Wood Diaphragms: Performance Requirements and Analytical Modeling

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Abstract

Wood diaphragms represent the principal mechanisms for resisting lateral loads in many light-frame buildings. While recent research has provided several mathematical models for predicting the strength and stiffness properties of these components. the design criteria prescribed by codes have not yet recognized these new procedures. Differences exist between the design criteria, the ability to accurately model wood building behavior, and the actual performance of buildings under real loads. The objective of this paper is to contrast these arenas and discuss some of the differences that limit efficiency and uniformity in the design of wood buildings.

Introduction

During the past several decades, structural engineers have greatly improved their knowledge of the performance of various building systems and have refined the analytical models used in design. While the wood engineering community has effectively developed new wood products and analytical models for various wood components, differences exist between the performance prescribed in our code-dictated design criteria and that predicted with the analytical models. This results principally from the deterministic

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approach to developing design criteria that provides for limited feedback on the actual performance of the structure.

In this paper, we discuss the current performance requirements prescribed by codes and standards for the design of wind-loaded and seismically loaded wood buildings and the status of available analytical models for these structures. Limiting our ability to efficiently and uniformly design wood buildings are the differences between each of these two arenas and actual building behavior. Specifically, we will look at racking walls and horizontal diaphragms.

Performance Requirements

Racking walls and horizontal diaphragms have found acceptance for resisting of lateral forces because of historically observed performance or standard laboratory test results. Diagonal bracing in walls and diagonal board sheathing in floors were commonly used in light-frame construction prior to World War 11. They provided adequate performance and thus became the benchmark of acceptable performance for later design.

Traditionally, two general methods have been used to quantify wall racking and horizontal diaphragm performance. The first is to perform lateral load tests and compare the results to what has been historically acceptable construction. The second is to empirically correlate racking strength to lateral nail strength, which represents the interaction between the framing and sheathing materials. Unfortunately, these methods do not provide a strong link to actual behavior.

Strength and Stiffness--The amount of shear allowed to be carried by a diaphragm is limited by the in-plane shear of the sheathing, the lateral fastener load at the diaphragm boundary, or the fastener load at discontinuous interior panel joints. The limits on the allowable shear load values are not restricting. Codes contain language allowing the use of any system that "may be calculated by principles of mechanics without limitation by using values of nail strength and plywood shear values as specified elsewhere in this code." (ICBO 1985)

Current building codes, such as the Uniform Building Code (UBC). prescribe the size. height, spacing, framing details, and bracing options for wood-stud walls used for lateral load resistance. Bracing options include the use of diagonal board, plywood, structural flakeboard, fiberboard, gypsum board, or particleboard sheathing.

In the United States, tests conducted in the late 1930s and early 1940s on wood-stud walls sheathed with various materials were the basis for the acceptance standards for the Federal Housing

Administration (FHA) (Anderson 1965) and. more recently, the Department of Housing and Urban Development (HUD).

Codes and standards for racking resistance of walls are generally based on the results of the standard ASTM E 72 test (ASTM 1976). The HUD Minimum Property Standards (HUD 1979) require that an 8- by 8-ft (2.5- by 2.5-m) wall section tested according to ASTM E 72 meet or exceed an ultimate load of 5,200 lb (2,360 kg) to be approved for shear wall application.

The ASTM E 72 standard was developed to provide a common basis for comparison of sheathing materials. Its use in the certification of wall performance has been questioned. A standard test more realistically reflecting component behavior is the ASTM E 564 test (ASTM 1984). This standard is intended for the evaluation of overall lateral wall performance rather than performance of the sheathing and permits variation in the holddown mechanism and wall configuration to more closely approximate actual wall performance.

Wood buildings are rarely built solely with 8-ft- (2.5-m-) long walls having no openings. Indications are that wall strength increases linearly with length and that sections containing openings do not contribute to racking performance (Wolfe 1983, Patton-Mallory et al. 1985). Therefore, current practice is to subtract the length of openings from gross wall length and multiply by a strength per unit length to estimate allowable load.

Horizontal diaphragms are designed based upon static floor tests performed by the Douglas Fir Plywood Association in the early 1950s (Countryman 1952, 1954). Various types of plywood sheathing, fasteners, and framing were considered. These tables were later expanded as a result of additional tests performed by Tissell for the American Plywood Association (Tissell 1967, Tissell and Elliott 1977).

Current codes and standards for horizontal diaphragms are generally based on the results of these limited tests. Several building codes list allowable shear resistance per unit length (ICBO 1985). However. these values are limited as to specific combinations of sheathing types, framing species and grades. and nail size and spacing.

The HUD minimum property standards specify an average total limiting deflection for racking walls of 0.2 in. at a 1,200-lb (545-kg) load. Residual deflection is limited to 0.1 in. These limitations are based upon the E 72 test standard.

