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A MULTILAYER SHELL ELEMENT FOR NONLINEAR ANALYSIS OF R/C SHEAR WALLS

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Abstract

The objective of this study is the development of a multilayer shell element for the nonlinear finite element analysis of reinforced concrete shear walls. The nonlinear shell element is based on a composite formulation for each integration (material) point, comprised of a number of layers with different thicknesses and material properties. For the analysis of R/C structural walls, concrete and steel nonlinear cyclic constitutive laws are assigned to each layer with isotropic plane-stress conditions for concrete and orthotropic conditions for smeared steel reinforcement, depending on their longitudinal or transverse direction. Strains at each individual layer are first derived from trial strains and curvatures of the respective integration point and then stresses are calculated by the respective layer material law. Forces and bending moments for each integration point are finally derived by numerical integration across all layers. At the present development stage, the above formulation is validated using a constitutive driver for various monotonic and cyclic strain histories, aiming eventually to its full integration into a commercial finite element code.

Keywords: Reinforced concrete; shear walls; finite elements; constitutive laws; nonlinear analysis; software

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1 INTRODUCTION

Reinforced concrete (R/C) shear walls are one of the most important lateral load resisting elements in mid- and high-rise structures, providing adequate stiffness, strength and deformation capacity, primarily against extreme earthquake and wind loading. Considering that (i) reinforced concrete is a highly nonlinear material, even under moderate loading (ii) nonlinear analysis at structural level with complex geometry is far more computationally demanding than at element level (iii) nonlinear static or dynamic (especially cyclic) loading conditions often impose convergence issues in practical applications (e.g. performance-based design or response assessment of existing structures), it is evident that providing solutions of improved accuracy, robustness and numerical efficiency for shear wall modeling is a challenging task.

In order to maintain a balance between accuracy and computational cost for nonlinear modeling of shear walls at structural level, the usual practice is to use linear elements (e.g. lumped or distributed plasticity) of equivalent section, together with rigid links or numerical constraints to provide displacement compatibility with the rest of the structure. Extending the wall element dimension to its natural planar type (e.g. membrane or shell elements), incorporating features such as plane stress conditions, out of plane response and cracking visualization, requires sophisticated element formulations and material constitutive laws. In this regard, the objective of this study is the development of a multilayer shell element for the nonlinear finite element analysis of reinforced concrete shear walls, aiming to be fully integrated into an existing commercial finite element software [1].

2 LITERATURE REVIEW

Over the years, a large number of numerical formulations for modeling planar R/C elements have been suggested in the literature, aiming to capture the inherent properties of concrete and steel materials under uniaxial, biaxial and triaxial stress states. From early nonlinear elasticity formulations, research has subsequently focused on plasticity and total-strain theory, fracture mechanics and (more recently) damage continuum mechanics, as well as hybrid formulations, blending more than one of the above categories. However, only a handful of the suggested solutions have managed to deploy themselves into finite element software (open source or proprietary) and therefore applied to real structural models. Reference is herein made to (i) VecTor and DIANA software, mainly including (total-strain) modified compression field theory (MCFT) [2] models, (ii) ATENA [3] software, including nonlinear elasticity as well as fracture-plasticity models, (iii) ABAQUS [4] software, with models based on damage-plasticity formulations and finally (iv) OpenSees [5], an open-source platform that accepts user contributions from the academic and engineering community. In this regard, a number of material models are available for two-dimensional modeling of shear walls, mainly based on a multilayered shell formulation, where both concrete and steel reinforcement models are attached, according to the wall section geometry. For concrete, a number of damage continuum mechanics models have been proposed, known for their simple, non-iterative formulation and computational efficiency in large, structural-level analyses: (i) the PSUMAT model by Lu et al. [6,7], using damage evolution curves under tension, as recommended by Løland [8] and under compression, as suggested by Mazars [9], (ii) the Mazars scalar elastic-damage model [9], implemented by Ramirez [10] and (iii) the two-scalar elastic-damage PRM [11] and "μ" [12] models, implemented by Lopez [13]. It is noted that materials (ii) and (iii) have not yet been included in the official OpenSees repository. By evaluating the performance and limitations of the above models, in the present study it was decided to adopt the layered shell formulation together with the Lu et al. concrete damage model, which has proved its numerical efficiency and robustness under large-scale structural analysis applications [6,7].

