THE OPENSEES BGL MODEL FOR NON-LINEAR ANALYSES OF CONFINED CONCRETE ELEMENTS

Franco BRAGA
Title Professor
University or Affiliation Dept. Of Structural Engineering, University "Sapienza" of Rome
Address via Eudossiana 18, 00184 Rome (Italy)
email address *franco.braga@uniroma1.it*

Rosario GIGLIOTTI
Title Assistant Professor
University or Affiliation Dept. Of Structural Engineering, University "Sapienza" of Rome
Address via Eudossiana 18, 00184 Rome (Italy)
email address *rosario.gigliotti@uniroma1.it*

Michelangelo LATERZA
Title Associate Professor
University or Affiliation Dept. Of Structural Engineering, University of Basilicata
Address C. da Macchia Romana, 85100 Potenza (Italy)
email address *michelangelo.laterza@unibas.it*

Michele D'AMATO
Title Research Fellow
University or Affiliation Dept. Of Structural Engineering, University of Basilicata
Address C. da Macchia Romana, 85100 Potenza (Italy)
*email address** *damato.mic@gmail.com*

Sashi KUNNATH
Title Professor
University or Affiliation Dept. Of Civil and Enviromental Engineering, University of California Davis
Address 95616 Davis (California)
email address *skkunnath@ucdavis.edu*

Abstract

A new uniaxial confined concrete material has been added in OpenSees. The material allows of performing non-linear analyses by using the confined concrete model proposed by Braga, Gigliotti and Laterza (named BGL model). The model takes into account different confining arrangements of transverse reinforcements and/or external strengthenings, such as FRP wraps or steel jackets. The BGL model has no tensile strength and degraded unloading/reloading stiffness in accordance to the work of Karsan and Jirsa.
The paper shows some applications of the BGL model in OpenSees for simulating the non-linear response of confined concrete elements.

Keywords: Concrete columns, confinement, fibers elements, non-linear analyses, stress-strain relations.

1. Introduction

It is well known that strength and ductility of compressed concrete elements may be improved thanks to lateral confinement contrasting the internal cracking and lateral expansion before the concrete failure. Usually confinement is provided by steel transverse reinforcements such as spirals, hoops in different arrangements and ties. They also reduce buckling length of longitudinal bars and improve the curvature ductility within the element critical region when inelastic deformations occur.

Nowadays, the confinement even regards reinforced concrete (RC) existing buildings where in many cases an additional confining action is applied by external strengthening (FRP wraps or steel jackets) over elements regions where inelastic deformations are expected.
In predicting the behavior of a RC columns by using fiber elements one has to assign to section materials the appropriate uniaxial stress-strain relationships. Usually, with this approach the confinement effects on core section are taken into account by assigning to fibers of section core the confined stress-strain law obtained by modifying the unconfined one.
This paper discusses of a new uniaxial material added in OpenSees. The new material may be applied for modeling the confined concrete of the section core in according to the model proposed by Braga, Gigliotti and Laterza (BGL model, [1]). The model is capable to evaluate the confinement effects due to different transverse reinforcements such as multiple hoops, spirals, ties and eventually external strengthenings (such as FRP wraps and steel jackets).

2. BGL model

BGL model [1] was proposed by using elasticity theory and based on the key assumption that confinement within the core section arises in plane-strain condition. Under this assumption, the confined concrete law may be obtained from the unconfined law with the expression (Figure 1):

$$\sigma_z(\varepsilon_z) = \sigma_{z0}(\varepsilon_z) + \Delta\sigma_z(\varepsilon_z) \tag{1}$$

where the strength increment $\Delta\sigma_z$ for a square given by [1]:

$$\Delta\sigma_z(\varepsilon_z) = 2\upsilon B l^2 \tag{2}$$

where ν is the Poisson's ratio; l is the semi-length of the core section; B is a constant of two Airy's functions introduced by authors for solving the analytical problem of a square section confined by a simple transverse hoop. B is given by the following expression [1]:

$$B = \frac{18E_cE_sA_s\upsilon\left[SE_cl^3 + 105E_sI_s(\upsilon+1)\right]}{l^2\left\{25S^2E_c^2l^4 + 6SE_cE_sl\left[315I_s(\upsilon+1) + 2l^2A_s(2\upsilon+5)\right] - 1890E_s^2I_sA_s(\upsilon^2-1)\right\}}\cdot\varepsilon_z \quad [FL^{-4}] \tag{3}$$

