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STRENGTH AND DUCTILITY CAPACITY OF HIGH STRENGTH CONCRETE ELEMENTS

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SUMMARY

The conceptual consideration of concrete has been changed lately. It becomes clear that even minor changes in its composition lead to a considerable improvement of its characteristics. For wide use of high strength concrete, (HSC) in modern engineering, it is necessary to precisely define its properties and behaviour under under different loading conditions. To acquire fundamental knowledge of interactive behaviour of HSC and steel, as well as for definition of strength and ductility capacity of HSC elements, complex laboratory-experimental-analytical investigations has been carried out at IZIIS -Skopje.

The comprehensive research programme involves several issues: define of methodology for manufacturing HSC with strength up to 100MPa from domestic resourses, experimental testing of large scale HSC elements exposed to cyclic force and analytical investigations for obtaining strength and ductility capacity of HSC elements and their nonlinear response. Analytical procedure along with the computer programe, (MPHI-HSC) has been developed. The obtaining of moments, curvatures and strains completely follows the concept of fiber model analysis. Taking into account the specific nature of HSC and steel, the corresponding stress-strain diagrams are introduced in the programme. The nonlinear response of HSC elements is obtaining using nonlinear quasistatic analysis by applying cyclic displacement history.

The part of the results obtained from the investigations are presented through strain distrubution along cross-section, histories of forces, displacements and strains, as well as hysteretic force-displacement relationships. The correlation between experimentaly measured and analytically obtained values are also given. Special emphasis are put on strength and ductility of HSC elements.

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The results from the tests have shown that with appropriate quality of materials and having done proper reinforcement and confining, the elements are characterised by ductile behaviour and energy dissipation. The date from the analytically defined response of HSC elements point to a good correlation with experimental results.

INTRODUCTION

Demographic expansion and concentration of population and material goods in urban zones - megalopolises impose new challenges in modern engineering. The design of high-rises and large span structures is practically not possible if traditional materials are used. The solution of the problem is seen in investigation and application of new materials.

Such trends in structural engineering have been the main incentive for the initiation of scientific-research projects in the field of development and application of high strength concrete in the Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Republic of Macedonia.Within the frames of those projects, synthesis of investigations reported in world literature has been made and complex laboratory-experimental-analytical investigations have been performed to give contribution to the definition of the joint behaviour of high strength materials (high strength concrete and steel) in the nonlinear range as well as definition of criteria and recommendations for application of these materials in seismically active regions.

In the period 1992 - 1998, the investigations were focused to definition of a technology for obtaining high strength concrete with compressive strength of up to 100 MPa, exclusively from domestic resources and by use of own technology Gavrilovic [1]. In the second phase of the investigations (1998 - 2000), complex experimental and analytical investigations of models of beams and columns designed of high strength materials were performed, Necevska-Cvetanovska [2]. These investigations were realized as a joint research project among IZIIS, stock holding company "Ading" and construction company “Beton”. The third phase of the investigations (2001-2003) has been finished recently. This phase involves analytical definition of the dynamic behaviour of elements, parts of structures and structures designed and constructed of high strength materials.

QUASISTATIC INVESTIGATIONS OF BEAMS AND COLUMNS CONSTRUCTED OF HIGH STRENGTH CONCRETE AND STEEL PERFORMED AT IZIIS

The original investigation programme has been defined involving experimental investigations of a series of six elements, (3 beams and 3 columns). The main goal of the experimental investigations was to define the strength and deformability capacity of the elements, constructed of high strength materials as a function of several chosen parameters which were varied during the tests, (concrete compressive strength and percentage and yielding strength of vertical and horizontal reinforcement). The behavior of the models exposed to cyclic loading was observed, from the phase of linear elastic behaviour until cracking of concrete and formation of plastic hinges.

Characteristics of the Built-in Materials

In order to completely control the designed and built-in concrete, laboratory investigations of the concrete to be built in the element models were done. Analyzing the results from those investigations, the characteristics of the concrete components, particularly the percentage of superplasticizer and water reduction, the properties of the fresh concrete mix with consistency that can provide workability of the concrete, as well as the obtained results for the compressive concrete strength, the mix proportions for the design class of concrete, MB60, MB80 and MB100 were adopted, Necevska-Cvetanovska [2]. The parameters for the design of the above concrete class are shown at the Table 1.

