MULTI-STORY WOOD-FRAME CONSTRUCTION

Kevin C. K. Cheung, Ph.D., P.E.
Western Wood Products Association, USA

ABSTRACT

Shortage of affordable housing is a problem shared by all major industrialized cities around the world. Three- to five-story wood-framed buildings offer economical housing through fast construction speed and low material costs. In the designing of multi-story wood-framed buildings, fire-safety and structural considerations are required by building codes. In addition, shrinkage and sound transmission do require special attention.

Three projects are presented to showcase multi-story wood-frame construction. Common to these projects, wood-frame was chosen over other systems for its economy.

Figure 1. Construction photo of a multi-story wood-frame building

INTRODUCTION

The world's population is increasing. Providing affordable housing is a problem shared by major industrialized cities around the world. Multi-story wood-frame construction offers a solution to rising land and construction costs. Three- to five-story wood-framed buildings offer economical housing through fast construction speed and low material costs.

In the U.S. Western states, major cities are turning to multi-story wood-frame construction to provide greater density of living units in the little remaining development spaces in the urban areas.

The popularity of multi-story wood-frame construction is spreading outside the U.S. and Canada in countries such as Japan and Australia, as well as in some European countries.

STRUCTURAL CONSIDERATION

Wood is a timeless building material. It has been desired for its structural capabilities and its aesthetic value. Wood strength is high in the direction of the grain but weak across the grain. Designed and used properly, wood has very few structural limitations.

Wood assemblies offer a high strength-to-weight ratio over those built with steel and concrete. This results to low inertia force during earthquakes. In wood-frame construction, a large number of walls are often used in a project, which reduces the loads shared by each wall. Structural walls and floors are used to transfer lateral loads induced by winds and earthquakes.

Lateral loads

Wood-frame construction generally, structural walls and floors sheathed with structural wood panels in particular, has long been recognized for providing superior performance against strong forces resulting from wind storms and earthquakes. These walls and floors maintain high stiffness and strength in the design range, and if pushed to their ultimate capacity, tend to yield only gradually while continuing to carry high loads -- these assemblies have high ductility which can absorb a great deal of energy before failure.

Observations from past earthquakes show that wood buildings have performed well. Current building code requirements for hold-down devices and shearwalls worked effectively in creating earthquake-resistive structures.

Much of the major damage to wood structures occurred to homes built before modern seismic codes were in place. Damage often resulted from inadequately braced or completely unbraced cripple short walls in crawl space construction; from houses sliding off foundations because they lacked foundation hold-down bolts; and the lack of shearwalls at the ground-level due to garage door openings -- soft story.

Vertical loads

To carry the high gravity loads on the lower floors, lumber studs in sizes of 2x6, 3x4, or 3x6 are often used in single, doubled or tripled construction. Figure 2 is a detail from Case study III (The Gatesworth) project showcased later in this paper. Eight 2x6 lumber studs were used on the lowest level of the 5-story wing to carry up to 35,000 lbs. of concentrated load under a 10' window header. Compression perpendicular to grain may control

