Effects of Roof Pitch and Gypsum Ceilings on the Behavior of Wood Roof Diaphragms

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Abstract: Ten full-size (3.7 × 4.9 m) plywood roof diaphragms were constructed using metal-plate-connected (MPC) common and hip wood trusses or joists, typical of single-family dwelling (SFD) construction. The specimens included three gable roof slopes of 33, 67, and 100%, a hip roof of 33% slope, and a flat roof, with a horizontal bottom chord. These roofs were constructed and tested in duplicate to make the total of 10 roofs. Gable and hip roofs were tested with plywood sheathing applied to the eaves, with plywood sheathing removed from the eaves, and with a gypsum ceiling attached to the bottom chord of the trusses. Roofs were tested following standard procedures and analysis. Results showed eave plywood had a negligible effect on diaphragm apparent stiffness; pitch affected gable roof apparent stiffness significantly but did not affect gable roof strength; hip roofs had almost the same apparent stiffness as flat roofs and had the same strength as flat roofs; gable roofs had apparent stiffnesses that were about 50% that of the flat roofs; and gypsum provided more than one-third of the total roof apparent stiffness at slopes of less than 33%. There was no effect of pitch on roof strength in any configuration; all roofs exhibited approximately the same shear strength. Failure modes of roofs included nail withdrawal, nail tear-through, metal plate tear-out on trusses, and chord tensile failure. **DOI: 10.1061/(ASCE)CF.1943-5509.0000490.** *© 2014 American Society of Civil Engineers.*

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Introduction

Wood-frame structures make up about 90% of the low-rise multi-family or single-family-dwellings (SFD) in North America (Ni et al. 2010). Most SFDs have sloped or pitched roofs, yet there has been limited study of pitched wood roof diaphragms in the United States to date, and few wood roof diaphragm tests performed for sheathing attached to metal-plate-connected (MPC) wood trusses. Gypsum sheathing has been studied for use in shear walls, and design values are provided in various references. But few studies have included gypsum ceilings on MPC trusses as part of a pitched wood roof diaphragm, and there are no design values for gypsum horizontal diaphragms in the present U.S. code documents. Wood diaphragms with nonplanar sheathing (such as gable or hip roofs) have only been studied on relatively low slope roofs, less than 33% slope, but current preferences in SFD design commonly use slopes greater than 33%.

This paper will refer to roof slope as a percent or fraction of vertical rise for each unit of horizontal travel. Pitches express the slope in units of rise (height) per unit of run (horizontal travel). A slope of 0.33 (or 33%) might be expressed as a ratio, 33:100 (4:12), using SI or U.S. customary units.

This study compares the apparent stiffnesses of 33, 67, and 100% (4:12, 8:12, and 12:12) pitched gable roofs and 33% (4:12) pitched hip roofs with that of flat roofs (0% or 0:12) which have been traditionally tested.

A substantial review of the roof diaphragm experimental literature was performed by Kirkham et al. (2014) in an examination of the "state of the art" in seismic design and testing of SFDs. The research relating to wood horizontal diaphragms will be briefly summarized here.

Substantial experimentation on wood diaphragms occurred during a period from 1950 to the early 1970s. These experiments were primarily to test different systems using plywood as sheathing. Most of the tests used large, flat diaphragms, loaded horizontally as a simply supported beam to determine maximum loads and the corresponding deflections. These studies were done by the Douglas Fir Plywood Association (Countryman 1952; Countryman and Colbenson 1954), at Oregon State University (Johnson 1955a, b, c; Johnson and Burrows 1956; Johnson 1956, 1968, 1971, 1972, 1974, 1979), and by the APA (Tissell 1967; Tissell and Rose 1993; Tissell and Elliott 2000, 2004). Countryman (1952) notes that their study was the first and only study of plywood roof diaphragms known to them, so it is unlikely that there was any research on plywood diaphragms before that year.

Concerns about the effectiveness or contribution of gypsum ceiling panels led to tests by Alsmarker (1991) and Walker and Gonano (1984), both occurring outside the United States. Their results do not appear to have been considered in the U.S. building codes.

Before 1988, the experiment programs tended to use static loading, while more recent testing has involved some dynamic loading (Kamiya and Itani 1998; Bott 2005).

Overall, few experimental programs have examined the effect of different roof geometries (hip versus gable, for example), roof pitch, or the use of light-framed MPC for seismic resistance. Most of the testing programs have used static or linearly increasing loading protocols.

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Between 1983 and 1995, substantial research into postframe construction was performed. The experiments with pitched, corrugated steel roofs on heavy wood trusses led to development of a strength reduction factor based on roof pitch (Gebremedhin et al. 1986). Steeper roofs were determined to be less rigid and have lower lateral load resisting capacity than roofs constructed at a shallower pitch.

Research Goals

There has been a shift in the goals of research related to wood roof diaphragms over the recent decades. In the initial experiments conducted in the period from 1950 to 1990, tests were performed on specific building components to determine reasonable design strengths or the "allowable loads" for that component. Factors of safety (FS) were applied to ultimate failure loads to determine reasonable allowable design loads. This is consistent with the building code goal of life safety. In later experiments, tests of whole houses became the focus, but results were difficult to express as an allowable load. Results tended to be expressed as allowable story drift ratios.

Recent experiments testing full-scale SFDs have concentrated on damage to nonstructural finishes. Shake tables used in these experiments provide a platform that can be programmed to simulate earthquake motions. The rapidly varying accelerations that shake tables provide make force evaluation difficult. In shake table testing, it is rare to see a report that indicates design loads for components. The connection between life safety based on strength or allowable stresses and damage to nonstructural finishes based on applied ground accelerations is unclear. It is not easy to apply these data to present design methods. The change in focus is partially due to an increased interest in performance-based design (PBD) as well as emphasis of the insurance industry on reducing losses. Many SFDs in recent earthquakes have been considered total losses by the insurer even though the structure was considered safely habitable by the city building inspectors.

