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It is with great pleasure that we introduce this volume of proceedings of the second OpenSees Days Italy, held in Salerno on 10 and 11 June 2015.
The first OpenSees Days were held in 2012 in Rome, where several scientists gathered to share their experience in using OpenSees in their research. In that occasion, the attendance was mainly from Italy and from some other European countries. In this new edition of the OpenSees Days we also have the participation of researchers from China and Iran, whom we warmly welcome.
The Scientific Committee has worked with enthusiasm to organize this event and we are proud to see that the number of papers has increased, as well as the active participation of both scientists and professionals, also thanks to the support of the University of Salerno and to the Chamber of Engineers of Salerno. All of our appreciation goes to these two fundamental Institutions.

Based on the topic, papers were presented in four different sessions and the chapters of this volume follow the same arrangement (in parenthesis the number of papers): Case Studies (3), Modeling and New Elements (7), Nonlinear Analysis (14), and Structural Reliability and Durability (6).

In between the presentations, the audience had the opportunity to listen to four highly appreciated keynote speeches. The keynote speakers, whom we warmheartedly thank for the interest raised by their innovative topics were:
Thomas Hsu: Cyclic Test of a Large Cylindrical RC Containment Vessel and its FEA Simulation using OpenSees,
Xinzheng Lu: Development and application of OpenSees for large-scale structures,
Frank McKenna: OpenSees: Past, Present and Future Challenges,
Asif Usmani: Challenges of Simulating Structural Response to Real Fires: An OpenSees Solution.

After these two successful events, we are already at work for the next edition, which will certainly witness stimulating advances. We expect to see interesting innovative applications in the field of civil engineering and, especially, we look forward to the development of new user interfaces, both, to assist in the implementation of new elements for research, and to simplify the use of existing elements for modeling and analysis of structures.

Giorgio Monti, OpenSees Days Chairman
Roberto Realfonzo, University of Salerno

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NUMERICAL SIMULATION OF FRP-CONFINED CIRCULAR BRIDGE PIERS USING OPENSEES

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Abstract

The material model proposed by Megalooikonomou et al. (2012) was added to the source code of Opensees as a uniaxial material, i.e. the '*FRPConfinedConcrete*' material. In order to evaluate the performance of this material model, it was implemented in the simulation of a series of cyclic loading tests performed by Gallardo-Zafra and Kawashima (2009). In particular, all specimens were simulated using nonlinear fiber elements, in which the FRP-confined concrete was modelled using the aforementioned material model. Comparison between the numerical and experimental hysteresis of the column is indicative of the effectiveness of the implemented modelling.

Keywords: Circular Columns, Concrete, Confinement, Cyclic response, FRP Jacket

1. Introduction

The library of materials, elements and analysis commands makes Opensees a powerful tool for numerical simulation of nonlinear structural and geotechnical systems. The Opensees library of components is ever-growing and at the leading edge of numerical-simulation models. Its interface is based on a command-driven scripting language which enables the user to create more-versatile input files. Opensees is not a black box, making it a useful educational tool for numerical modeling. Material, element or analysis tools can be incorporated into Opensees

Addition of a new uniaxial material module by the developer is achieved by providing a new C++ subclass of the *UniaxialMaterial* class, along with an interface function which is used to parse the input and create the new material. Unlike the C and Fortran modules, no information about the state of the model is provided as argument to the material routine. Retaining the required information and rejection of the unnecessary one is performed within the material model This information includes simultaneously (a) parameters, *i.e.* information needed to define the material, and (b) state variables or history variables, *i.e.* information needed in order to define its current state and, consequently, compute the applied stress and tangent.

The present work provides information on the implementation of a recently developed material model for FRP and Steel – confined concrete, proposed by Megalooikonomou *et. al.* [1], in Opensees under the name '*FRPConfinedConcrete'*. To date, the model has no tensile strength and uses the degraded linear unloading/reloading stiffness in the case of cyclic loadings based on the work of Karsan and Jirsa [2].

2. Envelope for 'FRPConfinedConcrete' Constitutive Model

The command used in order to construct the uniaxial '*FRPConfinedConcrete'* is provided in the following syntax:

```
uniaxialMaterial FRPConfinedConcrete $tag  $fpc1  $fpc2  $epsc0  $D    $c      $Ej     $Sj
$tj       $eju    $S       $fyh         $dlong      $dtrans          $Es          $vo              $k
```

Each input parameter defined above corresponds to the mechanical and geometrical properties of the FRP-confined element which affect its overall performance. Their description is provided in Table 1.

