A TOOL FOR NON-LINEAR ANALYSIS OF CONCRETE AND R/C STRUCTURES

Diego A. TALLEDO
PhD Student
Università IUAV di Venezia
Terese – Dorsoduro 2206 – 30123 Venezia
talledo@dicea.unifi.it

Leopoldo TESSER
Research Assistant
Università degli studi di Padova
Dipartimento ICEA, Via Marzolo, 9 – 35131 Padova
tesser@dic.unipd.it

Filip C. FILIPPOU
Professor
University of California, Berkeley
731 Davis Hall – CA 94720-1710
filippou@ce.berkeley.edu

Anna SAETTA
Professor
Università IUAV di Veneiza
Terese – Dorsoduro 2206 – 30123 Venezia
saetta@iuav.it

Abstract

This paper presents the development and the enhancement of Opensees introduced by the authors to make it an effective tool for non-linear analysis of concrete and R/C structures and for post-processing the outputs. A three-dimensional isotropic plastic-damage constitutive law developed by the authors has been implemented to improve the program capabilities in simulating the concrete behaviour. A R/C membrane element for two-dimensional problems and a R/C plate element for three-dimensional ones were defined and implemented. The reinforcing bars are simulated with a smeared approach such that multiple smeared layers with uniaxial stress-strain response can be simulated. A post-processing utility has been created permitting the interface with the pre- and post- processor GiD . Some showcases demonstrate both the ability of the model to simulate experimental tests and the potentiality of the enhanced OpenSEES for concrete and R/C inelastic analyses.

Keywords: Concrete, Damage, Non-linear analysis, Post-processing, R/C plate, Shear walls.

1. Introduction

Reinforced concrete panels and shear walls are commonly used as lateral force resisting systems of structures in seismic zones for serviceability, ultimate strength and ductility considerations. Moreover concrete and reinforced concrete elements are widely employed in existing structures in all the national and international construction panorama evidencing the need of effective and accessible numerical tools to properly assess the inelastic response of concrete and reinforced concrete elements. In the last decades several research teams have developed concrete constitutive models different for applicability, complexity computational

efficiency and reliability [1-6]. Even if some of them found their way in modern finite element programs, their accessibility, evaluation, comparison and testing are often limited and difficult. Some relevant US agencies, centres and organizations (Pacific Earthquake Engineering Research Center, Network for Earthquake Engineering Simulations, National Earthquake Hazards Reduction Program, Federal Emergency Management Agency) have consistently invested in order to achieve a reference framework for simulating the seismic structural response speeding up knowledge exchanges and research advancements.
Taking advantage of this platform some of the authors have developed a R/C membrane model based on a plastic-damage constitutive law for concrete that has shown to be reliable and efficient [7] and that it was extended for non-linear cyclic analyses of R/C plates and shear walls [8]. The concrete damage model is briefly recalled while more attention is spent in defining the R/C membrane and plate elements and their implementation into the OpenSEES framework. In order to improve the software potentiality a post-processing utility is presented using a combination of routines (some of them developed as new OpenSEES commands and some others developed as external MATLAB procedures) that permits that interface with post-processor GiD [9] to display the outputs. Some showcases confirm the ability of the enhanced OpenSEES to simulate experimental tests and to effectively present the results.

2. Material models

The general three dimensional plastic-damage model and the steel uniaxial constitutive law are briefly recalled here with two main aims. The first one is to provide the reader with the fundamental concepts to better evaluate the presented results and the second one is to underline the definition of the material behaviour as a preliminary step respect to the definition of the generic R/C element. No empirical formula to correct the material behaviour will be added while defining the membrane and plate models.

The authors would like to underline the suitability of the proposed approach for an object oriented programming where the choice of different material laws can be easily compared.

