CHARACTERISTICS OF WOOD DIAPHRAGMS: EXPERIMENTAL AND PARAMETRIC STUDIES[1]

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ABSTRACT

This paper further verifies a previously developed analytical model of sheathed diaphragms. Load-displacement behavior and frequency characteristic are studied, and comparisons are made between analytical and experimental results. An 8- × 8-foot wall with ½-inch plywood sheathing was used in sensitivity studies to quantify the effect of the variation of parameters, such as nail spacing, moduli of elasticity of materials, and joint stiffness, on the static load-displacement behavior and frequency of sheathed diaphragms. The major parameters affecting the load-displacement and displacement-frequency relationships of diaphragms were found to be nail spacing and the connection properties between sheathing and frame members. Sheathing arrangements were also found to affect the stiffness of diaphragms. Variations in mechanical properties of sheathing and frame members, however, had only a negligible effect on diaphragm structural behavior.

Keywords: Diaphragms, finite element methods, nonlinear systems, models, shear wall, wood, deformations.

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INTRODUCTION

Light-framed, low-rise wood buildings represent the largest percentage of buildings constructed in the United States and provide shelter for a large portion of our population. Diaphragms that include walls, roofs, and floors are major structural components of these buildings. They transmit in-plane shear forces between structural components and provide stability to the overall structure. Accurate analyses and full-size tests of diaphragms are complex and expensive; consequently, knowledge about their performance under dynamic loading substantially lags behind their importance.

A nonlinear finite element model for predicting the quasi-static load-deflection behavior of wood diaphragms was introduced in a previous paper (Itani and Cheung 1984b). The model is general in its formulation and does not impose restrictions regarding sheathing arrangements, load application, and geometry of distortions. This paper further verifies the model using experimental tests of full-scale walls.

The main objective is to extend the model to predicting the natural frequency of diaphragms. Quasi-static loading and free-vibration tests were performed to provide data for the verification of theoretical predictions. Sensitivity studies are conducted to evaluate the effect of input parameters on displacement and frequency of diaphragms.

STATE-OF-THE-ART

Past studies on the behavior of diaphragms were mostly limited to testing under static loading. Researchers have recently been concerned with the development of mathematical models for predicting the response of such structures (Itani and Faherty 1983); and Carney (1975) and Peterson (1983) have prepared an extensive bibliography of wood and plywood diaphragms. A subsequent workshop (Applied Technology Council 1980) evaluated the available information and determined priorities of research needs for horizontal wood diaphragms. Theoretical investigation of diaphragms in racking was performed by Foschi (1977, 1982), Tuomi and Gromala (1977), Tuomi and McCutcheon (1978), Itani et al. (1982), and Easley et al. (1982). Related investigations were conducted by Polensek (1978, 1976, 1975a; Polensek and Laursen 1984), who studied the analysis of wood-stud walls in bending and compression.

Floor and roof diaphragms have been tested by the Forest Research Laboratory at Oregon State University, the American Plywood Association, the United States Forests Products Laboratory, and others. The results (Atherton 1981; Corder and Jordan 1975; Hoagland 1981; Johnson 1979, 1968; Mayo 1982; Price and Gromala 1980) provided the data for diaphragm design by building codes (Uniform Building Code 1982). Itani and Cheung (1983, 1984a, 1984b; Cheung and Itani 1983) developed a nonlinear finite element model for predicting the static and dynamic response of diaphragms. The model was verified using experimental static tests of full-scale walls.

The model developed by Itani and Cheung was extended for studying the frequency and damping properties (Cheung and Itani 1984). Free vibration tests of 8- × 8-foot plywood sheathed walls were conducted to provide data for com-

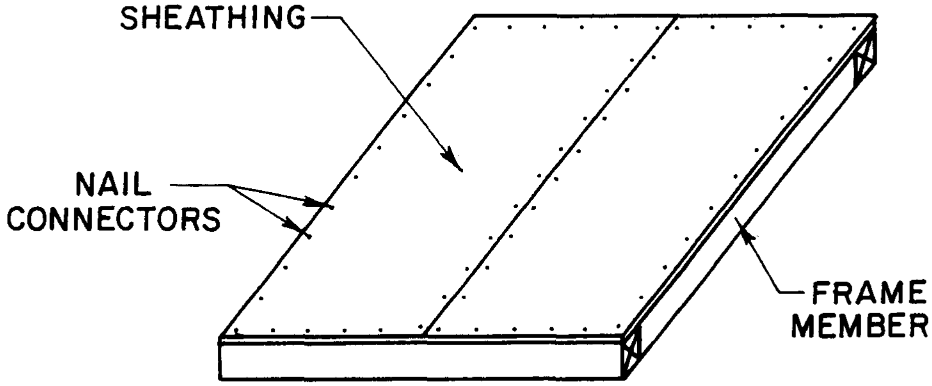


FIG. 1. Typical two-panel nailed sheathing diaphragm.

parison, and fair agreement was obtained between theoretical and experimental results.

In 1975, Polensek (1975b) reported on testing of 34 full-scale nailed wood-joist floors subjected to bending and in-plane free vibration. Natural frequencies of diaphragms under in-plane loads were found to range between 12–17 Hz.

In 1980, Soltis et al. (1980) summarized previous research conducted by other investigations. Based on 8- × 8-foot wood-wall tests, a natural frequency of approximately 15 Hz has been reported. Free vibration tests of wood-joist floors resulted in natural frequencies ranging from 14–23 Hz.

In 1981, Hirashima et al. (1981) conducted a test on a full-scale wood house and its wall elements. The free-vibration tests of wall elements resulted in an average natural frequency of 13 Hz.

These experimental studies were performed on diaphragms made with specific materials and joints that were generally not pretested for properties, such as stiffness moduli. The results, therefore, cannot provide reliable data for verifying the theoretical procedure. To address this point, careful testing is needed that includes an evaluation of local material and joint properties for the particular diaphragms tested.

FORMULATION

Finite element model

A typical sheathed wood diaphragm consists of wood framing, sheathing, and nail connectors (Fig. 1), which are modeled by beam, plane-stress, and joint finite elements, respectively. The details of model formulation are reported elsewhere (Itani and Cheung 1984b), and only a brief description of the model follows.

The one-dimensional beam and two-dimensional plane-stress elements are linearly elastic, which reflects fully elastic behavior in framing and sheathing under small stresses that occur in actual loading. These two elements are assumed to be the only elements that contribute mass to the model.

Nailed connections are the locations of high stresses and nonlinearity and the source of almost all of diaphragm displacement. Thus, it was essential to include nonlinear behavior into joint elements. The elements are nondimensional springs with two translational degrees-of-freedom. To reduce the overall degree-of-freedom of diaphragms analyzed, a special joint element was developed, which modeled simultaneous behavior of several nail connections.

Unlike previous studies, this finite element model is general in its formulation and does not impose restrictions regarding sheathing arrangements, load application, and geometry of distorted diaphragms. This model has been verified in a previous study (Itani and Cheung 1984b) where good agreements between experimental static load-deflection measurements of waferboard and plywood sheathed diaphragms and theoretical predictions have been obtained.