Table 1. '*FRPConfinedConcrete'* input parameters.

1	***tag***	Material Tag
2	***fpc1***	Concrete Core Compressive Strength
3	***fpc2***	Concrete Cover Compressive Strength
4	***epsc0***	Strain Corresponding to Unconfined Concrete Strength
5	***D***	Diameter of the Circular Section
6	***c***	Dimension of Concrete Cover
7	***Ej***	Elastic Modulus of the Jacket
8	***Sj***	Clear Spacing of the FRP Strips - zero if it's continuous
9	***tj***	Total Thickness of the FRP Jacket
10	***eju***	Rupture Strain of the Jacket
11	***S***	Spacing of the Stirrups
12	***fyh***	Yielding Strength of the Hoops
13	***dlong***	Diameter of the Longitudinal bars
14	***dtrans***	Diameter of the Stirrups
15	***Es***	Steel's Elastic Modulus
16	***vo***	Initial Poisson's Coefficient for Concrete
17	***k***	Reduction Factor (0.5-0.8) for the Rupture Strain of the FRP

The mechanical properties of concrete (strength, pseudo-ductility, energy dissipation) are substantially enhanced under a triaxial stress state. In practice, this is obtained by using closed stirrups or spiral reinforcement or even FRP wraps so that, together with the longitudinal reinforcement, the lateral expansion of concrete is limited. This kind of (passive) confinement improves the material behavior after the occurrence of internal cracking, which triggers the initiation of expansion.

For low strain values, the stress state in the transverse steel reinforcement is very small and the concrete performs basically as unconfined. In this range, steel and FRP jacketing behave similarly: the inward pressure as a reaction to the expansion of concrete increases continuously. Therefore, stating in terms of variable confining pressures corresponding to the axial strain level in the section and active triaxial models defining axial stress-strain curves for concrete subject to constant lateral pressure, it can be stated following the original approach of [3] that the stress-strain curve describing the stress state of the section has to cross all active confinement curves up to the curve with lateral pressure equal to the one applied by the stirrups at yielding. After yielding of stirrups, the lateral pressure is still increasing, but only thanks to the FRP jacketing, while the steel lateral pressure remains constant. The corresponding stress-strain curve of the section throughout this procedure converges to a confined-concrete axial stress-strain curve that is associated with a lateral pressure magnitude equal to the tensile strength of the FRP jacket added to the yielding strength of ties (excluding the strain hardening behavior of steel, since ultimate strain of steel is usually much higher than this of an FRP jacket). In order to model this behavior, a well-known FRP-confined concrete model [3] has been enhanced to include the steel ties contribution and thus model in a more consistent way circular columns with transverse steel reinforcement and retrofitted with FRP jacketing. The above model was based on an iterative procedure that was modified as illustrated in Figure 1.

In the procedure depicted in Figure 1, after imposing an axial strain on the section, a pressure applied by the FRP jacket is assumed. Then, the calculation of (a) the Poisson's coefficient until yielding of steel stirrups and (b) the lateral pressure by the steel ties is performed based on the BGL model [4]. Here, also the longitudinal bars' contribution and the arching action between two adjacent stirrups along the column are taken into account. Thus, the confining pressure in the concrete core is the summation of the contribution of the two confining systems (FRP and Steel) to the applied lateral stress. Beyond this point, the Spoelstra and Monti model [3] is used for the definition of the remainder of the parameters, applying on the two different areas of concrete, *i.e.* the core and the cover. It should be noted that cases with partial wrapping can also be simulated using the particular material model [1]. Such an approach also allows the consideration of two different concrete strengths in cases of element repair and retrofit, one for the additional layer of concrete applied externally and another for the existing concrete core, which may also be cracked due to former seismic loading [1]. Finally, due to several factors affecting the performance of the FRP wrap, such as the local stress concentrations near failure, an ultimate tensile coupon FRP strain, reduced by a k factor (ranging in literature between 50-80%), is used to end the iterative procedure when the FRP jacket reaches its rupture strain.

