Fire Safety Design of Multi-Storey Timber Buildings

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Abstract

In the past, timber was seen as a poor construction material because of its flammability. However, with modern design and construction techniques this is rarely the case. This paper discusses the methods for ensuring light timber and heavy timber multi-storey buildings achieve the required fire ratings. For light timber frame structures the thicknesses and density of wall and ceiling linings required for fire safety are generally less than those required to meet acoustic requirements. Although more care is required to avoid fires during construction, modern timber buildings are as safe in fire as their steel or reinforced concrete counterparts.

Introduction

The first shelters ever built were built of timber or other plant materials that were, of course, flammable. As buildings developed in size and complexity, and towns and cities grew larger, fires were then able to spread to other buildings, sometimes resulting in conflagrations. Historically, the first building controls were put in place to prevent or limit urban fire spread. For example in the third century BC there were many fires in Rome, culminating in the fire of 18 July, A.D.64 which burnt for 7 days (1). When the city was rebuilt water supplies were improved, party walls prohibited, space provided between buildings and stone specified in certain parts of houses.

As the population increased in Europe, cities become larger and more overcrowded, then as in Rome, fires could easily and rapidly spread throughout cities. The best known example is the Great Fire of London (2) in 1666 (Figure 1). Prior to this event the "Great Fire of London" was actually a reference to a previous fire that occurred in 1212.

Despite the spread of fire southwards being stopped by a gap caused by a previous fire in 1633, over 80% of the city was destroyed. This was despite the proclamations issued by Charles II in 1661 banning overhangs from houses above streets and in 1665 authorising imprisonment of offending builders and demolition of dangerous houses. These proclamations were generally ignored.

After the 1666 fire, streets were widened and most new construction was in brick or stone. In the United Kingdom there are few timber buildings left in the larger towns and cities. The European concept of brick or stone masonry buildings being "permanent" and fire resistant was exported to New Zealand where in the mid 19th Century it was seen as desirable to build substantial brick or stone structures as soon as possible to replace the "temporary" timber dwellings. Timber buildings became far more desirable and brick or stone buildings seen as a liability after the 1855 Wairarapa earthquake, which damaged or destroyed many "permanent" buildings in the region.

Figure 1. Great Fire of London 1666 (Artist unknown) (2).

Urban fires, albeit on a smaller scale have occurred in New Zealand. Take for example the 30 May 1901 fire which destroyed 22 houses in the suburb of Mt Victoria, Wellington (3).

The major contributing factor for these conflagrations was not the timber structure of the buildings, but the use of timber weatherboards and shingles and other combustible claddings such as thatched roofs. The use of combustible claddings is still the most significant factor in urban fire spread (4).

Historically the risk of fire has been an impediment to the use of timber as structure in urbanised areas and multi-storey buildings. The rationale behind this is both simplistic and dated.

As is the case with most materials exposed to fire, timber has its advantages and disadvantages. The remainder of this paper discusses these, makes comparisons with other materials and suggests how these may be addressed. The paper discusses light timber frame buildings and heavy timber buildings separately as different methods are used to provide fire resistance to these two structural types. Timber as internal finishes is also discussed as is the effect of the structural design on non-structural elements such as fire rated partitions.

Multi-Storey Light Timber Frame Buildings

Light timber framing as a structural system is suitable for buildings that contain large numbers of small spaces with limited floor spans and many load bearing walls (5, 6). Typically these are residential buildings with walls and floors normally lined with gypsum plasterboard. Gypsum plasterboard is non combustible (except for its paper facings). It is also an excellent insulator and absorbs a lot of heat both to raise the temperature of the gypsum and to remove and evaporate chemically bound water. Standard gypsum plasterboard systems on walls (~10 mm thickness) and ceilings (~13 mm thickness) typically are capable of achieving a fire resistance rating (FRR) of at least 15 minutes in an ISO standard test furnace test.

