ROLE OF DIAPHRAGMS IN THE MITIGATION OF NATURAL HAZARDS IN LOW-RISE WOOD FRAME BUILDINGS

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ABSTRACT

Diaphragms are components of low-rise wood frame buildings that resist lateral forces due to wind and earthquakes. The main function of these panel type structures is to resist in-plane shear forces and to provide stability to the overall structure. In this paper, the function and construction of wall, floor, and roof diaphragms is discussed.

A better understanding of diaphragm behavior is being realized through analytical studies and experimental testing. However, more research is needed in the development of analysis techniques for roofs and in the dynamic behavior of diaphragms in general.

INTRODUCTION

Low-rise wood frame buildings represent a significant percentage of the buildings constructed in the world and provide shelter for a large population. In the United States, most of the population live in these structures.

Mitigating the adverse effects of natural hazards encountered by wood frame buildings is essential for their safe performance. This is possible only through a better understanding of the components used in wood frame building construction. Components in low-rise wood frame buildings that resist the lateral forces due to wind and earthquakes are diaphragms.

This paper will discuss the function and construction of wall, floor, and roof diaphragms commonly found in low-rise wood frame buildings. Recent research investigating the behavior and performance of these components will also be discussed.

FUNCTION AND CONSTRUCTION OF DIAPHRAGMS

In general, low-rise wood frame buildings constructed in the United States have performed well when subjected to the dynamic forces of wind and earthquakes. Observations made of damage after such events as the 1964 Alaska earthquake (8.6 Richter), Hurricane Camille in 1969, and the 1971 San Fernando (California) Earthquake (6.6 Richter) verify this (13,26,38,39).

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Some of this performance can be attributed to the material characteristics of wood, such as high stiffness-to-weight and high strength-to-weight ratios. The low weight per unit stiffness of wood, compared to other common construction materials such as steel or concrete, results in a smaller inertial response force in a building. This reduces the overall deflection. Most natural hazards produce forces of short duration, and wood has the inherent ability to resist short-duration loads considerably above working stresses. Design codes for wood recognize this by providing a 33% increase in allowable stress for wind and seismic loads (32).

While structural components are commonly thought of as principally supporting vertical dead and live loads, diaphragms also play an important role in resisting the lateral forces due to wind and earthquakes. The main function of these panel type structures is to transmit in-plane shear forces and to provide stability to the overall structure. As an example, Figure 1 shows a distribution of shear forces due to wind to the various diaphragms in a small building.

Inspections after the natural hazards mentioned above indicated that wood diaphragms in various structures performed well when properly designed and constructed. Structural failures were normally due to the inability of these components to act as a unit, or because inadequate provisions were made to resist lateral loads. An important aspect of the current research effort investigating wood diaphragm behavior is the determination of economical material sizes, spacings, and construction configuration9 necessary for safe performance.

The three basic diaphragms (walls, roofs, and floors) found in low-rise wood frame buildings will be discussed next.

Wall Diaphragms

The basic function of a wall diaphragm is to carry lateral loads from the upper stories of the building to the foundation. Wall diaphragms are commonly referred to as "racking walls".

As shown in Figure 2, racking walls are usually constructed with sheathing material nailed to a wood-stud frame. Walls in wood frame buildings are typically 8' (2.4m) in height with a length dictated by the building design. In the United States, nominal 2" x 4" (51 mm x 102 mm) or 2" x 6" (51 mm x 152 mm) studs are used in wall construction. Usually, 4' x 8' (1.2 m x 2.4 m) sheets of plywood (or other manufactured materials) are used for exterior sheathing, while gypsum board (drywall) is used for interiorsheathing.

Current design practice ignores the structural contribution of this interior sheathing material in lateral load resistance. It does, however, exhibit some structural capacity in resisting load. Recent theoretical and experimental research has taken this capacity into account (5,22,37,42).

As a lateral load is applied to a wood frame wall section, the wood stud frame distorts and transfers the load through the nails to the sheathing. The nail joint distortion is nonlinear as shown in Figure 3

(11,12,17). The sheathing remains essentially rectangular due to its high in-plane stiffness.

