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Computer Modeling of Wood Shear Walls

Modèle de calcul assisté par ordinateur pour des parois de cisaillement en bois

Computer-Berechnungsmodell für Schubwände aus Holz

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SUMMARY
This paper describes a computer model for the analysis of wood walls acting in in-plane shear. Nonlinear solutions are compared with experimental results for single units. A solution for a unit with a door opening is compared with alternative methods. Linear analysis of multiple units in series is discussed.

RESUME
L'article présente un modèle sur ordinateur pour l'analyse de parois de cisaillement en bois. Des solutions non linéaires sont comparées avec des résultats expérimentaux pour des unités isolées. Une solution pour une unité avec une ouverture de porte est comparée avec d'autres méthodes. Une analyse linéaire est présentée pour plusieurs unités en série.

ZUSAMMENFASSUNG
Der Beitrag beschreibt ein Computer-Berechnungsmodell für die Untersuchung von Wänden aus Holzwerkstoffen unter Schubbeanspruchung. Nichtlineare Lösungen werden mit den experimentellen Ergebnissen aus einer Wand verglichen. Die Lösung für eine Wand mit einer Türöffnung wird mit den Lösungen anderer Methoden verglichen. Lineare Ansätze für mehrfache Wände werden beschrieben.

1. INTRODUCTION

The objective of this paper is to describe a computer analysis procedure to predict the performance of partially composite, double-layered wall-panel sub-assemblies loaded in-plane, with the nonlinearity of the connectors included.

A multi-purpose computer program called WANELS (WAll—paNEL Systems) was prepared [1]. The analytical model includes modeling the various structural components: sheathing panels, stud-frame members, semi-rigid frame joints (lateral, rotational and axial stiffnesses), panel-to-frame connections (nonlinear force-slip relationship), and the gap between discontinuous panels. Nonlinear connector load-deformation relationships are incorporated using a rapidly converging step-wise technique. A matrix flexibility model is included to perform the linear analysis of a series of wall-panels.

2. BACKGROUND

2.1. Analysis of Layered Wood Systems

Layered wood systems are widely used in light-frame construction. Perhaps, the most representative example of the use of layered wood systems is a conventional wood-frame house. Typically, sheathing is used either as flooring atop wood joists or as roofing atop wood trusses. Stud-walls with various exterior and interior coverings (henceforth, "wall-panels") are standard components.

Wall-panels, roofs and floors perform dual roles when acted upon by lateral loads (wind and earthquake). Side walls act as layered plates subjected to transverse loading. Roofs, floors and end-walls resist the sidewall reactions as in-plane forces acting in combination with gravitational loads and/or wind pressures. The ability of these layered subassemblies to serve as diaphragms and shear walls is of major importance in resisting lateral loads. Availability of accurate analytical tools to predict their response and strength is an important prerequisite to effective design.

Layered wood systems are extremely complicated to analyze. For illustration a typical wall-panel is shown in Fig. 1. Such systems are usually multilayered with each layer made of orthotropic materials. The individual components are connected with mechanical fasteners that behave as nonlinear, flexible elements and the composite behavior of the system is incomplete. Gaps between the sheathing panels also significantly affect the system performance. In addition, there is variability in the material properties in each component. Floor and roofs have equivalent complexity, making the formulation of a structural model for complete structures an imposing endeavor.

A proper structural modeling of wood structures subjected to lateral loads should embody 1) an accurate mathematical representation of the complete, interconnected structure, 2) a comprehensive nonlinear analysis package, 3) dependable knowledge of the loads and their dynamic characteristics and 4) a probabilistic format. Because of the enormous complexity of the overall task, progress toward these needs, although steady, has been slow and challenging. The first task alone, i.e., whole structure mathematical modeling, is not yet possible. Limited parallel research is being conducted on tasks 2, 3 and 4 but application to whole structure models and subsequent refinement must await completion of task 1. To date researchers have focused on separate studies of the various subassemblies such as the wall-panels addressed in this paper. The common goal has been to produce rigorous, experimentally verified analytical models for each subassembly. At some future time these individual models can be appropriately assembled into a viable model for systems analysis.

