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EXPERIMENTAL ANALYSIS AND NUMERICAL SIMULATION OF ULTRA-HIGH PERFORMANCE AND NORMAL CONCRETE COMPOUND COLUMNS

BY

MIRCEA POPA[1,*], ZOLTAN KISS[1], CIPRIAN ȚIBEA[2], GEANINA BOLCA[3], MARIA ȚIBEA[4] and HORIA CONSTANTINESCU[1]

Technical University of Cluj-Napoca
Faculty of Civil Engineering
[2]SC Consolis Engineering Services Romania SRL, Cluj-Napoca
[3]"Vasile Goldis" Junior High School, Cluj-Napoca
[4]"Apulum" Technical College, Alba-Iulia

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Abstract. The combination of Ultra-High Performance Concrete (UHPC) and conventional construction methods (the use of Normal Concrete – NC) results in columns with a high load capacity. Compared with columns made only of UHPC or High Performance Concrete (HPC), they provide a better ductility and superior fire resistance because the external layer of NC reduces the penetration of heat in the core made of UHPC. From the total of 16 columns which were tested in the experimental program, 12 columns had a compound and 4 columns had a simple cross section. An analogy is made between the results of the experimental test and the results achieved with the Finite Element Analysis (FEA) software TNO "Diana".

Key words: Ultra-High Performance Concrete (UHPC); Ultra-High Performance Fibre Reinforced Concrete (UHPFRC); Finite Element Analysis (FEA), Finite Element Model (FEM), concrete columns.

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[*]Corresponding author: *e-mail*: mircea.popa@dst.utcluj.ro

1. Introduction

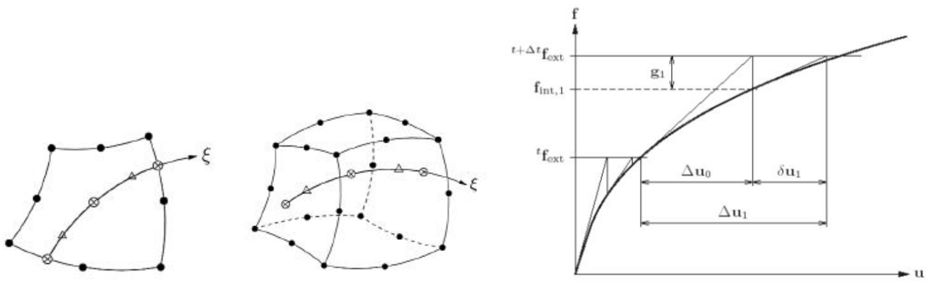
The combination of UHPC with the NC results in columns of high loadbearing capacity which are compared to columns made of HPC, UHPC or Ultra-High Performance Fibre Reinforced Concrete (UHPFRC), provide better fire performance, since the outer covering of NC reduces the ingress of heat in the UHPC core (Empelmann & Muller, 2009; Empelmann, 2011).

This topic was studied because of the following benefits: a low cost rate (the precast core made of UHPC or UHPFRC), ease of execution (the combination of the two methods of implementation: prefabrication and solidarity) and its visual aspect – high performance achieved by using tall and slender columns.

2. Numerical Simulation

Before the experimental program was started, a Finite Element Model (FEM) was developed in order to optimize the cross section of the columns and to have an idea about the load bearing capacity and of the equipment needed for the destructive tests that were carried out later.

The FEM was created in the software TNO DIANA and consisted of an UHPFRC central core (C150 concrete class) and a reinforced NC shell. The shell was assigned with the properties of a C50/60 concrete class. Both UHPFRC and NC shell were meshed using a quadratic 8 node brick element type (TNO Diana BV). The transverse reinforcement was consisted of stirrups made of S255 steel (trade name OB 37) and the longitudinal reinforcement was made of S355 steel (trade name PC 52). The reinforcement was modelled as embedded reinforcement with perfect bond characteristics (Fig. 1 *a*).



a *b*

Fig. 1 – Embedded reinforcement in solid (*a*); Regular Newton-Raphson Method (*b*).

