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Assessment of confinement models for SCC and SCFRC Columns

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Abstract: Properly detailed and closely spaced transverse reinforcement in reinforced concrete columns can ensure ductile behaviour during earthquakes. In high seismic regions, detailing requirements can result in heavily congested sections; self-consolidating concrete (SCC) can facilitate placement of concrete in these situations. Research has also shown that use of steel fiber reinforced concrete (SFRC) can improve the strength and ductility of columns by delaying cover spalling and improving core confinement. Recently research has also shown that the combined use of SCC and steel fibers can ease problems associated with the workability of traditional SFRC. Over the years several researchers have proposed confinement models for reinforced concrete. The majority of these models have been calibrated based on existing experimental tests on columns constructed with traditional concrete. Recently a limited number of confinement models have also been proposed for traditional SFRC. To examine the applicability of these models to columns constructed with SCC and SCFRC, various models in the literature are reviewed. The models are then used to predict the response of SCC and SCFRC columns having square cross-section tested by other researchers. The results show that models proposed for traditional concrete are also applicable for SCC. In addition, accurate confinement models for SCRFC need to be developed.

1 Introduction

To ensure adequate performance during earthquakes modern codes impose requirements related to the detailing and spacing of transverse reinforcement in columns. These requirements can often result in heavily congested sections that are difficult to construct. The use of self-consolidating concrete (SCC) can facilitate placement of concrete in these situations. Recently there have been a limited number of studies on the use of SCC in columns (Paultre et al., 2005, Aoude et al., 2009). Over the years several researchers have proposed confinement models for reinforced concrete, however these models have been calibrated based on experimental tests on columns constructed with traditional concrete. There is a need to verify the suitability of these models for SCC columns.

Research over the past few decades has shown that the use of steel-fibre reinforced concrete (SFRC) can improve the performance of RC structural members. In beams, the use of SFRC can enhance shear resistance and promote flexural ductility. Over the past couple of decades several researchers have also examined the potential of using SFRC in columns. Most of the research has focussed on SFRC columns tested under pure axial loading. This research has shown that the use of SFRC in columns results in enhanced core confinement and delayed cover spalling which results in increased load carrying capacity, post-peak ductility and damage tolerance (Massicotte et al., 1998; Aoude et al., 2009). A limited number of confinement models have also been proposed for traditional SFRC (Campione 2002, Aoude 2008, Paultre et al., 2010). One of the drawbacks of SFRC is that addition of fibers to a traditional concrete mix can cause problems in workability, particularly at the higher fiber contents required for structural applications. Researchers have proposed the combined use of SCC and steel fibers as a solution to this problem. A limited number of studies have recently been conducted on the structural use of self-consolidating fiber reinforced concrete (SCFRC) in columns. Given the interest in using SFRC and SCFRC to relax seismic detailing requirements, there is a need to verify the suitability of existing confinement models when steel fibers are combined with SCC.

2 Objective

Over the years several researchers have proposed confinement models for traditional reinforced concrete and steel fibre reinforced concrete. To examine the applicability of these models to SCC and SCFRC, various models in the literature are reviewed and then used to predict the response of SCC and SCFRC columns tested by other researchers.

3 Previous Research on SCC and SCFRC Columns

Although important research exists on the rheological properties of SCC and SCFRC, limited published research exists on the structural use of these materials, particularly in columns. Paultre et al. (2005) studied the axial load behavior of normal-strength and high-strength SCC columns. The columns were 235 x 235 x 1400 mm in size and variables included compressive strength (f'_c, 40-80 Mpa), tie configuration and yield strength of transverse reinforcement (f_{yh}, 410-820 MPa). In total nine SCC columns were tested and the results were compared to companion RC specimens tested by the same research group. The results showed that the SCC columns had slightly reduced axial capacity but improved ductility when compared to companion columns constructed with traditional concrete. As has been noted for traditional RC columns, confinement was more effective in columns constructed with normal-strength SCC when compared to high-strength SCC. The use of high-strength transverse steel was also found to be more effective in improving SCC column ductility when compared to SCC columns with normal strength steel. The authors noted that use of SCC ensured uniform placement of concrete in the heavily congested columns when compared to columns constructed with traditional concrete.