An important goal of this study was to better understand the performance of roof structures, with respect to diaphragm stiffness. Building deflections have a significant effect on the performance of nonstructural finishes. A flexible diaphragm may result in higher damage than more rigid diaphragms.

These were the major objectives of this study:

- Determine whether roof pitch had any effect on roof diaphragm apparent stiffness or strength.
- Determine whether hip roofs had the same strength and apparent stiffness as gable roofs of the same pitch.
- Determine whether roof diaphragm strength or apparent stiffness was increased by the application of gypsum ceiling, and how differing roof pitches affect this apparent stiffness.
- Determine how effective roof eave sheathing was when compared with the remainder of the sheathing.

Materials and Methods

ASTM E455 describes the testing of full roof diaphragms, either tested as a simply supported beam or as a cantilevered beam fully fixed at one end.

Data Collection

Data from the sensors were sampled once per second by a PC-compatible computer running *LabVIEW 8.6*. Data were collected from 11 channels during the course of each experiment.

An LCD display next to the computer, by the hydraulic controls, showed the raw load-deflection curve for the specimen that was being tested. This real-time feedback allowed the operator to determine when elastic tests had reached the limit of the elastic region, so a test could be terminated before significant damage occurred to the specimen. During the inelastic tests, observing the load-deflection curve gave the operator a method of determining when localized and overall failures were occurring in the test, and provided some warning when the test was reaching maximum values.

Test Specimens

Five different full-size (3.7 × 4.9 m) plywood roof diaphragms were constructed in duplicate from new materials. The configurations included three gable roof slopes of 33, 67, and 100%, a hip roof of 33% slope, and a flat roof as a reference. The gable and hip roofs were constructed using MPC common wood trusses with 38 × 89-mm members, typical of SFD construction. The common wood trusses were queen-post or fan trusses for the gable roofs and hip roofs, with a step-down truss and jack trusses to complete the hip roof. The flat roofs were constructed using 38 × 140-mm joists to act as references and for comparison to previously reported experiments by others. The bottom of the chords or joists lie in the same plane, so there is no effect of pitch on a gypsum ceiling if one is provided.

Diaphragm sheathing was 12-mm-thick type CD Exposure 1, species Group 4, APA Rated 32/16 nailed with 8d machine nails, 60 × 2.9 mm, 102 mm on center (o.c.) at the edges, and 208 mm at intermediate supports. "Bird blocking" was cut from 38 × 140-mm material and nailed between the trusses at the eaves with 8d machine nails, 60 × 2.9 mm. There was no other blocking in the diaphragm. The sheathing was not nailed to the eave or ridge blocking. The nailing was performed according to Table 2304.9.1 of the 2012 International Building Code (International Code Council 2011), Items 10, 11, 13, and 31 with footnote *n*, using Stanley/Bostich and Senco machine nailers. Machine nails are smaller in diameter than common nails and some adjustment needs to be made for their use in these diaphragms. Typical 8d common nails, (3.33-mm diameter) would have been used at 152-mm o.c. Footnote *n* reduces the spacing of 2.9-mm-diameter nails to 102-mm o.c., which is basically three nails per 305 mm instead of two nails per 305 mm. In ICC ESR-1539 (ICC Evaluation Service 2011), Table 10, 8d common nails 3.33-mm diameter at 152-mm o.c. have an allowable shear of 3.87 N/mmand 8d machine nails (2.9-mm diameter) at 152 mm o.c. have an allowable shear of 4.01 N/mm, a difference of slightly less than 4%. The statement of equivalence also occurs in Table 27 (ICC Evaluation Service 2011). Therefore, the reduced nail spacing of the machine nails is comparable to the common nails specified in the 2006 International Building Code.

Trusses were manufactured locally and designed by a licensed professional engineer. The top and bottom chords of all trusses were 38 × 89-mm DF-L #1. Trusses were fabricated with tails that were 407-mm long, measured horizontally. Trusses were connected to the double top plates with Simpson Strong-Tie H1 hurricane clips. The H1 clips were hand nailed with Simpson 10d short nails. Blocking was cut to length, fit between the trusses, and machine nailed with 10d (3.3-mm-diameter) nails per international building code (IBC). Measurements for moisture content were made with a capacitive moisture meter for all sheets of plywood, gypsum, wood members, and the trusses. Moisture content of the wood materials measured between 5 and 10% for all tests during this project.

Eaves were added to the basic roof structure by nailing sheets of plywood with a width sufficient to cover the distance between the

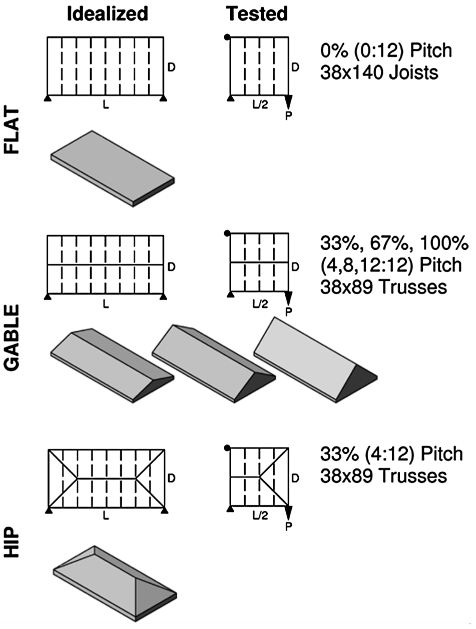


Fig. 1. Test specimens

top plates and blocking and the midpoint of the facia boards. Nailing was of the same size and spacing as the basic roof structure sheathing. Facia boards were 38 × 140-mm material and nailed to each truss end with (2) 16d (3.4-mm-diameter) nails. Sheathing was cut to fit the eave extensions. Eave sheathing was nailed to the trusses only with the same nails and nail pattern as the principle sheathing.

