Resisting Earth's Forces: Typologies of Timber Buildings in History

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Summary

Despite the fact that timber is perhaps the world's most versatile building material, few engineering students are attracted to make it the subject of their studies or specialization. With growing interest in energy conservation and sustainable construction materials, wood is now gradually gaining greater recognition for use in larger, engineered buildings. This essay explores its historical use, in combination with masonry, in earthquake areas over the past millennium from Roman Herculaneum, to Japan, Turkey and Kashmir. Pre-modern generations of builders have utilized timber to impart tensile strength and earthquake-resistance to masonry buildings over the centuries, and the resilience that these buildings have demonstrated in recent earthquakes that have felled hundreds of much newer reinforced concrete structures provides a good reason to revisit the modern-day potential of this time-honored material.

Keywords: braced frame; balloon frame; stud-frame; infill-frame; half-timber; timber-laced; Herculaneum; opus craticium; insulae; earthquake; Kashmir; Srinagar; Turkey; Armature Crosswalls.

Fig. 2: Seventeenth century substructure for the Kiyomizu Temple, Kyoto, Japan

Introduction

Only a small minority of students entering advanced training in architecture or structural engineering choose to specialise in timber structures. This is even true in North America, where over 90% of people live in timber houses. Elsewhere, reinforced masonry and reinforced concrete predominate as materials of choice; and students, practicing engineers and government officials usually express surprise at the North American situation. This view is widespread even in parts of Europe. The discussion that follows looks at typologies that exist in a historical context. Also, it illustrates that even in countries where wood is not regarded as a structural medium, its use could, in fact, have been a rich part of their societal history.

Fig. 1: Traditional log houses of recent vintage in rural Kashmir, India (Photocredit: Hakim Sameer Hamdani)

Typologies

Contemporary and historical timber buildings can be divided into those where the entire structural and enclosure systems consist of wood products, and those where timber is combined with other materials. Most likely, the oldest forms of timber construction still recognizable in modern practice were log buildings (*Fig. 1*). Saws and nails were technological tools that allowed transition from systems of stacked logs to the use of braced timber frames. In Chinese and Japanese temples and pagodas bracing was also accomplished using timber beams slotted through columns, thus avoiding visual disruptions by diagonal braces (*Fig. 2*).

The development of what became known as the "balloon frame", which evolved into the "platform frame" (also called "stud-frame"), originated in Chicago, USA, and is pervasive to this day (*Fig. 3*). It came to fruition when sawmill technology had evolved sufficiently to easily convert logs into members with consistent small cross-section dimensions. Another factor, beginning about 1850, was the manufacture of nails from steel wire that replaced hand-forging of iron nails. Prior to wire nails, people sometimes burned old houses simply to recover precious nails!

One might think that stud-frame structures would be weaker than heavy timber braced frames that preceded them, but the opposite is often the case. Even moderately well constructed stud-frame buildings can be very robust and have even been found to have maintained recognizable shapes if blown over or swept away by floods.[1]

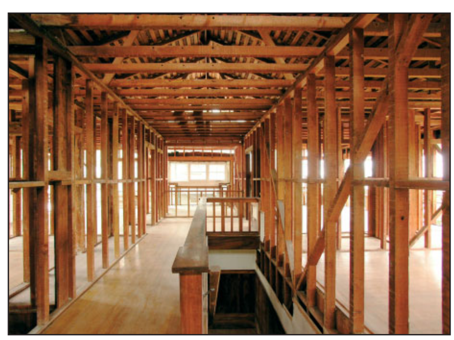

Fig. 3: Typical stud-frame of an early twentieth century house in California

Mixed Construction

Except for wood-abundant countries, buildings made entirely of timber are quite rare. Whether in sixteenth century Elizabethan England, or early twentieth century Turkey and Kashmir, the use of fired or unfired masonry as infill to timber frame (timber infill-frame) demonstrates what has often been a practical way of combining the assets of different materials. Some such buildings are quite tall. For example, few people may realise that many of the masonry facades of six- and seven-storey buildings of the seventeenth to nineteenth centuries in great cities like Madrid were in fact constructed on structural frames of timber (a fact only made visible after demolition of neighbouring buildings).[2]

