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Testing and Analysis of an Alternative Connection Method in Closed Panel Timber Frame Domestic Construction

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Mphil Thesis

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Abstract

Construction practices continue to evolve in tandem with the requirements for more energy efficient buildings, materials and construction methods. This steady and progressive move towards the development of the industry and its products comes, not in leaps and bounds, but in incremental advances across all areas of construction. The research detailed in this project is one such advancement. Timber frame construction has been in existence for centuries and its tried and tested methods have been utilised worldwide in both domestic and industrial building. In recent times, standard open panel timber frame construction has been enhanced by the development of closed panel timber frame construction. This method of timber frame construction permits more of the structure to be pre-fabricated in a factory setting resulting in less material exposure to weather conditions during construction. This research project examines the development of a new connection method in the assembly of closed panel timber frame walls which allows entire wall-panels to be pre-fabricated before deployment to site. The new connection method is achieved using tapered aluminium alloy fasteners pre-installed on each wall panel before on-site assembly. With the aid of a timber frame construction company, an action research process was put in place to critically assess and develop the application of the connection method across four live construction projects. Achieving a satisfactory connection detail then allowed for more considered structural and thermal testing to take place. A Thermal assessment of the details was carried out using both thermograhic camera surveys and thermal simulation software. Both compressive and lateral force structural tests were carried out on scale model wall panels in order to accurately compare the new connection method with that of a traditional screw-fixed connection detail. The results obtained from both forms of testing support and give impetus to the use of the new connection detail in preference to existing practices for future timber framed construction.

Declaration

I certify that this thesis which I now submit for examination for the award of Mphil, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for another award in any other third level institution.

The work reported on in this thesis conforms to the principles and requirements of the DIT's guidelines for ethics in research.

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Signature ___________________________________ Date _______________

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Table of Contents

Table of Figures

Table of Equations

Chapter 1

Introduction

1.1 Background

The Irish construction sector has seen a 78% drop in the volume of production across all building and construction activity from 2005 to 2012 (CSO, 2012). Such a dramatic decrease has led to many construction companies ceasing to exist or switching the focus of their operations to other countries. Having experienced unprecedented growth in the construction sector during the turn of the century, a common phrase was heard in Ireland; “concrete built is better built” (O' Murchu, 2007). This saying held some merit as during the “Celtic Tiger” boom time, the focus of many home builders and property developers was quick and efficient construction time ensuring a fast turnaround on investment. This was achieved by constructing the vast majority of developments in reinforced concrete or masonry. The rapid development in growth reached its peak in 2006 in terms of house building, where a total of over 90,000 housing units were completed; a record high for a population of 4.5 million people (The Department of the Environment, 2007).

The overall value of construction output at that time was over €38.5 Bn equating to 21% of GDP (DKM, 2009). Unfortunately the increased activity in the construction sector from that time appears, as many commentators have chronicled, a lost opportunity in terms of delivering sustainable and energy efficient construction. Irish building regulations (known as Part L) which deal specifically with the energy performance of a dwelling were not updated to an enforceable degree during the later nineties construction boom and the update in 2008 came at a time when construction had almost ground to a halt in the country as the value of construction output fell 54% between 2008 and 2009 (DKM, 2009).

Post-boom construction in Ireland is nowhere close to the heights of 2006, however there is now a greater emphasis and awareness on energy efficient construction and the overall reduction in CO_2 emissions. In order to adapt to these new demands, traditional masonry or concrete construction techniques are under review with large focus now being placed on increasing insulation and airtightness within all newly built structures. The more traditional methods of construction are now facing competition from modular methods such as Structural Insulated Panel building (SIP's), steel frame construction and timber frame construction.

There are a number of reasons why environmental impact and the reduction of energy in construction has become the key consideration. However, when viewed retrospectively. the main driving force behind the change stems from the Kyoto protocol which was entered into by the EU (including Ireland) in 1997 (EPA, 2012). In 2002, the European parliament and the council of the European Union issued a directive to all member states in respect of the energy performance of buildings. Known as the Energy Performance of Buildings Directive (EPBD), this document contains a range of provisions and requirements aimed at the improvement of the energy performance of residential and non-residential buildings required to be included in the general frame work for the calculation of energy performance of buildings (SEAI, 2012b).

This directive was adopted into Irish legislation in 2006 and is known as the Building Energy Rating Certificate (BER Cert). BER's became compulsory from 2009 and are used to assess the energy requirements for all commercial and residential buildings as needed (SEAI, 2012a).

1.2 Focus of Research

The focus of this research project is timber frame construction. Specifically, the research relates to the closed panel variety of timber frame construction. The research detailed throughout this project was carried out in conjunction with a small scale timber frame construction company (Company A). Company A are based in Ireland and pre-manufacture and assemble closed panel timber frame buildings, mostly in the domestic market. The company was keen to improve the method by which they manufactured and connected their wall panels with a need to reduce damage to the panels during transportation and assembly. This had further potential regarding the improvement of the thermal and structural performance of the connection points between wall panels when compared with traditional joining methods.

The current prefabrication and assembly process of closed panel timber frame walls by Company A is illustrated in Figures 1 and 2

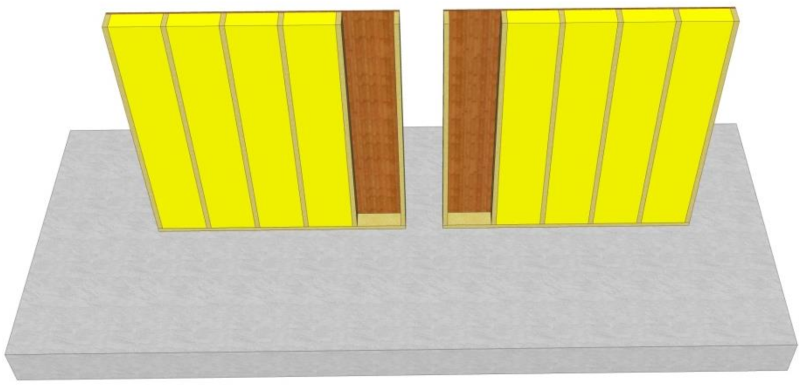


Figure 1: Positioning of prefabricated panels on site

The closed frame panels are prefabricated in a factory before transportation to site. They are then positioned as shown in Figure 1 prior to connecting. Figure 1 shows two walls with insulation between the vertical timber studs. Internal insulation and breather membranes have been omitted for clarity. Typically these materials are installed on each panel in the factory with both ends of each panel left unfinished as shown in Figure 1.

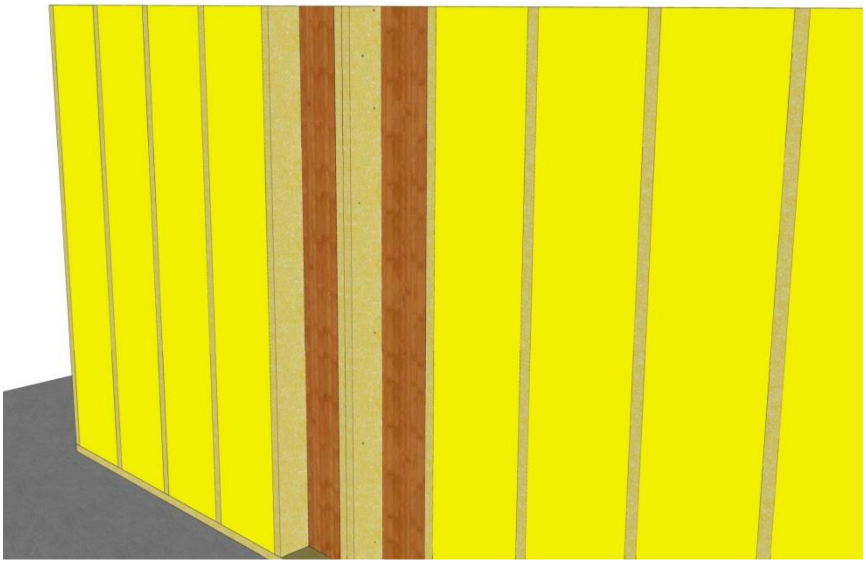


Figure 2: Wall panel's aligned and connected together by screw fixings

The unfinished and open ends of each panel allow workers to connect panels together using standard screw fixings. This is shown in Figure 2. After the panels are joined, insulation is inserted into the voids and the external and internal membranes are lapped and joined as required in order to complete the structure.

1.3 Research Aim and Objectives

The necessity in leaving the ends of each panel open was the core motivation behind the research. Company A wanted this situation to be evaluated and to determine if a better and more efficient method of pre-manufacture and connection/assembly could be developed. This established a primary aim of the research;

To develop an innovative, viable method of connecting closed panel timber frame walls and assessing if this method could improve the energy and structural performance of a timber frame building when compared with existing assembly practices.

This aim was achieved by concentrating on the following objectives:

- Research and critique current timber frame construction practice
- Improve existing methods of closed panel connection
- Thermal assessment of connection detail
- Structural assessment of new detail

1.4 Research Motivation

The research carried out in this dissertation strives to satisfy a problem both in a practical and academic sense. Company A wish to remove some of the more delicate on-site operations such as completing joints between panels and incorporate this into the prefabrication of each wall. This is essentially the focus point of the research. The development of a new connection detail, its testing and integration into a standard construction sequence not only provides the company with a new, viable connection detail but also provides a conclusion to the research. It is the successful development and satisfactory assessment of this detail that signals a contribution to existing knowledge is achieved as the layout of the detail has not previously been documented.

1.5 Chapter layout

Throughout this project, information and data relating to the subject matter and the course of the research process have been collected and compiled. The layout of this dissertation depicts the development of an improved method of connecting closed panel timber frame walls and this evolution is set out in various chapters. Chapter 2 investigates the world-wide development of timber frame construction from past to present and the extent of its use in today's construction industry. This chapter also looks at the preparation process of timber before it is used in construction. Chapter 3 outlines the development of closed panel timber frame construction from open panel timber frame construction. This chapter also gives an insight into the various materials used in this form of construction and the advances that have been made in the area.

Chapter 4 details the methodology applied to the entire research process. This chapter systematically outlines the methodology behind the different facets of the research such as Trial testing, structural testing and thermal evaluation. Chapter 5 details the development of a new connection detail and the steps involved in implementing it into an existing construction company. Chapter 6 outlines the process of validating the new connection detail in a number of live projects, the obstacles met and the adjustments that were made in pursuing a viable, alternative connection detail than that of standard screw fixing.

Chapter 7 details the refinement of the connection detail to that of a viable connection system that would work in live construction projects. Much of the refinement came as a direct result of the lessons learned during the trial process. Chapter 8 outline the thermal analysis of the details applied during live testing. Chapter 9 outlines the structural testing of the connection detail in order to compare and contrast it with that of a standard screw fixing method. This chapter is aimed at providing physical proof of the new connection details structural and thermal superiority as it is continued to be used in the future. Chapter 10 details the conclusions and findings from this research project.

Chapter 2

Worldwide Context of Timber Frame Construction

2.1 Preamble

The history of timber frame construction is a worldwide story and its progress through time has resulted in many changes and adaptations regarding its application and construction methods. Evidence of timber constructions date back at least six thousand years (UCL, 2009) but building in timber that would be recognizable today has existed since the thirteenth century and since that time there have been major advances both in the construction process and in contributing factors such as automation and industrial development. In order to truly gain a perspective of the evolution of timber construction, it is necessary to explore the journey of the method across continents and through history.

There are different forms of timber frame construction and these forms generally correspond with a specific historical time period. New and improved construction methods have been constantly developed in the timber frame industry; however, new practices were derived from old construction techniques and served to make the process quicker and more cost effective. This practice of refinement has allowed timber frame construction to remain both economically competitive and structurally sound in today's construction industry.

2.2 Timber construction in Asia

The earliest form of constructing in timber can be found in the Far East. This particularly applies to China, Japan and Korea. Timber buildings in these countries were not constructed of a simple post and beam structure but instead a more sophisticated arrangement of mortice and tenon joints grouped in bracket sets was commonplace (Pryce, 2005). The reason behind this elaborate form of construction stemmed from the ever present threat of earthquake activity. To combat this, a heavy roof structure supported by the sophisticated frame system provided strength and stability during seismic activity (Hairstans and TRADA Technology., 2010). The building practices of this era date back to the seventh century AD and the majority of buildings constructed in this method in Asia are temple-like structures with large curved hip roofs resting on wooden posts (Pryce 2005). The roofs had large overhanging eaves and were tile covered. The supporting wooden construction consisted of posts, purlins, and rows of short beams forming a framework, whose parts were only connected with pins. The infill walls did not have a load bearing function as the rest of the structure created an elastic wooden framework that could absorb strong vibrations of earthquakes (Pryce 2005). The intricate bracket sets such as those highlighted in Figure 3 first came to prominence in China before spreading to other Asian countries such as Japan and Korea.

Figure 3: Image depicting ornate craftsmanship at supporting bracket (Fu, 2012)

2.3 Post and beam construction

In continental Europe and in Britain, timber was widely used in the construction of cathedrals and barns due to the fact that timber roof structures could be assembled to cover the necessarily large spans. Roof framing methods evolved in tandem with larger buildings and roof spans, timber was hand cut to size allowing for the development of better roof systems incorporating rafters, purlins and struts. A typical timber roof frame during this time was a common rafter roof which offered a simple 'scissor brace' layout (Sunley and Bedding, 1985). Over time, the development of the cruck framing method gathered popularity, this method differed from the common rafter roof in its layout and construction method. Cruck framing involves the joining together of a series of timber frame portals to form a roof and building structure.

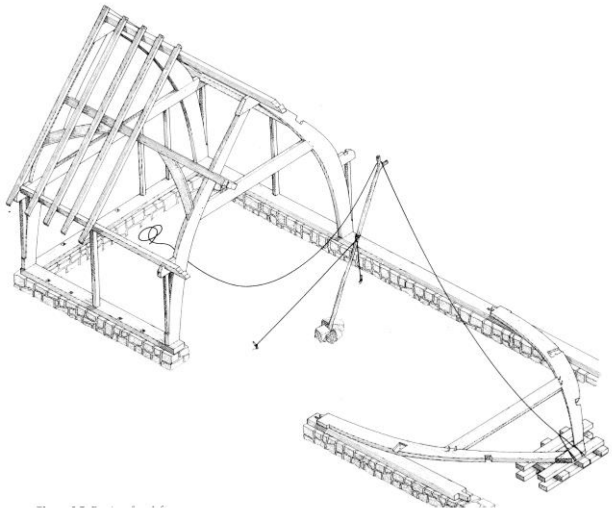


Figure 4: Image showing erection of Cruck frames (Sunley and Bedding, 1985)

Cruck framing, as shown in Figure 4 was also widely used in domestic construction such as cottages and houses. Over time however, a shift towards a post and beam construction process was adopted in Britain. This came to prominence during the thirteenth and fourteenth century for domestic dwelling construction (Grimsdale, 1985). The system of post and beam assembly is referred to in many different ways, namely; box frame construction and post and truss construction (Hairstans and TRADA Technology., 2010). Although differing in name and systematic approach, the principal behind each method remained the same. The construction process was relatively straight forward with large vertical posts set into solid clay or rock foundations. These posts carried the structural load of both the roof and any intermediate floors. Smaller vertical members known as studs were erected between the larger posts; these in turn had branches woven between them. These branches were then covered in clay or daub for a waterproof finish (Scott Deetz, Fennell, and Deetz, 2000). As the method evolved, clay and daub made way for timber and brick infill walls. All joints between timber members were made using traditional carpentry techniques such as mortise and tenon joints and dovetailing (Wachsmann, 1995).

2.4 Development of Balloon frame construction

With the discovery of the New World in the fifteenth century, opportunities arose for improving timber framing practices. European settlers brought the methods of post and beam timber framing to America. The settlers found an abundance of raw materials with 45% of the continent covered in forest. The vast supply of timber ensured that the natural resource remained an important part of the American economy for 300 years (Pryce, 2005) up until present times. During this time the heavy and intricate post and beam framing method remained popular. However, at the turn of the nineteenth century the industrial revolution had a large impact on the development of timber frame construction. The introduction of smaller dimensional lumber made possible by steam powered sawmills and the introduction of steel nails as a joining method revolutionised the speed and precision of domestic timber frame construction. Skilled carpenters were no longer needed to create the detailed joints commonly used in post and beam framing (Grimsdale, 1985).

The industrial revolution, combined with a rapidly expanding population, paved the way for the development of a quicker and more streamlined form of timber frame construction. This method is referred to as balloon frame construction and was primarily developed to satisfy the demand for housing. The balloon method of timber frame construction involves the external frame of a building being constructed in two-story heights as opposed to one. As highlighted in Figure 5, the vertical timber studs in the external walls run from ground floor level to eaves level (Covington, McIntyre, and Stevens, 1995). Intermediate floors are then fixed to the erected frame (Stirling, 2001). Although light, the frame was very strong and able to withstand heavy winds as the stress was spread over a large number of studs. Overall, this practice reduced the time and cost involved in timber frame construction and paved the way for speedy house building in rapidly developing western America and Canada (Grimsdale 1985).

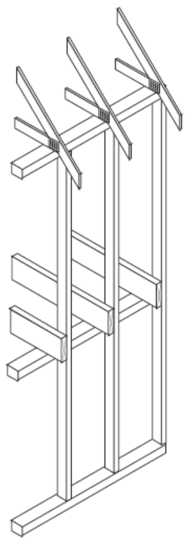


Figure 5: Balloon timber frame construction(Stirling, 2001)

Balloon framing established itself as the predominant form of timber frame construction at that time. In the overall development of timber framing, balloon framing is particularly important as it is a demonstration of the evolutionary nature of construction during the coming together of industrialisation and urbanisation. The adaption of the post and beam method was needed in terms of satisfying the housing demand and was facilitated as innovation provided the opportunity for rapid construction (Mete, 2009).

2.4.1 Adoption of Balloon framing in Australia and New Zealand

Formerly a British penal colony, Australia was first sought after for a new supply of timber to the Royal Navy. Unfortunately it was discovered that the Australian Eucalypts tree made up 75% of the tree population and is poor in quality for both ship and house building (Pryce, 2005). Usable softwoods were imported from the British Empire or the United States. The discovery of gold in 1851 brought with it a rapidly expanding population which in turn demanded quick-erect housing as was used in the United States at the time. As a result of the demand, timber was largely imported from the west coast of America and a derivative of balloon framing was adapted to suit the Australian climate (Hairstans and TRADA Technology., 2010). The Australian carpentry methods differed slightly from that of America as the structural timber frame was both lighter and thinner. In a change to the North American system, entire wall frames were assembled and nailed on the ground before being levered into position (Pryce, 2005). As Australia became more and more populated, the location of usable wood forests became the catalyst for settlement locations (Pryce, 2005).

Timber frame housing has been constructed in New Zealand for over 100 years (Beattie, 2010). The popularity of timber in the New Zealand construction industry stemmed from necessity. The country is susceptible to earthquakes and so rigid structures comprised of brick and stone quickly succumbed to the movement of the earth. Timber offered natural flexibility; ensuring buildings constructed using the material survived earthquakes and remained standing (Isaacs, 2010). Much like Australia, The balloon framing method of timber frame construction rose to prominence in the mid 1800's due to its speed of erection. This replaced the log-cabin timber construction which required large dimension timbers which placed greater demand on forests, ultimately leading to excessive deforestation (Isaacs 2010).

2.5 Development to Timber Platform Frame Construction

Platform or Western Frame Construction was developed in the western states of America during the building boom of the mid-nineteenth century. As balloon construction grew in popularity, its negative aspects called for a change in timber construction methods. The continuous ground to eave stud arrangement, synonymous with balloon construction, offered little in the way of fire stops between floors. Fire stops were required to be fitted after the erection of the framed walls contributing to increased building cost (Burchell and Sunter, 1987). Platform frame construction evolved from the balloon frame. This method uses the same dimensional lumber and connecting processes. However, buildings are constructed in single-storey height wall panels with the intermediate floor constructed on top of each storey as shown in Figure 6. The floor then provides a platform for the construction of the next storey (Grimsdale, 1985).

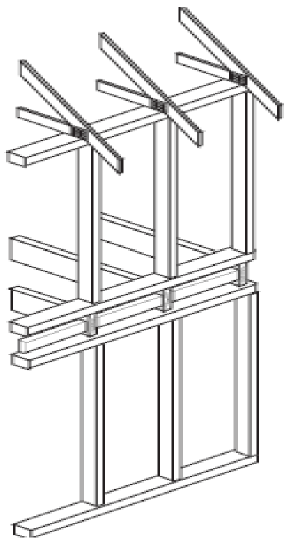


Figure 6: Timber Platform frame construction (Stirling, 2001)

A platform frame wall build-up consisted of timber uprights (studs), sole plates which were horizontal members running along the bottom of each wall and wall plates which ran horizontally across the top (Ruske, 2004). Due to the shorter dimensional requirements for wall studs, smaller trees could be used in the production of timber for platform frame construction. The separation of each floor also provided a fire break between stories; this coupled with increased accuracy in the timber manufacture, resulted in the need for less on-site skilled labour as the process was simplified (Burchell and Sunter, 1987).

From a technical viewpoint, the use of shorter dimensional lumbar minimized the potential of shrinkage defects. This allowed the use of unseasoned timber which was in abundance at the time (Burchell and Sunter, 1987). Horizontal weather boards were applied as an exterior finish to a platform frame house, this provided stability to the structure and protected against weather conditions. As the construction method progressed so did individual elements; gypsum wallboard began to be used for wall and ceiling linings. Concurrently, plywood bonded with a weatherproof glue was used as an external sheathing material for walls, floors and roofs (Burchell and Sunter, 1987).

2.5.1 European expansion of Timber Platform Framing

Timber frame construction in North America continued to grow in the twentieth century with over 1 million houses a year being built throughout the different climate zones of the country (Burchell and Sunter, 1987). As a result of its popularity and functional construction process, the concept of platform framing was exported to Europe. In Scandinavian countries such as Finland and Sweden, uptake of this form of construction was slow as the beginning due to the predominance of traditional log house construction. Over time however, this method of timber construction was eventually replaced in Scandinavia by the much quicker and less laborious platform framing system.

Further changes were made to the construction characteristics and wall make-up of platform framing. The inclusion of mineral wool insulation inside the framed walls and the application of a brick or rendered façade are two developments which are still common place today (Hairstans and TRADA Technology., 2010). In Britain, timber platform framing did not take hold until the 1950's. In a campaign embarked upon by the Canadian government and the UK Forestry Industry, a renewed focus was placed on domestic timber frame construction highlighting the benefits of a quick construction time and increased thermal insulation (Burchell and Sunter, 1987). As a result of the initiative, local authorities began to specify the use of timber framed housing for schemes throughout the UK. As a result, the level of timber frame house construction rose dramatically and this had a further effect on the evolution of timber framing as construction companies began to utilize factory-fabricated components to shorten on-site construction time (Burchell and Sunter, 1987). The factory-fabrication element of timber framing required less labour during the erection process. This proved advantageous as there was a shortage of skilled workers in Britain at the time (Burchell and Sunter, 1987).

2.6 Historical Building Practice in Ireland

Traditionally, Irish domestic construction has always been steeped in masonry practice. This stems from the dry stone wall construction methods of our ancestors. Vernacular stone houses were a common feature of the Irish countryside. The dwellings were constructed using locally sourced stone which varied according to the geology of the area (McAfee, 1998). The practice of dry stone wall construction varied from region to region. Stone walls were often constructed using a lime mortar, mud or were laid dry (McAfee, 1998). The typical layout for such dwellings involved a one-room design with two points of entry. Roofs were typically finished in a thatch covering. However, the social position of the owners had a large bearing on the appearance of the dwelling and often a lean-to roof covered in sod was applied (McAfee, 1998).