Table 1. Parameters for design of the concrete class MB60, MB80 and MB100

Concrete components	MB60	MB80	MB100
Aggregate (kg/m^3)	1815	1800	1800
Cement -C (kg/m^3) Pure portland cement, PC45$_C$, "Usje"	450	460	500
Water -W (l/m^3) From well suitable for concrete,W/C	180	138	150
	0.40	0.30	0.30
Additives:superplasticizer, SFL(kg/m^3) microsilica (kg/m^3)	9.0 (2% of C) /	18.4 (4% of C) 36.8 (8% of C)	17.5 (3.5% of C) 40.0 (8% of C)
Consistency of the fresh concrete mix, (cm)	10-12	8-10	6-8

MB (60, 80 and 100) is concrete compressive strength defined on cube 20/20/20cm with age of 28 days

The results from the laboratory investigations of concrete compressive strength, concrete tensile strength, (which were carried out at the Beton Laboratory) and static modulus of elasticity of the build-in concrete (carried out at the Institute for Testing of Materials, Faculty of Civil Engineering, Skopje) are presented at the Table 2.

Table 2. Material characteristics of the concrete class MB60, MB80 and MB100

Concrete class	Compressive strength [MPa]				Tensile strength [MPa]	Modulus of elasticity [MPa]
	3 day	7 day	28 day	*note		
MB60	46.4	53.2	59.8	74.5	7.62	31057
MB80	59.1	67.9	81.2	83.3	7.37	32216
MB100	64.0	74.8	98.0	102.5	9.12	33400

* The strengths values have been measured on the exact day of the experiments e.i. MB60 on 154day, MB80 on 140day and MB100 on 139 day.

To reinforce beam model MGR60 and column model MS60 ribbed reinforcement RA400/500, (ϕ20 and ϕ16) was used for longitudinal reinforcement and plain reinforcement GA240/360, (ϕ8) for shear reinforcement. The beam and column elements built of concrete class MB80 and MB100 were reinforced by ULBON steel, SBPD 1275/1420 [MPa] of nominal diameter of 13mm. It was manufactured by the Japanese company NETUREN. The mechanical characteristics of the ULBON reinforcement are given in Table 3.

Table 3. Mechanical characteristics of ULBON reinforcement

Type	f_y [Mpa]	f_u [Mpa]	Elongation at 8d, % min.	Relaxation, % max.
SBPD 1275/1420	1275	1420	5	4.0

Design and Construction of Models for Experimental Investigations

The beam and column models are full scale models designed according to the "National Code of Technical Regulations of Concrete and Reinforced Concrete", EC2, [3] and recommendation that are given in the world literature for design of HSC elements ACI Committee 363 [4], French [5].

The beam models are designed as fixed cantilever beam elements with l=2.29m and rectangular cross-section 25/40cm. The beam was threatened only to the point of inflexion. Strength characteristics of used concrete and steel, as well as percentages of reinforcement for three beam models are given in Table 4.

Table 4. Characteristics of materials built-in the beam models

Specimen	MB [MPa]	Longitudinal reinforcement			Transverse reinforcement			
		Steel grade	A_{zat} [cm^2]	$\rho_{v,mech}$ [%]	Steel grade	f_{yh} [MPa]	s [cm]	ρ_h [%]
MGR60	60	RA 400/500	12.57	0.139	GA 240/360	240	7.5	1.09
MGR80	80	SBPD 1275/1420	5.39	0.095	RA 400/500	400	7.5	1.29
MGR100	100	SBPD 1275/1420	5.39	0.076	RA 400/500	400	7.5	1.29

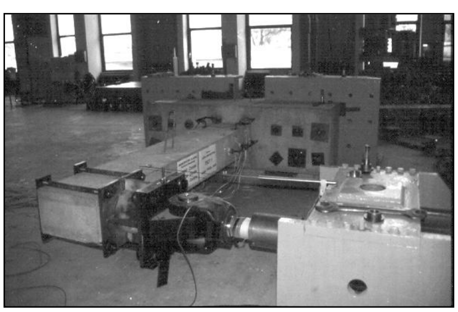
The models of the columns are designed as fixed cantilever column elements with l=2.0m and square cross-section 30/30cm. The column was threatened only to the point of inflexion. The level of axial forces is constant for all models, P=800kN. Strength characteristics of used concrete and steel, as well as percentages of reinforcement for three different columns are given in Table 5.

