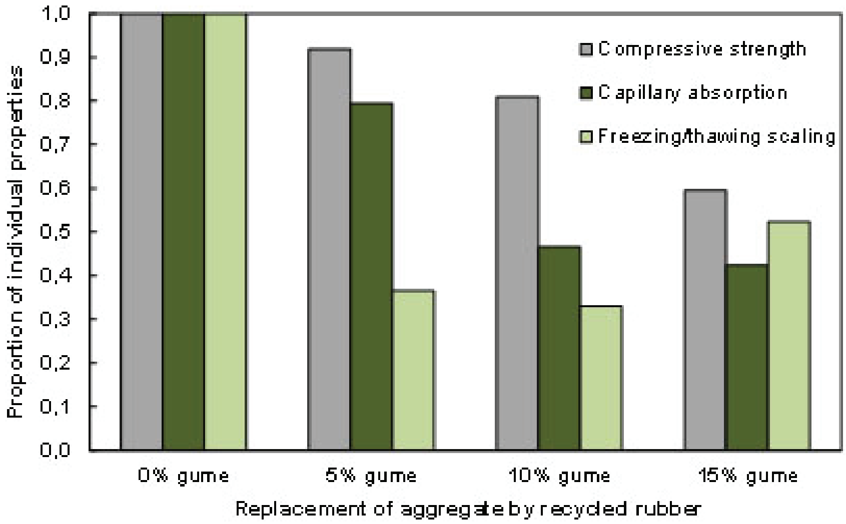
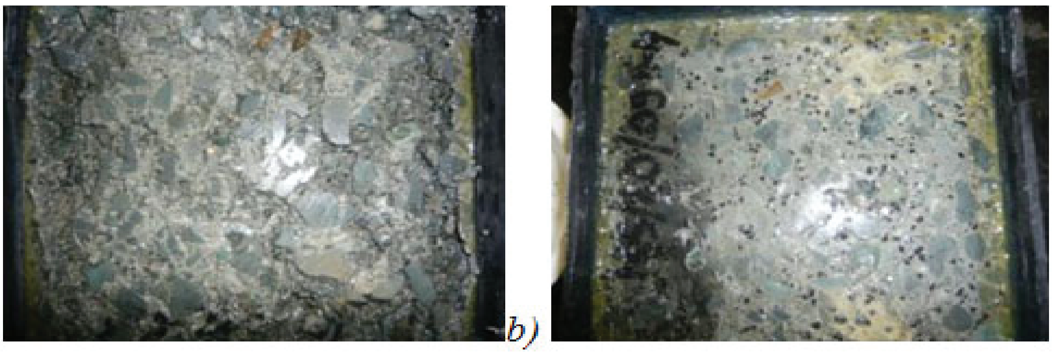


Figure 3: Influence of aggregate replacement with recycled rubber on hardened concrete



a) b)

Figure 4: Structure of concrete without rubber (a) and 10% of rubber (b) after exposure to freezing and thawing cycles with deicing salt

Presented main influences of incorporating rubber in concrete mixture make the recycled tyre attractive for use in construction industry, where compressive strength is not prevailing factor, but durability in aggressive environments. It is precisely because of these properties that new trends in the use of rubber in concrete are oriented toward development of products in which good use can be made of its insulating and absorbing properties [03, 09], its capacity to absorb energy in high-strength concrete [10], and as a replacement for chemical admixtures that are used for increasing resistance to freezing and thawing [05].

USE OF RECYCLED STEEL FIBRES

Studies conducted so far to define possibilities for the use of steel fibres from waste tyres have revealed several positive features of this material [03, 10, 11]. In fact, recycled fibres are an economically and environmentally justified alternative to industrial fibres, especially when used in greater proportions and if mixed with industrial fibres [12]. They limit propagation of cracks and increase toughness of the composite compared to ordinary concrete, even in case of separation and pulling out of the composite [13]. A comparison of fibre reinforced concrete containing industrial fibres, with fibre reinforced concrete containing the same and higher quantity of recycled fibres obtained by automobile tyre recycling, is presented in form of diagram in Figure 5. This diagram shows that the design of mixes with recycled fibres results in properties that are similar to those of mixes prepared with industrial fibres.

