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Structural Engineering - Issues with Multi Storey Timber Frame

Mehrgeschossiger Holzrahmenbau

Costruzione a telai in legno a più piani

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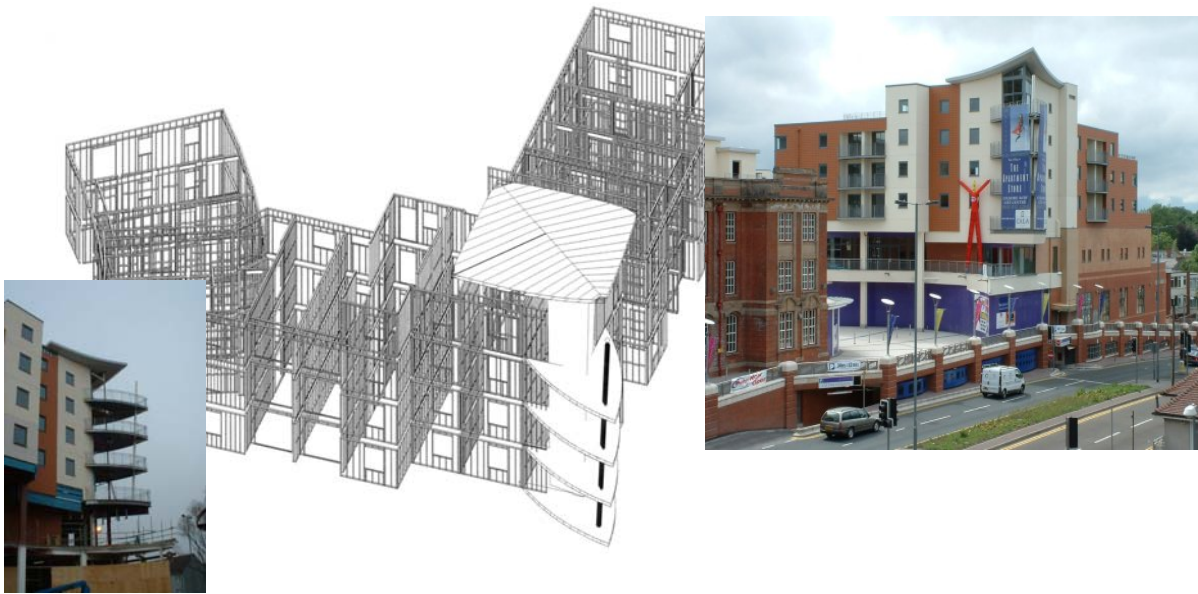


1 Introduction

Light frame construction for homes, hotels and multi storey accommodation buildings is an increasingly common form of construction in the UK. The use of pre assembled wall and floor panels to create a fast and accurate structural building envelopes has evolved from the two storey house to 5, 6 and 7 storey building. In the context of this paper buildings above 3 storey's are considered to be multi storey and below 4 storey referred to as low rise construction.

Small section timbers used in combination with panel products have long been a material of choice for the low rise light frame off site construction techniques. The UK supply chain for low rise timber panel construction is well established and has had significant success since the 1960's. The same supply chain has been attracted by the growing market for 5,6 and 7 storey multi storey building as manufacturing gains significantly by repeat framing which is clearly more likely in larger scale projects.

The growth of multi storey timber frame can be linked back to the research carried out by BRE and TRADA in the late 1990's on multi storey frame building. This research work eventually lead to the full scale 6 storey model testing at BRE Cardington(TF200) which was largely focused on productivity benefits and marginal structural issues. The dissemination of the project TF 2000 coincided with the drive for more off site forms of construction which lead to a natural market pull for timber frame multi storey rise buildings.



In recent years, and for a foreseeable future, the key commercial driver, other than price, for the use of timber in multi storey buildings is the contribution that this building method has to support the various sustainability requirements now being enforced in the UK.

