Multi-Story Wood Frame Construction in the United States

Don E. Wallace, Western Wood Products Association, USA
Kevin C.K. Cheung, Western Wood Products Association, USA
Thomas Williamson, APA - The Engineered Wood Association, USA

Abstract

Wood-framed buildings of four and five stories are becoming increasingly more common in the United States as developers are requiring greater project density to offset rising land costs. Driven by tight budgets and construction schedules, architects and engineers accustomed to designing two and three-story wood frame buildings, are facing new technical and structural challenges as wood-frame buildings push the limits of building codes and material properties. A growing body of successful projects suggests that the design community is successfully meeting this challenge.

Keywords: Multi-story, UBC, BOCA, SBC, Engineered wood products, Lateral loads, Shrinkage

Building Code Provisions

The majority of construction in the United States is regulated by three major model building codes, these being the Uniform Building Code (ICBO, National Building Code (BOCA), and Standard Building Code (SSBCI). Some major urban regions develop their own versions of these codes, and some states or municipalities adopt amended versions of the model codes. By the year 2000 the major model building code organizations anticipate the development of a single code to be known as the International Building Code. They have already published the International Plumbing and Mechanical Codes and are actively working on the development of the building code.

All of the model codes place limitations on building heights and areas, but they also recognize various factors involving the building occupancy, and the safety features of the building. The initial limitations are placed upon the allowed height and

floor area of a building based upon the occupancy use of the building and the materials used to construct the building. These limits can then be modified by the location of the building in relationship to the property lines, access for fire and emergency service, use of automatic fire suppression systems, and further protection of the structure through increased fire resistance, reduction of the fire area, and separation of identified hazardous areas.

Fire walls and area separation floors are commonly used as design tools to increase the maximum allowable floor area, or number of stories, of a wood-frame building (height cannot be increased). Fire walls can be provided to segment a structure into two or more separate buildings for determining allowable floor areas. Under some specific conditions the area separation is not limited to vertical wall elements. A common solution to the problem of on-site parking for multi-story multi-family residential structures in the Standard and Uniform Building Code regions is to incorporate a concrete garage at the base of the multi-story wood frame building. The horizontal (non-combustible) platform above the garage serves as a horizontal fire separation between residential occupancies and the parking structure, allowing an increase in the number of stories for the wood frame structure above. The same strategy can be applied to mixed-use developments under the UBC. Business and mercantile occupancies can also increase the number of stories that can be built above a concrete garage as long as they do not exceed the height limits in the code. Residential and commercial occupancies above a concrete parking structure are illustrated in the case studies.

Wood Materials

North American designers have a wide variety of wood materials from which to select when considering the use of wood for multi-story building construction. These include traditional wood framing products such as lumber, metal plate connected wood trusses and structural wood panels, and other glued engineered wood products such as prefabricated wood I-joists, glulam, laminated veneer lumber, and parallel strand lumber. The following sections briefly describe each of these products and the standards which govern their use in the U.S.

Structural Lumber

Traditionally, most sawn lumber used in multi-story construction has been visually graded and this continues to be true today. However, increased emphasis is being placed on using additional techniques for evaluating the structural performance of lumber in order to optimise yields of high quality material from the resource base. Machine Stress Rated (MSR) and Machine Evaluated Lumber (MEL) are the two most common non-destructive mechanical evaluation technologies used to segregate solid sawn lumber into stress categories.

Since the 1920's, the assignment of allowable stresses for visually graded lumber has been based on the application of the principles set forth in ASTM D-2555, *Standard Test Methods for Establishing Clear Wood Stress Values,* and *ASTM D-245, Standard Practice for Establishing Structural Grades and Related Properties for Visually Graded Lumber.* However, in 1991, the regional lumber grading agencies published new design values based on the results of a U.S. "in-grade" lumber testing program. The "in-grade" lumber testing program lasted over 12 years and involved physically testing over 70,000 pieces of lumber. As a parallel activity, a new *ASTM Standard, D-1990, Standard Practice for Establishing Allowable Properties for Visually Graded Dimension Lumber from In-Grade Tests of Full Size Specimens,* was developed and approved. *The American Softwood Lumber Standard, PS-20*, provides for the quality control of the lumber grading process in the U.S.

Metal Plate Connected Wood Trusses

One of the most common uses of structural lumber in multi-story buildings in the U.S. is in metal gusset plate connected wood trusses. Probably the single most significant breakthrough in expanding the use of wood trusses was the development of metal gusset nail plates as a joint-connection device for the lumber members.

Metal gusset plate wood trusses are virtually unlimited with respect to the configurations which can be achieved. In multi-story construction, parallel chord trusses are often used for floor construction whereas either parallel chord or pitched trusses are used for roof construction. Both the Truss Plate Institute (TPI), which represents the plate manufacturers , and the Wood Truss Council of America (WTCA), which represents the truss fabricators, have developed technical literature related to the design and installation of this type of truss.

