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A continuum theory of through–the–thickness jacketed shells for the elasto-plastic analysis of confined composite structures: Theory and numerical assessment

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A B S T R A C T

The paper proposes a generalized shell formulation devised for the triaxial stress analysis of Through-the-Thickness (TT) confining mechanisms induced by TT Jacketing (TTJ) devices in laminated composite structures, such as masonry walls retrofitted by stirrups-tied FRP sheets and TT jacketed concrete sandwich panels.

Assuming a smeared description of TT reinforcements, the proposed shell formulation is constructed as an enhancement of the classical laminated shell formulation based on the Equivalent Single Layer Mindlin First-order Shear Deformation Theory (ESL-FSDT). This enhancement captures TT stretching by adding the TT displacement field among the kinematic variables and permits to describe the smeared TTJ interaction between transverse uniaxial reinforcements and confined layers in terms of continuum equilibrium and compatibility equations. Statics and kinematics of the shell are developed by following standard work-association arguments and encompassing both TT-laminated and TT-functionally graded structures.

A nonlinear elasto-plastic constitutive behavior of the core material and of the TT reinforcements is considered and explicit representations of the elasto-plastic tangent operator are derived. The TTJ formulation is combined with a MITC finite element formulation and implemented in the research FE code Opensees.

Results of nonlinear structural analyses of walls subject to in-plane and out-of-plane bending show that the proposed TTJ approach provides physically meaningful predictions of the structural response and is capable to efficiently track a complex triaxial confining interaction which ultimately results into marked global structural effects of increased stiffness, strength and ductility.

1. Introduction

The employment of confinement techniques for improving strength and ductility of structural members has progressively grown in popularity in parallel with the use of analytical and computational tools capable of describing their mechanics.

Confinement devices find typical applications in the reinforcement of existing concrete and masonry structures by steel bars, plates or Fiber Reinforced Polymers (FRP) [1–4], to increase the bearing capacity of both 1D members, such as columns and frames, or 2D members, such as shear walls, panels, slabs and curved shells. Interest in the effect of through-the-thickness confinement in 2D elements has recently grown, in particular driven by innovative structural solutions. These concern several applications such as concrete sandwich panels [5] and masonry [6] in civil engineering, or more advanced ones in mechanical [7] and biomedical [8] engineering.

As well known, the desired gain in strength and ductility is an effect originated by the triaxiality, or biaxiality, of the stress state induced in the confined core material [9]. In line of principle, this effect can be enforced on members of any structural typology and depends on both the global geometry of the structure as well as on local details of the confinement device. However, for structural applications in civil engineering, the experimental characterization of confinement is mostly carried out over columns [10,11], and its

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effect in the structural analysis of reinforced members is prevailingly taken into account in a simplified form, separating global and local mechanical analyses.

Relying on this separation, confinement devices are not ordinarily included as components of the global analysis; rather, the approach typically employed is the following: a local experimental and/or theoretical analysis of a confining device is preliminarily carried out to obtain suitably defined constitutive parameters which are subsequently employed in the global structural analyses in uncoupled form [1,10,12,13]. For 1D elements, this simplified approach is generally considered to be sufficiently accurate, as shown by several experimental investigations [1,14,15], providing also a basis for building code prescriptions [16–18].

Nevertheless, the analysis of confinement in 2D structural members is more complex since these elements can take advantage of both in-plane and transverse Through-the-Thickness (TT) confinement. The former is essentially a global structural effect, primarily dependent on the boundary conditions and ordinarily addressed by using membrane or shell Finite Elements Analysis (FEA) [19] in conjunction with suitable biaxial strength criteria [20,21]; conversely, the latter is accounted for at constitutive level though it is not always consistently incorporated in the global analysis.

In real applications of TT confinement over concrete and masonry walls transverse confinement is induced by reinforcing rods passing through the shell core; they tie the opposite exterior confining layers and the tying elements are uniformly distributed over large regions of the shell surface in regular arrays.

In particular, in RC walls, these ties correspond to transverse stirrups, forming the ordinary transverse steel reinforcement, whose confining effect has been experimentally highlighted in several studies [22–24], and whose design is also regulated by building codes [18,25]. For masonry, TT confinement has proved to be a convenient retrofit strategy by several experimental campaigns, in particular for stone walls [6] and multi–leafs ones [26] by using both FRP ties [27] and steel ties [28].

