ABSTRACT

USDA Forest Products Laboratory research aimed at improved performance of structural components and more effective use of wood for light-frame construction is described. In addition, dissemination of research results through in-house publications and technology transfer is discussed.

INTRODUCTION

About one-half of the lumber and panel products produced in the United States is used for light-frame construction. In view of a potential shortage of sawlog and timber, the Forest Products Laboratory (FPL) of the Forest Service is conducting research aimed at improved performance of structural components (performance research) and more effective use of wood for construction (materials and products research). Since better utilization of wood and wood products depends to a great extent on the consumer, FPL publishes research results in a variety of practical handbooks. In addition, research on some projects is being widely disseminated through specific technology transfer plans. This paper presents an overview of light-frame construction research at FPL plus an extensive bibliography of publications covering all aspects of that research.

PERFORMANCE RESEARCH

Wood-frame systems must possess certain attributes to give satisfactory performance. Construction must be aimed at structural integrity, fire safety, durability, and a satisfactory living environment. A conference in 1981 addressed the state-of-the-art in predicting these attributes of a light-frame floor and wall system. The proceedings of this conference provided more detail than included in the following sections (FPRS, 1983).

Structural Integrity

Although the structural performance of a full-scale, light-frame house is not well understood, the low incidence of structural failure strongly indicates that the system is at least adequate and may even be overbuilt. In our research, we are developing methods to predict the structural characteristics of floor, wall, and roof systems individually. Then, we must understand how these components interact when assembled into a structure.

Floors: As a result of extensive research during the past decade, the structural performance of light-frame floors under uniform and concentrated loads is well understood. A comprehensive computer-based analysis program has been developed by researchers at Colorado State University (CSU) that provides a model of the structural interaction of the floor joist, sheathing and connectors (Thompson et al., 1977; Schaefer and Vanderbilt, 1983). In a cooperative research project, CSU and FPL used this model to predict the performance characteristic of floors (McCUTCHEON et al., 1981; Vanderbilt et al., 1983). Research at FPL also showed that a different type of model can closely predict the deflection performance of floors and this model can be easily adapted to microcomputers (McCUTCHEON, 1984). Additional work has been aimed at predicting the ultimate strength of floors (Wheat and Moody, 1984).

Most of the floor analysis work has been aimed at predicting performance under stationary or static loads. But there is some evidence that the dynamic or impact performance of floors may often be the critical factor in consumer acceptance. While some work in this area will soon be completed in Canada, the dynamic performance of floors needs to be better understood—particularly new products capable of spans beyond the traditional 4.27- to 4.88-m (14- to 16-ft) lengths become more widely available.

Walls: Walls perform several distinct structural functions which require different types of analysis. In a racking or shear mode, walls serve to keep the structure square and prevent other walls from “dominoing.” Analytical methods to predict both the strength and stiffness performance of walls under shear loading take into consideration the nailing between sheathing and studs to provide the shear rigidity (McCUTCHEON, 1985; Tuomi and McCUTCHEON, 1977). Recently, the significant contribution of gypsum board or “drywall” to the overall shear rigidity has been investigated (WOLFE, 1983; Patton-Mallory et al., 1984). Another function of walls is to transmit roof and/or second-story loads to the foundation through axial loads in the studs. A third function is to resist the bending loads acting perpendicular to the surface. These two functions are combined in an analysis procedure developed by Oregon State University (OSU) which requires the properties of interior sheathings, exterior sheathings, studs and fasteners to predict the strength and stiffness performance of light-frame wall systems. Cooperative work between OSU and FPL has yielded estimates of the effects of the major variable on wall performance (Polensek and Gromala, 1985).

Research on walls, similar to research on floors, has mainly considered only static loads. However, dynamic loads produced by earthquake or wind gust controls wall...
performance in many parts of the country (Soltis et al., 1981). Thus, new work is underway in the area of dynamic performance of walls under shear loading.

**Roof:** The excellent performance of the residential pitched roof system with trusses confirms that this system adequately resists structural loads. The trusses are the most highly engineered component of the wood framing. However, design does not take into account all the factors that influence the structural performance of roof systems. An extensive research program at FPL aims to better characterize the performance of light-frame roof systems. The objective of the research is to develop a model, similar to the models used in floor and wall research, to predict the load distribution and deflection performance of roof systems (Moody, 1984).