Structural Wood Panels

Structural wood panels include plywood, oriented strand board (OSB) and composite panels. Structural panels manufactured in the U.S. have traditionally been produced in 1220 mm (4 ft.) by 2440 mm (8 ft.) sizes but some newer technologies for producing these panels permits other larger sizes to be readily manufactured. Plywood is the oldest of the structural wood-panel products and is manufactured by adhesively bonding thin veneers of wood together in a cross-banded orientation. OSB is produced by bonding individual strands of wood together in a mat formed product. Composite panels, as the name implies, are products consisting of wood face veneers and a reconstituted wood core. Both composite panels and OSB are manufactured with the alternating layers, whether mats, veneers or wood based cores, oriented at 90 degrees to each other to produce a cross-banding effect similar to plywood.

Plywood has traditionally been produced in accordance with *U.S. Product Standard PS-1 for Construction and Industrial Plywood.* In addition, *Voluntary Product Standard PS-2, Performance Standard for Wood-Based Structural-Use Panels*, allows plywood, OSB and composite panels to all be produced for the same performance rated end uses (sheathing, structural I sheathing and single floor) under one common standard.

Glued Laminated Timber (Glulam)

Glulam was first introduced into the U.S. in 1935, after almost 40 years of use in Europe, and is used in a wide variety of structural applications including multi-story construction. Glulam is a stress-rated product produced by adhesively bonding together individual laminations of sawn lumber. All of the laminations are positioned with their grain approximately parallel to the length of the member, with the maximum thickness of any individual lamination being 2 inches. Long length laminations are achieved by bonding shorter lengths of lumber together with structural end-joints. Due to its inherent manufacturing characteristics, one of the advantages of glulam is that higher design stresses can be achieved as compared to sawn timber members.

Glulam is produced under the provisions of *ANSI Standard A190.1, Structural Glued Laminated Timber*, a prescriptive Standard that sets forth the manufacturing requirements. This Standard also specifies the various physical and mechanical tests that must be performed throughout the manufacturing process to assure that the finished product meets all provisions of the Standard. *ASTM Standard D-3737, Standard Practice for Establishing Stresses for Structural Glued Laminated Timber,* sets forth the methodology for assigning stresses to glulam.

Structural Composite Lumber (SCL)

Structural Composite Lumber (SCL) is a term that refers to a group of products including laminated veneer lumber (LVL), parallel strand lumber (PSL) and other composite lumber products. Laminated veneer lumber is created by adhesively bonding together relatively long strands of wood fiber (the least dimension of the strands shall not exceed 6.35 mm (0.25 in.) and the average length shall be a minimum of 150 times the least dimension) such that the strands are oriented in a parallel configuration with the long axis of the member. PSL is used as beams, headers and columns in much the same manner as glulams.

LVL is the most widely used of the SCL products. It is typically produced in 610 mm (2 ft.) or 1220 mm (4 ft.) billets. It is produced in varying thicknesses with 38 mm (1.5 in.) and 44.5 mm (1.75 in.) being the most common and is then ripped into a variety of sizes. The most common use of this product in multi-story construction is to use multiple pieces of 44 mm thick LVL mechanically fastened together to form beams or headers.

Since all SCL products used in the U.S. are produced as proprietary products, each manufacturer must obtain their own code acceptance through code reports. These reports establish the various strength properties for the products and define the quality assurance testing program that is required to assure that these stress levels are maintained. *ASTM Standard D 5456, Standard Specification for Evaluation of Structural Composite Lumber Products*, sets forth general criteria for evaluating the mechanical properties of these products and establishes test protocol for verifying the structural property assignments.

Prefabricated Wood I-Joists

Wood I-joists produced in the U.S. are manufactured in an "I" shape using either sawn lumber or LVL flanges with plywood or OSB webs. As with SCL products, all I-joists used in the U.S. are proprietary with each manufacturer maintaining code approval through code reports. These products are typically produced in depths of 241.3 mm (9-1/2 in.), 301.6 mm (11-7/8 in.), 355.6 mm (14 in.), 406.5 mm (16 in.) up to depths of 762 mm (30 in.) in multiples of 50.8 mm (2 in.). I-joists are used primarily in floor and roof construction in much the same manner as sawn lumber joists.

Because I-joists can be supplied in long lengths, they are ideally suited for use in multiple span applications such as may occur in floor systems for multi-story construction. The use of these products does introduce several unique design considerations. For example; how to transfer the relatively high loads at interior bearings of multiple spans, the necessity for special framing at cantilevered members, and the necessity to use web stiffeners, or the need for other reinforcement under design considerations such as when supporting concentrated loads.

ASTM Standard D 5055, Standard Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists, sets forth general criteria for evaluating the mechanical properties of these products and establishes test protocol for verifying the structural property assignments.