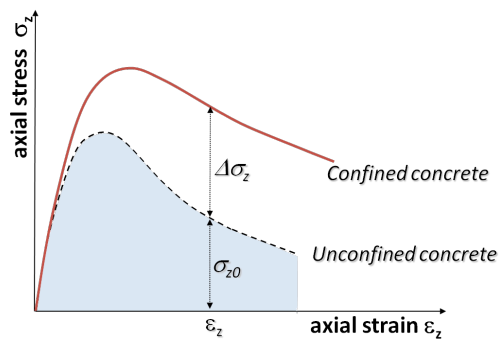

Figure 1. Increment of axial strength due to confining action.

Under the assumptions made the model provides that the increment of axial strength $\Delta\sigma_z$ is constant over the confined core at a given axial compressive strain level.
Moreover, it is possible to demonstrate that the mean value of radial pressure $f_{rm\text{-}eq}$ (Figure 2) acting along an internal circumference is equal to:

$$f_{rm-eq} = -Bl^2 \tag{4}$$

Relating Eq. (2) and Eq. (4) we obtain:

$$\Delta\sigma_z = -2\upsilon f_{rm-eq} \tag{5}$$

in which the strength increment is expressed in terms of radial pressure.
Whereas, the mean value of the shear stresses along all internal circumferences to core section is zero [1].

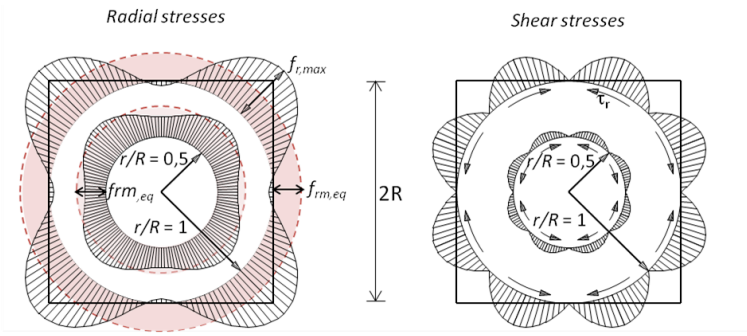

Figure 2. Confining pressures and shear stresses within the core of section in polar coordinates.

For circular section confined by hoops or spiral f_{rm-eq} is given by:

$$f_{rm-eq} = \frac{q}{S} \tag{6}$$

where S is the spacing hoops and q is the Airy's constant in the case of circular section:

$$q = \frac{E_c E_s A_s \upsilon S}{R_c E_c S + E_s A_s (1-\upsilon)(\upsilon \cdot \varepsilon_z + 1)} \cdot \varepsilon_z \tag{7}$$

The strength increment $\Delta\sigma_z$ due to confinement is expressed as:

$$\Delta\sigma_z(\varepsilon_z) = 2\upsilon \frac{q}{S} = 2\upsilon f_{rm-eq} \tag{8}$$

As briefly summarized, in the case of square and circular section it is possible to relate the strength increment $\Delta\sigma_z$ due to confinement directly to the mean value of the confining pressure f_{rm-eq}. For this reason f_{rm-eq} is named "*equivalent confining pressure*". It allows us to interpret each internal cylinder of core section as a cylindrical concrete specimen subjected to a triaxial compressive test.
Starting from the uniformly distributed confining pressure along the column, the confining action offered by longitudinal bars may be computed by means of the following equation [1]:

$$f_r = k_{sl} f_{rm-eq} \tag{9}$$

where k_{sl} is a reduction factor due to the bending stiffness of longitudinal bars given by:

$$k_{sl} = \frac{45\xi_{long}^3}{45\xi_{long}^3 + \beta\xi_{hoop}^3} \tag{10}$$

where $\xi_{long}=\phi_{long}/S$; $\beta=\phi_{hoop}/\phi_{long}$; $\xi_{hoop}=\phi_{hoop}/l$.

