CONFINEMENT OF HIGH STRENGTH CONCRETE COLUMNS: PARAMETRIC INVESTIGATION

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Résumé

L'utilisation du béton à haute résistance est devenue une réalité presque incontournable de par les exigences les concepteurs. L'objectif de cet article est de mettre en évidence l'influence du confinement sur le comportement des colonnes en béton de haute résistance en compression, du point de vue gain en résistance et en ductilité, ainsi que le comportement contrainte-déformation, par l'utilisation de certains modèles analytiques existants et à une exploitation des données expérimentales réalisées au cours de la dernière décennie. L'étude prend en compte l'influence de divers paramètres, tels que la résistance la compression du béton, la limite élastique des aciers transversaux de confinement, densité du ferraillage longitudinal par rapport à la section brute de l'élément, et la densité du ferraillage transversal par rapport au noyau confiné. Deux types de section brute ont été choisis, carrée et circulaire, avec différentes configurations des aciers transversaux. 143

Les résultats montrent que l'augmentation de la résistance à la compression représente le facteur le plus défavorable du point de vue gain en résistance et en ductilité, à l'inverse de la densité des aciers transversaux. La disposition de ces derniers joue un rôle important puisqu'elle offre un gain en résistance allant de 50 à 100%, et celui de la ductilité de 10 à 20%. L'augmentation de cette densité améliore aussi le comportement contrainte-déformation de l'élément colonne.

Mots clés *: : Poteaux, modèles de confinement, ductilité, gain, béton à haute résistance, déformation, contrainte.*

Abstract

The use of high strength concrete has become an almost unavoidable reality due to designers demand. The purpose of this paper is to show the influence of the confinement on the behavior of high strength concrete columns in compression, in terms of strength and ductility gain, as well as the stress-strain behavior, using certain existing analytical models and experimental data published over the last decade. The study takes into account the influence of various parameters, such as the compressive strength of the concrete, the yield strength of transverse reinforcement steel, the longitudinal reinforcement density relative to the raw section of the element, and the density of the reinforcement transverse to the confined core. Two types of section were chosen, square and circular, with different transverse steels configurations.

The results show that the increase in compressive strength is the most unfavorable factor in terms of strength and ductility gain, in contrary to the density of the transverse steels. The arrangement of the latter plays an important role since it offers a resistance gain ranging from 50 to 100% and that of the ductility from 10 to 20%. The increase in this density also improves the stress-strain behavior of the column element.

Key words*: Columns, confinement models, ductility, gain, high-stregth concret, strain, stress.*

ملخص

إن استعمال الخرسانة ذات المقاومة العالية أصبحت من الحتميات التي لا نستطيع تجنبها من حيث متطلبات المصممين. الهدف من هذا البحث هو إبراز أهمية تأثير التحضين الجانبي على سلوك الأعمدة المصنوعة من الخرسانة ذات المقاومة المرتفعة من خلال إظهار جانب الربح في المقاومة والمطيلية وأيضا من حيث قانون السلوك الإجهاد - التشوه، باستعمال نماذج تحليلية موجودة واستغلال معطيات التجارب المنجزة في العقد الأخير. أخدت هذه الدراسة بعين الاعتبار عدة بارامترات منها مقاومة الخرسانة، المقاومة المرنة للقضبان الجانبية للتحضين، كثافة التسليح العمودي بالنسبة لمقطع من عنصر وكثافة التسليح العرضي بالنسبة للنواة الموجودة تحت التحضين الجانبي. تم اختيار نوعان من المقاطع، مربعة ودائرية، مع أشكال مختلفة من التسليح العرضي.

أظهرت النتائج أن زيادة المقاومة عند الانضغاط لا يمثل عنصر إيجابي من حيث الربح في المقاومة والمطيلية، عكس كثافة التسليح الجانبي. تركيب هذه الأخيرة يلعب دور هام حيث يوفر ربح في المقاومة يتراوح ما بين 50% و 100%. وبالنسبة للمطيلية من 10% و 20%. ارتفاع هذه الكثافة نساعد أيضا في تحسين سلوك قانون إجهاد - تشوه للأعمدة.

