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HIGH STRENGTH CONCRETE INVESTIGATIONS IN MACEDONIA- RESEARCH, DEVELOPMENT AND APPLICATION

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ABSTRACT:
The IZIIS' contribution to development of high quality materials has been seen in realization of several scientific-research projects in the field of high strength concrete, (HSC) in the period from 1992 to 2006. Within the frames of these projects, synthesis of investigations reported in world literature has been made and complex laboratory-experimental-analytical investigations have been performed to contribute to: definition of the methodology for obtaining HSC exclusively from domestic resources; joint behaviour of high strength materials and elements in nonlinear range as well as definition of criteria and recommendations for application of these materials in seismically active regions. The selected results from these investigations are presented in the paper.

KEYWORDS:
high strength concrete, quasi-static investigations, nonlinear behaviour, ductility, confinement

1. 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.

In the course of the last few years, the conceptual consideration of concrete as material has been changed. It increasingly becomes clear that even minor changes in the composition of the concrete lead to considerable improvement of its characteristics. An exceptional step forward is the addition of silica fume that enables design of high strength concrete mixtures.

With its physical-mechanical characteristics, high strength concrete is the optimal variant for many design problems from the aspect of cost on one hand and efficiency of the solution from the other. For wide use of high strength concrete in modern engineering, it is necessary to recognize that the greater the compressive strength of concrete is, the bigger is the difference between its behaviour and behaviour of ordinary concrete under different loading conditions. The most important difference is in its stiffness, i.e. reduction of ductility. The current interest in this issue is reflected through the increasing number of research projects on world scale during the last ten years. The results from these investigations enabled acquiring of fundamental knowledge on the behaviour of high strength concrete and elements constructed of high strength concrete. The application of high strength concrete and particularly its increasing use in seismic regions poses the question about the applicability of the existing regulations for design of elements and structures of high strength materials in seismic loading conditions. Revision of a major part of design equations is necessary to be done in the regulations for the purpose of ensuring safe and economic application of high strength concrete.

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, (www.iziis.edu.mk). The investigations were carried out in four phases:

(1) First phase, (1992-1996-1998) – the scientific-research project *"Development of a Methodology for High strength Concrete"*, [8].
(2) Second phase, (1998-2000) - project *"Methodology for Obtaining High strength Concrete and its Applications"*, [1, 4].
(3) Third phase, (2000-2003) – project *"Dynamic Behaviour of Elements and Structures Constructed from High strength Materials"*, [1, 12].
(4) Fourth phase, (2004-2006) – project *"Seismic Resistance of High strength Concrete Buildings",* [13].

The principal objectives of investigations have been the following:

- Definition of methodology and design mix proportions for obtaining concrete with compressive strength of up to 100MPa exclusively from local materials and by use of own technology.
- Experimental and analytical investigations of models of high strength concrete beam and columns exposed to cyclic behaviour.
- Investigation of strength and deformability characteristics of elements constructed of high strength materials in conditions of cyclic loading with a special review of joint behaviour of concrete and reinforcement in the nonlinear range.
- Suggestions and guidelines for application of high strength concrete in seismically active regions and creation of a basis for future investigations.
- Following the world trends in development and application of high strength concrete in seismic areas for the purpose of applying the positive experience, recommendations and suggestions should be given for the national design practice.

2. METHODOLOGY OF INVESTIGATIONS

2.1 First phase of investigations, (1992-1996-1998)

The scientific-research project *"Development of a Methodology for High strength Concrete",* [8], financed by the Ministry of Science of R. Macedonia and realized in co-operation with the construction company "Beton", "Ading" and IZIIS, all from Skopje was initiated in 1992. The main purpose of the project was development of a methodology for obtaining high strength concrete from domestic resources. In the period of 1992-1998, experimental investigations of the physical and mechanical characteristics of the concrete components were performed. During this phase, concrete with compressive strength of up to 100 MPa was designed exclusively by using local materials and own technology.

2.1.1 Design Mix of Fresh and Hardened Concrete

Investigations of the physical and mechanical concrete components-aggregate, cement, water and plasticizers, which are necessary for the control of the design mix of high strength concrete obtained from local materials, were performed. All the investigations were performed according to the regulations and the Code of Technical regulations for Concrete and Reinforced Concrete, [17].

High strength concrete mix proportioning is a more critical process then design of ordinary strength concrete mixtures. For the purpose of finding an optimum mix design for high strength concrete, ample investigation of trial batches of fresh and hardened concrete were performed at the Laboratory of the construction company "Beton" and also with the cooperation of ADING, which is the manufacturer of the additives. The following parameters were investigated: consistency, water over cement ratio (W/C), porosity of the mix mass, and density of the fresh concrete, compressive strength and tensile strength.

Analyzing the results from the laboratory investigations, the characteristics of the concrete components, especially the percentage of dosage and water reduction of the superplasticizer, the properties of the fresh concrete mix with a 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[1], MB80 and MB100, were adopted, (table 1).

