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IMPLEMENTATION AND FINITE-ELEMENT ANALYSIS OF SHELL ELEMENTS CONFINED BY THROUGH-THE-THICKNESS UNIAXIAL DEVICES

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Abstract. *This contribution presents the implementation in OpenSees of an integration procedure based on a recently developed theory concerning stress integration along the chords of a shell element reinforced with uniaxial transverse links. Such a model has been developed in order to account for transverse confinement effects induced by through-the-thickness jacketing of masonry and reinforced concrete existing structures. In particular, transverse confinement induces a triaxial stress state in the core material of the shell increasing the stress spherical part and resulting in strength and ductility increments. In order to perform structural analyses with reduced computational costs, the presented tool permits to compute the response of plane elements confined by uniaxial devices. To this end, the implemented object accounts for the mutual interaction of uniaxial reinforcements with a triaxial core by means of equilibrium and compatibility equations involving several object classes of the OpenSees framework. Integration of the triaxial stress state along the thickness of a shell element is therefore performed by numerically solving the equilibrium/compatibility equation system. The adopted implementation strategy is summarized and modeling features are discussed. In conclusion, numerical examples show some possible applications of the proposed tool in common structural design practices.*

1 INTRODUCTION

The use of confinement devices in the retrofit of masonry and reinforced concrete structures has become a very popular approach for its capability of improving structural strength and ductility. More recently, use of confinement retrofit techniques has been extended also to the retrofit of planar structural elements. In particular, masonry panels in existing buildings are also confined by employing Through-the-Thickness reinforcing links connecting external reinforced render layers Jacketing the panel (TTJ) [1].

To model TTJ devices, a formulation of TTJ Shell (TTJS) has been proposed by the authors in a recent research paper [2]. It consists of an Equivalent Single Layer Mindlin First-order Shear Deformation Theory (ESL-FSDT) endowed by enhanced kinematics coupling the stress-strain states of a shell triaxial core material and of uniaxial transverse confining devices.

The present contribution briefly presents the TTJS formulation and illustrates the underlying implementation strategy in OpenSees of an MITC shell element based upon the TTJS theory. Numerical results and validation schemes are also presented.

2 THROUGH-THE-THICKNESS JACKETED SHELL THEORY

The TTJS theory [2] enhances in a simplest possible way an ordinary ESL MITC formulation. Its main idea is to enforce a set of equilibrium and compatibility equations, representing the interaction between the links and the core material over a generic transverse segment of the shell, named *Shell Chord*. For a shell core made of *n* layers these equations are:

$$\text{Compatibility:}\quad \sum_{i=1}^{n} \varepsilon_{33}^{i} t^{i} = \varepsilon_{TT} \sum_{i=1}^{n} t^{i}; \qquad \text{Equilibrium:}\quad \sigma_{33}^{i} + \mu_T \sigma_{TT} = 0; \quad i = 1..n \tag{1}$$

where ε_{33}^{i} and σ_{33}^{i} are the strain and stress components at the *i*-th layer along the direction orthogonal to the shell middle plane, ε_{TT} and σ_{TT} are the uniaxial strain and stress of the confinement devices, t^{i} is the thickness of the *i*-th layer and μ_T is the percentage area of the ties. The i-th layer refers to a specific class of triaxial material providing stress components $\sigma_{\mathrm{jk}}^{\mathrm{i}}$ as functions of $\varepsilon_{\mathrm{jk}}^{\mathrm{i}}$ and its derivative.

The compatibility condition in (1) enforces the deformation ε_{TT} to be equal to the transverse stretching of the shell core and the equilibrium condition enforces the core stress component σ_{33}^{i} to be in equilibrium with the term $\mu_T \sigma_{TT}$ representing the uniaxial stress resultants of the ties. In such a way, Eqs. (1) describe the interaction of all layers with the uniaxial ties where the role of transverse confinement is to contrast the transversal stretching of the shell, acting proportionally to the stiffness of the confinement devices.

