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New nonlinear lateral-vertical coupled shear element model for use in finite element structural analysis applications

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ABSTRACT

In nonlinear structural analysis, shear walls within whole-system models are often modeled using a spring model with a single degree of freedom where the lateral stiffness of the shear wall is modeled as a nonlinear spring. The stiffness of the spring is often described by the hysteretic relationship between the lateral restoring force and shear wall lateral deformation. In this study, a new shear element is introduced, which couples the lateral and vertical stiffness of the shear wall. This new shear element is able to better describe the behavior of shear walls in mid-rise and tall buildings. An illustrative example is presented to help explain the application of the new shear element in finite element modeling. In the examples, the new shear element is used to calculate displacement and internal forces for cold-formed steel frames. The results show that without including vertical wall stiffness, the lateral displacement is significantly underestimated. The difference increases with the height of the building and for a ten-story frame the new model demonstrates an increased lateral displacement at roof level of 64.1% when compared with current typical shear element model (lateral stiffness only).

1. Introduction

Shear wall systems play an important role in buildings subjected to lateral loading since their high capacity allows them to resist lateral load while still carrying gravity load. Over the past few decades, many studies have focused on shear wall modeling for light-frame structures, including wood and cold-form steel light-frame buildings. A detailed model was developed by Collins et al. [1], in which a pair of diagonal hysteretic nonlinear springs was used to describe in-plane behavior of a light-frame shear wall. Plate element and beam elements were used to represent the sheathing and frame, respectively. The frame intersections were modeled as pinned connections. Thus, the model can take account of the out-of-plane action of shear walls. Folz and Filiatrault [2] did an analysis of a wood shear wall under cyclic loading. In that study, the sheathing-to-framing connector behavior was modeled by a ten-parameter hysteretic model. This hysteretic model included pinching behavior and strength and stiffness degradation due to cyclic loading, resulting in the model capturing the behavior of wood shear walls very well. The result from the cyclic loading analysis can be used to model wood shear walls as a single degree of freedom spring, which can then be utilized in a 3-D model of a building for non-linear time history analysis of light-frame wood buildings. Based on the Folz and Filiatrault [2] hysteretic model, Pang et al. [3] developed an evolutionary parameter hysteretic model (EPHM) using sixteen parameters for modeling wood frame structures. This new hysteretic model included the degradation of the backbone curve itself as well as degradation of the unloading stiffness. Pei and van de Lindt [4] applied this EPHM in their study to develop a coupled shear-bending formulation for seismic analysis of multi-story wood shear wall systems. In that study, the shear walls were modeled using 3-D uncoupled springs and the stiffness of the shear wall and tie-down system in a story was lumped into representative story stiffness. A 3D building model was developed in ABAQUS by Xu and Dolan [5]. In this study, the single hysteretic spring model, which was similar to Folz and Filiatrault's model [2], was used to estimate spring parameter. Then, the diagonal-spring shear wall model, which was used in Collins's study [1], was applied for final simulation.

In addition to wood shear-wall modeling, there have been studies focusing on modeling of cold-formed steel shear walls. Kim et al. [6] conducted a shake table test of a two-story, one-bay structure with X-straps attached to resist the lateral load. The response measured during the test was then compared with numerically calculated values. In the numerical study, the columns were modeled using beam elements and the non-linear behavior was

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modeled using an inelastic rotational spring. The X-straps were modeled using inelastic truss elements with gap properties, which were assigned a bilinear hysteretic stiffness. In another study, Pastor and Rodríguez-Ferran [7] modeled X-braced shear walls by treating panels as single-degree-of-freedom (SDOF) structures. In their numerical model, only lateral force and lateral displacement were considered and the structure was also modeled using a bilinear hysteretic oscillator. They conducted non-linear time history analysis to compare the results between SDOF and multi-degrees-of-freedom (MODF) models. The results showed a good agreement for one-story X-braced shear walls between the two cases. Moreover, in a study in wall-stud cold-formed shear panels sheeted with corrugated sheeting and OSB, Fulop and Dubina [8] proposed a single degree of freedom system (SDOF) with a fiber-hinge accommodating the desired hysteretic behavior. The wall-stud cold-formed shear panel can be replaced with a pinned rectangular frame with dissipative diagonals. The hysteretic behavior was described by a tri-linear or a nonlinear model. The SDOF model was accurate enough to describe all the important aspects of the hysteretic behavior and simple enough to be integrated into global structural modeling. Similarly, other studies [9,10] modeled the shear wall, including steel sheathing and screw connections, by truss elements using the Pinching 04 material property in OpenSees software. The shear wall was modeled as a pin-connected panel with two diagonals. The model was validated and calibrated using a series of full-scale shake table tests for five single-story walls and five double-story walls (Shamim and Rogers, [9]). After that, the model was tested for a 3D 2-story building under displacement-controlled pushover analysis, nonlinear time history analysis, and IDA (Leng et al. [10]). Another approach was introduced by Martínez-Martínez and Xu [11], who developed a flat shell element with equivalent properties to model complete shear panels. The shell element was considered as a 16-node natural orthotropic element, and then the stiffness matrices for both linear and nonlinear analysis were derived.