الكلمات المفتاحية *: أعمدة، نمادج التحضين لجانبي، مطيلية او اللدانة، الربح، الخرسانة ذات المقاومة المرتفعة، التشوهات، الإجهادات*

Because of its nature to resist traction and compression forces, steel is also used to confine the concrete. Confinement clearly improves ductility and strength, particularly in the strongly compressed zones and highly subjected to shear forces. Confinement is also important at the longitudinal reinforcement zones presenting covering junctions bars. Indeed, in these junctions, the bars must exchange their stresses. However under great deformations, the bars are stretched in two opposite directions. The Poisson effect generates a side expansion of the surrounding concrete followed by relative movement between the two materials. Confinement surrounds the slip and the expansion, and helps the covering to develop the tensile strength of the bars.

The contribution of an adequate confinement at the junctions' column-beam is important. In these zones, story relative displacements and nodes rotations are very high. The transmission of tensile forces of the beam on both sides of its node must take place. At the same time, the transmission of the tensile efforts in the columns located on both sides is done through the same nodal zone. So the presence of confinement reinforcement will undoubtedly reduce the disruptive effect on the concrete core under the action of high shearing forces.

Tests showed that the effectiveness of confinement depends primarily on the quantity and the configuration of the volumetric ratio of transverse steels.

It proves that the use of the concrete with ordinary resistance is limited to non slender structures and whose sections are subjected to moderate compressive forces. Recent study showed the economical use of the high-strength concrete (HSC) columns in slender and semi-slender structures (Ho et al., 2003) [1]. In addition to the reduction of dimensions of the columns sections and the durability offered by this material, the use of the HSC is beneficial and advantageous with regard to lateral rigidity as to longitudinal shortening. Another advantage of the HSC compared to the OSC is the use of a uniform formwork of the columns along the structure. That is made possible by the use of the HSC in the columns of the lower levels and to reduce thereafter the resistance of the concrete along the height of the building while preserving same dimensions of the columns on all the height of the structure.

The objective of this paper is to highlight the influence of confinement on the behavior of the columns in HSC through a rigorous analysis of some existing analytical models and an exploitation of experimental data carried out during the last decade. The study takes into account the influence of various parameters, such as concrete strength, transverse steel volumetric ratio, transverse steel spacing, and transverse steel yielding stress, longitudinal reinforcement ratio and transverse reinforcement configuration.

1. HISTORICAL REVIEW OF THE MAIN MODELS FOR HSC

Many theoretical models to predict the stress-strain behaviour of confined concrete were proposed.

The majority of the models were developed on the experimental observations basis.

A summary of mathematical expressions of some universally established models, and also the gains in strength and deformations are briefly reported in Tables 1 and 2.

Authors	Expression for f_c		
	Ascendant Branch	Descendant Branch	Cross Section
Shah *et al.*	$f_c = f_{cc}\left[1-(1-x)^A\right]$	$f_c = f_{cc}\,exp\left[-k(\varepsilon_c-\varepsilon_{cc})^{1.15}\right]$	Circle
Yong *et al.*	$f_c = f_{cc}\left[\frac{Ax+Bx^2}{1+(A-2)x+(B+1)x^2}\right]$	$f_c = f_{cc}\left[\frac{Cx+Dx^2}{1+(C-2)x+(D+1)x^2}\right]$	Square
Razvi *et al.*	$f_c = f_{cc}\left[\frac{rx}{r-1+x^k}\right]$	$f_c = f_{cc} - \frac{0.15 f_{cc}}{\varepsilon_{85}-\varepsilon_{cc}}(\varepsilon-\varepsilon_{cc})$	Circle Square
Tanaka *et al.*	$f_c = E_c\varepsilon_c + \frac{(f_{co}-E\varepsilon_{co})}{\varepsilon_{co}^2}$ $0 \le \varepsilon_c \le \varepsilon_{co}$ $f_c = f_{cc} - \frac{(f_{cc}-f_{co})}{(\varepsilon_{cc}-\varepsilon_{co})^2}.(\varepsilon_c-\varepsilon_{cc})^2$ $0 \le \varepsilon_c \le \varepsilon_{co}$	$f_c = f_{cc} - \beta\frac{f_{cc}}{\varepsilon_{cc}}(\varepsilon_c-\varepsilon_{cc}) \ge 0.4 f'_{cc}$	Circle Square
Cusson *et al.*	$f_c = f_{cc}\left[\frac{kx}{k-1+x^k}\right]$	$f_c = f_{cc}.exp\left[k_1(\varepsilon_c-\varepsilon_{cc})^{k_2}\right]$	Circle Square

Table 1 : Stress-strain models for confined high-strength concrete

1.1. Shah model

The development of Shah model [2] is mainly based on two parameters controlling the ascending and the descending branches of the curve.