The Acceptable Solutions for Fire Safety C/AS1 (7) is a means of compliance for the New Zealand Building Code (NZBC) fire safety clauses. It has three requirements for the FRR of all buildings. The first two are shown in Table 1 below. The first, the minimum fire rating for escape, rescue and fire-fighting operations (the F rating) can be halved if sprinklers are installed, but only where sprinklers are not explicitly required for the Acceptable Solution for a given occupant load, height of building, type of building use and level of fuel load. The second fire rating, the structural (S rating) is to ensure the structure can survive a burn-out without compromising boundary walls. It ensures fire does not spread to neighbouring properties. Residential and accommodation buildings tend to have large and numerous windows. The high levels of ventilation result in less severe short hot fires that have less impact on a structure, as the structure has less time to heat up than during a longer cooler fire. As shown in Table 1, S ratings can also be halved if sprinklers are installed. The values for the S ratings in Table 1 are typical for residential and accommodation buildings. In some circumstances it may be higher or lower. The third requirement for a minimum FRR comes from the requirement that residential units or suites (including hotel rooms) be fire separated from each other and from common areas to a minimum FRR of 30. All these requirements are independent of the structural material used, a substantial change from the regime pre-dating the New Zealand, 1991 Building Act.

	Fire Rating for Escape (F Rating)		Fire Rating for Boundary Walls (S Rating)	
Escape Height	Without Sprinklers	With Sprinklers	Without Sprinklers	With Sprinklers
≤25	45	30	30-50	15-25
25-34	not permitted	30	30-50	15-25
>34	not permitted	45	30-50	15-25

Table 1. Minimum requirements for Fire Resistance Ratings in residential and accommodation buildings.(6)

The minimum required FRR therefore does not exceed 50.

Acoustic requirements are also mandated in the New Zealand Building Code. The NZBC Clause G6, Airborne and Impact Sound, requires a minimum Sound Transmission Class (STC) rating of 55 and a minimum Impact Isolation Class (IIC) rating of 55 between household units (8).

The commonly used Winstones GIB (9) proprietary wall systems that achieve this STC and IIC rating have a FRR of at least 45 and usually 60, except for double stud systems which have an FRR of 30. Of the four GIB floor/ceiling systems with STC and IIC greater than 55, three have a FRR of 60. Only one, a suspended grid system has a FRR of 30.

In hotels and motels a reasonable level of acoustic performance is not mandatory. However, in all but the cheapest accommodation, guests expect good acoustic separation. In more expensive hotels and apartments, higher STC and IIC ratings are desirable which lead also to higher FRR's.

A FRR for walls of 30 and 45 can be achieved with the commonly used Winstones GIB (10) proprietary wall systems with standard framing and 13 mm standard and 13 mm fire rated boards respectively. A FRR on floors and ceilings of 45 can be achieved with the commonly used Winstones GIB (10) proprietary floor/ceiling system with standard framing and 13 mm fire rated board. However, if the walls and floor/ceiling system are loaded more heavily, or walls are higher

or floor spans longer than the limits specified in the technical literature, then the fire rating listed for structural stability may not be achieved.

Given that the timber framing is protected from the fire for an FRR of 45-60 or more when the likely fire severity is 20-40 minutes for a full burn out of the structure, then the timber framing will not usually contribute fuel to the fire.

The load-bearing capacity of light timber frame walls subject to fire can be determined in ISO834 standard furnace tests, by extrapolation from tested systems using the method by Collier (11) or if necessary by numerical analysis as described by Thomas (12) or Clancey (13).

In summary, it is easier to achieve the required 30 minute or 45 minute FRR required in multi-storey light timber frame buildings than those that are required for acoustics. Load-bearing walls within residential units and suites may require slightly more expensive linings, however the extra cost is low and results in other benefits such as more resistance to mechanical damage, enabling better finishing and better acoustic performance between rooms within a unit.

Multi-Storey Heavy Timber Buildings

Heavy timber construction with long floor spans is suited to office buildings and multiple use buildings. The structure which achieves satisfactory fire performance is quite different than for light timber framing. Although it is possible to protect heavy timber using board products or intumescent paints, this is usually not necessary.

