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APPLICATION OF HIGH STRENGTH CONCRETE IN DESIGN OF SEISMICALLY RESISTANT STRUCTURES

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SUMMARY

The application of high strength concrete, (HSC) and particularly its increasing use in sesimic regions poses the questions about the applicability of the existing regulations for design of seismically resistant structures. Revision of the major part of design equations is necessary to be done in the regulations for the purpose of ensuring safe and economic application of HSC concrete. Such trends in structural engineering have been the main incentive for the initiation of research projects in the field development and application of HSC in the Institute of Earthquake Engineering and Engineering Seismology, IZIIS-Skopje. The need of special provisions to ensure sufficient ductility in application of HSC in design of seismically resistant structures was one of the main objectivities of these investigations

A synthesis of investigations reported in the world literature together with own complex experimental and analytical investigations have been carried out in IZIIS for definition of criteria and reccomendation for application of HSC in seismically active regions. In the process of analysis the main problems imposed in definition of ultimative bearing and deformation capacity of HSC elements are: definition of modulus of elasticity, tensile strength and stress-strain diagram of HSC. In the design procedure of seismically resistant HSC elements and structures among the other parameters, it is necessary to define the criteria for minimal and maximal reinforcement precentage, the effect of axial forces, as well as the efficiency of confinement reinforcement.

The part of the results obtained from the investigations carried out in IZIIS-Skopje, as well as the correlation between experimentally measured and analytically obtained results are presented in the paper.

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Based on world experience and own investigations, reccomendations and criteria for all above mention parameters, as well as for application of HSC in design of sesimically resistant structures are given.

INTRODUCTION

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 the behaviour of ordinary concrete under different loading conditions. The most important difference is in its stiffness, i.e., reduction of ductility. Hence, the fact that high strength concrete as a new construction material offers greater strength cannot be the only and decisive factor for its mass application. From the viewpoint of seismic resistance, investigations of deformability of this material as well as the possibility for absorption and dissipation of seismic energy are necessary.

The increased application of high strength concrete in seismic regions poses the question regarding the usability of the existing regulations for design of elements and structures of high strength materials for seismic loading conditions. The current interest in this issue is reflected through the great numbers of research projects have been realized within world frames for the last two decades. On the other hand, further investigations for complete regulations for design and use of high strength concrete particularly in seismically active regions are necessary.

Such modern trends of development and application of new materials have been the main motive and impulse for initiation of scientific-research projects in the field of development and application of high strength concrete also by the Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Skopje, R. Macedonia.

To contribute to the definition of the joint behaviour of the high strength materials (concrete and reinforcement) in the nonlinear range of behaviour as well as define recommendation and criteria for application of these materials in design of seismically resistant structures, ample analytical and experimental investigations have been done.

The principal objectives of these investigations have been the following:

- Investigation of strength and deformability characteristics of elements constructed of high strength materials in conditions of cyclic loading with a special review of the joint behaviour of concrete and reinforcement in the nonlinear range of behaviour.
- Definition of criteria and recommendations for application of high strength concrete in seismically active regions.
- Following of world trends in development and application of high strength concrete in seismic areas for the purpose of applying the positive experience, the recommendations and the suggestions in the national design practice.

INVESTIGATIONS IN THE FIELD OF HIGH STRENGTH CONCRETE-IZIIS EXPERIANCE

Within the frame of the research projects carried out in IZIIS, complex laboratory-experimental and analytical investigations have been performed.

In the first phase of investigations the designed mixture proportions for high strength concrete class MB60, MB80 and MB100 exlusively from domestic resources have been defined. The compressive strength, (note that in Fig. 1 values marked with * were measured on the exact day of the experiments e.i. MB60 on 154day, MB80 on 140day and MB100 on 139 day), the tensile strength and the static elasticity modulus values were obtained from the laboratory tests on trial samples performed in the laboratory of "Beton" and the Civil Engineering Faculty in Skopje, Necevska-Cvetanovska [1].

In the second phase of investigations design, construction and quasi-static tests on beam and column models composed of high strength materials (concrete and reinforcement) have been performed, Necevska-Cvetanovska [1]. For the needs of the experimental investigations, three beams and three column models were designed as fixed cantilever elements. The elements were designed in compliance with the requirements pursuant to the Book of Regulations for Concrete and Reinforced Concrete, (PBAB'87) as well as the recommendations and the suggestions given in the world literature for design of structural elements to be constructed of high strength materials, (ACI Committee 363 [2] and French [3]). The varied parameters were the concrete compressive strength (MB60, MB80, and MB100), the reinforcement percentage and the yielding strength of the vertical and horizontal reinforcement (RA400/500 and high strength steel ULBON with quality SBPD 1275/1420 produced by Japanese company NETUREN). The models were constructed to a geometrical scale of 1:1. The experimental investigations of the elements constructed of high strength concrete and reinforcement 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.