Aoude et al. (2009) studied the axial load behaviour of thirteen columns constructed with SCC and steel fibers. The columns were 300 x 300 x 1200 mm in size and included four specimens constructed with plain SCC and nine specimens constructed with SCC and steel fibers. A pre-packaged SCC mix having a specified compressive strength of 50 MPa was used in all of the columns and hooked end steel fibers at fiber contents ranging from 0-2% by volume of concrete were added to the SCC mix. The columns had 30 mm cover and were reinforced with 8-15M longitudinal reinforcing bars and transverse reinforcement was in the form of 10M ties. The confinement details were selected using the provisions of the 2004 CSA A23.3-04 Standard (CSA, 2004). The A-series columns were detailed in accordance with the requirements "conventional construction" (R_d = 1.5), resulting in a tie spacing, s, of 240 mm, while the B-series and C-series column were detailed in accordance with the requirements for "moderately ductile" (R_d = 2.5) and "ductile" (R_d = 4.0) columns, resulting in s = 120 mm and s = 65 mm, respectively. The results from SCC series confirmed that the use of closely spaced and well-detailed transverse reinforcement in SCC columns leads to enhanced load carrying capacity and ductility. The results from the SFRC series showed that the combined use of SCC and steel fibers improves confinement and delays cover spalling, leading to increased load-carrying capacity, ductility and damage tolerance. Test data also demonstrated that SFRC could potentially be used to relax transverse reinforcement detailing requirements in columns.

4 Review of Models for RC and SFRC Columns

Over the years models have been proposed for confined concrete as well as models that account for the buckling of longitudinal reinforcement in columns. A limited number of models have also been proposed for unconfined and confined SFRC. In order to assess the suitability of these models for SCC and SCFRC, various models are reviewed in this section.

4.1 Review of RC Confinement Models

Over the past few decades, there has been extensive research on the axial load behavior of traditional reinforced concrete columns. Research has included testes on circular, square and rectangular columns constructed with normal-strength and high-strength concrete. Based on this research data, several researchers have proposed models that can predict the complete stress-stress curve of confined concrete. Kent and Park (1971) developed a model for concrete that is confined by rectangular transverse reinforcement. This model neglected the increase in strength due to confinement but accounted for the increased ductility that resulted due to the presence of rectangular steel ties. This model was later modified Park et al. (1982) to take into consideration the potential strength gains at peak resistance. Sheikh and Uzumeri (1982) proposed the concept of "effective confinement" and related the additional strength gain and ductility in reinforced concrete columns to the spacing and arrangement of transverse reinforcement. The authors of this study suggested that concrete specimens that are confined by passive pressure from rectangular tie reinforcement are confined by a pressure that is not uniformly applied throughout the volume of the concrete core, suggesting that at high strains, part of the core region becomes ineffective. The authors proposed a model in which the enhanced behaviour of columns confined by rectangular ties is related to an “effectively confined” core area determined using the tie configuration and the principle of arching action in the concrete section. Mander et al. (1988) later used the same concept of arching action (based on vertical spacing and sectional arrangement of transverse steel) and proposed a coefficient for effective confinement area that has been widely adopted by researchers:

[1] $$K_e = \frac{\left(1-\frac{\sum w_i{}^2}{6c^2}\right)\left(1-\frac{s\prime}{2c}\right)}{(1-\rho_c)}$$

where K_e is the confinement effectiveness coefficient and the parameters s' and c represent the clear spacing between ties and the width of the concrete core region. The quantities $\sum w_i^2$ and ρ_c represent the sum of the squares of the clear spacing between adjacent longitudinal bars and the ratio of longitudinal reinforcement in the core region, respectively.