In a fire, heavy timber burns on the surface. This forms a layer of "char" which can be seen when a large piece of wood is burnt on an open fire. If a large piece of burning wood is removed from a fire and cut through it you will see that the interior is still intact as shown in Figure 2.
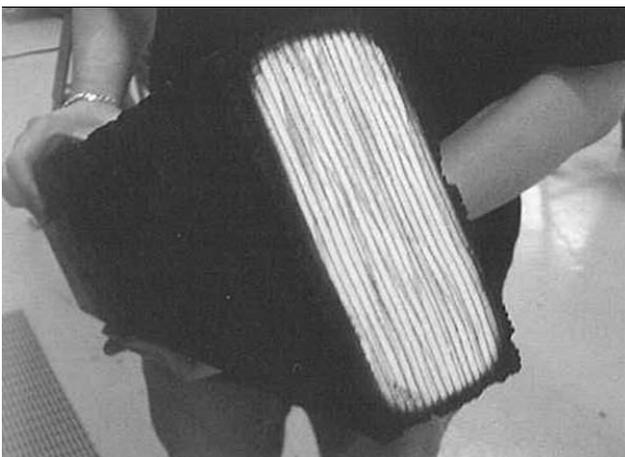

Figure 2. A charred section of LVL showing solid wood inside (5).

Char has a very low density and is porous. It is a good insulator. During a fire, this char layer progressively disintegrates on the outside and moves deeper into the wood. The charring rate is relatively constant and for *pinus radiata* is about 0.7 mm per minute in a fully developed fire. This charring rate only applies to pieces of timber that are "thermally thick"; that is the centre of the timber does not heat up. In thin pieces of timber (such as "kindling"), where the centre of the timber does heat up, the char rate is not constant and the piece burns very quickly. The cut-off point between "heavy" or "thermally thick" timber and light timber is about 75 mm for the lesser dimension (smaller of depth and breadth of the cross-section). Hence in fire rating terms standard studs of 45 mm thickness are "light" timber and burn quickly. If the external heat source is removed from a piece of heavy timber it is likely to smoulder and then self extinguish. Smaller pieces of timber will continue to burn by themselves.

Structures are designed to resist the maximum possible load they will be subjected to in their lifetime (14), be it excess weight of building contents or wind and earthquake forces. These are rare events, as is the event of fire in a building. The probability of a fire at the same time as one of the other rare events is extremely low and so can be ignored. In the fire condition, more typical long-term loading conditions are assumed. The maximum gravity load due to the weight on a structure is given in the Loadings Standard (14):-

$$Load = 1.2G + 1.5Q$$

Where: G is the dead load (weight of the structure itself)
          Q is the live load (weight of the building contents including occupants)

In the fire case the load combination is given by:-

$$Load = 1.0G + 0.4Q$$

This is typically about 50% of the load of the previous case, depending on the relative values for live and dead load. In timber structures, the dead load is usually smaller than the live load in steel or concrete structures, which are of course heavier materials. Hence in timber structures, the ratio of reduced gravity load for fire conditions to the maximum gravity load combinations is less.

When designing a timber member, the depth of charring of the timber is calculated by multiplying the known charring rate by the fire severity in minutes, giving a reduced section size as shown in Figure 3.
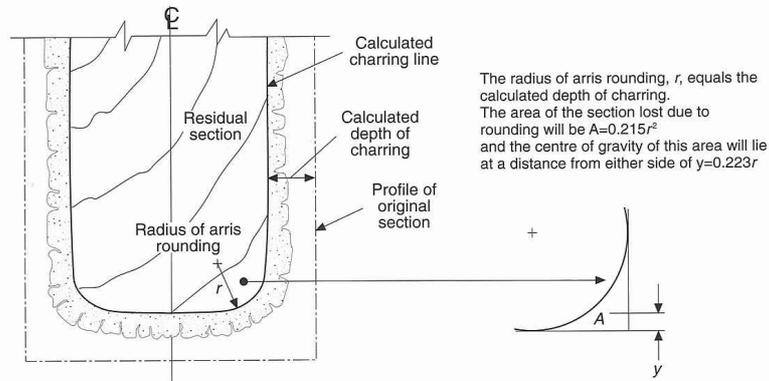

Figure 3. Definition of uncharred section area (15).

The reduced section size is then assessed for its strength in bending and shear. If it is still strong enough to resist the loading specified for the fire condition, then it is adequate. This process is described more fully in the Fire Engineering Design Guide (15) and illustrated with a worked example. As beams are usually exposed on the underside and both sides, it may be necessary to use wider and shallower beams than those chosen for normal load conditions. This may be desirable anyway to reduce inter-storey heights or allow more room for services running under beams. It is often necessary to protect exposed joints with intumescent paint on steel or board products to avoid premature failure at connections. Alternatively, joints can be hidden within the timber and protected by the timber itself or located above a fire rated ceiling where only the columns are exposed.

