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Equivalent parameterized beam model for nailed connections in low-rise residential buildings

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ABSTRACT

Increased frequency and intensity of coastal storms has renewed interest in the structural performance of coastal low-rise residential homes. Post hazard surveys indicate connections that form the load path from sheathing to framing to foundation play a pivotal role in the failure modes of these non-engineered structures. Nonlinear spring elements are a common means of modeling nailed connections for structural analysis based on experimentally observed behavior. Due to complex connection behavior, three independent springs are usually defined to consider 3D translational displacements. This common approach may introduce error in large displacement analyses due to independently defined directional spring properties. After a brief discussion of issues encountered with nonlinear spring element connection modeling schemes, an equivalent parameterized beam connection model is proposed to characterize softening-type connection behavior. Comparison analyses between the equivalent parameterized beam connector (EPBC) and equivalent nonlinear spring connector (ENSC) are carried out using 1D and 2D single element examples as well as 3D panel models. This new connection modeling scheme could greatly reduce meshing efforts in large models and provide more accurate solutions in critical areas of the structure such as corners and edges by coupling the axial and transverse connection responses.

1. Introduction

Single family residential homes (SFRHs) are usually non-engineered, light-framed, wooden low rise buildings. In this type of structure, the majority of connections rely on nails as fasteners to join members. Nailed connections are capable of resisting lateral and withdrawal forces as well as their combined effect [1]. Typical important connections in the load path of SFRHs include sheathing to frame, frame to frame, and frame to foundation. Connections are one of the most important, but least understood components in structural analyses [1]. In addition, connections are usually weaker than the structural members they join, making them one of the most vulnerable parts of a structure. Connection behavior may be further complicated by short and long term environmental effects such as corrosion and decay that alter structural performance. The anisotropy of wood coupled with degrading environmental effects on the connector, the wooden members it joins, or both of them, may further influence time dependent connection behavior. Building codes and residential construction practices aim to keep structural loads well below the design capacity, however these approaches may not adequately consider the interaction of the modular components such as shear walls that make up the entire building envelope. During high wind loads the load transfer mechanisms between components, especially in the corners and along the edges of buildings is not well understood and may be highly dependent on connection capacity. The complicated nature of load transfer mechanisms in non-engineered structures necessitates a global rather than component level finite element analysis to fully understand load path development and progressive failure of these structures. Furthermore, the load capacity of residential structures may be vastly over-predicted if connection nonlinearity is not considered. The ability to more accurately account for the load transfer mechanisms that contribute to progressive structural failure of residential homes may be useful for assessing the insured risk for existing homes and revising building practices for new construction.

Among all the connections in SFRHs, the most widely studied include those joining sheathing to roof framing and roof framing to wall plates. Historically, most of the observed failures of roof components in SFRHs are recognized in the aftermath of natural disasters rather than through analysis or testing [2]. In an effort to analyze global structural response, connection modeling schemes have been developed to predict the behavior of critical joints in the building envelope. Initially connections were treated

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as linear springs in analyses focusing on uplift capacity of sheathing panels and roof structures [3,4]. These linear connection models exhibited different behavior than the tributary nail area approach, especially as fastener spacing increased because each nail did not carry the same load [4]. Later on, nonlinear effects came into consideration and statistical models considering uncertainties in nail behavior, such as those affected by fastener spacing, were introduced [4]. Time dependent connection modeling including the effects of cyclic loading and hysteretic behavior is another area emphasized in nailed connection research [5,6]. Currently, investigators utilizing finite element methods gravitate towards either a microscopic or macroscopic approach in characterizing nailed connections depending on the nature of their work. Microscopic approaches use high resolution three dimensional solid elements often with contact schemes, friction and nonlinear material models and focus on a single connection [7,8]. Results from these high fidelity models demonstrate good agreement with experimental results. Detailed analytical modeling of nail-wood interaction also confirms the influence of material variations such as grain direction. Wang et al. have proposed a model showing 50–75% variation in performance depending on grain orientation and lumber properties [8]. Furthermore, microscopic approaches have the ability to model hysteretic and time dependent behavior through contact schemes and the deformation of solid element meshes. Although highly detailed connection models can produce good results, they are difficult to implement in larger structural analyses. The computational requirements to handle contact algorithms and refined meshes of solid elements may be prohibitive considering the number of connections present in a SFRH. Additionally, there may be further issues joining framing members represented with beam elements to the solid element mesh used for the connection due to rotational degrees of freedom.

