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# USE OF HIGH-YIELD STRENGTH MATERIALS IN SEISMIC ZONES: A STRATEGIC APPROACH

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## SUMMARY

The use of high-strength concrete (HSC) is still not common in seismic zones since it is considered as a fragile material. However, earlier experimental investigations have shown that HSC columns may behave in a ductile manner when subjected to moderate axial compression and reversed cyclic bending. For high axial compression, ductility is achieved with the use of a greater amount of confinement steel. In this case, high-yield-strength steel (HYSS) may be used to decrease the lateral steel content. However, the effectiveness of HYSS depends on many parameters. In a first part, this article presents design equations for the determination of confinement reinforcement for reinforced concrete columns that are related to the seismic demand. This approach is valid for any strength of lateral steel and concrete. In a second part, some elements pertaining to the use of HSC and HYSS are discussed for real structures subjected to seismic action.

## INTRODUCTION

High-strength concrete (HSC) is now readily available on construction sites. However, engineers are still reluctant to use this material in seismic zones as it is considered brittle. In the past ten years, extensive experimental and analytical research have been conducted on HSC columns in Canada as well as in other countries. Models have been proposed in order to predict the behaviour of HSC columns [Légeron and Paultre, 1999]. It has been shown that for HSC columns, a good confinement is necessary to reach sufficient displacement capacity. This could lead to the congestion of the reinforcing cages, in certain cases. Hence, high-yield strength steel (HYSS) has been used to decrease the amount of lateral steel. This was been found to be very effective, in certain cases, while totally inefficient in some others [Cusson and Paultre, 1994]; [Li et al., 1994]; [Azizinamini et al., 1994]. It is not possible to fully understand the effectiveness of HYSS, used as confinement reinforcement, based solely on experimental results. However, with a more rational approach, Cusson and Paultre [1995] were able to explain the effectiveness of HYSS on columns subjected to concentric compression. Légeron and Paultre 1999] extended the approach to columns subjected to constant axial compression and reversed cyclic flexure. It is now possible to predict fairly well the behaviour of HSC columns subjected to earthquake type loadings [Légeron and Paultre, 1999]. A practical approach to choose the concrete strength and yield strength of confinement steel on sound bases is still needed. This is the main objective of this article. In a first part, after a brief presentation of the confinement model used, new equations relating sectional ductility to geometry and material characteristics of the columns will be introduced. A strategic approach to the use of high-strength materials will then be discussed.

## CONFINEMENT OF CONCRETE COLUMNS

Seismic design of concrete structures is based on dissipation of earthquake input energy through inelastic deformation. The seismic demand is then represented by a couple of values (*S*, *D*) where *S* is the required strength of the member and *D* is the displacement demand. *S* increases when *D* decreases and vice versa. *D* is related to the displacement capacity of each member which is a function of the available sectional ductility of each section of the member. Seismic design is a trade-off between ductility and strength. Once the required

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sectional ductility, $\mu_\phi$, for each section of the structure has been determined, the confinement steel has to be computed accordingly.

The confinement reinforcement is not related to the seismic demand in the ACI code [ACI:389-95] and the Canadian Standard [CSA A23.3-94]. It was stated [Sheikh et al., 1994] and [Bayrak and Sheikh, 1998] that this amount of confinement could be very conservative for low axial load level, and non-conservative for high axial load level as well as for HSC columns. It was suggested that confinement steel should be related to seismic demand as it is implicitly the case in the New-Zealand Standard [NZS 3101, 1995]. The right approach is to compute the transverse steel required to meet the seismic demand. The applicability of this method is conditioned to the availability of an accurate confinement model. It was demonstrated by Cusson and Paultre [1995] that the current confinement models developed for NSC were not adapted for HSC and they proposed a model calibrated on a large number of experimental results. Légeron and Paultre [1999] extended the model to all strengths of concrete and all yield strengths of lateral steel. Based on this model, a procedure to compute lateral steel related to the seismic demand, $\mu_\phi$, is proposed.