Frequency analysis

In free-vibration tests, experimental digital data of displacement versus time were recorded. The Power Spectural Density (PSD) technique (Welch 1967) with the Fast Fourier Transform algorithm was used to estimate the experimental frequencies. Details of the algorithm are discussed in many vibration measurements texts (Blake and Mitchell 1972; Broch 1980). A plot of the PSD is a graphical display of the energy distribution of the vibration in a frequency domain, with the natural frequency of a specimen represented by the frequency of the highest peak on the PSD plot.

THEORETICAL AND EXPERIMENTAL RESULTS

Experiments, performed at the Forest Research Laboratory of Oregon State University, consisted of static cyclic loading and free vibration tests of 8- × 8-foot plywood sheathed panels. Two replications of three different construction types were tested. The Group 1 (Walls No. 1 and 2) specimens consisted of two 4- × 8-foot plywood sheets placed vertically as shown in Fig. 2. The Group 2 (Walls No. 3 and 4) and Group 3 (Walls No. 5 and 6) specimens were the same as Group 1 specimens, except Group 2 specimens consisted of two 4- × 8-foot and Group 3 specimens of four 4- × 4-foot plywood sheets, which were, for both groups, placed in a horizontal direction. Both Groups 2 and 3 specimens had nominal 2 × 4 blocking toe-nailed to studs at midheight to provide for connections between the plywood sheets.

The walls were constructed with double 2 × 4s for the top plate and a single 2 × 4 for the sole plate (bottom plate). The lower top plate and the bottom plate were butt-nailed into each stud by two 16d box nails. A steel U-channel was bolted with 6 bolts spaced at 16 inches on center over the top plate, and ran between two lateral guides to prevent out-of-plane motion. The bottom plate was bolted to a steel I-beam with 6 bolts spaced 16 inches on center. This was needed to prevent slip between the sole plate and support. Plywood was nailed to the sole plate with an edge distance of 0.5 inch. Single 2 × 4s placed at 16 inches were used for the interior stud members.

The test set-up was similar to the ASTM E-72 (American Society of Testing and Materials 1977), except no hold-down rods were used. All walls were tested in vertical positions.

The loading was applied by a hydraulic actuator connected to the steel U-channel on the top of the wall. An MTS system that powered the actuator induced three basic loading functions on each panel: static ramp, free vibration and seismic simulation, each conducted at three maximum amplitudes. The purpose of this

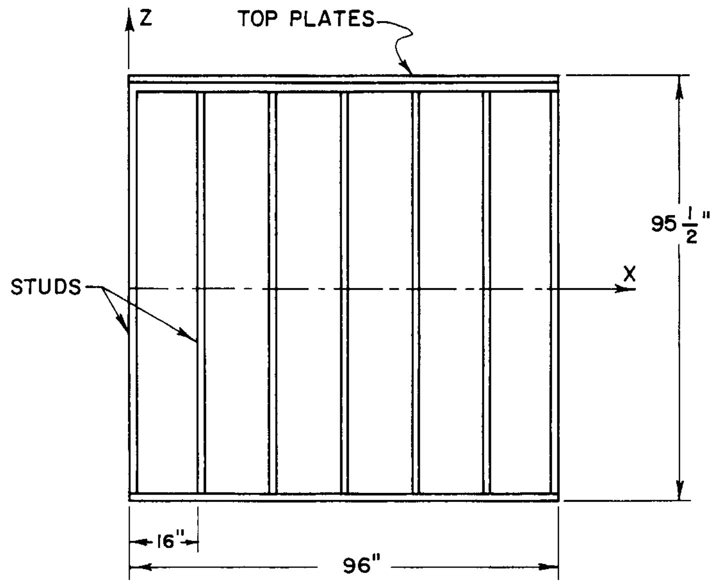


FIG. 2. Construction configuration of Group 1 plywood sheathed diaphragm test specimens.

testing was to evaluate dynamic characteristics of shear walls and their behavior under El-Centro spectra. Details can be found in a report to the research sponsor (Polensek and Laursen 1984). The tests were first performed at 0.25-inch amplitude and then successively at 0.50 inch and 0.75 inch. The final test consisted of applying the ramp load until the horizontal deflection of 2.00 inches was reached.

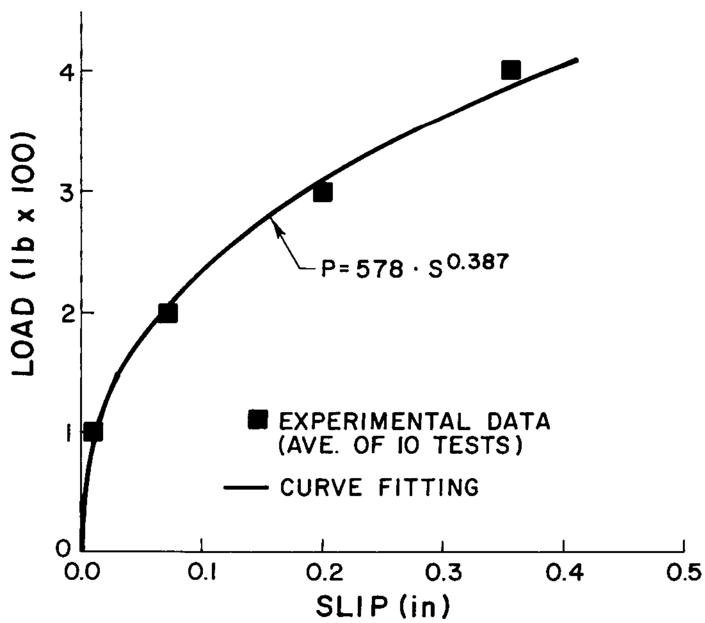


FIG. 3. Single nail joint test data and curve fitting results of load-slip relationship.

