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Abstract

This paper presents the new material developed inside the OpenSees by considering constitute model for the concrete subjected to reverse cyclic and monotonic loadings. The new material intended to provide the ability of model the cyclic behaviour of concrete subjected to compression in the computational programme. The analytical formulation proposed by the Braga, Gigliotti and Laterza (BGL model, 2006) is used for the envelope and reverse (loading and reloading) action of the material govern by the Yassin (1994) approach, which has given bilinear curve for unloading and loading. The lateral confinement of concrete enhances the strength and durability of the reinforcement concrete significantly. Introducing this uniaxial material inside the OpenSees is capable to model the influence of transverse hoops, ties and/or FRP, external wrapping with the section considered. Many numbers of great researches have been conducted to understand the real compressive and tension behaviour of the reinforced concrete based on the experimental programme and analytical formulations. Research on cyclic response of concrete is becoming a challenge of the earthquake engineering for modelling and capable prediction of hysteretic characters of the reinforced concrete. This research work is devoted to develop the computational methods to model and analyse the reinforced concrete structures subjected to reverse cyclic specially by applying the confinement influence to section (Beam, column or joint panel).

Key words: Reinforced Concrete, Confinement, Cyclic Load, Axial Stress, Axial Strain
1.0 Introduction

In the designing of earthquake resistant reinforced concrete structures of seismic engineering, ductility is basic requirement for determining the structural ability to undergo large deformation without significant losses. The confinement which influences the behaviour of structural element, particularly in plastic hinge region consequently affecting the overall behaviour of structural system to a considerable extent. The effect of confinement on compressive strength of concrete is governed by the quantity and arrangement of the transvers reinforcement, yield strength of transverse reinforcement, the spacing for the hoops ties and rate of loading.

It is required to reproduce the real behaviour of the Stress-Strain computational analysis of reinforced concrete subjected to dynamic and cyclic loading model. However, analysis of reinforced concrete structures are subjected to general loading condition requires realistic constrictive models and analytical reasonable procedure for accurate simulation the real behaviour of the Stress-Strain curves. This paper presents OpenSees implemented material best fitted for a unified approach to constitutive modelling of the cyclic and dynamic loading with different bilinear unloading reloading branch. The analytical Stress-Strain proposed by Braga, Gigliotti and Laterza (BGL model, 2006) is used in this for implementation inside the OpenSees with command language of C++.

2.0 BGL Model(2006)

The BGL model is a plain Stress-Strain analytical model based on the elasticity theory for determining the traverse reinforcement on the concrete core of reinforced section. When the reinforced column is subjected to axial load, steel hoops, ties, FRP and other type of passive confinement cause to induce the triaxial stress in the section (See Figure 1). The basic assumption made on BGL model is that stress increment is produced without any out stress in the concrete section [Laterza et al., 1996],[ Braga et al., 1998].

Figure 1: Strength increment due to confinement

\[ \sigma_z(\varepsilon_z) = \sigma_{z0}(\varepsilon_z) + \Delta \sigma_z(\varepsilon_z) \quad (1) \]

where the strength increment \( \Delta \sigma_z \) for a square is given by Eq. 1:

\[ \Delta \sigma_z(\varepsilon_z) = 2\nu Bl^2 \quad (2) \]

By using analytical BGL formulation can be expressed the confining pressure obtained for the square and/or circular sections with highly complex configuration of transvers reinforcements (See Figure 2). Also, model proposed the some strengthening methods to take in account to confining effect in the
section such as External jackets, FRP and steel (See Figure 3). Most important thing is that this model provides to facilitate the use of any combination out of these confinements for the computational modelling.

![Different type of transverse reinforcement configuration](image)

**Figure 2:** Different type of transverse reinforcement configuration (Square and circular)

![Different types of external jackets](image)

**Figure 3:** Different types of external jackets: (a) and (b) FRP and (c) steel

### 3.0 Cyclic loading

Most of the seismic actions are generally subjected to the reversed cyclic loading with loading and unloading action on Stress-Strain in reinforcement concrete elements. Some researches revealed that based on the experiment programme, Stress-Strain curves are independent from the cyclic loading and monotonic loading [Mander et al., 1988a] [Mander et al., 1988b]. But, cyclic loading strain envelope is always having an unrecoverable plastic strain in each cycle (See Figure 4: AD portion).