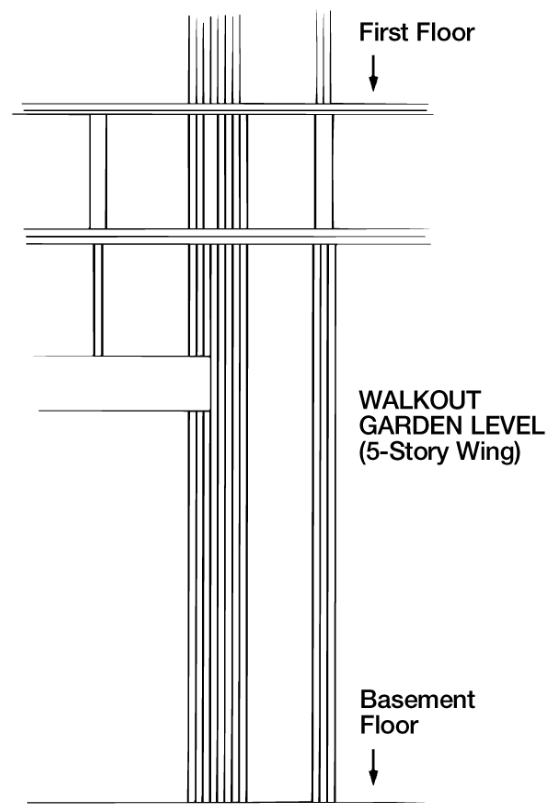


Figure 2. Multiply pieces of lumber studs are used together when needed to carry gravity loads at lower floors

stud size due to end-bearing requirements on the wall plates, or bearing plate sizing in beam and column design. Where joist, beams or studs bear on supports, some fiber deformation develops, requiring the bearing area to be of sufficient size to prevent excessive side grain crushing of the joist, beams or plates.

SHRINKAGE

Shrinkage results as wood dries. In most one- and two-story structures, the cumulative effect of shrinkage can be accommodated readily, even when unseasoned lumber is used. However, consideration for shrinkage is required by building codes for wood-framed buildings more than three stories. Using DRY (below 19% moisture content) lumber will minimize wood shrinkage problems like cracking of finish and distress in plumbing systems.

Wood shrinks from the fiber saturation point (28% to 30%) until it reaches equilibrium moisture content (EMC) with local atmospheric conditions. The EMC of wood products is about 8% to 12%. Factors such as climate conditions or mechanical air conditioning can cause variation in the EMC. Consequently, EMC should be established for each building location.

For softwood species, dimensional shrinkage of 0.2% per each 1% change of moisture content is a practical estimation for the thickness and the width dimensions (perpendicular to the wood grain) of solid wood members use horizontally.

Shrinkage in the parallel to wood grain direction is very small, and is generally neglected. It can be estimated as 0.005% of the member dimension per 1% change of moisture content.

The total shrinkage in a conventionally framed building can be calculated by summing the shrinkage of the horizontal wood members in the walls and floors, such as wall plates and floor joists. The overall shrinkage in multistory wood frame construction can be further reduced by placing floor joists in metal joist hangers off the walls instead of on top of the walls.

The cumulative effects of multi-story shrinkage can cause large expanses of interior and exterior drywall, paneling and siding to buckle. Example areas are stairwells, shafts, vaulted ceiling areas, atriums and continuous vertical siding applications. The solution is to break up these large surfaces with band boards, expansion joints or slip joint flashing at each floor level.

Wood products and systems

The most readily available seasoned 2" thick structural framing lumber is S-DRY (seasoned to a maximum 19% moisture content) lumber.

Wood I-Joist and wood-based composite structural members (LVL, PSL, etc.) have become more available and economical in recent years. These products are often made at moisture content lower than EMC, and will swell slightly in service.

Parallel chord wood trusses can be used instead of lumber joists to reduce shrinkage.

Differential shrinkage

Lumber shrinks due to drying, but subsequent dimensional changes are minimal after lumber reached EMC. Brick, concrete and steel will expand and contract with temperature changes. Differential shrinkage occurs when wood-framing is used with materials and components having different dimensional stability characteristics, such as brick veneer, a steel-framed atrium space, a concrete block elevator shaft or stair tower, or a wood-based system installed at a different moisture content.

If, for example, floor joists are supported by a wood-frame wall at one end and by the masonry block of an elevator shaft at the other end, differential movement may occur between opposite ends of the joists. This condition may require framing the wood so it is entirely independent of the block wall, framing the joists to the block wall after the wood-framed walls and joists reach equilibrium, or balloon framing the wall using dry plates.

Differential shrinkage can occur when joists are side-mounted to engineered wood beams such as glued-laminated timber or Parallel Strand Lumber. If mounted flush, the joists may shrink more that the beam, leaving the tops of the joists below the top of the support beam. Installing the joists about 1/4 inch proud of the beam will ensure a uniform finish floor.