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

Components/ Classes		MB60, $f_c^{'}$=60MPa	MB80, $f_c^{'}$=80MPa	MB100, $f_c^{'}$=100MPa
Cement	PC45 c "Usje"	C=450 kg/m^3	C=460 kg/m^3	C=500 kg/m^3
Aggregate	I-fr 0-4 mm	43%	40%	40%
	II-fr 4-8 mm	15%	20%	20%
	III-fr 8-11.2 mm	16%	18%	18%
	IV-fr 11.2-16mm	26%	22%	22%
		A= 1815 kg/m^3	A= 1800 kg/m^3	A= 1800 kg/m^3
Water	Well water	V=183 l/m^3	V=136 l/m^3	V=150 l/m^3
Additives	Superplasticizer	SFL = 9.0 kg/m^3	SFL = 18.4 kg/m^3	SFL = 17.5 kg/m^3
	Microsilica	/	Microsilica 36.8 kg/m^3	Microsilica 40.0 kg/m^3
Data on the fresh concrete				
Water/Cement		W/C = 0.407	W/C = 0.296	W/C = 0.30
Consistency		s = 13cm	s = 9cm	s = 7cm
Porosity		Not tested	Not tested	p=2.3%
Density	Fresh mixture	γ=2430 kg/m^3	γ=2460 kg/m^3	γ=2428 kg/m^3
	After 3 days	γ=2450 kg/m^3	γ=2500 kg/m^3	γ=2480 kg/m^3
	After 7 days	γ=2463 kg/m^3	γ=2465 kg/m^3	γ=2480 kg/m^3
	After 28 days	γ=2478 kg/m^3	γ=2480 kg/m^3	γ=2456 kg/m^3
	On testing day	γ=2456 kg/m^3	γ=2481 kg/m^3	γ=2477 kg/m^3

2.2 Second phase of investigations, (1998-2000)

Within the frames of the project *"Methodology for Obtaining High strength Concrete and its Applications"*, [4], a synthesis of investigations reported in world literature has been made and complex laboratory-experimental-analytical

[1] Concrete class represents standardized compressive strength of concrete based on the characteristic strength tested on concrete cubes (20x20x20cm) aged 28 days, [17].

investigations have been carried out for the purpose of contributing to defining of the interactive behaviour of high strength materials (high strength concrete and reinforcement) in the nonlinear range as well as definition of criteria and recommendations for application of these materials in seismically active regions, [15].

2.2.1 Quasi-static Investigations of High strength Concrete Elements Performed at IZIIS

In the second phase of the investigations, design, construction and quasi-static tests on beam and column models constructed of high strength concrete and steel have been performed, [10,11]. For the needs of the experimental investigations, three beam and three column models were designed as fixed cantilever elements. The elements were designed in compliance with the requirements of PBAB'87, [17] as well as the recommendations and the suggestions given in the world literature [2, 5, 6, 7, 14]. The varied parameters were the concrete compressive strength (MB60, MB80, and MB100), the reinforcement percentage and the yielding strength of the longitudinal and the transversal reinforcement (RA400/500 and high strength steel ULBON with quality SBPD 1275/1420 produced by the Japanese company NETUREN). The models were constructed to a geometrical scale of 1:1. The experimental investigations were performed in the Dynamic Testing Laboratory in IZIIS, by use of equipment for quasi-static tests and simulation of a cyclic loading regime, whereat was observed their behaviour in the linear and nonlinear range. A constant axial force was applied on the column models. All the models were tested in horizontal position.

2.2.2 Characteristics of the Built-in Materials

In order to completely control the designed and built-in concrete (tab.1) laboratory investigations of the concrete to be built in the models were done. Concreting of the models was performed in three series for three different concrete classes. Simultaneously with the construction and concreting of the models, several concrete samples, (cubes, prisms and cylinders) were taken. These samples were used for laboratory investigations of the concrete compressive strength, concrete tensile strength and modulus of elasticity of built-in concrete. Results obtained from laboratory investigations of concrete compressive strength, tensile strength and static modulus of elasticity are presented bellow, (table 2).

Table 2. Mechanical characteristics of concrete classes MB60, MB80 and MB100

Concrete class	Compressive strength [MPa]				Tensile strength [MPa]	Modulus of elasticity [MPa]
	3 day	7 day	28 day	* note		
MB 60	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 strength values have been measured on the day of the experiments i.e. MB60 on the 154th day, MB80 on the 140th day and MB100 on the 139th day.

2.2.3 Design and construction of models

The beam and column models are full scale models designed according to the "Code of Technical Regulations of Concrete and Reinforced Concrete", [17], EC2, [5] and recommendation and suggestions that are given in the world literature for design of high strength reinforced concrete elements [2, 7]. Chosen geometry of models dictates that the dominant mode of behavior is flexural bending. Strength characteristics of used concrete and steel, as well as percentages of reinforcement for beam and column models are given in Tables 3 and 4.

Table 3. Characteristics of materials built-in the beam models

Specimen L=2.29m	MB [Mpa]	Longitudinal reinforcement			Transversal reinforcement			
		Steel grade	A_{ten} [cm2]	$\rho_{v,mech}$ [%]	Steel grade	fyh [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

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

Specimen L=2.0m	MB [Mpa]	P/Po	Longitudinal reinforcement			Transversal reinforcement		
			Steel grade	A_{ten} [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

2.2.4 Equipment and Instrumentation

The experimental investigations were carried out in the Dynamic Testing Laboratory of IZIIS, under quasi-static regime of loading. The disposition of the beam and column models as well as the equipment for the quasi-static testing is given in Fig.1. Two types of instrumentation were used, internal (strain gages on reinforcement) and external instrumentation, (clip-gages). The experiments were conducted through displacement control. Depending on the observed behavior of the element models, the loading programme was corrected, [4].

Figure 1. Disposition of the beam and column models and the equipment during quasi-static tests

2.2.5 Results from the Experimental Investigations

The experimental investigations of elements were performed in two separate phases. In the first phase, a series of three beam models was tested, (MGR60-TEST1, MGR80-TEST2 and MGR100-TEST3). The column models, (MS60-TEST4, MS80-TEST5 and

MS100-TEST6) were investigated in the second phase. The results obtained from the experimental investigations are presented through hysteretic relationships between forces and displacements, force and strains, (in concrete and reinforcement) and displacement history, (fig. 2). The photos showing damage distributions on the models of beams and columns are also given, (fig. 3). Presented further are selected results obtained from the experimental tests. Obtained experimental results point to ductile behaviour of the models and energy dissipation, [4].