Table 5. Characteristics of materials built-in the column models

Specimen	MB [MPa]	P/Po	Longitudinal reinforcement			Transverse reinforcement		
			Steel grade	A_{zat} [cm^2]	$\rho_{v,mech}$ [%]	Steel grade	s [cm]	ρ_h [%]
MS60	60	0.179	RA 400/500	6.03	0.078	GA 240/360	7.5	2.37
MS80	80	0.126	SBPD 1275/1420	4.04	0.083	RA 400/500	7.5	2.57
MS100	100	0.105	SBPD 1275/1420	4.04	0.066	RA 400/500	7.5	2.57

Equipment, Instrumentation, Course and Results of Investigations

The experimental tests were carried out in the Dynamic Testing Laboratory of IZIIS, under quasistatic regime of loading. The test-setup for beam models is given in Fig. 1. One actuator with a capacity of 50tons was used to apply cyclic horizontal force and the second actuator of 100tons for applying constant axial force of 800kN. The experiments were conducted through displacement control. Depending on the observed behavior of the element models, the loading programme, (Fig 1.) was corrected.



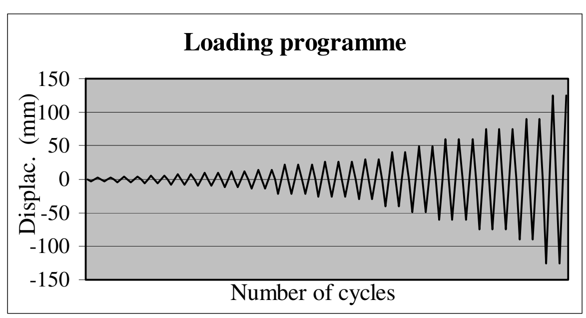


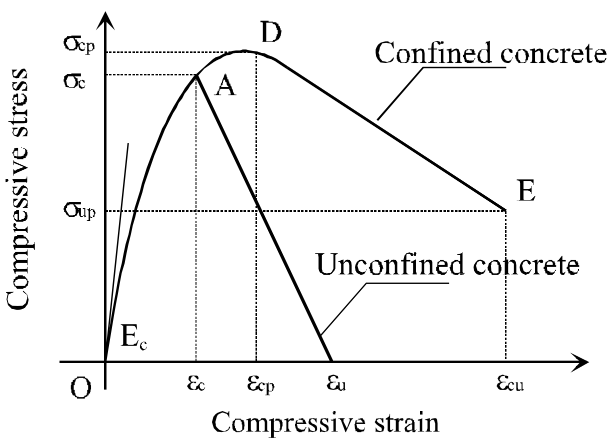
Figure 1. Test - setup for beam models and characteristics loading programme

The experimental investigations of elements were performed in two separate phases, (first phase-beam models and second phase-column models). The results obtained from the experimental investigations are obtained through hysteretic relationships between forces and displacements, force and strains, (in concrete and reinforcement) and displacement history as well as the damage distributions on the models during the tests. Presentation of the results from the experimental investigations are beyond the scope of this paper and they are given in details in Apostolska-Petrusevska [6], Necevska-Cvetanovska [7], Necevska-Cvetanovska [8] and Petrusevska [9].

ANALYTICAL MODELING OF NONLINEAR BEHAVIOUR OF BEAMS AND COLUMNS CONSTRUCTED OF HIGH STRENGTH MATERIALS

Analytical Definition of the M-Φ Relationship - Computer Program MPHI-HSC

For analytical definition of the bearing and deformability capacity of beams and columns constructed of high strength materials, an original computer program **MPHI-HSC** has been developed, Apostolska-Petrusevka [6]. The obtaining of moments and curvatures completely follows the concept of fiber model analysis of cross-section. An original σ-ε relationship for confined high strength concrete proposed by Muguruma [10], (Fig. 2) has been incorporated in the program.