3 MATERIAL MODEL FORMULATION

This section describes the theoretical background and the necessary additions and modifications for integrating a nonlinear multilayer shell element into the commercial finite element software RAF [1]; a suite capable of both linear and nonlinear analysis and design of building structures, adherent to various seismic codes, including Eurocodes (e.g. [14,15]) and the Greek Code for Interventions (KANEPE) [16].

A graphical overview of a typical shear wall modeling process is depicted in Fig. 1; it comprises two boundary regions (typically 15 % of wall length each [15]) with dense longitudinal and transverse reinforcement that resist flexure and a web with two parallel grids of coarse reinforcement, designed for shear actions. These regions are usually modeled with 4-node isoparametric shell elements (MITC4), combining membrane and plate response, in order to simulate both in-plane and out-of-plane stress states. The shell mesh is characterized by a global tangent stiffness matrix (**K_T**) assembled by individual element contributions, while force (**P**) and displacement (**U**) vectors follow either static (Eq. 1) or dynamic (Eq. 2) equilibrium during loading.

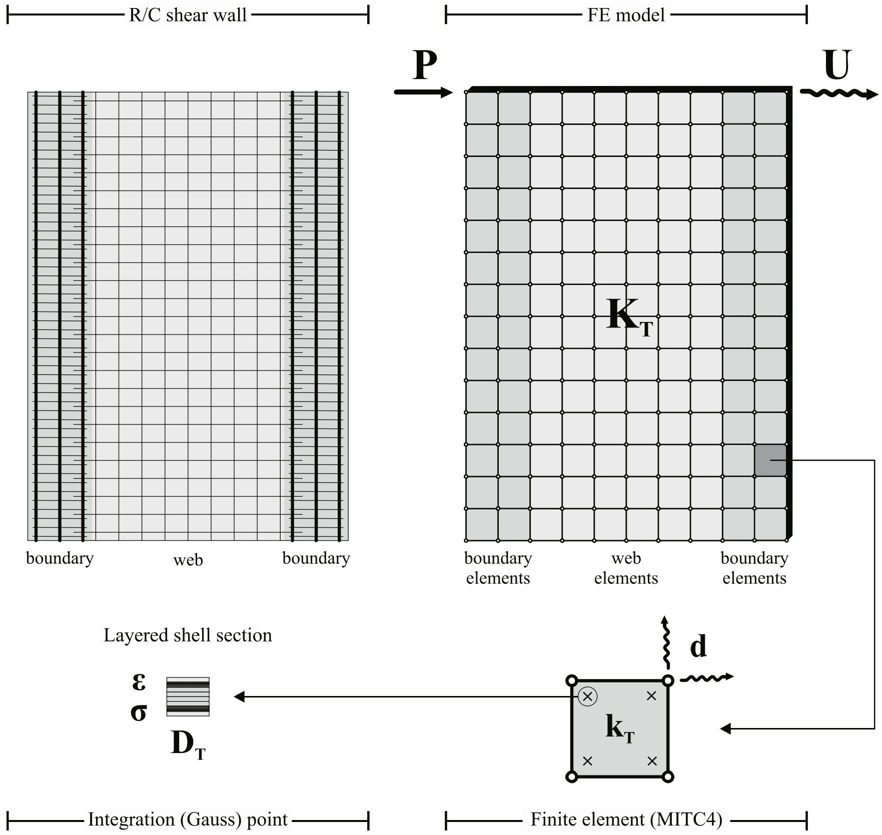


Figure 1: Overview of shear wall modeling process.

$$\mathbf{K_T U = P} \tag{1}$$

$$\mathbf{M}\frac{d^2\mathbf{U}}{dt}+\mathbf{C}\frac{d\mathbf{U}}{dt}+\mathbf{K_T U} = -\mathbf{M}\frac{d^2\mathbf{U}_g}{dt} \tag{2}$$

where **M**, **C** and **U_g** are the global mass, damping and ground displacement matrices, respectively.

