Fire test on a 5 storey timber construction

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SUMMARY

The well documented Timber Frame 2000 project provided a six-storey experimental timber frame building (Figure 1), the first of its kind in the world, for the sole purpose of investigating the performance and economic prospects of medium-rise timber frame buildings in the UK. The majority of associated research projects conducted on this building have been completed and the results presented on an international forum. This paper summarises the TF2000 project to date and provides salient results from research conducted on the experimental building.

![Figure 1: The Six-storey TF2000 Building](image)

INTRODUCTION

Until a few years ago, the number of storeys in timber frame buildings in the UK was limited by fire regulations; to build with more than three storeys required special waivers. This restriction was lifted in 1991\(^1\) allowing, for the first time, the number of storeys potentially to reach eight (in England and Wales) without any additional fire resistance requirements other than those existing for many three-storey buildings. Timber frame buildings of up to four storeys are being used quite extensively in the UK, however no comprehensive design rules exist for five storeys or more. As a result BRE and TTL carried out a joint feasibility study\(^2\) on such buildings and subsequently built a six storey experimental building in partnership with the UK industry and DETR. The feasibility study, construction of the experimental building and later testing of the building were all conducted as part of the Timber Frame 2000 project (TF2000) with the objective of providing the technical tools and commercial drivers for the safe and economic construction of medium-rise timber frame buildings in the UK.
The feasibility study

The aim of this feasibility study \[^2\] was to review the design issues relating to safety, and to examine the construction requirements for such buildings. Case studies involving a few real projects were investigated during 1994 - 1995. The feasibility report reviewed and summarised design and construction requirements affecting medium-rise timber frame buildings. Much emphasis was placed upon the economical and technical issues and potential of medium-rise (4-8 storeys) timber frames, as a desirable method of construction. The research requirements and design options for full-scale tests on at least a five-storey test building were highlighted. The lack of research data for design and construction was identified and a primary research programme (TF2000) to overcome the significant aspects within a full-scale test building was proposed\[^2\]. Consequently, a co-operative project entitled Timber Frame 2000 (TF2000) by Department of the Environment, Transport and the Region (DETR), UK timber frame industry, TTL and BRE was set up in October 1995. More detailed information is given in the references\[^2\].

The TF2000 project

Consequent to the feasibility study's findings and conclusions, the TF2000 project started in October 1995, preparing the way for proposed tests on a test building. The TF2000 project entailed a two-phase investigation. Phase I \[^3\], provided the background study and justification to recommend and approve core and non-core programmes of work (Table 1) for Phase II along with the detailed design of a full-scale medium-rise building to be used as a test-bed. Phase II comprised the construction and testing of the building and the preparation of authoritative guidance for the design of medium-rise timber frame structures.

BENCHMARKING AND PROCESS ENGINEERING

Benchmarking began with the acknowledgement of the need for change and the decision to use an analytical methodology to achieve greater competitiveness and improvements in the whole product supply chain. Used successfully within other industries such as automotive and aerospace, benchmarking has now found a new lease of life in construction. In essence, benchmarking can best be described as “the continuous process of measuring products, services and practices against the toughest competitors, or those companies recognised as industry leaders”. Typically, it takes one of three forms:

**Internal** -comparison of the same thing within different branches of the same organisation.

**External** -comparison of the same product or process provided by direct market competitors.

**Functional** -comparison of the processes with worldwide best practice.
Fire test on a 5 storey timber construction

These can provide both the means to evaluate and compare alternate building solutions (steel, concrete, masonry or timber frame for example) and perhaps more importantly, provide the opportunity for firms to set new targets to bring themselves up to world-wide best-practice.

The next step was to identify client requirements, place them in a measurable context and then to use the information to target improvements clients will seek in the future. These customer-focused requirements are defined as critical success factors (csf's). For TF2000, the key csf's for competitive benchmarking were identified as:

- **Lead time** – calculated in weeks with the start point as customer contract agreement with full information and the end, the manufacturing completion of the timber frame package.
- **Construction value** – calculated in £ per square metre.
- **Speed of construction** – calculated in m² per week with the start point being arrival of the structural frame on site and the end being a water tight timber frame.