Heavy timber structures perform significantly better in fires than unprotected steel structures, with progressive failure rather than the sudden failure that occurs in steel when it reaches a critical temperature. Examples of failure of heavy timber and unprotected steel structures are shown in Figures 4 and 5.
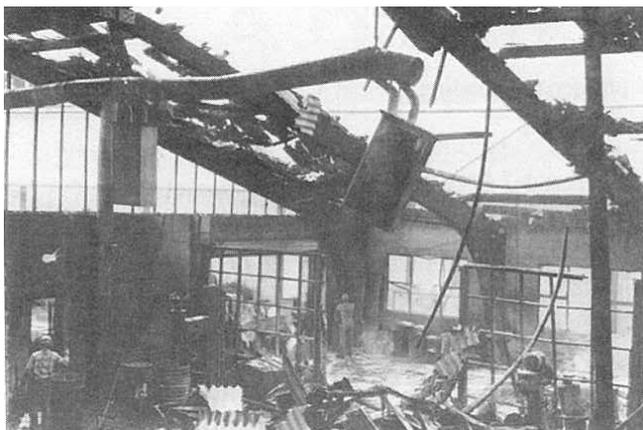

Figure 4. Unprotected glulam portal frame warehouse after a fire (15).   **Figure 5. Unprotected steel portal frame warehouse after a fire (15).**

The amount of fuel from the heavy timber frame in a building is not particularly significant and if a light timber floor is used, then the flooring, joists and possibly secondary beams would be protected from fire by ceiling linings. Examples of the difference in available fuel load between a timber building and non-combustible structural materials are given on the next page.

1. Office building, fuel load is 800 MJ/m^2 (7), 450*450 glulam columns, on a 6m by 6m grid with 3.0 m ceiling height. Assume a heat of combustion of timber of 18 MJ/kg and timber density of 450 kg/m^3. The fuel load from the contents is:-

$$6.0\,m \times 6.0\,m \times 800\,MJ/m^2 = 28,800\,MJ$$

The fuel load from the column is:-

$$0.45\,m \times 0.45\,m \times 3.0\,m \times 450\,kg/m^3 \times 18\,MJ/kg = 4,920\,MJ$$

This is a 17% increase if all the fuel is burnt. However assuming the fire duration is 40 minutes and a charring rate of 0.7 mm/min, the surface of the timber recedes 28 mm and the actual volume of timber burnt reduces to about 0.15 m^3, or 1215 MJ. This represents an increase of only 4% in the fuel load.

2. Office building, fuel load is 800 MJ/m^2 (7), 450*450 glulam columns, on a 6m by 6m grid with 3.0 m ceiling height and exposed 720*180 beams on a two-way grid. Assume a heat of combustion of timber of 18 MJ/kg and timber density of 450 kg/m^3. The additional volume of timber burnt at a recession rate of 0.7 mm/min is 0.5 m^3, increasing the fuel load by 4300 MJ, a total increase in fuel load of 19%.

This initially appears significant, however the timber will burn more slowly than typical building contents and since building fires tend to be controlled by ventilation, the extra flammable gasses emitted by the burning timber will be unlikely to have sufficient air to burn within the compartment. The effect of the timber on the fire severity is therefore less than what would be expected from a simple calculation of the additional fuel the structure provides.

Fire Rating of Non-Structural Elements

Traditionally, multi-storey buildings have fire rated floors. Floors are by definition structural and must be fire rated. They prevent fire spreading between floors. However openings in floors are required for stairs, lifts, ducts, and penetrations for services.

Lifts and stairs in most buildings are fire separated using light timber framing or possibly light steel frame construction. In reinforced concrete buildings, lift shafts and stairwell walls are often used as structural shear-walls. Services may also be run in vertical shafts that have fire rated walls.

One potential drawback of light timber frame walls and partitions is that there is a reduction in the fire rating of light timber frame walls after the damage caused by racking in an earthquake (16). The linings may crack, exposing timber, or fire rating treatment of penetrations may be damaged as services move independently of the wall they pass through. The magnitude of this problem depends on the horizontal deflections between storeys and the difference in stiffness between the partition and surrounding structure. As the Loading Standard limits inter-storey deflections to the same level regardless of the type of construction this problem is not necessarily more significant in timber buildings, although reinforced concrete shear-wall and steel braced frame buildings tend to have lower inter-storey deflections due to the greater inherent stiffness of the structure. However with light timber frame buildings, the stiffness of structural walls and non-structural partitions is similar and the softer timber structure has more "give" than hard steel or concrete, permitting more differential movement without damage.