Floor Diaphragms

Floor diaphragms resist shear forces transferred through the wall components continuously along one edge unlike wall sections that are loaded primarily at floor and roof lines. These diaphragms are typically constructed with nominal 2" x 8" (51 mm x 203 mm) to 2" x 12" (51 mm x 305 mm) joists spaced 16" (406 mm) to 24" (610 mm) on center. One or two layers of sheathing is nailed to the joists. As shown in Figure 4, the long side of the sheathing is generally placed perpendicular to the direction of the joists. Elastomeric adhesives are sometimes used with nails to fasten the sheathing to the joists. This not only increases the stiffness of the joint, but also reduces squeaking in the floor (15).

As a floor diaphragm deflects due to lateral load, the panels tend to distort as shown in Figure 5. Note that the panel edges come in contact as the panels individually rotate. The staggered panel pattern layout allows additional contact not present in the stacked panel configuration. This additional contact helps increase the stiffness of a horizontal diaphragm (3,19).

On the upper story of a wood frame building, the ceiling undergoes diaphragm action much the same way as a floor diaphragm (43). If roof trusses are used in wood frame building construction, the bottom chord of the roof truss will serve as the frame member of the ceiling diaphragm. Gypsum board is used as sheathing material on the bottom side of the roof truss chord. The only difference between a ceiling diaphragm and a floor diaphragm, with respect to diaphragm action, is the frame member size and spacing and sheathing material.

Roof Diaphragms

Though a roof's fundamental function is to shelter a structure from the abuses of weather, it also helps in resisting and distributing lateral loads. Much like floors, roofs resist gravity loads in bending and lateral loads by diaphragm action. In the United States, most roofs in low-rise wood frame buildings are constructed with roof trusses. This truss framed system ties together the roof, ceiling, and walls more efficiently than the traditional rafter system. As a result it may provide greater resistance to seismic motion (40). Observations by Gray (13) of damage due to the San Fernando Earthquake indicate good performance of wood truss roof systems.

As shown in Figure 6, the top chord of the roof truss serves as the framing member of the roof diaphragm. With sheathing (typically plywood) nailed to these top chords, diaphragm action similar to a floor is achieved. The roof diaphragm is tied at the apex of the roof and at the top of the wall section. See Figure 1. Inadequate ties between the wall and roof have proven to be a major cause of damage to wood structures during hurricane winds (38).

RESEARCH

Though conventional wood frame buildings have a history of good performance in resisting the hazardous effects of wind and earthquakes, measuring this performance is a difficult task. Wood structures are typically complex and exhibit a high degree of structural indeterminacy. Complicating this further is the inherent variability of wood material properties.

Recent research on diaphragms in wood frame buildings has been focused on a better understanding of component action. Current design procedures treat the components as acting independently; however, there is definite interaction that is necessary for the stability, strength, and integrity of wood buildings (4,16,40). This independent design approach usually leads to a safe design, but often a design that is overly conservative. Quantifying this factor of safety designed into our wood buildings requires a more complete understanding of its structural behavior.

Research in Wall Diaphragms

Early efforts in predicting the effects of lateral load on wall sections were for the most part experimental in nature and yielded empirical equations relating racking strength to results of lateral wall tests (34,44).

More recently, researchers have developed mathematical models for the analysis of these structures (7,10,17,18,22 – 25,41,42). Some of these models are based upon observed distortion patterns of racking walls in the laboratory (7,42). Tuomi and McCutcheon in 1978 (42) assumed a parallelogram frame distortion pattern to derive an energy equation for calculating the racking strength of framed panels. Itani et al. (18) in 1982 applied this theory to develop a simplified model using equivalent diagonal springs that would allow complicated wall configurations to be analyzed.

More recent models have begun to take into account the nonlinear load-slip behavior of nail joints (5,7,17,25,29). See Figure 3. Single nail coupon tests are performed to determine the load-slip properties of various fastener/sheathing combinations (11,22,37).

A great deal of experimental testing has been performed on wall sections. These tests have been performed not only to verify mathematical models, but to assist the wood industry in the evaluation of product performance (9,27,30).