The two parameters, as well as the stress peak and the corresponding deformation are expressed in terms of the strength of the non confined concrete and the confinement rate, taking into account the transverse steel yield stress, the lateral ties spacing and the diameter of the element.

1.2. Yong *et al.* model

The model of Yong *et al* [3] is based on experimental results and takes as starting point some pre-established equations, particularly those of Sargin *et al.* (1971) [4].

This model is fundamentally based on three parameters, peak strength and the corresponding deformation, the point of inflection on the descending branch, the resistance and the deformation of an arbitrary point selected on the descending curve.

The statistical analysis based on the experimental results made it possible to establish equations considering the three parameters mentioned above.

Table 2 : Strength (K_s) and deformation (K_d) gains

Authors	Proposed Equation for $K_s = \frac{f_{cc}}{f_{co}}$		Proposed Equation for $K_d = \frac{\varepsilon_{cc}}{\varepsilon_{co}}$	
	Rectangular Cross Section	Circular Cross Section	Rectangular Cross Section	Square Cross Section
Shah *et al.*	$1+\left(1.15+\frac{21}{f_{co}}\right)\frac{f_{co}}{f_r}$		$\left[14.61\times10^{-7} f_{co}+0.0296\frac{f_r}{f_{co}}+0.00195\right]\frac{1}{\varepsilon_{co}}$	
Yong *et al.*	$1+0.0091\left(1-\frac{0.245s}{h''}\right)\left(\rho_{sh}+\frac{n\phi_t}{8s\phi_l}\rho_l\right)\frac{f_{yh}}{\sqrt{f_{co}}}$		$\frac{0.00265}{\varepsilon_{co}}+\frac{0.0035\left(1-\frac{0.734s}{h''}\right)\left(\rho_{sh}f_{yh}\right)^{\frac{2}{3}}}{\varepsilon_{co}\sqrt{f_{co}}}$	
Razvi *et al.*	$1+\frac{f_{le}}{f_{co}}\left(6.7f_{le}\right)^{-0.17}$		$1+5\frac{40}{f_{co}}\frac{f_{le}}{f_{co}}\left(6.7f_{le}\right)^{-0.17}$	
Tanaka *et al.*	$-1.254+2.254\sqrt{1+7.94\alpha_s\frac{f_l'}{f_{co}}}-2\alpha_s\frac{f_l'}{f_{co}}$		$1+11.3\left[\frac{f_l}{f_{co}}\right]^{0.7}$	$1+384\left[\frac{f_l'}{f_{co}}\right]^{2}$
Cusson *et al.*	$1+2.1\left(\frac{f_{le}}{f_{co}}\right)^{0.7}$		$1+\frac{0.21\left(\frac{f_{le}}{f_{co}}\right)^{1.7}}{\varepsilon_{co}}$	

1.3. Razvi *et al*. model

Following an intensive experimental work, Razvi *et al*. [5], developed a model correlating the strength and the deformability under lateral pressure of the confinement.

It is based on the evaluation of the uniform equivalent pressure generated by the various configurations of the transverse reinforcement, approach already used in the development of the stress strain model for ordinary strength concrete proposed by Saatcioglu *et al* [6].

The model is valid for various sections subjected to concentric and eccentric loading.

1.4. Cusson *et al*. model

In 1994 and 1995 Cusson [7], [8] *et al*. proposed a model based on the concept of the effective confinement rate, function of the effective confinement pressure which depends on the transverse steel stress corresponding to the maximum confined concrete strength.

To determine this constraint an analytical method using an iterative procedure was proposed.

The confinement rate introduced permitted to classify the HSC columns in three categories: slightly, fairly and strongly confined.