In the case of negligible bending stiffness of longitudinal bars confining action is mainly due to the arching effect offered by transverse hoops. In this case in the Eq. (9) may be used the factor k_c calculated with the expression proposed by Sheik and Uzumeri [2]:

$$k_c = \left(1 - \frac{S}{4l}\right)^2 \tag{10}$$

with the restriction that $k_{sl} \geq k_c$.
The BGL model allows to calculate the confinement effects due to multiple transverse arrangements and external strengthenings such as FRP wraps and/or external steel jackets (Figure 3). This feature makes the model applicable even in the case of existing buildings where for improving the confinement level external strengthenings may be designed. How to calculate the confining pressure due to multiple arrangements may be found in [1, 3].

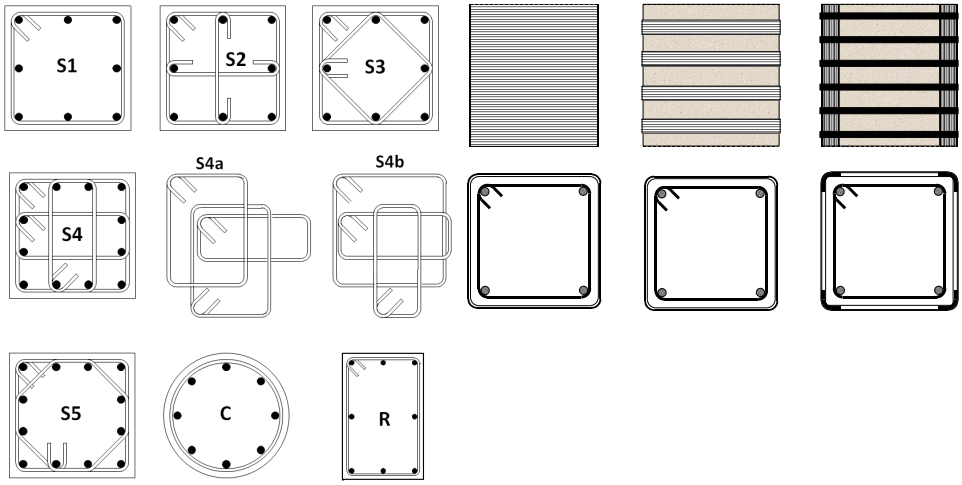

Figure 3. Different a) transverse arrangements and b) external strengthenings available by using the uniaxial BGL confined concrete model.

3. Implementation of the BGL model

The BGL model has been implemented in OpenSees with the *UniaxialMaterial* interface and named *ConfinedConcrete01*. To date, the model has no tensile strength and uses the degraded unloading/reloading stiffness in the case of cyclic loadings based on the work of Karsan and Jirsa [4].
Figure 4 shows the incremental procedure adopted for obtaining the envelope curve of new confined concrete material with respect to a square section reinforced with a simple transverse hoop [3]. The BGL model provides the equivalent confining pressure $f_{rm\text{-}eq}$ to be used in an active triaxial model for providing the stress-strain relationship of confined concrete at a given axial strain. Therefore, the sought confined curve will be obtained by crossing all different active curves up to the axial strain corresponding to the yielding of transverse hoop (where the confinement pressure becomes constant). To date, the active triaxial model published by Attard and Setunge [5] is used in obtaining the confined concrete relationship at a given $f_{rm\text{-}eq}$.
At each axial strain value ε_z an iterative procedure is required [3]. This is due to the fact that the BGL model works by using secant moduli of concrete and steel to be updated when a new increment of axial strain is applied to the column. As shown in [3] the adopted iterative procedure is stable and a small number of iterations at each step are required.
The implementation has been performed in the way that at first OpenSees builds and stores for each concrete confined core the related confined concrete relationship. Then, it assigns at each fiber the confined law and starts in performing the structural analysis.