Research on truss modeling has been updated with a modern analysis method for evaluating truss designs (Suddarth and Wolfe, 1984). Work is continuing to improve the methods of predicting the performance of trusses with metal plate connectors.

**Full structure:** To better understand the overall structural performance of the entire light-frame structure, investigators at FPL evaluated the structural performance of a conventional full-scale house during progressive stages of construction (Tuomi and McCutcheon, 1974). Wind loads and snow loads were simulated in a large structural test frame (Fig. 1).

In wind-load simulation, 9.5-mm (3/8-in.) plywood sheathing on the walls provided more than adequate racking resistance, probably far in excess of normal requirements. In fact, we were unable to really test the walls because the failures in tests occurred in the connection between the loaded wall and the floor and later at the connection to the foundation.

Commercially fabricated metal-plate connected trusses on 0.61-m (24-in.) centers were used for the roof system. Tests showed no evidence of distress in the roof system up to 2.1/2 times the design load. At this point, one member of one of the roof trusses failed, but no collapse occurred. The trusses failed at more than three times the design load; had this been a snow load, the roof would have collapsed.

**Fire Safety**

In the past, light-frame house construction was subject to few fire regulations. Room contents, which are major contributors to fire growth, are not regulated. However, increasing emphasis on consumer protection and the use of new types of materials have resulted in new fire regulations on construction and interior finish. Research in fire performance is conducted in two general categories — (a) evaluating and predicting the endurance of the structure under fire and (b) determining the rate of heat release of wood products exposed to fire.

**Fire endurance:** Fire-endurance criteria monitor structural integrity to insure safe evacuation of occupants in the event of a fire and to lessen the risk of building collapse (Schaffer, 1984). Floor, wall, and roof systems must maintain adequate strength for prescribed times when subjected to fire conditions. FPL research has concentrated on quantifying the fire endurance (Fig. 2). A model for predicting the endurance of unprotected wood-joist floors was developed and validated (Woeste et al., 1981; White et al., 1984), and a similar model was prepared for wood truss floors (Schaffer and Woeste, 1984). A fire-endurance model is being developed for walls.

Fire endurance can be improved and the flamespread reduced by the use of coatings or treatments. At FPL, investigators evaluated the performance of five resistive coatings (White, 1983) and the effectiveness of various fire-retardant treatments for wood shingles (Holmes and Knispel, 1981), cellulosic insulation (Wegner and Holmes, 1983), hardboards (Myers and Holmes, 1977) and particleboard (Syska, 1969).

Research on smoke has led to some concepts that will enhance the ability of small-scale tests to predict the performance of construction materials in large-scale exposure to fire (Brenden and LeVan, 1984).

**Heat release:** A major factor that determined the overall fire performance of both materials and assemblies is the rate of heat release. The rate of heat releases for an assembly can differ considerably from the rates measured for its individual components because of
Durability
Durability, which assures longevity of a house, can be enhanced in a variety of ways—through the design, by treatment with preservatives, through proper use of finishes, and by properly controlling interior moisture.

Design: The fact that untreated wood will decay when subjected to certain conditions has been overlooked in the design of many recent structures. Wood structures still exist that were built long before preservative treatments were commonly used, indicating that buildings can be designed to reduce the hazard of exposure to the elements. The real problem is to re-educate designers on proper use of untreated wood (Sherwood and Percival, 1984). For example, the hot, humid climate of the southeastern states is particularly conducive to the growth of wood decay fungi. In a cooperative study with the University of Florida, FPL developed a series of extension publications that address important design considerations for this climate, such as appropriate roof overhang, separation from soil moisture, appropriate flashing, finishes and siding, and landscaping (Sherwood, 1982; Sherwood, 1983b,c,d,e,f).

Preservative treatment: The toxicity of all of the commercial wood preservatives presently used in the United States prevents microorganisms from attacking wood. These preservatives are registered by the Federal Environmental Protection Agency (EPA) and are under constant review. Some states also have restrictions on the use of certain preservatives. Both EPA and state agencies should be contacted for current regulations governing preservatives.

There are three alternative approaches for decay control which are not based on toxicity: (a) chemical modification of wood—the wood is not recognized by organisms (Rowell, 1975); (b) investigation of the metabolic systems of microorganisms (Highley, 1975); and (c) prevention of chitin (the chemical building blocks) formation in cell walls of wood-destroying fungi.

Exterior wood finishes: FPL research on exterior wood finishes has focused on the pretreatment/primer/finish interactions that are important for good performance of wood and wood products. Results of many studies are easily translatable into practical information for wood and finishing industries and for the general public.