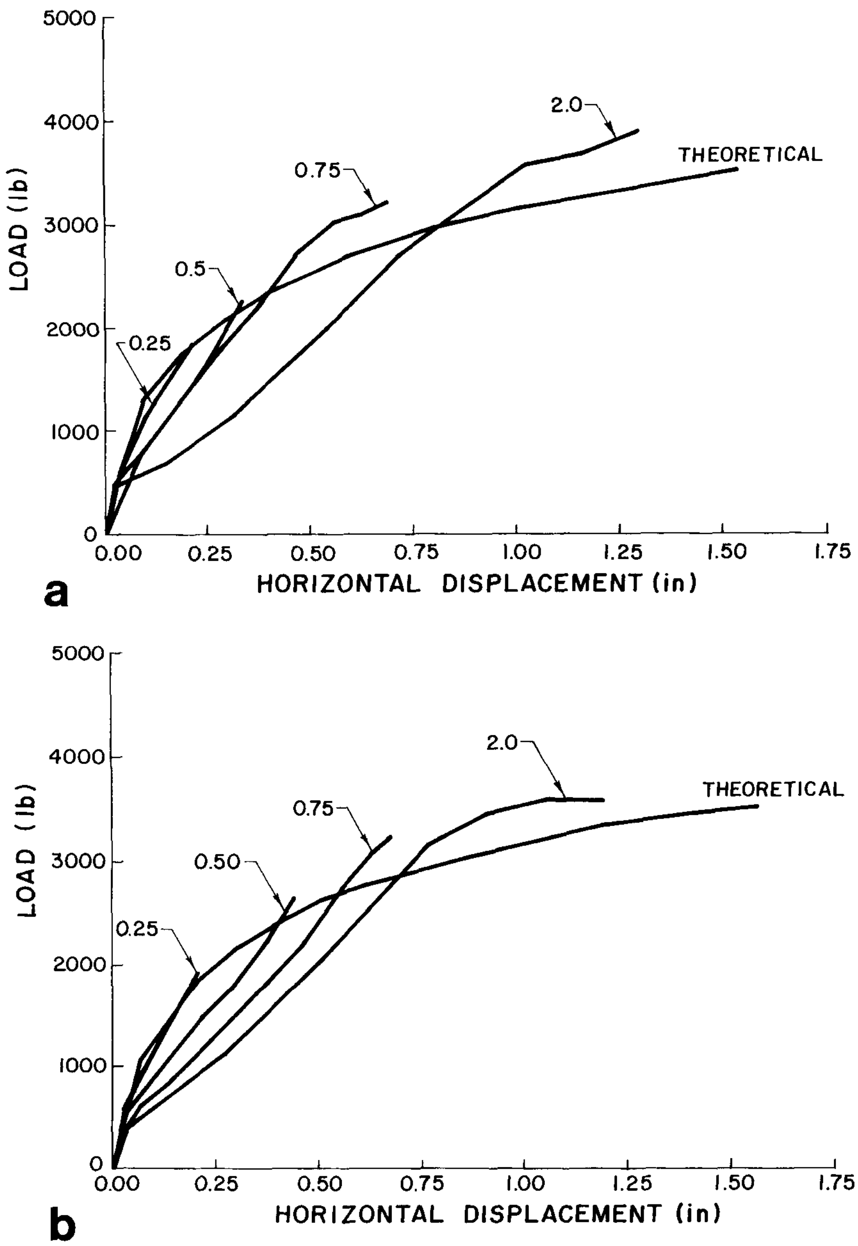
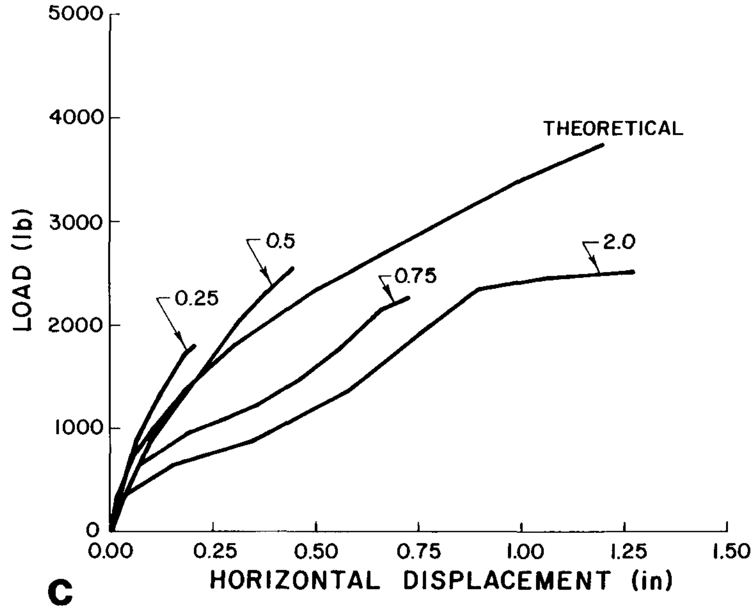


FIG. 4. Experimental and theoretical static load versus displacement results of plywood sheathed diaphragm test specimens (a) Wall #1 of Group 1, (b) Wall #2 of Group 1, (c) Wall #3 of Group 2, (d) Wall #4 of Group 2, (e) Wall #5 of Group 3 and (f) Wall #6 of Group 3.

Because this testing sequence introduced progressively increasing structural damage to wood joints, it was anticipated that panel stiffness was gradually decreasing during testing.

The walls were constructed from the same stock of materials, with framing



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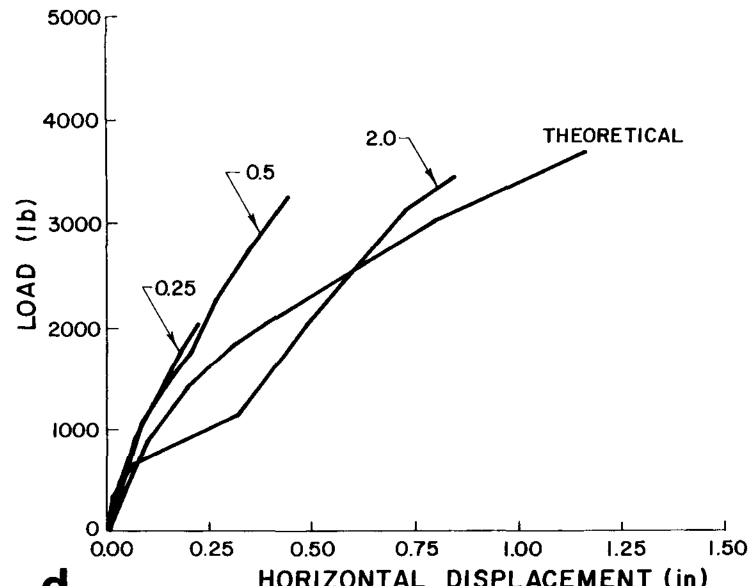

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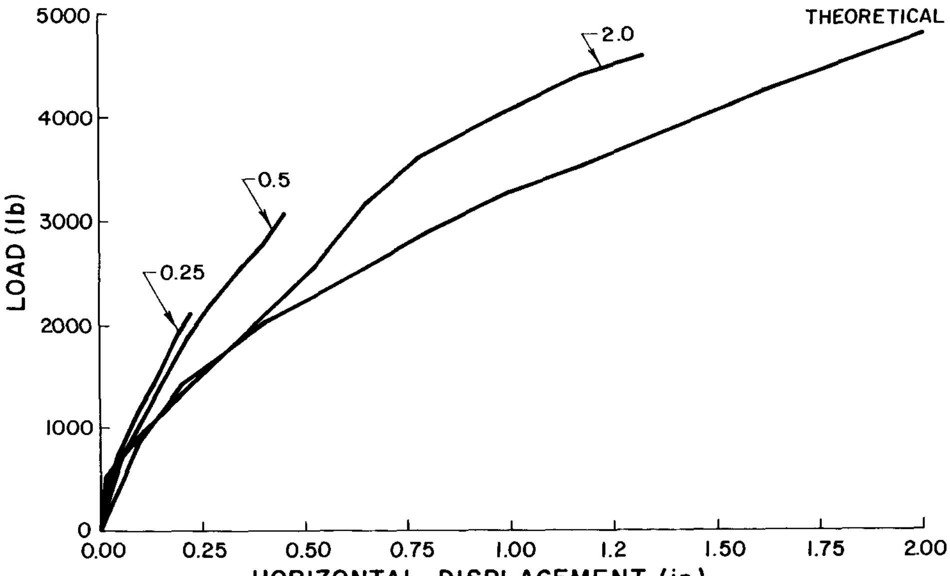
members of 2 × 4 Douglas-fir, 1750f grade, and sheathing of 0.5-inch Douglas-fir plywood. Studs and plywood sheets were nondestructively tested to determine their modulus of elasticity. Studs were loaded in bending about their weaker cross-sectional axes on a span of 90 inches by a concentrated load of 100 pounds applied at midspan in two 50-pound increments. To eliminate the effect of loose initial contacts at supports, the modulus of elasticity was based on deflection under the