Structural engineers involved in the design of timber panel frame buildings have for many years adopted low rise frame technology to the multi storey frame solution. The guidance in the UK has been minimal. A joint BRE and TRADA publication entitled "Multi Storey timber frame buildings – a design guide" published in 2003 is the only document that provides reference to buildings above 4 storeys. Until November 2007 the British Standard BS 5268 part 6.1, that covers specific aspects of timber frame, was limited to 4 storey height. The new revision now addresses buildings up to 7 storeys and has a number of key changes that reflect structural issues relating to the difference in low rise to multi storey timber frame buildings. It also addresses the need to ensure that the factor of safety does not become eroded by force fitting timber frame into unrealistic layouts and schemes that stretch the accepted basic cellular principles of timber panel frame structures.



This paper explores some of the issues relating to the changes in the British Standards and expands on the structural thoughts when increasing the height of small section timber panel frame construction and provides key design processes needed to ensure a robust solution.

2 Understanding the issues

2.1 Vertical load capacity

The use of small section timbers and panel products such as osb and plywood to form pre assembled structural walls, floors and roofs involves many structural interfaces that are well documented and understood, such as vertical load capacity. These issues are not influenced by storey heights except in that the loadings and number of studs may increase.

The vertical load capacity of a stud is dependent on the section, compression perpendicular to grain of the horizontal members and on the lateral restraints in place.

The increased loadings on a stud wall results in increasing the amount of timber in the wall. At some point the volume of studs in a wall panel become problematic.

Issues relating to increasing stud density are:

- 1) Mechanisms to provide lateral restraint – especially in multiple cripple stud arrangements.
- 2) Practical stud centers for sheathing and services & thermal bridging

2.2 Frame shortening

While not a conventional structural issue the calculation for frame shortening in timber frame it is an essential element for engineers. Clearly with increasing floors there is an increase in the accumulative cross grain in the frame and panel to panel junction interfaces. The closing up of joints when loaded produces a small amount of movement and even smaller is the contribution of elastic deformation and creep. However, significant shortening can occur due to shrinkage of timber. In the UK this movement is often referred to as differential movement, as it is the movement variation of the loaded timber frame structure to that of elements that are not vertically supported by the frame, such as masonry cladding.

Issues relating to differential movement are:

- 1) Use of timber products and understanding the behavior in changing moisture contents and in the tolerance of the material.
- 2) Construction loading to compress open construction joints
- 3) Interfaces with cladding and other laterally attached structures such as free standing balconies.

2.3 Resistance to Horizontal Forces

Horizontal resistance of a panel, in the plane of the panel, for use to resist shear forces is documented in the BS5268 part 6.1. The current conflict of the mathematical approach used in EN 1995 -1-1 and that of the empirical values given in the UK code are subject to many European wide discussions, but fundamental to this debate is the fact that the UK market place is sensitive to the more conservative Eurocode design procedures and this highlights the increased structural performance that the UK engineers are taking timber panel frame construction. Exploring the differences from the UK and Eurocode in shear panel capacity and in the approach to the design process, high lights the current issues now being faced by UK engineers for multi storey timber frame.

These issues can be listed as:

- 1) Increased exposure of the building to higher wind loads (eg for the same location higher wind loads)
- 2) Increased level arm to horizontal forces applied to the lower shear panels, which leads to significant overturning forces, which in turn results in higher vertical forces to hold panels in place.
- 3) Increased shear forces as the loads accumulatively transfer down through the building that in turn need to be transferred across the building at each floor to wall interface.
- 4) Variation of the Centre of Gravity and possible rotation of forces within different floor layouts with in the height of the building leading to concentration and unresolved forces.