#### 3.1 Karsa and Jirsa Model (1969)

The model proposed by Karsan et al.(1969) reported for plastic offset formulation for reverse cyclic concrete. Model clearly explained that starting from the unloading strain for the formulation of backbone curve (See Figure 4) up to next cycle unrecoverable plastic strain.
For loading branch:
\[ S_p = 0.093S_E^2 + 0.91S_E \]  \hspace{1cm} (3)

For unloading branch:
\[ S_p = 0.145S_E^2 + 0.13S_E \]  \hspace{1cm} (4)

where \( S_P \) and \( S_E \) are plastic stain ratio at a point where a given loading curve start and envelope curve respectively (See Figure 4). Both these unloading and loading branch consisted second degree parabola formula which always considered at the point.

![Figure 4: Loading and unloading curves: (a) fully unloaded (b) partially unloaded](image)

3.2 Yassin Model (1994)

The new approach has been proposed by the Yassin (1994) in his doctoral study by taking in account degradable of compressive concrete hysteresis, while retained computational efficiency. Stiffness of concrete can be expressed as an ability between cracks to resists the tensile stress and contribute to the flexural stiffness of the member. Advantaged to discrete nature of the cracks, concrete crack still bonded to the bar and continued to contribute to the stiffness. It is obvious that, while increased the load to section is formulated more cracks with close intervals. Due to the increasing this load, tension stiffness reduces in the stage of post-cracking. The modified Scott and Park model (1982) is proposed monotonic concrete Stress-Strain relation in three compression region described in Figure 5.

- Maximum envelope (line HD)
\[ \sigma_{\text{max}} = \sigma_m + E_r (\varepsilon_c - \varepsilon_m) \] \hspace{1cm} (5)

- Maximum envelope (line HE)
\[ \sigma_{\text{min}} = 0.5E_r (\varepsilon_c - \varepsilon_t) \] \hspace{1cm} (6)

where
\[ E_r = \frac{\sigma_m - \sigma_t}{\varepsilon_m - \varepsilon_r} \] \hspace{1cm} (7)
where \( \sigma_m \) and \( \varepsilon_m \) are stress and strain at the unloading point on the compressive monotonic envelop respectively (See Figure 5). For unloading and partial initiated with unloading modulus equal to \( E_c \) where shown in DE and GF lines.

3.3 Palermo and Vechchio Model (2003)

Palermo et al. (2003) had considered the compression response to illustrated loading and unloading as Figure 6. The unloading branch is consisted the second degree parabola as follows:

\[
\varepsilon_c^p = \varepsilon_p \left[ 0.166 \left( \frac{\varepsilon_{2c}}{\varepsilon_p} \right)^2 + 0.132 \left( \frac{\varepsilon_{2c}}{\varepsilon_p} \right) \right]
\]  

(9)

where

\[
f_c = f_{ro} + E_{c1} (\varepsilon_c - \varepsilon_{ro})
\]  

(10)

\[
E_{c1} = \left( \beta_d f_{\text{max}} - f_{ro} \right) / (\varepsilon_{2c} - \varepsilon_{ro})
\]  

(11)

\[
\varepsilon_{rec} = \varepsilon_{\text{max}} - \varepsilon_{\text{min}}
\]  

(12)

\[
\beta_d = \frac{1}{1 + 0.10 \left( \varepsilon_{rec} / \varepsilon_p \right)^0.5} \text{ for } |\varepsilon_c| < |\varepsilon_p|
\]  

(13)

and

\[
\beta_d = \frac{1}{1 + 0.175 \left( \varepsilon_{rec} / \varepsilon_p \right)^0.5} \text{ for } |\varepsilon_c| > |\varepsilon_p|
\]  

(14)
\( \varepsilon_{op} \) is plastic offset strain, \( \varepsilon_{p} \) is the strain at peak stress, and \( \varepsilon_{2c} \) is the strain at the point where unloading begins. This model represents the loss of unrecoverable plastic strain in the case of reverse cyclic load compared to other Yassin, 1994 model.