Studies in the literature describe the durability of natural wood finishes (Feist and Mraz, 1980); finishing of hardwoods (Feist, 1983); finishing of wood panel products (Cassens and Feist, 1980b); causes and cures of paint failure and discoloration (Cassens and Feist, 1980a,c); and selection, application, maintenance and expected performance of exterior wood finishes (Cassens and Feist, 1980d; Feist and Oviatt, 1983; Feist, 1984).

Interior moisture control: Efforts to conserve energy have led to the use of new construction materials and techniques in light-frame construction. While increased tightness of houses has reduced air leakage, it has raised the level of indoor humidity. The result is a high potential for mildew, finish problems, and possibly decay. Mathematical simulations (Fig. 3) have shown that when infiltration rates in a medium-sized house fall below 0.5 air changes per hour, mechanical ventilation appears to be a necessity in tightly built houses. Studies are being conducted to determine the amount of ventilation required and appropriate methods for ventilation.

The construction of walls with higher insulating values has instigated study on the effect of indoor humidity on moisture content of the walls. To observe actual moisture patterns and the potential for condensation, two test structures each containing eight types of insulated wall panels were exposed to a cold, dry winter climate and a hot, humid summer climate, respectively. Indoor conditions were controlled. In both climates, penetrating vapor retarder with an electrical outlet totally changed moisture patterns in all types of walls, indicating that air leakage often causes moisture to move through walls. Although condensation occurred for limited periods in some panels at both test sites, moisture content of framing did not rise to critical levels and all panels dried out at the end of the heating or cooling season. Low-permeance foam sheathing did not produce any more cold-weather condensation than other types of sheathing and was effective in maintaining low moisture levels in the walls during a long cooling season (Sherwood, 1983a; Sherwood, 1985). Controlled laboratory tests are being conducted to develop data for creating a model of moisture movement in walls.

Noise Control
The increasing construction of housing in multifamily units has necessitated means for noise control. Reducing sound transmission, particularly through party walls, has been studied under both laboratory and field conditions. A recent technique for noise control is the uncoupling of walls by using a double row of studs. Well-
sealed storm windows have been found to satisfactorily block exterior noise, such as car and plane traffic (Heebink, 1975). Designs for noise control are available from an FPL report by Rudder (1985).

It is important to recognize that acoustical efficiency, which involves higher mass, low stiffness, and decoupled construction, works in opposition to structural efficiency and fire endurance. This indicates the need for a multidisciplined research approach to multifamily dwellings.

**MATERIALS AND PRODUCTS RESEARCH**

Materials and products research is aimed at finding more effective ways of processing wood for light-frame construction. Forest Service research is aimed at postponing a sawlog shortage as long as possible: (a) by better defining lumber properties and design criteria so that wood products can be used more effectively; (b) by using underutilized species and wood logging residues to make reconstituted wood products; (c) by finding techniques to convert logs into lumber and panel-type products more efficiently; and (d) by using new technology to process surplus low-density hardwoods into structural lumber.

**Lumber Properties and Design Criteria**

Information is available for selecting construction lumber for various applications based on species and characteristics of wood (Oviatt, 1979). However, the assignment of strength properties covered a range of values, so selection is based on the lower end of the range and often results in over-design for much of the material. Research is being conducted to determine the actual strength and stiffness of material as used in the field and how the duration of time loads are applied affect the material.

**Field testing:** For years, tests of small, clear wood specimens formed the basis for developing engineering stresses for lumber. But recent evaluations have indicated that this method is inadequate when lumber is used in highly engineered applications. Thus, a very extensive field testing program, called the “In-Grade Testing Program,” is being conducted in cooperation with representatives of the lumber industry (Green, 1983). The program is expected to be completed and implemented in 1987. The major result of this extensive testing program should be increased quality control and more efficient utilization of lumber.

Duration of load adjustment factor: Historically, a duration of load (DOL) adjustment factor has been used in design to account for a strength reduction of wood members after an elapsed time under load (Gerhards, 1977). The DOL adjustment factor is one of the primary factors used to determine allowable design stresses from clearwood strengths, and has been obtained from bending tests on small clear specimens of only one species. It has been extrapolated to all stress conditions; i.e. bending, compression, tension, etc., as well as to all grades, sizes, and species of structural lumber containing a wide range of strength-reducing characteristics. This method of extrapolation is now being questioned. In response, FPL is conducting an extensive research program in cooperation with the Forintek Corp. in Canada to establish DOL relations for lumber that include the effects of stress condition, species, grade, and size. At FPL, several hundred test machines are being used to evaluate the longtime loading characteristics of structural lumber under bending or tension loads. Additional work on compression loading is being planned.