Until the 1940's conventional wood frame buildings used diagonal bracing or board sheathing for lateral load resistance. In 1949, guidelines were issued by the Federal Housing Administration for acceptance of panel sheathing to be used for shear resistance. These guidelines form the basis of standard tests used in this area (1).

Relatively little diaphragm research has been performed, either analytically or experimentally, for dynamic loading. While there is

considerable information regarding the general theory of dynamic analysis, knowledge about dynamic properties of wood diaphragms is limited. Damping is known to significantly affect seismic response in a wood frame structure.
A major factor in the dynamic performance of wood buildings is due to the absorbtion of large amounts of energy by wood joints. Various studies report equivalent damping ratios of such structures varying from 4% – 20% (6).

Difficulties arise in the dynamic modeling and testing of wood structures. Reasons for this are the generally complex dynamic behavior of structures, large material variability in wood, and nonlinear behavior of components and connections (36).

Cheung and Itani (5) in 1983 presented a finite element model to predict the static and dynamic load-deflection behavior of nailed shear walls. A joint element representing the nailed joints was derived using nonlinear nail load-slip properties. Compared to experimental tests, good results were obtained.

Ongoing research at Washington State University involves the development of a simplified analytical model to predict the response of a wall section of any configuration, with or without openings, and subject to static or dynamic loads. This model allows nonlinear load-slip behavior of the nails. Full-scale dynamic tests of wood walls will be conducted.

Research in Floor Diaphragms.

Much of the research effort on the behavior of floor diaphragms in the recent past has been directed toward floor bending. As a result, specific research on floor diaphragms under the influence of lateral loads is somewhat limited (3,5,8,12).

As in the modeling of walls, the analytical modeling of floors must take into account the interactions of the sheathing, frame or joist members, and the nail fasteners. Complicating this is the tendency for the sheathing of the floor diaphragms to contact, increasing the stiffness of the floor. See Figure 5.

In 1979, a workshop on the "Design of Horizontal Wood Diaphragms" was conducted by the Applied Technology Council (2). Participants evaluated available technical information and established priorities of research needs in the area of horizontal wood diaphragms.

Discussion of the materials used in horizontal diaphragm construction, as well as common design criteria and analysis methods, were included. Jephcott and Dewdney (20) concluded that the performance of nail joints govern the strength of a horizontal diaphragm and that the anchorage between the roof and walls govern the strength of the whole structure.

In 1977, Foschi (10) modeled diaphragm action using finite element techniques. Joists were modeled using plane frame elements with good results. A lumped parameters model was developed by Ewing, et al. (8) in 1980 to analyze the static and dynamic behavior of floor diaphragms. This model is intended to simplify a typically complex analysis.

Full-scale testing of floor diaphragms was performed by Atherton in 1981 (3). He conducted cyclic static tests on several 16' x 48' (4.9 m x 14.6 m) floor diaphragms with waferboard and particleboard sheathing. It was concluded that no significant increase in stiffness or ultimate load resulted from increasing nail size from 8d to 10d. However, increasing panel thickness from 7/16" (11 mm) to 5/8" (16 mm) or increasing the number of nails was shown to increase strength and stiffness. Staggered panel patterns were found to be slightly stiffer than stacked patterns at ultimate loads. It was concluded that load cycling had no effect on the ultimate strength of the diaphragm.

GangaRao (12) performed dynamic tests on full-scale 16' x 24' (4.9m x 7.3m) floor diaphragms. It was found that the behavior and failure patterns were about the same for dynamic or static loads, however, the ultimate load capacity of a dynamically loaded diaphragm was reduced by about 50% when compared to ultimate static load.

Current research at Washington State University involves the analytical modeling and experimental testing of full-scale floor diaphragms subject to static and dynamic loads. Variable panel arrangement, fastener type and spacing, and material properties are accounted for in the analytical model. Experimental testing includes dynamic testing of floor diaphragms of various aspect ratios.

Research in Roof Diaphragms

Compared to walls and floors, roof diaphragms have achieved the least amount of research attention. This is understandable since the behavior of a roof diaphragm is similar to that of a floor diaphragm. An understanding of roof behavior should be a natural progression once floor behavior is understood.