FIRE SAFETY

Building codes have height and area limitations on wood construction due to fire safety considerations. Building codes allow height and/or area increases for open space on two or more sides of the building, and automatic sprinklers. In addition, for the purpose of determining area, those portions of a building separated by one or more fire-resistive area-separation walls may be considered a separate building.

Common in multi-story wood-frame construction projects, code allowed height and area increases are used. One-hour fire-resistive construction is usually a minimum throughout. Higher fire endurance ratings are required for stairway enclosures and exit hallways.

Fire-tested assemblies

Fire tests have been conducted on assemblies utilizing gypsum products to provide fire resistance. Using the result of these tests, fire ratings have been established and tabulated in the "Fire Resistance Design Manual" published by the Gypsum Association, Washington, D.C.

Component additive method

Assembly fire endurance can be calculated using the Component Additive Method. Based on information from fire test reports, time values for contribution to fire endurance for each individual component was assigned. This method allows the calculation of fire endurance as the sum of the contribution from each component in the assembly. Time values for additional protection due to the use of cavity insulation and reinforcement of the membrane have also been assigned.

Fire-stopping and draft-stopping

Fire-stopping and draft-stopping techniques that have been traditionally required by the U.S. building codes provide effective methods of improving fire safety in wood-frame buildings. Fire-stopping prevents movement of flame and gases to other areas of a building through relatively small concealed passages in building components such as floors, walls, and stairs. Wood blocking is commonly used between joists and along wall plates. Non-combustible material is used around vents, pipes, ducts, chimneys and fireplaces.

Draft-stopping prevents the movement of air, smoke, gases and flames to other areas of a building through large concealed passages, such as attic spaces and floor assemblies with suspended ceilings or open-web trusses.

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 propriety product code reports. Lightweight gypsum concrete and other type of sealers are also often used to reduce sound transmission in multi-story wood-frame structures. The choice of structural wood component is often not as important as the choice of a system when designing to minimize sound transmission.

A sound transmission class (STC) ratings of 45 to 55 are commonly cited as good sound barriers.

For improved sound reduction, light weight concrete is used on the floor; 1-1/2" thick standard light-weight concrete of 60 to 90 pounds per cu. ft., and 3/4" thick gypcrete of 100 to 130 pounds per cu. ft. Light weight concrete is self leveling. The concrete is poured after framing is completed and all electrical and plumbing systems are installed. Expansion joints are created by metal T-channels often put at door openings along wall lines.

CASE STUDIES

Three projects are presented to showcase multi-story wood-frame construction. Common to these projects, wood-frame was chosen over other systems for its economy from the fast speed of construction for each building's size and occupancy type, and low material costs. Wood-frame allows easier construction of such details as fire-stops and blocking.

Case study I -- Copperfield Hill

Copperfield Hill is the first five-story wood-frame building built in Minneapolis, Minnesota. The building is a 165,000 square foot self-contained retirement community which provides apartment-style living spaces and common areas, including a kitchen and dinner facility, music room, library, card and game rooms, a craft shop, and an art center. Figure 3 shows a selected elevation of the project. The project was completed in 1987. The budget for the project was $9.5 million, which included the cost of land and $4.7 million for construction.