In order to have a realistic model, a nonlinear analysis type with physical nonlinearities was performed. The Newton-Raphson incremental-iterative method (Fig. 1 *b*) was used as the solver. This method derives at every iteration the tangent stiffness matrix. The force was introduced in 10 steps, with a value of 0.1 of the calculated ultimate load per step. After inspecting the results obtained from this analysis it was noticed that in order to know the exact peak value of the force–displacement diagram another method was necessary, one that could simulate the "snap-back" and "snap-through" behaviour (Fig. 2) and also the precise moment for the failure of the element. This method is called *Arc-Length* and was developed by Riks (1972) and Wempner (1971) and modified over time. This method modifies the quantity of load or displacement applied for each iteration in order to reach convergence for the model, unlike other methods like Newton-Raphson where the force or displacement are constant during the iteration steps. Arc-Length method considers the load factor or displacement factor as a variable and so those become new unknown factors in the equilibrium equation.

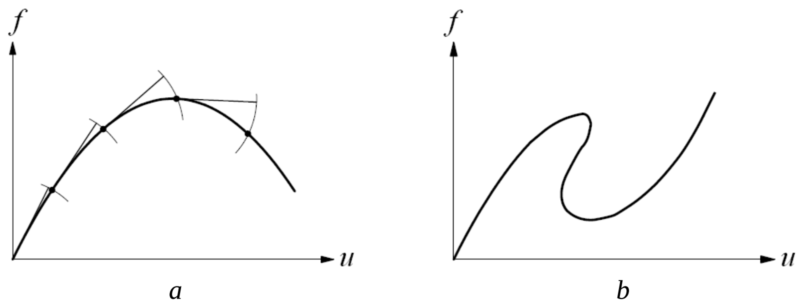
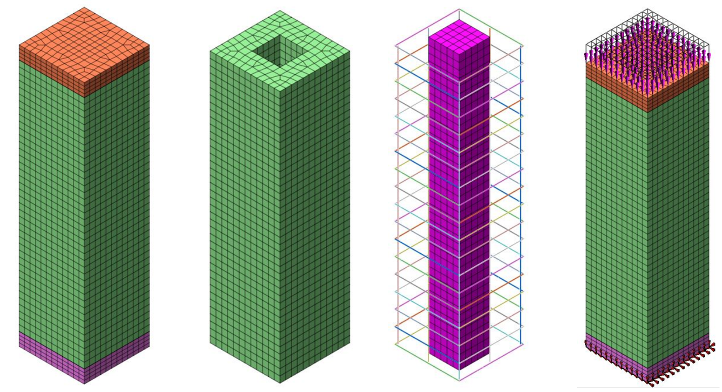


Fig. 2 – *a* – Snap-through behaviour simulated with Arc-Length method; *b* – Snap-back behaviour simulated with Arc-Length method.

After the geometry of the model was finalized (Figs. 3 *a*, 3 *b* and 5) the material characteristics were applied. For all materials present in the model, the characteristics of a nonlinear material were used. In the case of UHPFRC core (Fig. 3 *c*), an experimentally determined sigma – epsilon diagram which simulates the material behaviour in both compression and tension was applied. The tensile and compressive strength, the fracture energy, G_f, the Young modulus (elastic modulus, E_c), the transversal modulus, G and Poisson's ratio, μ, were also experimentally or theoretically determined. A total strain crack model was used in order to determine the crack widths. For the reinforcement and NC (C50/60 concrete class) the data present in the TNO DIANA library and calculated after Model Code 1990 was used. The interface between NC and UHPFRC was perfect bond.