2.1 Concrete

The isotropic plastic-damage model developed by some of the authors [7]. The split of the total strain tensor into “elastic-damage” and “plastic-damage” parts is assumed:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p \tag{1}$$

The effective stress tensor is defined by:

$$\overline{\boldsymbol{\sigma}} \equiv \mathbf{C}^0 : \boldsymbol{\varepsilon}^e \tag{2}$$

The relation between the Cauchy stress tensor and the effective stress tensor is obtained from the Clausius-Duhem inequality and writes:

$$\boldsymbol{\sigma} = (\mathbf{I} - \mathbf{D}) : \overline{\boldsymbol{\sigma}} \tag{3}$$

the fourth-order damage tensor can be defined by the following expression:

$$\mathbf{D} = \mathrm{d}^+\mathbf{P}^+ + \mathrm{d}^-\mathbf{P}^- \tag{4}$$

with $\mathbf{P}^+$ and $\mathbf{P}^-$ standing for the fourth-order projection tensors, positive and negative respectively.
For the damage criteria, the damage energy release rate functions are defined with the following formulas:

$$Y^+ = \sqrt{E^0 \overline{\boldsymbol{\sigma}}^+ : \mathbf{C}^{0^{-1}} : \overline{\boldsymbol{\sigma}}^+} \tag{5}$$

$$Y^- = \sqrt{3}\left(KI_1 + \sqrt{J_2}\right) \tag{6}$$

Where E^0 is the concrete Young modulus, I_1 and J_2 are the first invariant of the effective stress tensor and the second invariant of the deviatoric effective stress tensor and K is a material property that accounts for the increase of compressive strength due to biaxial compression.
The damage threshold in uniaxial tension and uniaxial compression is described by variable r^+ and r^-, respectively, and they monitor the size of the expanding damage surface. Taking advantage from the homogeneity of the equivalent stresses, the following unique expression can adequately account for the interaction between tensile and compressive damage evolutions:

$$g = \left(\frac{Y^+}{r^+}\right)^2 + \left(\frac{Y^-}{r^-}\right)^2 - 1 \leq 0 \tag{7}$$

The damage criterion, that constitutes the damage surface, is superimposed to the proposal by Faria et al. [10] in Figure 1.

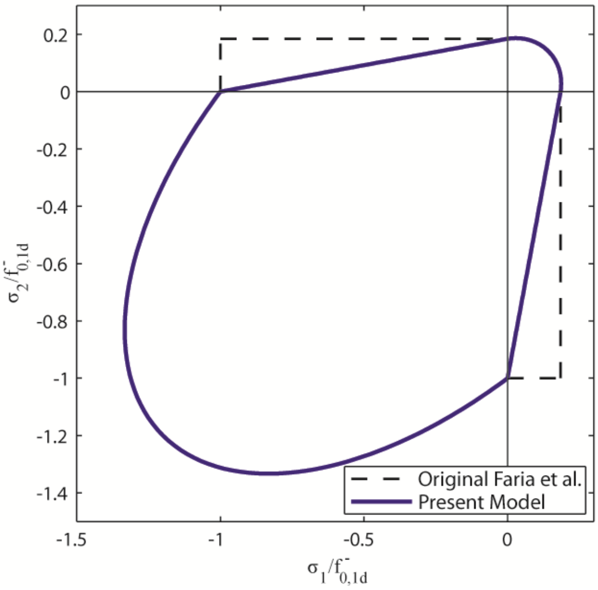

Figure 1. Initial damage surface for biaxial conditions.

In addition to the damage criterion the evolution of the damage threshold is determined by the following flow rule:

$$\dot{\boldsymbol{r}} = \dot{\gamma}\frac{\partial g(\boldsymbol{Y},\boldsymbol{r})}{\partial \boldsymbol{Y}} \tag{8}$$

where γ is the damage consistency parameter.
The constitutive model considers that damage criteria describes also the plastic surface so that the development of material damaging is simultaneous to the accumulation of irreversible strains for all the stress states. The following plastic evolution law is defined:

$$\dot{\boldsymbol{\varepsilon}}^p = \beta E^0 \frac{\langle \overline{\boldsymbol{\sigma}} : \dot{\boldsymbol{\varepsilon}} \rangle}{\overline{\boldsymbol{\sigma}} : \overline{\boldsymbol{\sigma}}} \mathbf{C}^{0^{-1}} : \overline{\boldsymbol{\sigma}} \tag{9}$$

having introduced β for the plastic strain coefficient. Additional details on the material model and the integration algorithm can be found in [7].