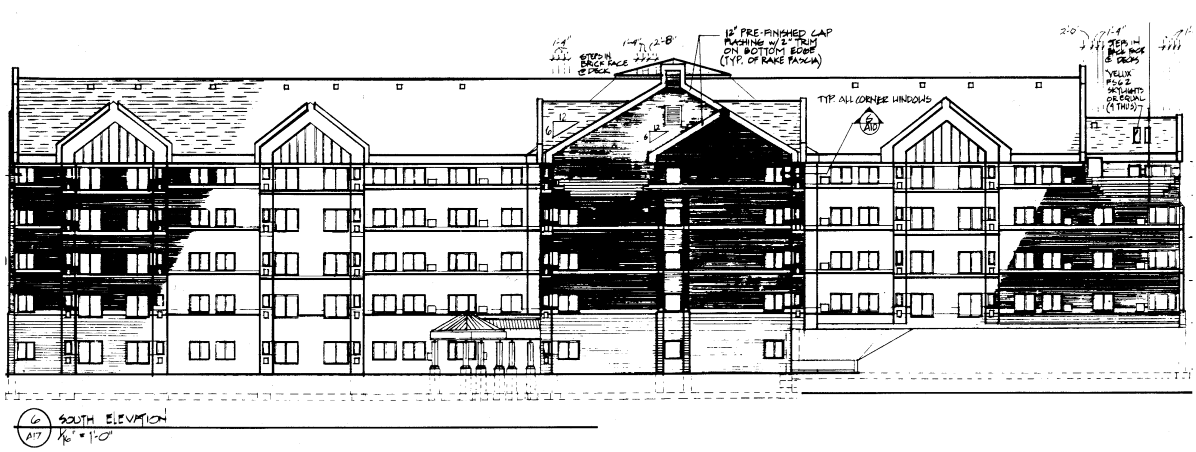
Wood-frame was chosen based primarily on cost compared to steel-frame. Bids for steel-frame came in at more than 75% higher than the wood-frame. The ease of wood construction allowed the building to be framed in just more than five months.
According to the 1985 Uniform Building Code, exterior walls were required to be constructed of non-combustible materials. The architect divided Copperfield Hill's living area into six "buildings" by the use of six area separation walls.

To minimize shrinkage, the project architect selected open web parallel-chord trusses for most floor joist members. Other than shrinkage consideration, this type of truss provides easy access for routing plumbing, mechanical, and electrical systems. Solid sawn lumber joists and wood I-joists were also used, but to a lesser extent. Steel was used to form the large open central atrium and to support the code-required non-combustible metal pan stairs.

For aesthetics and to meet the code requirement for non-combustible exterior wall assemblies, a brick facing was chosen. For framing within the exterior walls, the architects specified fire retardant-treated lumber covered by Type X gypsum wallboard on the interior.

Although the exterior brick walls reach 50 feet height in some places, they were constructed without the use of relieving angles. However, numerous vertical expansion joints and flexible brick ties were used to minimize cracking.

Wind was the main lateral force design consideration. No uplift problems were encountered in the design. To carry the high gravity loads on the lower floors, 3x4 lumber at 16" on center was typically used for the interior wall studs, and 2x6 lumber at 16" on center were used for the exterior wall studs. Hem-Fir Stud grade was specified for stud lumber.



Case study II -- Delancey Street

A trend in the Western U.S. cities (Seattle, San Francisco, Portland, San Diego, Las Vegas, and others) has been the construction of three- and four-story wood-frame residential structures over one-story of post-tensioned concrete parking and retail spaces. One such project is the Delancey Street Foundation Triangle Complex in San Francisco. The complex owner is the Delancey Street Foundation, an innovative and highly successful rehabilitation program for drug abusers and alcoholics.

The complex has seven buildings totaling 325,000 square feet of space. The complex contains a central court yard, a health club, pool, 500-seat assembly hall, a recreation building with a 150-seat screening room, a dry cleaner, an auto repair shop with an antique car museum, wood shops, and a 400-seat restaurant. The four residential buildings provide 177 living units. Areas below the three-story wood-frame structure provide commercial and retail space. Figure 4 shows an artist's project rendering.

The materials for the complex were donated, and the Delancey Street members did much of the construction themselves and learned valuable construction skills. The project was completed in 1989.

Each building has two exterior exit stairways, which are constructed of precast concrete treads, risers and landings. The buildings also have one interior exit stairway, which is of wood-frame. All wood-framing is Douglas Fir-Larch. To help reduce shrinkage problems, 2x lumber with a maximum of 12% moisture content was used as floor joists. No shrinkage calculations were performed.