The aforementioned models were calibrated based on extensive research on normal strength concrete (NSC) columns and thus are not applicable to high-strength concrete (HSC) columns which typically show reduced ductility. In addition, the models typically use the yield strength of the transverse ties to compute lateral confinement pressure, which can lead to over-estimation of lateral pressure (particularly in the case of HSC columns). Based on a large database of tests on HSC columns, Cusson and Paultre (1995) developed a confinement model which not only accounts for arrangement and spacing of transverse reinforcement, but also accounts for expected stress in the transverse steel at peak stress of confined concrete. They also proposed an "Effective Confinement Index", I'_E, which accounts for yield strength, configuration and spacing of transverse reinforcement:

[2] $$I'_E = \frac{f_{le}}{f'_{cu}}$$

Where f'_{cu} is the peak strength of unconfined concrete and f_{le} is the effective confining pressure that acts on the core, taken as (for square columns):

[3] $$f_{le} = \frac{K_e f_{hcc} A_{sh}}{sc}$$

Where A_{sh} and f_{hcc} refer to the total cross-sectional area of transverse reinforcement perpendicular to one direction, and the stress in the transverse steel reinforcement at maximum strength of confined concrete.

Razvi and Saatcioglu (1999) proposed a model that can predict the stress-strain behaviour of both NSC and HSC columns. The confinement model, which modifies a previous model for NSC by the same authors, is based on an "equivalent lateral pressure" concept and includes a relationship to consider expected stress in the transverse ties in HSC columns.

Légeron and Paultre (2003) modified and recalibrated the model previously proposed by Cusson and Paultre (1995) based on a large database of test results including columns having concrete strength ranging from 20-140 MPa and transverse steel strength ranging from 300-1400 MPa. One major improvement is that an explicit relationship for computing stress in transverse steel was proposed, replacing the iterative procedure in the previous model. The model is applicable to columns having both square and circular cross-section and having a wide range of concrete and transverse steel properties. **Table 1** summarizes the relationships for the peak confined stress and strain for some of the models discussed above.

4.2 Review of Models for Unconfined SFRC

While extensive research has been conducted on SFRC, the use of SFRC in design practice requires accurate stress-strain relationships to relate material behaviour to structural response. While reliable stress-strain relationships are available for plain unconfined concrete in compression, there is debate over the reliability of SFRC models proposed in the literature. Bencardino et al. (2008) provided a detailed review of models proposed in the literature for the compressive stress-strain behaviour of unconfined SFRC. In the first phase of the study, cubes and cylinders made from SFRC having fiber contents, V_f, of 1%, 1.6% and 3% were tested under compression. Various models in the literature were then used to predict the results from the test series as well as from eleven other published studies. The results showed that while many of the models showed good agreement with test results from which they were derived, there was wide scatter when the models were applied to other published test data. **Table 2** summarizes some of the relationships for peak stress and strain from some of these models. It can be seen that the majority of the equations are empirical and account for the contribution of the fibers through the so-called "reinforcing-index", RI:

[4] $$RI = \frac{V_f L_f}{D_f}$$

where V_f, L_f and D_f, represent the fiber content, fiber length and fiber diameter, respectively. **Figure 1** shows the stress-strain curves as predicted from the various models for a SFRC with compressive strength of 50 MPa and 1% fiber content; it is noted that the results show wide scatter.

4.3 Review of Confinement Models for SFRC

While several researchers have proposed models for the compressive stress-strain response of unconfined SFRC, only a limited number of models to the best knowledge of authors have been proposed to account for confinement in SFRC. These include models proposed by Campione (2002), Aoude (2008) and Paultre et al. (2010).

Campione (2002) developed an empirical model to express the stress-strain relationships of confined fibre reinforced concrete (FRC) in compression for both normal and high-strength concrete columns. The author of this study proposed that the contribution of FRC to confinement can be taken into account by replacing the parameter s' in Mander's expression for effective confinement coefficient, K_e (see Eq. 1) with a fictitious parameter s'_1:

[5] $$s'_1 = s' - 10 \times RI$$

The revised confinement coefficient is then used to modify the expressions for peak confined stress and strain in the model of Cusson and Paultre (1995) (see **Table 3**).