2.4 Robustness and Disproportionate Collapse

It would be common sense to appreciate that structural robustness becomes more of a design element on taller buildings. While it is expected that all buildings are robust for the general forces to which they are designed for there is also a requirement to design buildings such that they have inherent additional strength to cope with accidental forces or situations. More floors in building increases the probability that there will be a higher number of persons occupying the building leading to increased risk of casualties following an accident that would lead to a collapse, or partial collapse of the building. Hence the topic of robustness leads to the design against progressive collapse of a building. The current UK regulations stipulate that all buildings shall be designed such that in the event of an accident that the building shall not collapse disproportionate to the cause of the accident. The UK has adopted the principles of prEN 1991-1-7-2004 annex A, and in particular the use of table A.1, which is reproduced as table 11 in the UK Building Regulations, provides the class system to determine the risk category for a building. For timber frame buildings the category's 1, 2a and 2b are of relevance with category 2a up to 4 storey buildings and 2b for those in the 5,6 and 7 storey range.

Table 11 Building Classes	
Class	Building Type and Occupancy
1	Houses not exceeding 4 storeys. Agricultural buildings Buildings into which people rarely go, provided no part of the building is closer to another building, or area where people do go, than a distance of 1.5 times the building height
2A	5 storey single occupancy houses Hotels not exceeding 4 storeys Flats, apartments and other residential buildings not exceeding 4 storeys Offices not exceeding 4 storeys Industrial buildings not exceeding 3 storeys Retailing premises not exceeding 3 storeys of less than 2000m ² floor area in each storey Single storey educational buildings All buildings not exceeding 2 storeys to which members of the public are admitted and which contain floor areas not exceeding 2000m ² at each storey
2B	Hotels, flats, apartments and other residential buildings greater than 4 storeys but not exceeding 15 storeys Educational buildings greater than 1 storey but not exceeding 15 storeys Retailing premises greater than 3 storeys but not exceeding 15 storeys Hospitals not exceeding 3 storeys Offices greater than 4 storeys but not exceeding 15 storeys All buildings to which members of the public are admitted which contain floor areas exceeding 2000m ² but less than 5000m ² at each storey Car parking not exceeding 6 storeys

Extract from the UK Building Regulations 2004

For the engineer there are different design considerations to take a building from category 1 to 2 a, and from 2a to 2b. Currently there is no guidance in the UK for timber buildings but the amendment of BS 5268 part 2 that should be available early in 2008 will provide engineering guidance and rules to comply with each design category.

The issues facing the engineer for robustness is

- 1) Appropriate strategy to achieve the robustness needed to suite each class of building
- 2) Design values for materials and loading criteria for robustness calculations

3 Addressing the issues

3.1 Vertical load capacity

- 1) Mechanisms to provide lateral restraint – especially in multiple cripple stud arrangements.

Seldom is an actual calculation undertaken to determine the lateral restraint needed by a vertical member. The British Standard allows the sheathing attached to one side to provide stability. The engineer however has to ensure that this is in proportion to the stud spacing. Where stud spacing is less than 400 mm centers it is reasonable to check for the resolution of forces and that sheathing on both faces would be needed when centers closed up to 200 centers.

The problem becomes increasingly more problematic when multiple studs are used to carry point loads and ban of studs greater than 5 in number is unlikely to have adequate lateral restraint to allow the studs to share the loads. It is better to adopt engineered timber posts in this situation or to provide where possible noggins to brace the lateral forces back to shear walls.

None of the above is covered in the British Standards other than engineering design of columns that require justification for lateral restraint.