The Choice of Framing Materials

Because the U.S. designer has this wide variety of wood products from which to choose, a number of factors must be considered in making the final material selections. In most multi-story buildings, the majority of the wood framing elements are concealed from view through the use of sound and fire-rated wall, floor and ceiling assemblies. However, in some instances, the designers choose to expose the wood framing members for aesthetic reasons, and this influences materials selections.

Lumber joists, wood I-joists and parallel chord trusses are all frequently used for floor and roof construction, the choice between them being influenced by economics, project design requirements and designer preference. For example, if a suspended ceiling is to be used permitting the passage of ductwork and plumbing below the framing members, lumber joists may be the product of choice. However, if space below the framing is limited, and it is necessary to pass mechanical systems through the framing members, parallel chord trusses or wood I-joists offer the designer greater flexibility.

For pitched roofs, metal gusset plate wood trusses are often specified due to the high degree of flexibility and construction economies that can be achieved with these prefabricated components. Lumber joists and wood I-joists can also be combined with heavier structural components such as glulam ridge and valley beams, or SCL headers and beams, to form simple or intricate pitched roof configurations.

Regardless of the choice of structural framing members used, a wood structural panel is typically used to transmit both gravity and lateral loads to these members. All of the panel products including plywood, OSB and composite panels can be used in these applications. For roofs, these are typically specified as a rated sheathing product using a designation such as a 15/32" thick 32/16 panel grade. For floors, these may be single layer floors or may be a sheathing grade panel used in conjunction with an underlayment grade for the installation of finish floors such as tile or vinyl.

Bearing wall construction in multi-story buildings is an area where non-wood products may be used in an otherwise all wood framed structure. Designer preference, or building code restrictions, may dictate the use of exterior bearing walls constructed of masonry or concrete. When wood framing is used, it is virtually always sawn lumber construction with the size and spacing of studs depending on load carrying requirements.

As with floor framing, wood panels are used as structural components of the wall framing. These may be fabricated with any of the rated sheathing panels with the thickness and grade dependent upon the spacing of the lumber and the loads to be resisted. Wood panels are typically used on one or both faces of exterior walls when the wall is required to function as a shearwall as discussed in a later section. Structural wood panels are also used in combination with drywall although the contribution of the drywall to the shear resistance is quite low in comparison to the wood panels.

When aesthetics are an important design consideration, exposed sawn timbers or glulam members are often used. These are often used in conjunction with a sawn or laminated heavy timber decking product to allow all of the structural components to be exposed to view. This type of system introduces unique challenges to the designer with respect to the design and installation of mechanical and electrical systems such that the aesthetic aspects of the exposed timber is not compromised. An example of such an application is described in a later section.

Special Construction Considerations

Shrinkage

Most of the building codes utilised in the U.S. require a shrinkage analysis for any wood-frame structure of more than three stories. Shrinkage is a result of wood's natural drying process and is most noticeable in horizontal members such as floor joists, wall plates and beams. If not taken into consideration it can affect mechanical and plumbing systems, as well as interior and exterior finishes.

Softwood species used for structural framing have minimal longitudinal shrinkage characteristics so the need to analyze movement in that direction is generally eliminated. Design considerations for shrinkage are applied to the thickness and the width of wood structural members used horizontally. Shrinkage is normally uniform in structures using platform frame construction throughout, but special consideration must be given to designs that create an opportunity for differential change. For example, when a platform framed system is used in combination with a balloon framed system, or when a wood-frame structure is combined with masonry veneer, a steel-framed atrium space, a concrete elevator shaft or stairwell, or even when wood-based systems are installed at different moisture contents, specific attention must be given to assure the compatibility of the framing for shrinkage consideration .

Wood will shrink during the natural seasoning process from the fiber saturation point (28 to 30 percent) until it reaches "equilibrium moisture content" (EMC) with local atmospheric conditions. EMC is in the 8 to 12 percent range for most enclosed structures in the U.S., but building occupancy functions and air-conditioning systems can cause variations in the normal regional EMC.

In most one and two-story structures, the cumulative effect of shrinkage can be accommodated readily on the job site as the wood dries in place, even when unseasoned lumber is specified. However, for three, four, or five-story buildings, it is advisable to specify the lowest available moisture content for horizontal framing members. The most readily available, seasoned two-inch thick structural framing lumber is identified as "S-Dry" or "KD", indicating it was seasoned to a maximum moisture content of 19 percent at the time of surfacing. Actually, surveys reveal that the moisture content of "S-Dry" or "KD" lumber averages 15 percent or less at time of surfacing. Because larger (3 inch nominal thickness and thicker) solid sawn lumber is shipped unseasoned, the use of these members in locations where their dimensional change can impact subsequent floors should be avoided in multi-story wood framed structures. Other wood framing systems like built-up two-inch thick members, wood trusses, glued laminated beams or laminated veneer lumber beams are often substituted for solid sawn lumber in these instances. Wood I-joists and laminated veneer lumber are manufactured at moisture content levels lower than EMC and can actually be expected to swell somewhat when exposed to the weather during construction and then may shrink again as they reach EMC. Glued laminated beams are manufactured to a 12 percent average moisture content and are subject to minimal EMC dimensional change.