Gypsum 12-mm thick was attached to the underside of the wood trusses with 32-mm-type W bugle head drywall screws spaced 305-mm o.c. The edges of the sheets which could bear on other gypsum sheets (interior edges) were installed snug tight, but a gap of up to 12 mm was permitted at the top plates on the perimeter.

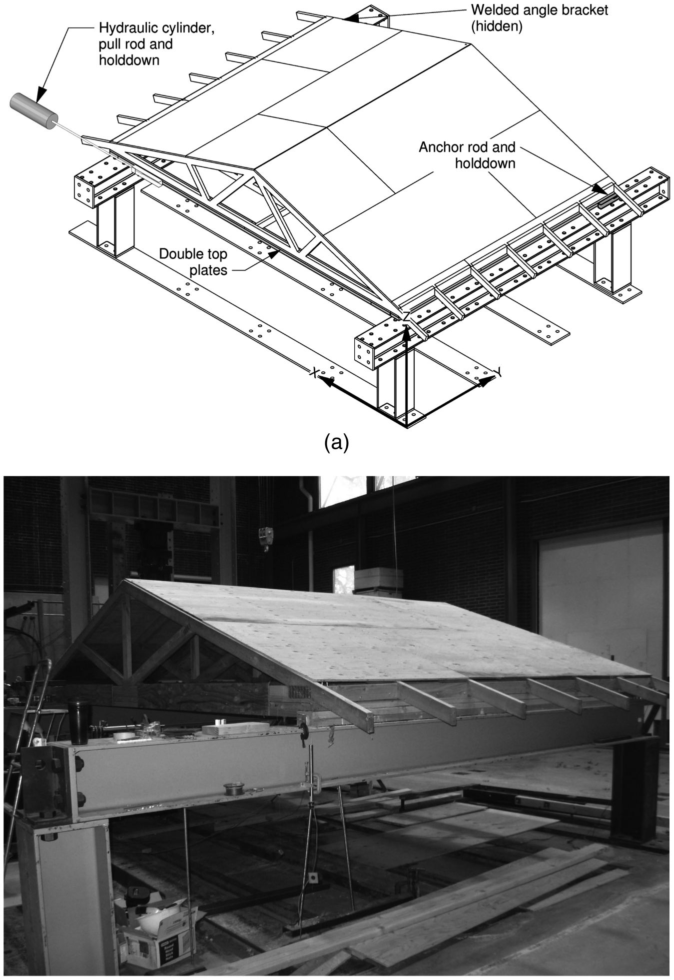
See Fig. 1 for a graphic explanation of all the roof configurations and Figs. 2(a and b) showing the testing equipment setup.

These experiments examine the system from the double top plates of a typical SFD, to the pitched plywood diaphragm. This is more representative of the actual construction of a SFD than the large, flat roof diaphragms previously examined.

Test Procedures

Test procedures were based on ASTM E455 (ASTM 2011). There were three experiment series for each constructed roof.

The first series is elastic with eaves. Eave plywood and facia boards were attached to the trusses. The elastic test series (with eaves and without eaves) was repeatedly loaded to a deflection of approximately 30 mm (1-1/4 in.), and then the load was removed. After allowing the roof structure to relax, the elastic test was repeated three to six times to obtain consistent performance. This ensured that elastic behavior was observed for both series. The maximum loads during the elastic tests are not relevant to the performance of the system and do not indicate the strengths of the system. These loads indicate only the maximum loads that were applied while remaining in the elastic range. In order to measure roof apparent stiffness in these elastic tests, a sufficient series of data points was needed to permit calculation of the apparent stiffness or slope of the experiment trace. Each elastic test trace ends at approximately the beginning of the reduction in apparent stiffness of the inelastic tests, plus, little if any curvature is observable at the upper limits of the elastic tests.



(a)

(b)

Fig. 2. Test rig diagram and 33% (4:12) test sample without eaves: (a) isometric view; (b) photo of test rig

The second series was elastic without eaves. Eave plywood and facia boards were removed from the trusses. Elastic tests were performed as in the preceding section.

The third series was inelastic with gypsum ceiling. After the gypsum ceiling was installed, load was applied until the roof had clearly failed. This was typically when some portion of the structure ruptured or until the load-deflection curve had peaked and was declining. There were two inelastic tests performed for each configuration of roof. These tests were performed once for each configuration, because the result of the test is a seriously damaged roof.

Data Analysis

The equations in ASTM E455 (ASTM 2011) were used to adjust the data to determine the apparent stiffness, G_a, which is adjusted for the diaphragm dimensions to obtain a unit shear value that can be used for design; the ultimate shear strength, S_u; and the adjusted displacement. The apparent stiffness, G_a, is useful where it is necessary to make comparisons to building codes or standards, when values are needed to demonstrate design principles. The adjusted displacement removes the effect of minor changes in position of the roof structure that occurs during the test.

Test Results

Wood roof systems involve the interaction of a number of members or components acting in multiple planes. There are so many connections and components in a roof system that it is very difficult to track all the forces. The stiffness and consequent deformations of members and their connections affect the portion of the applied load that is distributed to any member.

The framework of joists or trusses, plates, blocking, and braces support the roof sheathing. The framework design typically does not resist moments in any of the connections, but instead, the shear resistance of the sheathing when attached to the framework provides the lateral resistance of the assembled roof. The idealized test framework is assumed not to deflect in a manner that would reduce the sheathing apparent stiffness.