Stress at ascending branch OA

$$\sigma = E_c * \varepsilon + \left\{ \frac{(\sigma_c - E_c * \varepsilon_c)}{\varepsilon_c^2} \right\} * \varepsilon^2$$

Stress at ascending branch AD

$$\sigma = \frac{(\sigma_c - \sigma_{cp})}{(\varepsilon_c - \varepsilon_{cp})^2} * (\varepsilon - \varepsilon_{cp})^2 + \sigma_{cp}$$

Stress at descending branch DE

$$\sigma = \frac{(\sigma_{up} - \sigma_{cp})}{(\varepsilon_{up} - \varepsilon_{cp})} * (\varepsilon - \varepsilon_{cp}) + \sigma_{cp}$$

Figure 2. σ-ε relationship of high strength concrete

Stresses and strains calculated at characteristics points, (A, D and E) are given in the Table 6.

Table 6. Obtained values of stresses and strains after Muguruma, Watanabe et al.

Models	E_c (MPa)*	σ_c (MPa)	ε_c (‰)	σ_{cp} (MPa)	ε_{cp} (‰)	σ_{up} (MPa)	ε_{up} (‰)
MGR60	31057	49.63	1.95	51.93	2.58	32.54	4.33
MGR80	32216	67.39	2.19	70.92	2.99	36.57	4.87
MGR100	33400	85.05	2.42	88.57	3.12	47.06	4.73
MS60	31057	49.63	1.95	54.38	3.25	30.65	6.00
MS80	32216	67.39	2.19	73.53	3.58	38.64	6.30
MS100	33400	85.05	2.42	91.18	3.60	46.04	5.92

*E_c are obtained experimentally.

For analytical definition of the bearing and deformability capacity of beams and columns an idealized bilinear working diagram for the σ-ε relationship for steel is used.

Strain Distribution and Correlation with Experimentally Obtained Results

For Beam Models

For the purpose of getting a better insight into the behaviour of beams from linear elastic up to nonlinear range, three characteristics profiles (strain dsitribution along cross-section height) for different levels of strains, (ε_c=0.85‰-2.85‰ and ε_s=2.89‰-6.9‰) are chosen. The experimentally measured and calculated values for strains, curvatures and moments shown good correlation, (Table 7). Beam model MGR60 has flexural bearing capacity greater than MGR80 and MGR100 which is due to the higher mechanical coefficient of reinforcing and larger area of reinforcement. With the increase of the concrete strength in the models MGR80 and MGR100, their bearing and deformability capacity becomes similar to that of the model MGR60 although they have (30-50) % lower mechanical coefficient of reinforcement.

Table 7. Strain distributions, curvatures and moments for the beam models

MODEL MGR60					
Experiment	ε_c (‰)	ε_s(‰)	Φ [rad/mm] x 10^{-5}	M [kNm]	P[kN]
Profile 1	1.92	2.90	1.369	212.3	102.06
Profile 2	2.40	4.00	1.818	252.7	121.49
Profile 3	2.48	5.80	2.340	259.3	124.67
Analysis					
Profile 1	1.36	2.89	1.220	227.2	109.2
Profile 2	1.51	4.65	1.749	252.7	110.6
Profile 3	1.77	5.60	2.115	232.1	111.5
MODEL MGR80					
Experiment	ε_c (‰)	ε_s(‰)	Φ [rad/mm] x 10^{-5}	M [kNm]	P[kN]
Profile 1	0.90	2.90	1.050	112.1	53.9
Profile 2	1.80	5.98	2.160	242.2	116.4
Profile 3	2.00	6.90	2.470	260.0	125.0
Analysis					
Profile 1	0.87	2.90	1.040	103.2	49.6
Profile 2	1.57	5.86	2.060	225.2	108.3
Profil 3	1.72	6.48	2.280	239.4	115.1
MODEL MGR100					
Experiment	ε_c (‰)	ε_s(‰)	Φ [rad/mm] x 10^{-5}	M [kNm]	P[kN]
Profile 1	1.50	3.20	1.300	119.4	57.4
Profile 2	2.55	5.98	2.350	253.7	121.9
Profile 3	2.85	6.90	2.710	276.4	132.9
Analysis					
Profile 1	0.85	3.26	1.140	104.5	50.2
Profile 2	1.50	5.98	2.080	235.9	113.4
Profile 3	1.70	6.90	2.390	254.3	122.3