In the standard nonlinear finite element method, for every new load / time increment, an iterative solution algorithm (e.g. Newton-Raphson) imposes a vector of elastic trial strains ($\boldsymbol{\varepsilon}_{tr}$) on each element:

$$\boldsymbol{\varepsilon}_{tr} = \mathbf{Bd} \tag{3}$$

where **d** is the element nodal displacement vector and **B** is the strain-displacement matrix. Trial strains are inserted into the nonlinear material constitutive law that updates the *material* stress vector ($\boldsymbol{\sigma}_{n+1}$) and tangent stiffness matrix ($\mathbf{D_T}$):

$$\boldsymbol{\sigma}_{n+1}, \mathbf{D_T} = f(\boldsymbol{\varepsilon}_{tr}, \boldsymbol{\sigma}_n) \tag{4}$$

The *element* tangent stiffness matrix ($\mathbf{k_T}$) and force vector (**r**) are subsequently derived by integration over the element volume (using a number of integration (Gauss) points):

$$\mathbf{k_T} = \int_V \mathbf{B}^\mathbf{T}\mathbf{D_T}\mathbf{B}\,dv \tag{5}$$

$$\mathbf{r} = \int_V \mathbf{B}^\mathbf{T}\boldsymbol{\sigma}_{n+1}\,dv \tag{6}$$

Finally, the updated global stiffness matrix ($\mathbf{K_T}$) and force vector (**R**) are assembled from individual element contributions.

Since the employed software [1] already features 4-node isoparametric shell elements (MITC4) for elastic analysis, the present development focuses on the inclusion of a nonlinear material constitutive law (Eq. 4) and the subsequent volume integrations (Eqs. 5-6). The material law is based on a layered shell approach [6,7] applied to each element Gauss point (Fig. 1), as is outlined in more detail in Fig. 2. Specifically, the element section is represented by a stack of (n) individual material layers of different thicknesses (t_n), material angles (α_n) and constitutive laws $\{\sigma = f(\varepsilon)\}_n$. Trial strains ($\boldsymbol{\varepsilon}_{tr}$), assumed at the section midplane, are decomposed to the individual layers assuming plane-section conditions. The updated stress state for each layer is calculated by the corresponding material law and finally the updated stress state ($\boldsymbol{\sigma}_{n+1}$) and tangent stiffness ($\mathbf{D_T}$) for the whole section are derived using numerical integration over the total section thickness.

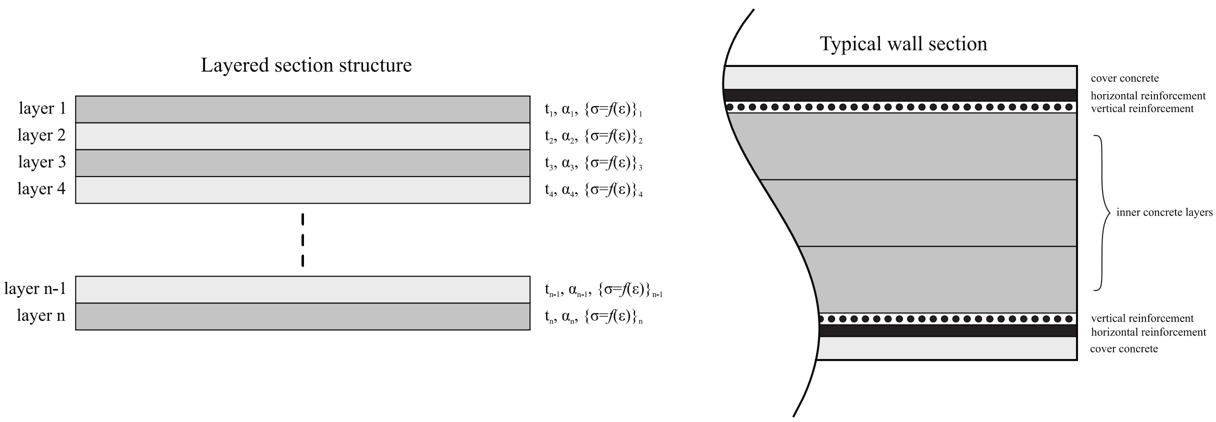
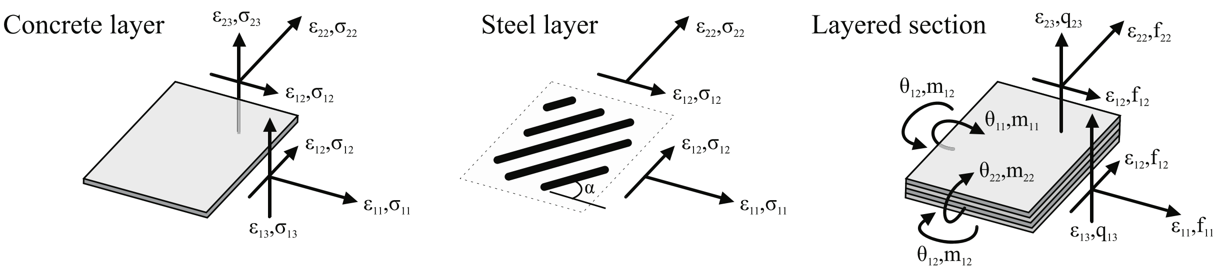