The early roof diaphragm experiments evaluated the stiffness of the plywood as nailed to a substantial supporting framework and blocking. In some cases, these roofs were constructed by nailing plywood to tongue-and-groove decking. The blocking and framework did not resist moments but were sufficiently stiff to ensure that weak-axis deformation of the framework members was not a factor in the experiments.

This paper examines the complete roof system including the double top plates of a typical SFD as well as the pitched plywood diaphragm and supporting structure. This is more representative of the actual construction of a SFD than the large, flat roof diaphragms in historic references. The apparent stiffness values from this paper directly show the apparent stiffness of the complete roof structure in a horizontal plane, rather than the plywood sheathing stiffness alone.

All elastic tests for a 33% pitch gable roof and all of the inelastic tests for flat roofs are plotted in Fig. 3. Fig. 3(a) shows a primarily linear response over the range of deformation shown, and comparison of Fig. 3(a) with Fig. 3(b) shows that deflections of 30 mm or less are within the elastic range for the tested structure.

In Fig. 3(a), the apparent stiffness is shown by the slope of each test. The average slope of the roof with and without eave plywood can be calculated, and the average increase in apparent stiffness from the eave plywood is 6.67%. Examining the slope of tests with and without the addition of gypsum ceiling showed that the gypsum board increased the apparent stiffness 25%, on average.

In this brief example, it can be seen that eave plywood adds some stiffness to the structure, but the added value is small. Gypsum added significant stiffness even in the configuration which was most advantageous to the plywood sheathing. Additional and more detailed calculations are provided in the following sections of this paper.

Overall, the inelastic tests show an increased apparent stiffness varying from 2.51 to 36.6%, due to the addition of the gypsum ceiling. These tests also demonstrate that the elastic tests were performed within the elastic range of the roof system. Fig. 3(a) shows only the elastic tests at a different scale for better examination.

For each system, the slopes of all the elastic load-deflection plots for the roof with or without eaves appear similar. Some have shifted right slightly due to the test framework adjusting as the test series proceeded. Though eave plywood provides a few percent increase in apparent stiffness of the roof, it is clearly limited in usefulness as shown in Fig. 3(a). There is more variation [13.7% coefficient of variation (COV)] due to individual roof construction than the 13.6% increase due to the addition of eave plywood (Table 1).

For three of the gable roof tests, one for each different pitch, an error in coding of the data acquisition system caused the higher loads to be omitted in some of the inelastic tests. This was caused by an incorrect scaling factor that provided high resolution for individual load points but resulted in the amplifiers saturating (or limiting out) before the roof actually reached maximum load. Nevertheless, the initial values are similar and provide information about the elastic phase of the experiment. Further, the data show the effect of the gypsum ceiling used in all the inelastic tests. The only data lost were the maximum load and deflection on those three test duplicates.

In subsequent sections, it should be noted the empirical equations are only from the size and setup tested here, other types and connection details will likely have a different formula. Different experimental layouts, materials, and constraints will likely produce different results. Correlation equations that follow should be applied only where the conditions are similar and using good engineering judgment.

Comparing Elastic Stiffnesses with Differing Roof Pitches

To examine the effect of differing roof pitches on the elastic apparent stiffness of the roof diaphragms (Fig. 4). It is reasonable to expect differences due to geometric considerations. A flat roof has joists that are solid members that may support both the gypsum ceiling and the roof sheathing. In a flat roof, the sheathing lies all in a plane, parallel to the applied shear load from the structure, and being in one plane together, the individual sheets of sheathing

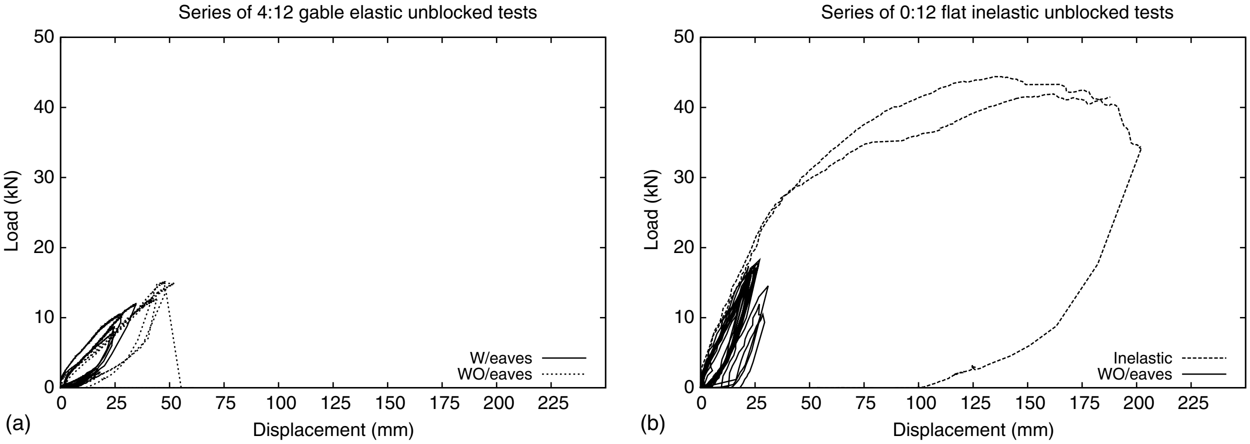


Fig. 3. Examples of load-deflection curves for individual tests: (a) 33% gable elastic; (b) 0% flat inelastic