To date, specific research on roof diaphragms has been limited to experimental testing (16,21,28,45). In the early 1970's, Johnson (21) and Zahn (45) tested roof diaphragms sheathing with lumber decking. It was found that the addition of adhesives greatly increased the lateral load resistance. In 1982, Mayo (28) performed roof tests constructed with roof trusses, where the lateral stability of the roof with different bracing systems in the plane of the rafter were assessed.

Future Research Needs

In October 1983, a Structural Wood Research Workshop was held to define areas of research needed in structural wood (33):

With respect to wall diaphragms, it was concluded that research is needed to develop simplified analysis and design methods. This development would make usable to code agencies and design engineers the results of current research.

With respect to floors, there is need for experimental and analytical studies of systems with openings.

Since little research has been performed in the past on roof diaphragms, development of an analysis technique is required. This may involve the use of existing diaphragm models. Testing of full-size roof systems is also recommended.

CONCLUSIONS

Diaphragms play an important role in resisting the lateral forces due to wind and earthquakes. Though these components have generally performed well when subject to the dynamic affects of natural hazards, continued research into their behavior will yield information necessary for designs that are safe, yet economical.

ACKNOWLEDGMENT

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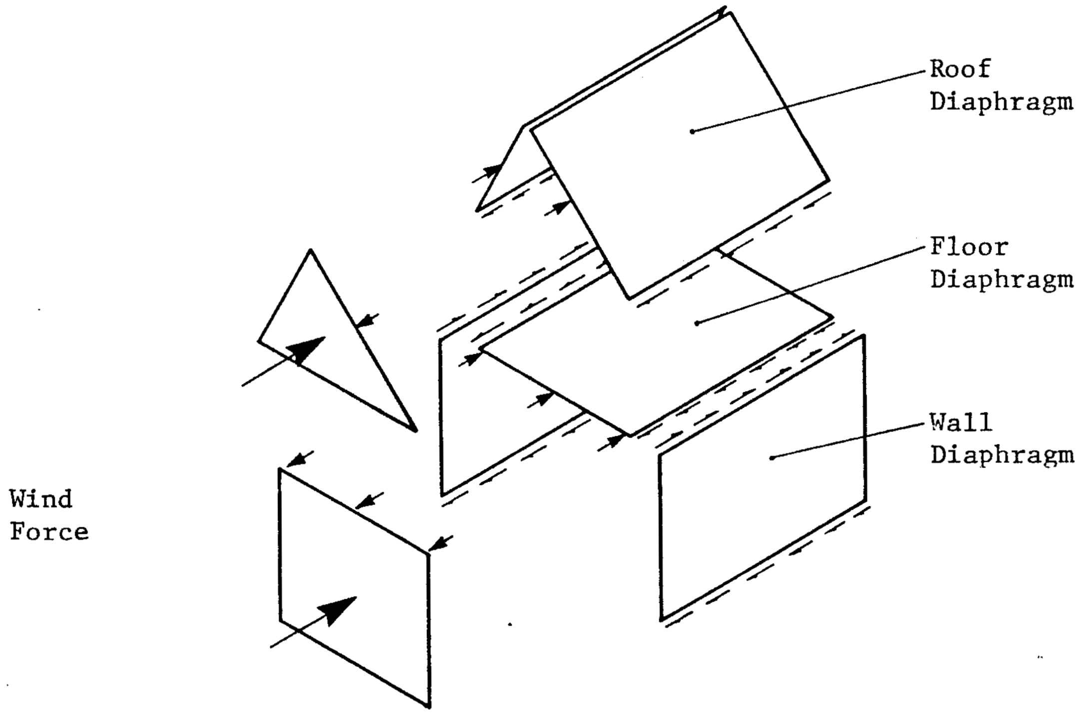