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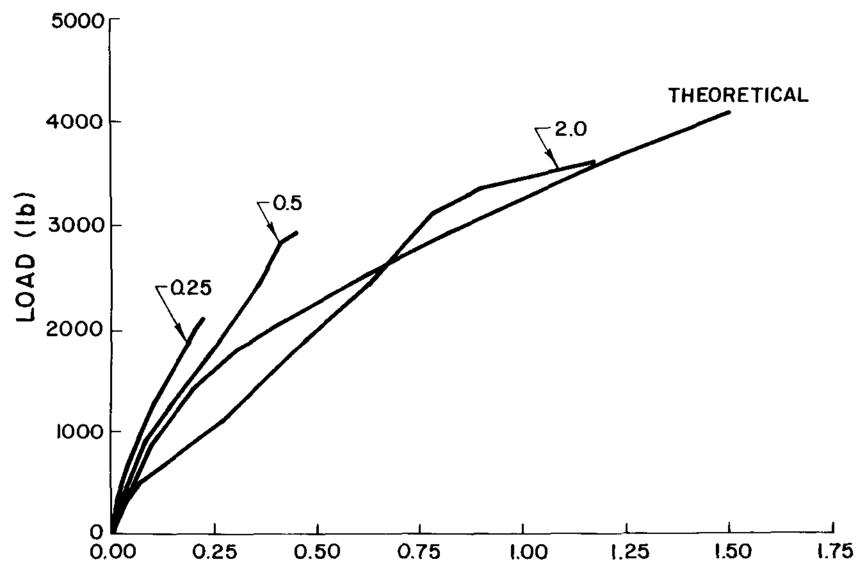

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second 50-pound load. For plywood sheets, the moduli of elasticity were determined similarly except that a 93-inch span was used. The moduli of elasticity for studs varied from 1,130 to 2,920 ksi, and the moduli of elasticity for plywood sheets varied from 1,120 to 1,410 ksi.

The nails between plywood and framing were 8d smooth galvanized box nails,

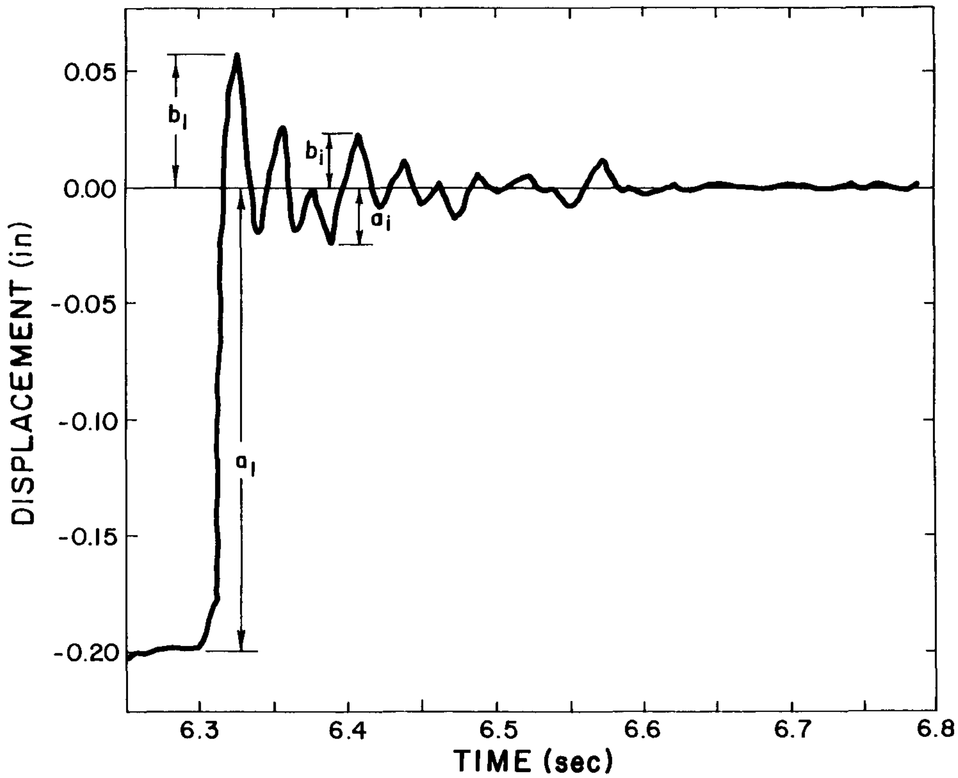


FIG. 5. Typical experimental time versus displacement curve.

6 inches on center along the plywood perimeter and 12 inches on center at interior locations. Load-slip property of nail joints (Fig. 3) used for theoretical analysis was based on test of nail joints constructed with materials from the same shipment and not the particular pieces used in the test diaphragms.

Theoretical and experimental deflections under static ramp loads are compared in Figs. 4a through 4f. For all walls, experimental traces display decreased stiffness under cycles of ramp loading at successively higher displacement levels. This decrease is caused by the damage in joints due to free vibration tests and simulated seismic tests that were conducted between two ramp-load tests. Thus, the slip modulus, associated with the parts of experimental traces with decreased stiffness, is different from that used in the theoretical analysis. Therefore, comparisons that are free from cycling effects can be made only for the traces from ramp loading with 0.25-inch deflection and top portions of 0.50-inch, 0.75-inch and 2.00-inch deflection. However, even the top portions of the traces for 0.50-, 0.75- and 2.00-inch deflection are affected by loading in previous cycles because of friction and plastic behavior in contact layers of nailed joints. An extreme among cycling effects can be observed on Wall #3; the wall lost most of its stiffness in cycling between 0.50- and 0.75-inch deflection, because it reached its ultimate load in the 0.50-inch cycle and could not take more load even at four times larger deflection. Therefore, only the 0.25-inch experimental traces can be expected to be close to theoretical values.