Work commenced on site in September 1997 and it took just 17 days to erect a six-storey building of 24 flats with a team of just six erectors (Figure 2). The results are summarised in Table 2 and comparison made with other materials in Table 3.

In comparison with steel and concrete framing, the benchmark costs have proved extremely competitive. The TF2000 figure is a total cost of £66 per square metre, including erection and labour, to give a watertight shell ready for the fitting of internal services and external cladding. This compares favourably with the target benchmark of £70 per square metre and a current industry figure of £85.

**Figure 2: Completed construction stage after 17 days**

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Target</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural frame</td>
<td>£70 m²</td>
<td>£60 m²</td>
<td>£58 m²</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erection cost</td>
<td>£15 m²</td>
<td>£10 m²</td>
<td>£8 m²</td>
</tr>
<tr>
<td>Lead time</td>
<td>6 weeks</td>
<td>5 weeks</td>
<td>5 weeks</td>
</tr>
<tr>
<td>Site production</td>
<td>225 m³/wk</td>
<td>750 m³/wk</td>
<td>656 m³/wk</td>
</tr>
<tr>
<td>Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3 – Benchmarking Comparison of timber with steel & Concrete**

<table>
<thead>
<tr>
<th></th>
<th>Steel</th>
<th>Concrete</th>
<th>TF2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural frame</td>
<td>£79 m²</td>
<td>£61 m²</td>
<td>£58 m²</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erection cost</td>
<td>N.A.</td>
<td>N.A.</td>
<td>£8 m²</td>
</tr>
<tr>
<td>Lead time</td>
<td>N.A.</td>
<td>N.A.</td>
<td>5 weeks</td>
</tr>
<tr>
<td>Site production</td>
<td>909 m³/wk</td>
<td>333 m³/wk</td>
<td>656 m³/wk</td>
</tr>
<tr>
<td>Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The comparative benchmark figures for the framing alone of steel and concrete structures are £79 and £61 per square metre respectively. The non-load bearing cladding walls and infill-walls still have to be built. Not only does this add to the eventual cost per square metre but also other work cannot proceed until these walls are in position, extending the overall building period.

Clearly, benchmarks can provide the team with the tools to dramatically improve construction performance. More details are given in⁴.
COMMERCIAL FINDINGS

Market - The UK construction market, in common with most construction markets world-wide, has come under increasing pressure to reduce costs and enhance client value, whilst maintaining or improving existing quality and performance standards. Maximising land usage, particularly on brown (inner city) sites, is also dictating increased storey heights for residential buildings from low rise (2-3 storey), to medium rise (4-8 storey). In the 5 - 8 storey markets, recent research demonstrated that a significant market existed for 5 and 6 storeys (Figure 3), but there is a much reduced demand for 7 and 8 storeys. Figure 5 was produced to gain some insight into the potential markets for medium rise buildings. It is based on a survey to evaluate the market for existing medium-rise residential stock. The methodology used was:

- Sample selection: 10 Towns were selected (Southampton, Portsmouth, Bournemouth, Reading, Oxford, Birmingham, London, Manchester, Liverpool and Aberdeen).
- Target sample identified as 100 recently erected residential buildings three storeys and above from each location.

![Figure 3: Market potential for timber frame buildings - (Number of storeys and relative share of potential market)](image)

There are strong indications that three- and four-storey timber frame buildings are becoming more readily accepted, demonstrated by the increasing number of buildings actually built. Despite the advances made in three and four-storey buildings there remain barriers to the acceptance of five and six-storey buildings (or higher) such as:

- Regulatory: Current regulations in Scotland inhibit timber frame medium-rise building because of non-combustibility clauses, particularly for protected shafts. The 11 m height restriction for floors constructed with combustible materials makes five-storey buildings the practical maximum at the moment.

- Build costs: The requirement to make specific design provisions for disproportionate collapse above four storeys and the market demand for lifts (beyond four storeys) adds significant costs, and can reduce the builders profit to the point that the extra storey is not considered economical.