Sound transmission between units was controlled by installing staggered 2x4 wall studs on a 2x6 plate. One face of the wall is covered with 5/8" gypsum board; the other side has 3/8" plywood with a 5/8" gypsum board overlay. 3-1/2" acoustic batting was woven between the staggered studs in the wall cavity. The entire assembly provides an STC rating of approximately 53.

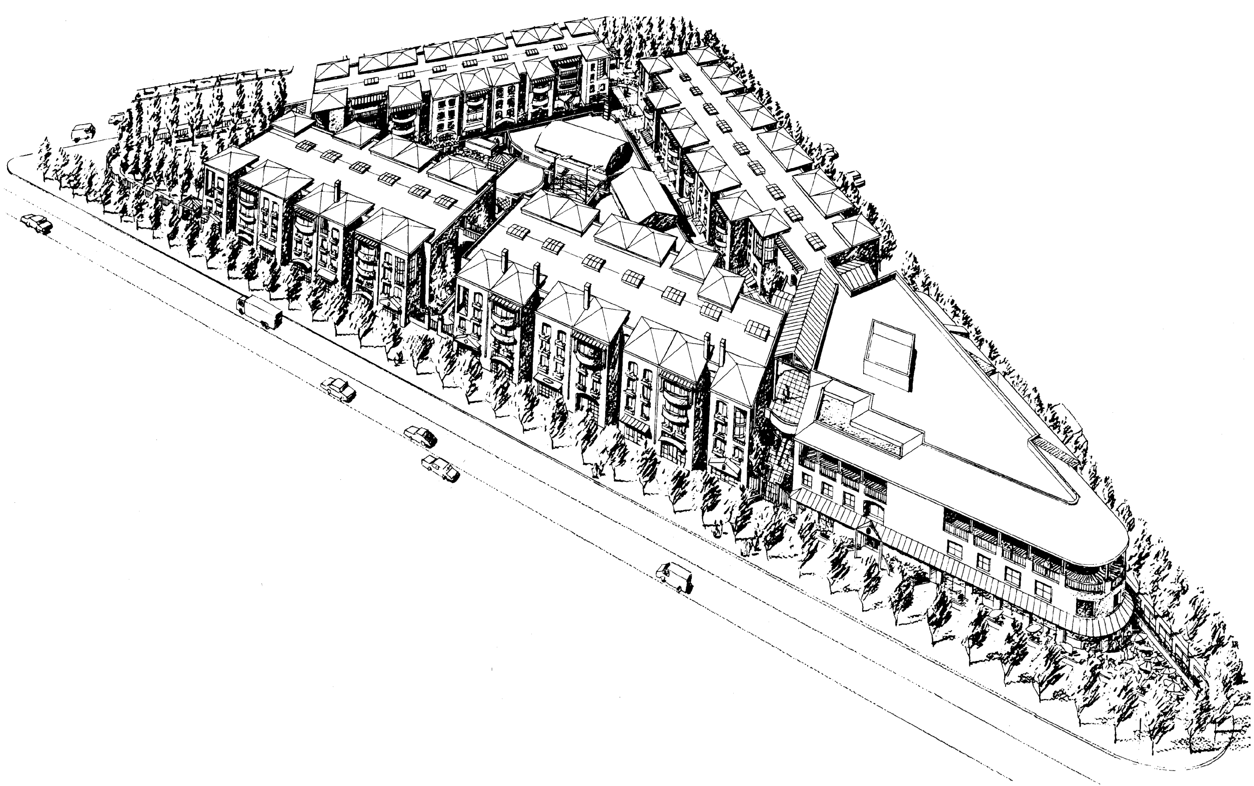


Figure 4. An artist's rendering of the Delancey Complex (courtesy of Backen, Arrigoni & Ross)

Case study III -- The Gatesworth

The Gatesworth is a four-story wood-frame building, with one five-story wing, near St. Louis, Missouri, U.S.A. As one of the larger wood-frame buildings in the Midwest, it contains 280,000 square feet of living area plus 65,800 square feet of parking under the building for a total of 345,800 square feet.