As construction practices progressed, stone remained the most common building material. During the eighteenth and nineteenth century two-storey houses became common in towns and cities across Ireland. Construction of such houses involved the sourcing of local stone for use in forming the superstructure. Quoin stones are stones cut in uniform shape and size and were used in the construction of the external walls of a dwelling. They were usually placed at the corners or at door and window openings to ensure the building's façade remained square (McAfee, 1998). The wall structure comprised of dual layers as stones were built on the internal side and the external face was usually finished in brick or stone rubble which was later plastered. These layers were commonly joined together by 'through stones' which stretch from the internal leaf to the external leaf (McAfee, 1998). A typical width of the external walls was roughly 600mm. This was primarily for resistance to rain penetration and to ensure the internal face of the wall was kept dry. Mortar or mud was used as bedding material for the stone and also served to create a solid wall mass (McAfee, 1998).

The exact development of the cavity wall system is unknown in Ireland but it is commonly believed to have come from UK building practice. Builders and architects started to experiment with cavity walls from early in the Victorian period in Britain. By the early 1900's, most construction details for houses included outer walls with two separate leaves of brickwork. Initially the development of the 'hollow' or cavity wall was to provide as much protection as possible from the elements (Ogley, 2010). During the mid-1900's cavity construction began to gain ground and became a common form of construction in Ireland.

The concept behind the cavity is simple; a typical layout involves an internal and external concrete block leaf separated by a 100mm wide cavity. The external block leaf is rendered in sand and cement and acts as a barrier to prevent the intrusion of rain and dampness. It is imperative that the cavity is not bridged in any way as this would provide a passage for moisture to travel to the internal face of the wall (Chudley and Greeno, 2005). This form of wall construction became common place throughout Ireland and was the main form of domestic construction during the peak construction period of 1997 to 2007.

2.7 Development of Timber Frame Construction in Ireland

Amendments to the UK building regulations in 1965 called for the limitation of the amount of energy that could be lost through certain construction elements in any new construction. The introduction of U-values required constructors to become more aware of heat loss through the fabric of a building and, as a result, timber frame construction has since remained the preferred method throughout Britain with 25% of all new houses currently being constructed in this manner (Hairstans and TRADA Technology., 2010). The method of timber frame construction in Ireland has closely followed that of the UK. However, the level of timber frame construction has been low by comparison. In 1990, just 1% of new housing was constructed in timber frame. This figure climbed to 26% during the construction boom time of 1997 to 2007 (ITFMA, 2013) and was projected to grow further, however the economic downturn diminished the possibility of significant further growth.

2.7.1 The Merit of Timber Frame in the Construction Industry

The construction industry today, both in Ireland and in the UK, incorporates three main methods of construction practice, they are; concrete built, steel built and timber built. It is uncertain what exact percentage of industry production each method accounts for, however, the majority is undoubtedly concrete or a mixture of concrete and steel as in the application of reinforced concrete. In Ireland, concrete construction prevailed as the most common material used in both residential and commercial projects. This was particularly apparent during the intense construction years of 2000 to 2007 as the mantra “concrete built is better built” was widely promoted (O' Murchu, 2007).

Today's Irish construction sector is continuing to redefine itself in the wake of the downturn in the construction industry. With over one hundred and thirty thousand job losses in the construction sector since 2007 to 2011, the construction industry in Ireland has undergone a radical change. This change has also applied to methods of construction used in the industry, particularly in relation to house building as there is much emphasis placed on reducing energy consumption, energy loss and minimising the production of greenhouse gases. Taking into account this change of focus within the industry, it is necessary to review the main construction materials in terms of their overall environmental contribution. This relates to the material’s overall carbon footprint associated with sourcing of raw material, the performance of the material during service and the recycling after use.

2.7.2 Concrete Manufacturing Process

The basic constituents of concrete are cement, aggregates and admixtures. The introduction of water results in a chemical reaction process known as hydration which hardens and strengthens the components resulting in concrete. The production of concrete requires large amounts of energy, particularly in the manufacturing of cement; this contributes to the production of large amounts of Carbon Dioxide (CO_2), one of the major greenhouse gases. The concrete industry accounts for 5% of world-wide man made CO_2 emissions with 900 kg of CO_2 being emitted for every ton of cement produced (Sabnis and Carter, 2011). This equates to over 500 million tonnes of CO_2 being produced each year during concrete production (CSI, 2013).

Cement can be classified into various types depending on the composition of each. The most common cement used in the Irish and global construction industry is type CEM 1 Portland cement which contains 95% clinker (ICF, 2013). Clinker is a substance which requires the use of carbon-intensive fuels, such as coal in its creation. Besides energy consumption, the clinker-making process also emits CO_2 from the calcination process (Worrell et al., 2001). Both of these emission sources and the accompanying electricity consumption single out cement production as an energy-intensive process.

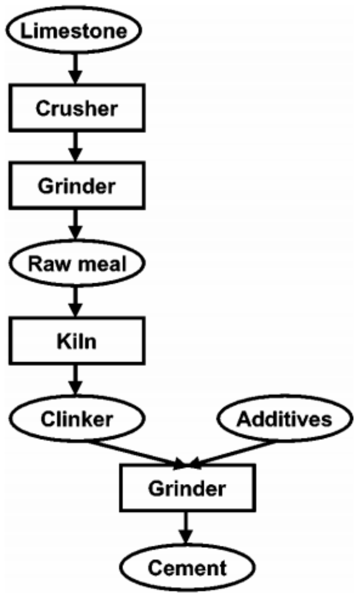


Figure 7: Systematic production of cement (Worrell et al., 2001)

CEM 2 and CEM 3 cements are manufactured with reduced levels of clinker. Typically CEM 2 cement has a content of 65% clinker and 35% slag, a by-product of steel manufacturing. CEM 3 cement contains almost 80% slag with 20% clinker content. The reduction in clinker is aimed at lowering the embodied energy contained in the cement manufacture, however the production of slag generates significant quantities of CO_2 with over 5 tonnes of CO_2 created for every 1 ton of slag (Bannon, 2006). The entire manufacturing process of cement is outlined in Figure 7. Limestone, chalk and clay are the most common raw materials used for cement production. The collected raw materials are selected, crushed, and ground before being burned at high temperatures in a kiln to produce clinker. Aggregates used in concrete are divided into three groups; sand gravel and crushed stone. Although there is less of a demand on energy resources to produce aggregate when compared with cement, there are environmental factors to be taken into consideration with regards to transport of materials from source to customer and the depletion of quarries (Khatib, 2009).

2.7.3 Improvements in the Environmental Impact of Concrete

In recent years cement manufacturers have begun to address the high level of CO_2 emissions associated with cement production. This however, is a slow process with many countries hesitant to change from the tried and tested methods of cement manufacture (Sabnis and Carter, 2011). The high level of energy consumption and CO_2 emissions cannot be drastically lowered considering the high levels of heat necessary to induce the calcination process of limestone. Instead, focus is shifting onto maximizing the efficiency of kilns and allowing the heating process to be carried out in the most energy efficient way possible of reducing CO_2 emissions.

Although cement is typically 10% - 12% of concrete, its embodied energy is directly associated with concrete's overall carbon footprint. To lower this, concrete manufacturers have adopted a recycling strategy with regards to the aggregate used in concrete production. Used concrete from buildings that have reached the end of their service life is highly recyclable after it has been sorted and crushed to a usable size. This does however require energy and leads to more CO_2 emissions as the removal of steel bars from reinforced concrete requires magnetic separation. As a result, recycling of crushed concrete is largely beneficial where there is a short transport distance between the demolition site and new building (Khatib, 2009). Recycled concrete can be used up to a certain proportion in new concrete (up to 20%) but it is mostly used as a substitute for natural aggregates in back fill and road construction (Berge and Knovel ebook., 2009)

2.7.4 Steel Manufacturing Process

Steel is the only iron based material used in the construction industry today and contains a carbon content of less than 2%. It is made from iron ore which is spread quite evenly throughout the world in many countries. The ore is extracted in quarries or deep mines before being transported to the steel production site (Berge and Knovel ebook., 2009). The conversion from iron ore to steel requires a number of processes. Initially the ore is broken up before being cleaned and added to the sinter strand. Sintering is the process of adding the raw material to combustible materials such as coal or coke breeze, this mix is then ignited, starting the sintering process. During sintering, chemical reactions take place and contribute directly to the production of CO_2 gasses (EPA, 2003). Once through the sintering process, the material is then smelted out and reduced in a blast furnace at temperatures ranging from 1700°C to 1800°C. Typically a blast furnace can produce 1000 tonnes of pig iron every 24 hours requiring a total of 440 – 600 tonnes of coal to produce 1 ton of iron (Berge and Knovel ebook., 2009).

Similar to cement, the manufacture of steel is energy intensive and produces large amounts of greenhouse gases in the form of CO_2. On average, 1.9 tonnes of CO_2 are emitted for every tonne of steel produced. Recent statistics on worldwide steel production indicate that over

1.5 billion tonnes of steel were manufactured worldwide in 2012 with almost 170 million tonnes manufactured in Europe (WSA, 2013b).

Such production figures support the fact that steel manufacture accounts for approximately 4-5% of total world CO_2 emissions (WSA, 2013b). As already mentioned, steel is typically used as reinforcement in conjunction with concrete. The concrete encases the steel protecting it from corrosion or rust. For a comparison with timber frame construction, steel is also produced in light sections with a galvanised or zinc coating for use in light steel frame buildings. In this instance, the steel is galvanised to give it a protective coating against corrosion, the process produces numerous environmental pollutants in the form of cyanides, phosphates and fluorides. (Berge and Knovel ebook., 2009)

2.7.5 Improvements in the Environmental Impact of Steel Production

The high level of CO_2 emissions has been recognised by the world steel association and efforts to reduce the emissions have been implemented. A key element in reducing the carbon emissions is to optimise the use of recycled steel material. Steel can be consistently recycled at the end of its service life without losing any of its properties (Figure 8). This is

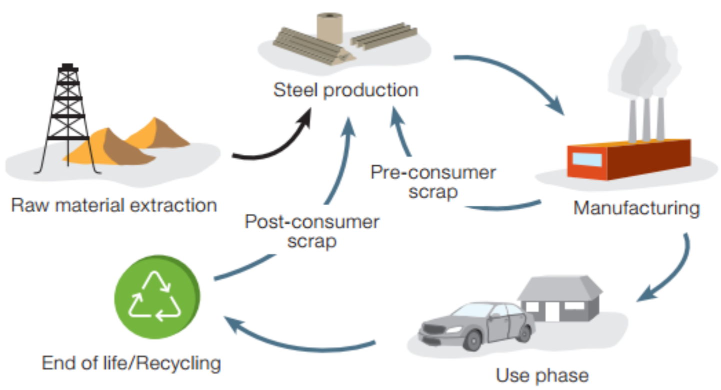


Figure 8: Steel's life cycle (WSA, 2013a)

the basis for the reduction of steel's carbon footprint as an entire life-cycle approach is viewed as the best way to manage the carbon emissions associated with steel (WSA, 2013a).

Avenues to reduce CO_2 emissions at production level, include encouragement of research in new steel making technologies, the upgrading of steel making plants to reduce emissions and the establishment of a common CO_2 measurement system in order for steel producers to monitor emissions and set reduction targets (WSA, 2013a).

As highlighted, both concrete and steel production requires heavy carbon emissions from the raw material stage to completion. In contrast to this, the use of timber as a building material offers significantly less energy and carbon emissions in its production and refinement. As wood is derived from trees, its source is renewable and occurs naturally. The process of conversion from raw material to usable product does require processing using machinery and equipment. However the levels of energy required are not to the same levels as needed in the concrete and steel industry.

2.7.6 Timber Properties

The wood used in the construction of timber frame buildings is sourced naturally from trees. Wood is a complex material with many factors and classifications associated with its manufacture and eventual use. It is necessary to examine the wood sourcing process in order to gain a deeper understanding of the timber frame practice.

2.7.7 The Tree

A tree is a living organism which can be broken down into three main sections; the roots, the trunk and the branches with their leaves (crown). The roots anchor the tree to the ground and also absorb water and dissolved mineral salts from the soil. The leaves absorb carbon dioxide from the air which is then combined with water to produce sugars and other organic substances that are absorbed by the trunk giving structural strength to the tree and promoting further growth (Lyons, 2007).

The exterior of the tree is protected from temperature extremes and mechanical damage by a hard outer layer called the bark. Trees grow both outwards and upwards both movements are caused by different cell behaviour. A thin delicate tissue known as the cambium exists between the outer bark and the inner wood of a tree. In winter months the cells contained in the cambium are dormant resulting in no growth. In spring, the cells contained in this layer subdivide radically resulting in the growth of the tree. This growth can be seen in a series of concentric layers of tissue known as growth rings (Desch and Dinwoodie, 1996).

Over the course of a trees existence, a band of sapwood in the outer zone of the tree is created. This area contains living cells in which food materials are stored. Reserve materials such as starch are extracted from the inner growth rings and deposited in the sapwood resulting in a heartwood core at the centre of the tree (Everett and Barritt, 1994). There is no difference in wood density between heartwood and sapwood zones; however, the sapwood appears lighter than the heartwood because it contains sugars, starch and water. As growth spreads outwards, the heartwood advances to include former sapwood cells; this transition decreases the moisture content in the sapwood and increases the acidity level of the wood strengthening it against fungal or insect attack (Desch and Dinwoodie, 1996).

2.7.8 Hardwoods and Softwoods

Commercial timbers are defined as hardwoods and softwoods. Softwoods (gymnosperms) are conifers or evergreen trees with narrow, needle like leaves. Hardwoods (angiosperms) are broadleaf, deciduous trees which lose their leaves in autumn.

2.7.8.1 Softwoods:

Softwoods are typically composed of long, slender cells called longitudinal tracheids. Tracheid's are usually 2.5mm to 3mm but can reach 10mm in length. They have hollow centres and are used to conduct food and water distribution and give strength to the tree (Haygreen and Bowyer, 1996). The cells vary in size between the rapid growth at spring (early wood) and the slower growth of autumn (late wood). Tracheids formed in the early wood zones are thin walled and function as conducting tubes for the movement of sap through the structure of the tree.

2.7.8.2 Hardwoods:

Hardwoods have a more complex structure when compared with softwoods. In hard woods, the conduction of sap takes place through long tubes known as vessels with smaller cells or fibres providing mechanical support. Hardwoods are divided into two distinct groups; the first is known as diffuse-porous hardwoods which contain vessels of a similar diameter distributed evenly across the timber, the second group is known as ring-porous hardwoods which contain large vessels in the earlywood zone and smaller vessels in the latewood zone. As in softwoods, this allows for visible growth rings to appear on the tree (Lyons, 2007).

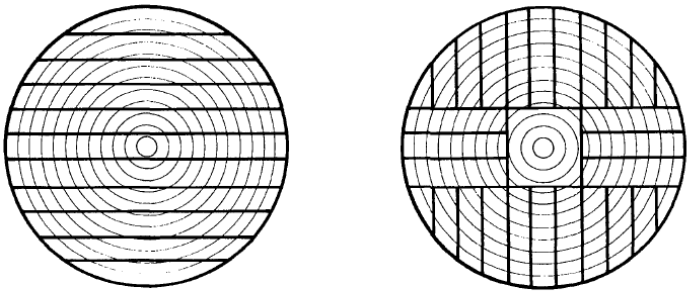


Figure 10: Through and through cut (left) and quarter cut with boxed heart (right) (Burchell and Sunter, 1987)

2.7.10 Conversion of logs into timber

Timber conversion is the process of cutting logs into sections prior to seasoning. This usually takes place in a sawing mill with the principal aim being to maximise output on a financial basis rather than on volume output. To achieve this, logs are sawn in a number of different ways, each designed to extract the most amount of useable timber. The two main types of cut are plain cut and quarter sawn (Lyons, 2007). Plain sawn timber has a more decorative appearance but is more susceptible to defects, particularly cupping. Quarter sawn timber is harder wearing and is less likely to flake. However, it is a more expensive cutting procedure as the log requires resetting for each cut.

Both types of cut are depicted in Figure 10. As can be seen, the through and through cut produces both plain sawn and quarter sawn timber whereas the quarter cut method produces just quarter sawn timber (Lyons, 2007). In some trees the central core of the trunk is much weaker than the rest of the heartwood. It is therefore necessary to ‘box’ around the heartwood as shown in Figure 10 (Findlay, 1975).

2.7.11 Timber Seasoning

After the timber logs have gone through the primary conversion process, it is then necessary to season the timber in order to reduce its moisture content and render it fit for purpose. This process has a primary aim of rendering the timber as dimensionally stable as possible and is an essential procedure in the preparation of the timber for adequate absorption of preservative treatment.

For the purpose of this research project, an interview and tour of Glennon Bros timber conversion plant located in Longford, Ireland was undertaken with factory manager Mr. Brendan Farrell. This interview and tour was carried out in order to gain a first-hand perspective of the processes involved in sourcing, converting and distribution of timber in Ireland today. A full transcript of the interview can be found in Appendix A.

2.7.12 Moisture Content of timber

Moisture is held in freshly felled trees in two forms: free moisture, which is contained in the cavities of the cells and is often referred to as sap and secondly there is bound moisture which is held in the cell walls (Pratt and Turner, 1986). When the timber is dried, the free moisture is the first to evaporate leaving the timber at fibre saturation point. When drying continues beyond this point, shrinkage will occur roughly in proportion to the amount of bound moisture lost. It is necessary for timber to be dried in order to prevent shrinkage and distortion in service. The amount of water contained in timber rises and falls in tandem with the humidity and temperature of the surrounding air, therefore it is not possible to prevent wood from expanding and contracting in service however, movement can be minimised by drying the wood so it stays in approximate equilibrium with the conditions of service (Desch and Dinwoodie, 1996). Drying timber also offers other advantages as a timber moisture content of below 20% results in the fibre of the timber becoming stronger, fungal attack is repelled and the timber becomes easier to machine and work with (Pratt and Turner, 1986). Glennon Brothers aim to dry their timber to a moisture content of 18%. This is to allow for eventual moisture regain when the timber is removed from the kiln

2.7.12.1 Methods of drying

The central element of the seasoning process is the drying of timber. Air movement around timber is essential in the drying process. If the surrounding air becomes stagnant, it will soon become saturated and stop the evaporation of moisture from the wood. This layer of air in immediate contact with the wood is heavy due to its humidity level. However, maintaining a passing airflow over the wood prevents the occurrence of stagnant air and allows for continuous wood drying (Pratt and Turner, 1986).

The rate of water movement outwards in a piece of wood depends largely on the vapour pressure of the outer layers being lower than the vapour pressure of the inner layers. Externally, the lower the relative humidity of the atmosphere, the greater amount of moisture will be removed from the woods surface. Technically, this movement of moisture can be attributed to a mixture of capillary action and diffusion through the timber structure (Pratt and Turner, 1986). If the rate of moisture evaporation from the timber surface exceeds the rate of moisture movement from the inner layers of the wood, then the moisture gradient within the wood becomes steeper, leading to the drier external surface having a tendency to shrink. Stresses develop in the fabric of the timber due to the contrasting wet and dry conditions leading to timber defects. It is therefore essential that the rate of evaporation matches the rate at which moisture reaches the timber surface (Pratt and Turner, 1986).

Two principal methods of drying used in industry are air drying and kiln drying:

2.7.12.2 Air Drying

As the name suggests, air drying is the process of drying timber in the open air. This method exposes freshly sawn timber to the external weather elements. The timber is stacked with spaces and gaps between each plank to allow for the movement of air in order to dry the wood and carry away any evaporated moisture (Pratt and Turner, 1986). Stacks should not exceed 2m in width, as very wide stacks result in slow drying of centre timbers. The sticks used to separate the timbers should be clean, dry softwood timber which allow a free circulation of air and also help prevent distortion during drying (Brown, 1965).

In the UK and Ireland, climatic conditions allow for a moisture content of 15% to be achieved through air drying. On average however, air dried timber will usually reach 20% moisture content. Once this level has been reached, continuous drying is not likely to reduce the moisture content significantly. It is therefore common practise to air dry timber for a period of time, allowing for a natural moisture content reduction, before further drying the timber in a kiln to reach the desired moisture content (Desch and Dinwoodie, 1996). In order to monitor the progression of air dried timber, sample pieces of wood are incorporated into a drying stack for moisture content testing purposes. The % content is assessed using the oven test method (Pratt and Turner, 1986). Air drying is a slow process and relies on the knowledge and expertise of the operator to ensure timber is not left drying for too long a period which can lead to defects in the timber structure. Although still used to great effect in temperate climates, air drying has largely been replaced by timber drying kilns.

At the Glennon Bros processing plant, 300m³ of timber is received in any one delivery from the initial processing plant in Fermoy, Co Cork. At the Fermoy plant, freshly cut trees are converted into usable dimensioned lumber. Chippers are also used to remove bark and branches before conversion; this waste material is collected and recycled, usually for agricultural purposes. Depending on product demand, this timber can be left to air dry for a period of time once it arrives at the Longford plant. However, it is more common to stack the timber and place it immediately in a kiln.

2.7.12.3 Kiln Drying

Kiln drying is a closed chamber method of seasoning timber. The kiln method of drying offers complete control in terms of the temperature of the timber and its drying speed and allows for year-round drying ensuring a steady timber supply to industry (Desch and Dinwoodie, 1996). An effective kiln should be capable of providing controlled heating, air circulation, ventilation, humidification and dehumidification. Heating is required to increase both the rate of moisture movement from the timber centre to its surface and from the timber surface into the surrounding air. Heat is supplied in two main forms; indirect and direct. Indirect heat sources include steam and hot water which are produced by a boiler and piped through heating ducts within the kiln. Direct heat sources conduct air from a controlled gas or oil flame burner through to the kiln (Pratt and Turner, 1986). Air circulation is critical in the transfer of heat from the heat source to the timber surface. Efficient and controlled air circulation is also essential in mixing both the heated and humidified air to achieve adequate distribution throughout the kiln chamber.

Ventilation plays an important part in kiln drying. As the kiln chamber is closed, controlled ventilation is necessary to maintain the relative humidity at the required level. Dehumidification is also an alternative to ventilation with surplus moisture laden air being returned to the kiln after dehumidification. Humidification is required to maintain the kiln humidity when the moisture coming from the wood is insufficient. Controlled humidification is typically needed at the beginning and end of a drying phase (Pratt and Turner, 1986). Regulation and control of the various elements described in kiln drying is essential for the effective seasoning of timber.

At the Glennon Bros factory, a total of seven kilns are available with a minimum of four in operation at any given time. The kilns are known as compartment kilns and use a direct heating supply with a large thermostatically controlled boiler employed to feed warm air into each respective kiln. The total drying time for each kiln is roughly 48 hours.

2.7.12.4 Compartment Kilns

This type of kiln is more traditional in nature as it consists of a single closed chamber in which stacks of timber are seasoned in a stationary position. Typically, the drying process begins with the air inside the chamber being kept at a high level of relative humidity and a low temperature. As the process continues, the temperature inside the chamber is raised and the humidity is reduced which increases drying conditions (Desch and Dinwoodie, 1996). The air is circulated by the use of fans which are mounted internally. Fans can be positioned overhead in either a longitudinal shaft design or a cross shaft design with air distribution flow varying between both options (Pratt and Turner, 1986).