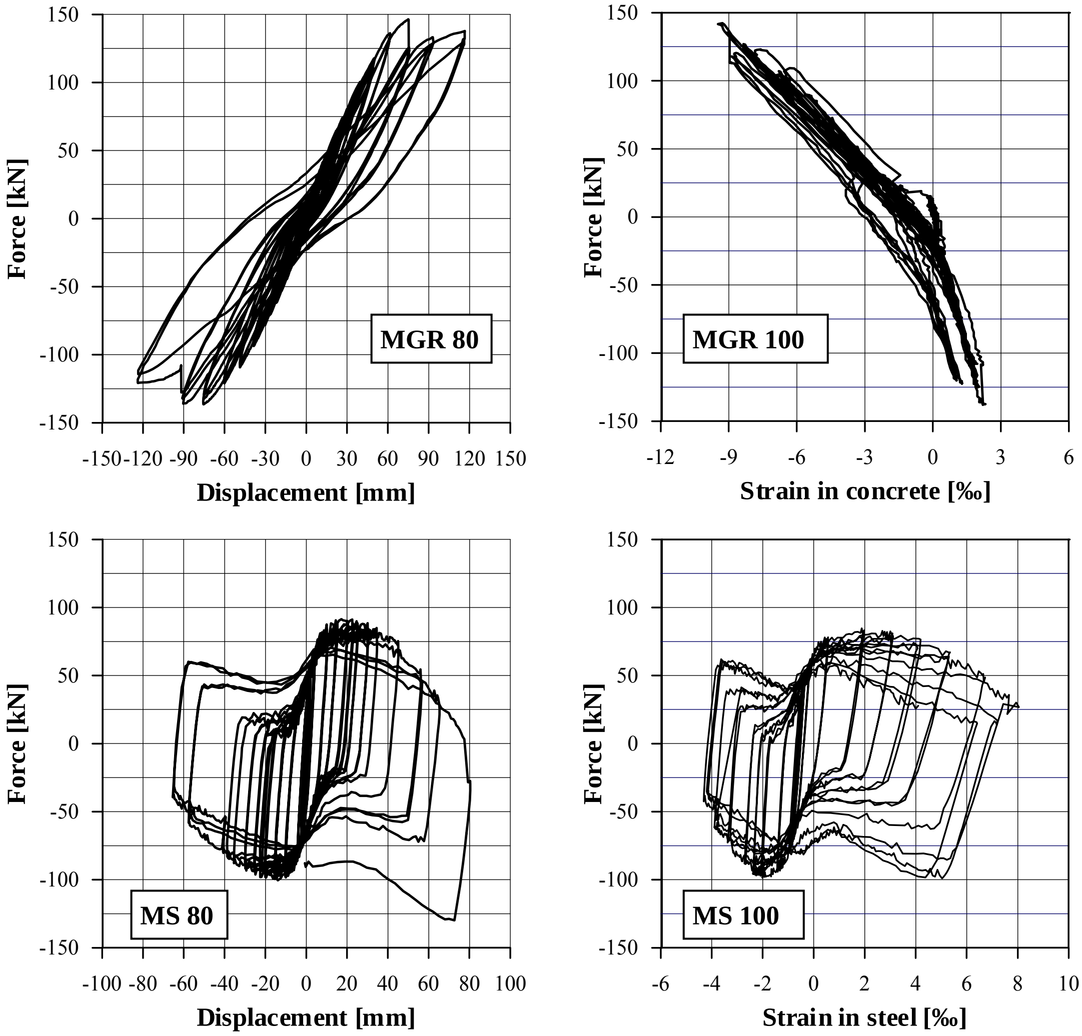


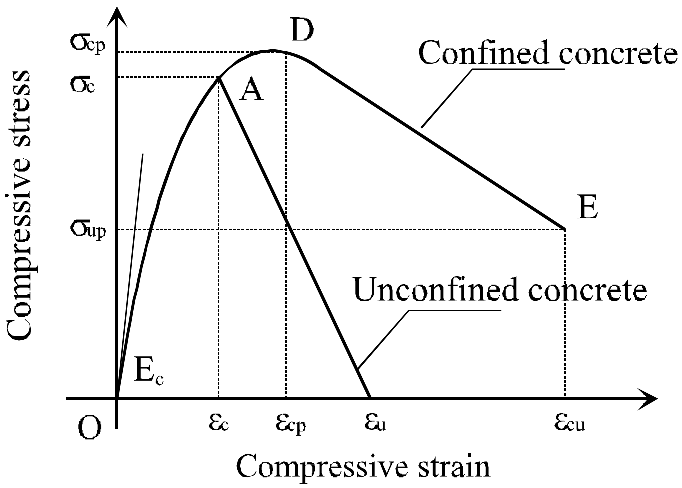
Figure 2. Results from experimental investigations of beam and column models, (selected part)

Figure 3. Experimental investigations of beam and column models, (damage observation)

2.3 Analytical Modeling of Nonlinear Behaviour of High strength Concrete Elements

2.3.1 Analytical Definition of the M-ϕ Relationship

The analytical definition of the M-ϕ relationship for the beam and column cross-sections made of high strength materials were done based on the "fiber model analysis" procedure [18]. For that purpose, the computer programme MPHI-HSC has been elaborated, [1]. Taking into account the specific nature of the high strength concrete as material, the original σ-ε relationship for high strength concrete proposed by Muguruma, Watanabe et al, [9], (fig. 4) was introduced in the programme. This relationship is relatively simple and sufficiently general to cover a wide range of compressive strength of concrete as well as different forms of cross-sections and reinforcement that are applied in practice.



The computer program MPHI-HSC has been used to analytically define moments, (M), curvatures, (ϕ) and strains in concrete, (ε_c) and steel, (ε_s), at selected points of the beam and column models. Presented further are the selected results of experimentally measured and calculated values for characteristics profiles of strains in concrete and reinforcement, a well as values of curvatures, moments and forces, (Table 5).