The results from the experimental investigations of beam and column models, (Apostolska-Petrusevska [4], Necevska-Cvetanovska [5] and Necevska-Cvetanovska [6]) are presented in the form of time histories of displacement, force – displacement and force-strains (in concrete and reinforcement). The photos showing damage distribution on the models of beam and columns are also given, (Fig. 2). The obtained experimental results show that by appropriate selection of the quality of materials and proper reinforcement, the models exposed to cyclic loads exert ductile hysteretic behaviour with favorable energy dissipation. In this way, the main disadvantages of the high strength concrete as material, i.e., its brittleness is overcome.

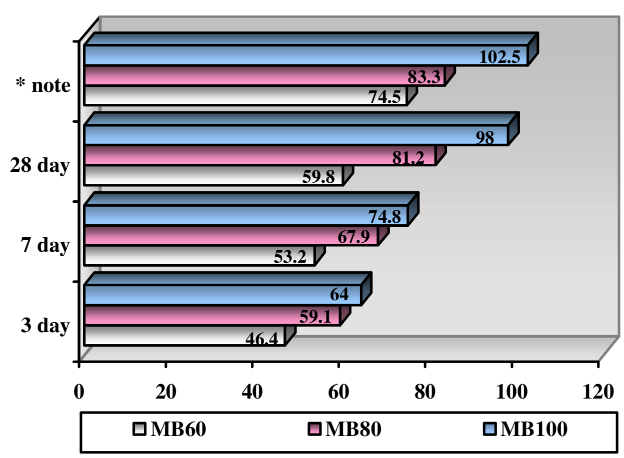


Figure 1. Concrete compressive strength, [MPa]

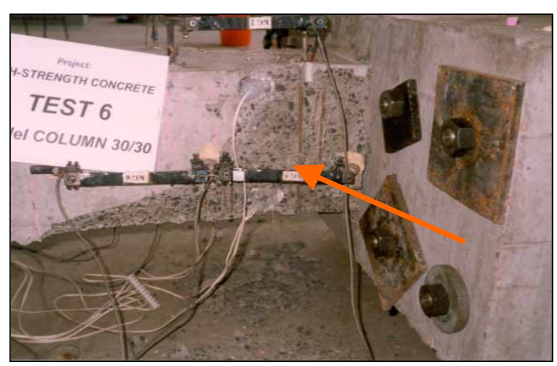


Figure 2. Damage distribution, column-MS100

The research investigations continued with analytical definition of the bearing and deformability capacity of the beams and the columns constructed of high strength materials for which computer programme

MPHI-HSC has been elaborated, Apostolska-Petrusevska [4]. The algorithm of definition of moments and curvatures with this computer programme completely follows the procedure of fiber-model analysis. Having in mind the specific nature of the high strength concrete as material, the original σ-ε relationship for high strength concrete proposed by Muguruma [7] that is many-faceted and widely applicable has been introduced in the programme. The computed moments and curvatures represent the input for the nonlinear quasistatic analysis performed by usage of the computer programmes IDARC2D, Valles [8] and DRAIN-2DX, Prakash [9] that enabled analytical definition of the hysteretic behaviour of the elements in conditions of cyclic loads. The analytically obtained results are presented in the form of histories of strains, displacements, forces and force-displacement relationships and these have been compared to the corresponding experimentally obtained results, (Fig. 3).