Compartment kilns offer flexibility during the drying process as the conditions contained within the kiln can be changed to suit the specific drying time of an individual timber species. This is essential in maintaining the efficiency and adaptability of a sawmill which changes both its timber stock and dimensions (Desch and Dinwoodie, 1996). This applies to the Glennon Bros factory as a number of different tree species are processed at the plant. The breakdown of species processed is 90% Stika Spruce, 5% Norway spruce and the remaining

5% is Larch. All three timbers are very common in appearance and are easy to dry whilst maintaining their dimensional stability.

Figure 11: External view of a compartment kiln located at the Glennon Bros factory Co Longford, Ireland

2.7.13 Seasoning Defects

As timber goes through the seasoning process, it is subjected to stresses and strains leading to defects regardless of whether the correct seasoning technique has been applied or not. Defects can be separated into two main categories, those associated with warping or distortion of the seasoned timber plank or those associated with rupture of the wood tissue.

2.7.13.1 Types of Warping

As illustrated in Figure 12, there are numerous defects commonly found in seasoned timber. These defects mostly contribute to differential shrinkage of individual timbers during the drying process (Pratt and Turner, 1986). Cupping is a defect in timber where distortion is visible across the width of the board in either a convex or concave shape. Cupping is a result of one face of the timber being in close proximity to the heart of the tree which develops a curved appearance when compared to the opposite side and causing it to shrink less during the drying process. As a consequence, the curve forms in the opposite direction to the curve of the growth rings. In square timber battens, this form of distortion will result in diamonding (Figure 12). It is possible to reduce the risk of cupping and diamonding by effective stacking of the timber before the seasoning process and using the quarter sawn method of conversion as it is resistant to such defects.

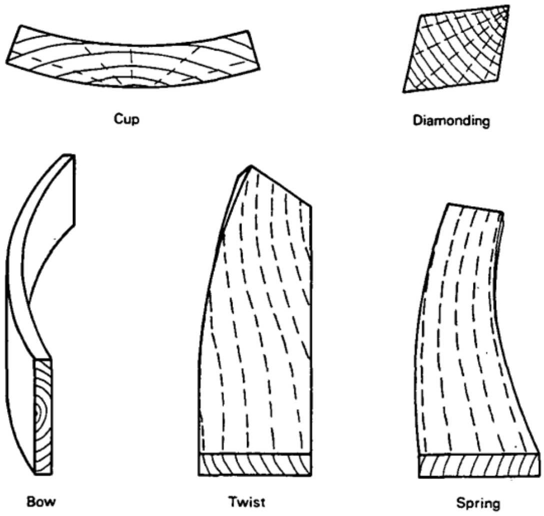


Figure 12: Various forms of warping in seasoned timber planks (Pratt and Turner, 1986)

Bowing (Figure 12) is curvature along the length of a plank or batten and is a defect brought about by incorrect stacking of timber prior to seasoning (Desch and Dinwoodie, 1996). Stickers placed too far apart in a stack of timber lead to the timber sagging resulting in bowing. Twisting (Figure 12) is a spiral distortion in a longitudinal direction along a plank of wood; it occurs when the plank has been cut through or near the centre of the tree. Occurrence of such a defect can be reduced but not eliminated by adding additional weight to the top of a timber stack prior to seasoning (Desch and Dinwoodie, 1996).

A spring defect (Figure 12), is another defect which takes the form of a convex or concave curve along the length of a timber plank but on the plane of the timber. This defect is commonly associated with the release of growth stresses contained within the timber during the seasoning process.

Figure 13: Timber processed through the dimensioning and testing section of the factory

At the Glennon Brothers factory, correct stacking and constant monitoring of the timber during the kiln drying process reduces the amount of timber defects in every batch. However defects in timber planks are still common and a visual inspection of the timber after it has been removed from the kiln is the first of a number of the factory's quality checks. Once removed from the kiln, the timber is processed through a dimensioning and testing section of the factory; this takes one day and after the timber is either shipped untreated or goes to the pressure treatment section of the factory. In the dimensional and testing section, the timber is planed and stress graded (Figure 13). This is a fully automatic process but is preceded by human input. As the timber is taken from the kiln to the dimension stage, each row of timber is checked for moisture content by a factory worker. This is also a visual inspection as any blatantly obvious defects are removed. Following this, the timbers are individually fed to an automatic planer via a conveyor system. Each timber is planed to the correct dimension as it passes through a large automated planer. This machine uses rotating plane heads to cut the timber to size along its length. Depending on the size and quantity of timber required, the planer heads can be changed and used to grade other timber sizes.

Directly after the automated process, every timber passes through a strength grading machine which automatically applies a stress test to each timber. The machine rejects any timbers which do not meet the strength standards. After this the timber is stacked into pallets ready for shipping. A visual inspection is also made at this point and any timbers which are visibly defective are removed by hand. This is in keeping with standards outlined by TRADA as 10% of timber can be removed after visual inspection. Once the timber is planed, graded and has passed a further visual inspection, a stamp is applied to show the timbers classification, grading, batch number and a 'CE' mark which is a new addition to the grading process and is required by BM TRADA EN14081-1.

2.7.15.6 European Standards

Timber preservation in Ireland is guided by European standards. These are similar to British Standards and follow the same criteria in the production and selection of preservative treatment. Currently, there is a transition taking place in the European standards as more of a focus is now being placed on the performance results of the preservative rather than its method of application (Woodspec, 2013).

This is in conjunction with a Hazard Class system which categorises the risk of deterioration to which timber may be exposed; graded from 1 (insect risk only) to 5 (maximum risk as experienced in a salt water environment). The varying degrees of risk are highlighted in Figure 15.

Both the British and European Standards assign the risk of timber decay to the situation where it is being used. Timber used below the Damp Proof Course (DPC) level has a higher risk than timber used internally within a building or for timber use above DPC level. Both treatment methods depend on preservative penetration and retention in order to be effective. With either the BS or EN system the specifier must decide:

- The desired durability required and assess the likely Hazard Class
- The relevant code of practice
- The type and method of preservative treatment (Woodspec, 2013).

Use class	General service situation	Description of exposure to wetting in service	Biological agents	
1	interior, covered	dry	Wood boring beetles	If termites also might be present the class is designated **1T**
2	Interior or covered	occasionally wet	As above + Disfiguring fungi + Decay fungi	If termites also might be present the class is designated **2T**
3	**3.1** exterior, above ground, protected	occasionally wet		If termites also might be present the class is designated **3.1T** or **3.2T**
	3.2 exterior, above ground, unprotected	frequently wet		
4	**4.1**exterior,in ground contact and/or fresh water	predominantly or permanently wet	As above + Soft rot	If termites also might be present the class is designated **4.1T** or **4.2T**
	4.2 exterior in ground (severe) and/or fresh water	permanently wet		
5	in salt water	permanently wet	Decay fungi Soft rot Marine borers	**A** Teredinids Limnoria
				B As in A + creosote tolerant Limnoria
				C As in B + Pholads

Figure 15: Hazard class system (335-1, 2006)

The main difference between the BS and EN standards is that the EN standards have introduced a system where a defined combination of penetration and retention of preservative must be achieved in the treated wood. The preservative may be applied using any process provided the end result meets the required level of penetration and retention.

The European standards require a demonstration of proof that the treatment used has produced the specified results. This is achieved through reference to chemical analytical methods. The preservative penetration and retention levels using the EN system are intended to be the same as those achieved by current British Standard-based processes.

The preservative treatment formulas and methods of application outlined and used by Glennon Brothers are the most common forms used in Europe and Ireland. Wood preservation is required to be applied to all non-durable timbers for use in construction. In terms of an open panel timber frame construction project, timber used for the sole plate, external battens and any timbers used outside the vicinity of the external walls are treated with preservative. A Closed panel timber frame project has the exact same requirements regardless of the fact that external wall battens are covered in the factory and do not become exposed to weather conditions during construction.

Chapter 3

Open Panel and closed panel Timber frame construction

Presently in Ireland, the most common form of timber frame construction is the open panel platform frame system. As detailed previously, this method has evolved through construction practices and procedures to the industry standard that is used today. Closed panel timber frame construction has further added to this evolution. Due to the fact that both open and closed panel forms of timber frame construction involve the same materials, dimensions and requirements, it is necessary to detail each aspect of their manufacture and design. The closed panel method is a key focus area of the overall research project, by providing a clear outline of the steps involved in the construction of an open panel timber frame system the progression to the closed panel system can be accurately detailed.

The following steps outline the typical construction methods, materials, and systematic completion of a typical open panel timber frame wall construction

3.1 Construction Site Preparation

In a typical timber frame construction project, the foundations are already in place prior to the on-site arrival of the pre-manufactured timber frame walls. The site layout plays an important role in the efficiency and speed of construction that is associated with timber frame builds. Space and ease of access is required on site to permit the free flow of trucks carrying timber frame elements in and out of the site. Often a mobile crane is used to position the timber frame walls and roof elements, sufficient manoeuvring room should be left for the crane as well as safe clearance zones for workers (Homebond. and O'Grady, 2008)

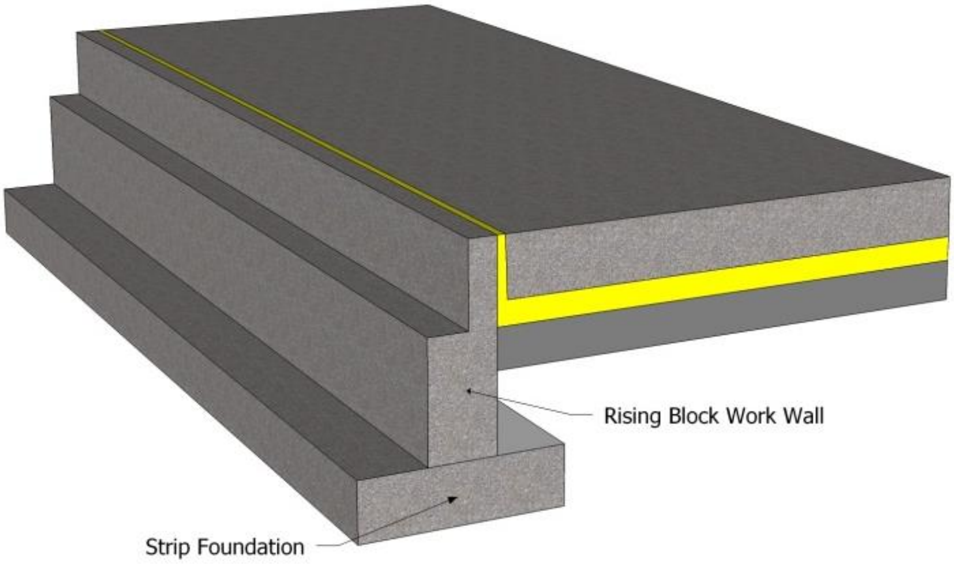


Figure 16: Typical strip foundation arrangement with solid ground floor

In order to assist in the correct assembly of a timber frame kit, all panels should be individually marked in correspondence with a panel layout drawing. It is also essential that the order of delivery of the panels corresponds with their use on site. Storage facilities are required on-site for the protection of components which are not immediately positioned on the building (Homebond. and O'Grady, 2008).

3.2 Foundations

The foundation system used in the construction of a timber frame building is similar to those which are used in standard masonry builds. Strip foundations and raft foundations can both be used in conjunction with a timber frame system. Timber frames are lighter than their masonry counterparts and so may reduce the size and cost of the foundations. However, all aspects of the sub-substructure should be designed and approved by a competent engineer (Burchell and Sunter, 1987).

Figure 16 depicts a standard strip foundation layout with a solid concrete ground floor. This is a typical layout for a timber frame internal leaf with a masonry or brick external leaf finish which is constructed after the timber wall has been erected. Open panel timber frame construction is commonly constructed in this manner however, closed panel construction with its emphasis on completing more of the buildings structure before transportation to site, can avail of external finishes such as concrete board or timber cladding during pre-fabrication in the factory.

Given the pre-manufactured nature of timber frame buildings, it is essential that the dimensions of the foundations on-site correspond with the manufactured walls. Both the dimensional and level accuracy of the foundations are required to be monitored and checked during construction. Usually a detailed layout drawing is provided by the timber frame manufacturer to ensure on-site dimensions comply with pre-manufactured walls.

Prior to the erection of the timber frame system, the foundations are checked for inaccuracies within the following tolerances:

Straight lengths of wall should be within +/- 10mm

Diagonal dimensions, maximum deviation +/- 5mm up to 10m (+/- 10mm for lengths greater than 10m)

The substructure should have a +/- 5mm tolerance in level (max variation 10mm) (Homebond. and O'Grady, 2008)

In the event of a discrepancy between onsite and manufactured dimensions, standard manufactured open panel structural frame kits can be altered on-site to comply with the as-built structure (Department Of Environment Heritage And Local Government, 2002). This is made possible as the manufactured walls consist of vertical and horizontal timber studs and do not, at this point, contain insulation, external sheathing or associated membranes. In contrast to this, on-site modification of closed panel timber frame walls requires more time and can prove to be difficult and costly. This is due to the fact that a closed panel wall is essentially a completed wall from external to internal surface and, in some cases, can contain electrical and mechanical services.

3.2.1 Sole Plate positioning

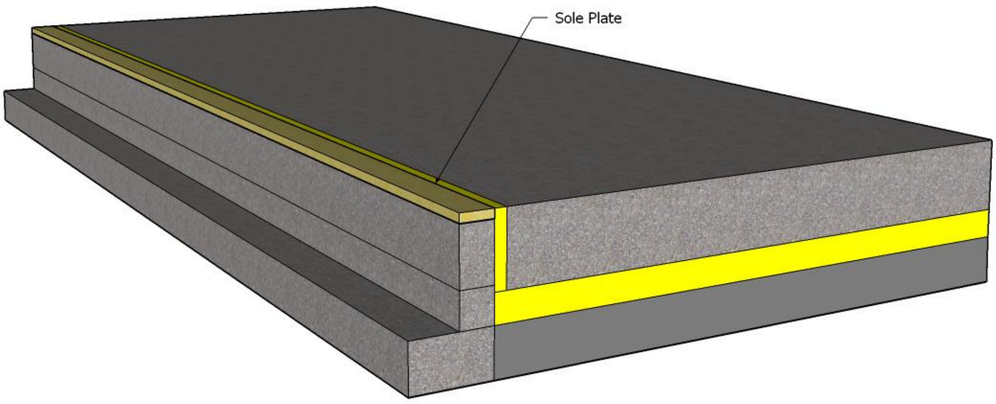


Figure 17: Position of Sole Plate level with floor slab

A sole plate is commonly used in timber frame construction. It is the first stage of the erection procedure of timber frame walls and is used as a guide and as a fixing point for the positioning of the pre-manufactured walls which are usually the same thickness as the sole plate. Figure 17 depicts the typical location of a sole plate, level with the ground floor and fixed to the rising block work from the foundations (Burchell and Sunter, 1987). The sole plate can be fixed to the substructure by masonry nails, shot fired fixings, bolts or stainless steel clips which are fixed to both the sole plate and the block work beneath (Homebond. and O'Grady, 2008).

A DPC is placed underneath the sole plate prior to its installation; a corresponding DPM is sufficiently lapped beneath the DPC to maintain continuous protection against rising damp (Homebond. and O'Grady, 2008). An open panel timber frame wall is then positioned on top of the sole plate and is fixed to the wall plate via nailing or screw fixing. Attaching an open wall panel to the sole plate is considerably easier when compared to a closed panel as there is complete access to the bottom rail of the wall for fixing purposes. The sole plate can be omitted in a closed panel system with the bottom rail of the wall performing the same function.

3.2.2 Timber studs

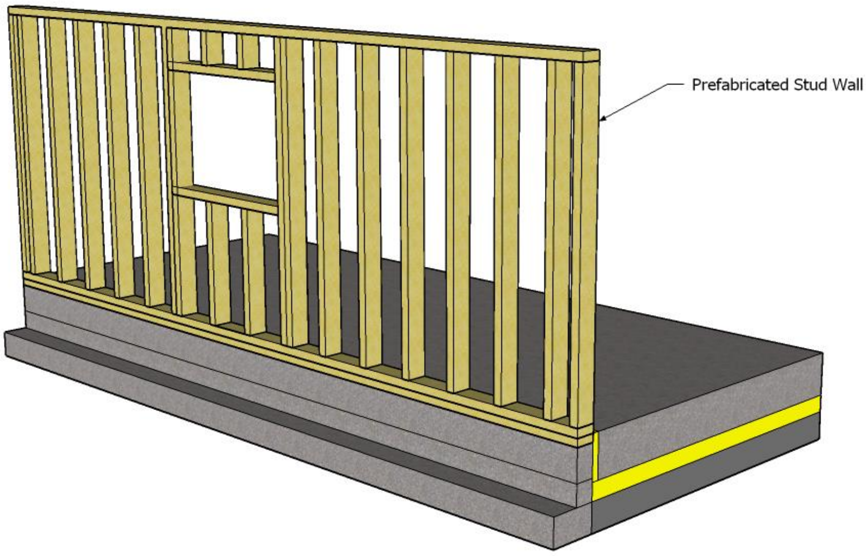


Figure 18: Typical Prefabricated timber frame wall positioned on top of soleplate

Once the foundations and soleplates are in position, the building structure can be erected. In an open panel timber frame project, panels are delivered to site via truck and it is necessary to have a scaffold system in position prior to the delivery. The scaffold should be constructed to the required building height and shape with an adequate space left around the building to allow for the construction of an external masonry wall (Homebond. and O'Grady, 2008). (Refer to Figure 18).

Once on-site, the open panel wall can then be dropped into place and secured via nailing or screwing to the soleplate. In a typical open panel timber frame kit, the walls are pre-manufactured to the set dimensions and erected in sequence. It is common practise to begin positioning walls at an external wall corner. From this initial set-up point, the rest of the external wall panels are erected before the internal load bearing wall panels are positioned (Homebond. and O'Grady, 2008). Traditionally, open panels are joined together via nailing or screw fixing. The internal loadbearing walls also act as bracing support for the external walls. Where this is not possible, propped braces are used to stabilise the external walls until the non-load bearing internal walls are positioned. Once all the walls are positioned, it is essential to check each panel to ensure they are both plumb and level. Any deviation in this may have an impact or be exaggerated in subsequent stories or when construction of the external masonry leaf takes place (Homebond. and O'Grady, 2008).

3.3 Wall Assembly

The assembly and production of timber frame wall panels typically takes place in a factory. In Ireland, factory production is the preferred method as quality control can be implemented and a system of production can be established. Manufacturing panels in this way also reduces the amount of work to be carried out on site as discrepancies or dimensional errors identified during production can be rectified (Department Of Environment Heritage And Local Government, 2002). Although panels are typically assembled by hand, automation is used on the assembly line in the form of nail guns, panel saws and gantry cranes. The use of computer technology to accurately map and cut certain timber sections is becoming more and more popular with a small number of large companies investing in fully automated systems (Department Of Environment Heritage And Local Government, 2002).

Timber frame wall panels are designed to transmit all of the vertical static and dynamic loads to the foundations beneath the structure and offer complete resistance to overturning or 'racking' under external wind loads (Burchell and Sunter, 1987). Timber frame walls are comprised of a series of vertical timber members known as studs and horizontal timber members known as rails. The spacing in between each stud is kept at a uniform dimension, usually 300mm, 400mm or 600mm. These spacing's not only add dimensional stability to the panel but also correspond with the sizes used in follow-on components such as external plywood and internal plasterboard (Burchell and Sunter, 1987).

Figure 19 depicts a standard production drawing of an open panel timber frame wall. The sizing of the studs and the rails are both the same at 38mm x 140mm Canadian Lumbar Standards or CLS. This refers to timber which has been dried to a moisture content of less than 19%, planed on all four sides and has been stress graded (Burchell and Sunter, 1987). Production drawings are used to generate a cutting schedule, with the sizes and number of

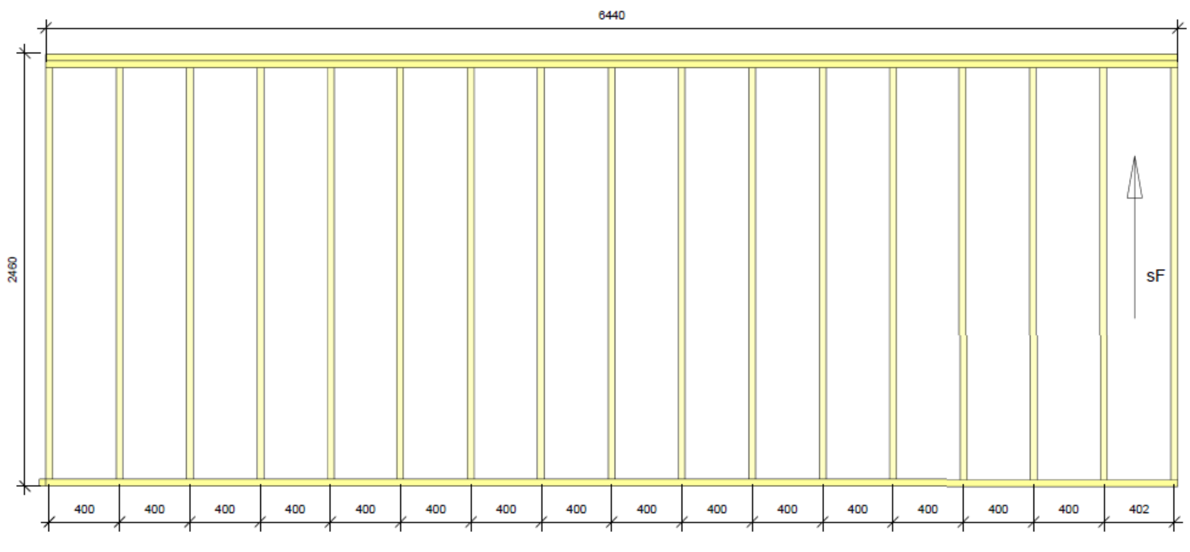


Figure 19: Typical production drawing of an open panel timber frame wall with 400mm vertical spacing

studs cut and arranged on a horizontal work bench. The timbers are then placed in their position and joined together, usually by employing a nail gun. It is imperative that the panel remains square during the assembly process; this is achieved by systematically checking the panel throughout the fabrication stage.

3.3.1 Openings in walls

Openings or spaces in walls are made to accommodate components such as windows and doors. At such openings, the vertical loads from the structure above are carried by large timber lintels above the opening and horizontal timbers positioned below (Pitts, 2011). These horizontal members are of the same dimension as the other studs in the wall and are supported by shorter length timbers known as 'cripple studs'. The cripple studs are in turn nailed or screwed to adjacent full length studs for support (Burchell and Sunter, 1987).