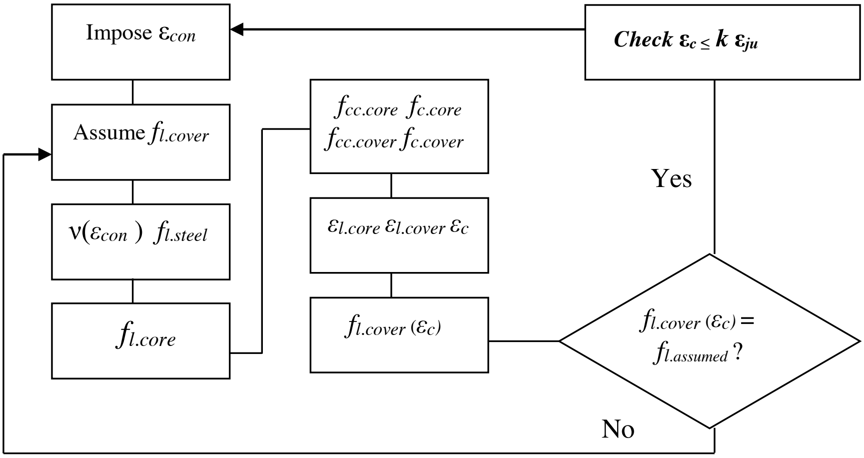

Figure 1. Iterative procedure of the '*FRPConfinedConcrete' material model.*

3. Numerical simulation and evaluation against experimental results

The experimental investigation performed by Gallardo-Zafra R. & Kawashima K. [5] contains a series of cyclic loading tests that were conducted on six reinforced concrete column specimens 400mm in diameter and 1,350mm in effective height. The specimens were grouped into two series (A and B), each of them consisting of three specimens: (a) an 'as-built' specimen without FRP jacket, and two laterally wrapped using (b) a single layer and (c) two layers of CFRP respectively. The tie reinforcement ratio was 0.256% (150 mm spacing) for the A-series and 0.128% (300 mm spacing) for the B-series. Figures 2, 3, 4 and 5 depict the comparison with the two groups of cyclic tests on bridge piers having different levels of confinement in terms of lateral steel reinforcement and FRP jacketing. Modelling of the bridge piers in this work was realized as in [5], using the Opensees software. No P-Δ effect was considered in the performed analyses.

To simulate the experimental behaviour of the columns, they were idealized by a discrete analytical model. The cantilever column was modeled by a linear beam element with the stiffness corresponding to flexural yielding and a fiber element used to capture the flexural hysteretic behaviour at the plastic hinge. The length of the fiber element was assumed to be half of the column's diameter. A rotational spring at the bottom of the column represents the longitudinal bar pullout from the footing. Its property was based on moment-rotation curve obtained from the experiment at small amplitude loading and was assumed to have an elastic stiffness. It is known that even under small amplitude loading, column stiffness is affected by the flexibility of the connection between the column and the foundation (in this case the footing). If the column is assumed to be rigidly fixed with the foundation, the computed initial stiffness of the column is smaller than the measured stiffness.

The fiber element is divided into a discrete number of sections along the member axis and the sections are further subdivided into longitudinal reinforcing steel and concrete fibers. The section force-deformation relation is obtained by the integration of the uniaxial stress strain relation of the fibers such that the nonlinear behaviour of the element is derived from the nonlinear stress-strain relation of the longitudinal steel and concrete fibers. While in the original proposal the fiber section needed to be divided in the concrete core and concrete cover and two different stress-strain relations were applied for the concrete core (confined by both FRP & Steel) and concrete cover (confined by only the FRP), in this work since the

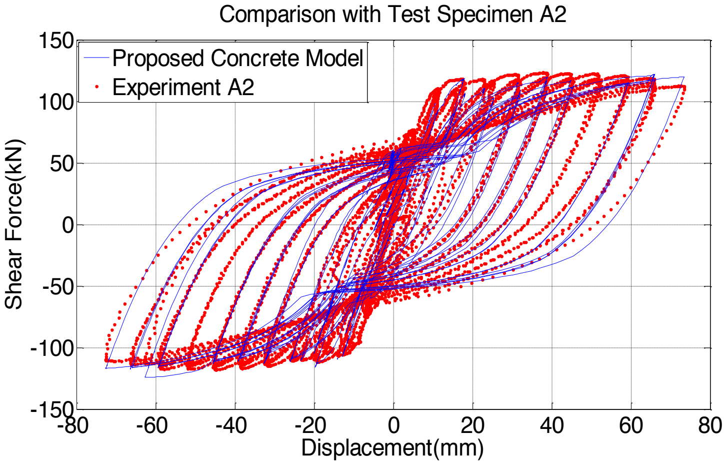

Figure 2. Specimen A2 – Numerical simulation vs. Gallardo-Zafra R. & Kawashima K. [5].