A set of routines integrating the mechanical state of the Shell Chord according to Equations (1) have been implemented in OpenSees v. 2.5.0 complying with its object-oriented architecture. In brief, the essential steps for the integration of an ESL-FSDT MITC formulation are the following. First, strain components along the shell chord are computed by shape functions. Next, the relevant stress state is evaluated layerwise by the constitutive routines, and, finally, the stress state is integrated in order to obtain generalized forces at the nodes. Solution of compatibility and equilibrium equations in (1) is performed by a Newton-Raphson algorithm. Finally, generalized stress components are computed by summation.

From a computational point of view, integration of generalized stress in performed at each Gauss point of the relevant finite element. The TTJS implementation in OpenSees uses the *ShellMITC4* element, a 4-noded, three-dimensional shell with 6 Degrees Of Freedom (DOFs) per node. Such an element is linked to instances of a *Section* object which defines the layers' geometry and performs the stress integration. Consistently with the OpenSees philosophy, the TTJS algorithm has been implemented as a subclass of *Section,* as shown in Figure 1: it receives from the parent object the values of the generalized strains and returns the values of the generalized stress and the tangent operator.

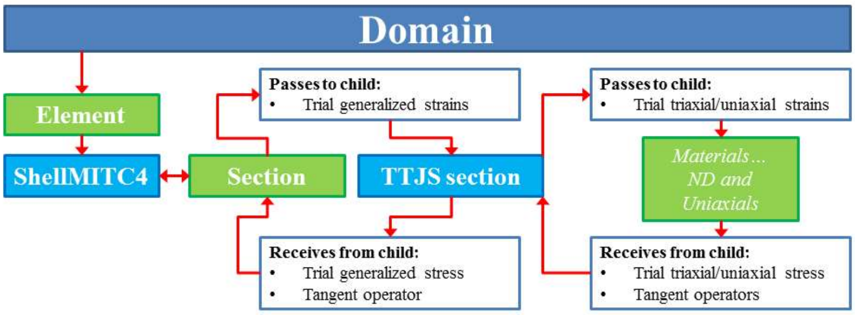

Figure 1 OpenSees parent (green) and child (blue) classes involved in the TTJS analysis

3 NUMERICAL RESULTS

The first numerical example herein reported consists of a reinforced concrete shear wall with steel transverse reinforcements. Core layers are modeled as an elastic – perfectly plastic Drucker Prager material while ties are elastic – perfectly plastic uniaxial rod elements. Results of a second application, the Scordelis Lo roof subject to vertical loads, are also reported showing the behavior of the TTJS in capturing coupling between flexural and membrane behavior.

Global structural responses in the two tests are shown in Figure 1 and Figure 4, respectively, in terms of load-displacement relationships and distributions of the confining stress σ_{TT}.

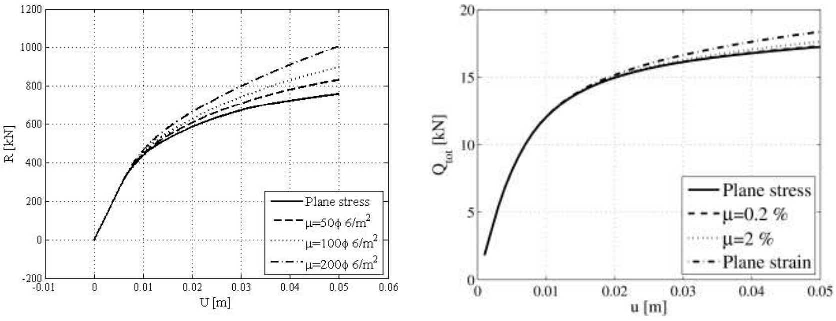

Figure 2 Load-displacement responses of the shear wall test (left) and Scordelis-Lo roof (right).

The load-displacement curves show that increase of the percentage of transverse confinement μ_T results in higher post-elastic stiffness and strength of the structures. Conditions of plane stress and plane strain represent natural boundaries for the responses relevant to all possible confinement ratios, as shown in Figure 2.