Figure 2: Layered shell formulation

In the case of a typical wall section, a layered decomposition may be simulated by two outer cover concrete layers and a number of inner concrete layers, separated by two reinforcement grids, each comprising a horizontal ($\alpha = 0°$) and a vertical ($\alpha = 90°$) smeared reinforcement layer. For concrete layers, the damage model by Lu et al. [6,7] is employed, with parameters derived by the characteristic concrete compressive strength (f_{ck}), according to EN1992-1-1 [14]. For steel layers, the uniaxial Giuffré-Menegotto-Pinto model is employed [17], with parameters derived by the characteristic steel yield strength (f_{yk}) and layer equivalent thicknesses by the corresponding steel reinforcement ratios. Fig. 3 shows the concrete, steel and layered section strain and stress states, as derived by respective constitutive laws and section integration, respectively. Eq. 7 describes the section strain decomposition to individual layers and Eq. 8 the section membrane force (f), moment (m) and shear force (q) integration from layer contributions (z_k is the distance between the layer (k) and section midplane).



$$\boldsymbol{\varepsilon} = \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{Bmatrix} \quad \boldsymbol{\sigma} = \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix}$$

$\sigma_{i3} = G \cdot \varepsilon_{i3}$

G : concrete elastic shear modulus

$$\boldsymbol{\varepsilon} = \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{Bmatrix} \quad \boldsymbol{\sigma} = \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix}$$

α : reinforcement angle

$$\boldsymbol{\varepsilon} = \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \\ \theta_{11} \\ \theta_{22} \\ \theta_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{Bmatrix} \quad \boldsymbol{\sigma} = \begin{Bmatrix} f_{11} \\ f_{22} \\ f_{12} \\ m_{11} \\ m_{22} \\ m_{12} \\ q_{13} \\ q_{23} \end{Bmatrix}$$

Figure 3: Layer and section strain/stress states

$$\begin{aligned} \varepsilon_{ij,layer\ k} &= \varepsilon_{ij,\mathrm{section}} - z_k \cdot \theta_{ij,\mathrm{section}} \\ \gamma_{ij,layer\ k} &= \gamma_{ij,\mathrm{section}} \end{aligned} \tag{7}$$

$$\begin{aligned} f_{ij,\mathrm{section}} &= \sum_{k=1}^{n} \sigma_{ij,layer\ k} \cdot t_k \\ m_{ij,\mathrm{section}} &= \sum_{k=1}^{n} z_k \cdot \sigma_{ij,layer\ k} \cdot t_k \\ q_{ij,\mathrm{section}} &= \sum_{k=1}^{n} q_{ij,layer\ k} \cdot t_k \end{aligned} \tag{8}$$

The above formulations were implemented in the form of several FORTRAN subroutines, operating on a single one-dimensional dynamic array that contains the required information (layer structure, material properties, stress states etc.) for all Gauss points corresponding to the nonlinear shell elements. Fig. 4 shows a simplified form of the developed code structure toward its integration in the commercial finite element program [1].