Table 1. Comparison of Roof Diaphragm Stiffness with and without Eave Sheathing

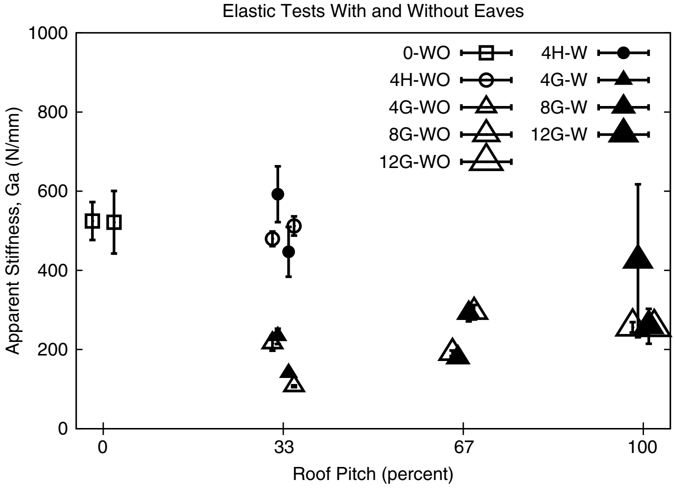
		Without eaves and gypsum			With eaves and without gypsum			
Shape	Pitch (%)	Apparent stiffness (N/mm)	Standard deviation (N/mm)	20% limit	Apparent stiffness (N/mm)	Standard deviation (N/mm)	20% limit	Change of stiffness (Δ%)
Hip	33	512.2	24.2	102.4	446.8	62.9	89.35	−12.8
Hip	33	479.7	18.5	95.93	592.3	70.5	118.5	23.5
Flat[a]	0	524.6	47.9	104.9	(No flat roof tests with eaves)			
Flat[a]	0	521.6	79.0	104.3				
4:12 Gable	33	215.7	18.6	43.15	233.2	19.5	46.64	8.10
4:12 Gable[b]	33	107.3	2.322	21.47	140.1	5.94	28.03	30.5
8:12 Gable	66	190.5	7.011	38.10	178.4	8.81	35.67	−6.38
8:12 Gable	66	294.1	18.3	58.82	290.8	19.7	58.16	−1.12
12:12 Gable[c]	100	256.0	13.1	51.19	424.1	193.2	84.81	65.7
12:12 Gable	100	254.7	4.39	50.94	258.7	44.0	51.74	1.57
		Average COV	6.04%		Average COV	14.1%	Average	13.6%
						Average without outliers		2.15%

[a] Flat roofs were not tested with eaves. "Without eave" data are duplicated for comparison.

[b] Line deleted because data acquisition system was out of calibration on test without eaves. Treated as outlier.

[c] High standard deviation suggests this line is not valid data. Any tests with standard deviation exceeding 20% of the tested value were excluded.

will bear on each other during diaphragm shear across the complete surface. A pitched roof composed of MPC common trusses has a top chord that is fastened to the roof sheathing, and a horizontal lower chord that is optionally attached to a gypsum ceiling. The flat roof joists have some mechanical restraint on the limits of their weak-axis deflection, because the joists are attached to both sheathing surfaces. Trusses have top and bottom chords that are seldom attached to the same sheathing or surface material. The joist experiences forces on the top and bottom from the different surfaces, but the truss has little ability to transfer weak-axis forces between the top and bottom chord. In addition, the sheathing of a pitched roof lies in different planes, due to the pitch. The planes of the sheathing are not parallel to the applied shear loads from the structure, and the two planes are free to move independently and do not transfer shear forces by impinging on each other as in a flat roof diaphragm.



Legend is coded as follows: {n}{H or G}, where,
n – Pitch as n:12
H/G – for Hip or Gable (no letter for flat roof)
W/WO - With or WithOut eaves
Thus a 100% (12:12) pitch Gable WithOut eaves is 12G-WO

Fig. 4. Elastic tests with and without eaves

As shown in Fig. 4, hip and flat roof configurations have similar apparent stiffnesses that are greater than the apparent stiffnesses of gable roof systems, in general, for similar pitches. Also, gable roof apparent stiffness appears to be as low as half of the apparent stiffness of flat or hip roofs. Hip roofs use approximately the same quantity of sheathing material as flat roofs. The primary difference between hip and gable roofs is the pitched sheathing at the diaphragm ends. It seems likely that having this pitched sheathing acts to restrain any torsion in the trusses, causing hip roofs to have similar stiffness properties to flat roofs. (Refer also to the section "Torsion on Gable Trusses.")

Gable roof diaphragms show increasing apparent stiffness with increasing pitch from 33 to 100%. This seems counterintuitive. The effect of increasing pitch is to move the shear resisting the plywood diaphragm web increasingly out of plane with respect to the applied force. This appears to be partially counteracted by other effects. As plywood is nailed at "100 mm on-center," and the roof pitch increases, the distance between nails decreases when projected onto the horizontal plane. That is, a 100-mm nail spacing measured parallel to the plywood surface on a 100% (12:12) pitch roof results in a nail spacing of 71-mm apart when measured on the projected plane beneath. Then 100 mm/71 mm = 1.41, or a 40% increase in nails along each top truss chord. Further, though the projected area of the plywood on the 100% (12:12) pitch roof is no different than the projected area of plywood on the 0% (0:12) pitch roof, there is more plywood used in construction of the 100% pitch roof and the projected thickness of 17 mm is also 1.41 or 40% greater than that of the flat roof at 12 mm. This increased projected thickness increases with pitch. Thus, the apparent stiffness increases with increasing pitch on the gable roofs. There may be other effects of geometry that are important here, but it is sufficient for this paper to show that the loss of efficiency in resisting applied shear can be counteracted to some extent by geometrical factors that also result from the increased pitch.