For Column Models

The selected characteristic distributions of concrete and steel strains along the cross-section of the column models are given in Table 8. The experimentally recorded strains show good correlation with the analytically obtained ones. Strains in concrete and reinforcement are in the range between ε_c=1.26‰-4.4‰, ε_s=0.9‰-6.9‰ which point to behavior of the models from linear elastic to nonlinear. Because all three models have similar mechanical coefficient of reinforcement, their flexural bearing capacity increases with the increasing of the concrete strength.

Table 8. Strain distributions, curvatures and moments for the column models

MODEL MS60					
Experiment	ε_c (‰)	ε_s (‰)	Φ [rad/mm] x 10^{-5}	M [kNm]	P[kN]
Profile 1	1.28	1.60	1.130	128.9	81.6
Profile 2	2.04	2.96	1.960	141.6	89.6
Profile 3	3.28	4.52	3.070	143.8	91.0
Analysis					
Profile 1	1.61	1.45	1.160	122.4	77.5
Profile 2	2.23	2.82	2.100	164.3	103.8
Profile 3	2.77	4.69	2.970	168.7	106.8
MODEL MS80					
Experiment	ε_c (‰)	ε_s (‰)	Φ [rad/mm] x 10^{-5}	M [kNm]	P[kN]
Profile 1	1.42	0.90	0.885	139.6	88.3
Profile 2	2.04	2.35	1.690	143.9	91.1
Profile 3	2.72	4.00	2.580	127.7	80.8
Analysis					
Profile 1	1.26	1.12	0.920	132.5	83.8
Profile 2	1.78	2.57	1.690	136.6	86.5
Profile 3	2.36	4.37	2.610	121.3	76.8
MODEL MS100					
Experiment	ε_c (‰)	ε_s (‰)	Φ [rad/mm] x 10^{-5}	M [kNm]	P[kN]
Profile 1	1.92	1.67	1.380	151.7	95.9
Profile 2	3.28	3.56	2.630	152.3	96.4
Profile 3	4.40	5.00	3.615	136.5	86.2
Analysis					
Profile 1	1.48	2.05	1.370	138.0	87.9
Profile 2	2.22	4.40	2.580	155.0	98.2
Profile 3	2.34	6.90	3.500	137.5	87.0

Presented further is part of the results obtained for the column model, MS100 (Fig. 3).