1.5. Bing *et al*. model

Later, Bing et al. [9] developed a model based on the mathematical formulations suggested by Mugurama *et al*. [10]. The analytical expression of the model introduces a series of parameters, in particular the type and the strength of the concrete as well as the mechanical characteristics of longitudinal and transverse steels. To take into account the effect of confinement, the model is governed by two equations for the ascending branch.

In the first expression, the effect of the confinement is neglected because of the passive action of confinement of the transverse reinforcement and the corresponding weak deformations. The second equation of the ascending branch includes the effect of the confinement which becomes in this area very important.

The curve ends for a deformation ε_{cu} corresponding to the crushing of the covering concrete due to the buckling of the longitudinal reinforcement.

2. PARAMETRIC STUDY

This study was conducted on the basis of experimental data collected from the work of several researchers, for confined and unconfined sections, and taking into account various parameters such concrete strength, transverse steel volumetric ratio, spacing, yield stress of transverse steel, longitudinal reinforcement ratio and transverse reinforcement configuration.

2.1. Gains in Resistance and Ductility

Figures 1, 2, 3 and 4 show the variation of K_s and K_d, respectively the strength and ductility gain factors of the confined columns, according to the concrete compressive strength f_{co}, the yield stress intensity f_{yh}, the longitudinal reinforcement rate ρ_l and the transverse steel volumetric ratio ρ_{sh}.

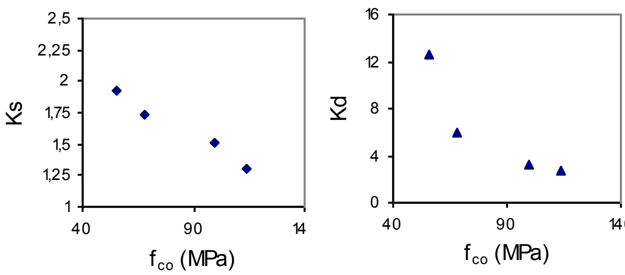


Figure 1 : f_{co} effect on K_s and K_d

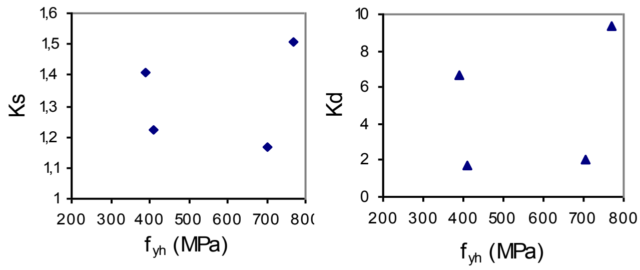


Figure 2 : f_{yh} effect on K_s and K_d

It can be noticed that the amplitude of the strength and ductility increase appreciably with the increase in the transverse steel yield stress (figure 1). This increase becomes less important with the increase in the rate of longitudinal reinforcement (figure 2). However, the effect of ρ_{sh} on the gains in resistance and ductility is noticeable.

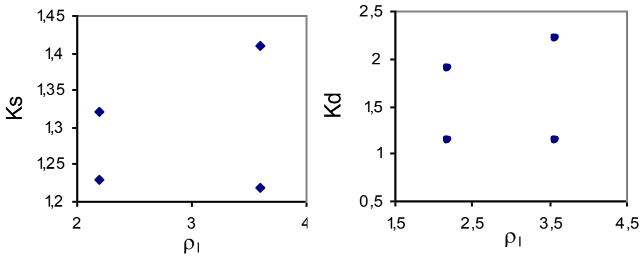


Figure 3 : ρ_l effect on K_s and K_d

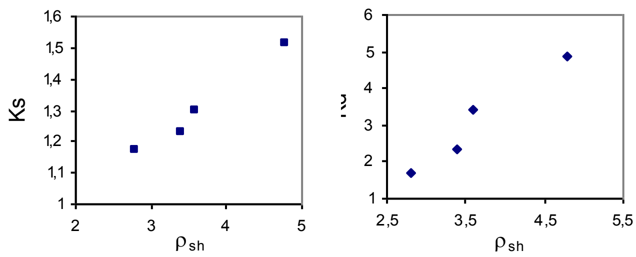


Figure 4 : ρ_{sh} effect on K_s and K_d

This figure indicates that these gains are about 4.8 times for the two cases. Figure 3, shows the favorable effect of ρ_l on the gains in strength and ductility. The influence of the concrete strength on these gains is illustrated in Figure 4.