The analysis of the elastic test data for gable roof apparent stiffness, both with and without eave plywood, as a function of pitch indicates that a linear equation fit to the data is about as good a predictor of apparent stiffness as any higher-order curve. This correlation applies only for roof pitches between 33 (4:12) and 100% (12:12):

$$G_a = 109.9x + 180.5 \tag{1}$$

where G_a = expected apparent stiffness (N/mm); and x = pitch as a ratio of rise over a horizontal distance (e.g., 4:12 pitch would be $x = 4/12 = 0.33$).

This can also be expressed as a pitch reduction factor, but dividing Eq. (1) by the average apparent stiffness of the flat roofs:

$$\Delta_{Ga} = G_{a\text{-gable}}/G_{a\text{-flat}} = (109.9x + 180.5)/(523.1) = 0.21x + 0.35 \tag{2}$$

So a gable roof with a pitch of 0.33 would be 0.419 times as stiff as a flat roof of the same size. Again, this correlation applies only for roof pitches between 33 (4:12) and 100% (12:12).

Comparing Elastic Stiffnesses with and without Gypsum Ceilings

Elastic tests without eaves or gypsum can be compared to the elastic range tests of the roofs with gypsum and without eaves. Though these tests with gypsum were inelastic, the elastic behavior remains a portion of the inelastic tests at low levels of deflection. Therefore, the elastic range can be extracted from the load-deflection curve for use in this comparison as shown in Table 2.

All roofs showed an increase in apparent stiffness when a gypsum ceiling was installed on the bottom truss chord. The least increase is for flat roofs, averaging 2.5%. This is not surprising because the plane of the plywood and the plane of the gypsum are parallel. If the top sheathing lies within the plane where the force is applied and the resistance is required, the top wood composite sheathing (plywood in this case) should have higher stiffness than the lower gypsum sheathing. If the top sheathing occurs in the plane at a pitch to that where the force is applied and the resistance is required, the sheathing (gypsum drywall in this case) should have the higher stiffness.

Hip roofs were about 3.6% less stiff than flat roofs tested without gypsum. When gypsum was added, only a negligible improvement occurred with the flat roof (2.51%). When gypsum was added to the hip roof, the apparent stiffness increased 21.4% compared to the hip roof without gypsum. This significant increase in apparent stiffness of the hip roofs tested with gypsum resulted in the hip roof with gypsum being about 12.3% stiffer than the flat roofs tested with gypsum.

For gable roofs only, increased apparent stiffness from adding gypsum in individual tests is about 13.0–59.4%, averaging 32%. The least increase is for the highest-pitched gable roofs.

Increasing gable roof pitch continues to result in increased horizontal diaphragm apparent stiffness. Analyzing the apparent stiffness values versus pitch indicates that a linear equation fit to the data is about as good a predictor of apparent stiffness as any higher-order curve. This correlation applies only for roof pitches between 33 (4:12) and 100% (12:12):

$$G_a = 44.01x + 284.3 \tag{3}$$

where G_a = expected apparent stiffness (N/mm); and x = pitch as a ratio of rise over a horizontal distance (e.g., 4:12 pitch would be $x = 4/12 = 0.33$).

Gable roof systems are about half as stiff as flat or hip roof systems, and gable roof systems increase in apparent stiffness with increasing pitch within the range of 33–100% pitch. Shown in Fig. 5 is a graphic comparison of the effects of adding gypsum.

Gable roofs showed increases in apparent stiffness of 27–37% with the addition of a gypsum ceiling, with the lowest pitch showing the highest increase. The higher increase in apparent stiffness at low pitch is not the result of any change in gypsum configuration or application. The gypsum ceiling is identical in all gable tests in all aspects. The reason for the higher increase in apparent stiffness of the gypsum ceiling is due to the lower relative (effective) stiffness of the plywood sheathing due to its differing pitch. There can be no real increase in gypsum ceiling stiffness because all ceilings are identical in construction; therefore, the contribution of the gypsum to the diaphragm apparent stiffness is the same in all configurations. It is only the reduced stiffness of the plywood that makes the gypsum contribution to the overall apparent stiffness appear higher.

Analyzing the increase in apparent stiffness values for gable roofs versus pitch with the addition of gypsum indicates that a

Table 2. Comparing Apparent Diaphragm Stiffness with and without Gypsum Ceiling

		Without gypsum					With gypsum					
		Apparent stiffness by roof			Apparent stiffness by pitch		Apparent stiffness					
Shape	Pitch	G_a average (N/mm)	Number tests	G_a standard deviation (N/mm)[a]	G_a average (N/mm)	G_a standard deviation (N/mm)[a]	G_a by roof (N/mm)	Number tests	G_a average (N/mm)	G_a standard deviation (N/mm)[b]	Increase (N/mm)	Change of stiffness (Δ%)
Flat	0	524.6	8	47.90	523.11	65.37	553.5	1	536.23	24.45	13.11	2.51
		521.6	8	79.04			518.9	1				
Hip	4	512.2	6	24.23	495.91	26.99	587.6	1	601.98	20.37	106.1	21.39
		479.7	6	18.48			616.4	1				
Gable	4	215.7	4	18.64	161.52	65.37	294.7	1	294.70	—	78.92	36.58
		107.3	4	2.324			116.5[c]	1				
	8	190.5	4	7.010	256.43	53.61	303.7	1	318.06	20.35	75.75	31.26
		294.1	7	18.29			332.5	1				
	12	256.0	4	13.11	255.20	9.80	313.6	1	326.18	17.82	70.85	27.75
		254.7	6	4.393			338.8	1				

Note: Average of all roofs 23.90%; average of only gable roofs 31.86%; average of only gable roofs 31.86%.