- 2) Practical stud centers for sheathing and services & thermal bridging

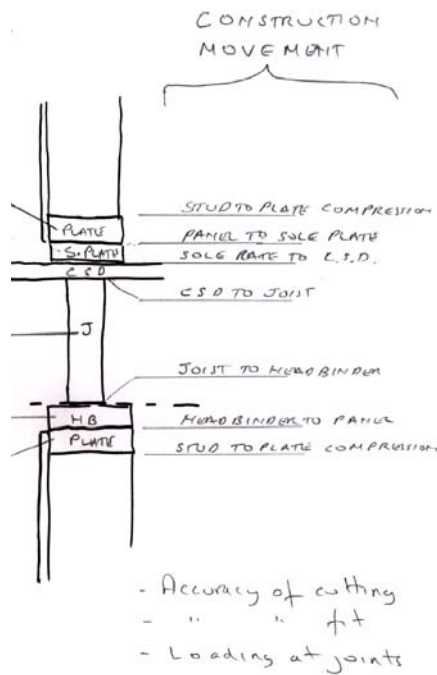
For external walls the percentage of timber in a wall will influence the amount of thermal bridging in a wall and influence the thermal value for the wall. This is largely ignored at present but increased reviews of sustainability ratings for buildings will soon make this a key issue in the design of timber frame walls.

Services in walls are typically vertical and so the need to drill horizontally should be avoided and the stud centers is not an issue.

3.2 Frame shortening or Differential Movement

- 1) Use of timber products and understanding the behavior in changing moisture contents and in the tolerance of the material.

The determination of cross grain timber in a frame and the amount of frame shortening that might occur has varied according to each engineer involved.



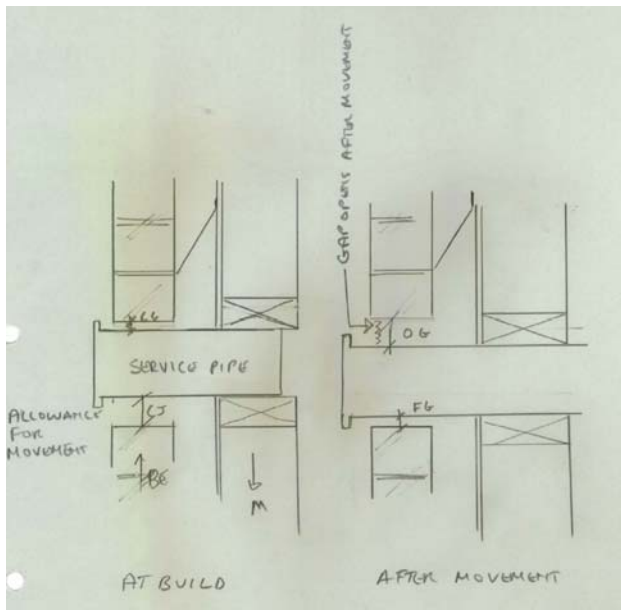
The November 2007, BS 5268 part 6.1, includes guidance for the differential movement of timber frame components. In the absence of specific data a table provides a calculation approach to determine the amount of cross grain shrinkage in a frame.

Frame material	Movement allowance
20% moisture content timber	2.8%
14% moisture content timber	1.2%
10% engineered wood products (e.g. laminated veneer lumber)	0.6%
NOTE 1 The depth of cross grain timber used in the above calculation should include all sole plates, rails, joists, and plates.	
NOTE 2 Moisture contents quoted in the table are average moisture contents taken at the time of erection.	
NOTE 3 The designer's attention is brought to the possible increased shortening caused by concentrated loads.	

2) Construction loading to compress open construction joints

The shortening of the frame can be added to by the amount of construction loading, which in turn can be advantageous if undertaken prior to the cladding and internal fittings have been applied.

3) Interfaces with cladding and other laterally attached structures such as free standing balconies and services.



The engineer is to ensure that any component that crosses the timber frame to elements that are not vertically supported by the frame have sufficient construction gaps (cg) to ensure when the frame has shortened that the vertical support has not created problems.

3.3 Resistance to Horizontal Forces

- 1) Increased exposure of the building to higher wind loads (eg for the same location higher wind loads)

This aspect is a straight code solution and is a natural fact of higher buildings - the number of storey's however lead to higher number of checks needed and roof uplift on the top storey becomes more critical.

- 2) Increased level arm to horizontal forces applied to the lower shear panels, which leads to significant overturning forces, which in turn results in higher vertical forces to hold panels in place.