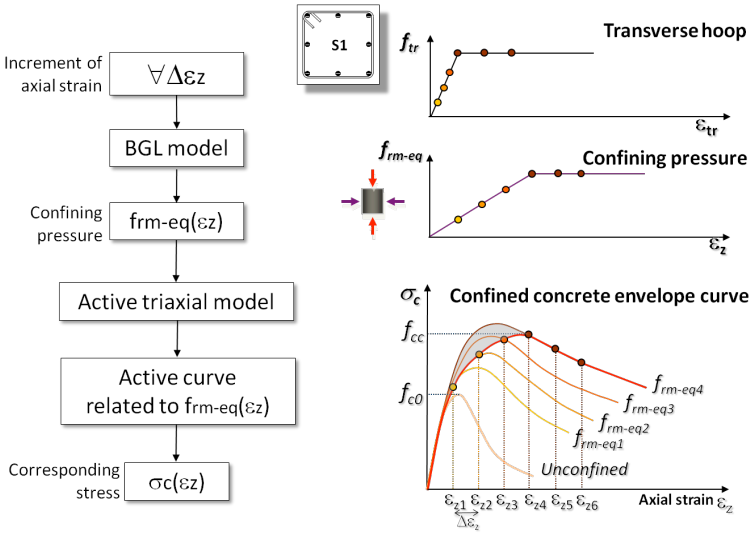

Figure 4. Incremental procedure adopted for obtaining the compressive stress-strain envelope curve.

4. Applications of BGL model in OpenSees on confined fibers elements

In this section are shown some applications of the BGL model implemented into OpenSees. The results refer to analyses carried out on concrete fibers, on a square RC section and on a RC column.

4.1 Confined concrete model in OpenSees

The command to construct the uniaxial BGL confined concrete model is the following:

uniaxialMaterial ConfinedConcrete01 $tag $secType $fpc $Ec (<-epscu $epscu> OR <-gamma $gamma>) (<-nu $nu> OR <-varub> OR <-varnoub>) $L1 ($L2) ($L3) $phis $S $fyh $Es0 $haRatio $mu $phiLon <-internal $phisi $Si $fyhi $Es0i $haRatioi $mui> <-wrap $cover $Am $Sw $fuil $Es0w> <-gravel> <-silica> <-tol $tol> <-maxNumIter $maxNumIter> <-epscuLimit $epscuLimit> <-stRatio $stRatio>

More details on each required parameter may be found at material page of OpenSeesWiki (http://opensees.berkeley.edu/wiki/index.php/Main_Page).

As examples in this paragraph are being shown confined concrete laws by referring to a square section with a simple (*S1 section*) hoop, a multiple hoop (*S4a section*), a rectangular section with simple hoop (*R section*), and a square section where external FRP wraps are applied in addition to a low reinforcing volumetric ratio. The last case reproduces what usually happens in RC existing buildings in which a local strengthening intervention is applied. In this case with the BGL model is possible to quantify the confinement effect due only to hoops or FRP wraps, and the combined one (hoops plus FRP wraps). Below are reported details regarding each analyzed case.

- *S1 section* (Figure 5a) : fpc=35 MPa, Ec=33721 MPa, epscu=0.03, L1=300 mm, phis=8 mm, S= 75 mm, fyh=450 MPa, Es=206000 MPa, haRatio=0.0; mu=1000; phiLon=18 mm; stRatio=0.85.
- *S4a section* (Figure 5b) : fpc=35 MPa, Ec=33721 MPa, epscu=0.03, L1=300 mm, L2=200 mm, L3=100 mm, phis=8 mm, S= 75 mm, fyh=450 MPa, Es=206000 MPa, haRatio=0.0; mu=1000; phiLon=18 mm; stRatio=0.85.
- *R section* (Figure 6a) : fpc=35 MPa, Ec=33721 MPa, epscu=0.03, L1=500 mm, L2=300 mm, phis=8 mm, S= 75 mm, fyh=450 MPa, Es=206000 MPa, haRatio=0.0; mu=1000; phiLon=18 mm; stRatio=0.85.

- *S1 section plus FRP wraps* (Figure 6b) : fpc= 25 MPa, Ec=25491 MPa, epscu=0.02, L1=300 mm, phis=6 mm, S= 100 mm, fyh=300 MPa, Es=206000 MPa, haRatio=0.0; mu=1000; phiLon=16 mm; stRatio=0.85. Wraps: cover=20 mm, Am=51 mm2, Sw=100 mm, ful=3900 MPa, Es0w= 230000 MPa.