Even though there have been numerous studies related to shear wall modeling for light-frame structures, most of these studies model shear walls using a spring model that considers lateral displacement as a SDOF. While the results from these studies help to reduce the number of degrees of freedom (DOF) for nonlinear time history analysis, and the modeling philosophy works well for shorter (e.g., one to four stories) buildings, it does not accurately model the vertical displacement on each side of the shear wall element in taller buildings. In mid-rise and tall buildings, the local and global overturning moments often cause additional vertical displacement of the hold-down rods in stacked wood shear walls or columns in a cold-formed steel frame system. This additional vertical displacement, in turn, causes larger lateral displacements and P-Δ effects.

In this study, a new shear element for light-frame structures is introduced to couple the lateral and vertical stiffness. With this coupled shear spring element, the effect of lateral displacement on the vertical component and the effect of the vertical component on lateral displacement are included. Non-linear behavior of the shear wall can be described by the lateral stiffness which is also included in the shear element stiffness matrix and the effect of large displacements will be discussed in detail later. The new model will allow predicting more accurate lateral displacement using experiment data. The effect of non-structural components can be included in the model if the test specimen includes non-structural components.

Moreover, the proposed shear element helps to reduce time and simplify the procedure in modeling. In finite element modeling, many researchers have tried to model substructures using super elements. Petersson and Popov [12] introduced a procedure called matrix condensation to systematically reduce the number of assembled equations on different substructure levels. Lee et al. [13] proposed a method using this substructuring technique and matrix condensation to analyze high-rise box system structures considering the effects of floor slabs. Kim and Lee [14] used the condensation technique to model concrete shear walls with openings. The condensation technique is well-known in structural dynamics and is essentially a technique that helps to reduce the number of nodes in a typical structural component model by pre-solving some of the equations of equilibrium for that typical component. This technique is helpful in a structure that has linear behavior under dynamic loading. For nonlinear structural dynamics, the stiffness matrix of the structure varies with time (or displacement), and therefore the condensation would need to be conducted at every time step after the stiffness matrix of the component has been estimated. Obviously under such a scenario the condensation technique would not help to reduce computational cost. The stiffness of the shear element introduced in this study is evaluated through the lateral stiffness and the dimension of the shear wall. Therefore, the substructuring and matrix condensation techniques are unnecessary. While no condensation technique is needed, the hysteretic parameters of the lateral stiffness of the shear wall must be provided.

2. Derivation of shear element stiffness matrix

In past studies, the lateral stiffness and non-linear behavior of a shear wall are often evaluated through its hysteresis. This hysteresis is often obtained either by numerical model starting at the non-linear model for nails [2] or by reversed cyclic tests of a shear wall [3,5,7,9]. In both these types of studies, numerical or experimental, the vertical displacement was assumed to be zero. In the current study, a stiffness matrix of a new shear element coupling both lateral and vertical stiffness is introduced. To do this, it is first assumed that there is only lateral displacement of the 4-node shear element, and the force acting on each side of the shear element is calculated. Then, the effect of vertical displacement on the lateral force is derived. The force on each side of the shear element is then transferred into the nodes as a function of lateral and vertical displacement of the shear element. The shear element stiffness matrix is evaluated based on the relationship between the nodal force and nodal displacement just derived.

Consider Fig. 1 showing the interactive forces acting on a 4-node shear element in the x and y direction. Let the total shear force acting in the x direction be F_x and in the y direction be F_y. Then,

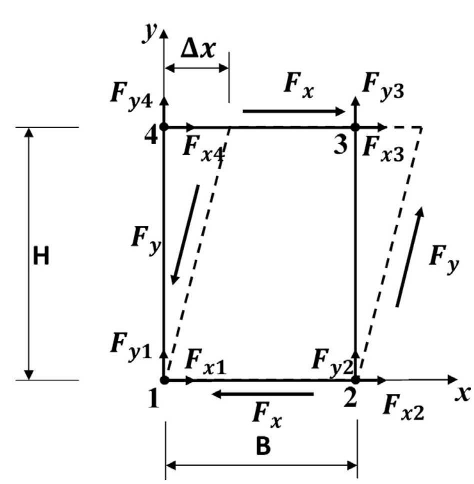

Fig. 1. Interactive forces acting on shear element.