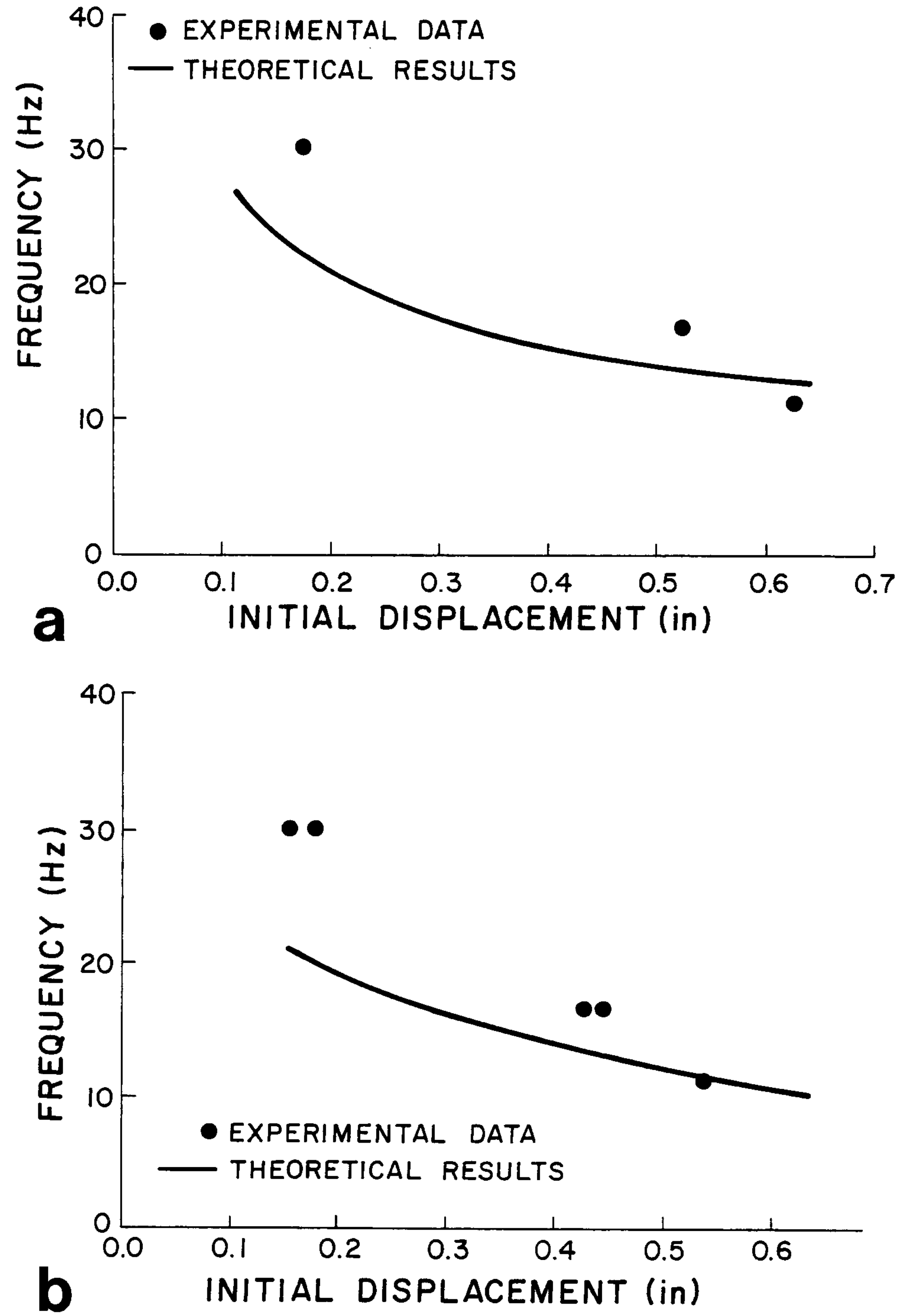
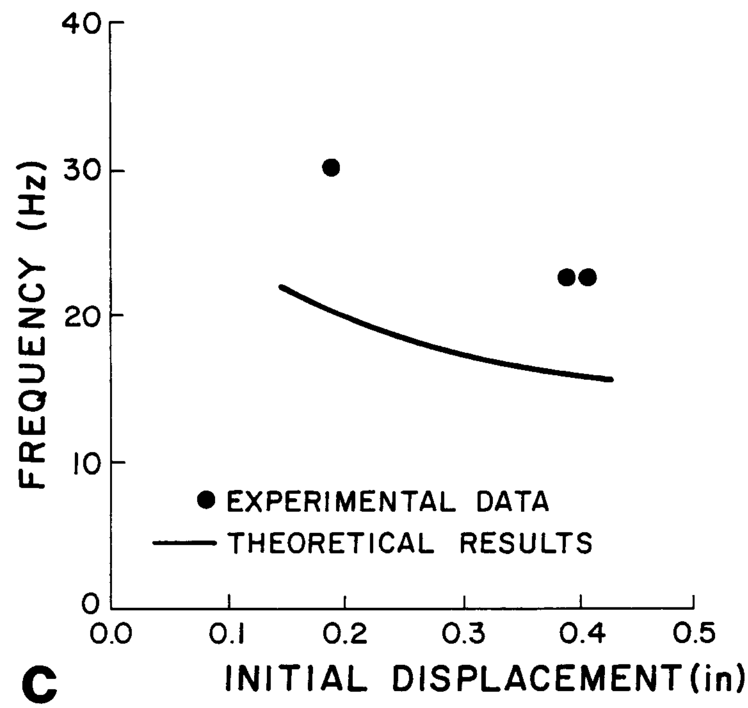


FIG. 6. Experimental and theoretical initial displacement versus frequency results of plywood sheathed diaphragm test specimens (a) Group 1, (b) Group 2, (c) Group 3.



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Considering the limitations of experimental data discussed above, it can be concluded that a good agreement was achieved for theoretical and experimental displacements of Walls #1 and #2 (Figs. 4a and 4b). The agreement is especially close for 0.25-inch traces. For the remaining walls, the experimental 0.25-inch traces appear somewhat stiffer than theoretical traces (Figs. 4c, 4d, 4e, and 4f), probably because of natural variation in joint stiffness. Joint stiffness dominates diaphragm behavior and theoretical analysis was based on the average joint properties of similar materials and not of materials used in wall construction. It is likely that Walls #4 and #5 must have been built with nail joints of stiffer slip moduli than those used in the analysis. Thus, the additional reason for the lack of theoretical/experimental agreement was the difficulty with assigning reasonably accurate joint properties to the theoretical analysis.

For the free vibration tests, a mechanical trigger was used to provide a sudden release of the header after an initial displacement of the header was achieved. A typical time versus displacement record is shown in Fig. 5. Such traces were analyzed by the PSD technique to determine the natural frequency of individual test panels.

The internal structural damage from previous tests perhaps was the main reason for highly irregular patterns that were observed in test records. The patterns induced difficulties in evaluating experimental data. Other difficulties resulted from local modal frequencies on panels. To remedy this, the PSD technique with the Fast Fourier Transform algorithm was used to determine the experimental

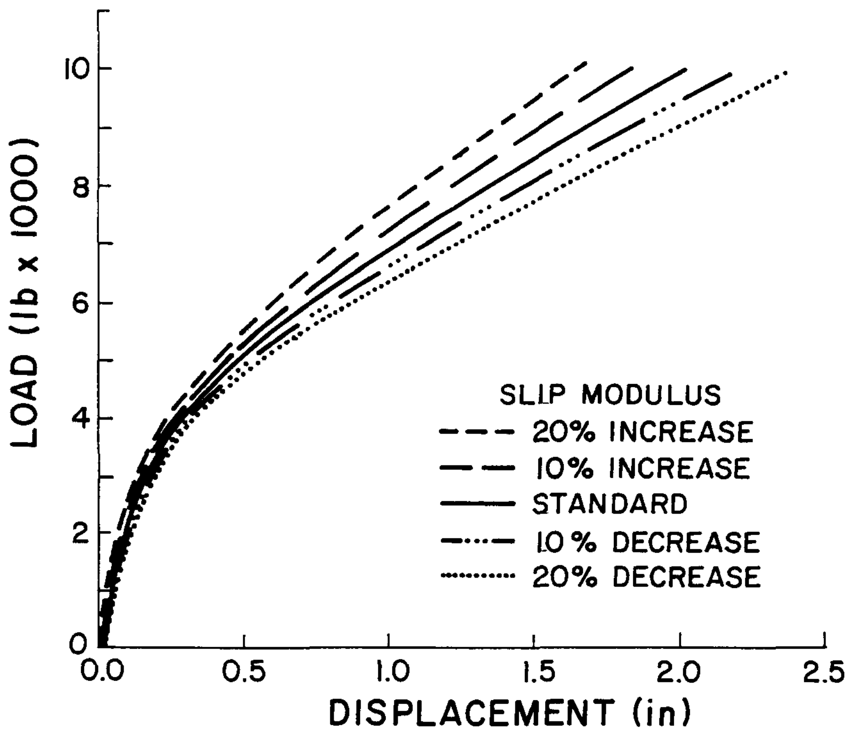

FIG. 7. Load-displacement for various joint slip moduli.

frequencies. Experimental and theoretical frequencies are plotted in Figs. 6a, 6b, and 6c.