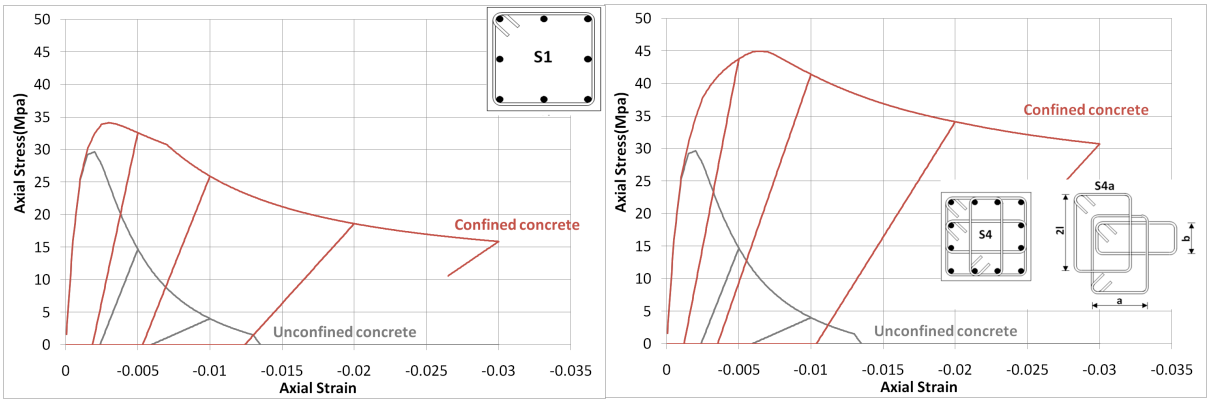

Figure 5. a) Section S1 and b) Section S4a considered.

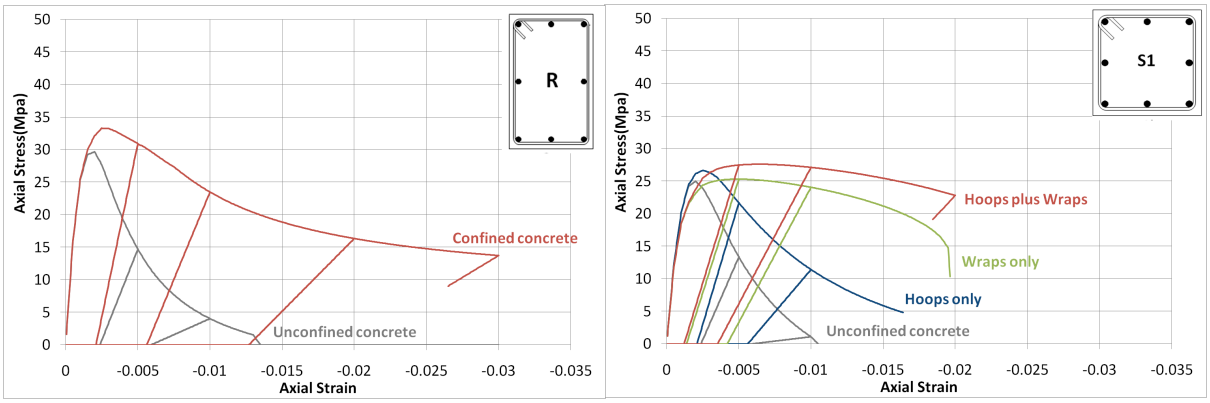

Figure 6. a) Section R and b) Section S1 plus FRP Wraps considered.

4.2 Moment-curvature relationships of a confined RC section

A square section reinforced with simple hoop (S1 section) has been utilized for performing different monotonic moment-curvature analyses by using a fiber section (Figure 7). Four levels of axial load ratio have been considered 0%, 20%, 40 % and 80%. Results are reported assigning either unconfined or confined concrete for section core. As it is easy to note the higher the axial load applied, the more important the confinement of concrete in modeling the response of a reinforced concrete section.