2.2. Pertinent Literature

The list of publications related to research on layered wood sub-assemblies is lengthy. An effective treatment of the current state-of-the-art is contained in the proceedings of a recent workshop [4]. A comprehensive bibliography of the literature particular to wood diaphragms is also available [9]. The most extensive developments have resulted from studies of wood floors subjected to transverse loads. A recent publication by Wheat et al. [12] describes the present analytical capability and presents their extension of past work to include a vital nonlinear connector feature. Independent work on floors has been conducted by Foschi [3] and on transversely loaded wood stud walls by Polensek [10].

In the U.S. the evaluation of racking strength of light-frame walls primarily has been limited to performance testing and the use of either simplified equations or empirical tables. Tuomi et al. [13] developed a simple equation (the "FPL equation") to predict the racking resistance of conventional wall-panels configured as shown in Fig. 2. The resistance, P, is given by

$$P = r \sin\alpha \left[n + m - \frac{2}{3} \left(\frac{n^2-1}{n} \cos^2\alpha + \frac{m^2-1}{m} \sin^2\alpha \right) \right] \qquad (1)$$

where r is the ultimate lateral nail resistance. It was assumed that the external load is essentially resisted by the nails as they distort linearly in a particular pattern. Interior nails are treated in the same manner. The resistance of the frame was included by adding an empirical constant to Eq. 1. The resistance of several panels placed either in series or parallel is obtained by applying Eq. 1 separately to each sheet and summing the results.

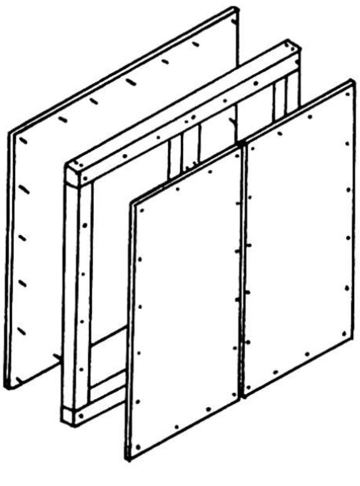

FIG.1. WALL-PANEL

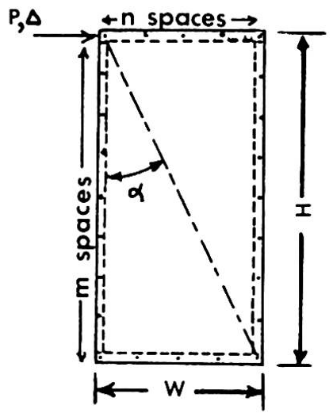

FIG.2 NOMENCLATURE

Recently, Easley et al. [2] proposed an alternative to Eq. 1, namely

$$P = \frac{W\Delta}{H(2H/KW\beta + 1/Gt)} \qquad (2)$$

in which β depends on the nailing pattern, G and t are the shearing modulus and thickness of the sheathing, respectively and Δ is the racking deflection. K is a linear lateral nail stiffness but a nonlinear stiffness can also be incorporated. Eq. 2 is intended for single layered wall panels and assumes a nail force pattern considerably different than the FPL assumption.

3. ANALYTICAL MODEL

3.1. Representation of the Structure

An example wall-panel was shown in Fig. 1. The structure is modeled as described in the following paragraphs.

3.1.1. Stud Frame

Conventional stiffness matrices for beam elements are used for the frame members. Axial deformation is included but shear deformation is neglected.

3.1.2. Connector Elements

Joints between frame members are considered nondimensional "connector elements." Lateral, rotational and axial stiffness are incorporated by use of three independent linear springs. The axial stiffness can be different for behavior in compression versus tension.

3.1.3. Sheathing Panels

Past research has indicated racking is primarily attributed to sheathing-to-stud connector deformation with the sheathing acting as a rigid body. Because any reasonably close representation of the sheathing layers would be sufficient, they were modeled by orthotropic, plane stress, constant strain triangular finite elements. Other elements considered would have unnecessarily complicated mesh generation and increased the number of structural unknowns.