Based on an experimental program on HSC columns constructed with steel fibers, Paultre et al. (2010) proposed a model for predicting the stress-strain behaviour of confined high-strength SFRC. In the model, the effective confinement index and expressions for peak confined stress and strain proposed by Paultre Légeron and Paultre (2003) are modified for high-strength SFRC based on additional confinement provided by fibers. Using a similar approach, Aoude (2008) proposed a model for normal-strength SFRC which modifies the well accepted models of Cusson and Paultre (1995) and Légeron and Paultre (2003) for traditional reinforced concrete. Confinement in SFRC columns is accounted for with an additional fiber confining pressure, f_{lfib}, that is function of fiber pull-out strength, which is obtained by multiplying the expected number of fibers per unit area by the pullout strength per fibre as proposed by Foster (2001):

[6] $$f_{lfib} = \propto \times RI \times \left[0.6 \times (f_c{}')^{2/3}\right]$$

The parameter $\propto$ is the fiber orientation factor (typically taken as 3/8), while $0.6 \times (f_c{}')^{2/3}$ is used to estimate the bond shear strength. This fiber confining pressure is scaled by a factor of 4.1 to determine the additional increase in peak confined stress in SFRC (see **Table 3**). The confining pressure and the ratio of effective to ineffective core area are then used to adjust the expressions for the descending branch of the post-peak stress-strain response.

Table 1: Relationships for peak confined stress and strain in RC confinement models

Authors	$\boldsymbol{f_{cc}/f_{co}}$	$\boldsymbol{\varepsilon_{cc}/\varepsilon_{co}}$
Sheikh & Uzumeri 1982	$1 + (b_c^2/140P_{OCC})[(1 - nC^2/5.5b_c^2)(1 - s/2b_c)^2]$	$1 + 248/C\,[1 - 5.0(s/b_c)^2]\left(\rho_{sh} f_s'/\sqrt{f_{co}}\right)$
Park et al. 1982	$1 + \rho_{sh}\ f_{yh}/f_{co}$	$1 + \rho_{sh}\ f_{yh}/f_{co}$
Mander et al. 1988	$-1.254 + 2.254\sqrt{1 + 7.94\,f_l'/f_{co}} - 2\,f_l'/f_{co}$	$1 + 5[f_{cc}/f_{co} - 1]$
Cusson & Paultre 1995	$1 + 2.1\ (f_{le}/f_{co})^{0.7}$	$1 + (0.21/\varepsilon_{co})(f_{le}/f_{co})^{1.7}$
Razvi & Saatcioglu 1998	$1 + k_1\,f_{le}/f_{co}$	$1 + 5k_1\,f_{le}/f_{co}$
Légeron & Paultre 2003	$1 + 2.4\ (f_{le}/f_{co})^{0.7}$	$1 + 35(f_{le}/f_{co})^{1.2}$

Table 2: Relationships for peak unconfined stress and strain in SFRC compression models

Authors	$\boldsymbol{f_{cf}/f_{co}}$	$\boldsymbol{\varepsilon_{cf}/\varepsilon_{co}}$
Fanella & Naaman 1985	$1 + (275/f_{co})RI$ (psi)	$(1/\varepsilon_{co})\left(0.00079RI + 0.0041\,f_{cf}/f_{co}\right)$ (psi)
Soroushian & Lee 1989	$1 + (3.6/f_{co})RI$	$(1/\varepsilon_{co})(0.0007RI + 0.0021)$
Ezeldin & Balaguru 1992	$1 + (3.51/f_{co})(RI)$	$1 + 446 \times 10^{-6}(RI/\varepsilon_{co})$
Nataraja et al. 1999	$1 + (2.1604/f_{co})(RI)$	$1 + 0.0006(RI/\varepsilon_{co})$
Mansur et al. 1999 *	1.05	$\left(0.0005 + 0.00000072(RI)\right)(1/\varepsilon_{co})(f_0)^{0.35}$
Bhargava & Sharma 2006	$1 + (0.45/f_{co}) + (8.89/f_{co})(RI)_s + (2.47/f_{co})\ (RI)_l$	$1 - 0.00026/\varepsilon_{co} + 0.001214(RI/\varepsilon_{co})_s + 0.00086(RI/\varepsilon_{co})_l$
Aoude 2008	1.0	$0.001684/\varepsilon_{co} + 0.000016\left(f_{cf}'/\varepsilon_{co}\right)$
Ou et al. 2012	$1 + (2.35/f_{co})(RI_v)\ Mpa$	$1 + 0.0007(RI/\varepsilon_{co})$

*-different values depend on horizontal or vertically casted members

Table 3: Relationships for peak confined stress and strain in SFRC confinement models