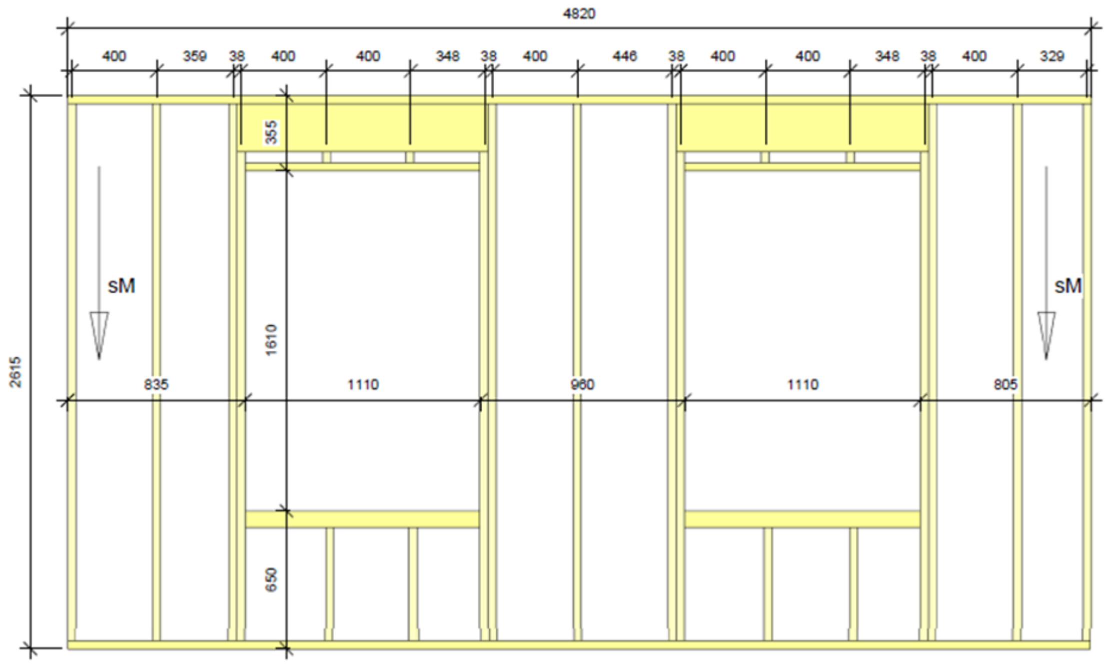


Figure 20: production drawing showing two openings wider than the structural grid.

As seen in Figure 20, both openings depicted are wider than the structural grid and, as a result, require timber lintels and supporting cripple studs. Both the size of the timber lintels and the number of cripple studs are calculated by the manufacturer or design engineer and are installed during the fabrication of the panel (Homebond. and O'Grady, 2008). In an open panel format, the window or door opening is formed and the component is then installed on site once the walls are erected. In a closed panel situation, the windows are required to be installed prior to the application of the external finish component (concrete board, cladding, etc.) As a result, window and door installation time on-site is removed and, once the building is erected, it is immediately weather proofed.

In terms of the actual installation process of windows and doors, it is virtually the same between open and closed panel construction. A 10mm tolerance space is required to be left in the window/door opening to allow for fitting. The component is then secured to the timber frame via metal fasteners and sealed to both the internal vapour control layer and the external breather membrane via propriety tapes. Where there is an external masonry wall constructed, it is necessary to use a mastic sealant between the window and the masonry (Burchell and Sunter, 1987).

3.3.2 External Sheathing

A sheathing material is fixed to each completed stud wall as part of the factory production process. All sheathing materials should be of a thickness and robustness so that damage during manufacture, transport and erection is avoided. The sheathing used can be a number of different materials, however plywood or oriented strand board (OSB) are the two most common forms used in Ireland and must conform to I.S EN 636 and I.S EN 300 respectively (Homebond and O'Grady, 2008).

3.3.2.1 Plywood

Plywood is manufactured by laminating a series of thin timber layers to a required thickness. This is achieved by peeling a slender veneer of timber from a log in rotation. These plies are then stacked on top of each other and glued with the grain directions at right angles to provide extra strength and stability. The composite is then cured in a hot press and trimmed to standard dimensions for distribution (Lyons, 2007). Due to its make-up, plywood displays greater strength than solid timber. It is highly resistant to splitting or cracking at its edges when screwed or nailed and can be used for a number of structural purposes including wall sheathing, floor decking, and roof construction (Everett and Barritt, 1994). Plywood is classified according to its physical properties and durability; this is largely based on the bonding classes which are Class 1 for dry condition (interior use), Class 2 for humid conditions (protected or used behind cladding) and Class 3 for exterior conditions. Class 2 plywood is most commonly specified for use in a timber frame building as it is protected by an external wall covering (Lyons, 2007).

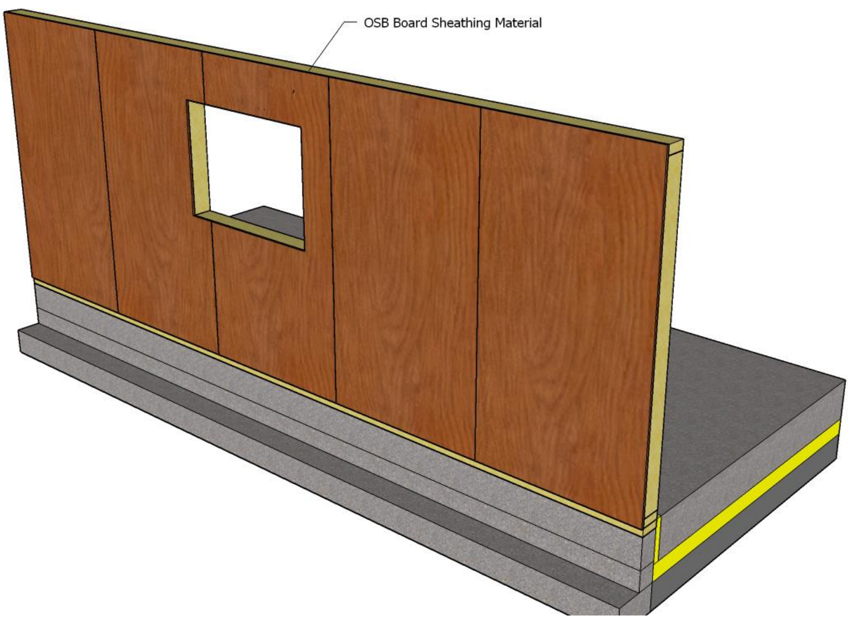


Figure 21: Application of external OSB sheathing to stud wall

3.3.2.2 Oriented Strand Board (OSB)

OSB board is manufactured from coarse, rectangular chips of crushed and peeled veneer. The chips are then processed into thin layers known as strands. Much like the manufacture process of plywood, these strands are stacked at right angles to each other at a required thickness and compressed to form OSB boards (Hugues, Steiger, and Weber, 2004). OSB is given a grading scale according to the anticipated loading and environmental conditions. The scale ranges from OSB 1 (for general purpose) to OSB 4 (Heavy duty, load bearing). OSB 3 is most commonly specified for use in the construction of a timber frame project as it offers both a capacity for load bearing and for use in humid conditions (Figure 21) (Lyons, 2007).

3.3.3.3 Sheathing Application

Sheathing has a number of functions;

- Provides the necessary stiffness to resist lateral loading (racking)
- Reduces wind penetration of the structure
- Encloses and supports wall insulation
- Reduces the risk of damage/distortion of panels prior to installation
- Provides a solid background to attach breather membrane
- Stiffens panels for handling and transportation (Homebond. and O'Grady, 2008)

3.4 Racking

Wall panels are subject to both vertical and horizontal forces. The horizontal forces are dealt with in the structural layout of each wall. However, horizontal wind loading has an effect of lateral forces being applied in the plane of the wall resulting in a wall stress known as ‘racking’. Racking in a timber frame structure becomes more pronounced as walls act in shear to resist wind forces on other walls at right angles. This puts enormous stress on the structure and can lead to collapse (Mayo, 1984). Other influences on racking include; location of window/door openings, vertical loads on walls and strength of holding down fixings. The application of correct sheathing helps to reduce the racking potential for each wall. Sheathing comes in standard sheet sizes of 1200mm x 2400mm allowing sheets to be fixed in position at each vertical stud. In order to give an adequate racking strength, plywood and OSB board sheathing is required to be fastened to the wall frame using 50mm nails at 150mm intervals (BS5268-6.2, 2001). Usually a 2mm gap is left between the edges of sheathing panels to allow for expansion should it come into contact with moisture (Burchell and Sunter, 1987).

Sheathing is factory-applied in both open and closed panel production. It does however become more susceptible to moisture and weather elements in the open panel process as wall panels are erected on-site with the sheathing exposed to the elements. In Contrast to this, the closed panel production system ensures that the sheathing is covered by the external breather membrane and, depending on the specified wall finish, can have the exterior façade finish also in place prior to on-site arrival.

3.5 Insulation

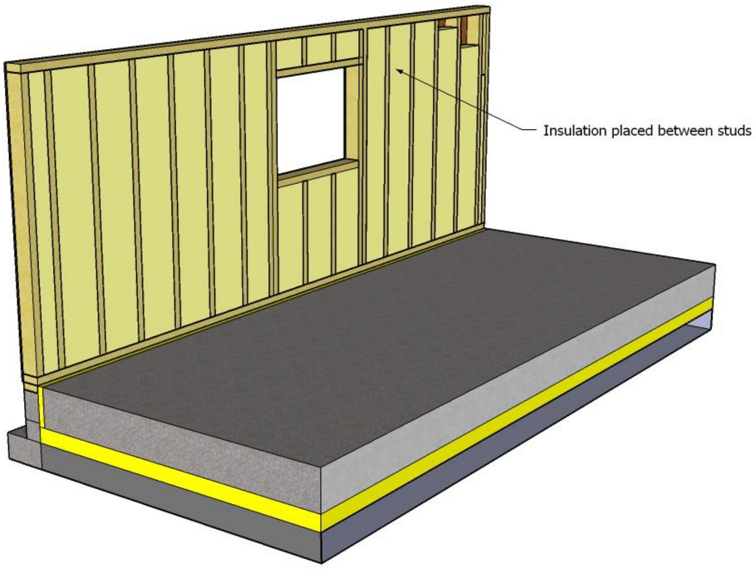


Figure 22: Insulation applied to the open panel wall

In both the open and closed panel construction process, insulation is installed in the voids between the vertical studs of the timber frame wall. The level and type of insulation used can vary according to specification and size of the wall. Currently in Ireland a completed external wall must have a minimum U-Value of 0.21 W/m²K. This is the basis for all wall compositions and an effective insulation material must be used to comply with this requirement. Refer to Figure 22.

3.5.1 U-Value

The U-value of a wall, roof or floor element of a building is a measure of how well the element transfers heat. Essentially this means the higher the U-value, the poorer the thermal performance of the building (REFERENCE). The U-value of a particular element of a building is calculated by taking the thermal conductivity (W/mK) of each material within the build-up of the particular building element and multiplying by the thickness of that material.

This establishes the Resistance or R-value (m^2K/W) of each layer. It is necessary to determine the R-value as the interaction of the building element to the outside environment is expressed in terms of surface resistance and so, for consistency, all materials within the building element are assessed in the same manner (REFERENCE).

There are nominal resistances put in place for external and internal R-Values. This is also the case for air gaps within each building element. The sum of R-values is established to give a total resistance for the building element.

In terms of formula, the U-value is expressed as:

$$\text{U-value } (W/m^2K) = 1/\text{Total resistance.}$$

In terms of this research project, the U-values of the walls used in the live construction projects conformed to the minimal U-value requirement. The subsequent software thermal assessment of the connection detail is based on the above U-value calculations however; the THERM software only requires the thermal conductivity of various materials and calculates the thermal performance of the wall based on this data.

There are many different forms of insulation that can be used in a timber frame project;

3.5.1 Mineral Wool

Mineral wool is the term used for the inorganic fibrous insulating materials glass wool and rock wool. Both are very similar and differ only in the raw materials used in their production, with quartz sand and limestone used to make glass wool, whereas rock wool is formed using various rock types such as diabase, dolomite and limestone (Pfundstein, 2007). The raw materials for both are melted together in a furnace at approximately 1500°C. The resulting liquid is then spun into fibres and coated with resin before being arranged in a mat formation at the required thickness. The mat is then compressed and cured in an oven before being cut into slabs or packaged in rolls (Lyons, 2007).

Mineral wool is particularly suited for application in a timber frame structure as the material is flexible and can be cut to different dimensions; this is particularly useful for filling the shorter cavities in a timber frame wall in areas above and below openings. The mineral wool can also be cut slightly wider than the cavity space to ensure a tight fit; this also compensates for wood shrinkage in the timber frame work, minimising thermal loss and noise through the structure (Pitts, 2011). Mineral wool is resistant to micro-organisms and does not rot, however it is crucial to keep the mineral wool dry as the presence of moisture significantly reduces its thermal performance (Hugues, Steiger, and Weber, 2004).

Mineral wool typically has a thermal conductivity of 0.035 – 0.045 W/mK (Pfundstein, 2007). Coupled with this, mineral wool is open to diffusion, a process of allowing small amounts of moisture to pass through its fabric. This is essential in a timber frame build making mineral wool all the more suitable. As mentioned previously, there is no difference in the method of application of mineral wool in an open or closed panel process. There is a difference however, in the time and location of its installation as in an open panel format, mineral wool is commonly cut and inserted into position on-site leaving it susceptible to wind and rain. In contrast to this, in a closed panel project, mineral wool is installed indoors ensuring that it does not come into contact with moisture. This also allows for a more rigorous quality control of the insulation process.

3.5.2 Polyurethane (PUR)

Polyurethane or PUR is composed of two main components; polyalcohol and polyisocyanate (Pfundstein, 2007). The manufacturing process of PUR used to involve the use of chlorofluorocarbons (CFC'S). Given the well documented impact of CFC's on the environment, a change to hydro chlorofluorocarbons (HCFC's) was made in the 1980's (Lyons, 2007). PUR is manufactured predominantly in two ways. The first method sees the foam mixture applied to a facing material which can be flexible sheeting, foil or bitumen. Once applied, the foam expands and adheres to the facing. The second method of manufacture involves the foam being injected into moulds, usually rectangular in shape and eft to cure. Once set, the boards are cut to shape and distributed (Pfundstein, 2007). Due to the closed cell structure of PUR which traps HCFC's the thermal properties of the material is enhanced, PUR offers a thermal conductivity of 0.024 – 0.030 W/mK, making it a very effective insulator (Pfundstein, 2007).

Given its ridged structure and chemical properties, PUR is highly fire resistant and is not susceptible to rot, mould, ageing or decay. PUR is only susceptible to ultraviolet radiation when left exposed. This is not particularly harmful to the material as damaged areas can be cut away (Hugues, Steiger, and Weber, 2004). PUR can be inserted into a timber frame building in the same manner as mineral wool.

Typically, large boards of PUR are cut to size using conventional saw tools and are placed in the timber frame wall. Due to its rigidity, precise cutting of the material is required for a snug fit (Pfundstein, 2007). Rigid insulations do not however, offer the same level of flexibility when compared with mineral wool as the ridged boards do not compensate for wood shrinkage in the timber frame structure (Hugues, Steiger, and Weber, 2004).

In order to achieve the required U-Values for wall construction, PUR is more commonly used as in internal layer of insulation between the external timber frame wall and the internal layer of plasterboard. As detailed in Figure 23, the PUR board is positioned behind the internal battens and held in place by fixing the battens to the vertical studs in the wall through the PUR board.

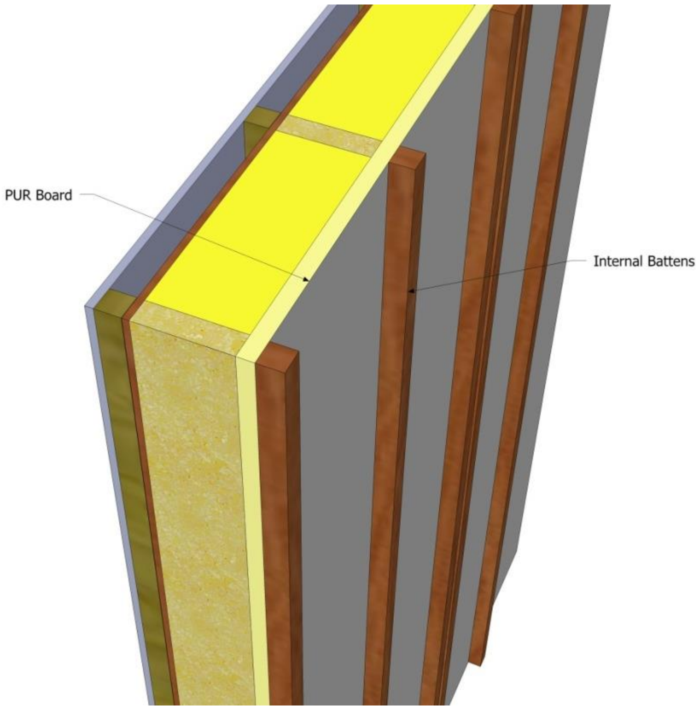


Figure 23: Use of PUR board as an internal insulation lining

3.5.3 Expanded Polystyrene (EPS)

EPS is another form of rigid insulation. It is manufactured in a number of stages involving the polymerisation of styrene into beads of 3mm. After this process the beads are expanded via steam treatment. This results in the beads sticking together forming a homogeneous material. This material is then pumped into moulds to form large EPS boards which are cut to distribution size (Pfundstein, 2007). EPS offers a thermal conductivity value of 0.032 – 0.040 W/mK making it an effective insulator but not to the same standard as PUR (Pfundstein, 2007). EPS was a more common insulation material used in cavity wall construction in a traditional block work construction. Its use however, has been replaced to a large extent by PUR as it offers better insulation properties. If used in timber frame construction, its application is similar to PUR with rigid boards being cut to form the required size and shapes. This again gives rise to the issue of the boards not being able to adapt to dimensional differences in the timber frame structure brought about by wood shrinkage. Given PUR's stronger thermal performance and the aforementioned inability to adapt to changes in the structure, EPS is not commonly used as insulation in timber frame walls.

3.5.4 Extruded Polystyrene (XPS)

Extruded Polystyrene is a closed cell, hard plastic foam which differs from EPS as a result of its manufacturing process. XPS is formed from polystyrene and blowing agents; the process involves melting a polystyrene compound at a high temperature in an extruder. The resulting foam is continuously pressed by air jets into boards (Hugues, Steiger, and Weber, 2004). The resultant material has 98% closed cell structure with a smooth surface on either side. XPS has three essential properties; low thermal conductivity (0.030 – 0.040 W/mk), high compressive strength and moisture resistance (Pfundstein, 2007). Much like EPS, XPS is not commonly used for insulation in timber frame construction, given its excellent moisture resistance XPS is more commonly used for basement insulation purposes or on inverted roofs where it offers excellent resistance to mechanical damage from foot traffic (Lyons, 2007).

3.5.5 Phenolic Foam (PF)

Phenolic foam offers a very high thermal conductivity value, typically between 0.022 – 0.040 W/mk (Pfundstein, 2007) coupled with an excellent fire resistance factor. It is formed from phenolic resin combined with the chemical Pentane. Both are mixed together and foamed in a continuous layer on a conveyor belt before being laminated on each side creating ridged blocks (Pfundstein, 2007). As mentioned, PF offers very good resistance to fire. In the event of a fire, the chemical make-up of PF releases formaldehyde which instantly dampens any fire threat leaving a charcoal-like residue on the material (Lyons, 2007). Given its excellent thermal performance and resistance to mould, rot and vermin, PF is used as insulation in a typical timber frame building. It is however, far more brittle when compared with PUR and so extra care is needed when cutting and inserting the insulation in the timber frame.

3.5.6 Organic Insulation Materials

Consideration of the thermal values of organic substances is becoming increasingly popular in construction. This applies to traditional masonry and concrete construction as well as timber frame. Organic insulation materials require much less chemical and mechanical process in their manufacturing when compared with inorganic materials. Because of the resulting reduction in embodied energy it is necessary to explore a number of the available organic insulation products in today's market.

3.5.7 Sheep's Wool

Sheep's wool is one of the oldest materials used for insulation properties. The raw material used in this insulation is composed entirely of shorn sheep's wool. The wool is thoroughly washed with soap before spraying with additives and chemicals to assist in the bonding process and to protect the wool from insect attack in use (Hugues, Steiger, and Weber, 2004). The wool is processed into thin layers which are laid on top of each other in a diagonal formation. These layers are then compacted to the required depth forming the insulation (Pfundstein, 2007). Sheep's wool is similar in properties to mineral wool and so it is an excellent form of insulation to be used in timber frame construction. The insulation can be cut to the required size and shape for insertion into the frame in the same manner as mineral wool. Sheep's wool provides a thermal conductivity factor of 0.040 – 0.045 W/mk and also offers excellent hydroscopic properties as it reversibly absorbs and releases water vapour (Lyons, 2007). During warm periods, wool contained in walls, releases its moisture which aids in the cooling down of a building. In cold periods, the reverse happens as the wool absorbs moisture from the air and keeps the building warm (Lyons, 2007).

3.5.8 Hemp

Hemp insulation is manufactured from the shrives and fibres of the Hemp plant. During the manufacture process, various additives are introduced for fire and water proofing properties (Pfundstein, 2007). Hemp fibres are used to create insulation fleeces similar to mineral or sheep's wool. These are then produced in slabs or in rolls. Processed hemp fibres are free from protein leaving them naturally protected against insect attack; hemp also has moisture absorption ability much like sheep's wool. This allows hemp to be used as internal insulation in a typical timber frame construction wall and assists in the control of the interior climate (Hugues, Steiger, and Weber, 2004). Hemp is not a rigid material and so will conform to any dimensional changes in the timber frame structure during use.

3.5.9 Cellulose

Cellulose insulation material is manufactured from shredded newspapers. The material is treated with Boric, a salt which improves fire resistance and resistance to rot and mould. The material can be applied in its loose state or in rigid boards. The boards are formed by mixing flakes with fibres and binders before compressing and cutting to size (Pfundstein, 2007). Due to the highly recyclable nature of cellulose, it has a very low level of embodied energy and offers a thermal conductivity value of 0.040 – 0.045 W/mk (Hugues, Steiger, and Weber, 2004). Cellulose insulation is hydroscopic and open to diffusion allowing it to compensate for minor humidity fluctuations in interior climates (Lyons, 2007). Cellulose flakes can be blown in its loose-flake form into prepared voids and compacted to form a seamless layer of insulation. The rigid cellulose board can be cut to suit particular voids such as those in a timber frame wall. However, it is difficult to form a clean and precise cut on the edges of the cellulose boards as they tend to fray; this leaves small gaps in the integrity of the wall allowing noise and heat to pass though (Pfundstein, 2007).

3.5.10 Other Insulation Materials

3.5.10.1 Multi-foil insulation

As insulation technology advances, new and improved products are introduced into the market. One such product which is slowly gaining recognition is multi-foil insulation. This material is comprised of multilayers of aluminium foil, fibrous materials and cellular plastics. It achieves its insulation values by reducing conduction, convection and radiation through the external walls or roof of a building (Lyons, 2007). Manufactures of multi-foil insulation claim that they achieve their apparent high thermal performance based on their ability to reflect long-wave radiated energy thus achieving low levels of heat transfer (Eames, 2009). Installation of multi-foil requires a non-ventilated cavity to be created either side of the material. This is essential in reducing heat radiation through the multi-foil as contact with another surface renders the product's ability to perform (Pfundstein, 2007).

There has been much debate as to the actual performance of multi-foil products when compared with traditional, heavier insulation. A tried and tested method of measuring values of thermal conductivity or thermal resistance of a material is the 'hot box' test. This is the construction of similar sized boxes lined with various insulation materials. Each box is fitted with a heat source and a separate electrical meter. In comparison to insulation materials such as mineral wool or PUR, Muti-foil insulation does not perform to the required standard in such a test. ACTIS, a multi-foil manufacturing company successfully brought about a British court ruling outlining that the hot-box test was an insufficient method of testing multi-foil products. Due to these findings, a separate method of assessing the thermal performance of multi-foils is now in development (Actis, 2013).

Although there are a variety of insulation materials outlined, for the majority of the timber frame projects highlighted in this research, the primary insulation materials used are Mineral wool, PUR and, on occasion, Multi-foil. While the other materials were not used in the course of this research, it is necessary to acknowledge their application, properties and relevance in today's timber frame construction industry.