3.1.4. Fastener Elements

A plate-to-frame connection is shown in Fig. 3a. This fastener is modeled by a pair of orthogonal springs having the same resultant lateral load deformation behavior in any direction. This behavior is known to be nonlinear, as illustrated in Fig. 3b, and its treatment is described later.

3.1.5. Gap Elements

A gap between adjacent panels could be subjected to axial and frictional interaction. Gap axial stiffness has been quantified by Jizba [5]. Under load, portions of the gap can either close or open. In WANELS this performance is approximated by springs placed between adjacent nodes of each plate (Fig. 4a). The springs are given the nonlinear load-deformation behavior shown in Fig. 4b. No research has been conducted to quantify frictional sliding and this feature is not yet included.

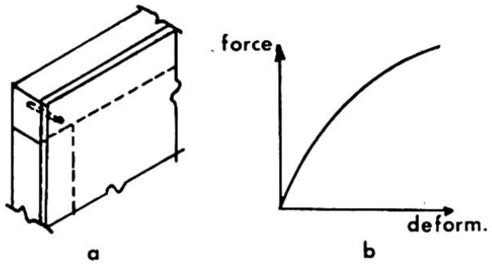

FIG. 3 FASTENER

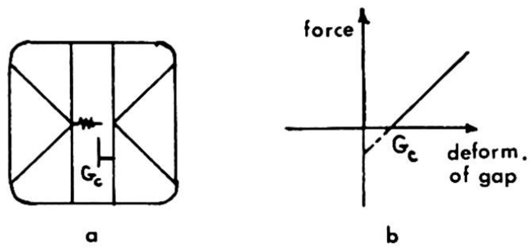

FIG. 4 GAP

3.2. Nonlinear Analysis Technique

When the nonlinearity is due to the connector force-slip relationship, the system stiffness equations are

$$[K(\delta)]\underline{D} = \underline{P} \tag{3}$$

where $\underline{D}$ is the vector of nodal displacements, $\underline{P}$ is the vector of applied loads, and the stiffness matrix $[K(\delta)]$ is a function of the interlayer slips. In WANELS a step-wise technique is used to solve Eq. 3. The method is based on a step-wise approximation to either nonlinear lateral nail resistance data or a chosen empirical relationship. Techniques for determining ordinates and abscissas are given in [1]. Basically, Eq. 3 is written as

$$[K(\delta)]\ \underline{D} = \underline{P} - \underline{E} \tag{4}$$

in which $\underline{E}$ is a vector containing the "extra-loads" of the connectors (an extra load is a segment y-intercept). Then Eq. 4 is solved by an iterative procedure. Treatment of the nails is depicted graphically in Fig. 5. The stiffness equations are coupled through degrees of freedom associated with frame connector, fastener and gap elements. Also, only those degrees of freedom related to nonlinearities are directly needed. The remaining degrees of freedom are partitioned and condensed prior to assemblage and initiation of the iterative procedure. Reformulation of matrices during iteration is further facilitated by similar partitioning of the extra loads vectors. Convergence is highly favorable when compared with other commonly used techniques [1].

