State-of-the-art structural modeling of light frame assemblies and buildings

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Abstract

This paper discusses analytical modeling in general and briefly reviews the various structural models available for the analysis of wood subassemblies and buildings. Important factors to consider when utilizing these structural models in a reliability-based design methodology are also discussed.

Introduction

During the past several decades, structural engineers have greatly improved their knowledge of the behavior of various building systems and have refined the analysis techniques used in design. Over the same period, however, the design procedure for light-frame wood construction has changed little.

As the wood industry moves towards a more rational design procedure incorporating reliability-based design, structural models will play a bigger role in the analysis and design of wood structures. To minimize costly and time-consuming experimental testing, these structural models will be utilized to establish resistance distributions for various wood components.

In this paper, we overview analytical modeling in general and discuss the various structural models available for the analysis of wood structures. In addition, we review some of the important considerations in utilizing these structural models in a reliability-based design.

Overview of analytical modeling

Analytical models developed to evaluate structural performance can be placed in three general categories (Fig. 1): a) basic analysis; b) deterministic design; and c) distribution simulation. The basic analysis model type is the foundation upon which the other two are built. It requires analog input consisting of member properties, a physical discription of the structural assembly, and load characteristics (location, magnitude, and direction) and gives an assessment of individual member stresses and strains.

The deterministic design model type includes optional design overides on the input, design decision logic in the analysis, and an evaluation of the structure's resistance/load ratio in the output. An example of this model type is the Purdue Plane Structures Analyzer II model (26).

The distribution simulation model type normally incorporates special input routines to recognize interdependent distributions of material property inputs. These models are designed to characterize the distribution of assembly structural capacity through repeated analyses. For each analysis, material properties having a significant effect on the stiffness and strength of the assembly are randomly assigned on the basis of the decision logic setup in the input routine. Output is usually oriented toward the load required to exceed established limit states and is in the form of a probability density data file.

Developed subassembly and full-structure models

Although one can envision a "supermodel" to collectively analyze floors, walls, roofs, and ceilings subjected to various dead and live loadings, researchers have chosen to develop separate models for individual subassemblies.

Because each subassembly carries loads in a different way, each requires a different analytical procedure. Walls act in compression to transfer upper floor or roof load to the foundation, in bending to resist normal wind loading, and as shear diaphragms in transmitting the lateral loads due to wind and earthquakes. Floors are also multifunctional in that they resist both bending and shear loads. Bending loads arise from uniform or concentrated live loading and dead loading applied normal to the plane of the floor. Floors act as horizontal diaphragms to resist lateral shear loads. Roof trusses (and systems) resist primarily bending loads from the dead load of the roof and live loads such as snow and wind. As with floors, sheathed roofs also act as diaphragms to resist lateral forces. The full structure resists all the previously mentioned types of loading through an interaction of the components.

This section overviews the various structural models that have been developed for the prediction of subassembly behavior and the attempts that have been made at quantifying the performance of a complete wood structure.

walls

The analysis of wood-stud walls subjected to lateral wind loads and vertical compressive loads has typically been oversimplified. Polensek (20) developed a finite element model for the analysis of wood-stud walls. This model, called FINWALL, accounts for composite action and load sharing in walls subjected to both axial and bending loads. Related studies (7, 21) investigated the characteristics of various input parameters. Use of this model has confirmed that walls with plywood or beveled siding on the exterior surfaces and gypsumboard on the interior would likely experience stud bending failures at load levels averaging over 100 lb./ft.[2], far exceeding most wind loading.

Kamiya (13) recently developed a buckling theory that is used to investigate the contribution of the sheathing to the overall stiffness and strength of wood walls.

Several models are available for determining the racking performance of wood stud walls. The use of energy formulations to characterize lateral wall displacement have been proposed by Gupta and Kuo (8), Kallsner (11), Kamiya (12), and Tuomi and McCutcheon (30). Models using the finite element method have also been developed by Easley et al. (2), Foschi (4), and Itani and Cheung (10).

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 (17, 25). The model developed by Naik (17) 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 (25) utilized the wall-racking theory of Tuomi and McCutcheon (30) in the development of their HACK3D model. Moody and Schmidt (16) analyzed several wood buildings using this model and found reasonable agreement with experimental results. The authors feel that incorporating a flexible floor diaphragm will result in better prediction of actual behavior.