2.2 Reinforcing steel

In the present work the Menegotto-Pinto law with the isotropic hardening introduced by Filippou et al. [11] has been profitably selected for its ability to evaluate precisely the hysteretic behaviour of the reinforcing steel.

3. Elements

3.1 Reinforced concrete membrane element

The general three-dimensional concrete law is constrained to plane stress to represent the behaviour of concrete panels.

In the present work reinforcing bars are simulated considering the superposition of different material models to create the membrane model (embedded approach). Thus the reinforcements shall be represented as smeared since the overall behaviour of the membrane shall comply with the panel kinematic. As a result the equivalence of the total strains of the different materials is imposed, therefore assuming perfect bond between concrete and reinforcing steel. Each steel layer can reproduce the behaviour of a set of bars oriented in a generic direction respect to the element principal axis. An important benefit of the membrane model is the possibility to reproduce the most common reinforcement configurations by simply adding the appropriate number of layers.

The reinforcing layer state determination starts with the projection of the generic total strain tensor in the direction of the bars. Then the total strain along the steel bar direction is used to compute the uniaxial steel material state determination. The material state in terms of steel stress and tangent modulus are therefore re-projected in the original element reference system. These layer responses are added to those coming from the other concrete and steel layers. It can be underlined that the membrane model can be applied to any two-dimensional finite element. The authors have carried out several analyses running different elements i.e. four-node and nine-node quadrilateral and three to six-node triangular.

3.2 Reinforced concrete plate element

In the three-dimensional concrete law the out-of-plane normal stress is condensed to represent the behaviour of concrete plates.

The section solicitation over the depth are integrated by 5 point Gauss-Lobatto rule such that 2 integration points are placed at the top and the bottom surfaces of plates.

The reinforcing bars are modelled by steel membranes that have exactly the same definition of those used for the R/C membranes.

Other integration points are placed over the section depth in correspondence of the physical transversal coordinates of the reinforcing bars to compute the contribution of the steel membranes in producing the section solicitations.

The finite element used is the 4-node MITC element by Dvorkin and Bathe. This element have shown absence of out-of-plane shear locking and excellent results in geometrically nonlinear analysis [12].

4. Implementation in OpenSEES

The presented model was implemented in the OpenSEES framework taking advantage of his high customizability and his open interface. The main abstractions of OpenSEES framework are ModelBuilder object (which is responsible for construction of various parts of a model and adding them to the domain), the Domain object (which holds the state of the model at time t_i and at time t_i+dt and store the objects created by ModelBuilder), the Recorder Object (which monitor and save user-defined parameters in the model during the analysis) and the Analysis Object (which moves the model from time t_i to time t_i+dt).

In Figure 2 is reported an overview of the hierarchy of Domain object. The presented model was introduced in that level with additional classes in Material abstraction.

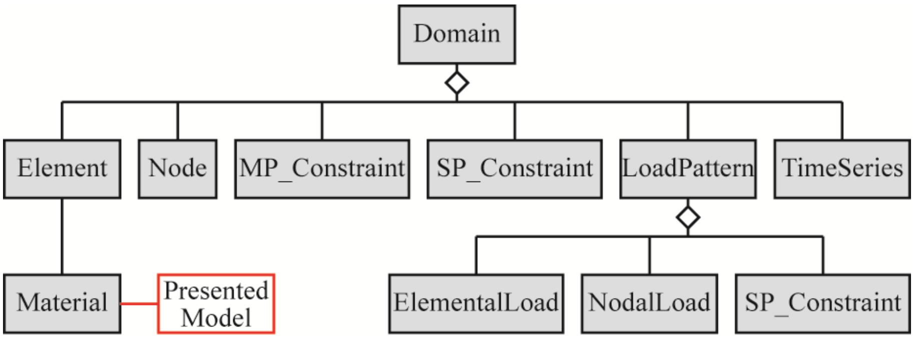

Figure 2. Domain Object structure.