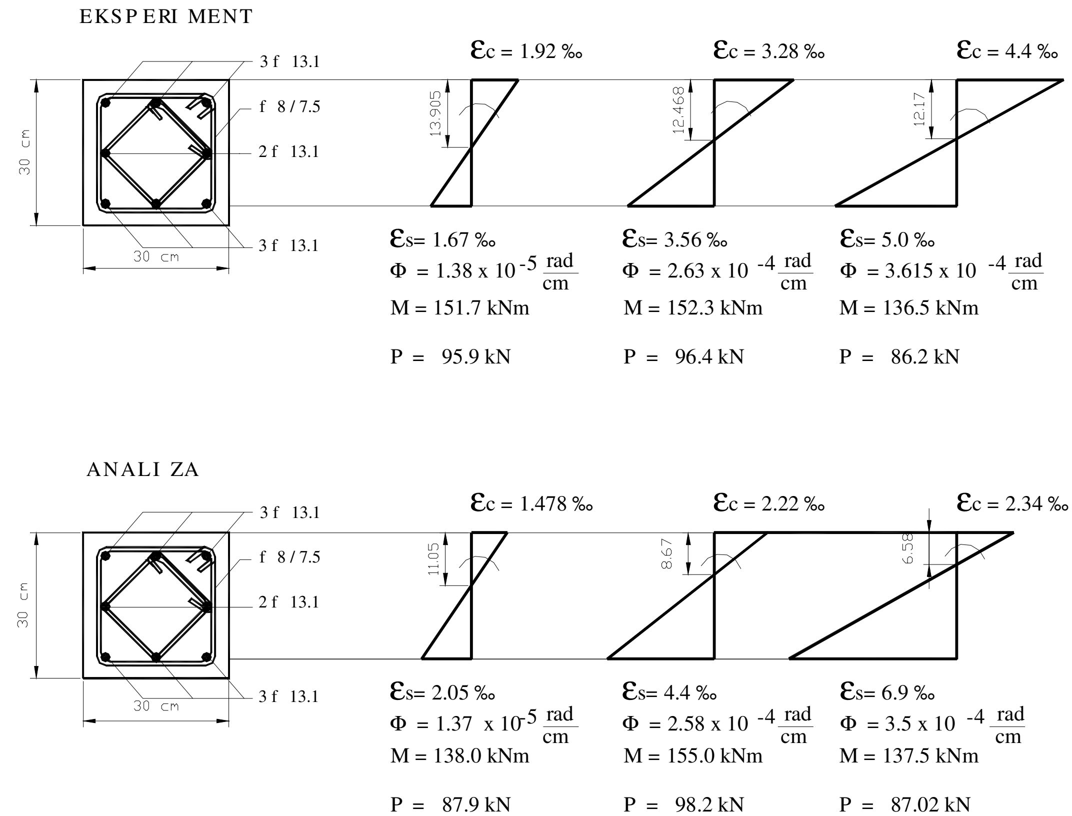


Figure 3. Strains, curvatures and moments for column model, MS100, (experiment and analysis)

NONLINEAR QUASISTAIC ANALYSIS AND RESULTS

The main purpose of the performed nonlinear quasistatic analysis is to define nonlinear behaviour of beams and columns constructed of high strength materials exposed to cyclic forces. The analysis was carried out by cyclic displacement time histories at the free end of the models, which correspond to the displacement histories during the quaisistatic testing. The element stiffness matrix has constantly been varied through the analysis according to the formulation of the spread plasticity model and the selected hysteretic model, ("smooth hysteretic model"). The presented results correspond to the specific set of parameters of this hysteretic model, which was used for modeling of the nonlinear behaviour of beams and columns. In the frame of investigations comprehensive parametric analyses were carried out for the purpose of obtaining as much as possible realistic response of the analyzed models. Nonlinear quasistatic analyses were performed using IDARC2D, Valles [11] and DRAIN-2DX, Prakash [12] computer programs.

Presented further is a selected part of the results obtained by nonlinear quasistaic analysis of models of beam, (Fig.4) and columns, (Fig. 5) constructed of high strength materials through time histories of displacement and forces, hysteretic force-displacement relationships as well as time histories of strains in concrete and reinforcement in the area of the plastic hinges. The correlation between the experimentaly measured and the calculated values are also given.