The treatment of penetrations for services and ventilation is very similar for both timber buildings and other buildings. Of course, it is much harder to penetrate a concrete floor or wall, but the fire rating a separation achieves is that of the weakest point, and since that is at penetrations, the material of construction is irrelevant.

Surface Finishes

The NZBC Acceptable Solution C/AS1 restricts surface finishes on walls and ceilings for unsprinklered buildings and on ceilings for sprinklered buildings as shown in Table 2. These requirements do not apply to smaller areas such as doors and trim.

The Spread of Flame Index (SFI) and Smoke Developed Index (SDI) are two early fire hazard indices that are measures of how fast a fire may spread along a lining material and how much smoke is developed in the initial stages of a fire. Bare paper faced gypsum plasterboard has values of SFI=0 and SDI=2 (17), but higher values have been reported. Generally acrylic or water based enamel paints on plasterboard will meet the requirements of Table 2. Some paints may not meet the criteria. The test used to determine early fire hazard indices is a ranking-type test and has known

limitations (18). It is expected to be replaced by International Standard Organisation rate of heat release tests in the future.

Purpose Group or Location	Maximum Permitted Index	
	SFI	SDI
Exit-ways in all purpose groups Sleeping areas in purpose groups SC and SD	0	3
All occupied spaces in purpose groups CS and CL excluding exit-ways All occupied spaces in purpose group CM with >50 occupants Sleeping areas in purpose group SA	2	5
Passages, corridors and stairs (excluding exit-ways) in all purpose groups except SH and SR	7	5
Minimum requirement for all occupied spaces except household units in SR and SH	5 or 9	10 or 8
Within household units in SR and SH	unrestricted	

Table 2. Maximum Spread of Flame Index (SFI) and Smoke Developed Index (SDI) for Surface Finishes on walls and ceilings in various occupancies (modified from Table 6.2, C/AS1) (7).

In apartments, there is no specific requirements for surface finishes, and in hotel rooms, the requirements are not particularly onerous. These requirements only apply to large surface areas and not finishing timber such as skirting, architraves and doors.

Linings made from solid timber or glulam with standard clear finishes may meet early fire hazard requirements in occupied spaces, except crowd spaces and exit-ways (17). Timber linings such as plywood or reconstituted board products, such as particleboard, with standard clear finishes do not (17).   Plywood and other board products may meet requirements for some types of spaces when finished with acrylic paint. There are intumescent clear finishes available, but these are rather soft and are not suitable for locations where they might be damaged. If sprinklers are installed then walls do not have to meet the requirements and the soft intumescent finishes can be restricted to ceilings. Judicious use of other non-combustible materials to break up large areas of material with a high spread of flame index is a practical solution, consistent with allowing smaller areas such as doors. Although, this solution is difficult to quantify using existing assessment methods and therefore may be difficult to get approved by the building control authority.

Exterior finishes are restricted depending on the distance to the boundary, height of the building and whether it contains sleeping occupants. This is summarised very well in the Timber Design Guide (5) in a table reproduced as Table 3.

Building Escape Height	Distance to Relevant Boundary		
	<1 metre	≥1 metre	
	All Purpose Groups	Sleeping Purpose Groups	Other Purpose Groups
Single-storey	No	Yes	Yes
Up to 7 metres		No	Yes
Up to 25 metres			Sprinklered buildings only
Over 25 metres			No

Table 3. Applications where non-fire treated timber products are acceptable as exterior cladding (derived from C/AS1 Table 7.5) (5,7).

Construction

The construction period is when the fire risk in a building is highest. This is more so for a light timber frame building, as fire resistant linings are not applied until after it is closed in. It is less of a problem in a heavy timber building, although the connections and floors may not be fire rated. Unlike a fire in a concrete building during construction, a severe fire will be likely to cause a light timber frame building to collapse and possibly a heavy timber frame building as well.   The risk of fire initiation during construction may well be less for a timber building because less hot work such as welding and grinding is required. However, should an ignition occur large quantities of readily available fuel in the form of unprotected timber frames may be present. There is no obvious solution to this problem other than being more vigilant during construction.