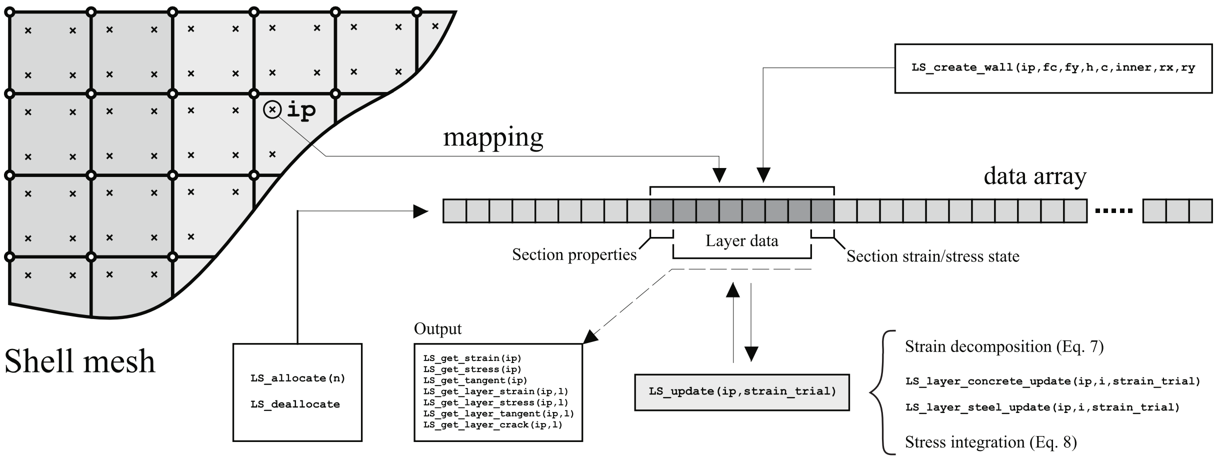


Figure 4: Simplified code structure

4 VERIFICATION

Following the code development, a set of primary verification tests was performed on the material and section level, for a single element integration point. Material parameters were based on typical C20/25 (f_{ck} = 20 MPa) and B500C (f_{yk} = 500 MPa) concrete and steel grades, respectively, according to EN1992-1-1 [14]. Wall section width was set equal 0.2 m with three inner concrete layers, and steel reinforcement ratios equal to 5.0 ‰ and 2.0 ‰ for horizontal and vertical grid directions, respectively. Fig. 5 shows the uniaxial stress-strain response for concrete and steel layers under various monotonic and cyclic strain loading histories. It is observed that the employed constitutive models reproduce well the expected response.

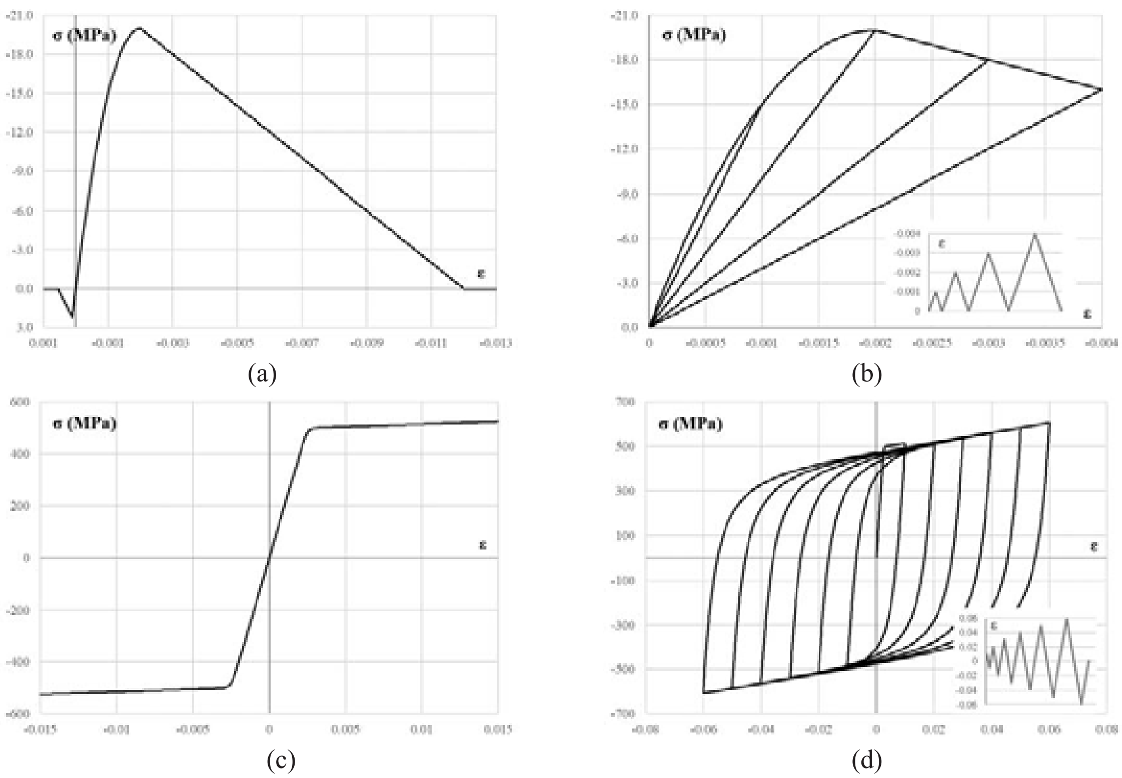


Figure 5: Uniaxial material response: (a) concrete monotonic (b) concrete cyclic
(c) steel monotonic (d) steel cyclic