3.6 Vapour Control Layer (VCL)

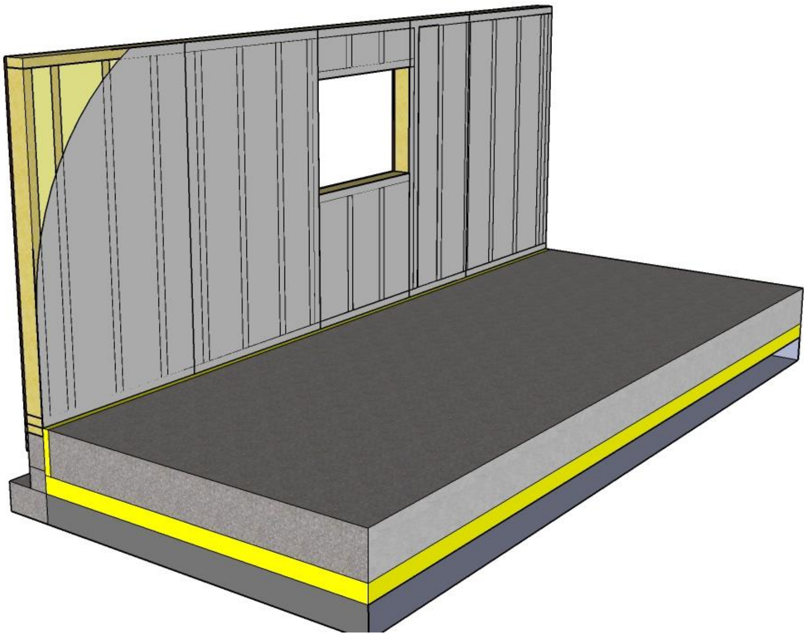


Figure 24: Vapour Control layer (VCL) positioned internally after installation of insulation material

Following the installation of insulation in the timber frame wall, the application of various membranes and linings take place. As shown in Figure 24, a Vapour Control Layer or VCL is applied on the internal or 'warm' side of the wall. In an open panel timber frame project this layer is installed on site prior to the fixing of internal battens and plasterboard. In a closed panel scenario, this layer is applied in factory conditions to each wall panel.

The function of the VCL is to reduce the amount of moisture vapour entering and passing through the external timber frame walls. This moisture is generated by the different internal and external temperatures and air pressure levels (Homebond. and O'Grady, 2008). The inclusion of a VCL prevents the build-up of interstitial condensation whereby heat from inside the building meets cold from the outside and mixes within the wall to form moisture. Closed panel timber frame wall panels are essentially solid walls which could provide ideal conditions for the formation of such interstitial condensation. However, stemming from traditional open frame timber frame construction, the inclusion of an internal VCL prevents the build-up of moisture within the timber frame wall which is damaging to the insulation contained within. The VCL is effective when used in tandem with an external breather membrane as both are vital components in timber frame construction as they facilitate the ability of the wall to breathe and allow water vapour to diffuse through the structure from the inside to the outside (TRADA, 2012).

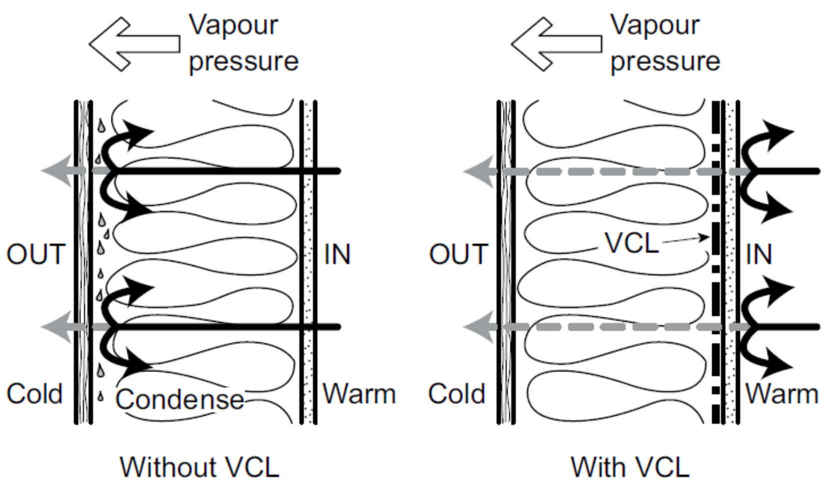


Figure 25: Section through a typical timber frame wall showing the potential for interstitial condensation in the absence of a VCL (TRADA, 2012)

As can be seen from Figure 25, omitting the vapour control barrier allows both moisture and vapour to enter into the insulation layer along the stud wall causing moisture to build up; the addition of the vapour control layer (VCL) prevents this. A VCL is not completely impervious, rather it allows the passage of water vapour into the timber frame wall but slows this diffusion to a rate at which it does not lead to insulation damage. This is made possible as the outer layers of the wall have a lower vapour resistance than the VCL resulting in a natural 'drag' of vapour from interior to exterior. As a rule of thumb, the vapour resistance on the inside should exceed that of the outside by a ratio of 5:1. This will reduce the risk of condensation build up within the wall (Pitts, 2011).

A VCL should comprise of a minimum of 500 gauge polythene with a vapour resistance of 250 Mns/g. Vapour resistance is a measure of the resistance of a homogenous layer to the passing of water vapour through the material when there is a unit difference of vapour pressure from internal to external climate (Everett and Barritt, 1994). Some VCL's are made from metal foil or layered paper with varying degrees of diffusion resistance. These VCL's are used in different circumstances where there is a requirement for a complete vapour tight layer (foil VCL) or where a more porous VCL is required in order to comply with an open diffusion wall (layered paper VCL) (Pfundstein, 2007).

The VCL is applied to the inside of the timber frame wall via stapling or by propriety tapes and sealants. All joints in the VCL must be lapped and taped efficiently. Horizontal laps should be a minimum of 100mm and vertical laps a minimum of 150mm. Services penetrating the VCL must be taped around effectively and any small tears must be repaired (Homebond. and O'Grady, 2008). The same care and attention is required when sealing around window and door openings in the wall structure as the VCL must be carefully cut and dressed into window and door reveals (Homebond. and O'Grady, 2008).

The secondary function of the VCL is to increase the air tight capability of the building as the layer is continuous on the internal face of the timber frame wall. The location and comprehensive cover of the VCL offers an airtight barrier which is an essential component in maintaining the buildings thermal performance. Timber naturally contains moisture. After they are felled, trees have high moisture contents; this is reduced during the air drying process before the timber is engineered for use in construction. Lowering the moisture content of the timber also leads to shrinkage across the grain of a timber section. The timber remains susceptible to growth and shrinkage depending on the humidity of its surrounding air, it is therefore important that an intact and correctly fitted VCL is in position to prevent moisture penetration of the timber frame structure (TRADA, 2012). Such ingress of moisture may have a detrimental effect on the timber frame structure as an increase in the moisture content of timber can lead to rot and fungal attack. As a precaution, the VCL must not be fitted if the moisture content of the timber is above 18% (Homebond. and O'Grady, 2008).

3.7 External Breather Membrane

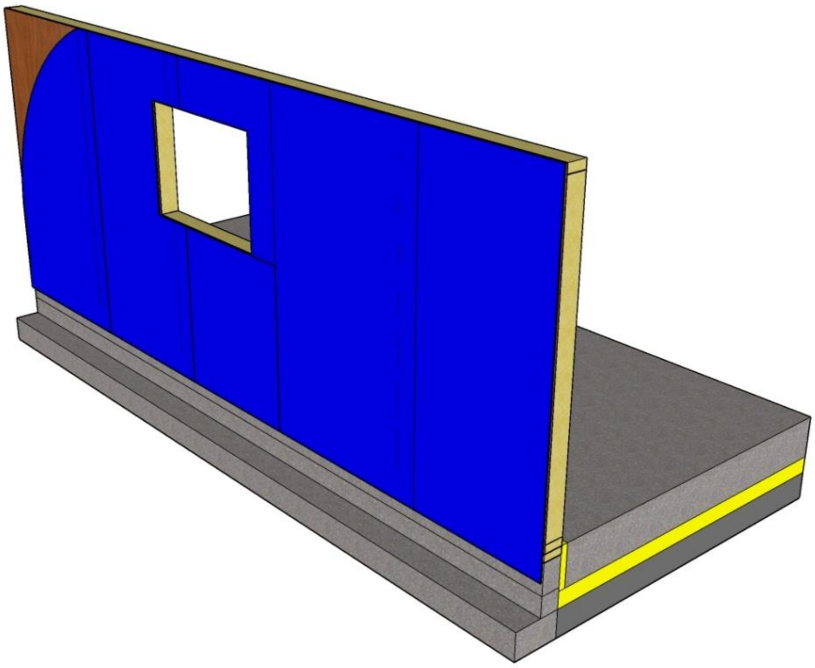


Figure 26: Image of breather membrane (Blue) installed on the external side of the timber frame wall

In conjunction with the VCL, an external membrane is applied to the timber frame structure to further assist in the moisture ingress into the external wall. The membrane shown in Figure 26 is a standard detail of the application of breather paper to the outside face of the timber frame wall. The membrane has a number of functions;

- It protects the fabric of the building from rainwater penetration during construction before external claddings are completed.
- It provides a second line of defence against water penetration during the life of the building as most claddings act as rain screens, rather than as complete barriers.
- It allows water vapour to escape from the construction.

- It can also contribute to air sealing the wall and reducing ventilation heat losses (TRADA, 2003).

The membrane is required to be water tight but must allow water vapour to pass through from the warm side of the wall. This is essential in the removal of moisture from the building as any vapour that gets through the initial VCL must be allowed to pass through the wall and be released into the ventilated cavity outside the wall panel. Failure to allow this release will result in a build-up of interstitial condensation inside the wall (Homebond. and O'Grady, 2008). As previously alluded to, it is vital that the external layers of a timber frame wall beyond the VCL are more permeable to vapour diffusion. Occupancy and heating inside a building ensure that the vapour pressure is usually higher on the inside than the outside; this results in a natural pull of vapour from the inside to the outside (TRADA, 2012).

The breather membrane is applied in a similar format to the VCL; the membrane is stapled into position on the external wall sheathing. All horizontal joints in the membrane should be lapped by 150mm with vertical joints lapped by 100mm. Propriety tapes and sealants are used in conjunction with the membrane to ensure a seamless cover of the sheathing. The membrane should also overhang the bottom of the timber frame wall by 60mm (Homebond. and O'Grady, 2008). The breather membrane offers a further enhancement of the thermal performance of the timber frame structure as it acts as a wind-proof cover for the building. The membrane wrapped around the building helps to protect the internal insulation from excessive cooling and prevents exterior air from infiltrating the structure (Pfundstein, 2007).

The correct application of both the VCL and the breather membrane is essential in the sustainability and the durability of the timber frame structure. As highlighted, the co-operation between both layers is critical to the movement and escape of vapour through the building's external fabric. In an open panel building, both layers are installed on-site leading to exposure to weather conditions. This can hamper the continuous barrier nature of both materials and can lead to tears or perforations forming in either layer. In contrast to this, the closed panel method ensures that both layers are fitted inside in factory conditions with the necessary lap dimensions of material protruding from the edge of each panel. The final lapping and securing of the layers in the closed panel format is carried out on-site and, although this allows some exposure to the elements, it is a very small percentage of the overall layer area allowing for ease of inspection.

3.8 Ventilated Cavity

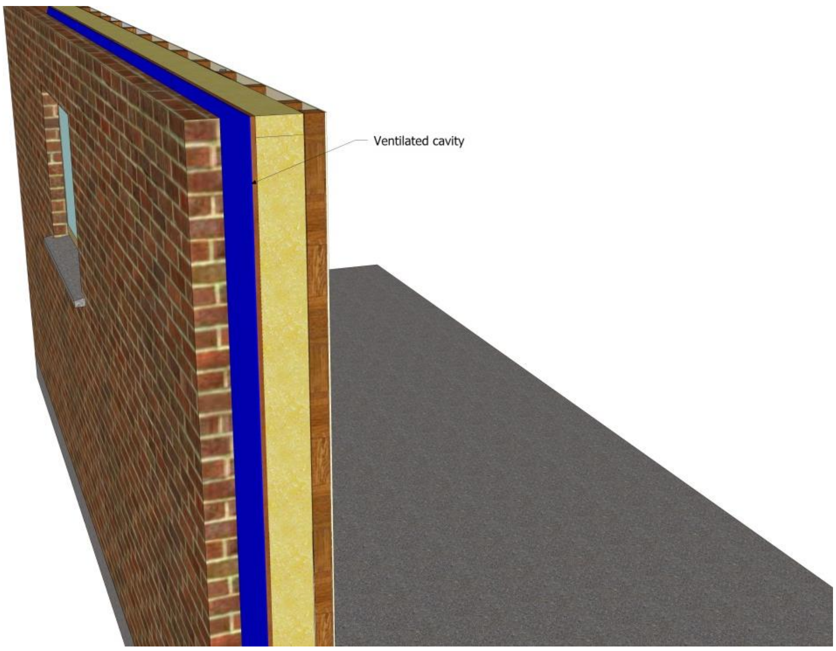


Figure 27: Diagrammatic section of standard open panel timber frame wall showing ventilated cavity

A ventilated and drained cavity must be maintained between the masonry external leaf and the timber frame internal leaf (Figure 27). The cavity permits any water that inadvertently enters the masonry wall to escape without infiltrating the timber frame wall. Vapour released from the timber frame structure is ventilated via the cavity. This is achieved by the use of propriety vents fitted at the DPC level in the bottom of the wall; the vents also act as drainage points for water in the cavity (O'Grady, 2008).

The exemption of a drained cavity wall can lead to the systematic failure and loss of thermal performance of a structure. Such instances have been collectively highlighted in a 2002 study on timber frame housing in Ireland. Known as ‘Leaky Building Syndrome’, three separate instances of interstitial condensation leading to the decline of the structural integrity of dwellings are highlighted. These instances happened in Canada, The USA and New Zealand. In all cases, houses built using traditional timber frame construction techniques were completed externally by an Exterior Insulation Facing System (EIFS). In this system, the external building is completed in a synthetic render system applied over polystyrene insulation (Department Of Environment Heritage And Local Government, 2002).

Moisture penetration of the building was the resulting problem associated with all three cases. The absence of a ventilated cavity space on the exterior of each building resulted in the inability of the external wall to release moisture resulting in the decay of both the insulation contained in the wall and the internal timber frame wall.

All three regions were affected by significant rainfall and mild weather which are factors that contributed to the moisture ingress; however the design and construction of each building should have provided resistance to such water penetration. The investigation into all three cases concluded that a ventilated and drained cavity should have been adopted as this offered the most robust resistance to moisture ingress and fungal decay (Department Of Environment Heritage And Local Government, 2002).

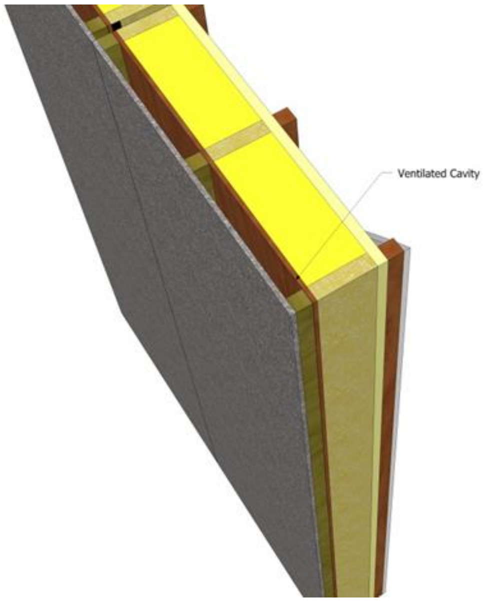


Figure 28: 3D image of closed panel wall with ventilated cavity created behind external fibre cement board cladding

As depicted in Figure 27, a brick wall is built outside the open timber frame wall forming a cavity. In the case of a closed panel timber frame wall as illustrated in Figure 28, a different approach is taken. A ventilated cavity is formed by fixing external treated timber battens into the internal wall studs through the timber sheathing. The battens create a void between the external sheathing and the fibre cement board which is in turn fixed to the battens. A mesh grill is fixed to both the bottom and top of the fibre cement board to allow air movement within the cavity and the escape of any unwanted moisture. The application of the fibre cement board can take place in the factory during production. This results in a significant reduction of time spent on site as once the fibre cement board is in place; the wall is completed and protected externally.

3.9 External Wall Finish

3.9.1 Brick/Block Masonry

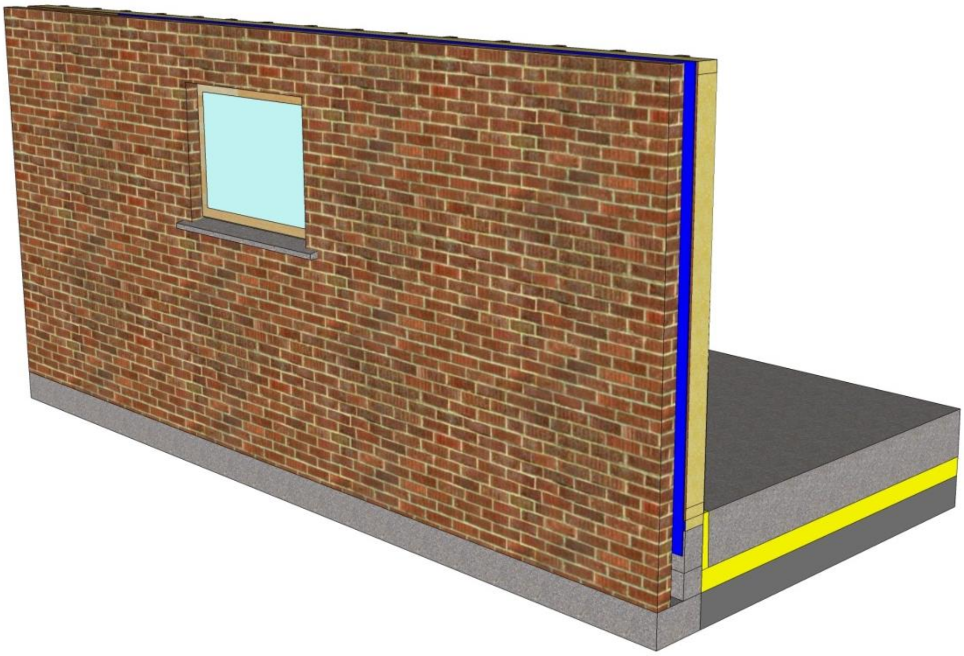


Figure 29: Image of brick built external wall outside timber frame internal wall

Open panel timber frame buildings can be completed in a number of ways, the most common being brick or block masonry finish. The external leaf acts as a rain screen offering the first line of defence against moisture ingress. The external leaf is tied to the internal wall using flexible stainless steel wall ties which are firstly fixed to the internal wall studs via nailing. The ties are then embedded in the mortar joints between the respective layers of brick or block masonry finish. There are standard horizontal and vertical spacing requirements of wall ties to offer sufficient strength and bonding for the external wall; these spaces are:

- Horizontal - 405mm or 605mm depending on stud centres
- Vertical - 450mm or 225mm at openings
- Vertical 225mm at movement joints (O'Grady, 2008)

3.9.2 Cement Fibre Board

As already mentioned, cement fibre board is commonly used in the production of pre-fabricated closed panel timber frame wall panels. Fibre cement boards consist of 40% Portland cement, 11% aggregate, 2% reinforcement fibre and 5% cellulose fibres and water.

Fibre cement boards offer excellent strength and resistance to rot, freeze-thaw action and are incombustible (Hugues, Steiger, and Weber, 2004). Cement fibre boards are screw fixed to the external battens on the external side of a wall. They should only be installed when the temperature is between 5°C to 25°C and relative humidity is not above 60% (BBA, 2009). There are a number of different fibre cement board suppliers in operation today; a prime manufacturer of such systems is Knauf USG which manufactures the Aquapanel brand of fibre cement board. (Refer to Figure 30).

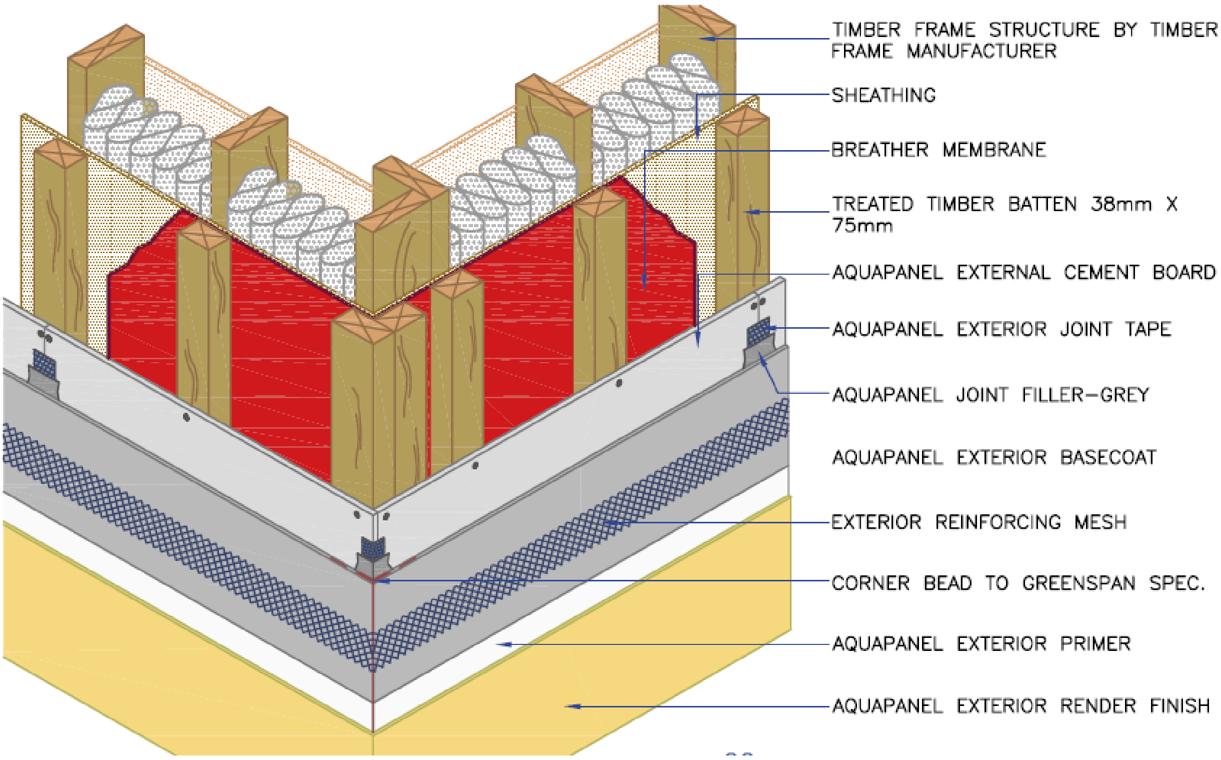


Figure 30: Detailed image of the application of Aquapanel fibre cement board (BBA, 2009)

Aquapanel boards come in sizes of 900mm x 1200 x 12.5mm thick and have a weight of 17.5 Kg. Installation of the Aquapanel system involves a number of systematic steps in completing its application to a closed panel building format;

1. The cement fibre boards are fixed in position
2. A Portland cement exterior basecoat mortar containing dry latex polymers is applied to the boards to provide a seamless platform for further render.
3. A reinforcing mesh is then embedded in the basecoat to give strength and flexibility. The mesh is made of glass fibre with an alkali resistant coating. A reinforcing tape is applied at joints, corners and around openings for extra stability.
4. An exterior primer is applied to the mesh, the primer coat is also alkali resistant and is spread in an even 5mm coating
5. The final exterior coat is then applied. This coat can be a silicon synthetic resin plaster or an acrylic-based render. The exterior coat has a very low water permeability rating and is resistant to the growth of mould or fungus (Greenspan, 2013).