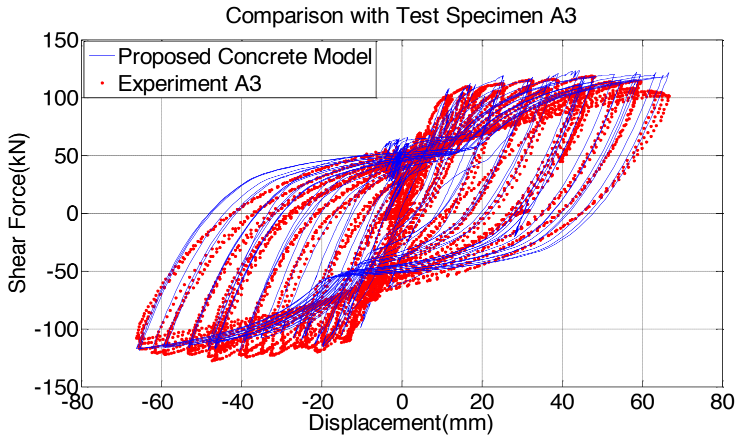

Figure 3. Specimen A3 – Numerical simulation vs. Gallardo-Zafra R. & Kawashima K. [5].

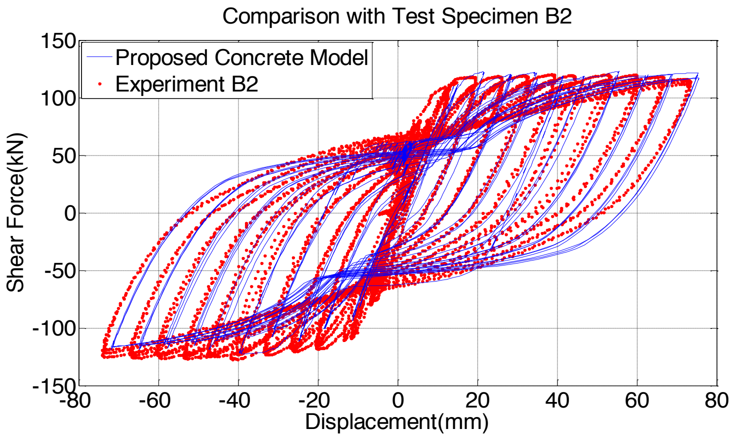

Figure 4. Specimen B2 – Numerical simulation vs. Gallardo-Zafra R. & Kawashima K. [5].

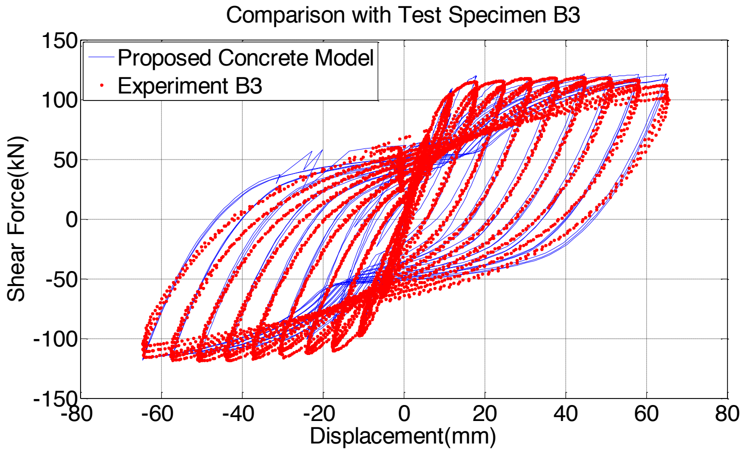

Figure 5. Specimen B3 – Numerical simulation vs. Gallardo-Zafra R. & Kawashima K. [5].

material response is already averaged based on the different responses of those two regions, the same stress strain law is applied for each fiber. This is the main advantage to the applied material model. It can be noticed that the results are very close to the experimental ones.

4. Conclusions

A recently developed material model for FRP and Steel – confined concrete [1] was implemented in Opensees under the name '*FRPConfinedConcrete'* with no tensile strength and degraded linear unloading/reloading stiffness in the case of cyclic loadings based on the work of Karsan and Jirsa [2]. In case of bridge pier modelling with a fiber nonlinear beam-column element in which the developed constitutive law for concrete is implemented, the averaged response of the two different regions - concrete core (confined both by the FRP & the existing reinforcement) and concrete cover (confined only with the FRP wrap) - in the cross-section allows the assignment of a unique stress-strain law for all the fibers/layers of the circular section. The results yielded by the analytical modelling of the cyclic loading procedure of FRP-confined bridge piers are indicative of the effectiveness of the applied material model, *i.e.* the *'FRPConfinedConcrete'*, as they were found to simulate with adequate accuracy the records of the experimental procedure.

5. Acknowledgements

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