Fig. 6 shows the wall section response in membrane force vs. strain terms, derived by layer integration (Eq. 8) for (a) uniaxial tension in the horizontal direction followed by unloading and reloading in compression, (b) for equibiaxial compression ($\varepsilon_1 = \varepsilon_2$) and (c) for compression in the vertical direction together with tension in the horizontal direction ($\varepsilon_1 = -0.1\varepsilon_2$).

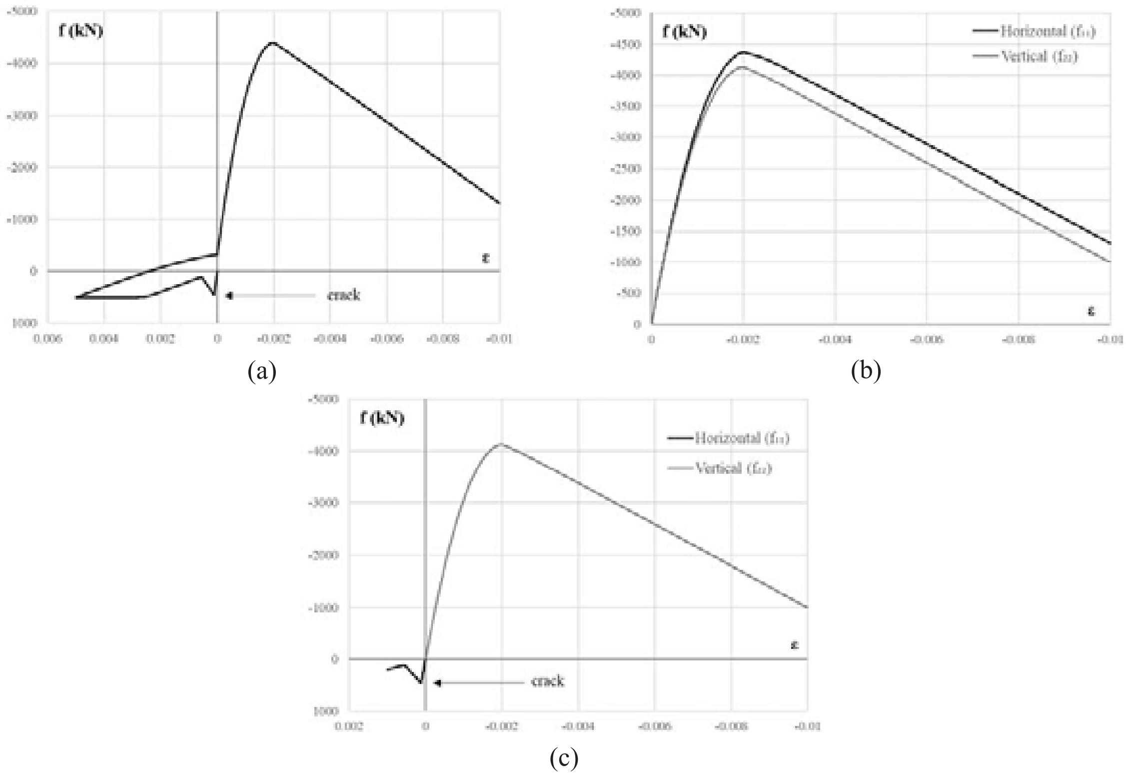


Figure 6: Membrane force vs. strain response for wall layered section

5 CLOSURE

In this ongoing study, a multilayer shell element for the nonlinear finite element analysis of reinforced concrete shear walls was developed, for integration into an existing commercial structural analysis software [1]. A new, modular FORTRAN-based code, operating at integration point level and based on existing formulations and inelastic constitutive models from the literature was compiled. Primary validation tests against simple loading histories at element (Gauss point) level demonstrated a satisfactory performance. This section material model will be subsequently mapped to MITC4 shell finite elements and will be further validated, for finally assembling structural models ready for nonlinear static and dynamic analysis.

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