Authors	f_{ccf}/f_{co}	$\varepsilon_{cc}/\varepsilon_{co}$
Campione 2002†	$1 + 4.1\ (K_e{}'f_l/f_{co})$	$1 + 20.5(K_e{}'f_l/f_{co})^{0.7}$
Aoude 2008	$1 + 2.4\ (f_{le}/f_{co})^{0.7} + 4.1\left(f_{lfib}/f_{co}\right)$	$1 + 0.21/\varepsilon_{co}\ (f_{le}/f_{co})^{1.7}$

†$s_l' = s' - 10RI$ is used in calculation of $K_e{}'$ to consider effect of fibers

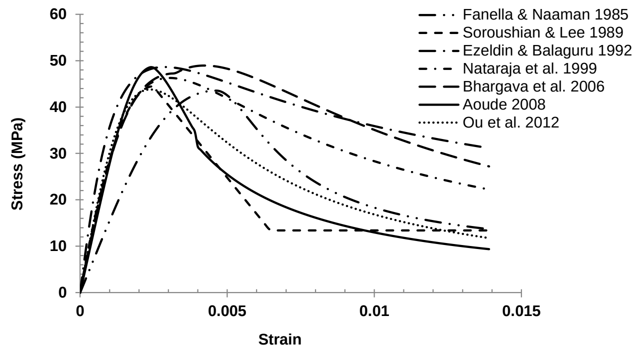


Figure 1: Comparison of predicted stress-strain response from various unconfined SFRC models proposed in the literature (for f'_{cuf} = 50 MPa, V_f = 1%)

4.4 Accounting for Buckling of Longitudinal Reinforcement

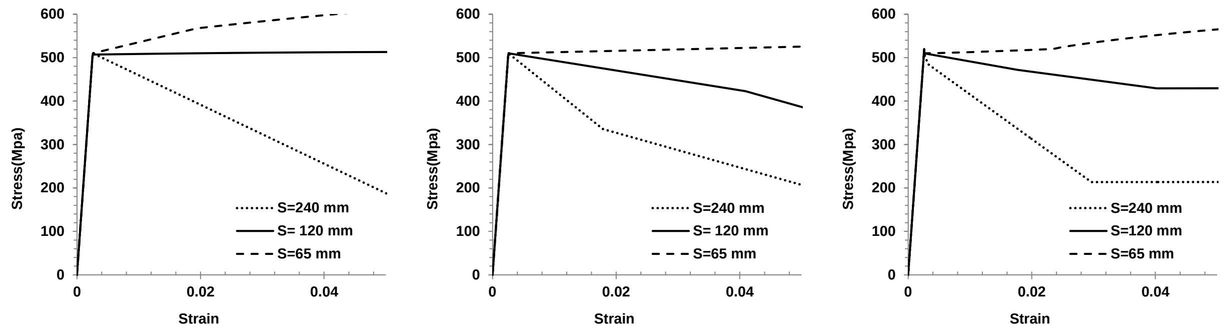
In order to accurately model the axial load response of reinforced concrete columns it is important to account for buckling of longitudinal reinforcement, particularly in cases of columns with large hoop spacing. Several models for the inelastic buckling behaviour of reinforcing bars under compressive loading have been proposed in the literature. These include models proposed by Yalcin and Saatcioglu (2000), Dhakal and Maekawa (2002) and Bae et al. (2005) which were developed based on extensive experimental data which indicates that the inelastic buckling behaviour of longitudinal reinforcing bars is very sensitive to the aspect ratio (L/d_b), which is defined as the ratio of unsupported length, L, and diameter of the longitudinal reinforcement, d_b. In the model proposed by Yalcin and Saatcioglu (2000), the stress-strain response is assumed to show stable response and is not affected by buckling at aspect ratios of less than 4.5. At aspect ratios less than 8.0 the stress-strain behaviour shows limited stability while for aspect ratios greater than 8.0 the model assumes stability of the reinforcing bar is lost upon reaching yield. In the model proposed by Bae et al. (2005) effect of buckling is taken into account by modifying relationships for post-yield stress and strain based on transverse displacement caused by buckling (which is function of the L/d_b ratio). Similarly, Dhakal and Maekawa (2002) developed expressions for stress-strain response of reinforcement in compression which are function of the square root of the yield strength and aspect ratio of the longitudinal reinforcement. **Figure 2** shows the compressive stress-strain behaviour predicted by the models proposed by Yalcin and Saatcioglu (2000), Dhakal and Maekawa (2002) and Bae et al. (2005) for reinforcement having d_b of 16 mm and L of 240, 120 and 65 mm (corresponding to the hoop spacing in the columns tested by Aoude et al. (2009)). It can be seen that all three models predict the instability in the post-yield branch of the stress-strain response in the case of bars with large unsupported length. It is noted that observations by Aoude et al. (2009) during their experimental program has indicated that SFRC does not have a significant effect on delaying buckling of longitudinal reinforcement in columns.