The presented model was implemented at Material level. Material has three abstractions in OpenSEES framework: UniaxialMaterial, NDMaterial, SectionForceDeformation. UniaxialMaterial defines the stress-strain or force-deformation response of a one-dimensional material. In this case the behaviour is described by scalar quantities. NDMaterial is the extension of UniaxialMaterial for three-dimensional case. SectionForceDeformation is used to describe the stress resultant models which are used to describe plate and beam-columns responses. Within this framework, the implementation of the Reinforced Concrete model falls into NDMaterial and SectionForceDeformation abstractions as it is shown in Figure 3. The damage model presented in section 2.1 is implemented in Concrete class that can be used with all finite elements that require a NDMaterial. Currently the valid material formulations are generic three dimensional model, plane stress model and plane strain model. For this reason the material can be currently used in quad, brick and shell elements. The UniaxialLayer class is a wrapper interface used to define a set of parallel bars of reinforcing steel as described in section 3.1. The potentiality of this approach is that the user can select any uniaxial material model in the OpenSEES material library to describe the reinforcement behaviour (e.g. Elastic, Steel01, Steel02, ecc…).

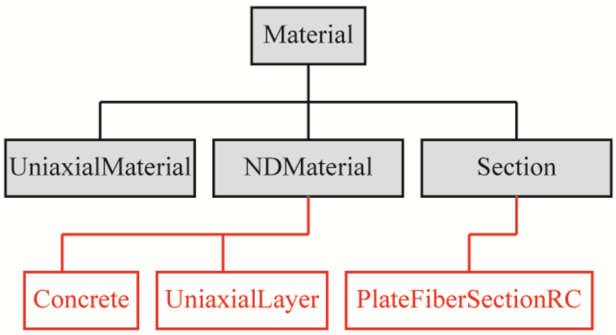

Figure 3. Implemented classes.

Finally, the PlateFiber section class of OpenSEES was enhanced by adding integration points to consider reinforcing steel as described in section 3.2. This class takes some plate fiber materials (concrete and appropriate number of reinforcement layers) and, by integration over thickness, creates a plate section appropriate for shell analysis.

4.1 Post-processing of results

A new command is introduced in OpenSEES to export mesh information in a format compatible with GiD [9] (a pre- and post-processor developed by CIMNE, Barcelona). Also a set of Matlab routines where released to read output from OpenSEES recorders and save it in a format compatible with GiD. In this way it is possible to have a GUI for generating result views for examined models. The procedure could be further enhanced integrating these routines inside OpenSEES framework, making it capable of produce output files in a format natively compatible with GiD.

5. Examples

5.1 Double T cross section: specimen S5

The specimen S5 of the experiments of Maier and Thürlimann [13] has a double T cross section and it is simulated by a plate model. The height of the wall is 1200 mm, the web width is 980 mm while the flange width is 400 mm. Both web and flanges are 100 mm depth. The vertical reinforcement ratio is 1.16% and the horizontal one is 1.03%. The specimen is subjected to a constant axial load of 416 kN and to horizontal load reversals with cycles of increasing amplitude.
The comparison between the numerical and the experimental results in terms of load-displacement curve is reported in Figure 4. The distribution of the concrete damage parameter for the middle section of plate when the model reaches the positive maximum displacement of 20 mm is also shown in Figure 4. The proposed model shows to be efficient and reliable in representing the complex behaviour of these structures. The damage parameters are useful scalar values that can help to interpret the damaging process of the wall very efficiently resuming essential information of non-linear behaviour of concrete material.