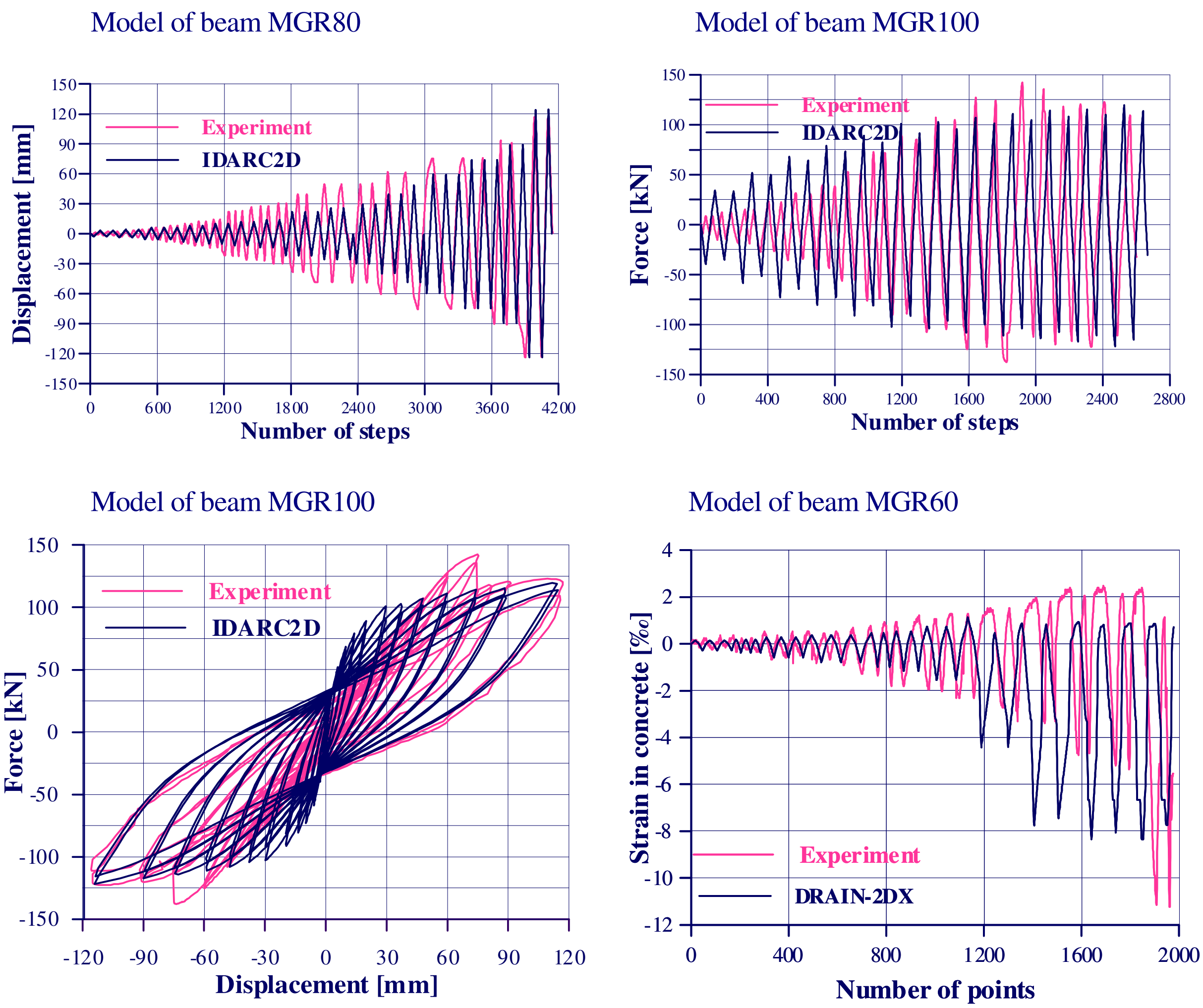


Figure 4. Results from analysis of beam models, (selected part)

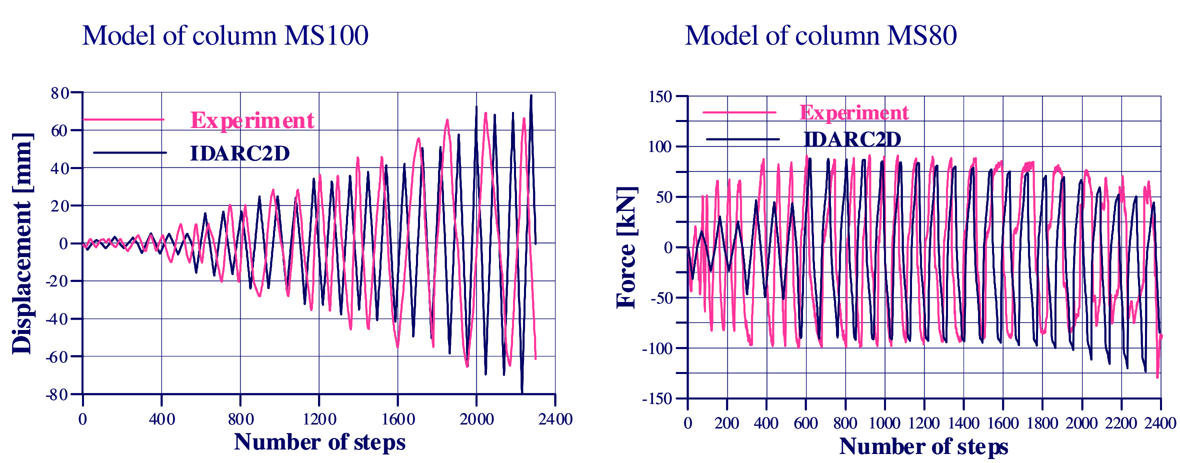


Figure 5. Results from analysis of column models, (selected part)