- Market: Clearly (Figure 3), the viable market is in the 3-6 storey range at present, with 7-8 storey buildings representing only a very small percentage of present markets.
Awareness: The majority of designers, quantity surveyors, contractors and fabricators in the UK are not aware of the capabilities, the potential benefits and many advantages that timber frame buildings offer, such as:
- Fast construction times.
- Reduced loading on foundations.
- Off-site manufacture/less on site storage areas required.
- Reduced direct cost savings on labour, material waste, plant hire, etc.
- Minimum disruption to neighbouring buildings.
- Dimensional accuracy.
- Thermal and acoustic efficiency.
- Good environmental credentials.
- Design flexibility.

The considerable savings that can be gained from off- or on-site prefabrication (Figure 4) and the use of specialist erection teams make medium rise timber frame very attractive. The professional designers and surveyors, and large sections of the contracting and building industry still have to be made aware of timber frame's potential and be convinced of its advantages. This has and continues to be achieved through Timber Frame 2000, which has brought enormous publicity for timber frame buildings.

**ENGINEERING DESIGN & SPECIFICATION**

The following sets out the basis for the preliminary calculations and the principles, which were agreed by the Technical Committee.

Raft concrete foundation was used for the building. The preliminary structural calculations were based on BS5268: Part 2: 1996, BS5268: Part 6: Section 6.1: 1996 was used as a basis for judgements concerning the timber frame wall designs. BS5268: Part 3: 1985 was used to indicate the roof structure. Parallel design checks to applicable sections of DD ENV 1995-1-1: 1994 and its National Application Document (NAD) was carried out. The following were used for the preliminary calculations:

- CP3: Chapter V: 1972 - Basic wind data for the design of buildings.
Strength Class C16 to BS EN338\textsuperscript{13} was used throughout the calculations, in order to ensure that the tests on the structure will demonstrate the performance of such a building when using softwood from any suitable supply source (including the UK.). In consideration of the desirability of minimising differential movement, a decision was taken to designate special target moisture content at the time of erection. This was 12\% ± 2\% for floors and 18\% ± 2\% for walls.

The following general specifications for key elements were proposed and agreed (Figure 5):

- The ground floor is notionally a concrete slab-on-ground. Walls consist of two layers of plasterboard with a vapour control layer and 89 x 38 mm C16 timber studs with mineral wool insulation in between. The sheathing is 9 mm OSB, Type F2 (OSB3). The cavity is 60 mm with single leaf brick cladding tied with stainless steel ties to timber frame.

- Internal load bearing walls consist of C16 timber studs with two layers of plasterboard and 9 mm OSB, Type F2 sheathing to one side, where needed for wind bracing. The internal non-load bearing walls consist of C16 timber studs with one layer of plasterboard to each side. The compartment walls are twin leaf with C16 timber studs and mineral wool insulation in between. OSB Type F2 sheathing is used where wind resistance is required.

- Compartment floors consist of two layers of plasterboard ceiling lining and C16 joists with mineral wool in between. OSB Type F2 is used as a floor deck. Floating floors contain proprietary resilient battens with plasterboard and Type C4(M) chipboard.

- The roof is the trussed rafter type with hipped ends supporting concrete interlocking tiles.

More information is given in reference 14.

DIFFERENTIAL MOVEMENT

Differential movement between the timber frame and masonry cladding is an important consideration for the design of medium-rise timber frame buildings. Since the amount of differential movement between the timber frame and brickwork cladding increases with respect to the number of storeys, alternative methods to those currently adopted may be required for providing connections between the timber frame and cladding and other building components.

Over 93 instruments installed on the TF2000 building have provided data on the movement of wall and floor panels with detailed measurements of the joist, top rail, stud, bottom rail and sole plate throughout the construction and use of the building. Instruments also

![Figure 6: Predicted movement of the TF2000 timber frame due to](image)
provided data on the timber moisture content, supported stud loads, humidity and temperature.
Fire test on a 5 storey timber construction

Analysis of this data in combination with the results of laboratory tests, used to determine the cross grain shrinkage and compression, have enabled predictions to be made for movement of the timber frame had the TF2000 building been fully occupied. This prediction, shown in figure 6, assumes that any bedding-in displacements of timber members taking place in the uptake of load has already occurred during construction.