A decrease in frequency with an increase in initial displacement can be observed for both the experimental and theoretical results. This was due to the fact that with an increase in the initial displacement, there was a corresponding reduction in stiffness of the nailed joints. In general, the theoretical results predicted frequency values that were lower than the experimental data. No significant variation of experimental frequencies was found between Groups 1, 2 and 3, even though sheathing arrangements of these groups were different.

SENSITIVITY STUDY

Sensitivity studies were performed to quantify the effect of the variation of parameters and construction configurations on stiffness and frequency of diaphragms. These parameters consisted of nail spacing, moduli of elasticity of sheathing materials, joint stiffness, separation between sheathing and sill plate, and sheathing arrangements. In these studies, an 8- × 8-foot wall was chosen as a control system that is referred to as a standard diaphragm. This wall was of the same construction as Group 1 walls, except the separation between the sill plate and the sheathing was not allowed. The frame modulus of elasticity was 1,800 ksi, the sheathing thickness was 0.5 inch, and the sheathing modulus of elasticity

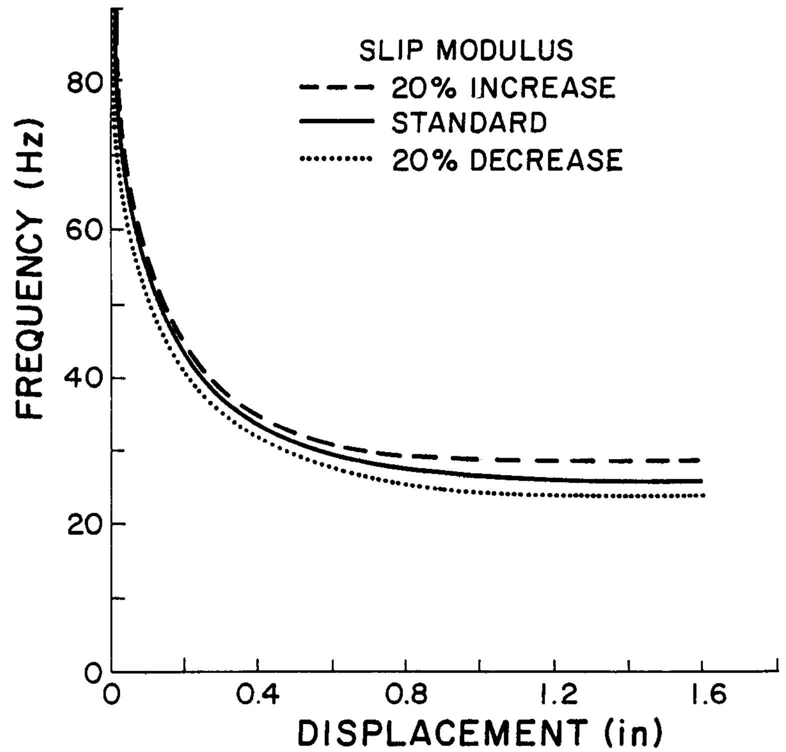

FIG. 8. Frequency-displacement for various joint slip moduli.

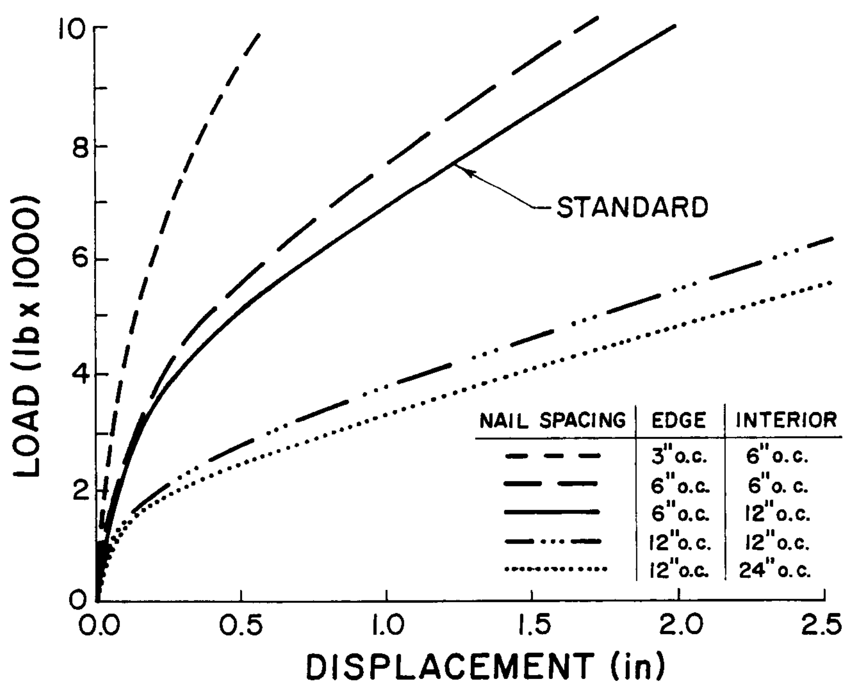

FIG. 9. Load-displacement for various nail spacings.