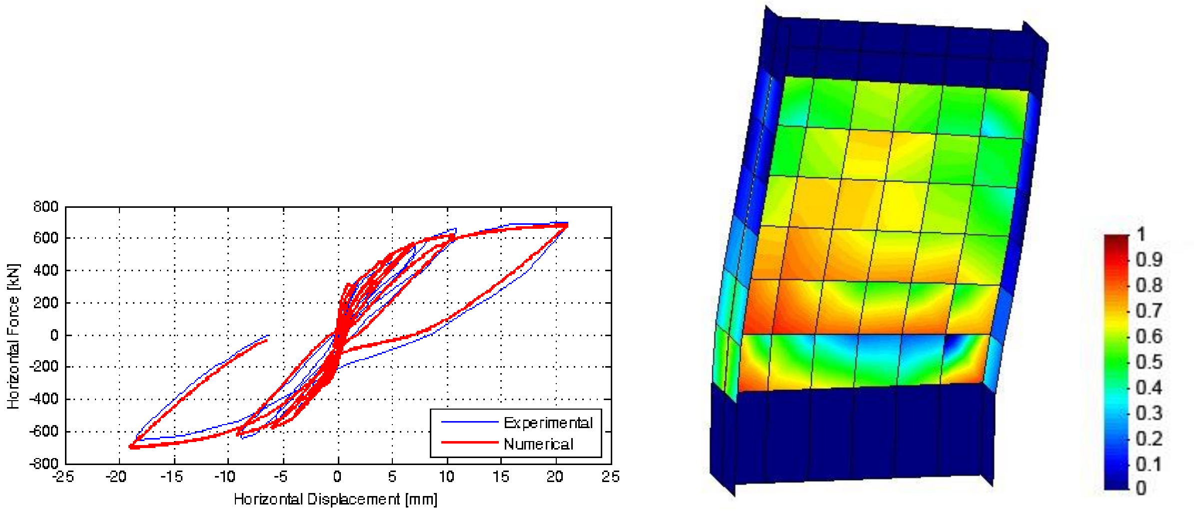

Figure 4. Force-Displacement curve and negative damage parameter at 20 mm for specimen S5.

5.2 U-shaped shear wall

The U-shaped shear wall tested by Pégon et al. [14] is simulated with the R/C plat model. The height of the wall is 3600 mm while the section is a U-shape with side size of 1125 mm x 1125 mm and thickness of 250 mm. The top section ends in a transversal plate with a thickness of 600 mm which constraints twist. The specimen is subjected to a quasi-static horizontal load carried out imposing top cyclic displacements in the two principal directions of the U-shaped section.
The experimental results are compared in Figure 5 in terms of force-displacement curves for both the principal directions. In Figure 6 is reported the deformed shape with the distribution of the concrete damage parameter related to compressive part of the stress state corresponding to a top displacement of -40 mm in both directions. Looking at this distribution, it can be seen the ability of the model in describing the failure mode that takes place in the bottom section of the web and which occurs due to both flexural and shear solicitations.

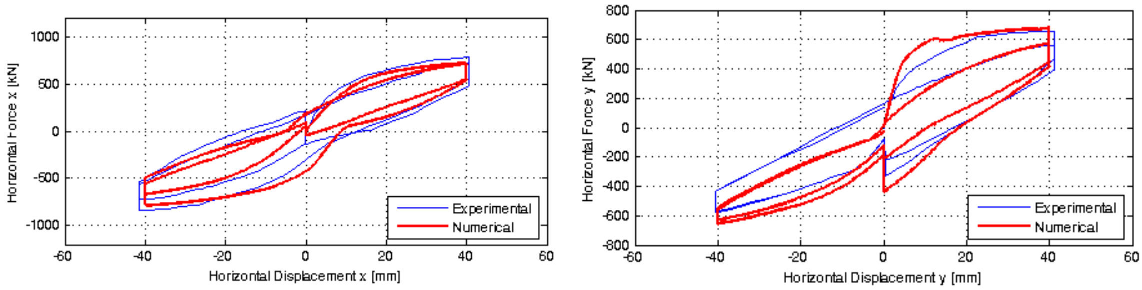

Figure 5. Comparison between experimental and numerical results in the direction parallel to the web and parallel to the flanges.

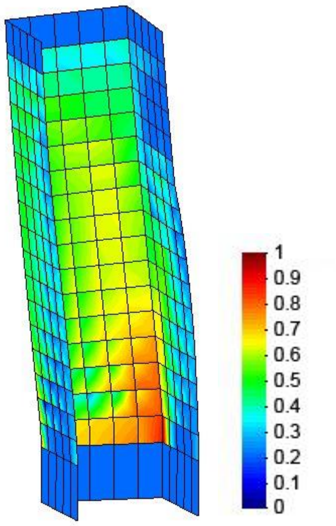

Figure 6. Negative damage parameter distribution at a displacement of -40 mm in both directions.