Figure 4. σ-ε relationship of high strength concrete after Muguruma, Watanabe et al.

Table 5. Strain distributions, curvatures and moments for the beam and column models - selected results

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
Profile 3	1.72	6.48	2.280	239.4	115.1
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

The experimentally measured and calculated values for strains, curvatures and moments have shown good correlation.

2.3.2 Nonlinear quasi-staic analysis and results

The main purpose of the performed nonlinear quasi-static 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 quasi-static experimental investigations. 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"). Nonlinear quasi-static analyses were performed using IDARC2D, [18] and DRAIN-2DX, [16] computer programs.

The results from the analyses are presented through time histories of displacement and forces, hysteretic force-displacement relationships as well as histories of strains in concrete and reinforcement. The correlation between the experimentaly measured and the calculated values are also given. The presented results correspond to the specific set of parameters of the hysteretic model. Presented further is a selected part of the results, (fig. 5) obtained by nonlinear quasi-static analysis of models of beam and columns constructed of high strength materials, [1].

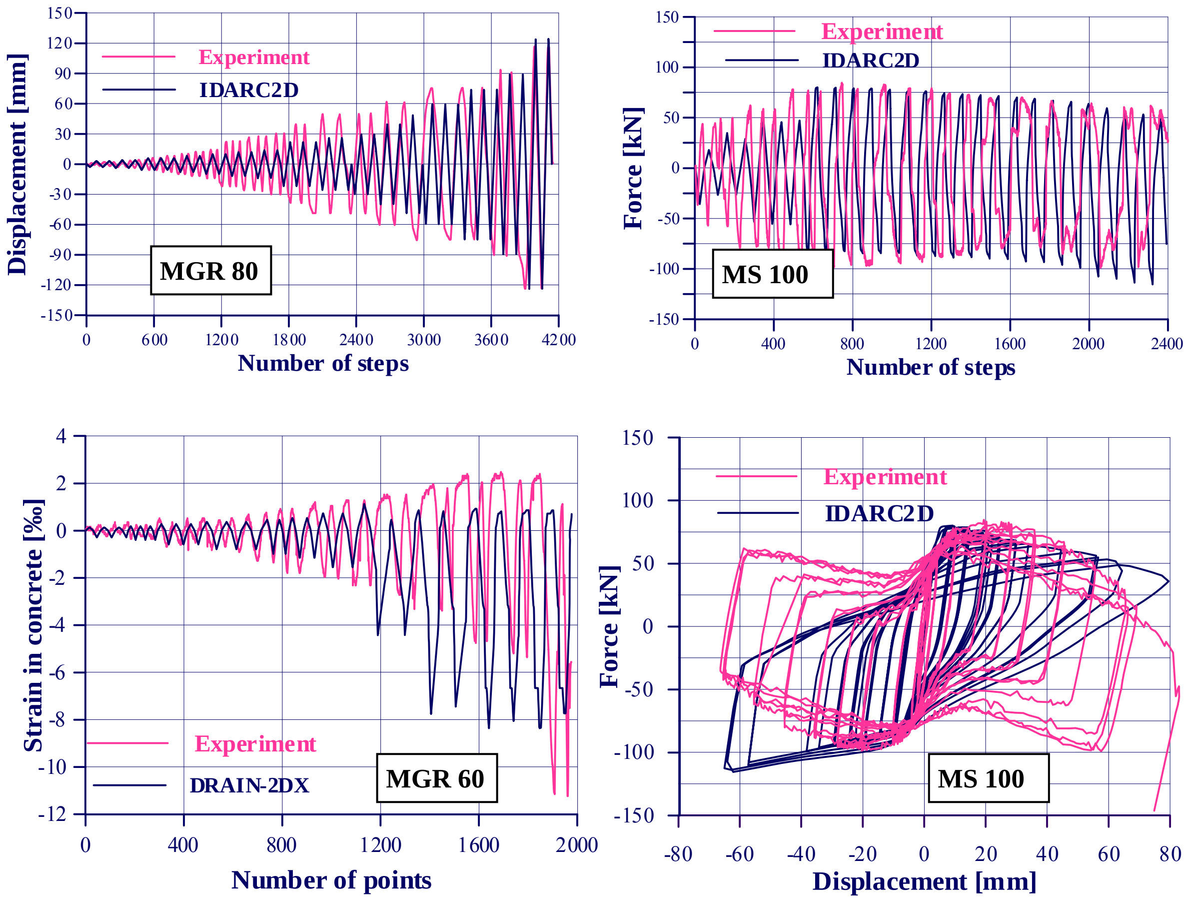


Figure 5. Selected results from the analysis

2.4 Third phase of investigations, (2000-2003)

The results from the previously performed quasi-static investigations represented the basis for the realization of the third phase of investigations, [12]. The main purpose of the project was analytical definition of nonlinear behaviour of high strength RC building structures exposed to real earthquake effects. Within the frames of this project, experimental and analytical investigations of dynamic behaviour of elements and structures made of high strength materials, worldwide have been presented. Comparative analytical investigations of dynamic behavior of reinforced concrete five story building design from different classes of concrete exposed to real earthquakes have also been performed (fig. 6).