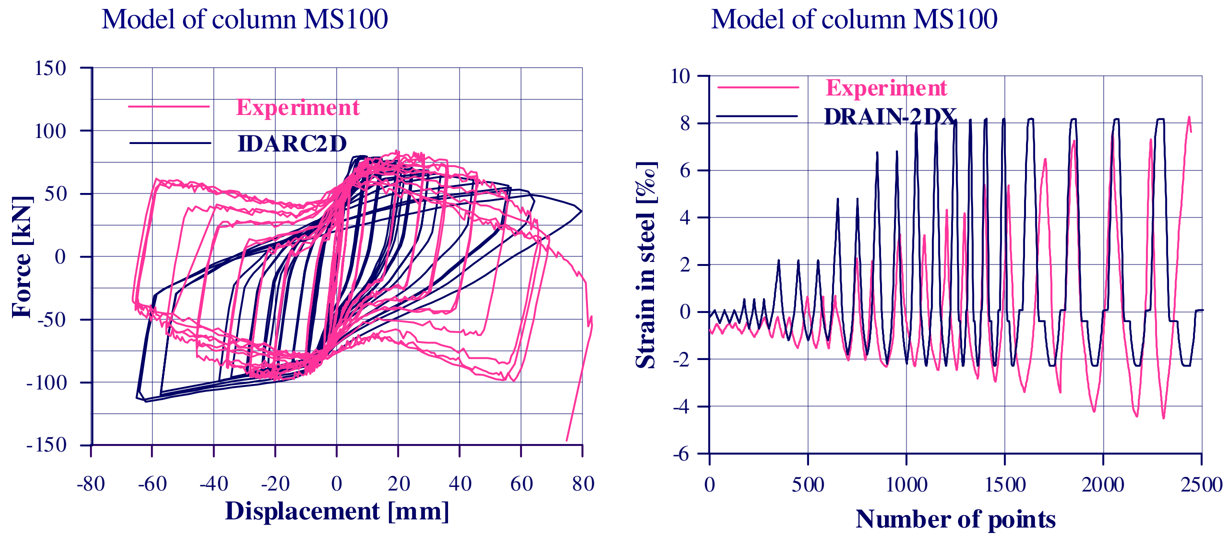


Figure 5. Results from analysis of column models, (selected part) – (continued)

DISCUSSION OF RESULTS AND CONCLUSIONS

Based on the results from the analytical investigations and their correlation with the experimentally obtained ones, the following can be summarized:

- The computer programme MPHI-HSC has been elaborated for obtaining moments, curvatures and strains in concrete and steel for beams and columns constructed of high strength concrete and high quality steel. Taking into account the specific nature of these materials, the corresponding stress-strain diagrams are introduced in the programme. The original σ-ε relationship for high strength concrete proposed by Muguruma [10] is used. The stress-strain diagram of steel is idealized in a bilinear form.
- The comparison between the experimentally recorded and the analytically obtained strain distributions in concrete and steel along cross-sections point to a good agreement for all beam and column models.
- The nonlinear response of the beams and the columns constructed of high strength materials is obtained using nonlinear quasistatic analysis by applying of cyclic displacement history at the free end of the models.
- The results from the nonlinear analysis of the beams and the columns are expressed via histories of displacements, forces and strains in the concrete and in the reinforcement as well as P-Δ hysteretic relationships compared to the experimentally measured ones.
- The correlation between the <u>displacement</u> obtained as a response from nonlinear analysis and applied displacement as an external load is obvious. The maximum displacements, (applied and calculated) in the nonlinear range are similar for all elements.The comparison between the experimentally recorded and the analytically obtained <u>P-Δ relationships</u> point to a good agreement. The obtained hystertic loops for all models of beams and columns are stable and show significant capacity of elements for energy dissipation. The experimentally recorded and the analytically obtained <u>histories of strains in concrete and steel</u> point to a good agreement for all beam and column models. The numerical model gives slightly higher values of strains in the beginning of the loading cycles.
- The results from performed experimental and analytical investigations have shown that with appropriate quality of materials and having done proper reinforcement and confining, the elements are characterised by ductile behaviour and energy dissipation.

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