3.3. Modeling a Series of Wall-Panels

A series of adjacent wall panels is modeled as depicted in Fig. 6. Flexibility

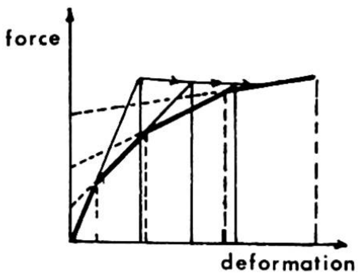

FIG.5 STEP-WISE SOLUTION

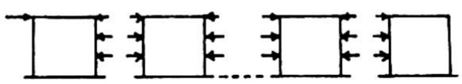

FIG.6 WALL-PANELS IN SERIES

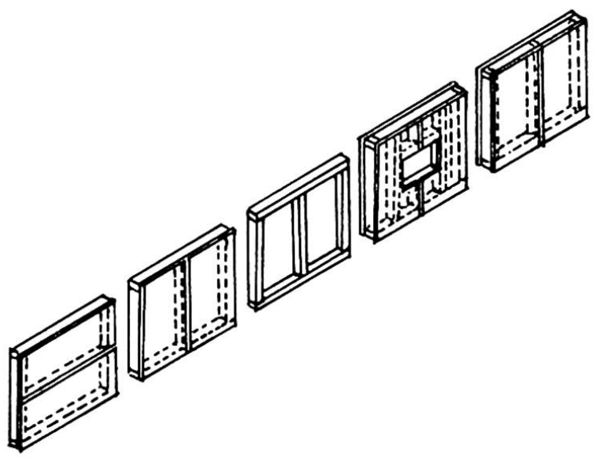

FIG. 7 HYPOTHETICAL SYSTEM

coefficients are generated by applying unit loads at each linked node and externally loaded node. Flexibility equations are then solved for the interactive forces. The response of each wall-panel is found by superposing the separate responses due to its interactive and external loads. Although this capability is presently limited to linear solutions, even geometries as complex as the hypothetical case in Fig. 7 would be readily solved in WANELS.

4. VERIFICATION OF PROGRAM WANELS

The accuracy of WANELS was examined and fully reported in [1]. Prediction of wall-panel load-deflection response was verified using test data obtained by Patton-Mallory et al. [8]. Ten replications of each of 20 different reduced size wall-panel specimens were tested to destruction. Four of these wall panel sets were used in verifying WANELS. Results for one of these are reported herein.