**Confinement Model**

The passive confinement provided by transverse hoops and ties is progressive, starting from zero when there is no transverse strain to maximum when transverse strains reach yielding strain of the reinforcement. Earlier confinement models developed for NSC were based on the assumption that yielding of transverse steel is always reached at the peak of the confined concrete stress-strain curve. The key parameter in the proposed confinement model is the determination of the actual stress level in the transverse reinforcement. To simplify the presentation, we consider a square section with concrete confined core sides equal to *c*. The approach can be extended to rectangular columns. The volumetric ratio of transverse reinforcement is defined as:

$$\rho_s = \frac{2A_{sh}}{cs} \qquad (1)$$

where $A_{sh}$ is the total area of lateral steel and $s$ is the spacing of ties. The confinement stress, $f_l$, is determined by equilibrium consideration [Cusson and Paultre, 1995]:

$$f_l = \frac{1}{2}\rho_s f_{hcc} \qquad (2)$$

where $f_{hcc}$ is the stress in the steel at peak strain, which is assumed to be equal to the yield strength, $f_{yh}$, in traditional models for NSC. To account for the so-called arching effect, Sheikh and Uzumeri [1982] introduced the effective confinement pressure $f_{le}$ defined as folllows:

$$f_{le} = k_e f_l$$

where $k_e$ is the geometric coefficient of effectiveness [Mander et al., 1988]:

$$k_e = \frac{\left(1-\sum\frac{w_i^2}{6c^2}\right)\left(1-\frac{s'}{2c}\right)^2}{1-\rho_g} \qquad (3)$$

where $w_i$ is the clear spacing between tied longitudinal bars, $s'$ is the clear spacing between ties, and $\rho_g$ is the volumetric ratio of longitudinal reinforcement. Defining the effective lateral steel content as

$$\rho_{se} = k_e \rho_s \qquad (4)$$

The effective confinement stress is

$$f_{le} = \frac{1}{2}\rho_{se} f_{hcc} \tag{5}$$

The stress-strain curve should be capable of replicating the progressive action of lateral steel. Assuming yielding of transverse steel was well adapted to NSC columns tested in the past. However, Cusson and Paultre [1995] showed that this is not the case for HSC columns and tests by Li et al. [Li et al., 1994] proved that this assumption was not adapted to NSC columns confined by HYSS as well, since yielding of lateral steel is not always reached at peak of confined concrete stress-strain curve. The basic idea that was introduced in the Cusson and Paultre confinement model [1995] is to calculate the effective confinement stress, $f_{le}$ , at peak of the stress-strain curve of confined concrete, accounting for the actual stress, $f_{hcc}$ , in the transverse steel at this point. This is achieved by both equilibrium and strain compatibility considerations. The effective confinement index is defined as [Légeron and Paultre, 1999]:

$$I_e = \frac{f_{le}}{f_c^{'}} \tag{6}$$

Further details on the model can be found in Légeron and Paultre [1999]. Predictions made with this model on 140 large-scale columns tested in compression, or in compression and reversed cyclic flexure, compared very well with the experimental results [Légeron and Paultre, 1999]. The model is also able to predict when lateral steel yields at peak stress of confined concrete and hence can predict when HYSS will be effective.

**Relation between ductility and the effective confinement index**

The relation between required ductility and the effective confinement index depends on many variables. In order to investigate the influence of each variable, a parametric study on 120 columns subjected to constant axial load and flexure was conducted. The behaviour of the columns was predicted with the model presented. The investigated variables were:

- The axial load level, *n*, defined as the ratio between the axial compressive load and $A_g f'_c$ , where $A_g$ is the gross concrete cross-section.
- The effective confinement index $I_e$
- The concrete strength $f'_c$
- The mechanical longitudinal reinforcement ratio $w = \rho_g \frac{f_y}{f_c^{'}}$ , where $f_y$ is the longitudinal steel yield strength

Based on this study, it was possible to relate the required effective confinement index to the sectional ductility demand and the level of axial load as follows:

$$I_e = 0.0018\mu_\phi e^{3n} \tag{7}$$

This equation highlights the preponderant influence of axial load level. Also, for a given ductility and axial load level, the required confinement index is constant regardless of the concrete strength. However, it has to be emphasized that this results in a very different confinement pressure. If concrete strength is doubled, the required confinement stress will also be doubled, resulting in a higher demand for confinement steel. This fact is confirmed by experimental evidence.