To more easily model connection behavior in the context of a global structural model, macroscopic approaches are used. Macroscopic connection modeling schemes emphasize modeling the effect of the connection on global structural behavior rather than local behavior of the individual connector. As such, the physics is simplified or largely not considered. Instead of accounting for the true governing mechanisms of nail to wood interaction, the response is lumped as input and output behavior as it affects the global structural response. Typically, researchers seek to recreate experimentally observed connection data in the context of their global structural model. Nonlinear spring elements have proven to be the method of choice for many researchers due to their simplicity and ability to adapt to nonlinear experimental data [9–13]. Although a nonlinear spring element can be used for each nodal degree of freedom, in many cases only translational effects are modeled. In 2008, Dao and van de Lindt proposed an updated nonlinear spring element approach to include both rotational and displacement effects of nailed connections [9]. Using this updated approach, connection behavior now influenced all nodal degrees of freedom. Micro and macroscopic approaches both seek to imitate experimental connection behavior, either through direct consideration of the physics occurring or through a model with equivalent behavior. For global structural analysis, detailed modeling of connections may not be feasible due to computational requirements or mesh implementation issues. Therefore, equivalent nonlinear spring connector (ENSC) elements are a common connection modeling scheme for large scale structural analysis.

In the present study, a new equivalent parameterized beam connector (EPBC) model is proposed to characterize strain softening-type connection behavior. The paper is organized in the following way. After a brief introduction of the ENSC modeling scheme, the theoretical background for the EPBC model is introduced. Using the EPBC definition, single element comparisons between EPBC and ENSC formulations are presented. Performance of the two connection modeling schemes is compared in the linear and nonlinear response regimes as well as for one dimensional and multi-dimensional loading. EPBCs and ENSCs are used to fasten sheathing to both a centrally located exterior wall panel with symmetric boundary conditions and a corner panel. These two examples seek to compare the large displacement response computed by each modeling scheme at different locations in the building envelope. EPBCs are found to closely replicate current state of the art translational ENSC behavior for linear responses and more accurately couple multidirectional displacement effects in geometrically nonlinear analyses.

2. Modeling schemes

2.1. Equivalent nonlinear spring connection models (ENSC)

A single nonlinear spring element can closely replicate experimental force deflection behavior in one dimension and it operates in a nodal coordinate system. In order to define unique translational behavior in three dimensions, three elements are typically used for each connection to create a *connector set*. If the rotational stiffness is to be modeled as well, an additional 3 rotational spring elements are required and up to 6 elements could be necessary to completely define the connection behavior with ENSCs. Due to a lack of an intrinsic coordinate system, the nodes connected by ENSCs should have the same orientation. This issue has been addressed by Judd and Fonseca with their oriented vs. non-oriented spring pair models, however often times the non-oriented spring pair model is favored for ease of implementation [13,14]. The end node orientation of ENSCs must align correctly with the axial and transverse directions of the connector for which deflection behavior is defined. If connections are between a single node pair, nodes can be issued auxiliary coordinate systems as necessary such that axial and transverse directions with respect to the connection are accounted for. If more than one set of connector elements are not collinear, the shared node between sets cannot adapt to the axial and transverse directions of both connector sets. The issue is best illustrated considering a corner or edge where multiple pieces of sheathing must be fastened to the same framing member. This scenario is illustrated in Fig. 1 where a top-down cross section of a typical framed corner of a home is translated to a finite element model approximation. If axial properties were defined in the global Z direction, node 1 cannot adapt a coordinate system that satisfies the axial direction of the connector from 1 to 3 and 1 to 2 at the same time. A commonly used modeling scheme involves creating a duplicate node on top of location 1, assigning it the necessary auxiliary coordinate system and then coupling its degrees of freedom to the original node. Another option is to define redundant sets of force deflection data so that as necessary, nonlinear springs with the same global degrees of freedom are assigned different directional stiffness depending on their orientation. Both of these alternative methods involve considerable manual intervention in meshing increasing the opportunity for error and still exhibit some of the potential calculation difficulties of ENSCs as discussed below.

Accuracy of nodal displacement solutions may suffer due to the ENSC's lack of intrinsic coordinates. For large displacement analyses, deformation in the axial direction of the connector may be decomposed incorrectly if the current deformed axial direction does not match the initial axial direction the nodal coordinates are set in. Fig. 2, below illustrates improper directional stiffness decomposition due to the use of nodal coordinates. The displacement of node 3 from state 3′ to 3″ occurs along the axis of the connector from nodes 1 to 3′, however it is no longer purely in the Z