Figure 1

Distribution of Lateral Forces due to Wind
in a Wood Frame Building

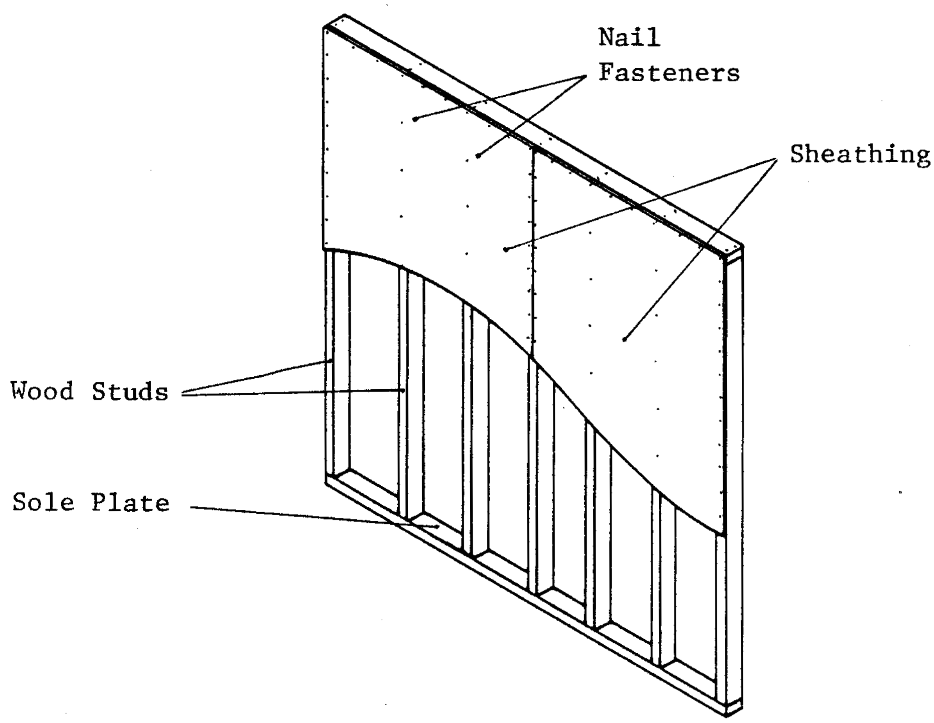


Figure 2

Typical Wall Diaphragm

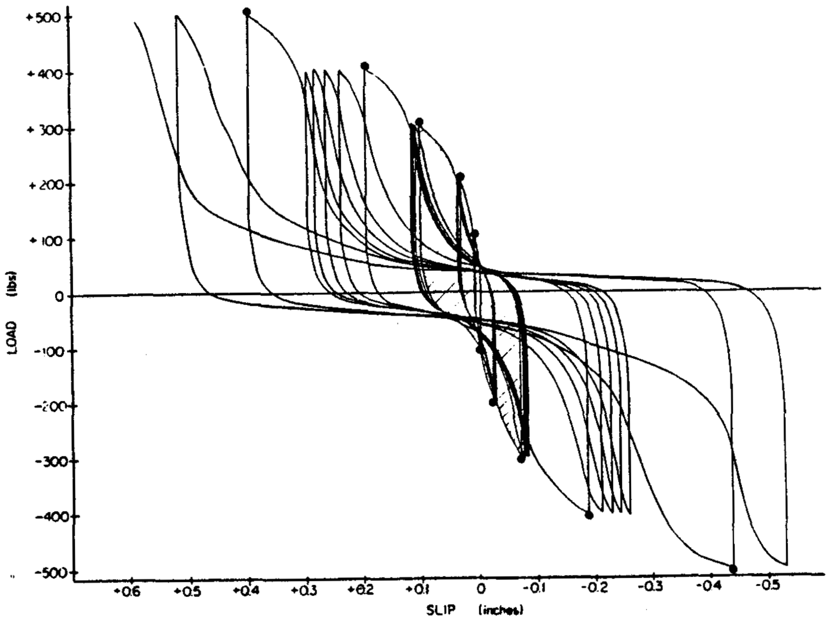


Figure 3

Nonlinear Load – Slip Curve of Fastener
Due to Load Cycling

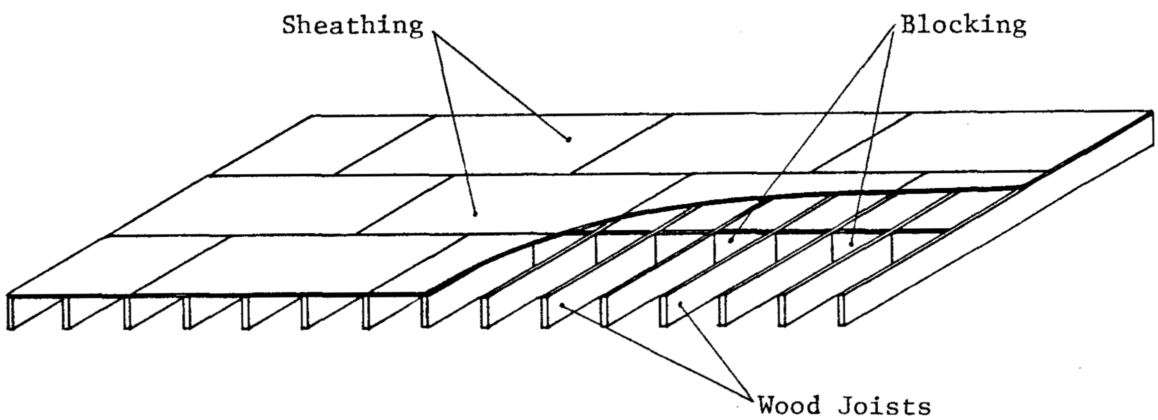
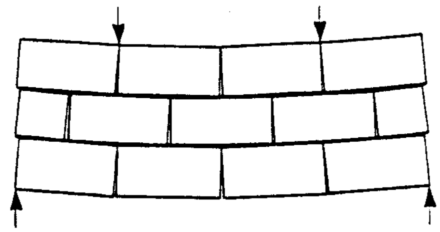
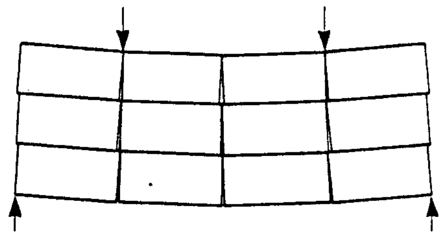


Figure 4

Typical Floor Diaphragm



(a) Staggered Sheathing