The increased lever arm is a direct result of the height of the building. However independent checks on the panels to ensure that there is sufficient holding down to stop the panel rotating under the applied horizontal force. It is essential to distribute the forces through the building and additional shear walls may be necessary to achieve the factor of safety against overturning.

- 3) Increased shear forces as the loads accumulatively transfer down through the building that in turn need to be transferred across the building at each floor to wall interface.

Normal wind load transfer should account for the shear interface – but checks are needed to identify if high shear walls have sufficient capacity to take the forces down through the building and into the foundations.

- 4) Variation of the Centre of Gravity and possible rotation of forces within different floor layouts with in the height of the building leading to concentration and unresolved forces.

The layout of shear panels needs to be evenly distributed to ensure that the forces are transferred across the building. The use of perpendicular shear walls might be proven if sufficient diaphragm action can be proven and that the building does not twist to take up the forces.



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3.4 Robustness and Disproportionate Collapse

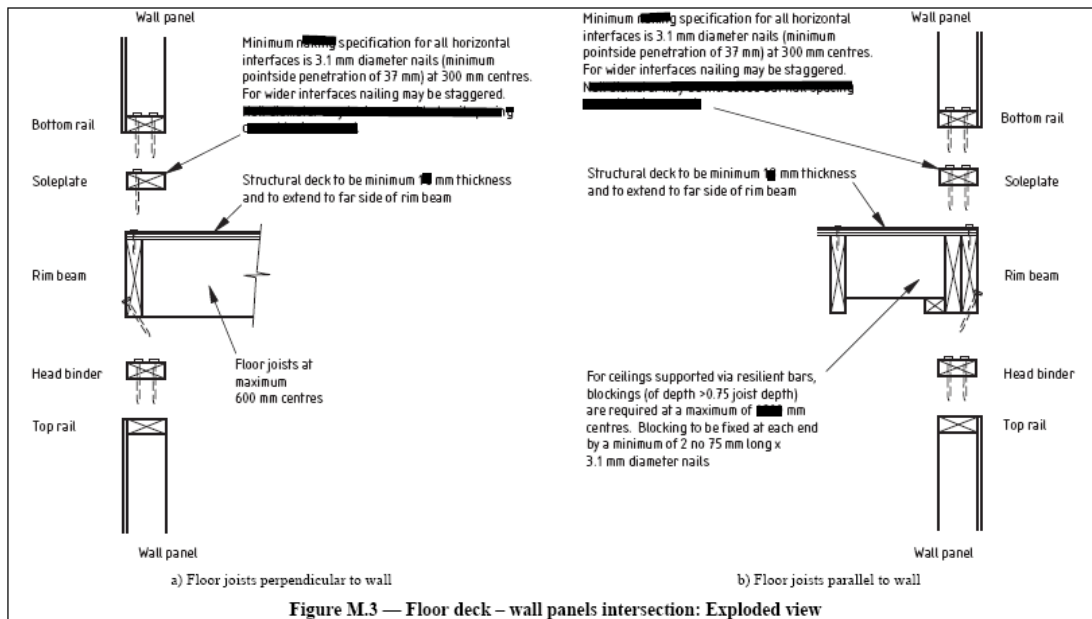
- 1) Appropriate strategy to achieve the robustness needed to suite each class of building.

The guidance for engineers to design for disproportionate collapse has been limited and it will not be until the new BS5268 part 2 is released in 2008 that official rules and strategies will be available. The following provides extracts from the new update and some explanation as to the meaning of the clauses.

The first point is for the engineer to allocate the class of building. For multi storey frame the category will either be Category 2A or 2B

For Class 2A frames the engineer may calculate the horizontal force at each junction of wall to floor or adopt minimum requirements of fixing the walls to the floors.

The minimum fixing is provided in an annex and the draft text is shown in Figure M3.