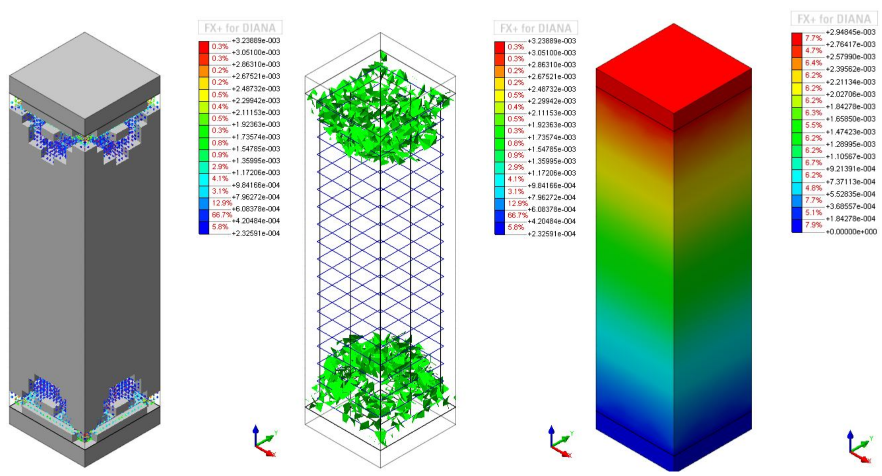
The bottom of the element had a fixed constrain and a 5,000.00 kN load was introduced at the top part to simulate the compressive behaviour of the column. The force was applied on a steel plate as pressure load (Fig. 3 *d*).



a *b* *c* *d*

Fig. 3 – *a* – meshed model; *b* – C50/60 mesh; *c* – UHPC core and reinforcement layout; *d* – applied pressure load and supports.

The results of the FEM are shown in Fig. 4. The column was analysed from the point of view of cracking. At every step newly created cracks, the closure of some or opening of others was observed. As FEM is a numerical method only the most important characteristics such as the maximum load force and displacement were reported. Several models were tested and only afterwards the experimental program started. Through analysis it was determined that the maximum force is situated around 4,500 kN.



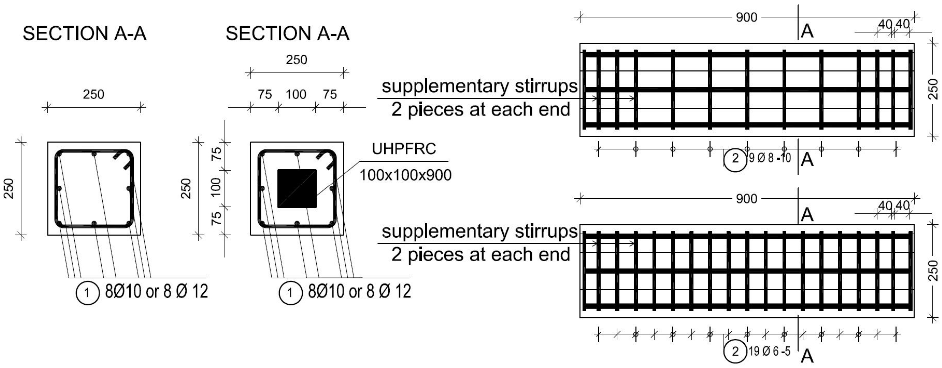
a *b* *d*

Fig. 4 – *a* – Deformed shape at peak load; *b* – crack model at peak load; *c* – nodal displacement in *Z*-direction.

3. Experimental Program

The experimental models were optimized by using numerical analysis.

Specimens with cross sections identical to those analysed by means of FEA software were cast (Fig. 5) using a concrete mix adapted by Popa *et al.*, (2013).



a *b*

Fig. 5 – Cross section: *a* – transversal; *b* – longitudinal.

The FE model used for these simulations was calibrated for a specific type of column and was experimentally verified. A parameter study of geometrical and structural parameters had to be carried out to identify the parameters with the largest influence (Lohaus, 2012).

3.1 Test Results

The experimental program verified the results obtained by FEA (Fig. 6). The first major crack occurred at 3,878 kN force (when the angle of the Load – Deformation diagram changed).

The experimental ultimate load was insignificantly lower than the ultimate load determined using FE analysis.