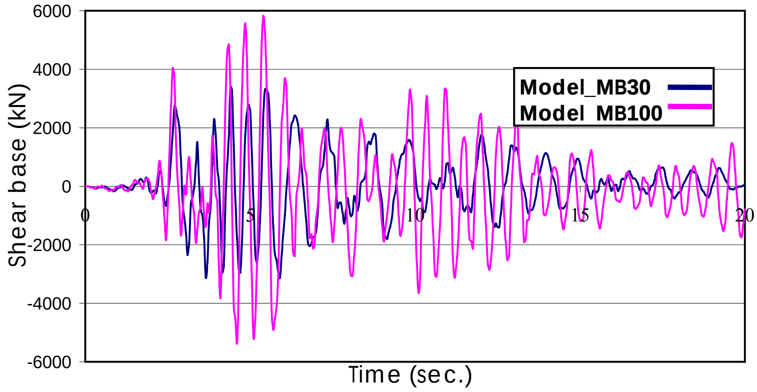


Figure 6. Shear base time history

2.5 Fourth phase of investigations, (2004-2006)

The main objective of the investigations within this phase is definition of the nonlinear response and seismic resistance of buildings designed of concrete with compressive strength of 60 to 100MPa exposed to actual seismic effects of different intensity and frequency content, [13]. To realize this goal, the bearing and deformability capacity of elements designed of high strength concrete and steel has analytically been defined. Presented further are the realized parametric dynamic analyses of the designed models exposed to actual seismic effects. The subject of the analyses have been four models of buildings designed as: 7 storey frame structure – model M1, 15 storey frame structure – model M2, 15 storey structure composed of frames and walls – model M3 and 25 storey structure – mixed structural system – model M4, (fig. 7).

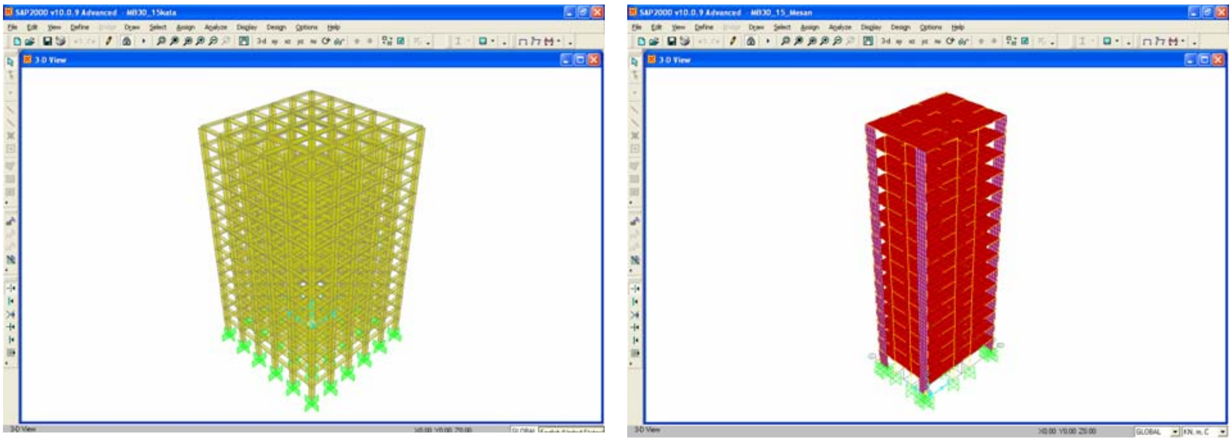


Figure 7. 3D- view of models M2 and M3

The results obtained from the analytical investigations of the nonlinear response of the models of RC buildings designed of high strength concrete exposed to actual seismic effect show that the designed models have favorable dynamic characteristics, (fig. 8).

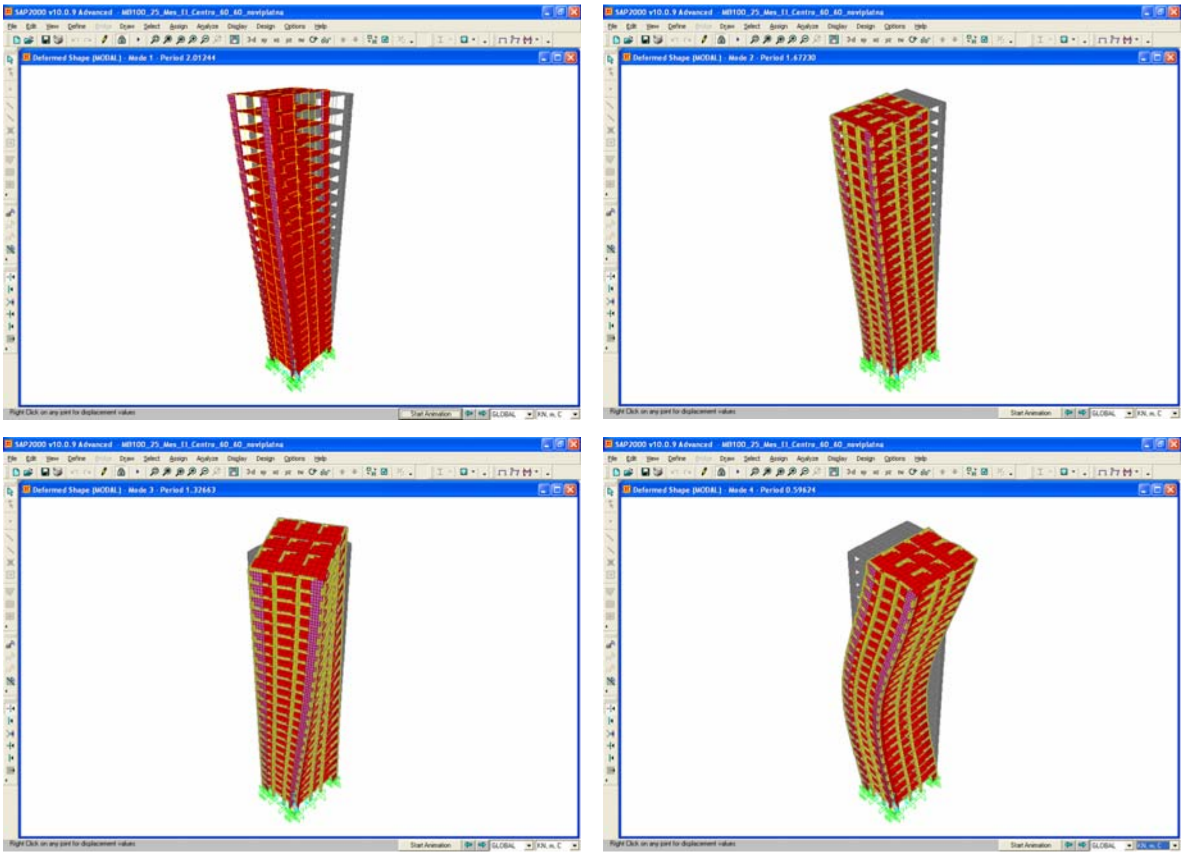


Figure 8. Vibration modes of the model M4

Results from dynamic response of the structural system of model M3 design with concrete compressive strength of 100MPa and different steel grade compare with referent model M3 design from normal strength concrete are presented in table 6.