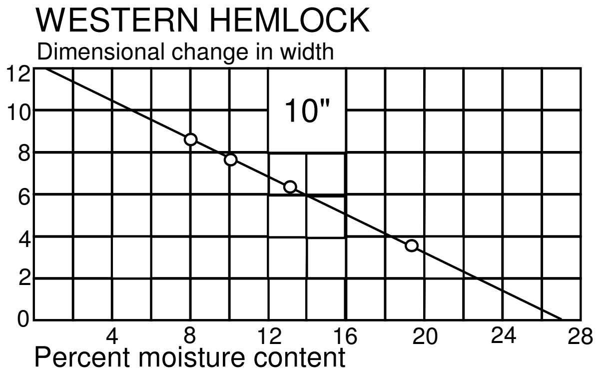
As multi-story wood-frame technology continues to evolve, details are being developed to minimize the effects of shrinkage and offer options to designers. Framing walls up to floor-level heights and supporting joists with steel hangers is a technique often used to eliminate wide face cross grain shrinkage. To avoid potential shrinkage-related plumbing problems, contractors should add flexible connectors and extra elbows for flexibility, and where possible maintain good clearance between pipes and framing. The effect of the shrinkage of wood floor trusses supported by steel beams can be minimised by supporting the trusses from a reinforced top chord rather than having the bottom chord bearing on top of the beam.

Dimensional change may affect exterior and interior finishes differently. Finishes such as wood siding, drywall, and stucco can be detailed to allow movement at each floor level. Band boards, slip joint flashing, and expansion joints are usually adequate as long as the finish material is not continuous across multiple horizontal framing elements. The calculated differential movement of wood framing with brick veneer is more significant because brick can expand as the wood framing shrinks. Windows are usually isolated from the brick veneer and flexible stainless steel anchors are used to tie the veneer to the frame and allow for movement.

Thought should be given to the sequence of construction activities when analysing individual floor shrinkage and overall shrinkage. For example, post occupancy evaluations of multi-storey wood-frame buildings with brick veneer show that the actual differential movement is usually considerable less than the calculated difference because the platform framing often is allowed to nearly reach equilibrium moisture content prior to the application of the veneer. Interior finishes should be looked at in a similar manner.

The following dimensional change chart indicates that an average Western Hemlock 2x10 would change in width nearly 8 mm (5/16 in.) from the surfaced "S-Dry" size at 19 percent moisture content to an equilibrium moisture content of 8 percent, and indeed it may, but is that scenario valid in the overall shrinkage analysis? As previously discussed, most lumber that is manufactured to a maximum 19 percent moisture content averages 15 percent at time of surfacing. In addition, the lumber will then continue to attempt to reach the EMC of 8 percent during construction.

A more realistic look at the dimensional change prior to the application of interior finishes may be a comparison of a 13 percent lumber moisture content and an EMC of 10 percent during interior finishing. This relates to less than a 3 mm (approximately 1/8 in.) change as the lumber dries from 13 to 10 percent, and an ultimate change of slightly over 3 mm as it reaches EMC. The "S-Dry" 2x10 may change from the "S-Dry" size of 235 mm (9-1/4 in.) to just under 229 mm (9 inches), but only about 3 mm of that shrinkage may occur during this phase of construction. Thus, each multi-story building must be looked at individually with the understanding that the sequence of construction activities, and the climatic conditions, play a major role in the actual dimensional change which may be expected to occur.



Sound Transmission

Sound transmission is an important non-structural design consideration for multi-story wall and floor construction that may control material choice whether the structure is a multiple family residential application or a commercial building. A variety of wood framing systems have been tested for sound transmission properties and these are published in industry brochures, textbooks, handbooks and in proprietary product code reports. Lightweight gypsum concrete and other types of sealers are also often used to reduce sound transmission in multi-story structures. The choice of structural wood component is often not as important as the choice of a system when designing to minimise sound transmission.

Lateral Load Design

General Considerations

All structures are subjected to lateral loads generated by wind forces, and in many areas of the U.S., to lateral forces induce by the movement of their foundations during earthquakes. The importance of properly providing for the adequate transfer of lateral loads induced by seismic or wind events is of paramount importance in multi-story wood framed buildings where the accumulation of these forces can reach relatively high magnitudes. The three model building codes in the U.S. set forth the load requirements for both seismic and wind forces. It is the designer's responsibility to adequately account for these forces in the building design.