It is noticed that the amplitude of the increase in strength and ductility decrease with the increase in the concrete strength because of the least volumetric dilatation of the HSC and its brittle nature.

2.2. Stress – strains Curves

2.2.1. Concrete strength effect, f_{co}

HSC is characterized by a less lateral expansion compared to the OSC, because of its higher elastic modulus and its weak phenomenon of internal micro-fissuring.

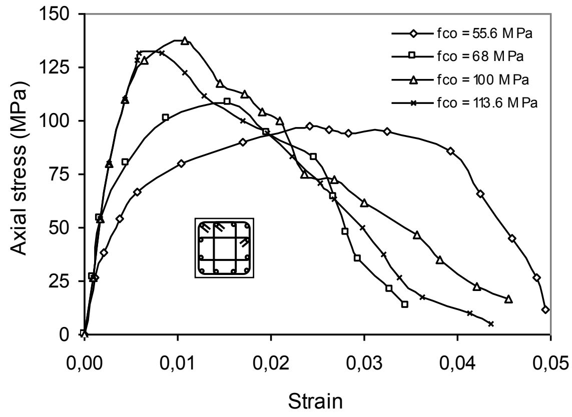


Figure 5 : Concrete strength effect (square confinement)

Consequently, the effect of the confinement of reinforcement appears lately, which reduces the effectiveness of passive confinement. Figures 5 and 6 indicate that there is an important gain in terms of strength and ductility, due to confinement. However these gains decrease with the increase of the concrete strength.

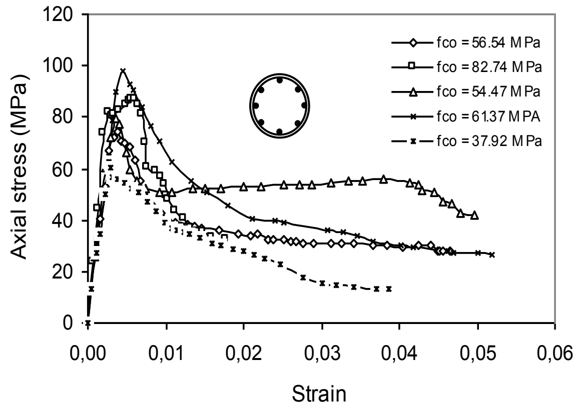


Figure 6 : Concrete strength effect (circular confinement)

2.2.2. Transverse steel volumetric ratio effect, ρ_{sh}

Figure 7 shows the lateral pressure of confinement soliciting the concrete core is directly related to the rate of transverse reinforcement.

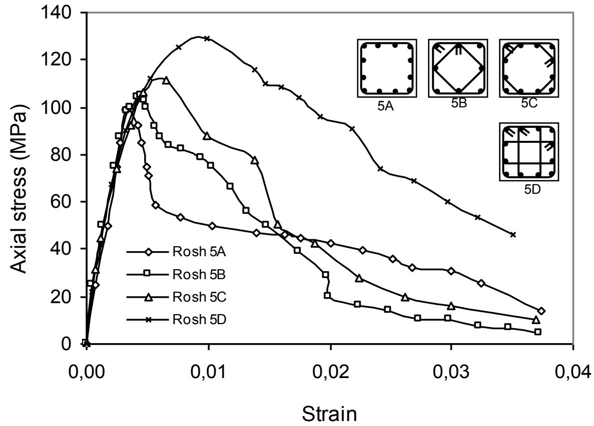


Figure 7 : Transverse steel volumetric ratio effect (square confinement)

Consequently, the effectiveness of confinement increases with the increase in the lateral pressure. However, initial rigidity seems not to be affected by the variation of ρ_{hs}, since the confinement phenomenon appears much later.

2.2.3. Spacing effect, s

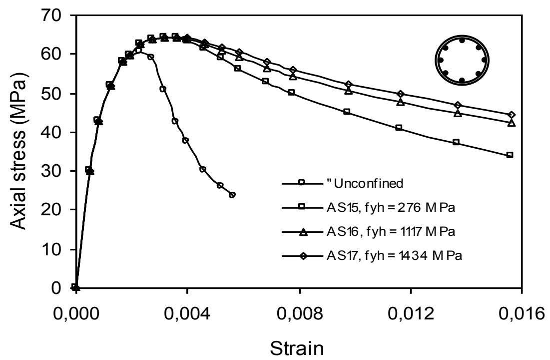
The effect of spacing on the stress-strain curve is illustrated in Figure 8. It can be noticed from this figure that the pre-peak behavior is independent of the spacing variation. The post-peak branches show that ductility grows when the spacing is reduced.