Table 6. Results from comparative analysis of M3 model

	b/h [cm]	f_Y [MPa]	ρ [%]	K	T_1 [sec]	$\Delta_{Y,top}^{(*)}$ [cm]	$\Delta_{doz,top}$ [cm]	S_{BASE} [kN]	CR
MB30	**75/75**	**400**	**1.11**	**0.218**	**1.187**	**4.18**	**7.50**	**2576**	**0.344**
MB100(1)	40/40	400	3.6	0.218	1.305	4.49	7.50	2168	0.226
MB100(2)	40/40	1300	1.11	0.218	1.305	4.45	7.50	2168	0264

(*) Note: Displacement are calculated based on EC8 design spectra

Dynamic response of the building model M4 exposed to El-Centro earthquake with Amax=0.32g are express through time histories of the absolute displacement at the top of the structure and shear base force, (fig.9).

The seismic response of the designed models are expressed in the form of maximum displacements at the top of the structure, time histories of displacements and forces and actual stress in the columns due to critical loading combinations compared to their capacity - (CR). Results from analysis of building models design from high strength concrete show good correlation with the referent models designed of traditional materials.

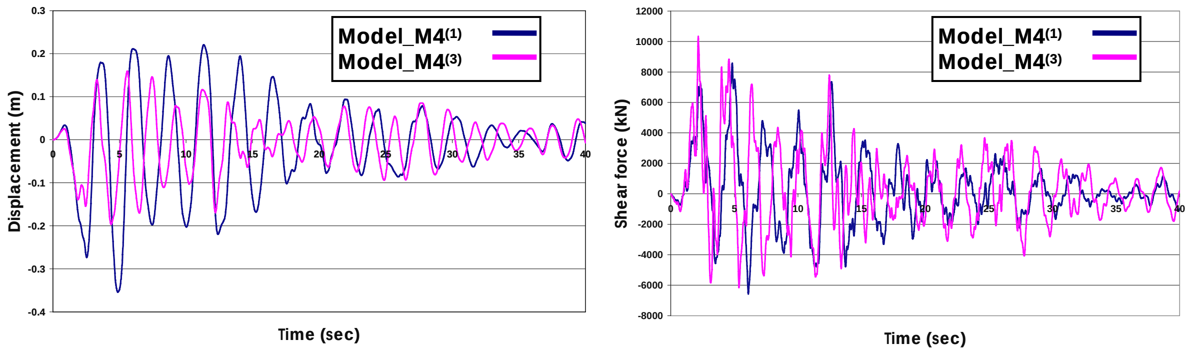


Figure 9. Time histories of top displacement and shear base force – model M4

Note: Both models (M4(1) and M4(3)) are design with concrete compressive strength of 100MPa. The model M4(3) has additional walls in x-x direction.

3. RECOMMENDATION AND CRITERIA FOR ANALYSIS AND DESIGN OF HIGH STRENGTH ELEMENTS

Based on the investigations of the world experience and own analytical and experimental research, [1], efforts have been made to give recommendation for analysis, (elasticity modulus, tensile strength and the stress-strain diagram of the concrete) and design, (minimal and maximal reinforcement percentage, volume percentage and the yielding strength of the confining reinforcement) of bearing elements constructed of high strength concrete.

3.1 Modulus of elasticity

Presented in the table 7 are the calculated values of the static modulus of elasticity of three different classes of concrete according to suggestions given in the world literature. In all investigations, modulus of elasticity is expressed as a function of concrete compressive strength and volume mass of concrete, [7].

Table 7. Recommendation for the static modulus of elasticity of high strength concrete, [7]

	E_c (MPa)	MB60	MB80	MB100
*ACI 318-95	$0.043\rho^{1.5}\sqrt{f_c^{'}}$	37431	43694	48294
ACI 363	$3320*\sqrt{f_c^{'}}+6900$	30329	33953	37147
Lambotte	$9500\left(f_c^{'}\right)^{1/3}$	34953	38469	41440
Cook	$2.8*10^{-5}\rho^{2.55}\left(f_c^{'}\right)^{0.315}$	43326	48319	50837
Ahmad	$3.38*10^{-5}\rho^{2.5}\left(f_c^{'}\right)^{0.325}$	36794	41137	43394
Tachibana	$3950\sqrt{f_c^{'}}+1560$	29435	33747	37546
CEB, Bulletin 228	$E_{co}\left[\left(f_c^{'}+\Delta f\right)/f_{cmo}\right]^{0.3}$	37239	40169	42671
Macedonian code, PBAB	$9.25\sqrt[3]{f_{bk}+10}$	38000	**	**
*** Experimental investigations performed by authors		31057	32216	33400

*Equation is not calibrated for high strength concrete and gives bigger values for $f_c^{'}$ >40MPa

** In Macedonian Code, (PBAB) concretes with compressive strength bigger that 60Mpa are not allowed

*** Mean values of measures from three concrete samples-cylinders

Based on world experience and the recommendation of the great number of researchers, as well as own performed experimental investigations it is suggested that the expression, (eq.1) given in the recommendations of the ACI Committee 363, [2] can be used for computation of the static modulus of elasticity of high strength concrete,

$$E_c = 3320 * \sqrt{f_c'} + 6900 \qquad (1)$$

f_c' - cylinder concrete compressive strength, [MPa]

3.2 Tensile Strength

The brief review of the possible equations using for calculating tensile strength of high strength concrete is given in Table 8, [7].