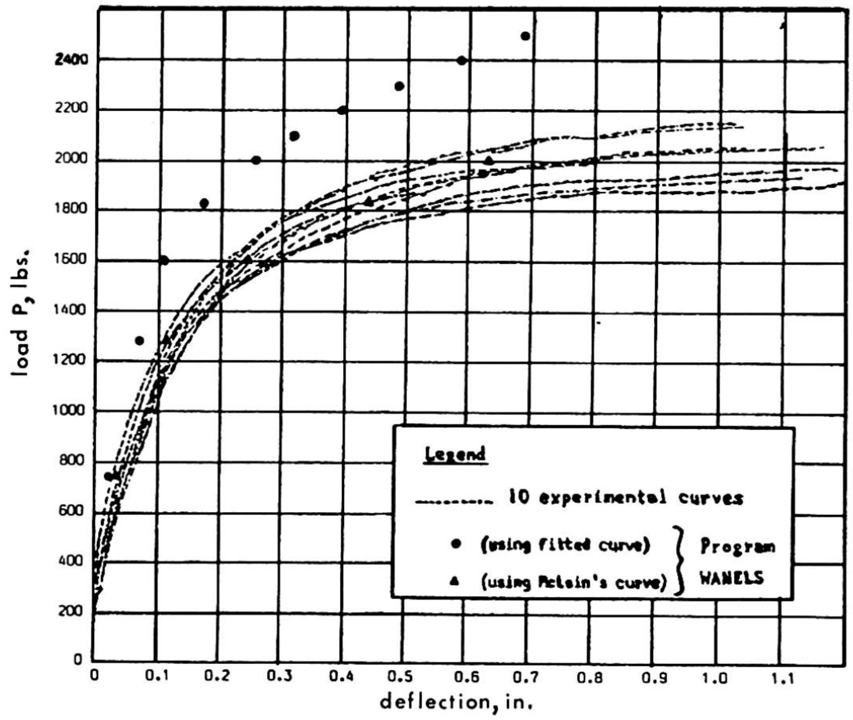

FIG 8. COMPARISONS WITH TEST DATA

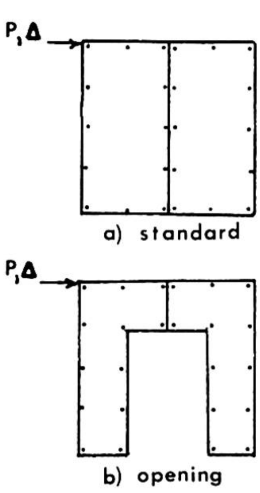

FIG.9 EXAMPLES

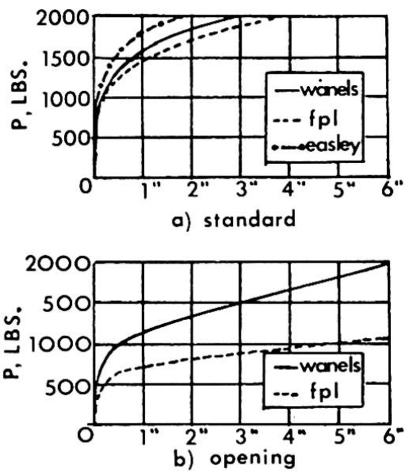

FIG.10 ANALYSIS

The test panel configuration was as shown in Fig. 1 except three studs were used. The frame's outer dimensions were 24 in. wide x 22 in. high. Nominal 2 in. x 4 in. Standard and Better Douglas-fir lumber was used. Sheathing materials employed were: 1/2 in. thick gypsum wallboard, and 1/2 in. thick 4-ply CD exterior Douglas-fir plywood with the face grain horizontally oriented. The Gypsum sheets and plywood panels were attached with 1-1/4 in. drywall screws 8d common wire nails, respectively. Connector spacings and support conditions are detailed in [8].

Patton-Mallory conducted 13 single shear tests (in accordance with ASTM D176-74) on each connector-sheathing combination used in her study. For 8d nails, a 16 segment step-wise curve was fitted to the 13 experimental curves for use in WANELS. Because the single-shear nail tests were performed immediately after specimen preparation no interlayer gaps existed. In contrast, at least one month elapsed between wall-panel construction and testing. Due to changes in moisture content and shrinkage interlayer gaps probably existed during testing. If so, the curve fitted to ASTM nail tests would overestimate the in-place stiffness of the nailed connections. Empirical relationships developed by McLain [7] allow consideration of the interlayer gap. Therefore, WANELS solutions were also obtained using a 16 segment step-wise fit based on McLain's relationships. It was assumed the effect of time on the drywall gap was minimal and an 11 segment fit was made to Patton-Mallory's ASTM data.

Each frame member was divided 4 planar frame elements with connector elements used to join the header and sill to the studs. The gypsum panel was divided into 64 finite elements with 19 nail locations. Each plywood panel was divided into 32 finite elements with 12 nail locations. Support conditions and loading simulated the actual test set-up.

Load-deflection results obtained from WANELS are compared with the experimental curves in Fig. 8. Use of McLain's relationships dramatically improved the prediction. Load deflection comparisons up to the 2000 lb load level are presented in Table 1. Nail force and slip output are examined in [1].

	ASTM			McLain		
Load P (lb)	WANELS Deflec D (in)	Avg.test load for (2) (lb)	Difference (1)-(3)/(1) (%)	WANELS Deflec D (in)	Avg.test load for (5) (lb)	Difference (1)-(6)/(1)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
740	0.0224	507	+31	0.0333	614	+17
1280	0.0573	821	+36	0.1104	1178	+ 8
1600	0.1049	1149	+28	0.2400	1580	+ 1
1830	0.1686	1404	+23	0.4335	1823	0
2000	0.2488	1597	+20	0.6316	1941	+ 3

Table 1. WANEL Results.

Single-layer wall-panels with the plywood configurations depicted in Fig. 9 were also studied. Nonlinear solutions based on the FPL and Easley equations were compared with WANELS. Nail force-slip behavior was based on McLain's approach. Fig. 10 shows the deflection comparisons. For the standard condition, the FPL method reasonably matched WANELS and was conservative. Easley's method produced greater error and was unconservative. Itani et al. [5] describe an approximate technique for applying the FPL equation to walls with openings. However, for the door opening case in Fig. 9b Itani's procedure greatly underestimates the system stiffness and overestimates the nail forces obtained from WANELS. This outcome is not unexpected. The primary difficulty is the nail force directions assumed in the FPL equation differ greatly from the WANELS output. Also, Easley's equation is not applicable when openings exist. Complete input and extensive results for these problems are presented in [1].

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