This reduction in spacing between two successive ties increases the volume of confined concrete and ensures a better effectiveness of confinement, while controlling the longitudinal bars buckling.

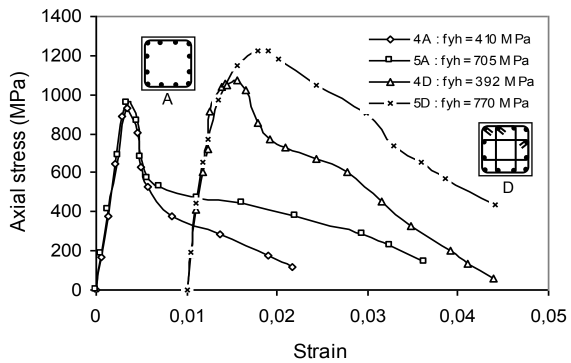
2.2.4. Transverse steel yield stress effect, f_{yh}

Figures 9a and 9b, respectively, represent the influence of f_{yh} on the stress-strain curves of the concrete for circular and square sections. It is noticed that the stress peak is not affected by f_{yh} for ρ_{sh} of 1.48%. However the increase in this limit appears to influence the slope of the descending branch of the curve.

For the square sections, figure 9b reveals that the strongly confined specimens 4D and 5D (ρ_{sh} = 4.8%) develop gains in resistance and ductility higher than those recorded for specimens 4A and 5A (ρ_{sh} = 2.8%).



a. Circular cross section



b. Rectangular cross section

Figure 9 : Yield stress of transverse steel effect for a circular and rectangular section

2.2.5. Longitudinal reinforcement ratio effect, ρ_l

Figure 10 shows the rate effect of longitudinal reinforcement ρ_l. Keeping the number of bars constant while varying their diameter, we can notice through figure 10 that premature buckling is prevented for larger longitudinal steel sections. Furthermore a gain of ductility is accentuated with the increase of longitudinal reinforcement ratio.

2.2.6. Transverse reinforcement configuration effect

The configuration of transverse steels determines the surface of the effectively confined core, which increases with the adequate fitting of the longitudinal bars around the core. It can be noticed that strength peaks related to the configurations A and B are appreciably equal, (figure 11).

However, a light reduction in strength peak for configuration D is noticeable. The post-peak behaviors for the various configurations converge.

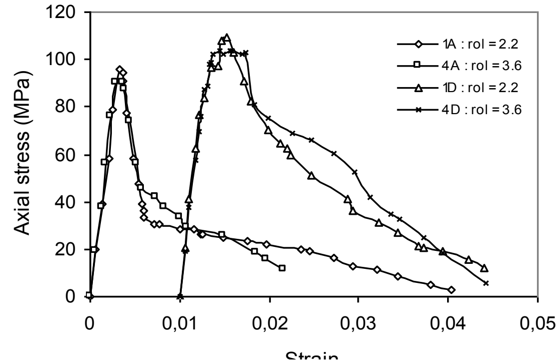


Figure 10 : Longitudinal reinforcement ratio effect

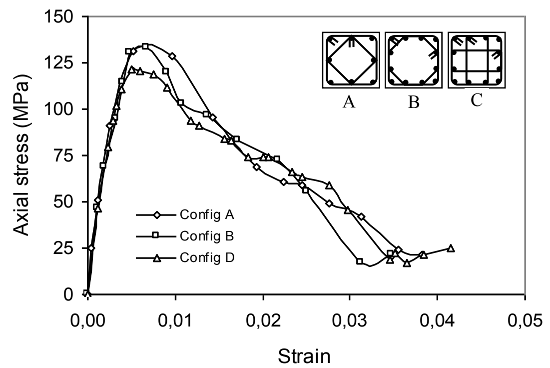
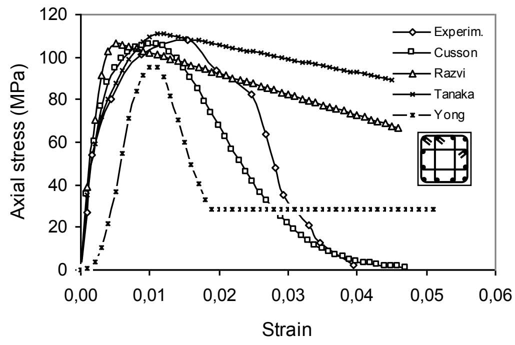