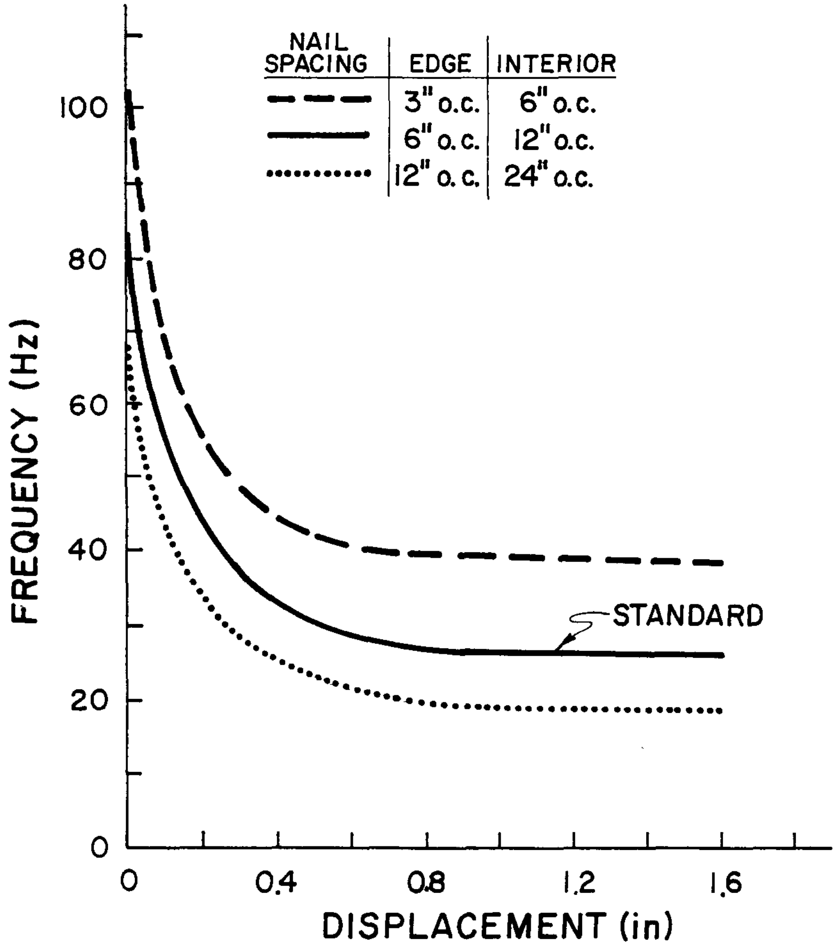

FIG. 10. Frequency-displacement for various nail spacings.

was 1,800 ksi. The standard diaphragm was modified for one parameter at a time and analyzed.

The effects due to various sheathing and frame moduli of elasticity and slip modulus of connectors were studied by using a plus and minus 20% variation in these values. This 20% variation represents approximately one standard deviation (plus and minus) of the stiffness properties for lumber (Douglas fir), plywood, and tested nailed joints.

The standard diaphragm was first analyzed statically for changes in the sheathing moduli of elasticity. The load-displacement results showed that the tangential stiffness of the diaphragm changes less than 2% when varying the sheathing modulus of elasticity by 20%. Load-displacement results are not plotted because the effect due to variation of sheathing modulus of elasticity is very small.

The standard diaphragm was also analyzed with various moduli of elasticity of frame members. The load-displacement results showed that the tangential stiffness of the diaphragm changes less than 6% when varying the frame member

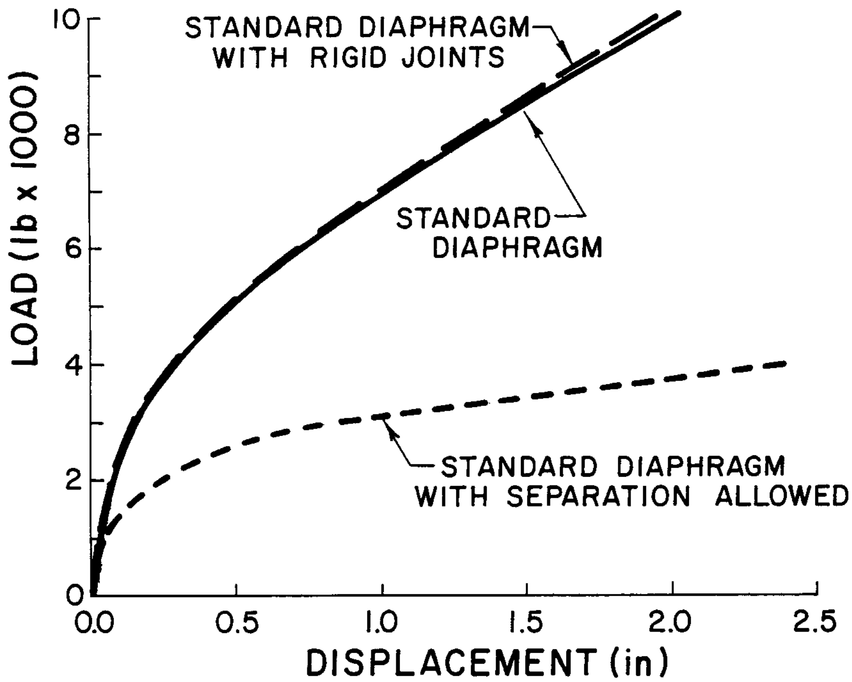

FIG. 11. Load-displacement for different joint rigidity and separation.

modulus of elasticity by 20%. Load-displacement results are not plotted because the effect due to the variation of frame member modulus of elasticity is considered small.

The standard diaphragm was analyzed with various tangential slip moduli of connections between sheathing and frame. The nail joint load-slip relationship is shown in Fig. 3. The load-displacement results are plotted in Fig. 7. These results showed that the tangential stiffness of the diaphragm decreases consistently by about 11%, corresponding to an overall decrease of 20% in slip modulus. Likewise, the stiffness of the diaphragm increases by about 16% with an increase in the joint slip modulus of 20%.

The frequency-displacement curves were determined for the standard diaphragm with various tangential slip moduli of connections between sheathing and frame. These curves are plotted in Fig. 8. The results showed that the frequency of the diaphragm decreases consistently by a value of about 8% when the joint slip modulus is decreased by 20%. Likewise, the frequency of the diaphragm increases consistently by about 11%, corresponding to an increase of 20%.

The standard diaphragm was analyzed with various nail spacings. The nail spacings of the standard diaphragm are 6 inches on center along the sheathing perimeter and 12 inches on center at interior locations. The load-displacement results are plotted in Fig. 9. When doubling nail spacings, the tangential stiffness of the diaphragm decreases. The results showed a maximum reduction of stiffness of 61% at a displacement of about 0.35 inch. Likewise, the stiffness increases by reducing the nail spacings. By reducing the nail spacing to half, the results showed

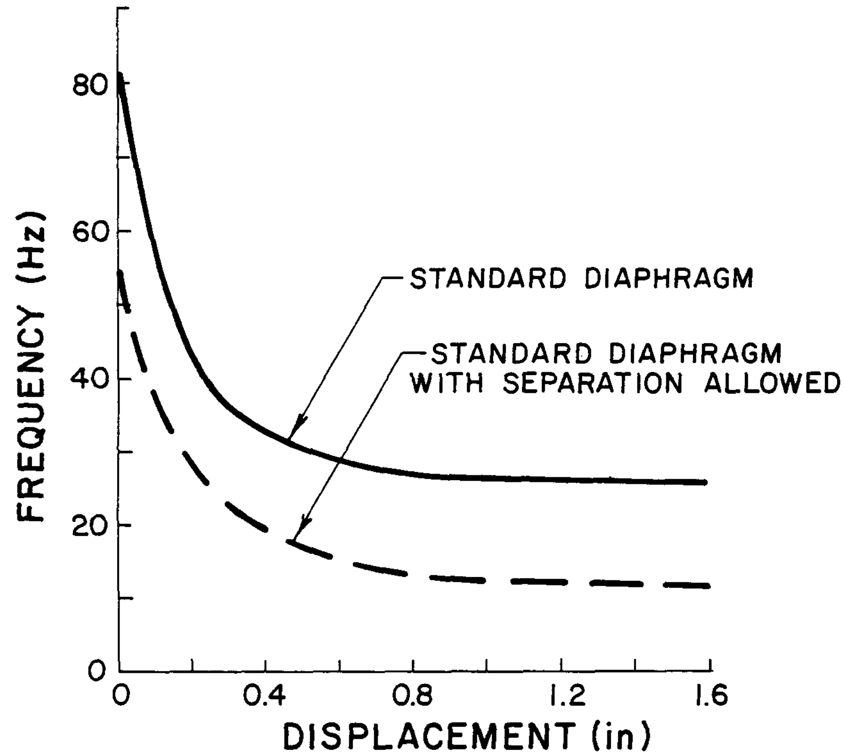

FIG. 12. Frequency-displacement for allowing and not allowing separation.

a maximum increase in stiffness of 216% at a displacement of 0.075 inch. The frequency-displacement curves were determined for the standard diaphragm with various nail spacings, and are plotted in Fig. 10.