Figure 6: Hysteresis models for concrete in compression (a) Unloading (b) Loading

4.0 OpenSees

OpenSees is an open system software frame for simulation the earthquake engineering object in the finite element. This software has been developed with the language command of C++ and uses several Fortran and C for numerical libraries. Since it is open source can be used for the new open-source code development, education and comminute discussion in engineering. [http://opensees.berkeley.edu/]

4.1 Uniaxial material: ConfinedConcrete01

As a part of Michele D’Amato’s PhD studies (2009) new material has been added to OpenSees for modelling the confined reinforced concrete sections. BGL analytical concrete formulation is used as a concrete model for his implementation inside the OpenSees. This material is can be effectively used for demonstrate the confinement influences of concrete in the computational analysis [D’Amato et al., 2012]. Moreover, in the case of reverse cyclic loading uses the unloading (Eq.9) and reloading (Eq.10) branch proposed by the Karsan and Jirsa (1969).

- The command for ConfinedConcrete01

```
uniaxialMaterial ConfinedConcrete01 $tag $secType $fp $Ec (<-epscu $epscu> OR <-gamma $gamma>) (<-nu $nu> OR <-varub> OR <-varnoub>) $L1 ($L2) ($L3) $phis $fy $fyh $Es0 $haRatio $Snu $phiLon<-internal $phiS $Sf $Es0i $ShaRatioi $Smui>-<wrap $Scover $Am $Sw $Sfui $Es0w>-<gravel>-<silica>-<tol $Stol>-<maxNumIter $SmaxNumIter>-<epscuLimit $epscuLimit>-<stRatio $stRatio>
```

where, $tag is Integer tag identifying material, $secType is Tag for the transverse reinforcement, $fp is Unconfined cylindrical strength of concrete specimen, $Ec is Initial elastic modulus of unconfined concrete, <-epscu $epscu> OR <-gamma $gamma> is Confined concrete ultimate strain, <-nu $nu> OR <-varub> OR <-varnoub> is Poisson's ratio, $L1 is section measured respect to the hoop centre.
line, ($L2), ($L3) is Additional dimensions when multiple hoops are being used, $\phi$ is Hoop diameter. If section arrangement has multiple hoops it refers to the external hoop, $S$ is Hoop spacing. $f_{yh}$ is Yielding strength of the hoop steel, $E_s$ is Elastic modulus of the hoop steel, $\gamma_{a}$ is Hardening ratio of the hoop steel, $\mu$ is Ductility factor of the hoop steel. $\phi_{Lon}$ is Diameter of longitudinal bars. $f_{pc}$, $E_c$, $\epsilon_{pcu}$, $L_1$, $\phi$, $S$, $f_{yh}$, $E_s$, $\gamma_{a}$, $\mu$, $\phi_{Lon}$ are Optional parameters for defining the internal transverse reinforcement. If they are not specified, they will be assumed equal to the external ones (for S2, S3, S4a, S4b and S5 types). $\epsilon_{pcu}$, $L_1$, $\phi$, $S$, $f_{yh}$, $E_s$, $\gamma_{a}$, $\mu$, $\phi_{Lon}$ are Optional parameters required when section is strengthened with FRP wraps. Figure 7 shows the Stress-Strain enveloped by considering S1 type confining fiber section with Hoops only. The Figure 8 shows the S4a section with Hoops with same parameter.

- The parameters for Figure 7
  **S1 section**
  $f_{pc}=35$ MPa, $E_c=33721$ MPa, $\epsilon_{pcu}=0.03$, $L_1=300$ mm, $\phi=8$ mm, $S=75$ mm, $f_{yh}=450$ MPa, $E_s=206000$ MPa, $\gamma_a=0.0$, $\mu=1000$, $\phi_{Lon}=18$ mm, $\gamma_{a}=0.85$.