The Numerical Analysis results compared with the Experimental ones in regards to the failure force shows that the difference was less than 1%. The force obtained with FEM was 4,516 kN and the experimental failure force recorded for the same type of column was 4,472 kN. TNO Diana proved to be a very reliable tool in our work, providing very accurate results.

The difference in what concerns the displacements is caused by the difference in applying the force in the experiment compared with FEM. In the experiment the force was applied in steps and each step was maintained constant until the displacements stabilized. In FEM the force was applied continuously without load stationed at the steps. Such an analysis (Time Step

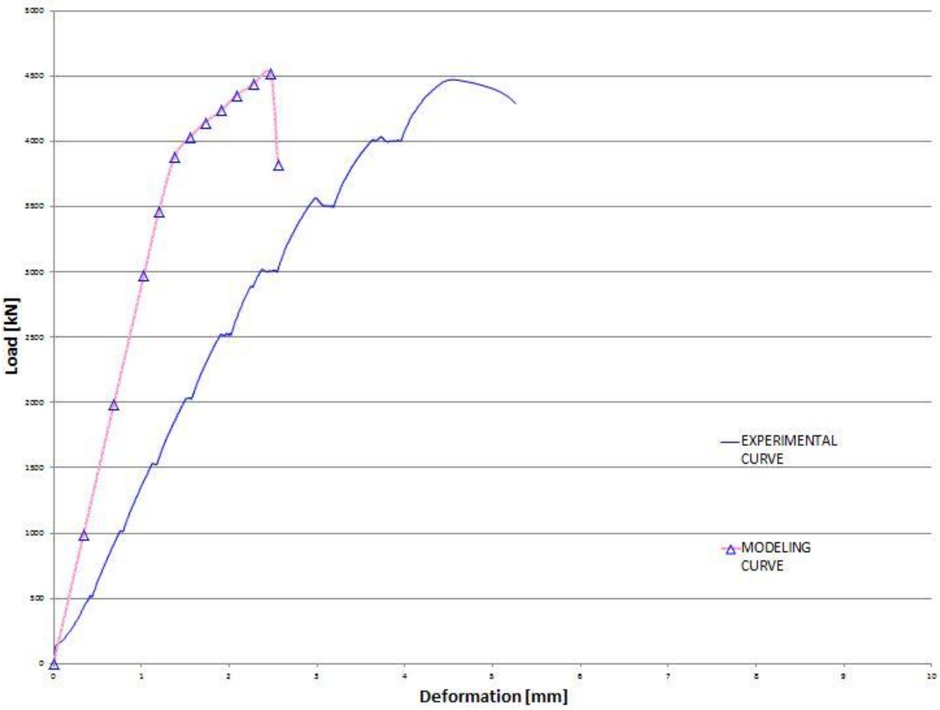


Fig. 6 – Experimental and numerical load – deformation diagram.

a *b* *c*

Fig. 7 – Failure modes: *a* – simple columns; *b* – compound columns; *c* – UHPFRC core split.

Analysis) is also possible but given that the goal was to establish the failure force, nonlinear analysis was taken into consideration. The Arc – Length method is needed in this case, considering that the convergence criterion is more stable in the latter compared with Nonlinear Time Step Analysis.

It can be observed that the core (Fig. 7 *c*) fails by shear fracture (Lohaus, 2012). The central core was split and looked like a prism fracture with a 45 degree angle crack. Because of the high forces (~5,000 kN), even in the case of UHPFRC system, the behaviour can be characterized as brittle (Heinmann *et al*., 2012).

A summarization of the average loads obtained by experimental tests and numerical computations is shown in Table 1.

Table 1
Experimentally Determined and Calculated Values

Column type by longitudinal reinforcement	Column type by cross section			
	Simple		Compound	
	Experimentally (average results) kN	Calculated kN	Experimentally (average results) kN	Calculated kN
Φ10	2,718	2,928	4,707	4,413
Φ12	2,733	3,048	4,709	4,540

In order not to deteriorate sensitive instruments (digital gauges and linear variable digital transducers) the ultimate strains were not recorded, strains were recorded up to 0.9 of the maximum force. In the experimental program the load was applied gradually, with a space of about 1 MPa/s as suggested in the procedure (RILEM, 1994) but in the FEM it was applied uniformly and in a continuous manner.