[a]There were multiple elastic tests for each constructed roof without gypsum, so a standard deviation can be calculated for each constructed roof and shown in line with that constructed roof.

[b]There was only one test for each constructed roof with gypsum because that test was also for ultimate strength (nonlinear). Therefore, the standard deviations for the tests with gypsum are calculated for two different constructed roofs and shown centered vertically between the tests in the table.

[c]It appears that the low strength was caused by a sensor malfunction, so this test was not included in the analysis.

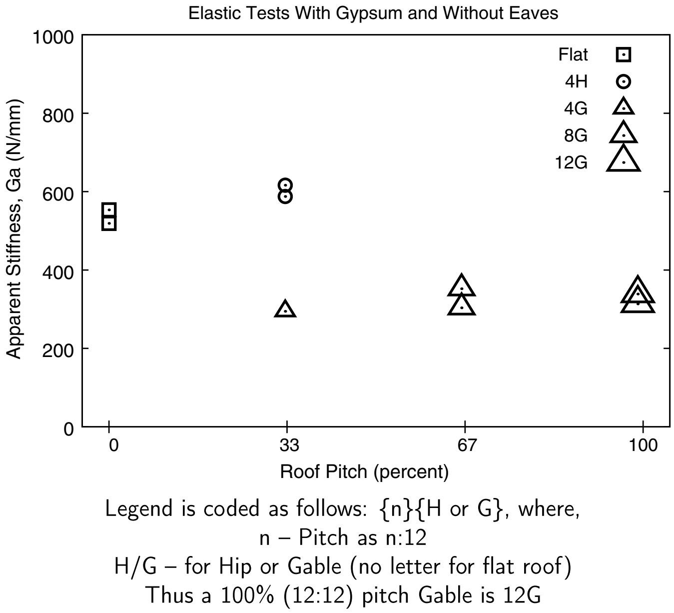


Fig. 5. Elastic tests with gypsum and without eaves

linear equation fit well to the data. This correlation applies only for roof pitches between 33 (4:12) and 100% (12:12)

$$\Delta\% = -0.131x + 0.423 \tag{4}$$

where $\Delta\%$ = percentage increase in apparent stiffness with the addition of gypsum as a function of pitch, and x = pitch as a ratio of rise over a horizontal distance (e.g., 4:12 pitch would be $x = 4/12 = 0.33$).

At gable roof pitches below 0.33 or 33%, about 38% or more of the elastic roof apparent stiffness is due to the added gypsum ceiling.

Elastic roof behavior is observed below the design strength of 23.9 kN, corresponding to deflections that are about 30 mm for flat and hip roof configurations.

Diaphragm drift can be calculated as follows:

$$30\ \text{mm}/3,658\ \text{mm} = 0.82\%$$

Gypsum ceilings can be expected to perform well with minimal damage at these drift levels. Therefore, consideration of gypsum ceiling stiffness could be important to understanding the actual performance of SFDs that remain in the elastic range.

Gypsum increases the apparent stiffness of gable roofs by an average of 32% and hip roofs by 21%. The increase in apparent stiffness for flat roofs is negligible. Gable roofs with gypsum show increasing apparent stiffness with increasing pitch.

Effect of Additional Plywood on Eaves

Table 1 shows the results of the tests of diaphragm apparent stiffness with and without the eave plywood. Averaging all data produced a net increase of 13.6%, but when excluding likely outliers the average improvement was only 2.2%. Therefore, the contribution of eave plywood to the strength of a roof diaphragm should be disregarded.

Torsion on Gable Trusses

During the course of the experiments at high loads, it became apparent that there was substantial deformation to the end gable truss top chord. The loading caused the gable truss top chord to assume an "S" shape (for the three pitches of gable roofs), with the gable truss heels and peak appearing at approximately the original, unloaded conditions (Fig. 6). This behavior is observed on both ends of the roof; thus, it is likely that each truss in the structure shows a similar deformation. This is believed to be due to the effect of a couple developing between the plywood sheets and the diaphragm chord, to resist the deflection of the plywood sheathing. This behavior was also noted by Johnson and Burrows (1956) without explanation. Diaphragm shear deformations result in double curvature bending of the top truss chords. The stiffness of the system is due to the ability of the individual components and connections to resist deformation caused by the shearing force. Thus, the weak axis bending of the gable trusses significantly reduces the system apparent stiffness resulting in the performance shown in Fig. 4.

Common trusses with pitched top chords and horizontal bottom chords have a smaller weak-axis moment of inertia than flat roofs; therefore, the truss will bend more in weak-axis bending during roof shear than a flat roof joist. Flat roof joists can be attached to gypsum and plywood on both the top and bottom of each joist, which restrains joist and reduces weak axis bending.

This behavior was not observed on the hip roofs during these experiments. It is likely that this torsional behavior in the gable roof trusses is partially responsible for the lower system apparent stiffness in the gable systems.