The lateral reinforcement provided should ensure the development of the confinement pressure. This is usually achieved by a trial and error procedure. However, this is not very practical. For design purposes, direct equations relating the effective confinement index to the lateral steel are needed. It can be shown from the preceding equations that the effective lateral steel content is given by:

$$\rho_{se} = \min\begin{cases} \dfrac{0.0014 I_e \, f_c^{'0.74}}{I_e + 0.05} \\ \dfrac{f_c^{'}}{\left(1000 + 1180 f_c^{'0.2}\right)} \end{cases} \quad \text{but} \quad \rho_{se} \geq \frac{2 f_c^{'} I_e}{f_{yh}} \geq \tag{8}$$

Further simplification may be achieved by decomposing the geometric coefficient of effectiveness in two parts:

$$k_e = k_h k_v \tag{9}$$

where $k_h = \dfrac{\left(1 - \sum \dfrac{w_i^2}{6c^2}\right)}{1 - \rho_g}$ and $k_v = \left(1 - \dfrac{s'}{2c}\right)^2$

For usual column size and geometry, it is possible to further simplify the procedure as:

$$A_{sh}\left[\frac{2}{s} - \frac{1.6}{c}\right] = \rho_{se} \frac{c}{k_h} \tag{10}$$

Noting that $c$ and $k_h$ are usually known, one has to find a couple of values ($A_{sh}$,$s$) that satisfy Equation (10). Usually, $A_{sh}$ is known and one has to finds:

$$s = \frac{2}{\dfrac{\rho_{se} c}{A_{sh} k_h} + \dfrac{1.6}{c}} \tag{11}$$

The procedure can then be summarized as follows:

- Determine the sectional ductility demand on the section, $\mu_\phi$
- Determine $I_e$ with Equation (7)
- Determine $\rho_{se}$ with Equation (8)
- Determine $A_{sh}$ and s with Equations .(10) and (11).

## USE OF HIGH-STRENGTH MATERIALS

Two important questions in the seismic design of reinforced concrete columns using high-strength materials are:

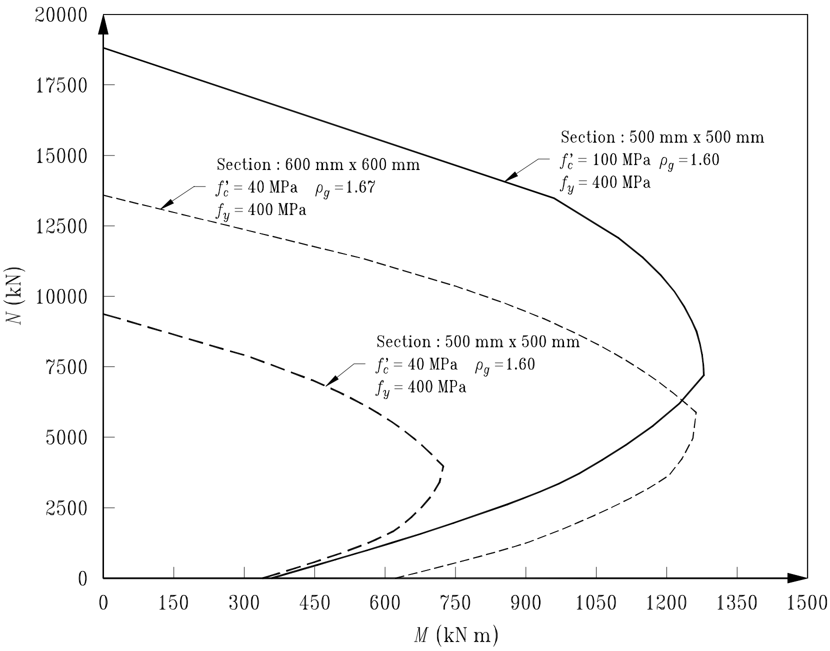


**Figure 1: Moment-axial load interaction curves**

- Is it economically worthwhile to use HSC to reduce the size or the number of columns?

- What is the maximum effective yield strength of steel that can be used?

There is no clear answer to the first question, as it depends on the type of project involved. However, some guidance is given regarding the use of HSC in the following paragraph. As for the second question, an equation and a design graph are presented and provide the maximal effective yield strength of confinement steel that may be used, given the effective confinement index and the concrete strength.