4.5 Accounting for Cover Spalling

In RC columns, the cover is assumed to spall away abruptly at a very early strain. Foster (2001) suggested that cover spalling in RC columns is initiated due to the tri-axial stress condition that occurs between the confined core, the tie reinforcement and the cover shell which causes cracking to initiate at the core-cover interface. As lateral confinement is provided to the core, tension stresses are initiated at the core-cover interface, and the inevitable consequence of this triaxial stress state is the cover spalling mechanism. Although cover spalling cannot occur before this crack initiation, several “driving force mechanisms” (such as buckling of the longitudinal bars on the surrounding concrete) are required to cause the cover shell to buckle. However in all cases, due to the weakness of the concrete in tension after cracking, the spalling mechanism occurs rather suddenly. It is well established that the use of SFRC has an important effect on delaying cover spalling. In traditional RC columns, buckling of reinforcement may play a secondary role, but since SFRC can carry tension across the core-cover interface after the initiation of cracking, the amount of buckling that occurs in the reinforcement can have a significant effect on the acceleration of the spalling mechanism. Aoude (2008) has proposed a "spalling factor" which can be used to scale the unconfined stress-strain response of SFRC to account for spalling:

[7] $f_{cuf_{cover}} = f_{cuf} \times \varphi$

where f_{cuf} is the stress at a given strain in unconfined SFRC, φ is a spalling factor and $f_{cuf_{cover}}$ is the stress in SFRC taking into account spalling. A graphical representation of the spalling-factor is shown **Figure 3** (shown are the factors corresponding to unsupported lengths of 240 mm, 120 mm, and 65 mm). As shown in the figure, the factor is taken as 1.0 up to a strain of 0.003 (when spalling is assumed to initiate) and then reduces gradually to 0.5 at a strain of 0.005. Thereafter the factor reduces due to account for effective spalling caused by buckling of the longitudinal reinforcement. It can be seen that the factor decreases rapidly when the reinforcing bars have large unsupported length, and remains stable in the case of small unsupported length. A typical stress-strain response for unconfined SFRC with and without spalling factor is shown in **Figure 4**.



(a) (b) (c)

Figure 2: Model predictions for post peak buckling of reinforcement as predicted by the models of (a) Yalcin and Saatcioglu (2000), (b) Dhakal and Maekawa (2002) and (c) Bae et al. (2005).

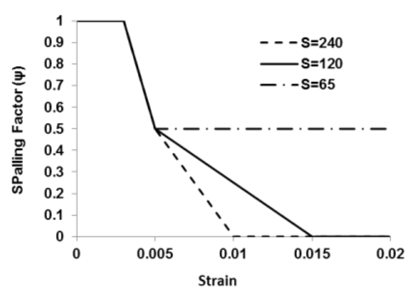


Figure 3: Spalling Factor proposed by Aoude 2008

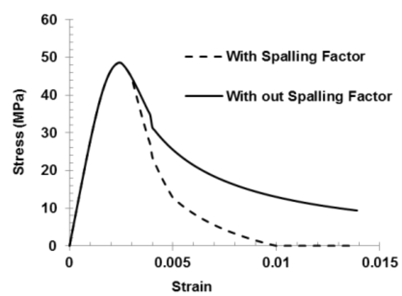


Figure 4: Typical stress-strain response with and without spalling factor

5 Prediction of SCC and SCFRC Column Axial Load Behaviour

In this section the experimental load-strain curves from the SCC and SCFRC column tests from Aoude et al. (2009) are predicted using various confinement models proposed in the literature. Included in the analysis are columns A0, B0 and C0 which were constructed with plain SCC and had detailing corresponding to low, moderate and high confinement, respectively, in addition to columns 10BSCC and 10BSCCO tested by Paultre et al. (2005). Also included in the analysis are specimens A1, A15, B1, B15, C1 and C15 tested by Aoude et al. (2009) which were constructed with SCC and steel fibers. The column properties are summarized in **Table 4.**