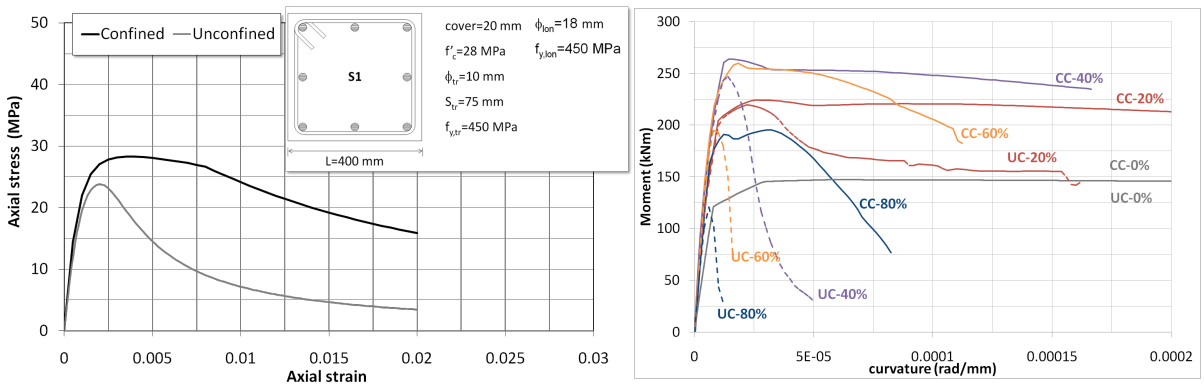

Figure 7. Moment-curvature relationships referred to the section considered.

4.3 Non-linear analyses of confined concrete columns

The implemented confined concrete model is applied for performing two non-linear analyses on well-confined RC columns and comparing the obtained results with the experimental ones. The columns have been modeled into OpenSees by using a *BeamWithHinges* fiber element whose hinge length L_p is assumed equal to the section depth h of the column. Longitudinal bars have been modeled with the uniaxial material *Steel02* and no bond-slip has been considered with respect to the surrounding concrete. Both columns were tested with a vertical load kept constant during the test and subjected to reversed lateral cyclic displacements. More details on the analyses here reported may be found in [3].

The first comparison regards the Spec. BG5 tested by Saatcioglu and Grira [6] (Figure 8). The column was subjected to an axial load ratio of 54 % kept vertical for inducing P-Δ effect on the response. In Figure 8 are reported the comparisons between the experimental response and the one obtained by neglecting (Figure 8a) and accounting (Figure 8b) for the confinement effects with the BGL model. Both the analytical simulations have been obtained by using the P-Delta Coordinate Transformation (*geomTransf PDelta*) for considering the second-order effects of the vertical load.

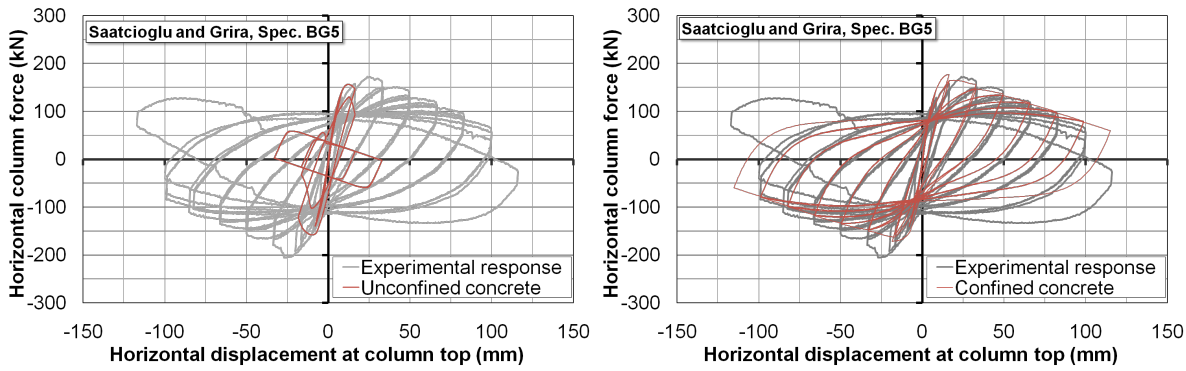

Figure 8. Comparisons with the experimental response by a) neglecting and b) accounting for the confinement effects with the BGL model (Saatcioglu and Grira, Spec. BG5 [6])

The second comparison, instead, regards a circular RC column (Saadtmanesh et al., Spec. C-2R [7]) repaired with FRP wraps and subjected to an axial load ratio of 20%. Figure 9 represents comparisons of the experimental response with the numerical simulations without (Figure 9a) and with (Figure 9b) the confinement offered by the external FRP wraps. No P-Δ effects have been considered in the analyses.