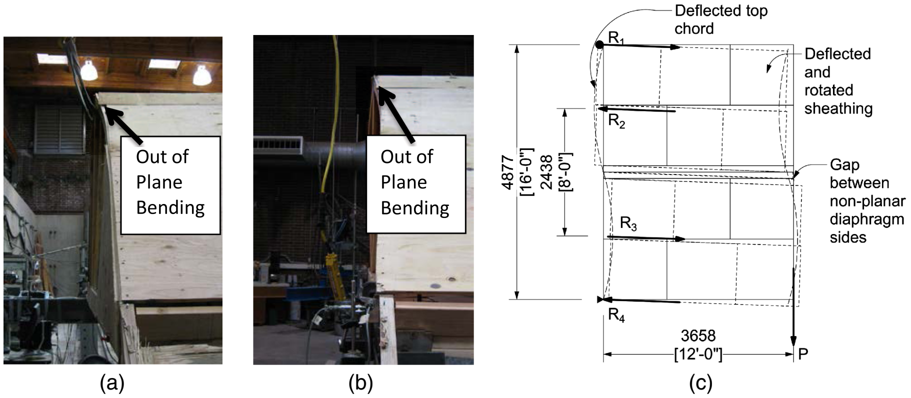


Fig. 6. Observed out-of-plane truss chord bending: (a) west end from SW corner; (b) east end from northeast corner; (c) forces developed in tested roof

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Table 3. Roof Strength by Configuration and Pitch

Configuration	Pitch	Roof strength R_u (kN)	Mean by configuration and pitch S_u (kN/m)	Deviation from mean (%)	Postframe pitch reduction (%)
Flat	0	41.9	8.85	2.91	0.00
		44.4			
Hip	4	44.2	8.41	−2.20	−10.00
		37.9			
Gable	4	8.54	1.75	—	−10.00
	8	37.0	7.59	−11.70	−30.77
	12	46.2	9.48	10.27	−50.00

Ultimate Roof Strength

A goal of this experimental program was to verify whether a strength reduction factor is needed for the shear capacity of gable and hip roofs of various pitches. Roofs previously tested by other researchers had relatively low pitches, so the effect of pitch could not be verified for certain. By testing roofs of up to 100% (12:12) pitch, the postframe strength reduction equation indicates a 50% reduction should be applied (Table 3). This should be sufficient reduction that it would be obvious in these test results if this reduction equation is applicable to SFD construction. It was planned to load each roof to ultimate failure and record the results. Unfortunately, calibration problems adversely affected roof specimens 1 to 3 and 5, resulting in no good data for the 33% (4:12) gable inelastic strength tests, and only one test rather than two for the remaining gable roofs. Results presented here are the best data that were available and appear to indicate that there is no reduction in roof strength as a result of differing roof pitch.

Maximum shear strength was determined from data records, and the value of S_u was calculated as described in ASTM E455 (ASTM 2011), based on the horizontal projection of the pitched roof diaphragm and shown in Table 3. In order to compare these experiments with the values shown in the Special Design Provisions for Wind and Seismic with Commentary (SDPWS) [American Forest and Paper Association (AF&PA) 2005], some additional calculations are required. The nominal shear capacity without any resistance or safety factor, for 8d nails in 9-mm (3/8-in.) or thicker plywood, loaded perpendicular to the long axis, is 7.01 kN/m (480 plf in Table A4.2B, AF&PA 2005). The AF&PA does not provide design values for gypsum ceilings, so the effect of the gypsum must be estimated from AF&PA data (as presented in Table 4.3A, AF&PA 2005). For shear walls with ½ in. gypsum wallboard attached with #6 screws, 200 mm (8 in.) o.c. on the edges and 300 mm (12 in.) o.c. in the field of the panel is 120 plf. For plywood, Table 4.2B for horizontal diaphragms, 8d nails, 15/32 in. thickness, 2 in. framing, nails 6 in. o.c. has a shear value of 480 plf. Table 4.3A, for shear walls, identical conditions, has a shear value of 520 plf. Thus, for a gypsum ceiling, [(480 plf)/(520 plf)](120 plf gypsum shear wall) = 111 plf (1.62 kN/m). Note that this violates paragraph 4.3.3.2.2 which prohibits summing shear capacities of dissimilar materials for seismic design but permits it for wind design.

All tests lie within ±12% of the S_u mean. Based on the results of the postframe design experiments, it might be expected that there would be up to a 50% loss of strength on the steepest roof pitch that was tested, as shown in the rightmost column of Table 1. But these data show that the steepest gable roof was the strongest gable roof tested. There is no indication that roof pitch adversely affects the strength of roofs constructed of plywood sheathing and MPC trusses. Tests showed average strength values within 1% of AF&PA (2005) tabular values. Though roof stiffness (and therefore deflection) is affected by pitch, roof strength appears uniform for all pitches tested.

In wood construction, gable roofs are not as stiff as flat roofs, because the upper truss chord can significantly displace relatively and independently from the bottom truss chord as shown in Fig. 6. The joists supporting a flat roof take on both of the roles of the top and bottom chords.

Conclusions

The following conclusions can be drawn based on the testing of pitched wood roof diaphragms:

- Gable roof systems have lower apparent stiffnesses than flat or hip roof systems. Gable roof apparent stiffness can be as low as half the apparent stiffness of flat or hip roof systems, and gable roof systems increase in apparent stiffness with increasing pitch within the range of 33–100% pitch.
- Eave plywood resulted in a net increase of 13.6%, but if outliers were excluded, the average improvement was only 2.2%. Therefore, the contribution of eave plywood to the strength of a roof diaphragm should be disregarded.
- Hip and flat roof configurations have similar apparent stiffness.
- Diaphragm shear deformations result in double curvature bending of the top truss chords, significantly reducing diaphragm apparent stiffness.
- Gypsum increases the apparent stiffness of gable roofs by an average of 32% and hip roofs by 21%. The increase in apparent stiffness for flat roofs is negligible. Gable roofs with gypsum show increasing apparent stiffness with increasing pitch.
- Common trusses with pitched top chords and horizontal bottom chords have a smaller weak-axis moment of inertia than flat roofs; therefore, the truss will bend more in weak-axis bending during roof shear than a flat roof joist. Flat roof joists can be attached to gypsum and plywood on both the top and bottom of each joist, which restrains joist and reduces weak-axis bending.
- Though roof apparent stiffness (and therefore deflection) is affected by pitch, roof strength appears uniform for all pitches tested.

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