The use of super dried timber for the joists installed with moisture contents of about 12% ensures that the downward movement of the timber frame with time is reduced to less than 20mm. This in combination with brickwork cladding of a low moisture movement can result in a design value for differential movement of less than 30mm for the six-storey TF2000 building. Assuming this amount of total movement at eaves level would enable flexible wall ties to be used for the construction of cladding on a similar building. These results will be used to provide generic guidance on differential movement in medium-rise timber frame buildings for a variety of claddings and counter measures such as the use of engineered wood products in the floor construction. More information is given in reference 15.

WHOLE BUILDING RACKING STIFFNESS

This part of the test programme has been completed. One of the many items of interest in the construction of the TF2000 is the contribution of the various building elements (e.g. plasterboard, brick cladding, etc.) to the overall stiffness of the structure. However, measuring the overall stiffness of a six-storey building is not a simple task, and dynamic testing was selected as an indirect way of determining the required information.

Measurements of the frequencies of the building were made using a laser system (Figure 7) to monitor the ambient response of the structure, i.e. its natural vibration caused by air movement within the BRE Cardington Hangar. These measurements are processed to produce an autospectrum, which is used to identify the frequencies of the modes of vibration. The laser has the advantage that the measurements can be made remotely from the building.

More comprehensive forced vibration tests (Figure 7) were also undertaken at a number of key stages. These are used to determine all of the characteristics of the fundamental modes of vibration, i.e. frequency, mode shape, stiffness & damping. This provides detailed information but required the use of a vibration generator attached to the building.

Figure 7: Stiffness measurements of the TF2000 building
The following stages show the overall tests carried out:

Stage I - Timber frame alone (blocks of flats, stairs, roof, roof tiles)
Stage II - Stiffness of timber frame plus all plasterboard wall and ceiling linings
Stage III - Stiffness of completed building including masonry cladding

The following analyses were carried out:

- Lateral stiffness of timber frame only
- Lateral stiffness of timber frame and plasterboard linings
- Lateral stiffness of whole building (with brick cladding)

The results show that the addition of plasterboard linings increased the stiffness by a factor of 3.3, indicating that these items play an important role in the overall stiffness of the structure at that stage. The addition of the brick cladding introduced a further overall stiffness of the structure by a factor of 5.3 (to a total factor of 17.5 over the original timber frame). These results are being analysed for codes and standards and amendments will be made to the codes in due course. More detailed results are given in reference 16.

DISPROPORTIONATE COLLAPSE

This part of the programme has been completed. England/Wales and Scotland/Northern Ireland Building Regulations and Standards all refer to the need for disproportionate collapse robustness for buildings above four storeys.

The objective of this part of the programme of tests is to enable an evaluation of the actual behaviour of the TF2000 building when selected vertical load bearing wall panels are removed. This evaluation is to verify that the inherent stiffness of cellular platform timber frame construction can provide the necessary robustness so that, in the event of an accident, the building will not suffer collapse to an extent disproportionate to the cause. This is best achieved by designing in such a way that a beam, column or section of wall can be removed without the structure above collapsing (although damage to the building is allowed). To achieve this, beams are incorporated within floor depths over external walls, or the walls themselves are made to act as beams.

The building was loaded using weighed sandbags positioned on each floor above the full flat area where the tests were carried out in similar manner to that set out in the other material codes for checking disproportionate collapse. The following rules were defined for the TF2000 building:

- The horizontal length of any load-bearing wall to be notionally removed in any given instance is the length between intersecting internal/return walls or special vertical support system.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Vertical Deflection (mm)</th>
<th>Floor</th>
<th>Wall above</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For internal wall removed:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 minutes</td>
<td>13</td>
<td>No significant movement</td>
<td></td>
</tr>
<tr>
<td>4 hours</td>
<td>19</td>
<td>No significant movement</td>
<td></td>
</tr>
<tr>
<td>20 hours</td>
<td>26</td>
<td>No significant movement</td>
<td></td>
</tr>
<tr>
<td>For external wall removed:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 minutes</td>
<td>3.7</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>20 hours</td>
<td>4.0</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>No cracking of masonry cladding</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 - Summary of disproportionate collapse results

Table 4 shows a summary of the results and more information can be found in reference 17.
A full analytical review of the building was undertaken to predict the effect of removing each of the load bearing wall panels so that the ‘worse case’ could be chosen for the tests. For maximum vertical load effects and practicality, ground floor panels were chosen.