Before modern saws and nails became available, wood could only be added to what were primarily masonry buildings. Timber was embedded in load-bearing walls of masonry (timber-laced masonry) many centuries ago and has been found in ancient Knossos. An example of the timber infill-frame was unearthed from the volcanic debris in Herculaneum (*Fig. 4*), and holds clues as to how seven- and eight-storey tenements, known as *insulae,* were constructed in ancient Rome. Masonry-bearing walls would have been too thick at the base to fit on their known footprints, implying use of timber frames with infill walls of masonry. Those walls would have resisted seismic forces known to have affected both Rome and Herculaneum.

Fig. 4: Infill-frame house unearthed in the archaeological site of Herculaneum, Italy after being buried in the eruption of Vesuvius in 79 A.D.

Both timber-laced bearing walls and timber infill-frame construction existed during the eighth-century Byzantine Empire, and then continued to spread throughout what later became the Ottoman Empire and beyond.[3] In the late eighteenth century, after earthquakes in Portugal and Sicily, timber infill-frames were even specifically promulgated and patented for earthquake resistance.[4]

Long-term use of timber-laced bearing walls and timber infill-frame construction is evident in Kashmir (*Fig. 5*). In 1148, Kalhana noted the use of timber in his Rajtarangani ("Chronicle of Kings"), which stated *"Srinagar in the 12th Century Hindu Period: The mansions of the city, which reached the clouds and were mostly built of wood."* In the sixteenth century, Muhammad Haidar Dughlát in his Tarikh-i-Rashidi (A History of the Moghuls in Central Asia) said *"In the town are many lofty buildings constructed of fresh cut pine. Most of these are at least five storeys high…. [causing viewers to] bite the fingers of astonishment with the teeth of admiration."* In 1885, the city was struck by a large earthquake, and British writer Arthur Neve reported that "*Srinagar … the general construction…is suitable for an earthquake country; wood is freely used, and well jointed; clay is employed instead of mortar, and gives a somewhat elastic bonding to the bricks,…. The whole house, even if three or four storeys high, sways together, whereas more heavy rigid buildings would split and fall...*". Clearly, even before the invention of wire nails, other steel fasteners and plywood, construction that was heavily reliant on wood had distinguished itself for its earthquake resistance, even when buildings were tall.

For the past two millennia, during which evolution of effective earthquake-resistant multi-storey building systems evolved, people have relied on construction methods that are very different from those in common use today. Modern-day engineers often neither understand nor can easily justify by calculations how these systems worked. Interestingly, the 2005 Kashmir earthquake left some buildings with infill-frames above unreinforced masonry walls suspended in the air, high above the collapsed walls below. Many masonry structures that lacked the timber lacing or frames collapsed completely.

In Turkey, the 1999 Kocaeli and Duzce earthquakes killed at least 20,000, and maybe as many as 45,000 people in reinforced concrete buildings;[5] but left standing most of the timber infill-frame buildings that were near them, even if the timbers were in an advanced state of decay. In the city of Adapazari, for example, out of 930 reinforced concrete structures in total, 257 collapsed or were severely damaged, and 558 were moderately damaged. None of

(a) (b)

Fig. 5: Srinagar, Kashmir (a): timber-laced bearing wall house, referred locally as taq (b) timber infill-frame house, locally known as Dhajji dewari

400 traditional infill-frame buildings collapsed or were badly damaged.[6]

Because of this striking performance, and also inspired by eighteenth and nineteenth century timber infill-frame systems in Portugal and Italy, the author, together with research engineers in Italy, Turkey and the USA has proposed a modern adaptation of traditional systems. The new system is called "Armature Crosswalls" and is intended as a means of preventing modern reinforced concrete buildings from collapsing. Under the Armature Crosswalls concept, instead of having a weak infill-masonry wall, the infill panels are constructed with a subframe, and then the gaps are filled with masonry. Thus, the infill walls can are converted from a liability to an asset. If timber is used for the subframe, risk of fire-spread is extremely low because the wood is imbedded in masonry and hidden behind plaster.[7]

Using Timber for Mid-Rise Buildings

Employing wood within infill panels in tall framed buildings is an idea that might not concern engineers very much, but using it in the primary structure might. In the USA, stud-frame construction is generally limited by building codes to either three or four storeys with local relaxations of regulations often needing to be carefully justified. If sprinklers are installed, a prescriptive allowance of one extra storey is common. Such restrictions are mostly artifacts of quite recent history.