Proprietary corner and angle beads are used to establish edge joints and profiles. The fibre cement board is required to stop 150mm above ground level with a drip bead used to complete the bottom of the system. In terms of a closed panel timber frame building, it is common to apply the cement board, basecoat and reinforcing mesh in factory conditions. Once panels are then placed on-site, the exterior primer and final coat can be applied to give a smooth seamless finish.

3.10 Internal Completions

In a typical timber frame construction development, the internal finishes commence after the roof and external completion items such as doors and windows are installed. Internally, after the VCL layer is fixed in position, internal battens are nailed or screwed into the structure stud walls. The battens have a depth of 35mm which creates a void between each one. This space is used for electrical and mechanical services and allows a continuous void to be created from the top of the wall to the bottom. Figure 31 depicts the dropping of an electrical switch and socket from ceiling level; this is a typical arrangement for such electrical service installation. For both open and closed panel methods of timber frame construction, the installation of services typically takes place on-site. This is due to the fact that service installation is made easier once the entire structure is erect and in its final resting place.

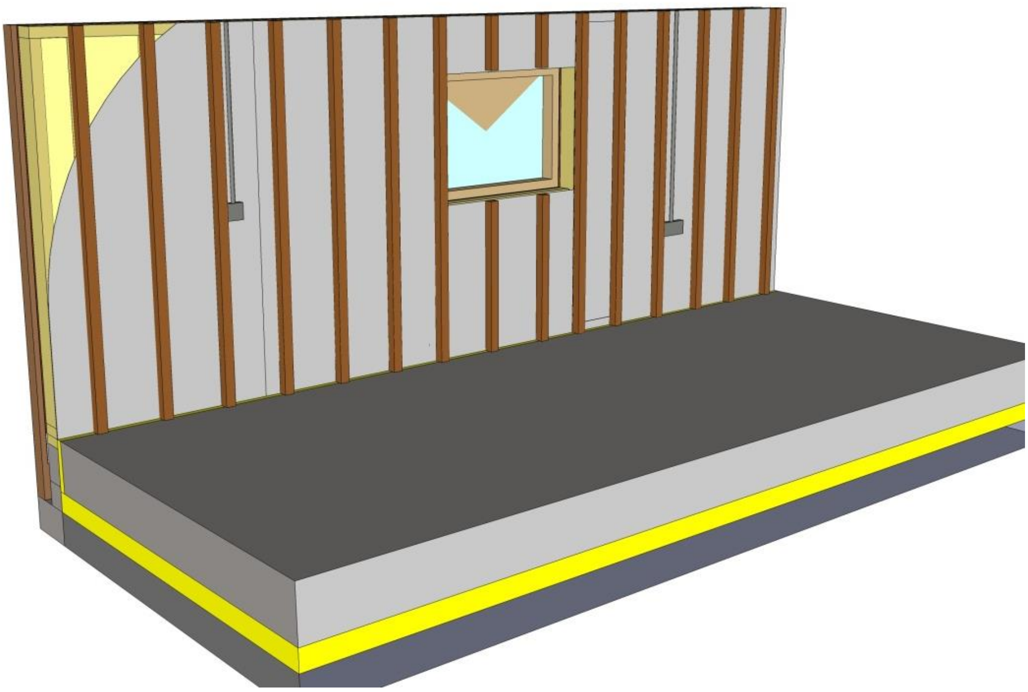


Figure 31: Internal view of open panel wall with electrical services in voids between battens

Figure 32: Image illustrating the application of plaster board and skim-coat internal wall finish

Once the services are positioned, standard plasterboard is installed in the internal side of the wall and completed in a skim-coat plaster. Plasterboard is manufactured from rock gypsum which is crushed and ground into a fine powder. Production of plasterboard takes place on a conveyor belt as the calculated ground plaster is mixed with additives before being sprayed onto a base and formed into boards together with cardboard lining. The combination of both the plaster core and the cardboard lining result in the plasterboard having excellent tensile strength and flexibility (Hugues, Steiger, and Weber, 2004). Different plasterboard can be manufactured for different requirements e.g. fire-protection plasterboard, sound impact plasterboard and x-ray plasterboard (Lyons, 2007). Internal plaster finishes are enhanced by the use of angle and stop beads which are manufactured from stainless steel and provide level edges to complete and protect the edges of the plaster. In order to prevent cracking at joints between plasterboard slabs, a reinforcing mesh material called 'scrim' is used. This is a glass-fibre mesh that offers extra strength to resist thermal movement during the life span of the wall (Lyons, 2007).

3.10.1 Open panel development to closed panel

The individual sections highlighted are part of both open panel and closed panel construction methods. In terms of the actual construction of either wall, it is commonly seen that closed panel manufacturing methods allow for more construction to take place inside the factory rather than out on site. This is extremely beneficial in terms of the lifelong performance of the structure as components remain dry and unaffected by weather. This reduces the risk of fungal attack or rot and reduces the possibility of insulating components becoming saturated or damaged.

As can be seen from the continuous comparison between open and closed formats, the actual construction, function and make up of each wall does not deviate as the same U-Value requirements and building regulations dictate the level of insulation and component positioning in each wall. The addition of cement fibre board has paved the way for a complete external facing system that can be applied prior to site assembly. Installation of such a system has led to the development of complete wall panel and as a result a further evolution of timber frame construction. It is the premise of this research project that closed panel timber frame construction is the future of the timber frame industry as it follows closely existing practices but adds a further dimension that is both practical and beneficial to designers, constructors and end users.

3.10.2 Client requirements

From Company A's commercial point of view, client requirements result in the need to adapt or change wall build-ups from project to project. As highlighted in this chapter, the use of extra studs at openings, larger timber members over windows and doors, establishing channels for electrical and plumbing services behind the plasterboard and installation of breather and VCL membranes are common throughout all projects. A durable external wall finish is also necessary but as previously alluded to, the option to use external concrete board is available to the client as opposed to standard brick or block rendered finish. The same applies for internal finishing of each project as depending on client requirements, the internal finish can be upgraded from standard plasterboard to insulation backed board adding to the thermal performance of the wall. These extra elements are client dependant as Company A must supply a wall structure that conforms to the current regulated U-Value of .21W/mK. The build-up of each wall however does not impact the use of the new connection detail as it is fitted on the end stud of each wall panel and is not affected by the thickness or layout.

Chapter 4

Research Methodology

"Research is a learning process… perhaps the only learning process"

(Fellows and Liu, 1997).

The following chapter outlines the research methodology chosen for this dissertation. It is the aim of this chapter to provide the reader with an insight into the different methods of research carried out in the development of a practical solution to answer the research aim:

"To develop an innovative, viable method of connecting closed panel timber frame walls and assessing if this method could improve the energy and structural performance of a timber frame building when compared with existing assembly practices".

In order to satisfy the overall research aim, a systematic approach allowing for the assessment of different elements of timber frame construction was adopted. These elements were broken down into objectives which will be used to support and validate findings and conclusions reached during the course of the research. The aims were:

- Research and critique current timber frame construction practice
- Improve existing methods of closed panel connection
- Conduct a thermal assessment of the connection detail
- conduct a structural assessment of the new detail

4.1 Background to the research

The initiating factor behind the research presented in this enquiry stems from an Irish based timber frame construction company who were seeking to improve the assembly process of their closed panel timber frame projects. This removed the process of defining the research question as the scope of the enquiry was already established. In respect of this, a comprehensive research methodology was put in place to ensure the research aims and objectives were adequately satisfied.

4.2 Research Methodology

In the undertaking of any research project it is necessary to develop a research methodology and process. However, before this stage, a basic understanding of knowledge and research philosophy is required. Epistemology concerns the theories of knowledge, its nature and how we acquire it (Knight and Ruddock, 2008). As research is intended to contribute to knowledge, it is vital that a researcher is aware of their relationship with their study subject. Creswell defines this relationship as “interrelated not independent” and closeness follows between the researcher and that being researched which will manifest through the entire research process (Creswell, 2007). Research methodology is derived from the same principals of epistemology but rather than being concerned with the philosophy of how we come to know, research methodology involves the practice and the methods of obtaining knowledge (Trochim, 2006).

In order to ascertain the best method of research, it is necessary to explore different research areas and gathering techniques. Research requires a systematic approach by the researcher regardless of what is to be investigated (Fellows and Liu, 1997). For this research enquiry the development of a research methodology stems from the application of two forms of research; Quantitative and Qualitative. Both of these methods have underlying philosophical origins and will be explored in greater detail.

4.3 Quantitative

Quantitative research adopts scientific methods in which initial study of theory and literature yields precise aims and objectives with propositions and hypotheses to be tested (Fellows and Liu, 1997). The essence behind the quantitative approach stems from the philosophy of positivism. This is the theory that the aim of research and knowledge is to describe the phenomena that we experience (Trochim 2006). Quantitative research is therefore more concerned with facts and figures than in emotions or feelings involving a particular subject.

4.4 Qualitative

Qualitative research follows an unstructured, flexible and open approach to enquiry. It aims to describe rather than measure and explores perceptions and feelings rather than facts and figures (Kumar, 2005). The Qualitative research method in many respects is deemed as the opposite to the Quantitative research method. This form of research stems from post-positivism which is a rejection and counter argument against positivism (Trochim 2006).

Quantitative research is perhaps best suited to the field of construction and in this research enquiry as the nature of the research is technical and will require measurement and presentation in a quantitative sense. However, qualitative research will also form part of the overall enquiry as popular opinion, people's perceptions and common practices in relation to timber frame construction will be assessed.

or method of construction adopted were outlined as recommendations and were put in place for the next project. This process continued until a satisfactory, functional connection detail was established.

4.6 Mixed Method research

The action research applied in the course of the overall research project is, in essence, a form of qualitative research as a qualitative stance was used in the observation and recording of each construction sequence. However, the importance of the action research, its application and findings merits it as a method used in conjunction with both Quantitative and Qualitative research in an overall mixed methods research approach.

Using a mix of both quantitative and qualitative research methods allows the researcher to develop a research design. The quantitative approach identifies the extent of the problem to be examined whilst the qualitative approach identifies its nature (Kumar 2005). The central premise of mixed method research is that using a combination of quantitative and qualitative research methods together will develop a better understanding of a research problem than just using one method alone (Creswell 2003). A further advantage to the mixed method approach lies in its openness and practicality as the approach allows the researcher to use all methods possible to investigate a problem (Creswell 2003).

4.7 Overall research process

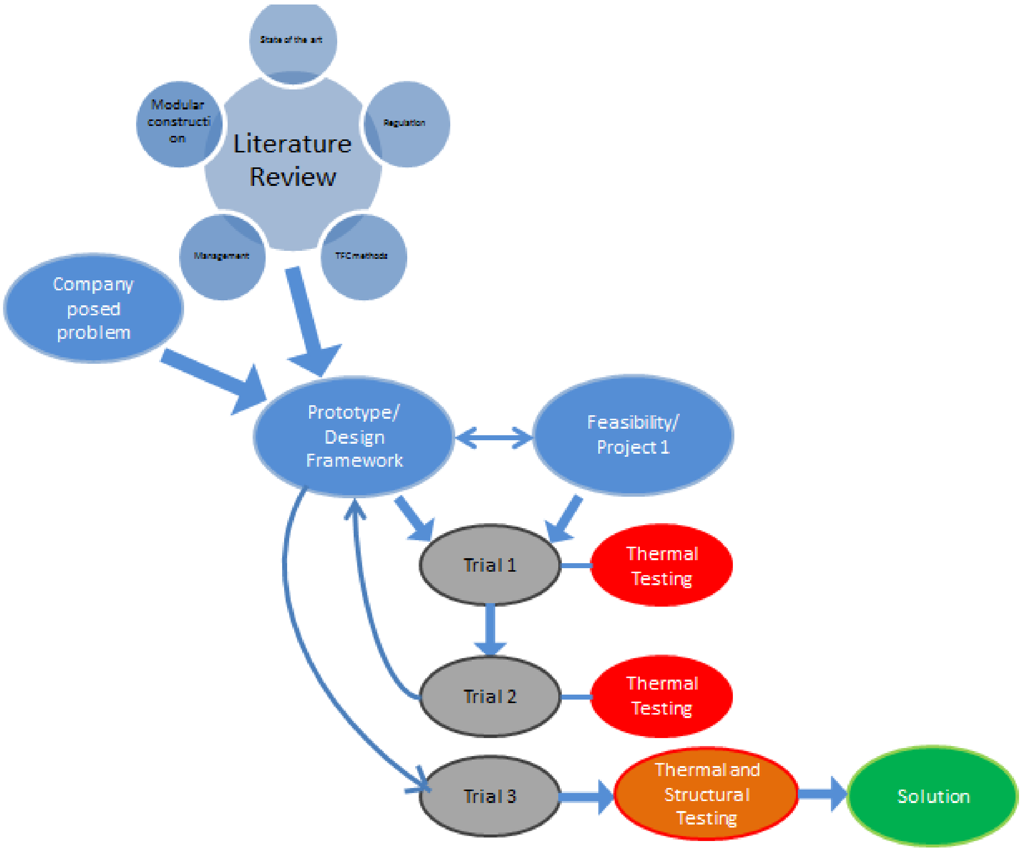


Figure 4 FILL THIS IN!!

As outlined in Figure ??? the overall research process used during the course of the research project is quite detailed however, the process follows a systematic flow. The initial stages of research were general in nature and dealt with timber frame construction in its entirety. This included methods used in manufacture, assembly and erection to regulations adhered to in the industry. The beginning of the research focus began on approach from company A regarding the issue of connecting panels on site and if this process can be improved and removed from site activity. This led to a design frame work and the development of a prototype connection detail. Key to this initial research was the availability of a live construction project, Project 1 which determined that the connection detail worked and had merit to be explored further.

Three subsequent trials were to be utilised in the development of a viable connection detail. Trial 1 proved successful in terms of the detail working to create solid connections between wall panels however, it became apparent during this trial that dimensional inaccuracy's between the timber and the connector slowed down the build process. The only extra facet of detail testing that could be carried out at this stage was thermal testing. Trial 2 became the most important trial in the course of the research. It became obvious during this Trial that the connectors did not allow enough tolerance when compared to the timber. With this in mind, a revisit to the design framework was necessary.

After a revamped connection detail, progression onto Trial 3 yielded far more positive results. The newly adopted connectors afforded more tolerance within each connection and so proved successful. At this stage, both a thermal and structural test of the detail could be carried out resulting in the successful thermal performance and superior structural characteristics of the connection detail. The results provided a solution to the companys posed problem and a comprehensive conclusion to the research.

For the manufacture and assembly observations, the existing process used by Company A provided both a benchmark and an information source in terms of the manufacture time, the system of manufacture in place, the assembly process and the overall project delivery process of each build. For the detailed timber manufacturing process, a semi structured interview and visit to a timber processing factory provided the majority of the practical insight into timber manufacture as needed in the scope of this research process.

Establishing the background to timber frame construction, it methods and technical requirements, provided a solid basis to pursue research into the development of an improved method of connecting closed panel timber frame wall panels. The success of the simple scale model connection test paved the way for the connection system to be used on a live construction project (Project 1). The further success of this coupled with the support of Company A allowed the research process to expand and incorporate action research over the course of three trial projects which truly established the suitability of the connection detail in use with a timber framed structure and its development into a functional connection system. This functionality is supported further in the course of the research by utilising both computer simulated heat transfer analysis of the connection system in use and practical, laboratory based structural testing of the connector in comparison with standard screw fixing. The analysis of the results of this research process brought together the outcomes of practical testing, computer simulated testing and structural testing. Each of these facets, although removed from the initial background research of the topic, correlates to support the use of the connectors over standard screw fixing.

The overall research methodology for this project is complex but comprehensive in its application. The construction industry is, by its nature, an ever changing one. This is evident throughout the duration of the research process particularly in the cases of the live construction projects used in the action research phase. Preparation and knowledge of each project was essential. However, on-site changes, dimensional differences and delays are commonplace in the construction industry. Awareness of this, and the ability to extract the necessary data and results while not interfering with the natural course and flow of a construction project was paramount. As a result, the most concise information has been extracted from each project and has allowed the research process to develop and become further supported through the external facets as described.

4.8 Primary and Secondary Research

In order to compile a diverse range of information, primary and secondary research is used. Referred to as ‘fieldwork study’ and ‘desk top study’, both methods are used to establish greater insight into the chosen topic (Naoum, 1998).

4.8.1 Primary Research

Primary research sources provide first-hand information (Kumar, 1996). In relation to the level of research undertaken by this project, typical primary research included:

- Interview
- Thermal Imaging
- Simulated Thermal Evaluation
- Structural Testing

4.8.1.1 The Interview

It is stated that “interviews are used to fully understand someone’s impressions or experiences or to learn more about their answers to questions” (Knight and Ruddock, 2008). Typically there are three main forms of interviewing; structured, semi-structured and unstructured. A structured interview is when the interviewer asks a series of questions to the interviewee and may not add anything else (Kumar, 1996). Unstructured interviews are the direct opposite of structured interviews. In this instance the interviewer has no set list of questions and instead questions are asked during the course of the interview. The interviewee is encouraged to explore all of their thoughts on a given subject (Denscombe, 2007). In semi-structured interviews the interviewer has a pre-determined set of questions but can ask supplementary questions should an area of interest arise (Rugg and Petre, 2007). This form of interview also allows the interviewee to develop ideas and speak more widely on the issues raised by the interviewer (Denscombe, 2007) A Semi-structured interview was used in the research for this project. The Interview we carried out with Brendan Farrell of Glennon Bros timber company to establish the processes behind timber manufacture. In order to get the most information from this interviewee, a set list of questions were prepared, however, during the course of the interview extra questions were asked to allow for elaboration.

4.8.1.2 Thermal Imaging

Thermal imaging or thermography is the process of using infrared technology to determine the energy performance of a building or building element. The use of thermography is mostly associated in post-construction situations where thermal images are used to check the correct application of insulation and air-tight layers. However it is becoming increasingly common to use thermography during the course of construction to ensure such details are correct before the completion of a building (Hart, 1990).

Thermal images use infrared radiation (IR) to determine the various temperature differences in any given image. IR is emitted by all objects warmer than -273˚C. It travels through space much like visible light but at longer wavelengths (Pearson, 2002). Figure 35 shows the electromagnetic spectrum and depicts both shortwave (SW) and long wave (LW) bands used for thermal imaging. Every object emits a certain amount of infra-red wavelength and this varies with the surface temperature of that object. Correct capturing of the infrared also depends on the emissivity of the objects surface, the distance from the object and transmissivity of the air between the source and the observer (Pearson, 2011).

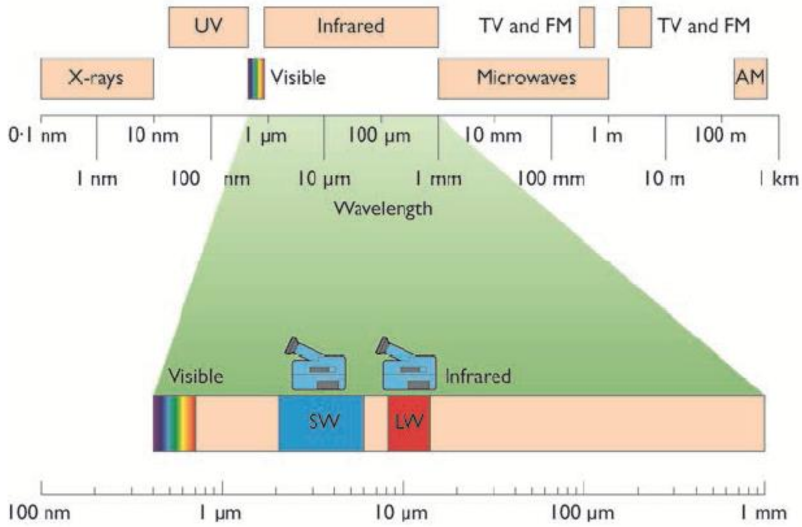


Figure 35: The electromagnetic spectrum (Pearson 2011)

An infra-red camera detects the thermal radiation emitted by an object and presents it in a black and white or coloured display. The capturing of this image can be made using a normal camera and film which is referred to as a thermogram.

Each thermographic survey must be carried out in a systematic approach. The survey must collect sufficient information to show that all surfaces have been inspected and that any anomalies found must be captured in a way that leaves them suitable for analysis and interpretation (UKTA, 2007). Where anomalies are detected in the fabric of the building, additional data must be collected to correctly analyse any defects, this includes:

- Internal temperature in the region of the anomaly
- External temperature in the region of the anomaly
- Emissivity of the surface
- Background temperature

- Distance from the surface

Thermal images were taken of two Trial Projects post construction and re-occupancy. Using thermal imaging presented direct information which assisted in adding support to the promotion of the new connection system. This was in the context of the airtight capabilities of the structure when compared with standard screw-fixing. Thermal imaging was the only invasive means of assessing the thermal performance of the building at the disposal of the research project. The findings of the thermal survey are viewed collectively with the results of simulated thermal performance to give an overall assessment of the thermal detail.

4.8.1.3 Simulated Thermal Evaluation

The most efficient and up to date method of assessing the thermal performance of the connection detail is using a programme developed by software developers LBNL known as THERM. The software is predominantly used to assess the thermal capabilities and the heat transfer effect of assembled construction products such as windows and doors but can be applied to assess the thermal performance of building components such as walls (Arasteh, 2006). The premise to the software is simple; a typical completed timber frame wall is made up of many different layers. Each of these layers has its own specific thermal conductivity factor. The software allows the user to assign thermal conductivity factors to different layers with a wall structure, a temperature difference is then set and a computer simulated indication of the thermal performance of the wall is generated. This is better explained in Figures 36, 37, 38 and 39 which show how the THERM evaluation of the connection detail was carried out on the feasibility project.