Shearwall and Diaphragm Basics

The most commonly used concept for transferring lateral loads through a wood structure to the foundation is to introduce shearwalls (vertical elements) and diaphragms (horizontal elements) into the framing system to resist the imposed code specified lateral loads. The APA publications, *Diaphragms, Plywood Shear Walls and Plywood Diaphragms* provide the basic methodologies for designing a structural wood panel diaphragm or shearwall. Other related APA publications are *Wood Structural Shear Walls with Gypsum Wallboard* and *Openings and Performance of Wood*

A diaphragm is considered to be analogous to a horizontal wide flange beam with the chords resisting the bending forces while the structural panels carry the in-plane shear forces. Diaphragms are further assumed to be flexible with the distribution of loads based on tributary areas and lengths, resulting in a uniform shear across the width of the diaphragm.

While the lateral load analysis of rectangular shaped buildings is relatively straight forward, the designer is often challenged by how to transfer the calculated shear and overturning forces within the structure, particularly in buildings with discontinuous shearwalls having numerous openings, with narrow shearwall elements, or irregular (non-rectangular) diaphragm shapes. These conditions require considerable consideration to detail adequate connections within the lateral load resisting subassemblies to ensure that they act as integral units, and to then interconnect these subassemblies to ensure that the building as a whole can withstand the forces.

The McGraw-Hill *Wood Engineering and Construction Handbook* by Faherty and Williamson is one reference that provides a complete analysis of wood framed diaphragms and shearwalls including connection detailing recommendations.

Load Considerations

Another complexity of multi-story timber design in the U.S. is that it may not be readily apparent which lateral loads control the design. Because timber structures are relatively light-weight, it is often the case (even in high seismic risk areas) that the lateral forces induced by wind loads are greater than the static seismic forces imposed on the building. In some cases, such as long rectangular buildings, the wind loading in one direction can be the controlling design condition whereas the seismic loading can control in another direction.

For wind loading, forces on a wall section are assumed to be transferred equally to the top and bottom of the wall. However, for earthquake loads, the wall is assumed to act as a simple cantilevered beam element. Thus, it may not be obvious which loading condition controls design, particularly for the design of the connections.

Special Design Considerations

Due to their flexible nature, wood diaphragms cannot effectively distribute torsion loads such as may be introduced in a cantilevered (three sided) diaphragm. Thus, loads distributed to some of the supporting structure may be magnified significantly, and the open side of the diaphragm could undergo excessive deflection and cause damage to finish materials. This is just one of may special design considerations that may be associated with diaphragms.

Shearwalls also can present many unique design considerations. When shearwalls are offset, the designer must address out-of-plane reactions as well as providing for the overturning forces down to the base. Discontinuity's due to openings also create design challenges as the U.S. building codes do not provide specific design guidance for discontinuous shearwalls. Thus, the designer must provide for increased forces in the walls due to lesser energy-absorbing capabilities, and provide additional strength in columns supporting the ends of discontinuous walls. Some designers have used simple frame models and provided metal straps or ties to help distribute the moments.

In typical multi-story wood framed buildings in the U.S., the walls and floors are platform framed which does not allow the vertical panel walls to run through the floor framing. This creates a difficult design problem for transferring forces in high load shear walls since conventional nailing may require such close spacing that splitting may occur. One solution is to use steel angles attached to the double top plate of the wall and the rim joist to transfer these forces.

The overturning forces must also be transferred through the floors in platform frame construction. One way to accomplish this is by using threaded hold-down rods attached to metal connectors at the wall framing above and below the floor. Another proprietary system provides for hold-down rods running from the foundation continuous to the roof of multi-story buildings. Various types of steel straps running from one story to the next can also be used depending on the loads involved.

On some occasions, a combination of materials are required. For example, it is often necessary to introduce a braced steel frame at the first floor of multi-story structures when the wood panel shearwalls are penetrated by large openings. An understanding of how steel and other materials work with wood frame systems to resist design forces is imperative to achieve a successful building design.

Story drift is becoming more of a design consideration in multi-story construction. Fortunately this has not been a major problem with wood framed structures. These structures have the inherent presence of redundancies in the lateral force resisting system due to a substantial number of interior partition walls which are not designed as shearwalls but contribute significantly to the resistance of lateral forces. This combined with the ductility of wood construction provides a multi-story construction system which performs well when subjected to lateral forces.