**Use of High-Strength Concrete**

HSC may be 2 to 3 times more expensive than NSC to produce and, when casting price is considered (including casting manpower), the difference is usually reduced to less than 50% for strength up to 100 MPa. Reducing the size of members, or reducing the number of members, is therefore necessary to lower the cost of the structure such as high-rise buildings, long-span bridges and high bridge piers. Usually, economic gain is reached by reducing (i) the size of the members; (ii) the construction cost, specially in bridge construction; and (iii) the cost of foundation. Figure 1 shows the interaction diagrams for columns with a 500x500-mm cross-section made with 40 and 100 MPa concrete and a 1.6% ratio of longitudinal reinforcement. The interaction diagrams are computed with the program MNPhi [Paultre, 1997] using the rectangular block of the Canadian Standard for Design of Concrete Structures [CSA A23.3-94], which has been modified to account for high-strength. When the column is subjected to only a small axial load, the flexural strength is not much enhanced by using HSC. Hence, NSC is more justifiable than HSC for a low level of axial load. For columns subjected to a high axial load, the use of HSC results in a significant increase of flexural strength. Figure 1 also presents the interaction diagram for a 600x600-mm column with 40 MPa concrete and 1.67% of longitudinal reinforcement The flexural strength of this column is about equal to the flexural strength of the HSC column, at an axial load of about 6200 kN which corresponds to axial load levels n=0.45 and n=0.25 for the columns made with 40 MPa and 100 MPa concrete, respectively. Hence for high axial load, the use of HSC leads to a significant reduction in concrete cross-section and a substantial increase in usable floor area. For a 45% axial load level in a 40 MPa column, it is possible to reduce the size of the section by about 30%, with a corresponding reduction of longitudinal steel if 100 MPa concrete is used.

