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A nonlinear quadrilateral layered membrane element with drilling degrees of freedom for the modeling of reinforced concrete walls

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ABSTRACT

In this article, the formulation and verification of a nonlinear quadrilateral layered membrane element with drilling degrees of freedom for the nonlinear analysis of reinforced concrete (RC) walls under static and cycling loads are presented. The formulation is based on a quadrilateral element with twelve degrees of freedom (DOF), two displacements and one drilling DOF per node, which is defined by a blended field interpolation for the displacements over the element, and a layered system for the element section consisting of fully bonded, smeared steel reinforcement and smeared orthotropic concrete material with a rotating angle formulation, and a stiffness tangent approach. The drilling DOF refers to the incorporation of the in-plane rotation as a DOF at each element node. The blended field interpolation has the advantage of producing a smoother strain distribution inside each element, which facilitates element convergence, and the layered section formulation allows for the properties of the concrete and steel over the thickness of the wall to be modified to properly represent the different wall components, such as the concrete cover, steel rebar and confined concrete. Additionally, the formulation introduces a rotational DOF at each node, which allows the membranes to connect directly to beam and column elements. Moreover, this formulation incorporates the coupling of axial, flexural and shear behavior observed on the different configurations of RC wall structures. To verify this formulation, the results of a set of available experimental data reported in the literature for RC wall elements, with different configurations (slender walls, squat walls, wall with irregular disposition of openings) and levels of confinement, under monotonic and reversed loads are compared with the results obtained from the corresponding analytical model. The formulation is notably consistent with the experimental data and can predict the maximum capacity, the global (force vs deformation) and local responses (strain along the wall) and incorporate the coupling of axial, flexural and shear behavior observed in the different configurations of RC wall structures.

1. Introduction

Although the design of RC walls is a relatively simple procedure when using current codes, the behavior of RC walls is actually highly complex because they behave differently depending on their configuration (wall size, height/length ratio, steel reinforcement, etc.) and loading conditions. This scenario implies that the behavior of RC walls depends on the interrelation and coupling of a combination of flexural, shear, and axial deformation over their cross-sections at different levels, along with other complex mechanisms such as rigid body rotation for the bond slippage of the longitudinal reinforcement at the base of the wall, effects of confinement, dowel action in reinforcement, cracking, aggregate interlock, creep, and tension stiffening, which have been demonstrated by various researchers [1–4].

For example, the walls used in mid- to high-rise buildings exhibit mainly flexural behavior, with the deformation concentrated at the larger moment, typically near the ground level. Failure in this type of wall is characterized by horizontal cracks at the edges of the wall. In low-rise buildings, however, the walls behave primarily in shear, and diagonal cracks are produced. These main behaviors typically occur in isolated walls. Once these walls are combined with other elements or walls in the building, the behavior can change, producing combinations of flexural, compression and shear failure. Such behavior has been described in the reports of the Reconnaissance team of the Los Angeles Tall Building Structural Design Council [5–8] and of the ERRI Reconnaissance team [9] after the recent Chilean earthquake. Because of this

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complex behavior in RC walls, a large amount of research and experimentation in recent decades has been dedicated to providing enough data to represent the walls and develop analytical models that can accurately predict their behavior and important material characteristics, such as concrete stiffening, cracking, bond slippage and vertical strain distribution along the walls.

Typically, analytical models can be separated into two main groups, macroscopic models and microscopic models. Macroscopic models are based on predicting the overall behavior of a wall element using simplified assumptions and idealizations [10]. This process is typically carried out by creating a system of springs, in which each spring has an independent hysteric curve that represents a portion of the wall's behavior. Examples of such systems include the multi-component-in-parallel model or multi-vertical-line-element model and the truss-type model. The multi-vertical-line-element model, or fiber-based model, is characterized by the combination of several axial, shear, and rotational springs, some connected in parallel and others in series, to represent the global response of reinforced concrete. The behavior of each spring is typically modeled using complex, experimentally based hysteretic rules. Some examples of this type of element have been proposed by Kabeyesawa et al. [11] in 1982, Vulcano and Bertero [10] in 1987, Orakcal et al. [3] in 2006, Massone et al. [12] in 2009, Jiang and Kurama [13] in 2010, Panagiotou et al. [14] in 2012, and Kolozvari et al. [15] in 2015.

These macroscopic models are simple and intuitive and have been incorporated into structural nonlinear programs. However, they tend to be problem-based [10], which means they apply only in certain cases.