Figure 36: layout and material build up a typical wall used in the feasibility project

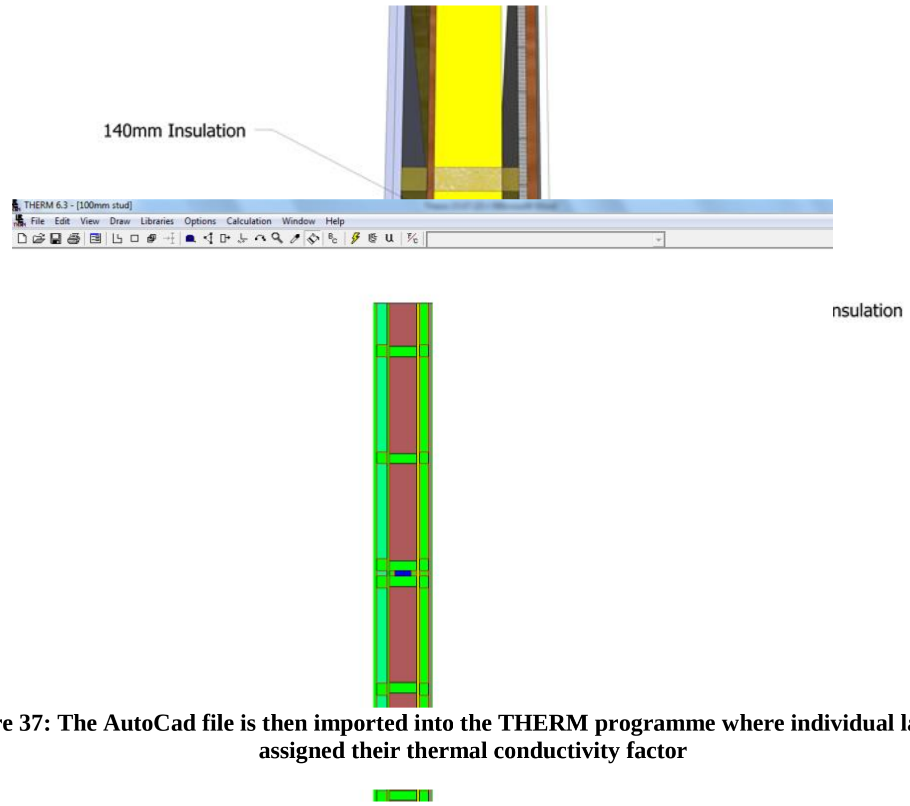


Figure 37: The AutoCad file is then imported into the THERM programme where individual layers are assigned their thermal conductivity factor

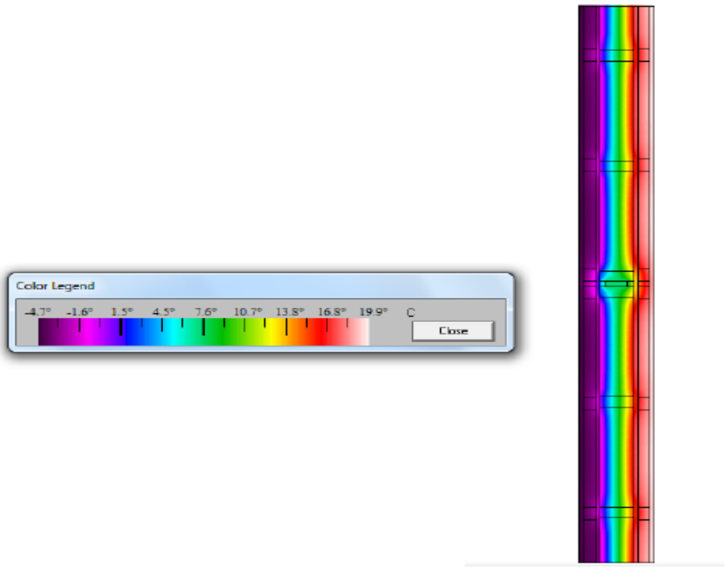
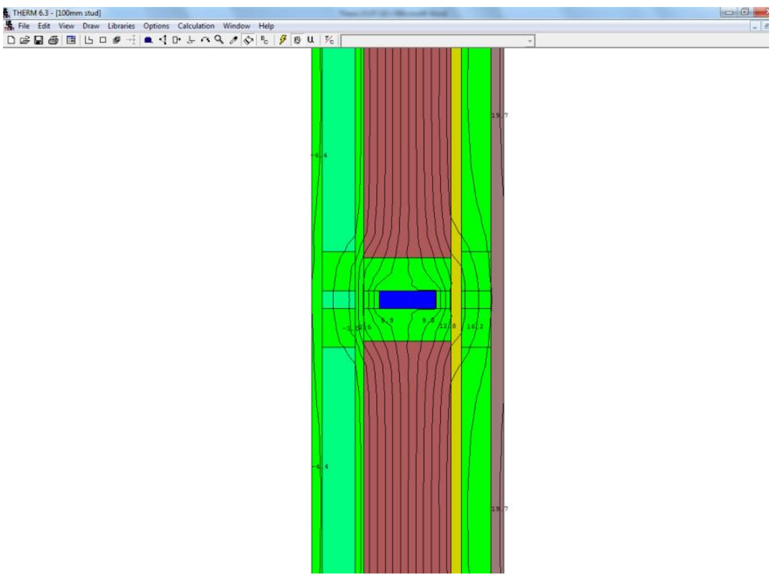


Figure 38: Once the conductivity factors have been assigned, a gradient calculation of thermal activity is carried out.

Figure 39: The internal and external temperature is then set. The software is then capable of demonstrating the different thermal flux throughout the wall at the differential temperatures. Note the deviation of temperature at the point of connection in the centre of the wall

The above image shows the range of thermal gradient around the Sherpa™ connector in the wall (blue component)



Material	Conductivity W/mK

Concrete Board	0.36	(BBA, 2009)
Timber Batten	0.12	(CIBSE, 2006)
OSB	0.12	(CIBSE, 2006)
Timber Stud	0.12	(CIBSE, 2006)
Insulation	0.34	(Isover, 2012)
Polyurethane	0.22	(Xtratherm, 2013)
Actis Multifoil	0.04	(Actis, 2013)
Timber batten	0.12	(CIBSE, 2006)
Plasterboard	0.21	(CIBSE, 2006)
Aluminium Sherpa	160	

Figure 50: Table of thermal conductivity values

In order to accurately assess the heat transfer through the walls of each project, the thermal conductivity of the material used in the construction of each wall had to be established.

As outlined in the above table, the various materials were assigned thermal conductivity factors based on the calculations used in industry and from manufactures specifications.

The wall panels used in the feasibility project were a mixture of 100mm and 140mm stud walls incorporating multifoil insulation. The walls used in the subsequent trials were 140mm stud walls using the same build-up across all three projects. Using the THERM software, each component in the wall assembly was assigned its thermal conductivity factor. The edges of the wall were assigned as ‘boundary’s’ allowing the software to distinguish where each wall and layer finished. Both the external and internal cavities found in the wall structure remained neutral. It was necessary to use the THERM software in this research project to provide accurate and reliable data in supporting the change to and use of the new connection detail by Company A. Using the software gave clear evidence into the performance of the Sherpa™ connector located at the centre of each connection point; this is information that otherwise could not be gathered during a thermograhic survey, as that method of analysis is not as detailed or as precise as the simulated results.

4.8.1.4 Structural Testing

Following the completion and thermal evaluation of the three trial projects, it was necessary to carry out a number of tests to determine the structural integrity of the new connection detail and compare it with the standard methods of connecting closed panels. After consideration, it was felt that the most accurate process of establishing the structural integrity of the connection detail was to construct scale models of standard timber frame walls. The test models were based purely on the timber frame skeleton consisting only of rails, studs and external sheathing. Before panel assembly began, the type and format of testing was established. In order to accurately test and compare the new detail to the standard method of connection, two test procedures were established. The first test procedure was aimed at establishing the strength offered by the connection detail at corner joints under a compressive force. The second was aimed at establishing the lateral or racking strength offered by the Sherpa™ connectors when compared with standard screw connecting panels.

Test panels were assembled from standard timber which is used in typical timber frame construction projects. Before assembly, a cutting list was drafted outlining the number and size of the timber members needed for each panel. In total there were 8 timber frame panels needed to carry out two comparative structural tests. 4 of the panels were arranged in a standard timber frame stud layout and the remaining 4 were assembled in accordance with the new connection detail as used in Trial project 3 (Figure 41 and 42).

The panels were constructed using 140mm x 38mm CLS timber studs with 20mm plywood sheathing fitted externally. In keeping with industry practice, the CLS timber was joined together using 55mm nails with the external sheathing fixed to the frame using 30mm nails. Each wall panel was 1060mm in length, 158mm wide and 1200mm in height with a standard stud dimension of 400mm centre to centre.

Figure 41: Exploded view of the layout of test panels using the new connection detail

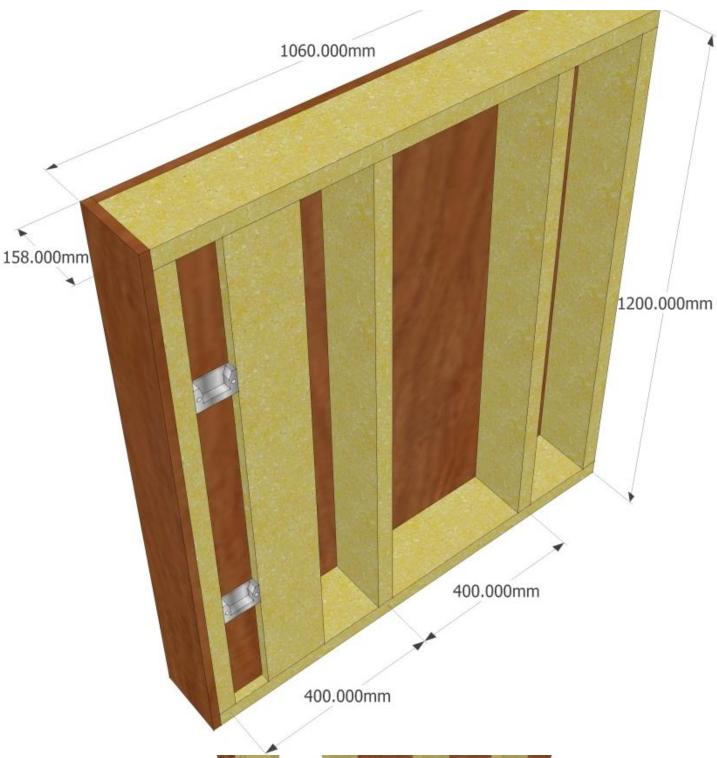
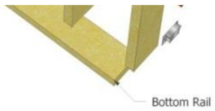


Figure 42: Completed wall panel with dimensions



The structural test comparison of the panels was the last area of primary research to be undertaken. Assessing the strength of the connectors in both a compressive and lateral environment and comparing the results to standard screw fixing was necessary in the course of this research project. The connection detail had a fundamental requirement of outperforming a standard screw fixed counterpart. It was essential that detailed and accurate tests were carried out in which conclusive evidence of the connectors performance could be contrasted to those of a standard connection method used in industry. All testing was carried out in the structural laboratory of DIT Bolton Street and all movement readings taken during each test were correlated and presented in Microsoft Excel™ spread sheet. The data collected from these tests gives significant credibility to the acceptance and use of the new connection detail as it consistently outperformed the existing methods of connection used in the industry. Due to the clear results found during this structural testing, the necessity to assemble and destroy test panels is justified. The structural testing clearly alludes that there is not only merit in the adoption of the connection system into mainstream construction but also there is scope for further assessment and structural analysis.

4.8.2 Secondary Research

Secondary research (or desktop research) is defined by (Rugg and Petre, 2007) as "useful for numerous purposes but does not usually lead to breakthroughs in human knowledge". In essence, secondary research is the sifting through and recording of secondary data which has already been collected (Kumar, 1996). The secondary research undertaken for this dissertation involved several different information sources. Technical information surrounding timber framing standards and practices were largely sourced from renowned timber frame construction providers such as TRADA and the Building Research Establishment (BRE) which corresponded to the method and practices used by Company A on actual construction projects. Extensive background reading was carried in the technical areas relating to wood characteristics, production and limitations in use and is reflected in the research approach to the tacit areas of this form of construction. Extensive detail and guidance are also provided for the various materials and layouts of timber frame structures as used in today's construction industry. Such information, while not contributing directly to the development of the connection detail, offers insight into the constantly developing and improving timber frame model of construction. Secondary research obtained from books and data sheets were sourced directly from the Library of the Bolton Street DIT campus.

"Secondary research traditionally involved a lot of time in libraries, though now it is increasingly likely to involve a lot of time on the internet"

(Rugg and Petre, 2007).

A large portion of the secondary research compiled for this dissertation has been internet based. This is due to the instant availability of data, technical guidance documents and structural layout documents all relating directly to many different areas of the research subject. Information databases also proved to be key electronic information resources. 'Info4education' a database provided by DIT was used extensively as it has a direct connection to technical construction information provided by BRE.

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4.9 Triangulation

"The logic behind the use of multiple measurement techniques is elegantly simple. It is referred to as triangulation"

(Gray et al., 2007)

In order to gain a better understanding of the topic selected, triangulation is used to support findings. This method of research minimises the inadequacies of single-source research as two sources complement and verify each other (Bailey-Beckett and Turner, 2001). Denscombe (2007) puts forward many different varieties of triangulation such as; methodological, data, investigator and theory. However, methodological is the most commonly used form as it compares quantitative data with qualitative data in order to arrive at a conclusion (Denscombe, 2007). As both quantitative and qualitative research methods are utilised in this research project, methodological triangulation is used.

A key instance of the occurrence of triangulation in the research is seen as the initial Sherpa™ connectors are used on the feasibility trial. During the on-site assembly of the project, the connectors offer outstanding strength and rigidity when the structure is complete. This sets the precedent of a strength comparison between the Sherpa™ and standard screw fixing. Further and more detailed research into this area demonstrated that the Sherpa™ connectors used in the developed connection detail offered significant improvement in terms of structural strength when compared with standard fixing methods. This is one instance of triangulation being applied in the course of the research to not only support a theory or hypothesis, but to develop an imperative strand of the research, further enforcing its findings.

4.10 Limitations of the Methodology

The research methodology applied during the course of this research project was extensive in its compilation of background information and data surrounding the subject area. The methodology also comprehensively covered the inception and shaping of the focus of the research; to develop an innovative and viable method of connecting closed panel timber frame walls. This area of the research, as already described, required a methodology that could be adapted and tailored to suit individual, important live construction projects. This was achieved by the inclusion of action research in the methodology. Taking both the background information regarding timber frame construction and the subsequent development of a new connection detail, the focus of the research changed to verifying the detail.

An assessment of the connection detail in use was necessary to support any findings put forward by the action research trials. The methodology surrounding both the thermal and structural assessments was quantitative and succinct in its nature and application and proved that the connection detail adequately outperformed the standard screw fixed connection method. In essence the overall research methodology for this project was a combination of various research methods each designed to extract the most information and clarity from each area of the research. More important than this however, was the ability of the methodology to present conclusive evidence and factual data relating to a construction topic which future research can be based upon.

It is within this context that the methodology is limited. Further research into this area may require a more robust and stringent methodology where focus is placed on both the structural and thermal performance of the connection detail over a longer period of time.

Chapter 5

Development of a new connection detail

Company A is a small off-site timber frame construction company. The company has four to five operatives who carry out both the prefabrication of the timber frame wall panels and the on-site assembly. From previous projects carried out by Company A, they felt that unnecessary damage was being caused to open ended wall panels from their point of manufacture to installation on-site. This contributed to a loss and damage of materials contained within the wall panels, such as insulation, membranes and battens. Company A were also keen to reduce the amount of on-site delays stemming from the additional time needed to complete joint details between walls and to construct each wall assembly project with greater accuracy and efficiency. In this case, Company A wished to concentrate on a method of producing a completed wall panel which could be quickly and easily connected on-site without requiring additional time and manpower to complete the open joints between panels. As Company A mainly operated in the home extension sector of domestic construction, it was imperative that the structure of each project be completed in as quick a time as possible to a high level of quality and without dimensional errors.

5.1 Present method

Company A prefabricate all wall panels in a factory setting. Figure 43 depicts the layout of the factory floor in terms of the prefabrication process. The area marked 1 is the cutting area where all vertical and horizontal timber pieces are cut to the required size. Area 2 is the initial joining area where the vertical studs are fixed to the horizontal top and bottom rails of each wall. The external OSB sheathing is also fixed into position in this area. Wall panels are then passed from area 2 to area 3 via a sliding work bench; insulation is inserted in the voids between the vertical studs of each wall at area 3. If required, an internal vapour barrier or additional ridged insulation can be added before the internal battens are fixed into position.

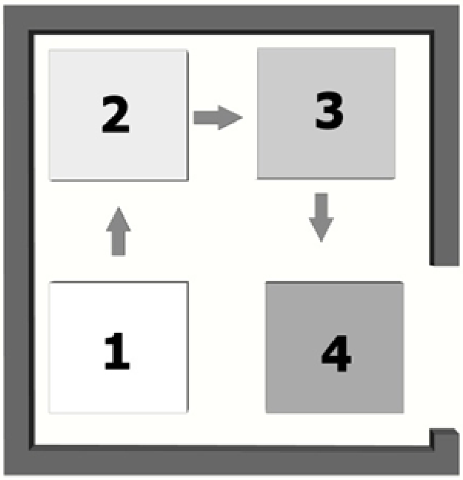

Figure 43: Factory floor layout of Company A

Once ready, the wall panel is then lifted into an upright position (Area 4) and is placed on an 'L' frame. Once upright, the external breather membrane is applied. External battens are then fixed into position and, if required, external concrete board is added. Once enough panels are stacked on an 'L' frame, they are removed from the factory using a forklift. Both ends of a completed panel are left open and without insulation, this is to allow on-site workers access to screw the panels together once they are positioned.

On average it takes 1 hour for a wall panel to be cut, assembled and fabricated. This duration works well for Company A as they are restricted by their factory size and must maintain a constant production flow to ensure walls are prefabricated and removed from the factory, creating more space for workers. Any improvements to the manufacturing process must not add time to the production of each panel and allow for a continuously smooth prefabrication operation.

Once on-site, the assembly of the wall panel structure is relatively straight forward. Walls are positioned using a mobile crane. Once in their final resting place, the walls are checked for level and accuracy. When this is satisfactory, the walls are nailed or screw fixed to each other and secured to the ground using stainless steel brackets by fixing through the bottom rail of each wall into a wall plate below. Following the positioning of the walls and roof, the omitted insulation infill is inserted at each wall junction. After this, the external breather membrane and the internal vapour barrier are sufficiently lapped and secured. Fixing of both internal and external battens at each side of the joint then follows, completing the timber frame system. Internal and external work cannot proceed until all the joints in the timber frame structure are insulated, protected from moisture ingress and prepared for internal/external finishes.

5.2 The need for improvement

From the outset of this research project, Company A expressed an interest in pursuing a new and improved method for connecting closed timber panels. From observing both the prefabrication and assembly elements of Company A's processes, the introduction of a new joining method is achievable and can potentially benefit the on-site assembly of timber structures. However, it was essential that the new method was managed properly and did not add additional time to the prefabrication process as this would delay factory production and, in turn, delay arrival on-site. It was also important to consider training of company workers to ensure they fully understood and complied with any new instructions relating to both the prefabrication and assembly process.

Company A also expressed their concern at the damage caused to both membranes and insulation during transportation and assembly on-site. Leaving both ends of each panel unfinished, affords the opportunity for both membranes to become snagged and torn on other panels, workers tools, lifting equipment etc. In conjunction with this, completing the works around each panel joint once all the walls are positioned leaves the joint at the mercy of the weather. Wind and rain can penetrate the joint during the completion process making it difficult to seal both membranes and this can draw moisture into the building, damaging the insulation and promoting wood decay.

5.3 Development of an improved practical solution

The managing directors of Company A had an underlying idea of using existing connection systems in the construction market to work in conjunction with the wall panels. Initial research into the types of timber connector's available yielded a plethora of potential solutions. Each possible connector was assessed in terms of its ability to lend itself to closed panel timber frame construction and to the requirements outlined by Company A;

5.3.1 Strongtie™ Double sided timber connector

This type of connector as shown in Figure??? Is commonly used when joining timber beams or posts together. A tight joint is made between both timbers as the double sided, pre-galvainsed steel toothed plate grips the beam faces. A bolt passing through the toothed plate is tightened to ensure a firm hold is established. This type of connection however was not feasible for use with closed panel timber frames as it would have required sections of the panel to remain open to allow bolts to be inserted on-site and tightened. Having each panel completely sealed prior to site installation was a requirement put forward by Company A.

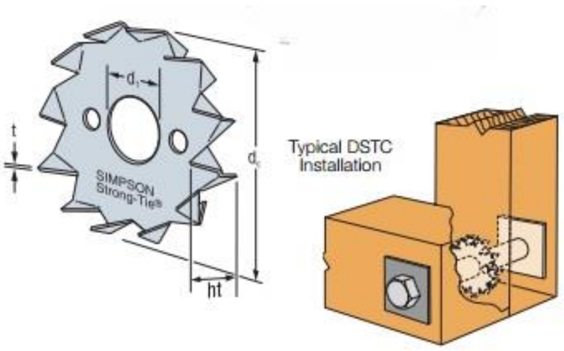

Figure 6: Strongtie™ Double sided connector

5.3.1 Timberlinx™ Connector

The Timberlinx™ connector is commonly used in the assembly of large glu-lam beams or heavy timber beam assemblys. The connection piece is inserted into the joining pieces of timber and is then tightened via a locking nut that is accessible external to the joint (Figure ???)

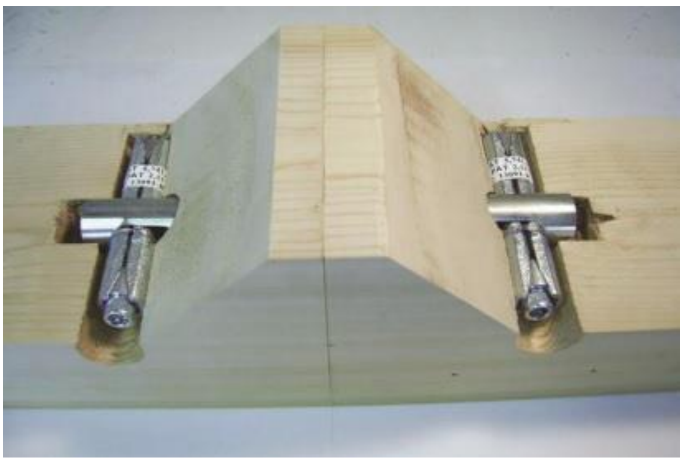

Figure 7: Timberlinx™ connector in position with external timber omitted to show locking mechanism

This type of connection suited the requirement of using a connection system that could be installed in each wall panel during the prefabrication process in the factory. The key drawback with the connection detail however was the external locking mechanism which would have required extra timber studs to house and also would have required an opening in each panel for access to tighten the connector.

5.3.2 Sherpa™ Connector

Refining the search to connection systems that would be robust enough to be fixed to the joint faces of each panel highlighted one company which has a range of fixing mechanisms for use in timber construction. Sherpa™ are an Austrian based company specializing in timber connection systems.

The Sherpa ™ Company was first established in 1995 by Austrian Vinzenz Harrer. Since then the company has expanded through research and development and now offers the world's largest 'slide-in' connection systems (Harrer, 2010). The range of connectors can support loads of 5kN to 280kN and are available in a wide selection of sizes.

Figure 44: Sherpa™ Type B Connector and its application in a scale model wall test

When determining which connector would best work in the joining of timber frame walls, the dimensions of the different connectors was a key consideration in the decision making. It was necessary to use a connector that could fit between timber frame walls, which varied from 100mm wide timber studding to 140mm wide studding, as these were the two most common sizes used by Company A. After assessing the dimensions and strength capabilities of many of the different Sherpa™ connectors available, the 'Type B' connector was selected (Figure 44).

This selection was based primarily on the dimensions of the connector with an overall width of 65mm, a length of 120mm and a depth of 20mm ensuring that the connector fitted between adjoining wall panels. According to Sherpa™, the 'Type B' connector can support a horizontal force of 12kN which is more than adequate to deal with any lateral forces applied to walls after installation (Harrer 2010). The 'Type B' connectors are typically used in the fixing of large structural members such as glue-laminated or solid timber beams and, as they are made from aluminium-alloy, there was a reduced risk of the connectors cracking or breaking under pressure.

In order to assess the connector as a method of joining timber panels, two scale sized wall panels were constructed and the 'Type B' connector was used to connect both panels together. As shown in Figure 34, the ‘Type B’ connector was a success in terms of its ease of connection and the rigidity and strength of the joint between both panels. Countersinking the connector into the end stud of the scale-sized wall ensured a rigid and close-fitting joint between the panels. Given the success of this initial trial of the connector, it was decided to continue to use the ‘Type B’ as the method of panel connection on a live construction project.

5.4 Developing a functional connection layout

Having established the most suitable connector to be used in assembling closed panel buildings, Company A wanted to pursue the application of an airtight joint that could permit the complete pre-fabrication of sealed wall panels from the factory. The Sherpa™ connector already provided a solid connection between both panels. However, in order to provide extra assurance regarding air permeability; an airtight product was needed to complete the connection detail. After assessing various options, a self-adhesive, self-expanding tape was specified to be used in conjunction with the Sherpa™ connectors.