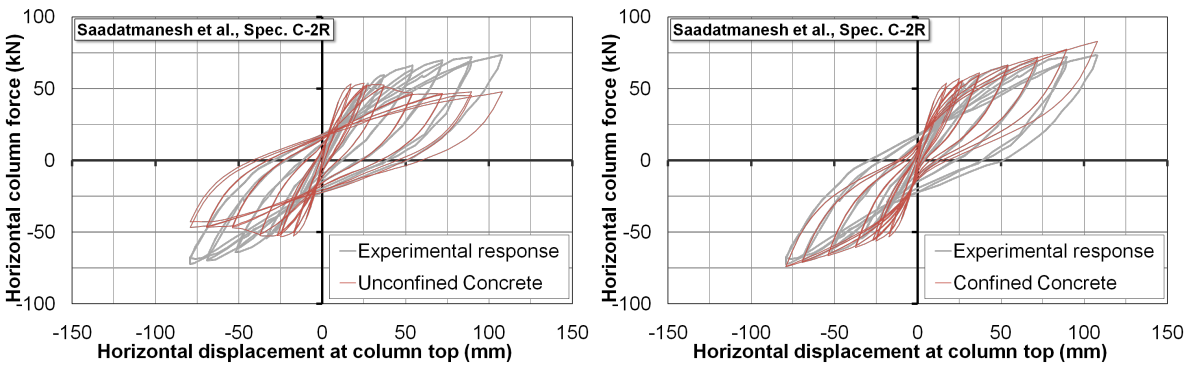

Figure 9. Comparisons with the experimental response by a) neglecting and b) accounting for the confinement effects with the BGL model (Saadatmanesh et al., Spec. C-2R [7])

5. Conclusions

A new uniaxial material for concrete fibers has been added in OpenSees. The new material implements the confined concrete model proposed by Braga, Gigliotti and Laterza (BGL

model, [1]) and requires, in obtaining the compressive envelope curve, an incremental and iterative procedure [3]. To date the model has no tensile strength with degraded unloading/reloading stiffness in accordance to the work of Karsan and Jirsa [4].
The model may be applied for non-linear analyses of RC structures and allows of taking into account different arrangements of transverse reinforcements and additional external strengthenings. The latter feature makes the model particularly adapt to perform non-linear analyses regarding RC existing buildings where such local interventions are very common.

6. Acknowledgement

The implementation of the model was carried out at University of California in Davis, where Michele D'Amato was a Visiting Scholar during his PhD studies. The authors gratefully acknowledge the collaboration of Newton Lee for his assistance in implementing the BGL model into OpenSees.

7. References

[1] Braga, F., Gigliotti, R., and Laterza, M., "Analytical stress-strain relationship for concrete confined by steel stirrups and/or FRP jackets", *Journal of Structural Engineering ASCE*, 2006, 132(9), pp. 1402-1416.

[2] Sheikh, A. A., and Uzumeri, S., M., "Strength and ductility of tied concrete columns", *Journal of Structural Division ASCE*, 1980, 106(5), pp. 1079-1102.

[3] D'Amato, M., Braga, F., Gigliotti, R., Kunnath, S., and Laterza, M., "A numerical general-purpose confinement model for non-linear analysis of R/C members", *Computers and Structures Journal*, 2012, (accepted for publication, in press).

[4] Karsan, I. D., and Jirsa, J. O., "Behaviour of concrete under compressive loadings", *Journal of Structural Division ASCE*, 1969, 95(12), pp. 2543-2563.

[5] Attard, M. M., Setunge, S., "Stress-strain relationship of confined and unconfined concrete", *Material Journal ACI*, 93(5), 1996, pp. 432-444.

[6] Saatcioglu, M., Grira, M., "Concrete columns confined with welded reinforcement grids", *Report OCEERC*, 1996, 96-05.

[7] Saadatmanesh, H., Ehsani, M. R., and Jin, L., "Repair of earthquake-damaged RC columns with FRP Wraps", *ACI Journal*, 1997, 94(2), pp. 206-214.