6. Conclusions

Straightforward formulations of a R/C membrane and R/C plate models have been proposed by superimposing different materials, concrete and reinforcing steel, to create a single membrane model with smeared reinforcement of general orientation.

Implementation of the model in the OpenSEES framework is described, showing the new classes introduced in the Material abstractions.

Simulations of R/C panels and shear walls are carried out. In particular double T and U-shaped sections are presented. The examples show clearly the ability of the proposed model to reproduce the main features of the experimental panel behaviour such as: the yield strength, the panel peak strength even when governed by concrete shear failure, the subsequent hardening/softening behaviour, the residual deformation at load reversals and energy dissipation capacity.

The developed post-processing utility let an effective visualization of the program outputs, including the concrete material damage parameters, creating a useful interface with the post-processor GiD.

7. References

[1] MAZARS, J., PIJAUDIER-CABOT, G., "Continuum Damage Theory: Application to Concrete, Journal of Engineering Mechanics ASCE, 892, 345–365, 1989.

[2] VECCHIO, F.J., COLLINS, M.P., "The Modified Compression-Field Theory For Reinforced Concrete Elements Subjected To Shear", *ACI Structural Journal*, Vol. 83, No. 2, March 1986, pp. 219-231.

[3] BAZANT, Z.P., OZBOLT, J., "Nonlocal Microplane Model for Fracture, Damage, and Size Effect in Structures", Journal of Engineering Mechanics, Vol. 116, No. 11, November 1990.

[4] LEE, J., FENVES, G., "Plastic-Damage Model For Cyclic Loading Of Concrete Structures", *Journal of Engineering Mechanics ASCE*, Vol. 124, No. 8, August 1998, pp. 892-900.

[5] MANSOUR, M., HSU T.T.C., "Behaviour Of Reinforced Concrete Elements Under Cyclic Shear. II: Theoretical Model", Journal of Structural Engineering ASCE, Vol. 131, No. 1, January 2005, pp. 54-65.

[6] CERVENKA, J., PAPANIKOLAOU, V.K., "Three Dimensional Combined Fracture-Plastic Material Model For Concrete", *International Journal of Plasticity*, Vol. 24, No. 12, December 2008, pp. 2192-2220.

[7] TESSER, L., FILIPPOU, F.C., TALLEDO, D.A., SCOTTA, R., VITALIANI, R., "Nonlinear Analysis Of R/C Panels By A Two Parameter Concrete Damage Model", *III ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Corfu, Greece, May 2011.

[8] TESSER, L., TALLEDO, D.A., SCOTTA, R., VITALIANI, R., "Nonlinear Analysis Of R/C Shear Walls Subjected To Seismic Loadings", *XIV Convegno ANIDIS "L'Ingegneria Sismica in Italia"*, Bari, Italy, September 2011.

[9] GiD, "The Personal Pre And Post Processor", http://gid.cimne.upc.es.

[10] FARIA, R., OLIVER, J., CERVERA, M., "A Strain-Based Plastic Viscous-Damage Model For Massive Concrete Structures", *International Journal of Solids and Structures*, Vol. 35, No. 14, May 1998, pp. 1533-1558

[11] FILIPPOU, F.C., POPOV, E.P., BERTERO, V.V., "Effects Of Bond Deterioration On Hysteretic Behavior Of Reinforced Concrete Joints", *Earthquake Engineering Research Center*, University of California, Berkeley, Rep. No. UCB/EERC-83/19, August 1983.

[12] BATHE, K.J., DVORKIN, E.N., "A Four-Node Plate Bending Element Based On Mindlin/Reissner Plate Theory And A Mixed Interpolation", *International Journal For Numerical Methods In Engineering*, Vol. 21, No. 2, February 1985, pp. 367-383.

[13] MAIER J., THÜRLIMANN, B., "Bruchversuche An Stahlbetonscheiben", *Birkhäuser Verlag Basel*, Switzerland, No. 8003-1, January 1985.

[14] PÉGON, P., PLUMIER, C., PINTO, A., MOLINA, J., GONZALEZ, P., TOGNOLI, P., HUBERT, O., "U-Shaped-Wall: Description Of The Experimental Set-Up", *Report*, Joint Research Center (J.R.C.), Ispra, Italy, 2000.