Table 8. Recommendation for the tensile strength of high strength concrete

	f_r' (MPa)	MB60	MB80	MB100
ACI 318-95	$0.62 * \sqrt{f_c'}$	4.37	5.05	5.65
ACI 363	$0.94 * \sqrt{f_c'}$	6.63	7.66	8.56
New RC	$1.26 * \left(f_c'\right)^{0.45}$	7.31	8.32	9.20
Ahmad and Shah	$0.44 * \left(f_c'\right)^{0.67}$	6.03	7.31	8.49
Setunge	$0.44 * \left(f_c'\right)^{0.65} \pm 25\%$	7.54/4.52	9.13/5.48	10.6/6.4
CEB, Bulletin 228	$f_{ctko,m} * \left((f_{ck} + \Delta f)/(f_{cko} + \Delta f)\right)^{0.6}$	3.62	4.22	4.76
Macedonian code, PBAB	$0.25 * \sqrt{f_{bk}^2}$	3.8	**	**
*** Experimental investigations performed by authors		7.62	7.37	9.12

Using own experimental investigations in correlation with world experience, two expressions are recommended: the first one, (eq. 2) according to ACI Committee 363, [2] and the second one, (eq. 3) is the outcome from the research within the frames of the New RC - Japan Project, [7].

$$f_r' = 0.94 * \sqrt{f_c'} \qquad (2)$$

$$f_r' = 1.26 * \left(f_c'\right)^{0.45} \qquad (3)$$

3.3 Proposed Models for the Stress-strain Relationship for High strength Concrete

From the own analytical and experimental investigations, [1] as well as from the investigation of different σ-ε relationships for high strength concrete given in literature, for analytical definition of the bearing and deformability capacity of elements constructed of high strength materials two different mathematical models are proposed.

Muguruma & Watanabe et al. [9] model, (fig. 10) and Cusson & Paultre, [3] model, (fig. 11) are proposed for application in detailed analytical investigations.

- **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**

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

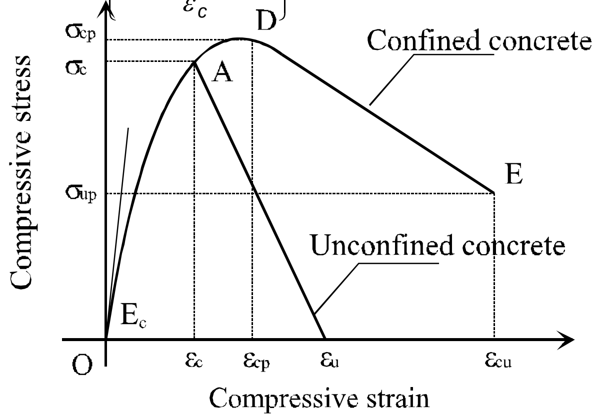


Figure 10. σ-ε relationship of high strength concrete, Muguruma & Watanabe et al.

- **Ascending branch (OA)**

$$\sigma_c = f_{cc}' * \left[\frac{K * (\varepsilon_c / \varepsilon_{cc}')}{K - 1 + (\varepsilon_c / \varepsilon_{cc}')^K} \right]$$

- **Descending branch (ABC)**

$$\sigma_c = f_{cc}' * e^{\left[K_1 * (\varepsilon_c - \varepsilon_{cc}')^{K_2}\right]}$$

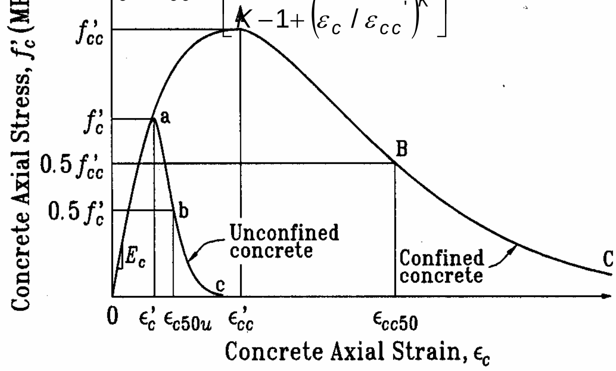


Figure 11. σ-ε relationship of high strength concrete, Cusson & Paultre

As to the design practice two options are generally recommended for the distribution of the compressive stresses, i.e., the triangular and the rectangular distribution. Here, certain modifications should be introduced in parameters α and β that define the block of stresses.

3.4 Minimum Reinforcement Ratio for High strength Concrete Beams

Using the investigations in the world literature for obtaining of the minimum reinforcement ratio for high strength concrete beams with rectangular cross-section, it is suggested that ACI Committee 363, [2] recommendation, (eq. 4) is acceptable.

$$\rho_{min} \geq \frac{\sqrt{f_c'}}{4.5 * f_y} \qquad (4)$$

(f_c', f_y in MPa)

f_c' - cylinder concrete compressive strength

f_y - yield strength of longitudinal reinforcement

The minimum reinforcement ratio for high strength concrete beams according to ACI regulations, [2] and our national code, [17] for two different yield strengths of longitudinal reinforcement are presented in Fig. 12. It is obvious that for the same concrete compressive strength, the increase of the yield strength leads to a decrease of the minimum reinforcement ratio.