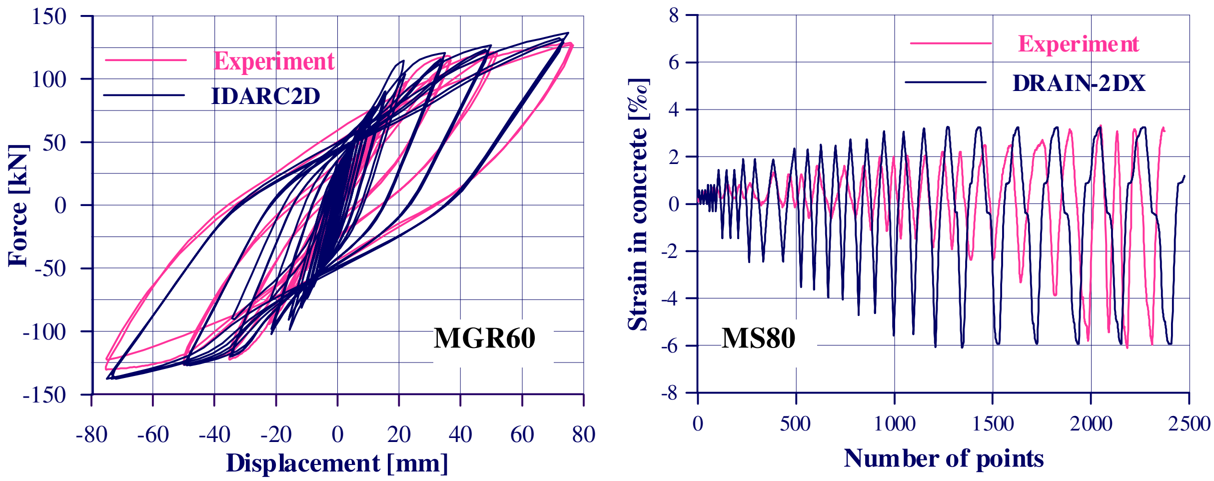


Figure 3. Force-displacement relationship and history of strain

Detailed presentation of all research investigations carried out in IZIIS can be found in Apostolska-Petrusevska [4], Necevska-Cvetanovska [1], Gavrilovic [10], Necevska-Cvetanovska [5], Necevska-Cvetanovska [6] and Petrusevska [11].

RECOMMENDATION AND CRITERIA FOR ANALYSIS AND DESIGN OF HIGH STRENGTH CONCRETE ELEMENTS-BRIEF REVIEW OF WORLD EXPERIENCE AND RESEARCH PERFORMED IN IZIIS

Based on the investigations of the world experience and own analytical and experimental research performed in IZIIS, efforts have been made to give recommendation for analysis and design of bearing elements constructed of high strength concrete.

In the process of analysis, the main problems imposed in definition of the ultimate bearing capacity and deformability of beams and columns constructed of high strength concrete are: definition of the elasticity modulus, tensile strength and the stress-strain diagram of the concrete.

To design seismically resistant high strength reinforced concrete elements - beams and columns, it is necessary to define: the criteria for minimal and maximal reinforcement percentage, the effect of axial forces in the columns, the effect of volume percentage and the yielding strength of the confining reinforcement, the anchorage length etc. Based on world experience and the performed investigations within the frames of the research projects carried out in IZIIS, the recommendations presented further for design of beams and columns exposed to short and long term loading can be applied.

Recommendation and Criteria for Analysis

Modulus of Elasticity

Presented in the table 1 are the calculated values of the static modulus of elasticity of three different classes of concrete acording to sugestions 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.

Table 1. Recommendation for the static modulus of elasticity of high strength concrete, French [3]

	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	$9500(f_c')^{1/3}$	34953	38469	41440
Cook	$2.8*10^{-5}\rho^{2.55}(f_c')^{0.315}$	43326	48319	50837
Ahmad	$3.38*10^{-5}\rho^{2.5}(f_c')^{0.325}$	36794	41137	43394
Tachibana	$3950\sqrt{f_c'}+1560$	29435	33747	37546
CEB, Bulletin 228	$E_{co}\left[(f_c'+\Delta f)/f_{cmo}\right]^{0.3}$	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 with the maximum aggregate size of 16mm

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

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

f_c' – cylinder concrete compressive strength

Tensile Strength

The brief review of the possible equations using for calculating tensile strength of high strength concrete is given in Table 2.

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

$$f_r' = 0.94*\sqrt{f_c'} \qquad \text{[MPa]} \qquad (2)$$

$$f_r^{'} = 1.26\left(f_c^{'}\right)^{0.45} \qquad \text{[MPa]} \qquad (3)$$

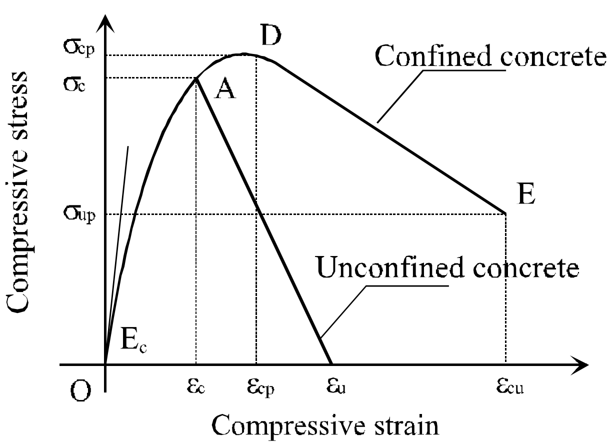
Table 2. Recommendation for the tensile strength of high strength concrete, French [3]

	$f_r^{'}$ (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	$f_{ctko,m}\left(\left(f_{ck} + \Delta f\right)/\left(f_{cko} + \Delta f\right)\right)$	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

Proposed Models for the Stress-strain Relationship for High Strength Concrete

From the ample analytical and experimental investigations performed by the authors as well as from the investigation of different σ-ε relationships for high strength concrete given in literature, for analytically defining of the bearing and deformability capacity of elements constructed of high strength materials two different mathematical models are proposed.