For the SCC columns, confinement was taken into account using the models proposed by Sheikh and Uzumeri (1982), Park et al. (1982), Mander et al. (1988), Cusson and Paultre (1995), Razvi and Saatcioglu (1999) and Légeron and Paultre (2003). For the SCC columns, cover response was modeled using the unconfined concrete model proposed by Popovics (1973). Spalling was assumed to initiate at a strain of 0.003 and a complete loss of cover was assumed at a strain of 0.004. For the SCFRC columns the confinement models proposed by Campione (2002) and Aoude (2008) were investigated, while the cover response was modeled using the unconfined SFRC model and spalling factor proposed by Aoude (2008). For both the SCC and SCFRC columns, buckling was taken into account using the model proposed by Dhakal and Maekawa (2002).

Figure 5 shows the load-strain response predictions for columns AO, BO and CO. In general, the results demonstrate that the RC confinement models can be used to predict the axial load response of SCC columns. The best results are obtained using the Légeron and Paultre (2003) and Cusson and Paultre (1995) confinement models. Acceptable results are obtained using the Razvi and Saatcioglu (1999) model, while the remaining models provide results with reduced reliability. **Table 5** presents the ratios of peak predicted-to-experimental axial capacities for columns A0, B0, CO as well as columns 10BSCC and 10BSCCO tested by Paultre et al. (2005). While good agreement is obtained for some columns, the capacities are generally under-predicted.

Figure 6 shows the load-strain predictions for columns A1, B1 and C1. The results demonstrate that the confinement model proposed by Aoude (2008) provides good predictions of the axial load-strain responses for the SCFRC columns. The model proposed by Campione (2002) generally under-predicts the responses. **Table 6** presents the ratios of peak predicted-to-experimental axial capacities for the SCFRC columns with 1% and 1.5% fibers. In general the capacities are under-predicted using both models.

Table 4: Details of SCC and SCFRC columns studied in the analysis

	Specimen	*Type*	*f'c (Mpa)*	*dimension (mm)*	*cover (mm)*	*fy-long (Mpa)*	*Traverse hoops*	*fyh (Mpa)*	*S (mm)*	*Fibers*	*Vf (%)*
Paultre et al. 2005	10BSCC	square	39.1	235 x 235	20	418.5	Diamond	820	50	---	0
	10BSCCO	square	41	235 x 235	20	418.5	Diamond	410	50	---	0
Aoude et al. 2009	A0	square	49.5	300 x 300	30	515	square	409	240	---	0
	A1	square	42.6	300 x 300	30	515	square	409	240	hooked-end	1
	A15	square	47.6	300 x 300	30	515	square	409	240	hooked-end	1.5
	B0	square	45.9	300 x 300	30	515	square	409	120	---	0
	B1	square	42.6	300 x 300	30	515	square	409	120	hooked-end	1
	B15	square	47.6	300 x 300	30	515	square	409	120	hooked-end	1.5
	C0	square	45.9	300 x 300	30	515	diamond	409	65	---	0
	C1	square	42.6	300 x 300	30	515	diamond	409	65	hooked-end	1
	C15	square	47.6	300 x 300	30	515	diamond	409	65	hooked-end	1.5

Table 5 – Ratio of Analytical to Experimental Peak Axial Capacities for SCC columns

	$(P_{max,})_{pred}/(P_{max})_{exp}$				
	Aoude et al. 2009			*Paultre et al. 2005*	
	A0	B0	C0	10BSCC	10BSCCO
Sheikh & Uzumeri 1982	0.925	0.876	0.827	0.711	0.812
Park et al. 1982	0.983	0.968	1.053	1.02	1.083
Mander et al. 1988	0.981	0.969	0.998	0.889	0.972
Cusson & Paultre 1995	0.973	0.976	0.903	0.783	0.861
Razvi & Saatcioglu 1999	0.987	0.953	0.946	0.876	0.942
Legeron & Paultre 2003	0.976	0.966	0.927	0.802	0.886