Investigations have also highlighted differences between the effect of Through-the-Thickness Jacketing (TTJ) observed in shear walls and in columns [29], since the strength increment due to confinement is critically influenced by the geometry of the reinforced structural member [30]. These experimental evidences show the meaningfulness of devising analysis methods for 2D shells/members removing the simplified assumption of a *tout-court* uncoupling between local and global responses.

Modeling of TT confinement requires a proper account of the presence of triaxial stress states inside the core material, on one side, and of differential TT elongations between the stirrups/ties and the confined core material, on the other one. Typically, in FEM analyses, both in–plane and through-the-thickness confinement are addressed by using 3D brick elements (core material) interacting with confining devices modeled as trusses, rods or external constraints (see, e.g., [31–33]). Regrettably, such a highly detailed 3D description requires significant computational efforts and can be hardly extended to global analyses of real structures in ordinary structural design.

On the other hand, it can be easily recognized that capturing of TT confinement, even in simplified form, in the context of a less computationally expensive 2D structural theory, is not trivial and cannot be achieved by ordinary theories of plates and shells. In particular, in order to have full development of TT confinement, differential displacements must be allowed at the core-tie interface. Moreover, a multilayered descriptions is required to account for the coexistence of exterior confining layers and interior confined core with different mechanical properties and stress states.

However, to the best of the authors' knowledge there exists no structural 2D continuum layered formulation suitable for describing the interaction of TT by-passing ties and confining/confined layers. This conclusion is gained after scoping the multiplicity of 2D formulations of layered plates and shells available to date, including Equivalent Single Layer (ESL) theories [34], the class of kinematically enriched shell formulations accounting for non-plane stress regimes [35,36] and/or addressing through-the-thickness stretching, or in the shell finite element proposed in Ref. [37], which introduces a transversal elongation degree of freedom (see, e.g., [38–40]).

A suitable formulation capable of describing TT confinement in simplified form seems to be not available even among nontraditional theories of plates and shells [41] or within the larger family of kinematically richer 2D shell theories, gathered under different denominations such as *layer-wise theories*, *discrete-layer theories* [34], *zig-zag theories* [42,43]. In particular these theories enforce interlaminar stress continuity by making the number of displacement variables dependent upon the number of constitutive layers of the shell.

Actually, while all the above mentioned formulations are well suited to address the presence of in–plane reinforcements [44–47], the TT interaction between ties and core material introduces an infringement of deformation continuity, as differential strains are typically present at the ties-core interface, and does not admit a simple layer-wise description since ties are punctual devices implying, on principle, a point-wise description.

In addition, it should also be observed that the mechanics of confinement–bearing devices becomes even more complex in the nonlinear range when, e.g., steel stirrups may yield or a crushing core may implode, as well as in presence of pre–stress.

On the basis of the previous considerations, aim of the present paper is the development of a suitable 2D continuum structural formulation for capturing the effects of TT confinement in nonlinear elasto-plastic structural analyses of layered shells.

A continuum theory with the above mentioned features is herein formulated proceeding from the adoption of a simplest possible enhancement of the classical laminated shell formulation based on ESL Mindlin First-order Shear Deformation Theory (ESL-FSDT). Such a theory is devised in order to capture the onset of triaxial stress states in the core material and to provide in a smeared form the description of the TTJ interaction, between transverse uniaxial reinforcement and confined layers, in terms of continuum equations of equilibrium and compatibility.

More specifically, the detailed objectives of the present work are to:

i) present the generalized kinematics and statics of the enhanced TTJ formulation following standard work-association arguments, within a more general description which accounts for the presence of a smeared distribution of TT reinforcement encompassing both TT-laminated and TT-functionally graded structures;
ii) derive a TT-continuum theory, with the related system of compatibility and equilibrium equations, from the more general continuum framework, and the related continuum tangent operator to be employed in return mapping schemes for the analysis of the confining interaction adopting elasto-plastic laws for the ties and the confined materials;
iii) combine this theoretical/numerical framework with established finite element formulations in order to carry out nonlinear structural analyses assessing the predicted global response for plane shells.

With specific reference to point 1), structural simulations herein reported have been carried out by implementing the laminated TTJ