Results of the DOL study and of the in-grade testing program will provide a comprehensive definition of the engineering properties of lumber. The objectives of these studies are to promote structural designs that use wood efficiently and to form a data-base for future reliability-based design codes.

**Residues and Underutilized Species**

Logging residues and underutilized species can be effectively used to produce particles for manufacture of both panels and structural members (Youngquist, 1981a,b). Current research is directed toward chemical treatments and processing prior to bonding for improved performance of the final product. Research on chemical treatments for dimensional stability and reduced water absorption have been given the highest priority, but fire retardants, preservatives, and bonding agents are also being studied. New processes and designs are also being developed for manufacturing structural members from composites of particles and wood (Laufenberg, 1985; Youngquist, 1983). The manufacture of flakeboard that is more than 38.1 mm (1-1/2 in.) thick has been made possible by steam-injection pressing technology. Economical press systems using this technology can produce lumber-type substitutes made entirely of low-grade hardwoods or of mill or forest residue (Laufenberg, 1984). The high speed of pressing using steam injection can also provide impetus to produce molded parts on a continuous basis, such as I-sections, corrugated panels, and rib-stiffened components.

**Conversion of Logs into Lumber**

Two programs of the State and Private Forestry branch of the U.S. Forest Service evaluated mill operations for efficiency and quality production. Since 1973, hundreds of mills nationwide have improved their recovery of lumber through the efforts of the Sawmill Improvement Program (Lunstrum, 1982). An analysis of the program from 1973 through 1977 showed an average improvement in recovery of lumber of 4.5% for mills that were studied (Lunstrum, 1981).

The second program, the Veneermill Improvement Program (Danielson, 1984), was initiated in 1984, and a dozen studies have been completed in both softwood and hardwood veneer mills. Preliminary results show an average improvement in recovery of about 6%.

**Hardwoods for Structural Lumber**

In the past 20 years, the volume of surplus merchantable hardwoods has rapidly increased. Many of the surplus species are low to medium density and are suitable for structural lumber. Although warp had been a major deterrent to the use of hardwood studs and joists, the Saw-Dry-Rip (SDR) process, a new process for manufacture, has produced straight, stable studs and joists. SDR overcomes the problems of inherent growth stresses in hardwoods (Maeglin and Boone, 1981). Tests in laboratory and commercial settings have been made with a dozen species, including yellow-poplar (Maeglin
and Boone, 1983; Weik et al., 1984), aspen and red alder (Maeglin, 1985; Huber et al., 1984), cottonwood (Trachsel, 1982), paper birch (Layton et al., 1983; Larson et al., 1983), red maple and basswood (Maeglin and Boone, 1985). Volume yields with SDR are comparable to yields from conventional processing while quality yields are 15 to 60% greater than conventional processing yields.

DISSEMINATION OF RESEARCH RESULTS

Publications
Forest Service research results are widely distributed through U.S. Department of Agriculture (USDA) handbooks. Although these handbooks do not emphasize recent research, they are nevertheless valuable to the building community.

Wood and wood products: The widely read Wood Handbook (U.S. FPL, 1974) was published in 1935 and is currently undergoing its fifth revision. The handbook describes wood and wood products from an engineering standpoint. Chapters cover the properties of both wood and wood-based products and the principles of drying, fastening, finishing, and preservation. The Wood Handbook contains information that has been gathered over 8 decades from engineering and allied investigations as well as knowledge of everyday construction practices and problems. A new edition will be available soon.

Wood-frame house construction: Many wood houses that were built more than 200 years ago exist today. The wood-frame house is not only long lasting but economical and can be constructed in any location. Few, if any, materials can compete with wood framing in house construction. The handbook Wood-Frame House Construction (Anderson, 1975) provides information on materials and building practices to guide builders and prospective homeowners in erecting a well-built house that requires a minimum of maintenance. The handbook presents methods for assembling and arranging parts of a well-designed wood-frame house. While details may vary with building locality, the fundamental principles of the established methods of construction are the same.