A smaller cross section provides considerable savings associated with material costs and reduction of dead loads (Sungjoong, 2007).

4. Conclusions

The results of the numerical simulation were almost the same as the experimental program.

Columns show more brittleness as the concrete compressive strength increases.

The studied compound columns had a load bearing capacity ~50% higher than the simple columns cross section.

Based on the obtained results, design regulations could be made so as to estimate the load bearing capacity of the conceived system. Besides this, construction rules will try to be established for a robust behaviour post cracking of the compound column, based on: adding steel fibres, considering longitudinal reinforcement with a high resistance (S670/800 steel) and/or increasing the transversal reinforcement percentage.

The combination of UHPFRC and NC shows an improved cross section and takes advantage of the qualities of each type of materials as opposed to the disadvantages of each one of them taken separately.

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REFERENCES

Empelmann M., Muller C., *Fertigteil-Stutzen – Neuebetontechnologische Möglichkeiten*. Betonwerk + Fertigteil-Technik, **10**, 4-12 (2009).

Empelmann M., *Precast Columns of High-Performance and Ultra-High Performance Concrete*. Proc. Betonwerk + Fertigteil-Technik, **02**, 48-50 (2011).

Heinmann M., Holger S., Graubner C.-A., *Probalistic Modelling of UHPC Slender Columns*. Proc. of Hipermat 2012, Kassel, 725-732.

Lohaus L., Jurgen G., Lindschulte N., Krominga S., *Experimental Analysis and Numerical Simulation of Ultra-High-Performance Concrete Tube Columns with a Steel Sheet Wrapping for Large Sized Truss Structures*. Proc. of Hipermat 2012, Kassel, 741-748.

Popa M., Corbu O., Kiss Z., Zagon R., *Achieving Mixtures of Ultra-High Performance Concrete*. Constr. J., Bucharest, Romania, **1**, 40-46 (2013).

Sungjoong K., *Behavior of High-Strength Concrete Columns*. Ph.D. Diss., North Carolina State Univ. U.S.A., 2007.

* * * *CEB-FIP Model Code 1990*. CEB Bulletin no. *213/214*, 1993

* * * RILEM, *Technical Recommendations for the Testing and Use of Construction Materials*. E & FN Spon, St. Edmundsbury, Great Britain, 1994.

* * * TNO Diana BV, *Diana Finite Element Analysis User's Manual Release 9.4.4*. Delft, The Netherlands.

ANALIZA EXPERIMENTALĂ ŞI SIMULAREA NUMERICĂ A STÂLPILOR CU SECȚIUNE COMPUSĂ ALCĂTUIȚI DIN BETON DE ULTRA ÎNALTĂ PERFORMANȚĂ ŞI BETON OBIŞNUIT

(Rezumat)

Combinația dintre Betonul de Ultra Înaltă Performanşă (BUIP) şi metodele de construcție convenționale (utilizarea betonului obişnuit – BO) are ca rezultat stâlpi cu o capacitate portantă mare. Comparativ cu stâlpii realizaţi numai din BUIP sau din Beton de Înaltă Rezistenţă (BIR), stâlpii cu secţiune compusă oferă o ductilitate mărită şi rezistenţă superioară la foc deoarece stratul exterior din BO reduce penetrarea căldurii în miezul din BUIP. Din totalul de 16 stâlpi, care au fost testaţi în cadrul programului experimental, 12 stâlpi au avut secţiune compusă, iar 4 stâlpi au avut secţiune simplă. Se face o analogie între rezultatele programului experimental şi rezultatele obţinute cu programul de Analiză a Elementului Finit (AEF) TNO Diana.