In the nineteenth century, large wood-balloon frame hotels were constructed in the USA.[8] Heavy timber construction has been permitted in modern building codes from its origins in early nineteenth century New England factories when it was referred to as "slow-burning construction". The tallest of these brick and heavy timber factories rose as high as nine storeys filled with vibrating heavy machinery. Many were six or seven storeys in height. Sprinklers were originally invented to protect these buildings. Ironically, the earliest large mills had cast-iron columns, but those constructed after the American Civil War until well into the twentieth century had wooden columns instead. The reason for using timber was that in 1852 a poorly made cast-iron column broke in the Pemberton Mill in Lawrence, Massachusetts, leading to the sudden collapse of the fully occupied building.

With the advent of electricity and modern modes of transportation, multistorey factories ceased to be common because industrial practices adapted to take advantage of changed conditions. However, mainly in North America, construction of multiple-storey timber buildings has continued for housing, and it remains common today in countries where timber and carpenters are available and thus competitively priced.

Trends

Five-storey housing projects are highly reflective of modern construction for which timber options can be competitive (*Fig. 6*). Such buildings are constructed with lightweight materials with steel and timber usually most competitive. Taking Oakland, California, as an example, a prominent quantity surveyor made the observations that: *"In recent years, light steel and stud-framed wood have been of roughly equal cost, but with the recent increases in the price of steel (43% in 2004 alone), the cost advantage now has shifted to wood. And, because of the heavy use of energy to make steel compared to wood, the cost of steel has increased along with the rise in price of fuel, and is expected to continue to rise."* As of late 2007, "steel is approximately 20% to 40% more expensive in residential construction than wood" for comparable five-storey structures.[8]

In contrast with much of the rest of the world, concrete construction is much less common for mid-rise dwelling structures in the USA until, as Oakland's Principal Civil Engineer observed, they typically exceed about eight storeys, because at about that height reusing the formwork becomes economical.[10] As steel reinforcing bars and concrete both require a large quantity of energy to make, the cost differential of these, relative to alternatives, has recently become greater. In other countries, lower labour costs together with higher costs of wood products may well favour concrete. In California, and other seismic regions, concrete is often avoided because of its greater seismic mass, a problem that has had devastating results in a number of countries. One would think these repeated calamities would lead to greater use of alternative systems such as timber, but to-date this has been rare. In time, this may change.

Obviously, the specifics of choosing between materials and construction methods change from region to region, or even from city to city. Nevertheless, a clear overall global trend is developing, especially as commodity prices continue towards global equalization. There clearly are sound business reasons why "the timber option" is likely to begin to appeal to developers and other building owners over the long term, especially for mid-rise building projects of about six–ten storeys. If timber solutions are technically feasible, and performance, particularly fire protection, is comparable and pricing is competitive in construction and operation phases, they will be selected.

To illustrate, the nine-storey Murray Grove Tower is now under construction in London, UK. It is built from solid cross-laminated timber walls and floors that are like large sheets of plywood. It can be said to be a modern variation of the "slow-burning" construction invented in New England, because of its lack of pocket

Fig. 6: Massive multi-block sized five-storey apartment complex under construction in 2007, Oakland, California

walls which would allow rapid spread of fire.[11,12]

Conclusion

This paper has not sought to investigate exotic one-off timber structures, but instead has put emphasis on those typologies suitable for widespread applications. Timber is very versatile as a building material and is readily available in most regions of the world. Its use helps combat global warming by sequestering carbon directly in the fabric of buildings and supplanting steel and concrete, both of which require far more fuel in their manufacture.

Here, an expansive definition of timber construction is adopted to include systems where wood elements are constraining elements within a composite of materials. With that inclusiveness, it is clear that with a little imagination and by learning from literally millennia of experience and past masters of the art, timber can fulfill construction needs beyond what is often the perceived norm.

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