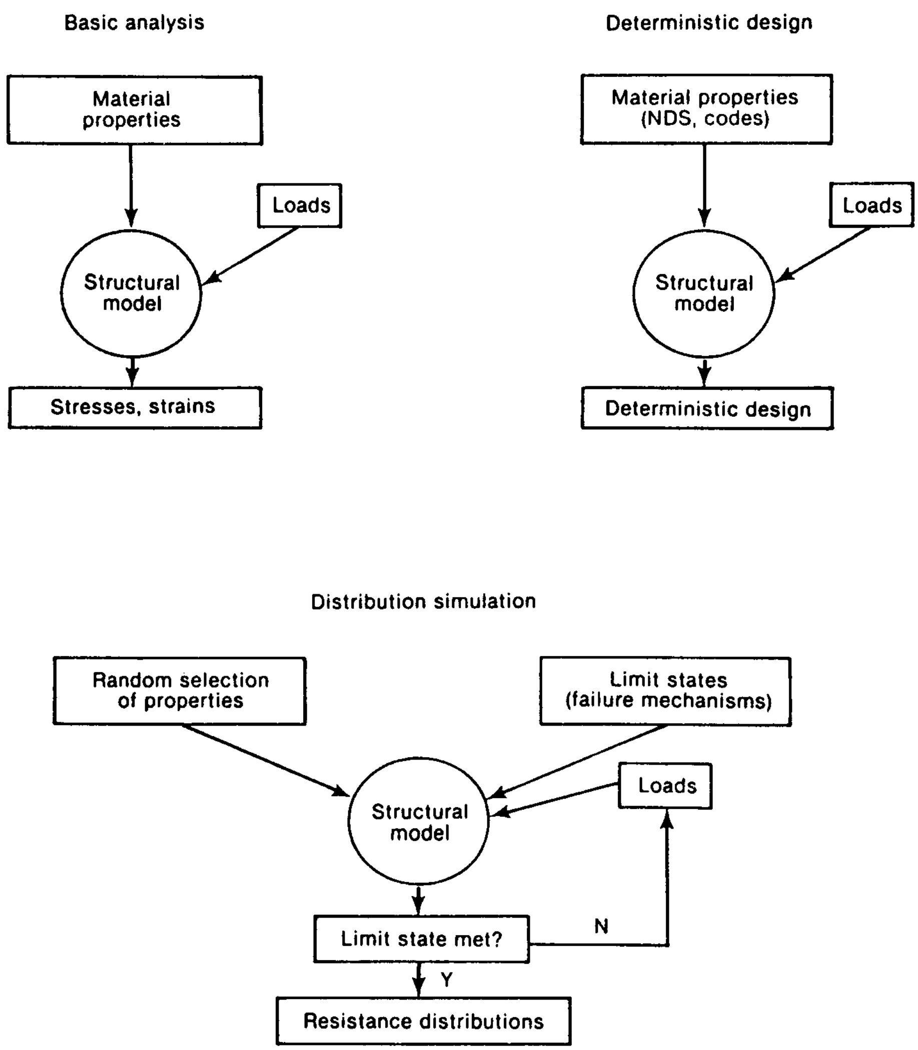

Figure 1. - Types of analytical models.

Floors

Several different approaches have been taken in analyzing the structural performance of wood-joist floor systems under bending loads. Polensek (19) proposed a wood floor system model and used a combination of T-beam elements to represent the stiffened joists and rectangular orthotropic plate elements to represent sheathing. The plate elements accounted for load sharing.

Researchers at Colorado State University (27, 28) developed a comprehensive finite element program, called FEAFLO, to predict the response of multilayer systems to both concentrated and uniform loading within the service load range. The analysis technique considers partial composite action and the two-way action of sheathing. Many of the factors contributing to overall floor performance have been extensively researched with this model (24).

Wheat et al. (32) developed a nonlinear version of FEAFLO to account for fastener behavior; their version predicts the stress conditions in both the joists and the sheathing near failure.

While these floor models have been very

helpful in identifying the important parameters affecting floor performance, a simplification in the modeling process has allowed a reduction in computational effort. A simplified T-beam model to analyze the composite action of joists and sheathing under uniform loading was presented by McCutcheon (14) in 1977. This model has been further modified to account for load-sharing effects (15). This formulation condenses the T-beams into springs and the sheathing into a load distributor beam. To allow the analysis of various loading arrangements, the model is being modified to include concentrated loads.

Foschi (5) developed a Floor Analysis Program (FAP) that utilizes a combined Fourier series and finite element analysis. This program models the effects of partial composite action between the sheathing and the joists, two-way action, and open sheathing gaps perperdicular to the joists.

Though each of these models has its own advantages and disadvantages, all account for the important factors in floor bending— load-sharing and partial composite action.

It is apparent that a significant amount of research has been performed on modeling the bending behavior of wood floors; however, relatively little work has been performed to model diaphragm action. The modeling of this behavior is especially important for buildings in earthquake zones. Foschi (4) developed a diaphragm analysis model that considered lateral force interaction among the sheathing, joists, and the connections both between the sheathing and the frame and between the members of the frame. GangaRao et al. (6) used a plane elasticity approach to derive partial differential equations for determining the displacement characteristics of wood diaphragms. More recently, Falk and Itani (3) developed a two-dimensional finite element model for the distribution and stiffness of fasteners between the sheathing and framing of horizontal and vertical wood diaphragms.

Roofs

One of the earliest attempts at roof assembly modeling was by Brown (1). His work focused on an innovative folded-plate roof design that took advantage of the diaphragm shear and plate bending properties of plywood. Although this design concept and model did not receive widespread acceptance, its straightforward simplicity would make it relatively easy to adapt to a reliability-based design format.