Draft BS 5268-2:2002/Amd 1
August 2007

It is still left to the engineer to provide appropriate fixings and ensure that the diagrammatic fixings shown in the figure M3 can be installed. Where floor cassettes are used alternative screw fixings are favored. It is pointed out that in most design cases the fixings are dictated by the horizontal shear needing to be transferred at the interfaces and fixings above are likely to be exceeded.

For class 2B frames the engineer is faced with the practical solution of Notional removal of load bearing elements. The important point is that it is notional and it is not asking for slip joints to be provided at the notional point – this unfortunately has to be stated as some engineers have adopted this route to ensure panels can be removed at predetermined locations- clearly not appropriate at all for a robust structure.

The proposed code requirements are as set out below

1.6.3.5 Notional removal of load-bearing element

The structure should be checked for the effect of the removal, within each storey, of each supporting column, or beam supporting column(s) or load-bearing wall(s), or any nominal length of load-bearing wall, one at a time, to ensure that disproportionate collapse does not occur. The portion of the building at risk of collapse should not exceed the lesser of 15% of the floor area of that storey or 70 m².

If the area at risk exceeds the limits given then the column, beam or load-bearing wall should be designed as a key element in accordance with 1.6.3.6.

The nominal length of a load-bearing wall should be taken as:

- In the case of an external wall, the length measured between vertical lateral restraints.
- In the case of an internal wall, the length measured between effective vertical lateral restraints but not exceeding $2.25h$, where h is the height between horizontal restraints as shown in Figure M.2.

When considering the residual structure the loading should be as defined in 1.6.3.7. The capacity of any relevant elements should be calculated in accordance with 1.6.3.8 and their connections should be calculated in accordance with 1.6.3.9.

The design solution checks the structure – one wall at a time for the removal of the supporting wall. The design values for materials will be provided in the code as given below.

There are several solutions open to a designer to achieve the structural robustness once the load bearing panels have been notionally removed:

Rim beam method:

The rim beam is incorporated loose in the floor zone at the end of all simply-supported joists to prop the wall panel and floor structure at each level, following notional removal of a wall panel between intersecting return walls or defined key elements beneath the rim beam.

Continuous / cantilever joist spans:

Continuous joist spans (I-joists and open web joists are easily available and transportable in lengths of up to 11m) are used wherever possible to avoid the need for rim beams on internal supports. Where internal load bearing walls are notionally removed, the joists are assumed to act in double span at each level and support the floor loads described above plus the weight of a (now non-load bearing) wall panel supported off the double-spanning joists.

Wall “beams”

The wall above the notional removed wall is designed as a deep beam – this is troublesome solution as the continuity of the joints need to be carefully considered.

Allowable collapse

If the collapse of the floor / roof / wall above provides limited distress and can fall within the area and storey impact rules then allowable collapse solutions can be adopted.

2) Design values for materials and loading criteria for robustness calculations

1.6.3.8 Permissible stresses for accidental load cases

When considering the probable effects of misuse, accident or particular hazards, or when computing the residual stability of the damaged structure, the designer should normally multiply the values recommended in BS 5268-2 for all long-term permissible stresses by a factor of 2.25.

1.6.3.9 Permissible fastener load for accidental load cases

When considering the probable effects of misuse, accident or particular hazards, or when computing the residual stability of the damaged structure, the designer should normally multiply the values recommended in BS 5268-2 for all long-term permissible loads on fasteners by a factor of 3.0. In the case of fastenings through particleboard the values recommended for long-term permissible loads should be increased by a factor of 4.0.

4 References

BS 5268-6.1:2007

BS5268 2. – draft for comment 2007

BRE – Multi storey timber frame – a design guide -2003

IStructe paper - MULTI-STOREY TIMBER FRAME CONSTRUCTION, by Guy Lewis CCB evolution

Building Regulations 1991 HMSO. London 1992. England & Wales: Approved Document

A,B,C,E & L.

The UKTFA Technical Bulletin Number 3 dated March 2005 ‘Design Guidance for Disproportionate Collapse’