Muguruma. model,[7] (Fig. 4) and Cusson & Paultre model, [12] (Fig. 5) are proposed for application in <u>detailed analytical investigations</u>.



Stress at ascending branch OA

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

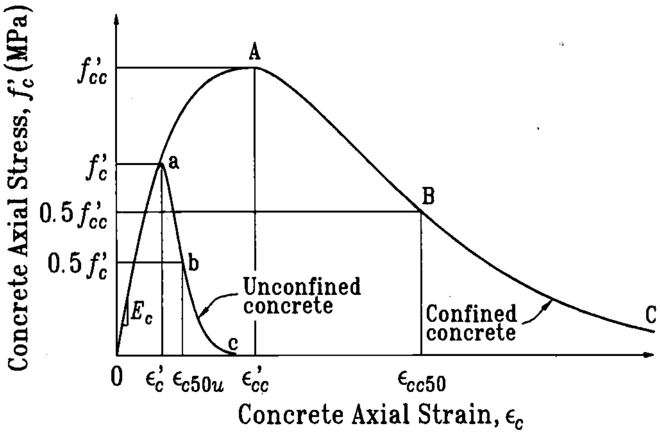
Stress at ascending branch AD

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

Stress at descending branch DE

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

Figure 4. σ-ε relationship of high strength concrete



Ascending branch (OA)

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

Descending branch (ABC)

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

Figure 5. σ-ε relationship of high strength concrete

As to 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, (Table 3). Such modifications have already been included in many design regulations like the American ACI 318-89, the Canadian CAN3-A23.3-M84 and the New Zealand's regulations NZS 3101:1995.

Table 3. Stress block parameters for high strength concrete

References	$k_1 k_3 = \alpha_1$	$k_2 = \beta_1$
ACI 318-95	0.85	$1.09 - 0.008 f_c^{'}$ $0.85 \geq k_2 \geq 0.65$
Attard & Stewart *	$1.2932\left(f_c^{'}\right)^{-0.0998} \geq 0.71(k_3 DB)$ $0.6470\left(f_c^{'}\right)^{0.0324} \geq 0.58(k_3 SL)$	$1.0948\left(f_c^{'}\right)^{-0.091} \geq 0.67$
CSA94	$0.85 - 0.0015 f_c^{'} \geq 0.67$	$0.97 - 0.0025 f_c^{'} \geq 0.67$
NZS 3101:1995	$1.07 - 0.004 f_c^{'}$ $0.85 \geq k_1 k_3 \geq 0.75$	$1.09 - 0.008 f_c^{'}$ $0.85 \geq k_2 \geq 0.65$
Mendis and Pendyala	$0.85 - 0.0025\left(f_c^{'} - 57\right)$ $57 \leq f_c^{'} \leq 100 MPa$	$0.65 - 0.00125\left(f_c^{'} - 57\right)$ $57 \leq f_c^{'} \leq 100 MPa$
Park et al.	$\alpha_1 = 0.85 - 0.004\left(f_c^{'} - 55\right) \geq 0.75$	$\beta_1 = 0.85 - 0.008\left(f_c^{'} - 30\right) \geq 0.65$
Ibrahim et al.	$0.85 - 0.00125 f_c^{'} \geq 0.725$	$0.95 - 0.0025 f_c^{'} \geq 0.70$
Macedonian code, PBAB	α_1=0.809	β_1=0.416

* The values of the parameters are calculated using probabilistic methods.

It should be mentioned that α_1 and β_1 parameters are applied for unconfined concrete and they are conservative in the cases of well confined reinforced concrete columns.

Recommendation and Criteria for Design

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.

$$\rho_{min} \geq \frac{\sqrt{f_c^{'}}}{4.5 f_y} \qquad (f_c^{'}, f_y \text{ in MPa}) \tag{4}$$

$f_c^{'}$ – cylinder concrete compressive strength, f_y - yield strength of longitudinal reinforcement

The minimum reinforcement ratio for high strength concrete beams according to ACI regulations and our national code, (PBAB'87) for two different yield strengths of longitudinal reinforcement are presented in Fig. 6. 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.