Two main areas of the building were subjected to the notional removal of walls, namely: (a) an internal wall and (b) a part of an external wall, between return walls (Figure 8).

The agreed limit level of serviceability (a function of the practical limit of deflections) for floor spans of 3600mm was chosen to be 300mm (approx. L/12).

It was recognised that it is difficult to develop mathematical models for engineers to check compliance to disproportionate collapse criteria simply. More reliability-based design research is needed to advance engineering models for prediction of actual behaviour.

FIRE SAFETY

One of the objectives of TF2000 project is to examine issues where there is disharmony between the three sets of building regulations existing in the UK with the objective, if possible, of achieving a closer degree of uniformity. The main discrepancy is the use of combustible material for construction beyond 11m in height. In this respect the fire safety principles are similar for low and medium-rise structures in that compartmentation must be assured for the fire duration. This has been assessed on the TF2000 building by conducting a fire test in a complete flat, detailed in the section below.

Another regulatory requirement for the whole of the UK is the use of non-combustible materials in stair and landing construction. This conflicts with the fast erection process for timber frame and the aim of providing stair access for the construction process itself. The combustibility and compartmentation of timber stairs in dry lined timber frame shafts has also been assessed as a part of the TF2000 project.

The compartment fire test

The primary objective of the TF2000 compartment fire test was to evaluate the fire resistance of a medium rise six storey timber frame building subject to a severe natural fire exposure. The test provided the opportunity to demonstrate that this form of construction can meet the functional requirements of the Building Regulations for England and Wales and the Building Standards for Scotland for such buildings.
In order to assess the performance of the structure in maintaining both the safety of the occupants and the integrity of the compartmentation for the required period of time the building was comprehensively instrumented. Instrumentation included thermocouples to measure the temperatures in the compartment and the heat rise in the cavities surrounding the compartment. Load cells were used to yield data on the rate of heat release in the compartment and automatic fire detection, gas analysis and heat flux meters were used to provide information on the tenability criteria.

The fire was ignited in the living area of the flat and progressed to flashover after approximately 24 minutes (Figure 9). Initial burning was concentrated in the front of the living area closest to the ventilation opening. To accelerate the time to flashover the Fire Brigade was asked to intervene by breaking a single windowpane in the kitchen area. This took place 21 minutes and 30 seconds from ignition. Following flashover the Fireline boards over the windows to the floor above were subject to a heat flux of approximately 30kW/m² (peak plume temperature in excess of 500°C). The timber frame of the window would, if exposed, have ignited. Peak temperatures in the living area of the fire flat reached approximately 1000°C and remained at this level until the test was stopped at 64 minutes having reached one of the planned termination criteria.

Maximum temperatures in the structural voids forming the boundaries of the compartment generally remained below 100°C with the exception of the localised areas where the timber members were exposed to fire for a period of time. The test data indicated that the TF2000 fire was approximately 10% more severe than a 60-minute fire resistance test exposure. In spite of this, there was little charring of the joists observed after completion of the test.

**The staircase fire test**

One of the main advantages of Timber Frame in the construction market is the speed at which buildings can be erected and commissioned. If a significant part of the construction involved the construction or casting of masonry elements then such benefits would be largely lost at cost to both the developer and client. This gave rise to a research proposal, supported by DETR and the timber construction industry, to carry out an experimental programme investigating the actual fire performance of timber stairs in a timber frame building.
It was necessary to define at an early stage the fire performance objectives for a stair in such a residential building during a fire situation. In meeting the fire safety requirements of the Building Regulations the fundamental consideration for the stair is as follows:

The stair has to remain usable for firefighting after initial evacuation of occupants immediately at risk and for subsequent evacuation by the other occupants of the flats who are initially advised to remain in their dwellings.