- The parameters for Figure 8
  **S4a section**
  $f_{pc}=35$ MPa, $E_c=33721$ MPa, $\epsilon_{pcu}=0.03$, $L_1=300$ mm, $L_2=200$ mm, $L_3=100$ mm, $\phi=8$ mm, $S=75$ mm, $f_{yh}=450$ MPa, $E_s=206000$ MPa, $\gamma_a=0.0$, $\mu=1000$, $\phi_{Lon}=18$ mm, $\gamma_{a}=0.85$.

![Figure 7: Section S1 with ConfinedConcrete01](image1)

![Figure 8: Section S4a with ConfinedConcrete01](image2)

More details are available regarding ConfinedConcrete01: [http://opensees.berkeley.edu/wiki/index.php/ConfinedConcrete01_Material](http://opensees.berkeley.edu/wiki/index.php/ConfinedConcrete01_Material).
5.0 **OpenSees: ConfinedConcrete02 implementation**

The ConfinedConcrete01 used the linear unloading reloading branch proposed by the Karsan *et al.* (1969) for cyclic reverse loading. Main objective of implementation of the new uniaxial ConfinedConcrete02 is introduced the bilinear unloading reloading (Yassin, 1994) branch for reverse cyclic loading. The ratio ($\text{rat}$) between initial (EC0) slope and unloading slope is introduced additionally for making the unloading branch as bilinear (See Figure 5) instead of linear used in ConfinedConcrete01.

The command for ConfinedConcrete02.

```
uniaxialMaterial ConfinedConcrete02 $tag $secType $fpc $Ec ($-epscu $epscu> OR $-gamma $gamma>) ($-nu $nu> OR $-varub> OR $-varnoub>) $SL1 ($SL2) ($SL3) $phis $Sfyh $SEs0 $ShaRatio $Snu $SphiLon $-internal $SphiS $Sfyi $SEsi $ShaRatioi $Smui> $-wrap $Scover $Am $SSw $Sfuel $SEs0w>$-gravel>$-silica>$-toll $stol>$-maxNumIter $SmaxNumIter>$-epscuLimit $SpescuLimit>$-stRatio $SstRatio>$-rat $Srat>
```

Four analyses have been done for compare the new material developed (ConfinedConcrete02) with the one already inside the OpenSees (ConfinedConcrete01) by considering two different section types (See Figure 9 and Figure 10).

- The parameters for Figure 9
  - **Hoops Only**
    ```
    #uniaxialMaterial ConfinedConcrete02 $tag $secType $fpc $Ec -epscu $epscu $nu $SL1 $phis $Sfyh $SEs0 $ShaRatio $Snu $SphiLon -stRatio $SstRatio -rat $Srat
    ```
    ```
    uniaxialMaterialConfinedConcrete02 1 S1 -epscu -0.03 -varub 300.0 10.0 100.0 206000.0 16.0 -stRatio 0.85 -rat 0.10
    ```
    - **Hoops and Wraps Only**

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![Graph](image-url)  
**Figure 9:** Reinforced Square section (S1) with Hoops and Hoops, Wraps
The parameters for Figure 10

- **Hoops Only**

- **Hoops and Wraps Only**

6.0 **Results discussion and conclusion**

By concluding results obtained for case of analysed, fully unloading strain is always greater than the strain of ConfinedConcrete01 for the same cycle. New parameter (rat) can be used for defining the required energy dissipation capacity according to unloading and loading stiffness. The energy dissipation capacity is always represented the area under the Stress-Strain curves for particular envelope. For same strain of the analysed cases, each loading and unloading cycle of the ConfinedConcrete02 (See Figure 9 and Figure 10) dissipated more energy than ConfinedConcrete01 as per the results. Hence, this new material can be used in computational modelling to make the different energy dissipation for same displacement. This new material gives the better opportunity to model the degradable stiffness depend on the requirement during reverse cyclic loading action.
References