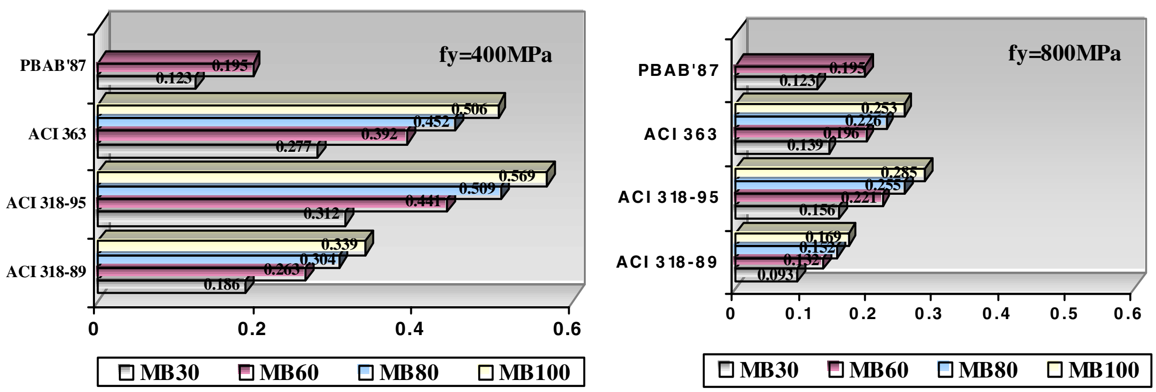


Figure 6. Minumum reinforcement ratios for high strength concrete beams

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 maximal percentage of reinforcement in beams $\rho \leq 2.5\%$ (for seismic regions) according to ACI 318-95 is adequate also for high strength beams. If they are applied in seismic prone areas, compressive reinforcement and stirrups will also be necessary.

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 aseismic 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 and from the results of the investigations performed by authors, 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)

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

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.

Bond and Anchorage

There is very limited information available on the bond between concrete and steel under cyclic loading. The best source is ACI 408 State-of-the-Art Report on Bond under Cyclic Loads, (French [3]) whose recommendation is to hold the bond stress to approximately 80% of ultimate bond stress or less. The regulations allow decreasing the anchorage length of reinforcement by increase in compressive strength of concrete. Still, due to lack of experimental data, ACI318-89 and NZS 3101:1995 recommend that shortening of the anchorage length be done only up to compressive strength of 69 MPa. It should be pointed out that, due to insufficient number of experimental data, there is still no possibility of defining design recommendations as to the anchorage length and bond stress level.

The necessary anchorage length according to New Zealand's Code, (French [3]) is given in the Table 4.

Table 4. Anchorage length-New Zealand's Code recommendation, French [3]

	MB30	MB60	MB80	MB100
NZS 3101, $L_{db} = \frac{0.5 * \alpha_a f_y}{\sqrt{f_c^{'}}} d_b \geq 300mm$ –without hooks	104.2	73.7	63.8	62.2*
NZS 3101, $L_d = \frac{\alpha_b}{\alpha_c \alpha_d} L_{db} \geq 300mm$ – without hooks	69.8	49.4	42.7	41.7*
NZS 3101, $L_{db} = 0.24 * \alpha_b \alpha_1 \alpha_2 \frac{f_y}{\sqrt{f_c^{'}}} d_b \geq 8 d_b$ – with	38.5	27.2	23.6	22.9*

* In calculation of the anchorage length NZS 3101:1995 limits concrete compressive strength up to 70MPa. If it is bigger it should be taken equal to 70MPa.

where,

L_{db} - basic development anchorage length

L_d - anchorage length

d_b - nominal diameter of longitudinal reinforcement

α_a - 1.3 for the top reinforcement where more than 300mm of fresh concrete is cast in the member below the bar or 1.0 for all other cases

α_b =1.0 (sesimic default)

α_c =1.5, α_d =1.5 (seismic default)

α_1 =0.7 for d_b<32mm with the side cover normal to the plane of the hooked bar not less then 60mm and the cover on the tail extension of 90° hooks less then 40mm or 1.0 for all other cases

α_2 =0.8 when the distance between ties is less then 6 d_b or 1.0 for all other cases

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

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.

However to enable mass application of high strength concrete and generally of high strength materials in design and construction of structures in seismic regions, it necessary to focus further investigations to:

- Definition of dynamic behaviour of elements, parts of structures and structures exposed to actual seismic loads. The investigations should be both analytical and experimental.
- Definition of criteria and codes for design and construction of seismically resistant structures that shall be underpinned in the national technical regulations and standards for design and construction of structures of high strength materials.

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