Conclusion

Traditionally fire safety has been seen as an impediment to building large buildings in timber. This impediment is more perceived than real. Heavy timber structures perform well in fire and are not prone to sudden collapse. Light timber frame structures can be readily protected against fire, often with requirements for linings being less onerous than that necessary for adequate acoustic separation. The timber in a building structure does not add greatly to the fire load and is either not involved in the early stages of the fire or has a slower burning rate than the contents, resulting in a minimal effect on fire severity. Timber as internal linings or external claddings may require fire resistant coatings and is not appropriate in some circumstances. The risk of serious damage in a fire during construction is higher in timber buildings but can be managed. Provided buildings are designed well and fire safety is properly taken into account there is no reason why timber buildings should not be seen to be as safe as buildings constructed from other materials.

Acknowledgements

References

1. Klitze, R.A. *Roman Building Ordinances Relating to Fire Protection*. *The American Journal of Legal History.* 3(2), April 1959, pp173-187 (http://www.jstor.org).
2. http://www.angliacampus.com/education/fire/london/history/greatfir.htm
3. McLean, G. *New Zealand Tragedies; Fires and Firefighting.* Grantham House, Wellington, 1992.
4. Cousins,W.J., Thomas, G.C., Lloydd, D.A., Heron, D.W. and Mazzoni, S. *Estimating Risks from Fire Following Earthquake.* Institute of Geological and Nuclear Sciences, Client Report 2002/60. Wellington. 2002. (http://www.fire.org.nz/research/reports/reports/Report_27.htm).
5. Buchanan, A.H. (Editor), 2007, *Timber Design Guide,* New Zealand Timber Industry Federation, 3ʳᵈ Ed., Wellington.
6. Thomas, G.C., *The Feasibility of Multi-Storey Light Timber Frame Structures.* University of Canterbury, Department of Civil Engineering Research Report 91-2, Christchurch, 1991.
7. Department of Building and Housing, *C/AS1 Approved Document for New Zealand Building Code Fire Safety Clauses (and amendments),* DBH, Wellington, 2001.
8. New Zealand Government, *"The New Zealand Building Code", Building Regulations 1992 (and amendments), First Schedule,* New Zealand Government, Wellington, 1992.
9. Winstone Wallboards Limited, *GIB® Noise Control Systems, March 2006,* Auckland, 2006.
10. Winstone Wallboards Limited, *GIB® Fire Rated Systems, January 2006,* Auckland, 2006.
11. Collier, P.C.R., *Design of Loadbearing Light Timber Frame Walls for Fire Resistance*, Building Research Association of New Zealand, Porirua , Part 1, BRANZ Study Report no. 36, 1991 and Part 2, BRANZ Study Report no. 43, 1992.
12. Thomas, G. C., *Fire Resistance of Light Timber Framed Walls and Floors*, University of Canterbury, Fire Engineering Research Report 97/7, Christchurch, 1997.
13. Clancy, P., *Time and Probability of Failure of Timber Frame Walls in Fire,* Ph.D. Dissertation, Victoria University of Technology, Melbourne, 1999.
14. Standards New Zealand, *AS/NZS1170: Structural Design Actions*, Standards New Zealand, 2002.
15. Buchanan, A.H. (Editor), *Fire Engineering Design Guide,* Centre for Advanced Engineering, Christchurch, 2ⁿᵈ Ed, 2001.
16. Collier, P.C.R., *Post-earthquake Performance of Passive Fire Protection Systems.* Building Research Association of New Zealand, Porirua, BRANZ Study Report no. SR147, 2005.
17. CSIRO. *Fire Performance of Wall and Ceiling Materials - Final Report with Supplement,* Fire Code Reform Centre, Project Report FCRC – PR 98-02, September 1998. (https://www.abcb.gov.au/index.cfm?objectid=0870A459-01FB-FF19-3CC5762A44D55235)
18. Wade, C.A., *Building Fire Safety and Hazard Assessment Methods for Combustible Surface Finishes,* Building Research Association of New Zealand, Porirua, BRANZ Conference paper no. CP085, 2001.