The handbook is extensively used as a training guide for carpenter apprentices in the United States and has been translated into several foreign languages. It is considered the nationwide guide by which to judge the quality of house construction. To keep pace with modern materials and techniques, the handbook is currently undergoing extensive revision in cooperation with the National Association of Home Builders (NAHB) Research Foundation, and it is scheduled to be reprinted in approximately 3 years.

Rehabilitation of older homes: The demolition of an older home to build a new one constitutes a waste of resources. Although many old homes have been well maintained and remodeled to keep pace with changing lifestyles, others lack modern conveniences and/or have deteriorated through neglect. Many of these homes could be rehabilitated at a lower cost and with less material than needed to construct a new home. In addition, the advantages of rehabilitation are that the homeowner can stay in familiar surroundings, that work can progress as finances become available, and that the character of the older home is preserved.

The publication New Life for Old Dwellings (Sherwood, 1975) was developed to promote the two-fold advantage of lower-cost housing and conservation of our natural resources. This handbook is divided into two sections: (a) the procedures for appraising an old structure for possible rehabilitation, and (b) actual rehabilitation. In the appraisal section, guidelines are presented for a systematic approach to inspecting the building and evaluating the results of inspection. The second portion of the handbook guides the planning and process of rehabilitation.

The handbook is useful to homeowners and prospective buyers of older homes. It may also be of interest to carpenters, contractors, lending agencies, and groups who seek to maintain and improve communities.

Wood decks: Decks provide outdoor living areas for homes on steep sloping sites and are increasingly popular for homes on level ground as well. To assist in planning and construction, the USDA Handbook (Construction Guides for Exposed Wood Decks (Anderson et al., 1972) was written. This handbook offers guidelines in the design, finishing, and treatment of outdoor wood decks. Good and poor construction practices are illustrated for the benefit of architects, builders, and homeowners.

The Truss-Framed System: The Truss-Framed System (TFS) (Fig. 4) is an innovative wood-frame construction method developed by FPL for residential buildings, which integrates customary construction components—roof trusses, floor trusses, and wall studs—into unitized frames. The NAHB Research Foundation cooperated with the FPL in developing a manual of practice, Truss-Framed Construction (NAHB, 1983). It includes sections on overall design, details of construction, and the construction process. The generously illustrated text provides a complete guide for builders or designers for using truss-frame construction.

Technology Transfer
Research findings are of no value until they are put to practical use. In its simplest form, “technology transfer” is transmitting information to potential users in a form that the user can understand and apply. The TFS System is a recent example of carefully planned technology transfer. When direct written and verbal inquiries to FPL exceeded 100,000, it became obvious that a formal plan was needed to disseminate the technology. A national Technology Transfer Plan was developed in regard to the TFS by the State and Private Forestry group of the Forest Service, and a new position,
Construction Specialist, was created to lead the effort. The Technology Transfer Plan was initiated in January 1981 with two specific goals to be accomplished within a 3-year period: (a) obtain acceptance of TFS technology by a major government regulatory agency, and (b) have TFS structures built in 30 states. It is estimated that this nationwide plan exposed 2.5 million people to TFS, and both goals were achieved ahead of schedule.

Based on the success of this national Technology Transfer Plan, two additional research topics were identified and approved for technology transfer: timber bridges and SDR technology. Although budget constraints have prevented our hiring a Construction Specialist for the bridge project, some progress has been made on the SDR project. One workshop was held in the Lake States emphasizing the manufacture of structural lumber from aspen. Two additional workshops are planned in the South involving the manufacture of yellow-poplar lumber using SDR technology.

Another effort, sponsored by the Federal Extension Service of USDA, is underway to improve the transfer of research and technology. For the past year, an extension specialist was assigned to FPL to develop a national model for wood products technology transfer. This work is being continued by a part-time specialist, and a plan is being developed which facilitates dissemination of information through the federal, state, and county extension network.

SUMMARY

The Forest Products Laboratory is conducting light-frame construction research in both performance of components and properties of materials and products. Performance research includes structural integrity, fire safety, durability, and noise control. Materials and products research includes lumber properties, use of residues and underutilized species, efficient conversion of lumber, and use of hardwoods for structural lumber. Much of this research is being incorporated into handbooks that can be used by designers and engineers, builders, and homeowners. These handbooks also provide valuable training guides for the building trades.

Obviously, research results must be applied at the consumer level if the mission of extending the timber supply through better utilization is to be accomplished. The interest and cooperation of academic and industry representatives are vital to technology transfer.

References

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