Figure 11 : Configuration effect

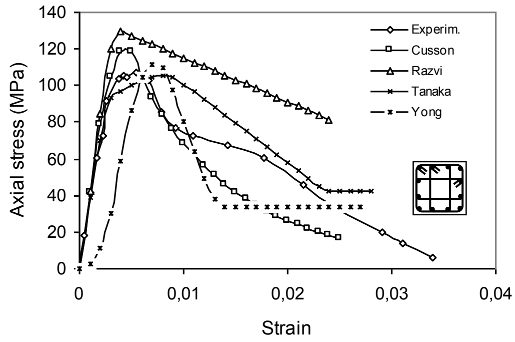
3. COMPARATIVE STUDY

Figures 12a to 12d represent respectively the analytical stress-strain curves as they are predicted by the various models for the square sections.

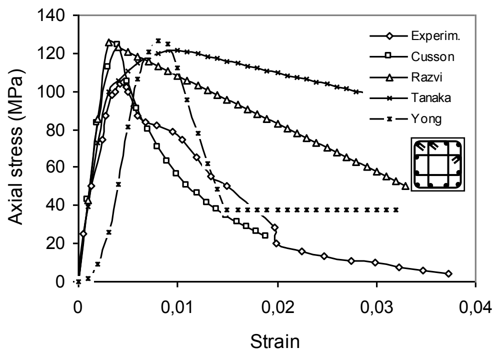
Except for the model of Yong, the whole analytical behaviors in the ascending area are satisfactory.



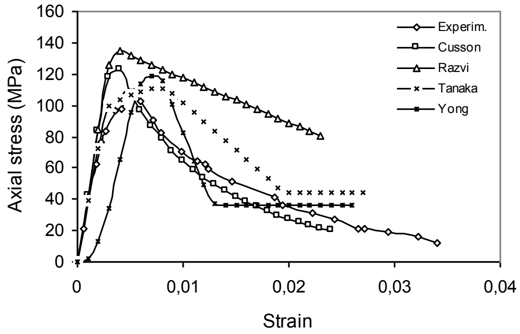
a. Spécimen 7D, f_{co}=68MPa, ρ_l=3.6%, ρ_{sh}= 4.8%



b. Spécimen 4D, f_{co}=93.1MPa, ρ_l=3.6%, ρ_{sh}= 4.8%



c. Spécimen 5B, f_{co}=100MPa, ρ_l=3.6%, ρ_{sh}= 3.4%



d. Spécimen 1D, f_{co}=100MPa, ρ_l=2.2%, ρ_{sh}= 4.8%

Figure 12 : Analytical and experimental curves comparison

CONCLUSIONS

- HSC is characterized by a brutal disintegration of its surface, showing a loss of the ultimate capacity of the element. However, gains in resistance and ductility were recorded for the case of the columns whose concrete cores were carefully confined. This indicates that only the surface of the core must be taken into account in the evaluation of the behavior of the HSC columns. It was also observed that in spite of the low effectiveness of the confinement of the HSC compared to the OSC, a judicious layout of the longitudinal and transverse reinforcements clearly improves strength and ductility of the concrete. Gain from 50 to

En effet les résistances prédites par l'EC4 sont généralement non conservatives, pour les spécimens pour les élancements géométriques inférieures à 20, et restent très proches de ceux obtenus par l'analyse proposée pour D/t ≥ 40 supérieures à 40.

Par contre, les résistances déterminées à partir de l'ACI pour l'ensemble des poteaux restent conservatives du fait de la non prise en considération de l'apport de l'étreinte latérale due au confinement du béton par la chemise en acier. Les résultats analytiques ont montré l'effet favorable du confinement sur la capacité portante de ce type de structure.

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