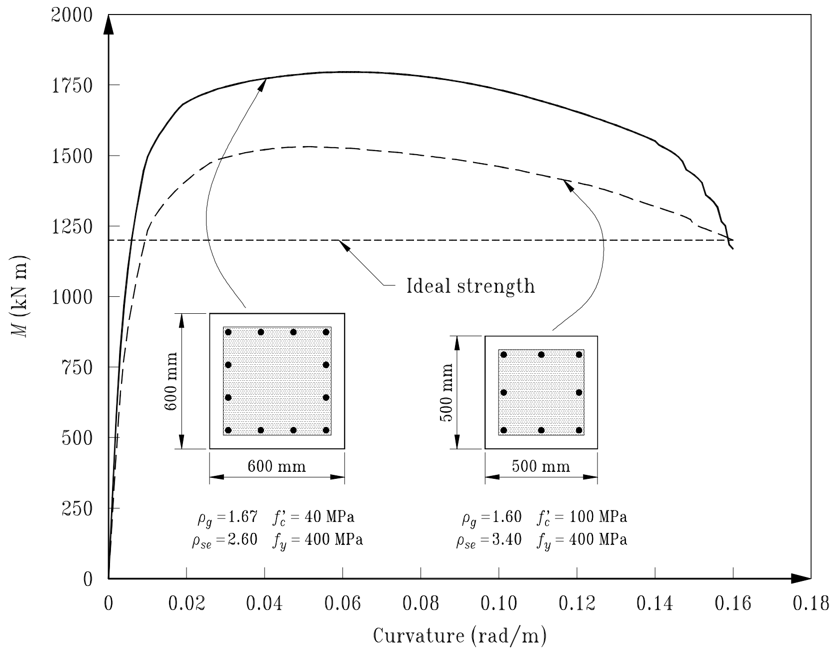


**Figure 2: Moment curvature response**

Hence, the effective confinement index requirement for the HSC column is also lower at a constant ductility demand, since the axial load level is reduced. Obviously, the HSC column is more flexible due to a smaller cross-section and hence, the seismic load will usually be lower on the HSC structure. The complete design of the columns, with the procedure described earlier, shows that the total lateral steel volume is constant for the two columns, due to a lower demand of effective lateral pressure on the HSC columns. The resulting sectional behaviour of the two sections is presented in Fig. 2. The prediction of the moment vs. curvature response of the two sections was made with the MNPhi program, using the confined stress-strain relationship developed by Légeron and Paultre [1996] The 40 MPa column exhibits a higher strength gain due to confinement, because the axial load ratio being higher in this case, the NSC column is therefore more confined. Even though confinement is quite different for the two sections, they however display comparable ductility. A series of designs carried out with different parameters showed that the use of HSC is competitive when the axial load level is above 20%. For an axial load level of about 45%, the cost of NSC and HSC elements may be similar due to a reduction of quantities and seismic loads on the HSC member. In this latter case, the use of HSC is generally economical even if the lateral steel content may have to be increased slightly.

**Use of High-Yield-Strength Steel**

In the example described earlier, the quantity of lateral steel in the case of HSC is very high, that is approaching 5%. In practical applications, this results in a congestion of the reinforcing cage and the casting of concrete is difficult. In this case, the first solution is to increase the size of the column but this results in higher costs. It has been suggested that HYSS may be used to decrease lateral steel content. However, earlier research suggested that HYSS is not always fully effective [Cusson and Paultre, 1994]; [Li et al., 1994] [Azizinamini et al., 1994]. A recent study by Saatcioglu and Razvi [1998] suggested some criteria to account for the use of HYSS, and some restrictions on the effective yield strength that may be used to compute confinement pressure from 600 to 800 MPa. Engineering judgement is also requested to use higher values of yield stress. However these values are based on a small number of tests and are not supported by analytical work. The procedure proposed earlier fully accounts for such restrictions on the effective yield strength of lateral steel. Therefore, it is possible to predict when higher yield strength may be used effectively. The maximum effective yield stress of the transverse steel is obtained from Equation (8):

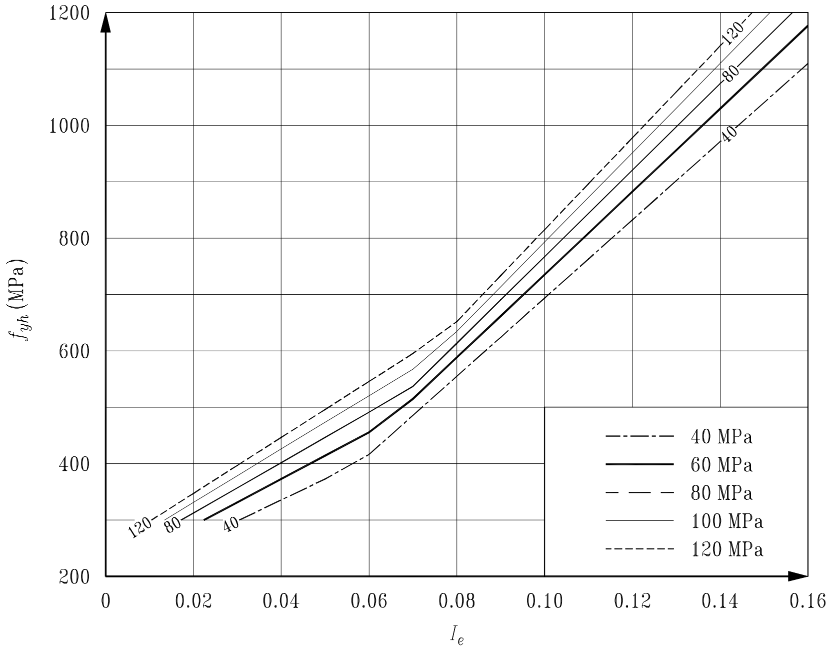


**Figure 3: Effective lateral steel yield strength as a function of concrete strength and effective confinement index**

$$f_{yh}^{\max} = \frac{2 I_e f_c^{'}}{\min\left( \dfrac{0.0014 I_e \; f_c^{'0.74}}{I_e + 0.05} ; \dfrac{f_c^{'}}{\left(1000 + 1180 f_c^{'0.2}\right)} \right)} \qquad (12)$$

This equation is plotted in Fig. 3 for different concrete strengths. Using this equation, one may compute the maximum yield strength of transverse steel that may be used in the column in order to be fully effective. This is of very practical interest as engineers can select the yield strength of lateral steel to be more effective. For example, for $I_e$ = 0.05 and $f'c$ = 100 MPa, yield strength steel up to about 500 MPa may be fully effective, for $I_e$ = 0.10, steel up to 800 MPa may be used, and 1200 MPa may be fully effective for $I_e$ = 0.15. A graph such as the one presented in Fig. 2 is of great help to design engineers to select optimal yield strength of lateral steel.