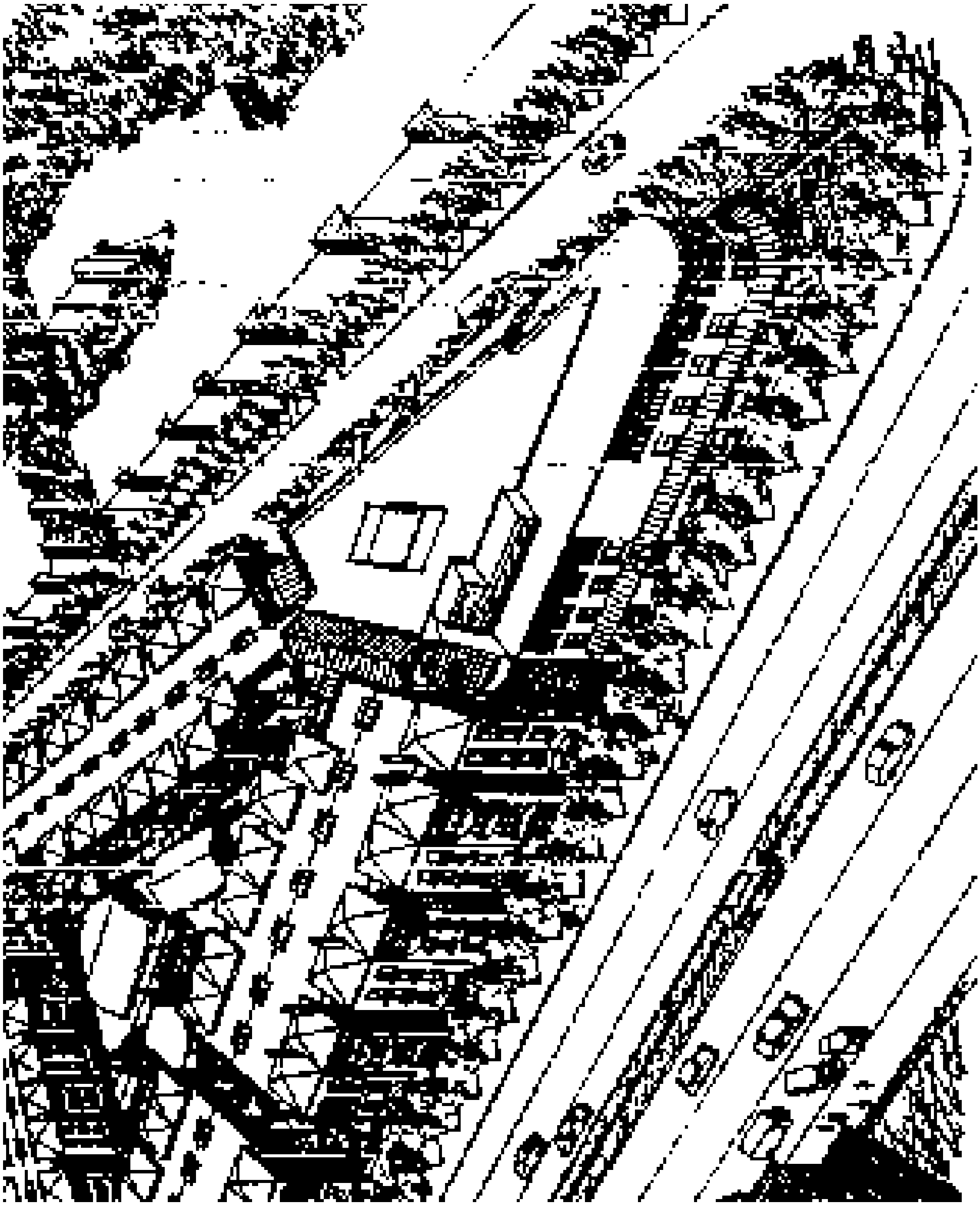
Typical Applications - Case Studies

The following projects are provided to illustrate typical multi-story wood-frame projects in the U.S. Wood frame was chosen over alternative systems for these projects because of its economy, ease and speed of construction, structural performance and designer preference.

Delancey Street Foundation Triangle

A trend in San Francisco has been the construction of three and four-story wood-frame residential structures over a one-story parking or retail space. One such project is the Delancey Street Foundation Triangle Complex. The Delancey Street Foundation is an innovative and highly successful rehabilitation program for drug abusers and alcoholics.

The complex has seven buildings totalling 30,195 m^2 (325,000 sq. ft.) (see artist's rendering). The buildings contain housing and work space for several hundred people, a central courtyard, a health club, pool, 500-seat assembly hall, and a recreational building with a 150-seat screening room. In addition, 138 covered parking spaces are provided. Commercial spaces are provided on one side of the complex on the street level.
To help eliminate shrinkage problems the structural engineers specified a locally available finger-jointed 2x10 joist product which is manufactured at a 12 percent maximum moisture content. Because the 12 percent matches well with the local equilibrium moisture content, the engineers did not feel it was necessary to perform shrinkage calculations.



Artist's Rendering - Delancey Street Foundation Triangle Complex

The Delancey Street complex is located in Seismic Zone 4. The area is in proximity to a major fault system where extensive damage may occur in the event of earthquakes. The structure was severely and unexpectedly tested as the project neared completion, when Loma Prieta, a 7.1 Richter-scale earthquake struck San Francisco. The project is located within a few blocks of the Embarcadero Freeway overpass and the Bay Bridge, both of which were severely damaged, yet the Delancey Street project suffered no damage, not even a crack in the plaster.