(b) Stacked Sheathing

Figure 5
Typical Sheathing Arrangements for Floor Diaphragms

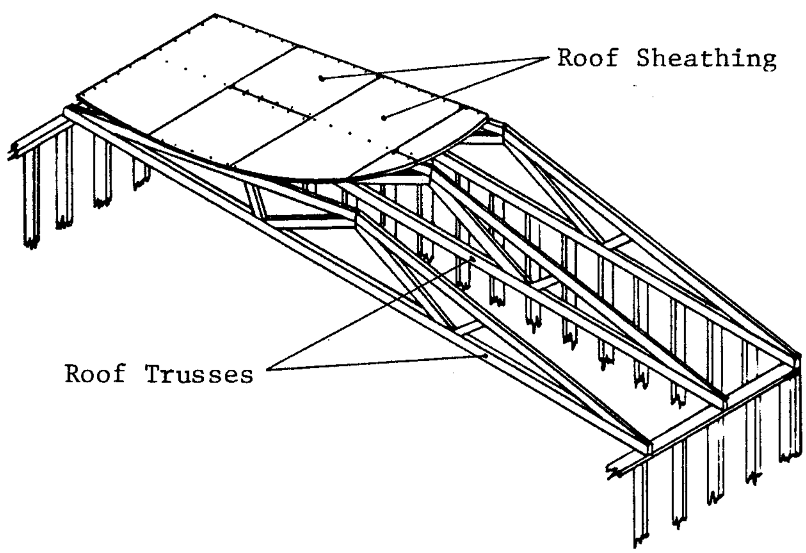


Figure 6
Typical Roof System

In: Role of Diaphragms in the Mitigation of Natural Hazards in Low-rise Wood-Framed Buildings, Falk, R.H.; Cheung, C.K.; R.Y. Itani; 1984 Proceedings of the CIB-W73 International Conference on Natural Hazards Mitigation, October, New Delhi, India.
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