The building is a retirement community with shopping, cultural activities, banking and churches. The facility was designed to offer its residents comfort, flexibility and freedom, and to complement the architecture and ambience of the surrounding residential neighborhood. The multi-wing building includes 219 one- and two-bedroom apartments with balconies and full kitchens, a theater-style auditorium, greenhouse, fitness center, arts and crafts center, library and lounge areas, and formal and informal dining rooms. Figure 4 shows a project floor plan.

Wood-frame was chosen because the developer's and the builder's familiarity and experience with this type of construction. The project's total cost was $25 million which included land, financing and marketing expenses. Of the total, $2 million was for land and $16 million was for site development, labor and construction materials. The project took 15 months to construct and was completed in 1988.

The main section and two wings are four stories on top of a poured-in-place parking garage. A four-story skylight atrium in the center of the main building serves as a gathering place. Steel components were used for parts of the parking garage and for the open-frame public area which includes the four-story atrium structure.

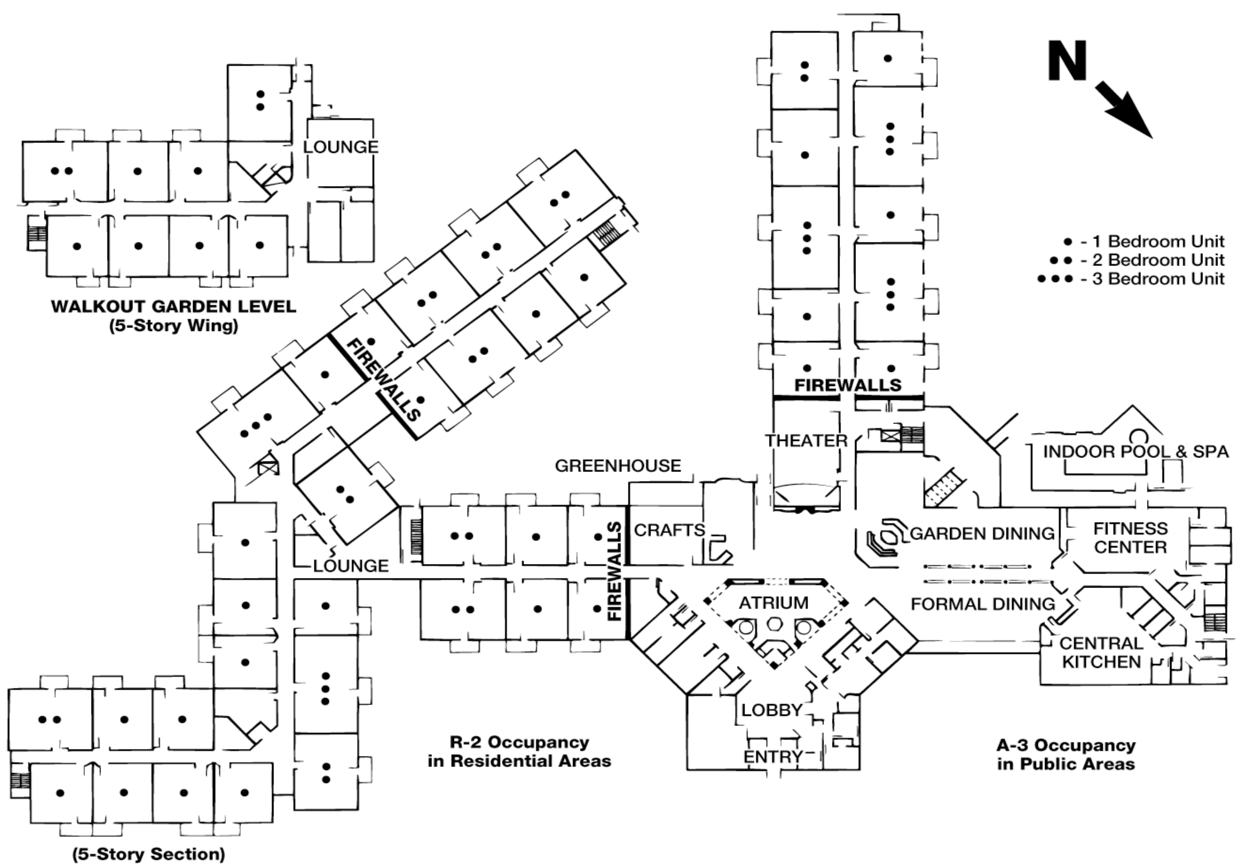


Figure 4. Floor plan of the Gatesworth project (courtesy of Arthur J. Sitzwohl & Associates)

The project was designed using three fire-separation walls to divide the building into four different building sections. A two-hour rating was required for the exit hallways, stairway enclosures and assemblies separating the parking garages from the living areas above. The two-hour rated walls have two layers of 5/8" Type X gypsum wallboards on each side.

Two-hour fire-resistance rated floor separating the parking garage from the living areas is 2x12 lumber joist floor sheathed with two layers of 5/8" Type X gypsum wallboards on the garage ceiling and 1-1/2" of lightweight concrete over 5/8" plywood on the first story floor. The balconies on each unit were framed with fire-retardant treated lumber to maintain the required fire-resistance rating of the exterior walls.

Interior walls have a Sound Transmission Class rating of 55-60. Typical wall construction was an inner layer of 1/2" sound board on both sides, with an outer layer of 5/8" Type X gypsum wallboard. Floor/Ceiling separations have a Sound Transmission Rating of 50-55. This was achieved by insulating between the trusses and 5/8" Type X gypsum on the ceilings. The floors are 5/8" plywood covered with 1-1/2" of lightweight concrete.