The strength increment turns out to be the result of confinement increasing the spherical part of the triaxial stress. As well known, this effect is beneficial in pressure-dependent frictional materials and it is found to be ordinarily captured by the employed Drucker-Prager model, as shown by the family principal stress paths plotted in Figure 3 as function of μ_T.

Figure 4 shows that peak values of the confining stress σ_{TT} are clustered in the compressive regions. This issue highlights the benefits of using shells instead of beam elements for analyzing confined shear walls: a beam accounts for confinement by assuming an average strength increment uniformly distributed among the cross section. On the contrary, Figure 4 clearly shows that distribution of confinement effects depend on geometry and loads.

Results for the Scordelis Lo roof show that, while the confinement effect is less pronounced due to the predominant flexural behavior of this structure, the TTJS-MITC element seems to correctly capture membrane-flexural coupling combined with TTJ coupling.

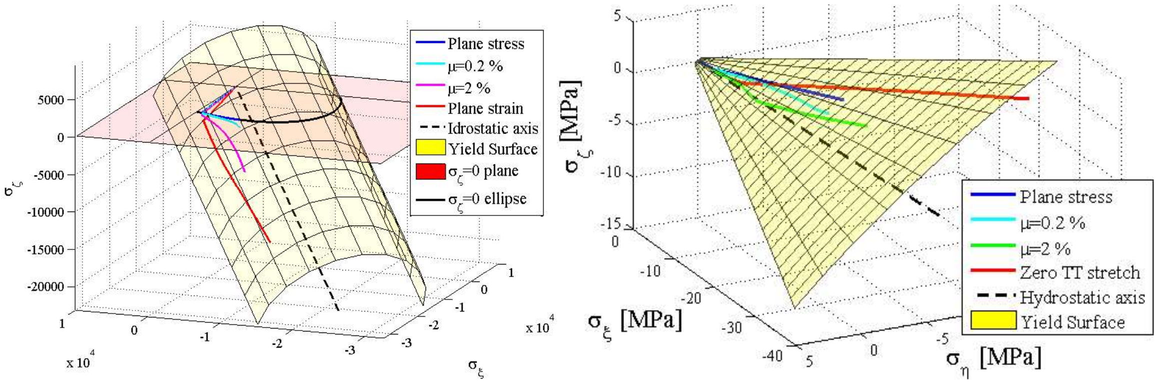

Figure 3 Path of the core principal stress on the Yield surface: Von Mises (left) and Drucker Prager (right).

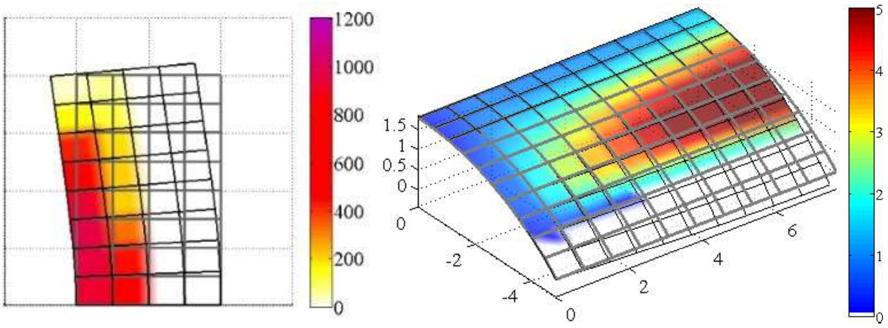

Figure 4 Distributions of confinement stress σ_{TT} of the shear wall test (left)and Scordelis-Lo roof (right).

4 CONCLUSIONS

The TTJS Section object recently implemented in Opensees permits to model the confinement effects induced by transverse reinforcement within a simpler shell FE formulation and to combine structural analysis with the analysis of triaxial stress states. Thanks to the object-oriented philosophy ruling the OpenSees framework, a quite simple implementation of this structural object is possible. The resulting numerical tools are open to be combined with a vast variety of constitutive models for the core material and for transverse reinforcements.

Ongoing research activities are centered on the use of the TTJS formulation in dynamic analyses and in structural reliability applications. Future developments will address the use of TTJS combined with damage-based material models.

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