Microscopic models, on the other hand, are typically based on the finite element method (FEM) and theory of continuum mechanics. In this methodology, a RC wall is divided into a series of elements, over which the respective constitutive law, representing the behavior of the reinforced concrete material, is imposed in a stress–strain space or other possible mixed representation, and the equilibrium equation is satisfied in an average sense with integration over each finite element. The existing microscopic models for reinforced concrete walls can be grouped into three main categories: membrane elements, shell elements and 3D solid brick elements, with the membrane element model being the most commonly used.

The membrane or panel elements display only in-plane behavior (plane stress), typically with two DOFs per node (two displacements). One of the first membrane element formulations used in FEM formulation for the nonlinear analysis of RC walls was that proposed by Cervenka and Gerstle (1970, 1971, 1972) [16]. Cervenka [17] used a quad element with four nodes and two DOFs per node (one horizontal and one vertical displacement), along with a von Mises yield condition, to model concrete. Various researchers have used this type of element or a variation with a larger number of element nodes (i.e., higher elements) but with only two DOFs per node. The main differences between the membrane element formulations proposed over the years have been the constitutive material laws used in the analysis to represent reinforced concrete.

The constitutive laws used to model material behavior are usually nonlinear material models, fracture mechanics models, orthotropic models, plasticity models, hypo-elastic material models, microplane models or nonlocal continuum mechanics models [18,19]. Among the constitutive laws used to represent reinforced concrete in the plane stress condition, the orthotropic models are one of the most widely used types among many researchers [19]. These orthotropic concrete material models are based on the assumption made by Darwin and Pecknold [20] in 1974 and Darwin and Pecknold [21] in 1977. In this assumption, the behavior of a material in biaxial stress can be represented by an equivalent uniaxial strain–stress relation along the principal axis of orthotropy. Orthotropic concrete models have been proposed by Darwin and Pecknold [21], Cervenka [22], Vecchio and Collins [23], Izumo et al. [24], Shin et al. [25], Bolander and Wight [26], Hsu [27], Belarbi and Hsu [28], Pang and Hsu [29], Pang and Hsu [30], Ayoub and Filippou [18], Vecchio [31], Vecchio [32], Palermo and Vecchio [33], Foster and Marti [34], Mansour and Hsu [35], Mansour and Hsu [36], and Zhong [19].

In addition, membrane elements typically use two types of representation to incorporate steel inside RC walls. One type assumes the steel to be a smeared material, which means steel bars are represented as being distributed homogeneously over the element area along the direction of the bars. The second approach uses a truss-type element to represent an actual steel bar. The main drawbacks of this second representation are that the element mesh needs to coincide with the position of the bar in the wall, and elaborate connecting elements between the bar and the membrane element are required to account for bond slippage, if it is considered.

The membrane or panel models generally yield good results compared with experimental data and provide a better and more refined definition of wall structures' local responses. These models tend not to be problem-specific, which allows a variety of problems to be represented with the same procedure. However, the membrane element displacements are typically defined by bilinear interpolation and cannot be easily used in combination with beams because only two displacement degrees of freedom are used at the nodes, and they are more computationally demanding than the macroscopic elements.

This paper develops and presents a formulation of a new quadrilateral layered membrane element with drilling DOFs, which allows for a smoother strain variation over each element and helps the analysis achieve convergence. In addition, this element incorporates one rotational degree of freedom per node, which allows the formulation to be used as a basis for the creation of a shell element to model more complex RC wall structures or to connect the element to beam-type or column-type elements.

The membrane element formulated in this article consists of a quadrilateral element with a total of twelve DOFs, three per node (two displacements and one in-plane rotation) and uses a blended field interpolation for the displacements over the element. The membrane section consists of a layered system of fully bonded, smeared steel reinforcement and smeared orthotropic concrete material with a rotating angle and stiffness tangent formulation, which allows the internal nonlinear behavior of the reinforced concrete wall to be modeled. Additionally, the layered section formulation allows the concrete and steel properties to be changed over the wall thickness and the different wall components, such as the concrete cover, steel rebar and confined concrete, to be properly represented.

The evaluation of the accuracy, applicability, and usefulness of the nonlinear layered quadrilateral membrane in modeling reinforced concrete walls is also presented. A set of experimental results for RC wall elements under monotonic and reversed loads, which are available in the literature, is compared against the results obtained from an analytical model that uses the proposed formulation. These experimental data have previously been used as benchmarks for other models.

2. Quadrilateral layered membrane element with rotational DOF formulation

Membranes are in a state of plane stress, in which only in-plane behavior is considered ($\sigma_z = \tau_{zx} = \tau_{zy} = 0$). The finite element formulation for this type of element, using a displacement-based approach, is well known and can be found in almost any text on