The upper floor uses gypsum board for about half of the shear walls in the party walls. Corridors, some unit walls, and the remaining party walls are of 9.5 mm (3/8-in.) plywood. Exterior walls are a combination of 12.7 mm (1/2 in.) plywood and 12.7 mm (1/2 in.) gypsum board on the top stories and 12.7 mm (1/2 in.) plywood on both faces of the stud wall framing for the lower two floors. Straps were used to tie the upper floors to the lower floors. Standard commercial hold-downs were used in the lower stories to transfer loads. Party walls between units, some unit walls, and the corridor walls were used to obtain the necessary shear wall resistance. The exterior sheathing also provided shear wall resistance but it was not relied upon in the shear wall calculations.

The site is located on an artificial fill over bay mud. The mud covers sands and clays, which overlay bedrock. The foundation engineer specified pre-cast concrete piles be driven to support the structures. A concrete one-story parking and commercial structure was built upon the pilings and the wood-frame structures were built on top of the concrete structure.

Sound transmission between the units was controlled by installing staggered 2x4 studs on a single 2x6 plate. One face of the wall is covered with 15.9 mm (5/8 in.) gypsum board; the other side has 9.5 mm (3/8 in.) plywood with a 15.9 mm (5/8 in.) gypsum board overlay. Acoustic batting was woven between the staggered studs. The assembly provided a sound transmission class rating of approximately 53.

Complete costs for the project are difficult to estimate because many of the materials were donated and much of the construction labor was provided by members of the Foundation under the supervision of the project coordinator.

The Gatesworth at One McKnight Place

This National Association of Home Builders (NAHB) award winning senior housing facility is one of the largest four and five-story wood frame buildings in the Midwestern U.S. The multi-wing building includes 219 one and two-bedroom apartments with balconies and full kitchens. The Gatesworth also includes a theater-style auditorium, arts and crafts center, greenhouse, fitness center, library and lounge areas, as well as formal and informal dining rooms.

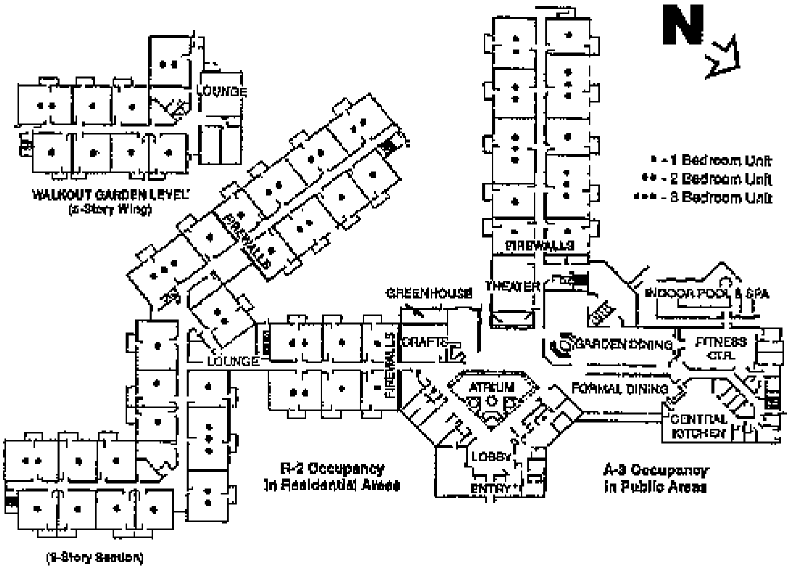


Figure 1 - Floor Plan for The Gatesworth at One McKnight Place

The main section of the building and two of its wings are four stories on top of a cast-in-place concrete parking garage. The five-story section extends from the building's south-eastern end. Due to the mixed use occupancies and the floor area requirements, the designer provided 3 two hour rated separation walls as indicated on the floor plan (Figure 1). The two-hour walls were achieved by using two layers of 5/8-inch gypsum wallboard on each side of the wood frame wall assemblies. The building was provided with an automatic fire-suppression system to take the allowable one-story increase and the five-story wing was achieved by a variance on the overall heights restriction and by considering it, in essence, a walk-out basement with four stories on top of it.

Seismic forces were not significant factor because St. Louis is located in Seismic Zone 1 (now Seismic Zone 2). Wind loads were the main consideration for lateral forces design. The basic wind speed for St. Louis is 70 mph. The Gatesworth was designed to resist an approximate load of 718 Pascals (15 lbs./sq. ft.) of projected area. To resist these forces, gypsum sheathing was used on all exterior, interior, and partition wall faces. Some selected walls have plywood as well as gypsum sheathing for added resistance.