The next level of complexity are those models used to design roof subassemblies with little consideration for the contribution of sheathing elements. These models vary in flexibility regarding options for representing loads and the structural analog. Two subassembly programs, widely noted for their use in analyzing roof trusses and frames, are the Purdue Plane Structures Analyzer II program (26) and the Structural Analysis of Trusses (SAT) program (4). The Purdue model contains design decision logic commensurate with the National Design Specification for wood construction (18). This program basically incorporates a stiffness matrix analysis of linear one-dimensional elements. It permits uniformally distributed loads as well as concentrated loads at or between node points. In the area of member connections, it incorporates "fictitious" members to model effects of joint eccentricity and flexibility. The SAT model is an analytical tool rather than a design tool. Its unique feature is the nonlinear metal plate connector analogue. Both programs have influenced the development of a number of other analytical and design programs for evaluating trusses and frames. One advantage of the SAT model is that it can easily be used for simulation analyses to generate resistance distributions.

Still at the theoretical level are the more complex full roof assembly models that are aimed at evaluating the performance of redundant assemblies. Two models currently in evaluation and development stages are the Roof Analysis Program (RAP) (31) being developed at Forintek Canada Corp. in Vancouver, and a program called ROOFSYS currently being developed at the University of Wisconsin. Both of these programs consider the diaphragm and plate action of the roof sheathing as well as partial composite action between sheathing and framing members. They will both include the capacity to evaluate the nonlinear behavior of truss connections. The RAP model is slightly more complex in that it incorporates diaphragm and plate elements to model sheathing contributions; ROOFSYS uses beam elements for both these effects.

Intercomponent connections

Intercomponent connections are thought to play an important role in the stiffness and damping of a wood building; however, little research has been performed to quantify the behavior of these connections (22, 23). The connections between various walls, the sill plate and roof, and the sole plate and floor, for example, need modeling before a complete wood building can be accurately analyzed.

Full structure

Though no comprehensive model currently exists for the three-dimensional modeling of a wood building, when developed it will likely incorporate aspects of the described component and intercomponent models. 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 behavior than for gravity loads.

Gupta and Kuo (9) 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 (16) does not address intercomponent connections.

Use of models in a reliability-based design format

In the previous section, we reviewed the models that are currently available for predicting subassembly and whole-building behavior. While these models can provide the structural analysis portion of a reliability-based design procedure, they must be refined.

The degree of verification of the model must be considered. Using the results of experimental tests, the models discussed have been verified; however, the extent of this verification varies because of practical limitations in test facilities and budgets. Testing a 100- by 200-foot plywood diaphragm, a size not uncommon in the construction of commercial buildings, would not be possible in most test facilities. We must therefore rely on verification using smaller, testable diaphragms. This raises questions regarding the confidence placed on the verification of a model used in a reliability-based design format. A confidence factor may need to be applied to account for the uncertainty in, or unability to verify, certain geometries, loading cases, or subassembly sizes.

To use a reliability-based design format, limit states must be defined for the subassembly or whole structure, or both. Depending on the type of construction or the loading, failure is determined by either serviceability or ultimate load. Residential construction would probably be limited by serviceability, while commercial construction might be limited only by ultimate load criteria.

The refinement process involves performing sensitivity analyses to evaluate the ability of the model to predict assembly performance at designated limit states. In many cases, this will involve development of failure criteria and assembly checking routines.

Once the model has been shown to give acceptable limit state predictions, it should be used to identify those variables that have the most significant effect on assembly performance. Table 1 shows the relative influence of various component properties on assembly behavior, based upon our review of the literature. The deflection of a floor in bending, for example, is highly dependent on the properties of the joists; however, the lateral deflection of the same floor is influenced little by the properties of the joists.

After the analytical model is refined and all relevant random variables are identitied, variable distributions and interactions must be characterized. It is this portion of the model that may be influenced most by the results of the in-grade test program results. Correlations between lumber modulus of elasticity, specific gravity, and the various lumber strength values are needed to evaluate limit state criteria.

Another important input to this model is the load distribution. While load information has been developed by the American National Standards Institute for full-structure loads, some refinements may be necessary to reflect how full-structure loads are distributed to various subassemblies.

Concluding remarks

At this point, we have a wide range of structural models with which to evaluate the performance of wood structural assemblies. A number of these have been refined to the point where they may be used to perform sensitivity analyses required for the selection of relevant random variables. Our greatest need, however, is to establish the databases for verification of assembly models and characterization of relevant material property distributions and interactions.

Results of the In-grade Testing Program represent a major step toward providing an essential element for development of reliablility-based design models.

TABLE 1. – ***Relative importance of material property variation for components of subassemblies.***

Subassembly	Importance of property variation' Sheathing	Joist and framing	Connections
Floor			
Bending stiffness	L/M	H	M/H
Diaphragm stiffness	L	L	H
Walls			
Bending and compression	L/M	H	M/H
Racking stiffness	L	L	H
Roofs			
Trusses			
Strength	--	H	H
Stiffness	--	H	H
Truss roof systems			
Strength	L	M	M
Stiffness	M	H	L

[a]Levels of importance: L = low; M = medium; H = high.

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