The UBC is more general in its limitations. It states, "Permissable deflection shall be that deflection up to which the diaphragm and any attached distributing or resisting element will maintain its structural integrity under assumed load conditions, i.e., continue to support assumed loads without danger to occupants of the structure". (ICBO 1985)

Japanese building codes utilize an effective wall length method in which a racking wall resistance factor and wall length are used in conjunction with limiting story deflection for earthquake-resistant design (Sakamoto et al. 1984). This limits building deflection to 1/120 radian when subjected to a 0.20g loading. This method is tied closely to results of experimentally tested wood buildings.

Various limitations have been placed on the use of horizontal wood diaphragms. Limits are placed on the physical shape in plan in terms of a ratio of the depth of the diaphram in the direction under load to the span between vertical supports providing reactions. This ratio is limited to 3:1 or 4:1 depending on whether conventional straight board sheathing, diagonal board sheathing, or panel sheathing is used. These rather arbitrary limits were probably set based upon the maximum ratios of the floor diaphragms tested to establish code-based allowable shear load tables and limit deflection to an ill-defined acceptable level.

Current design assumptions include support conditions that are either a simple span or fully continuous. Codes require a design that corresponds to the highest moment and shear obtained from either of these conditions. Often these support conditions do not exist in real structures. Work by Tarpy et al. (1985) is directed towards developing more practical criteria for assessing continuity conditions of supports.

<u>Ductility and Energy Absorption</u>--Current building code recommendations regarding seismic performance of wood buildings are simplified by not considering the energy-absorbing characteristic of the numerous connections between the framing and the sheathing. This connection characteristic is undoubtably significant in the performance of wood buildings during earthquakes.

Researchers in New Zealand recognized this characteristic and have focused on a ductility approach to timber building design for earthquake resistance (Moss 1984, Buchanan 1983). Accounting for ductile behavior allows for plastic deformation of the component, permitting designed resistance to loading at levels less than those imposed if it had remained fully elastic. Realizing that the timber itself is a brittle material, the connections are designed to provide ductility under severe earthquake loading. This ductility reduces the base shear of the structure since energy can be dissipated in the form of hysteretic damping. Plywood-sheathed shear walls, however, exhibit pinched hysteresis loops under cyclic loading, which can result in severe stiffness degradation (Dean et al. 1986).

The present earthquake design philosophy of New Zealand encourages the use of fully ductile structures without load or stiffness degradation in seismic-resisting components during cyclic loading. While full-bodied hysteresis loops are generally desirable, designing wood buildings that always behave in this manner is difficult (and uneconomical). The New Zealand code states that "In determining the effect of earthquakes on timber structures, due consideration shall be given to the likely response of the structure, its potential for energy absorption, level of damping, and possible mode of failure." (SANZ 1981)

These are excellent recommendations that direct design towards more realistic building behavior.

Analytical Modeling

This section overviews analytical models that have been developed for predicting racking wall and horizontal diaphragm behavior and the attempts that have been made at quantifying the performance of a complete wood structure.

Racking Walls--The dependence of racking strength of nailed walls on lateral nail strength has long been recognized. This led to the development of empirical relationships for specific sheathings and nail geometries (Neisel and Guerrera 1956, Neisel 1958, Welsh 1963). This approach has obvious limitations--a set of tests is required for each new sheathing-framing-fastener combination. As a result, the analysis of wood-stud walls subjected to lateral loads has typically been oversimplified.

Using a more rational approach, several mathematical models have been developed for determining the racking performance of wood-stud walls. The use of energy formulations to characterize lateral wall performance have been proposed by Tuomi and McCutcheon (1978), Kamiya (1981), and Kallsner (1983). These models incorporate a geometric derivation of nail forces and use load/displacement characteristics of the fasteners to evaluate total energy, which is related to horizontal wall displacement. These models are generally limited to static, monotonic loading and ignore the contribution of sheathing. but they are in fairly good agreement with experimental results within typical serviceability ranges. Earlier models assumed that nail load/displacement was linear, limiting displacement prediction to lower levels of loading. More recent models include modifications to incorporate nonlinear effects (McCutcheon 1985, Gupta and Kuo 1985, Patton-Mallory and McCutcheon 1987). This allows displacement prediction up to failure load.

Wall models using the finite element method have also been developed (Foschi 1977, Easley et al. 1982. Itani and Cheung 1984, Gutkowski and Castillio 1988, Cheung et al. 1988). These models have been important in identifying the individual effects of framing, sheathing, and fasteners on overall wall performance.

The distribution of lateral forces to the various walls in a wood building is dependent not only on wall stiffness but also on the location of the walls in the plan of the building. Two models have been developed to analyze an assembly of walls subjected to lateral loads. The model developed by Naik et al. (1984) assumes that each shear wall is modeled by a set of springs and that the floor diaphragm to which they attach is completely rigid. Schmidt and Moody (in press) utilized the wall racking theory of McCutcheon (1985) in the development of their RACK3D model. Moody and Schmidt (1988) analyzed several wood buildings using this model and found reasonable agreement with experimental test results of whole wood buildings.

