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Structural Performance of Woodframe Housing: State-of-the-Art and Research Needs

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ABSTRACT

This paper presents the state-of-the-art in development of analytical procedures to predict the structural performance of woodframe houses and identifies areas of needed research. It is found that while significant progress has been made in analytical modeling of shearwalls and diaphragms, only limited progress has been made on the modeling of complete houses and intercomponent connections. Most of these analytical procedures are used primarily as research rather than design tools.

INTRODUCTION

Woodframe buildings consist of several components such as walls, floors, and roofs joined by intercomponent connections such as nails, anchor bolts, metal plates, and other propriety connectors (e.g. hold-down brackets). The performance of woodframe buildings is influenced by the behavior of the individual components and their connections. Therefore, an understanding of the behavior of the different structural components and connections is essential to accurately predict the performance of a housing unit under different types of loading.

Woodframe buildings perform well under gravity loads. Considerable damage, however, has been observed in such structures under severe and moderate earthquakes and major hurricanes. It is, therefore, important to understand the behavior of woodframe buildings subjected to lateral loads generated by earthquakes and hurricanes so that the risk to life and property can be reduced. By using accurate analytical tools to model the different structural components as well as the complete structure, performance parameters can be reliably predicted. Multiple simulations to study the influence of different parameters on the structural performance may, therefore, be conducted more cost-effectively than by testing. Experiments, however, are still required to verify and refine the analytical tools. The end result promises improved design standards that enable buildings to resist the expected earthquake and wind loads without significant damage or collapse.

Analyzing the structural components of a woodframe building subjected to lateral loads is a difficult task due to several sources of nonlinearity, the complex nature of the connections and fasteners, and the wide variability in material properties and construction techniques. Since shearwalls are the most important elements in resisting lateral loads, they have been extensively studied by several researchers since the early 1970s. Simplified methods and finite element analyses have been performed to predict the behavior of the walls under static and dynamic lateral loading. The development of tools for analyzing complete woodframe houses started in the mid-eighties. This step included analyzing the different structural components as well as the intercomponent connections in an assembled model.

A recent report (Yancey et al., 1998) by the National Institute of Standards and Technology (NIST) includes a summary of experimental and analytical research conducted on woodframe houses with a complete list of references. The following sections present a brief description of the analytical studies performed on different structural components and connections as well as the complete building.

WOOD STUD SHEARWALLS

Wood stud shearwalls are commonly used in residential and low-rise buildings to provide lateral stiffness and transmit in-plane and out-of-plane forces to the foundation. A typical wall consists of vertical studs at constant spacing, horizontal upper and lower plates, and sheathing panels which are fastened to the framing members. The behavior of wood shearwalls is complicated because of the nonlinear characteristics of the connections, the discontinuity (gaps) in the sheathing material, and the non-isotropic behavior of wood and wood composites. It should be noted that the in-plane diaphragm behavior of the floors and roofs is similar to that of shearwalls. Therefore, it is important to understand the load-deformation behavior of shearwalls, or diaphragms in general. Several investigators have analytically studied the behavior of shearwalls and attempted to predict their behavior under different loading patterns and to correlate the results with those from experiments. Most of those analytical studies can be divided into the following two categories:

1) Closed form and simplified methods: Closed form solutions and simplified methods to calculate the racking strength of wood shearwalls were developed by several investigators who assumed a distorted shape for the wall framing and sheathing

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panels and used energy principles to derive the load deformation relationship for the walls. Linear and nonlinear nail load-slip behaviors were assumed. In addition, simplified models for dynamic analysis have been developed.

2) Finite element analyses: Several investigators developed 2- and 3-D, static and dynamic finite element models to predict the performance of walls under shear loading. The models generally consisted of linear beam or shell elements for framing members, linear plane stress or plate elements for sheathing, and nonlinear springs for nail connections and sheathing interface elements. In addition, reduced 3-D models of shearwalls that can be used in the analysis of a complete house have been developed. Experimental results were used to verify the mathematical models and generally good agreement between analytical and experimental results was reported.

FLOORS AND ROOFS

Floors in woodframe structures are typically made of a system of parallel wood beams (joists) covered with sheathing panels made of plywood or wood composites. They carry gravity loads and transfer the in-plane and out-of-plane forces to the vertical substructures and to the foundations. Roofs are used to transmit gravity loads to the supporting walls and act, together with ceilings, as horizontal diaphragms. Different roof constructions ranging from rafter systems to pre-fabricated trusses have been used. Wood trusses with metal plate connections have been widely used for roof framing. A number of investigators had developed finite element models for floor and roof systems to study their performance under loading. These studies showed that floors and roofs behave linearly for the normal range of design loads. The results of the analytical studies have been compared with those from experiments, and a good agreement was observed.