Table 6 – Ratio of Analytical to Experimental Peak Axial Capacities for SCFRC columns

	$(P_{max,})_{pred}/(P_{max})_{exp}$					
	Aoude et al. 2009					
	A1	A15	B1	B15	C1	C15
Campione 2002	0.844	0.807	0.815	0.793	0.868	0.718
Aoude 2008	0.910	0.895	0.964	0.932	0.993	0.856

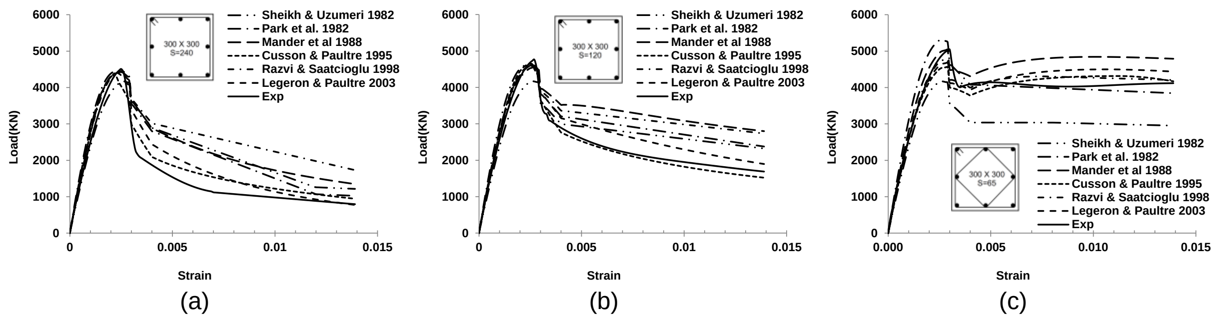


Figure 5: Confinement model comparison for columns (a) A0, (b) B0 and (c) C0

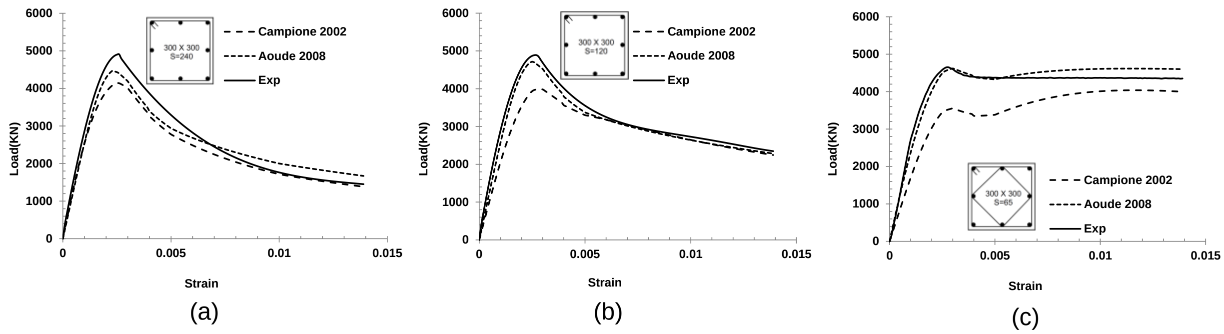


Figure 6: Confinement model comparison for columns (a) A1, (b) B1 and (c) C1

6 Conclusions

Over the years several researchers have proposed confinement models for reinforced concrete. The majority of these models have been calibrated based on existing experimental tests on columns constructed with traditional concrete. Recently a limited number of confinement models have also been proposed for traditional SFRC. To examine the applicability of these models to columns constructed with SCC and SCFRC, various models in the literature were reviewed in this paper. The models were then used to predict the response of SCC and SCFRC columns having square cross-section tested by other researchers. The results demonstrate that well-established confinement models for reinforced concrete are applicable for SCC. In particular the model proposed by Légeron and Paultre (2003) provides good prediction of SCC column response under axial loading if cover spalling and buckling models are included in the analysis. In the case of the SCFRC columns, while good agreement is obtained when using the model proposed by Aoude (2008), the peak column capacities are somewhat under-predicted. Additional research and experimental data is needed to develop accurate confinement models for SCRFC.

7 References

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