Horizontal Diaphragms--Traditional analysis methods used to design horizontal diaphragms assume the diaphragm behaves like a deep beam with the chords acting as the flanges and the sheathing acting as the web. Most designers still utilize this methodology (ATC 1981).

Relatively little work has been performed to model diaphragm action in horizontal floors, ceiling, and roofs. The modeling of this behavior is especially important for .buildings in earthquake zones. Foschi (1977) developed a diaphragm analysis model that considered lateral force interaction among the sheathing, joists, and connections both between the sheathing and the frame and between the members of the frame, GangaRao et al. (1980) used a plane elasticity approach to derive partial differential equations for determining the displacement characteristics of wood diaphragms. More recently, Falk and Itani (in press) developed a two-dimensimal finite element model for the distribution and stiffness of fasteners between the sheathing and framing of horizontal and vertical wood diaphragms.

These models have been verified by comparison to the test results of isolated diaphragms. The lateral load response of a whole building is dependent on not only the walls and floors but also the intercomponent connections between these elements. Intercomponent connections are thought to play an important role in the stiffness and damping of wood buildings; however, little research has been performed to quantify the behavior of these connections (Polensek and Laursen 1984, Polensek and Schimel 1986). The connections between various walls, the sill plate and roof, and the sole plate and floor, for example, need to be modeled before a complete wood building can be accurately analyzed.

Full Structure Considerations--Though no comprehensive model currently exists for a three-dimensional wood building, it will likely incorporate aspects of the described component and intercomponent models. The development of such a model will permit a more accurate prediction of load transfer within a wood structure and allow an optimization of shear wall geometry and location. The importance of such a model is probably dependent on the mode of loading under consideration: that is, it will be more useful for quantifying lateral load than gravity load behavior.

Two attempts have been made at modeling a full wood building. Gupta and Kuo (1987) presented a model to perform lateral load analysis of a wood building without intercomponent connections. Though the roof was modeled using sheathing patterns typically found in walls and material properties were estimated, the analysis indicated good agreement with experimental results. Similarly, the model developed by Moody and Schmidt (1988) does not model intercomponent connections.

Differences Between Performance Criteria. Analytical Models. and Actual Behavior

Design approaches for wood buildings, as dictated by current codes, are dominated by deterministic methodologies, which are characterized by the use of specified minimum material properties, specified load levels, and prescribed procedures for assuring acceptable. but often overly conservative. performance. This deterministic approach does not provide for a feedback loop reflecting the actual behavior of the structure. For example, deflections are rarely observed or measured, actual stresses are often unknown, and since most structures do not fail. the reserves of strengths are generally unknown.

Current code approaches can also be limiting in their contribution to improving design efficiency. For example, racking loads in buildings are assumed to be resisted totally by end walls, each of which carries an equal share of the total load. The contribution due to interior partitions or effects of variation in racking stiffness is ignored. These approaches also base wall design on ultimate strength. giving no guidelines or stiffness information for estimating deflection limitations.

Traditionally accepted analysis methods for horizontal diaphragms assume a deep beam analogy in which the moment resulting from applied forces is resisted by a compression and tension couple in the diaphragm chord members and the total shear is carried by the sheathing material (acting as the web of the beam). This assumption is quite conservative in that it ignores any moment resistance provided by the web. While this assumption provides an upper bound on the magnitude of the chord forces, insufficient data exist to assess the contribution of the web to moment resistance.

A difference also exists between the actual behavior of a wood building and an available model to simulate its behavior. While several models exist for the analysis of wood building components, these models have yet to be incorporated into a realisitic model for full structure analysis. Modeling efforts have, for the most part, been directed primarily towards single components assumed to be unaffected by the rest of the structure. Information on the intercomponent action or load transfer mechanisms among components and between components and the foundation are needed to more realistically assess the transfer of loads throughout the structure and the resistance needed by the various components.

Development of a full structure model will provide a more realistic means to assess the actual performance of a wood building. While this model will require verification through testing and monitoring of full-size structures, integrating the results of analysis with this model into the codes will provide the needed feedback information on the actual behavior of wood buildings.

Concluding Remarks

The past performance of wood structures subjected to the lateral forces of wind and earthquakes has indicated that traditional analysis and design methodologies have generally provided adequate performance. In many instances, however, our design and analysis methods are simplified and, as a result, probably conservative. Also, these deterministic approaches to design provide limited feedback on the actual performance of the structure.

While progress is being made in quantifying some of the important performance factors that affect wood building behavior, such as ductility and energy-absorption effects, differences still remain between the performance prescribed in our code-dictated design, the behavior predicted with developed analytical models, and actual building behavior. Not until we develop models for whole-building analysis, verify these models compared to tests of full-size buildings, and incorporate the knowledge from these techniques into codified design procedures can we expect uniform and efficient performance from our wood buildings.

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