The designers decided to use consistent 610 mm (24 inches) on center framing throughout the building in order to allow vertical members to carry the majority of the load. Loads are carried by double 2x6 walls on the bottom two stories of the four-story building to the spread footings. Triple 2x6's were necessary to carry the load on the first floor of the five-story structure. Floors were framed with a combination of conventional floor joists and parallel chord wood floor trusses. The building was framed entirely with standard wood fasteners, such as nails and light gauge metal connectors. Standard 12.7 mm (1/2 in.) diameter anchor bolts secure the building to its concrete foundation.

To alleviate shrinkage problems all horizontal members in The Gatesworth were specified to be maximum 19 percent moisture content and the designer used parallel chord trusses for all floors above the first floor. Whenever possible the floor trusses were hung from their double top chord so as to minimize vertical shrinkage. Pitched roof trusses bear on the exterior walls and the interior corridor walls with each half of the roof trussed separately with a gap provided at the ridge to allow for any movement which may take place. This arrangement virtually eliminates the potential for cracks on the interior finishes due to differential shrinkage.

SW Washington Medical Office Building

This structure, located in Vancouver, Washington illustrates how a variety of wood products including lumber, wood I-joists, wood trusses, structural panels and glulam can be combined into an efficient and cost competitive structural system. This four- story office building has medical related firms as tenants and is located adjacent to a major hospital.

The primary structural framing is glulam beams bearing on steel columns. The wall construction is conventional 2-inch stud walls with the exception of two exterior reinforced concrete block masonry walls which function as the primary shear walls to transfer lateral loads to the foundation.

Floor construction consists of wood I-joists spaced 610 mm (24 in.) on center between the glulam beams. These I-joists support 18.2 mm (23/32 in.) thick 48/24 rated sheathing with the floor designed as a horizontal diaphragm. Roof construction consists of metal gusset plate wood trusses at 610 mm (24 in.) on center with 11.9 mm (15/32 in.) thick 24/12 rated sheathing, which also serves as a horizontal diaphragm to transmit lateral loads. This project is an excellent example of a U.S. multi-material utilitarian wood frame structure.

Beacon Bay Office Building

Although not a totally all wood framed structure, the Beacon Bay office building in Newport Beach, California is an excellent example of the use of exposed wood framing in a multi-story building. This five-story structure uses steel columns, glulam beams and reinforced masonry for the primary structural members. The glulam beams run in the narrow direction of the building and have an interior span of 12.2 m (40 ft.) with 3.65 m (12 ft.) cantilever extensions on each end. Steel beams form the structural support in the long direction of the building.

The floor and roof construction consists of 3-inch nominal heavy timber decking installed over the glulam beams. Since the exterior walls make extensive use of glass curtain walls, the floors and roof became key elements of the lateral load resisting system and were designed as horizontal diaphragms. To resist the high shear forces induced in Seismic Zone 4, 12.7 mm (1/2 in.) Structural 1 rated plywood sheathing was installed over the heavy timber decking to increase the diaphragm capacity. All lateral forces are transferred to two heavily reinforced masonry towers which contain the stairwells and elevators.

The glulam beams and heavy timber decking are exposed throughout the structure. Mechanical and electrical systems were carefully designed and detailed to blend into the structural framing and maintain the desired aesthetics of the exposed wood members.

Marriott Courtyard Hotel

One of the largest multi-story hotels built in the Washington, D.C area became the forerunner of 190 Marriott Hotels nationwide. Marriott's Courtyard Hotels had been previously built with masonry hollow-core walls and precast panels. The use of conventional wood frame provided a savings of 10 percent when they analyzed this project in comparison to masonry and steel construction.

The second and third floors were constructed using 10,365 lineal m (34,000 lineal ft.) of wood I-joists. Glulam beams support pitched trusses which were built in two pieces to bear on a center wall. A total of 80 glulams were used in the 146 room project. The roof trusses, which utilized nominal 2x6 top and bottom chords with 2x4 webs, were spaced 610 mm (24 in.) on center. Spans vary from 6.1 m to 18.3 m. The Marriott Corporation construction manager reported that the wood design provided sound proofing that is superior to the masonry and steel designs under consideration. The floor sound isolation was accomplished by applying a 25.4 mm (one-inch) thick gypsum-based underlayment over the plywood sheathing and wood I-joists.

Summary

In the United States, wood framing systems have proven to be a viable construction method for building multi-story structures. While long used for two and three-story construction, the advent of new technologies and innovative designs have expanded the use of wood framing to four story and greater construction. These have primarily been for multi-family residential and office building applications as highlighted in this paper.

Enhancements of existing wood products and the development of new engineered wood products will further enable designers to use wood in multi-story construction. In addition, the U.S. wood products industry has undertaken a nationwide educational program focused on providing designers with increased educational opportunities in wood engineering. This effort is expected to expand the horizons for the use of wood framing in multi-story building construction using a variety of innovative wood products and framing systems.