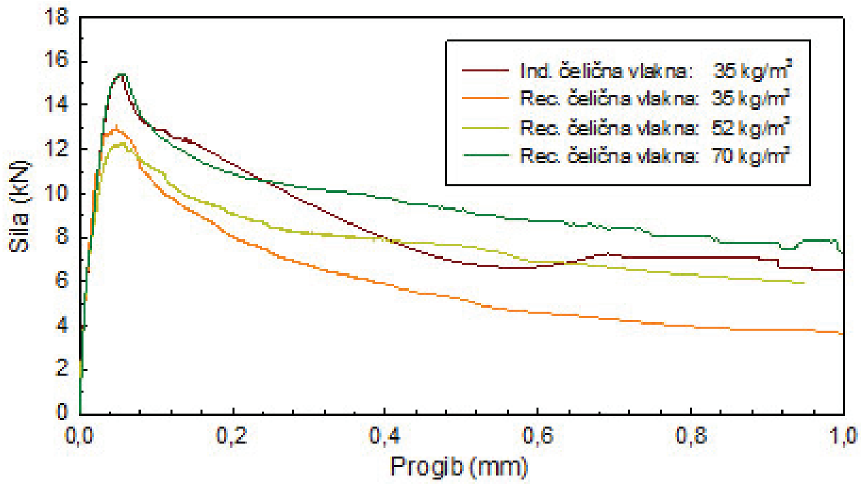


Figure 5: Working diagram of fibre reinforced concretes containing different types and quantities of steel fibres during ductility testing

In addition to its influence on ductility, the introduction of steel fibres in fibre reinforced concrete can result in some other benefits. Preliminary research has revealed that fibre reinforced concrete mixes prepared with cleaned recycled steel fibres are characterized by lower incidence of scaling when subjected to freezing and thawing cycles [14]. In addition, it was established that such fibre reinforced concrete is less susceptible to wearing and corrosion when exposed to aggressive marine environment [15, 16]. Therefore, recycled steel fibre reinforced concrete can be used for preparation of prefabricated elements in cases where a considerable resistance to bending, and also to dynamic and impact load, is required, such as prefabricated railway tracks on concrete bedding [17].

USE OF RECYCLED TEXTILE FIBRES

The last product of waste tyre recycling is textile fibres. These fibres have not so far found their use in construction industry. Preliminary research has shown that the influence of recycled textile fibres on the reduction of shrinkage due to drying is similar to that of industrial polypropylene fibres (Figure 6) [18]. If an increase in deformation due to concrete drying is compared with values for the same concrete without fibres, calculated according to Eurocode 2, it can be seen that the reduced shrinkage can be observed in the first days of the concrete matrix hardening process. When such recycled fibres are used, the concrete shrinkage is visibly reduced, and hence the risk of cracking due to improper or insufficient curing is also lowered.

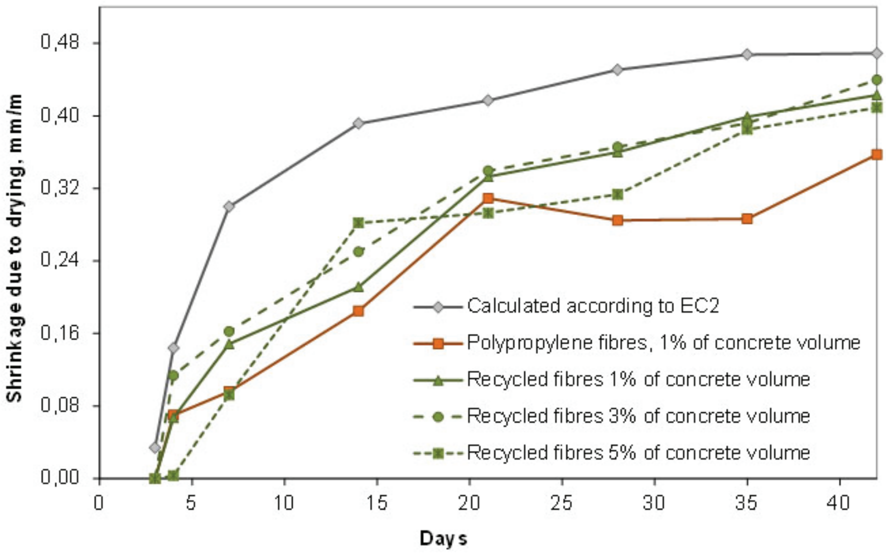


Figure 6: hrinkage due to drying calculated according to EC2 for ordinary concrete, and measured for textile fibre reinforced concrete

In addition to reduced shrinkage due to drying, the recycled textile fibres have also some other positive influences on concrete durability, such as a higher resistance to penetration of chlorides and a reduced penetration of water. These results show that the potential application of textiles is in repair mortars, where it is extremely important to prevent occurrence of micro-cracks and penetration of aggressive substances.

CONCLUSION

Three types of materials are obtained in the waste tyre recycling process: rubber granulates, steel fibres, and polymer fibres. The way in which concrete properties are influenced by each of these materials, when used as secondary raw materials, is explained in the paper. Rubber granules reduce compressive strength of concrete but, at the same time, they increase resistance to freezing and thawing, and the sound absorption capability. The addition of recycled steel fibres increases ductility of concrete, and prevents propagation of cracks. The addition of textile fibres reduces deformations due to shrinkage, and positively influences durability properties of concrete. Taking into account their influences on concrete, each of these materials can be used to prepare ecologically, technically and economically competitive alternative to products that are nowadays dominantly used in the engineering practice.

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