INTERCOMPONENT CONNECTIONS

Intercomponent connections such as nails, anchor bolts, or metal plates (hangers and T-straps) are used in woodframe construction to connect different substructures such as walls, floors, roof, and foundation, and to transfer forces between them. The behavior of intercomponent connections is complex because of the nonlinearity of the materials, interlayer gaps, material variability, and diversity of construction techniques. It has been observed that damage to or failure of woodframe buildings during earthquakes and hurricanes are, in most cases, due to failure of intercomponent connections. Intercomponent connections, however, have not been widely studied either experimentally or analytically. Very few studies have developed finite element models for the analysis of wall-to-floor, roof truss-to-wall, exterior wall-to-exterior wall, and partition-to-exterior wall connections. The models accounted for the nonlinear behavior of wood materials and nailed joints as well as intercomponent gaps. Good agreement between analytical results and experiments was reported.

COMPLETE STRUCTURES

Experimental investigations of full-scale woodframe structures are limited because of the high costs and difficulties associated with experimental testing. Analytical procedures which can accurately represent the behavior of a complete house can be efficient tools for understanding and predicting the behavior of woodframe houses. Since the mid 1980s, a number of investigators have attempted to analytically study the behavior of complete houses, predict their behavior under different loading conditions, and compare the computed results with those from the experimental studies. Those studies included: 1) simplified models that considered several simplifications and assumptions such as linear behavior of joints and connections and rigid diaphragms, and 2) finite element models that included analyzing the different components and connections in an assembled mode. Three-dimensional, static and dynamic finite element models have been developed, and their results were compared with those from experiments where a reasonable agreement was reported. The majority of the finite element models utilized the super-elements concept and condensation techniques to reduce the number of degrees-of-freedom of the structure.

RESEARCH NEEDS

Based on the summary presented above and the NIST study reported in Yancey et al. (1998), further research in the following areas is recommended to provide accurate and reliable analytical procedures for woodframe structures that can be used in the development of performance evaluation criteria as well as guidelines for performance based design:

<u>Refined and simplified analytical procedures</u>

1. *Study the behavior of intercomponent connections:* Very few studies have considered modeling of intercomponent connections. More research should be directed to accurately model the behavior of the connections based on experimental results. The effort should also include the hysteretic modeling of nail joints and intercomponent connections. The models should include pinching, slip, and stress and stiffness degradation.

2. *Study the coupling between bending, shear, and axial stiffness of shearwalls:* In addition to carrying axial loads, walls may be subjected to out-of-plane bending under wind pressure while acting simultaneously as in-plane shear diaphragms. An investigation of the wall behavior under the combined loading conditions is needed.

3. *Investigate the torsional behavior of woodframe structures:* Designs of new houses often call for unsymmetric plans with long spans and large openings. Under such designs, structures subjected to lateral loads will experience torsional moments. The analytical procedures should be capable of modeling the torsional stiffness and strength of the building.

4. *Develop simplified analytical methods for a complete building:* Available studies on the analysis of complete houses are either too complicated and time consuming or so simplified that their accuracy is questionable. Further research is needed to develop simple and accurate static and dynamic procedures to predict the building performance.

Performance, measurements, and standards

1. *Evaluate analysis procedures and design factors:* Current seismic design provisions specify linear or nonlinear, static or dynamic procedures to be used for the seismic design of buildings. Comparisons between the linear static, linear dynamic, and nonlinear static procedures and the more sophisticated nonlinear dynamic procedure are required to assess the reliability of the simplified procedures. Furthermore, for the linear procedures, building codes recommend the use of modification factors that account for energy dissipation through inelastic behavior. The validity of the modification factors recommended for woodframe buildings should be investigated.

2. *Conduct performance and parametric studies:* The parameters that significantly affect the response of a woodframe house to different loading conditions should be identified. The influence of material properties and fastener/connection behavior as well as building configuration and irregularities on the safety and serviceability of woodframe buildings should be studied.

3. *Predict damage states and failure modes of the building:* The analysis procedure for woodframe buildings should include the capability of predicting the damage state of the building as well as its failure mode(s) for an expected level of seismic or wind excitation. This will greatly benefit home-owners and insurance companies as it provides them with accurate measures of expected earthquake and hurricane losses. Such studies will also be used to develop performance criteria and to relate the design of buildings to their performance; issues that are crucial in the development of performance based design procedures for woodframe buildings.

4. *Perform reliability assessment and sensitivity studies:* Probability based design methodologies form the foundation of engineering design by establishing an acceptable basis for determining the risk of failure and should be used to investigate the reliability of woodframe houses and to establish target reliabilities.

5. *Develop Performance Standards:* Performance standards for structural safety and serviceability need to be developed through the consensus process. Such standards should present clearly the performance objectives, criteria, and evaluation methods.

SUMMARY

Significant progress has been made in recent years in the analytical modeling of woodframe building components, especially shearwalls and diaphragms. Several investigators have proposed models that accurately capture the nonlinear behavior of shearwalls. Analytical models have also been developed for floors and roofs under uniform pressure. Only limited research, however, has been directed toward the analysis of a complete building or the intercomponent connections. This paper outlines several areas where further research is required, especially in regard to development of refined and simplified analytical procedures as well as performance, measurements, and standards.

REFERENCES

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