Wind was the main lateral force design consideration in lateral force. Basic design wind speed is 70 mph, approximately 15 lbs./sq. ft. on the projected area. To resist the lateral forces, gypsum sheathing was used on all exterior, interior and partition wall faces. Some selected walls were built with plywood as well as gypsum sheathing installed on the exterior faces. Douglas Fir-Larch Stud grade 2x6 lumber was doubled at 24 inches on center for the first- and second-floor bearing walls to carry loads that were as high as 5,000 lbs./ft. Tripled 2x6 lumber studs were used for the lower level walls in the five-story wing.

The consistent 24" on center spacing throughout the building allowed the vertical members to carry most of the loads. Loads are carried to the ground through the alignment of the vertical bearing members, on the ends of each floor truss, to the vertical load-carrying studs directly below. This reduced the load on the horizontal members.

The building was framed entirely with standard wood fasteners, such as nails and light-gauge metal connectors. Standard 1/2" diameter anchor bolts hold the building to its concrete foundation. No special ties between floors were needed because the gypsum or plywood sheathing overlapped each floor on the exterior walls. Connections of wood floor trusses to steel-frames were made by bolting a continuous wood plate to the top of the steel beam, thus making a standard wood-to-wood connection possible.

The floor members were 24 inches deep parallel chord trusses, except for the joists supporting the first floor. The 2x12 first floor lumber joists were blocked with short vertical pieces under the bearing walls, see Figure 2. This arrangement takes advantage of wood's negligible longitudinal shrinkage and allows the vertical blocking to carry the load if the 2x12 joists shrink across their width.

In most cases, wood floor trusses were hung from the steel beam to avoid differential shrinkage between wood and steel. Commercial brick anchors were used between the wood-frame and brick veneer which allowed for a differential movement of 1" or less.

Movements between the ceiling and the interior partitions near the middle of the building can result to cracks on the surfaces. To prevent this potential problem, four bearing lines through the cross section of the building were used. The interior corridor partitions were designed as bearing walls to support the roof and floor trusses. The center corridors were then bridged with 2x8 lumber. Each half of the roof was trussed separately with a gap provided at the ridge to allow for any movement that might take place. This arrangement virtually eliminates the potential for cracks on the interior finishes due to differential shrinkage.