## CONCLUSION

An up-to-date and simplified uniaxial confinement model for RC columns has been presented. Calibration on a large number of experimental results allowed the development of equations relating the seismic ductility demand to the lateral steel content. The adopted approach, based on performance demand, is well adapted to new methods of seismic design i.e., performance-based and displacement-based designs. The approach is straightforward and can easily be adapted to design code formulations. Analysis of some simple design cases allowed us to express some practical considerations on the use of HSC and HYSS. Although the successful use of these high-strength materials depends on each project, the availability of materials at a competitive cost, and a knowledgeable manpower, it is believed that the considerations presented are as essential as these factors. The use of HSC in projects located in seismic zones is a viable alternative as opposed to more traditional materials. The key parameters to a successful design is the expected performance of the members, the axial load level and the effective confinement index.

## BIBLIOGRAPHY


ACI Committee 318 (1995): *Building Code Requirements for Reinforced Concrete, ACI 318-95, and Commentary, ACI 318R-95,* American Concrete Institute, Farmington Hills, MI.

CSA A23.3-94 (1994): *Design of Concrete Structures,* Canadian Standard Association, Rexdale, ON., Canada, 220 p.

Azizinamini, A., Baum Kuska, S.S., Brungardt, P. and Hatfield, E. (1994): "Seismic Behavior of Square High-Strength Concrete Columns," *ACI Structural Journal,* Vol. 91, No. 3, 336-345.

Bayrak, O. and Sheikh, S. A. (1998): "Confinement Reinforcement Design Considerations for Ductile HSC Columns," *Journal of Structural Engineering, ASCE,* Vol. 124, No. 9, 999-1010.

Cusson, D. and Paultre, P. (1995): "Stress-Strain Model for Confined High-Strength Concrete," *Journal of Structural Engineering, ASCE,* Vol. 121, No. 3, 468-477.

Cusson, D. and Paultre, P. (1994): "High-strength Concrete Columns Confined by Rectangular Ties", *Journal of Structural Engineering, ASCE,* Vol. 120, No. 3, 783-804.

Li, B., Park, R. and Tanaka, H. (1994): *Strength and Ductility of Reinforced Concrete Members and Frames Constructed Using High-Strength Concrete*, Research Report No. 94-5, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, 373 pages.

Paultre, P. and Légeron, F. (1999): "Seismic Behavior of High-Strength Concrete Tied Columns", *High Strength Concrete*, American Society of Civil Engineering, 159-172.

Légeron, F., and Paultre, P. (1996): "Seismic Behaviour of High-Strength Concrete Columns," *4th International Symposium on High Performance Concrete Utilization*, Paris, ENPC, Vol. 3, 883-892.

Mander, J.B., Priestley, M.J.N. and Park, R. (1988): "Theoretical Stress-strain Model for Confined Concrete,"' *Journal of Structural Engineering*, ASCE, Vol. 114, No. 8, 1804-1826.

NZS 3101: Part1: 1995, *Code of Practice for the Design of Concrete Structures,* Standards Association of New Zealand, Wellington, New Zealand, 1995.

Paultre, P. (1997): *MNPhi: User Manual,* Research Report SMS-9701, Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Canada.

Saatcioglu, M. and Razvi S.R. (1998): "High-Strength Concrete Columns with Square Sections under Concentric Compression", *Journal of Structural Engineering, ASCE,* Vol. 124, No. 12, 1438-1447.

Sheikh, S.A., Shah, D.V. and Khoury, S. S. (1994): "Confinement of High-Strength Concrete Columns," *ACI Structural Journal,* Vol. 91, No. 1, 100-111.

Sheikh, S.A. and Uzumeri, S.M. (1982): "Analytical Model for Concrete Confinement in Tied Columns," *Journal of the Structural Division, ASCE,* Vol. 108, No. 12, 2703-2722.