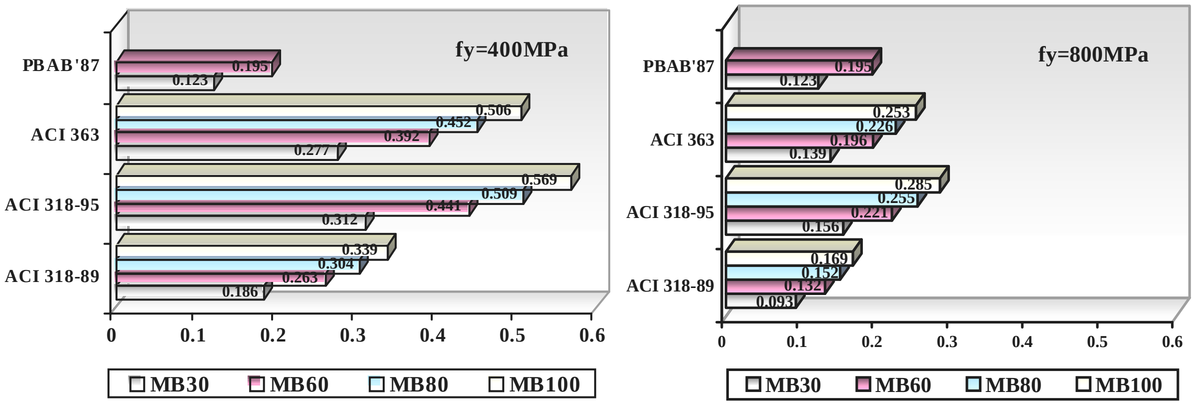


Figure 12. Minumum reinforcement ratios for high strength concrete beams

3.5 Maximum Reinforcement Ratio and Ductility of High strength Concrete Beams

In order to provide ductile behaviour of high strength concrete beams the definition of the maximum reinforcement ratio is necessary. Research connected with ductility of high strength concrete beams has shown that the current limitation of the maximum percentage of reinforcement in beams $\rho \leq 2.5\%$ (for seismic regions), [7] is adequate also for high strength beams. If they are applied in seismic prone areas, compressive reinforcement and stirrups will also be necessary.

3.6 Confinement and Ductility of High strength Concrete Columns

Ductility of the high strength concrete columns is a key issue in providing overall strength and stability of seismic design structures. Investigations show that high strength concrete columns are brittle elements except when they are properly confined. For the same distribution of reinforcement, the compressive strength of concrete and the ductility of the column are inversely variated.

From the investigations given in literature, [7, 9] the following suggestions should be taken in account in design of seismically resistant high strength concrete columns:

- The relationship between the confined concrete core and the total cross-section of the high strength concrete should be greater than the defined critical value (0.7 according to NZS 3101:1995).
- Having no definite design criteria, it can be inferred that the New Zealand' codes NZS 3101:1995 are acceptable for computation of the necessary area of confining reinforcement, (eq. 5)

$$A_{sh} = \left(\frac{1.3 - p_t m}{3.3}\right) s_h h'' * \frac{A_g}{A_c} * \frac{f_c'}{f_{yt}} * \frac{N^*}{\phi f_c' A_g} - 0.006 s_h h'' \qquad (5)$$

where: $p_t = \frac{A_{st}}{A_g}$ and $m = \frac{f_y}{0.85 f_c'}$

A_{st} - total cross-sectional area of longitudinal reinforcement

A_g - gross section of concrete

A_c - cross-sectional area of concrete core measured center-to-center of outer tie
s_h - center-to-center spacing between sets of ties
h'' - depth of concrete core measured out-to-out peripheral hoop
f_{yt} - yield strength of transverse reinforcement steel
N^* - axial load
ϕ - strength reduction factor

- The current experimental results point out that the effect from the transverse reinforcement configuration and the axial force level must be taken into account in design of confining reinforcement. Because of high percentage of transverse reinforcement (higher than 4%) which is hardly feasible in practice, the solution to the problem could be the use of high strength reinforcement. NZS 3101:1995 limit the yielding strength of transverse reinforcement to 800 MPa.

4. CONCLUSIONS AND RECOMMENDATIONS

- High strength concrete is a composite material consisting of a filler, cement, water and additives of the type of silica powder, fly-ash and additives for water reduction (plasticizers).
- High strength concrete is characterized by high strength and low deformability. The experimental investigations that have been performed throughout the world show that HSC elements having sufficient strength and deformability can be obtained by special construction of elements (i.e. confinement of concrete).
- Following the modern world trends, it is already more then 10 years that IZIIS has been working in the field of development and application of high strength concrete in modern engineering practice. An original methodology for production of high strength concrete with compressive strength of up to 100 MPa from domestic resources has been developed. Quasi-static experimental investigations of beams and columns constructed of high strength concrete and steel exposed to cyclic forces have also been performed. The ample laboratory, experimental and analytical investigations that were performed within the frames of the above outlined scientific research projects and the synthesis of knowledge from the world literature have led to definition of criteria and recommendations for application of high strength concrete in design of seismically resistant structures.
- The results obtained from the performed experimental and analytical investigations carried out in IZIIS have shown that, by appropriate selection of the quality of materials and proper reinforcement and confinement, the elements constructed of high strength materials exposed to cyclic loads exert ductile hysteretic behaviour with favorable energy dissipation.
- The investigations reported in world literature and the experimental and analytical investigations performed in IZIIS have provided considerable knowledge on the application of high strength concrete in design of seismically resistant structures. It should be point out that the safe and economic application of high strength concrete in seismically active regions depends on the relationship between the required ductility and area and the configuration of the transverse reinforcement. When the columns are exposed to large axial forces, considerable amount of transverse reinforcement is necessary.

To enable mass application of high strength concrete in seismic prone regions, further investigations should be focus to experimental and analytical investigations for more realistic definition of nonlinear behaviour of elements, parts of structures and structures exposed to actual seismic loads.

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