The effect of separation between the sill plate and sheathing on the stiffness of the diaphragm was studied by comparing the response of the standard diaphragm with and without separations. The Group 1 specimen is an example of a diaphragm without tie down rods, while the standard diaphragm and its modifications had tie down rods. The theoretical load-displacement and frequency-displacement results are plotted in Figs. 11 and 12, respectively. The results showed that, by allowing separation to occur, the tangential stiffness of the diaphragm decreases as much as 80%, and the frequency decreases by up to 57%.

The standard diaphragm was analyzed with rigid joints between frame members. The load-displacement results are plotted in Fig. 11. The results showed that rigidity of frame joints has insignificant influence on the diaphragm stiffness.

An additional sensitivity study was performed for experimental Groups 1, 2, and 3 walls. The theoretical load-displacement and frequency-displacement results are plotted in Figs. 13 and 14, respectively. The result of load-displacement showed that tangential stiffness of the Group 1 diaphragm (vertically sheathed) is 175% stiffer for displacements above 0.81 inch than the Groups 2 and 3 diaphragms (horizontally sheathed). Sheathing arrangements have no significant influence on displacement-frequency relationships.

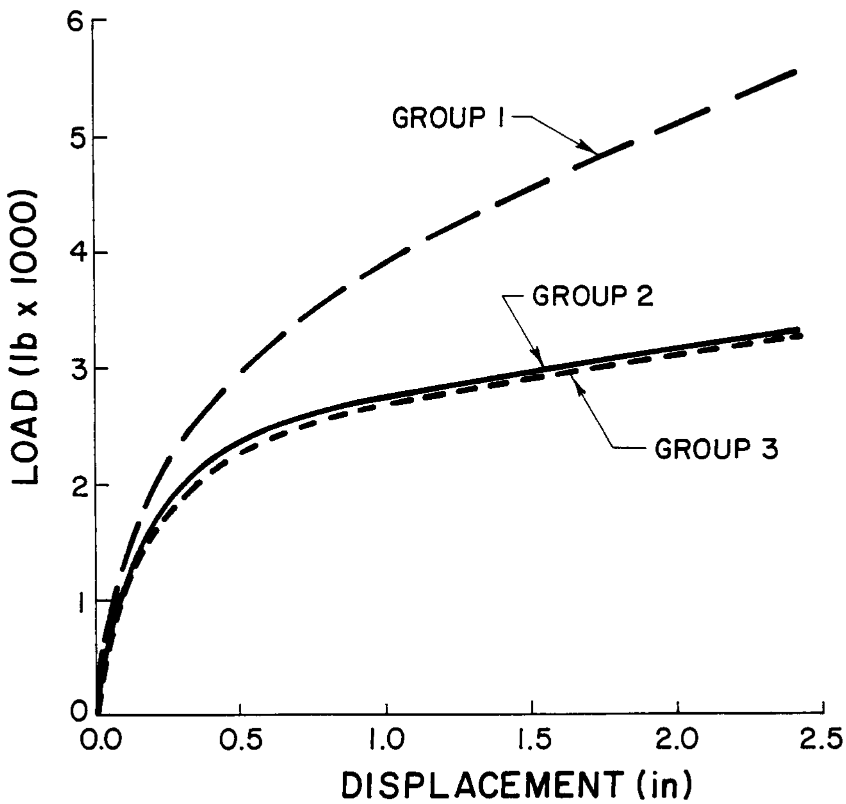

FIG. 13. Load-displacement for various sheathing arrangements.

CONCLUSIONS

A previously developed finite element model for wood diaphragms is further verified with quasi-static loading tests of full-size sheathed wood diaphragms. Agreements were obtained between experimental and theoretical data.

The frequency response of diaphragms was studied theoretically with the use of the finite element model. Free-vibration tests of full-size diaphragms were conducted to provide data for verification. The theoretical results predicted lower frequency values than the experimental values.

The sensitivity study indicated that connection properties between sheathing and frame members dominate the overall stiffness of diaphragms. The results showed that the moduli of elasticity of sheathing and frame members have little effect in the overall stiffness, while nail spacings have significant influence. More than a 50% decrease in system stiffness was found by allowing separation between the sill plate and sheathing. No significant change in the behavior was found for rigid or nonrigid joints between frame members. Walls with vertical sheathing were found to be somewhat stiffer than those with horizontal sheathing.

Both the nail spacing and separation were found to have significant effect on natural frequencies. The joint slip modulus was shown to have less effect on frequency. No significant change in frequency was found due to different sheathing arrangements.

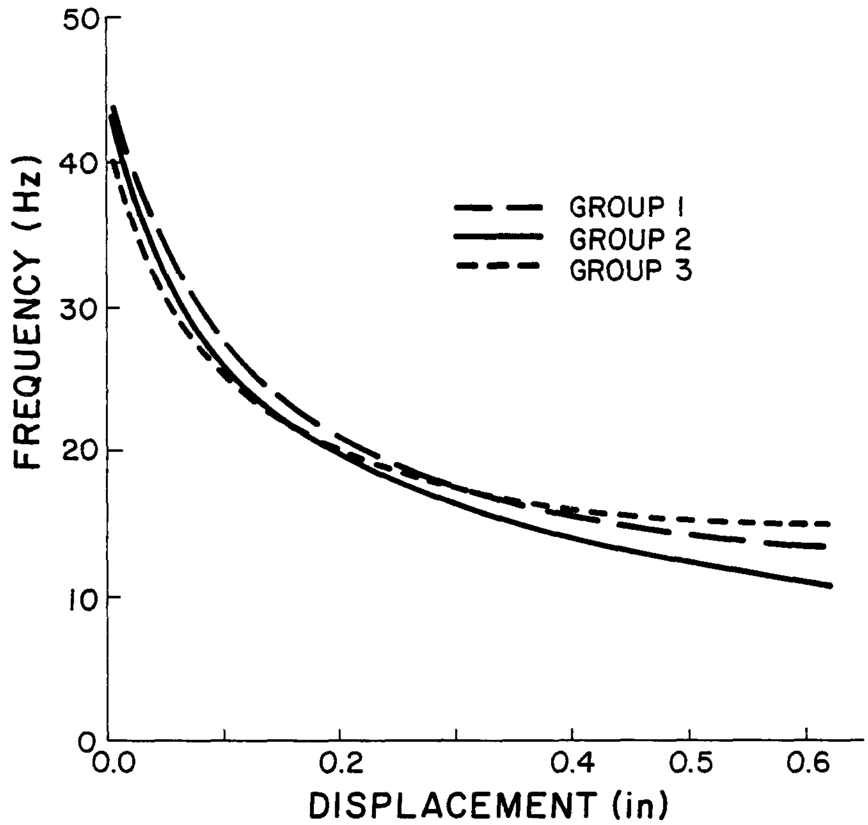

FIG. 14. Frequency-displacement for various sheathing arrangements.

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