To prove this criteria initial trial tests established suitable methodology and specifications for the fire compartment, stair construction and fire characteristics; these were:

- Stairs would be treated using Dricon by Hickson Timber Products
- Thermosetting adhesive (i.e. not thermoplastic) was used in the assembly of the stairs from the treated components. A Urea Formaldehyde adhesive type was selected.
- Stairs were underdrawn with a single layer of 12.5mm Gypsum Wallboard fixed using clout nails at 150mm centres to the stringers of the stair only
- For the fire load, the test included a double mattress located on the ground floor of the building and tied back to the handrail and spindles of the lower stair flight. In addition a single crib, was built under the lower flight of stairs on the ground floor, and strips of paraffin soaked fibre board were placed on the first five treads. All of these ignition sources were lighted simultaneously.
- Following burn out of the fire load an inspection was carried out to assess the capability of the stairs as a means of access and escape

Fire development was very rapid following ignition. Flames could be seen licking around the newel post and handrail approximately 1 minute from ignition. The fibre strips soaked in paraffin ignited some 3 minutes into the test and continued to burn for approximately 12 minutes. At no stage was there any spread of fire from this source. The mattress burned extremely intensely and had been largely consumed by about 4.5 minutes into the test.

Despite the areas of inlet and exhaust ventilation being similar to those used in the trial an appreciably faster flow of air was established in the test in the TF2000 stair shaft. The velocity of smoke exhausting from the 5th floor (level 6) stair shaft window was noted as being significant and was estimated at approximately 5 metres per second. This through draught very evidently dictated the path of flames at the seat of the fire.
The fire lasted for approximately 31 minutes. At this stage the fire load had reduced to a few smouldering embers. The Fire Brigade attended the test but did not have to intervene to suppress the fire. Following combustion of the fire load the integrity of the stair was confirmed by asking Fire Brigade personnel in full equipment to use the stairs to access the first and second floors as recorded in figure 10. More detailed information is given in reference 19.

**ACCOUSTICS**

The main objective was to identify and develop enhanced performance solutions for Timber Frame buildings (using a whole-building approach) to address current client and occupier concerns regarding noise transmission between and within existing (masonry and timber frame) housing stock.

Acoustic tests have been carried out on 19 different types of wall and floor construction designed to meet the current building regulations and enhanced sound insulation targets. The research team set Enhanced targets in view of the Governments Business Plan for Safety and Health in Buildings. This seeks to "significantly improve the standards of sound insulation for both new and established dwellings and to reduce the estimated 20% or more households affected by noise nuisance".

To achieve a superior level of acoustic performance the wall and floor construction would need to be significantly better than the current building regulations. An enhancement of 3dB to the sound insulation is generally accepted as significantly noticeable and was included in the following sound insulation target values for wall and floor constructions:

- Airborne sound insulation for walls – 55dB (min)
- Airborne sound insulation for floors – 54dB (min)
- Impact sound transmission for floors – 59dB (max)

Most of the floors tested to-date met the target values of 54 dB (minimum airborne value) and 59 dB (maximum impact value). Wall test results are outstanding and they all meet the target value of 55 dB. More detailed information of the types of floating floors tested and their performance can be found in reference 20.

**FORWARD LOOK**

- The results of the racking stiffness are being converted to code values.
- The following codes and standards are being updated:
  - BS5268: Part 2
  - BS5268: Part 3
  - BS5268: Part 4
  - BS5268: Part 5
  - BS5268: Part 6
  - EC5 and CEN standards where appropriate.
- Harmonisation of Building Regulations and their update are being considered by relevant departments.
- Authoritative Guidance Document for design and construction of medium-rise buildings is being drafted.
ACKNOWLEDGEMENT

The TF2000 partnership is unique – international competitors throughout the supply chain have united to create a peerless example of the 90’s approach to innovation, pooling state-of-the-art knowledge on technology, product and process development. This project would not have proceeded without the support of the following organisations. The Building Research Establishment Limited (BRE) and TRADA Technology Limited (TTL) would like to thank the following organisations for their financial support and technical co-operation without which the findings of this project would not have come to fruition:

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- Woodbridge Timber
- Brick Development Association
- British Gypsum Isover
- Crown Timber
- UKFPA
- British Gypsum
- CSC Forest Products
- Marley Building Materials
- The A Proctor Group
- ITW Paslode
- Simpson Strong-tie
- SODRA Timber
- Hanson Brick
- Trus Joist MacMillan
- Rugby Joinery UK

16
REFERENCES