There were two reasons for this selection. Firstly, it was essential that the completed panels remained untouched once they were positioned on-site. In this regard, affixing a tape onto the end of the completed closed panels ensured that the panels and their pre-installed vapour and breather membranes were not interfered with. Secondly, as the timber used in the construction of the panels has a tolerance level of +/- 5mm, the tape needed to be expandable in order to fill any gaps between the panels. The most suitable tape available is the Compriband TP600 impregnated joint sealing tape.

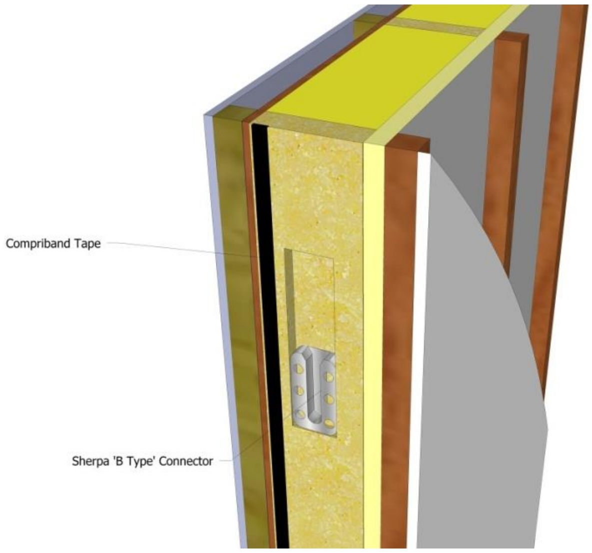

Figure 45: Layout of Sherpa 'Type B' connector and Compriband tape

This tape has British Board of Agreement testing approval and has an air permeability factor of < 0.1m³ / [h.m.(daPa)n], a U-value of 0.055 W/m/K and a 25 year life expectancy (Illbruck, 2011). The tape has an overall width of 20mm, ensuring that it can be applied beside the Sherpa™ connector on the end face of each panel. The tape can expand up to 15mm after application, filling any uneven gaps or spaces between the panels and forming an effective moisture and air tight seal. As can be seen in Figure 45, the tape was applied to the wall panel on the outside of the Sherpa™ connector. Unlike the connector however, the tape is required to be applied on-site, immediately prior to the connection of two wall panels.

With a new method of connection established, Company A began the assessment of the detail by using it on a live construction project.

5.5 Feasibility study of the connection detail on a live Project

5.5.1 Project Background:

The project required a two-storey extension to be built onto an existing two-storey house. Before construction work took place, the ground floor layout of the house consisted of a living room, sitting room, kitchen and bathroom. The first floor layout consisted of two bedrooms and an office. The house is of Georgian style and was originally constructed in the 19^{th} century. The existing bathroom and kitchen are part of an extension. It is not known when this extension was constructed., However, this type of bathroom/kitchen extension is a common feature of a house dating from the Georgian era.

The owners of the house wanted a more spacious kitchen area and also wanted an adequately sized bathroom facility. With these requirements in mind, it was decided to design a two-storey extension incorporating a kitchen on the ground floor and a bathroom on the first floor. This was deemed the best design and layout as minimal alterations to services were required and the overall footprint of the building would remain the same. Construction of the new extension required the demolition of the existing kitchen/bathroom extension. This was carried out whilst the new extension was being pre-assembled in a factory setting. As the existing extension was only connected to the ground floor, an opening was required to be formed in the first floor external wall to allow access into the new bathroom facility. This was completed during the demolition works.

Access to the rear of the property was severely restricted as it was a mid-terrace house. As Company A are a closed panel timber frame manufacturing company, the extension was to be lifted over the house panel by panel and dropped into position. Constructing the extension this way not only reduced the amount of workers and material passing through the existing building but also reduced the projected construction time by four weeks.

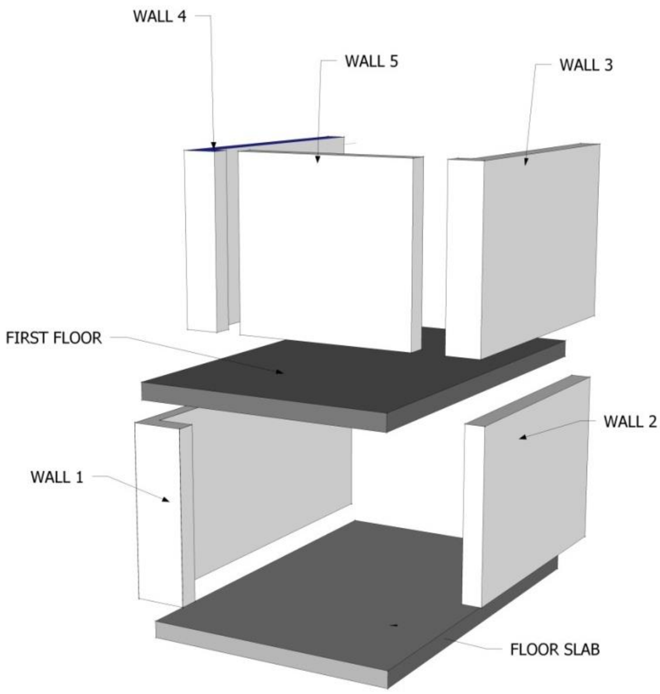

Figure 46: Exploded view of project depicting the position of each wall and floor component

5.5.2 Construction

The entire extension was pre-constructed and pre-assembled in Company A's factory before transportation to site (Figure 47). This facilitated excellent accuracy in the positional layout of floors, walls and roof elements before on-site assembly.

The construction sequence for the feasibility project was uncomplicated. The ground floor slab was the first component to be lifted into position. This was then followed by wall 1 (which had two sections) and wall 2. The first floor slab was then positioned on top of the ground floor walls before walls 3, 4 and 5 were all positioned. The final component to be dropped into place was the roof panel (refer to figure 46).

Figure 47: Complete pre-construction of project in factory setting

5.5.2.1 Foundation/Floors:

The only structural element of the project to be undertaken on site was the foundation system used to support the extension. A series of pad foundations were formed on site to support the floor slab at various positions. The ground floor slab was manufactured off site and was fabricated using steel ‘C’ section (225mm deep) and timber bridging’s. As can be seen from Figure 48, ridged insulation was placed between the timbers with 18mm ply fixed to both the underside and top surfaces.

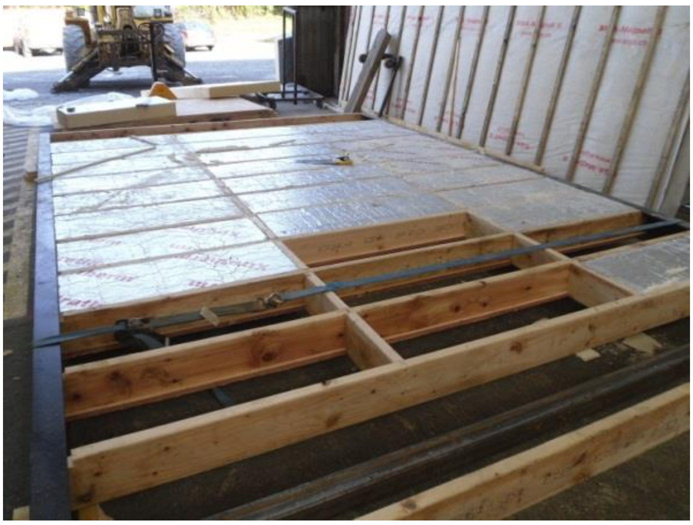

Figure 48: Image of floor slab during pre-fabrication

The first floor did not contain any steel and was instead constructed entirely from timber and matched the ground floor in dimension and was insulated using fibreglass insulation.

5.5.2.2 Walls:

There were two closed panel wall build-ups used on the construction of the extension project. The first (Figure 49) consisted of 15mm of plasterboard, a 20mm void for services, 18mm multi-foil insulation, 38mm vertical batten, 140mm vertical timber stud (containing 140mm fibreglass insulation), a 38mm external batten and an external concrete board finish. This wall build up was used for the majority of the external walls (panels 2 – 5) and has a U-Value of 0.13 W/m/K. The second wall build-up (Figure 50) was used on the ground floor of the extension along the adjoining property (wall 1). This wall was required to have less width than the other build-up to allow for an extra layer of concrete board for fire proofing requirements. The wall had a U-Value of 0.21 W/m/K with a build-up consisting of a 15mm plaster board, 20mm void for services, 3mm vapour barrier, 100mm vertical stud (containing 100mm of fibreglass insulation), a 38mm vertical batten completed with two layers of concrete board.

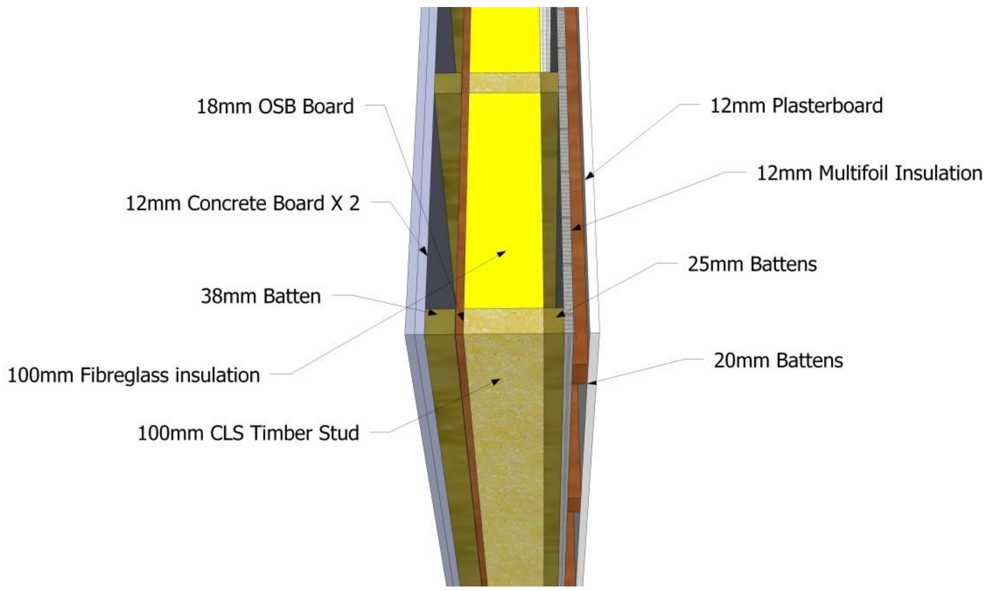

Figure 49: Section view of the build-up of the larger 140mm external wall panels

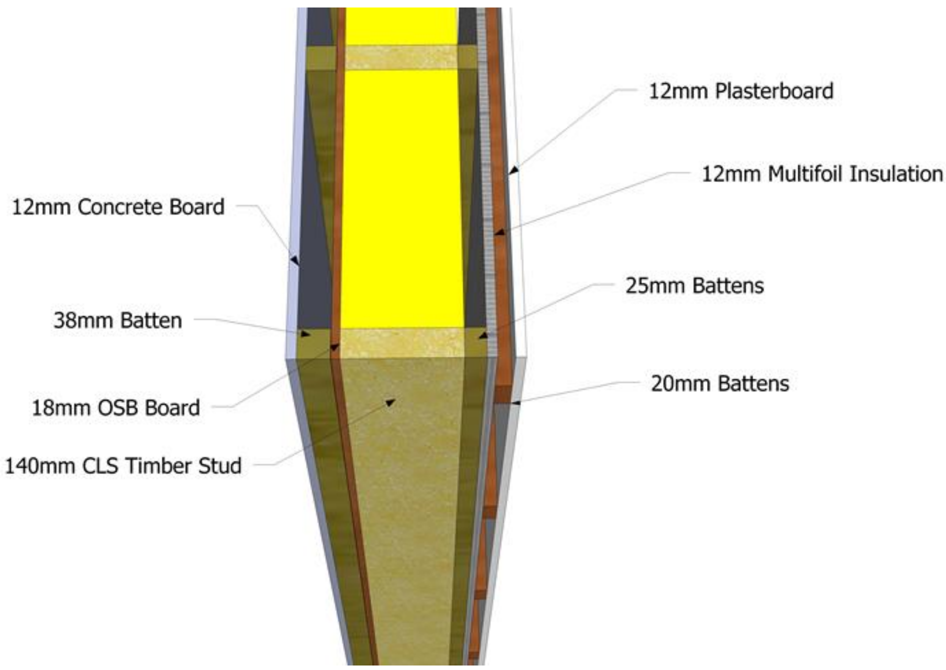

Figure 50: Section view of the build-up of the 100mm external wall

5.5.2.3 Roof:

The entire roof of the extension was also fabricated in a factory setting, allowing for exact measurements of the corresponding wall plate between the upper walls and roof to be adhered to. The roof was completely assembled from internal timber clad finish right through to external slate finish. A skylight window was also installed in the roof

Figure 51: Image of roof section during pre-fabrication

5.5.2.4 Connection details

As already outlined, Company A were satisfied and compliant with the use of the Sherpa™ 'Type B' connector. The factory based pre-assembly of the feasibility project allowed for the positions of all panel joints and dimensions to be located well in advance of arrival on site. With this aspect organised, the sequence of construction could be determined and an agreed system of use for the Sherpa™ connectors could be planned.

The Sherpa's™ were fixed onto the end studs of each wall, they were not counter-sunk into the studs as in the preliminary research phase. This adjustment was for two reasons; firstly so a visual inspection could be made of the connectors before and after installation and secondly, if the connectors did not work properly, they could be removed and the panels joined as normal. Each Sherpa was to be positioned in the centre of both the 100mm stud walls and the 140mm stud walls. This prevented the aluminium alloy connector from coming into contact with either the internal or external surfaces, avoiding a potential thermal bridge.

Rather than fix both the Sherpa™ connectors and Compriband tape to every wall panel, it was decided to use one Sherpa™ for the first wall connection and build up with the possibility of using two if they proved successful. The Compriband tape could then be used at this point to determine its suitability for the project. Smaller 'L' shaped brackets were also to be used at the base of every wall panel in order to provide a solid connection. The first use of the Sherpa™ connectors was in the joining together of two 100mm thick closed panels. Only one Sherpa™ connector was used close to the top of the wall. Using only one allowed for proper alignment of the wall and more space in terms of dropping the wall into position. The single connector acted like a guide-pin, aligning the two walls perfectly and with no connection issues (Refer to Figure 52).

Figure 52: Joint between the 100mm wall panels after positioning

Building on the first panel connection, it was decided to use two Sherpa™ connectors for the second connection joint. The positioning of the second wall went relatively as smoothly as the first as both connectors aligned with little difficulty. However it was noted that the vertical stud at the end of one of the panels had a slight concave cupping across the face of the stud, when the panels were joined together, the stud repositioned itself slightly in order for the connectors to align correctly. This adjustment of the vertical stud is due to the 'zero tolerance' joint between the connector. The term 'zero tolerance' in this context is a misnomer since in actuality all mating components are made within specified tolerances.

The components in question had very precise running fits as a result of their machining tolerances, In order for the connections to work, there must be virtually no deviation between the two meeting studs and this necessity is magnified when using two sets of the Sherpa™ connectors in a wall connection. Although no structural damage was done to the stud in the panel, the occurrence was noted for further assessment (Figure 53).

The next assessment of the connection system was to position the final wall of the structure (Figure 54). This would be the most difficult panel to drop into place as it was required to fit between two pre-positioned panels. In order to connect the panel properly, four Sherpa's™

Figure 53: Application of SHERPA connectors to positioned wall

were required to be placed on the wall before dropping into position. Placing the final wall in this way was the ultimate test of the pre-constructed building method as all three wall panels had to align precisely. Due to the level of accuracy involved, it was decided to attach one side of the final panel to an already positioned wall using two connectors and attach the other side of the final panel using one connector.

Figure 54: Image of final panel sliding into position (Compriband tape visible)

Positioning also afforded the opportunity to use the Compriband TP600 tape along with the SHERPA's. It was decided to apply the tape to both faces of the adjoining panels resulting in the tapes expanding to meet each other and provide an airtight and moisture proof joint. As had been noted with the previous wall connection, all the vertical studs were checked for defects such as warping or twisting. After passing a visual inspection, the Sherpa™ connectors were positioned on both the receiving walls and the final wall panel.

The Compriband tape was then applied to all adjoining faces; the tape does not expand immediately and so gave sufficient time to slide the panel into place. The final panel dropped into place without moving or correcting any of the vertical studs on the joining face of the panels. Given the extremely precise nature of the final wall panel positioning, the connection system proved to be very effective. After the final wall panel had been positioned, it was noted that the wall on the side of the panel where two Sherpa's™ were used, was level in both the vertical and horizontal planes. The wall on the side where one Sherpa™ was used had to be adjusted slightly to bring the panel to the correct vertical and horizontal level. This in effect showed the capacity of the connector and of its fixings to remain square and level even under the weight of the wall panel. The Compriband tape remained compressed for long enough to allow the panel to be positioned. As the walls were connected flush to each other, a complete visual inspection of the tape after installation could not be made.

5.5.2.5 Conclusion in respect of this construction method

Construction of the extension project using the Sherpa™ connectors proved to be successful and facilitated the erection of the structure in just over 9 hours. From a construction point of view, the connectors made the locating and aligning of the wall panels much easier than a traditional closed panel build. There is no doubt however, that the pre-assembly of the extension also had a large bearing on the ease of assembly on site. Using the connection details revealed more about the strength and workability of the Sherpa™ connectors. The connectors themselves offer 'zero tolerance' in terms of positioning and joining. This may prove to be troublesome in future testing as timber, by its nature, is not precisely engineered and is prone to changes in its dimensions when exposed to heat and cold. The most positive aspect of the testing proved to be in the joining of the last panel, as using two SHERPA's not only resulted in a strong joint but also adjusted the already positioned wall in the vertical and horizontal planes. This did not happen on the side where one Sherpa™ was used and is encouraging for future testing as it demonstrates the potential of the system. Although not adequately tested, the Compriband TP600 tape worked well with the Sherpa™ system.

However, its application to each panel just prior to positioning added to the overall time spent putting the panel in place as the panel had to be lowered to allow the tape to be applied and then lifted into its final position. After assessing the use of the connection detail during the extension project, the following recommendations were made for future testing:

5.5.2.6 Recommendations relating to this construction method

- Two SHERPA connectors to be used in all joints between closed panels,' this will allow the determination of whether the tolerance difference between the connector and the timber is too great to work together efficiently

- The feasibility project had been pre-constructed before arriving on-site. Not all projects will be constructed in this way and so the performance of the connection system must be monitored on projects which are assembled for the first time on-site.

Chapter 6

Further Trialling

The overall success of the application of the connectors in the feasibility project merited the carrying out of further research and testing. Company A were satisfied that the connection system offered more ease of assembly onsite and wished to use the connection detail in future projects. This allowed the research to move to a trial-testing phase in which the connection detail was applied to three separate construction projects

6.1 Trial 1; Single storey extension

6.1.1 Project Background:

This project provided the first trial test for the connection system. The end result of the project was a single storey extension to an existing two storey, mid-terrace house. Before the extension was constructed at the client's home, it was entirely pre-constructed by Company A as a showpiece home extension for a leading home exposition show. Using this marketing opportunity as effectively as possible, Company A decided to construct the client's extension for the duration of the show and to then dismantle the building before bringing it to the actual site for reconstruction. This presented an ideal opportunity to test the Sherpa™ connectors in two locations on each wall panel.

For the exposition show, Company A were instructed to assemble the extension in a designated section of the arena. Once the structure had been completed, interior designers would then decorate the interior of the extension for the weekend-long show. Following the conclusion of the expo, the extension would then be dismantled and transported to the job site and reconstructed.

 

Figure 55: Images of existing rear elevation

Trial 1 is an extension design that adds 40m² floor area onto an existing house. The extension is single storey and will be used as a new kitchen/living room. The existing ground floor layout of the house is comprised of a sitting room, kitchen/dining room, living room and utility room. The new extension will be incorporated into the kitchen/dining room area elongating the room to form a new kitchen space. The first floor comprises of three bedrooms and this layout will not be altered. As in the case of the feasibility project, demolition of an existing living room extension had to be carried out in order to create a space for the new structure (Figure 55).

The clients wanted the extension to provide them with more space and light in the existing house. In order to do this, a large sliding door was incorporated into the design along with large roof lights to allow maximum solar gain.

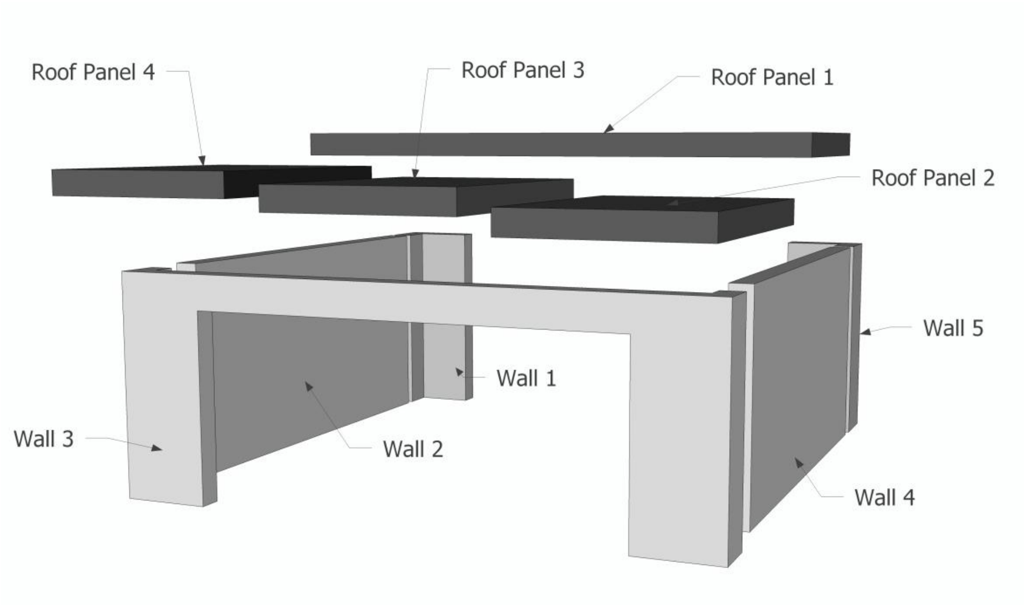

Figure 56: Exploded view of Trial 1 extension

6.1.2 Construction

Although project Trial 1 was not pre-assembled in a factory, it was first erected for the purpose of the exposition show before being re-erected at the client's home. This allowed Company A to complete a 'dry run' of the assembly so the accuracy and positioning of the wall and roof panels could be determined before arrival at the client's home (Figure 56).

6.1.2.1 Foundation:

For ease of construction, it was decided by Company A to use a traditional concrete strip foundation with a poured, reinforced concrete ground floor slab. This removed the need to construct a floor panel as part of the structure, resulting in fewer panels to transport and less time needed to construct the project in the factory. The foundation system was not needed at the expo show as the walls simply rested on a 100mm high decking which ran beneath the entire extension.

6.1.2.2 Walls:

The walls of the extension were completely fabricated for both the expo show and for the actual construction site. This meant that the structure used in the expo show contained the required levels of insulation to comply with current building regulations. The external to internal build-up of the walls (as shown in Figure 57) was; 12mm concrete board, 38mm batten, 10mm OSB board, 140mm vertical stud (containing 140mm fibreglass insulation), 25mm ridged insulation, 38mm batten, 12mm internal plasterboard.

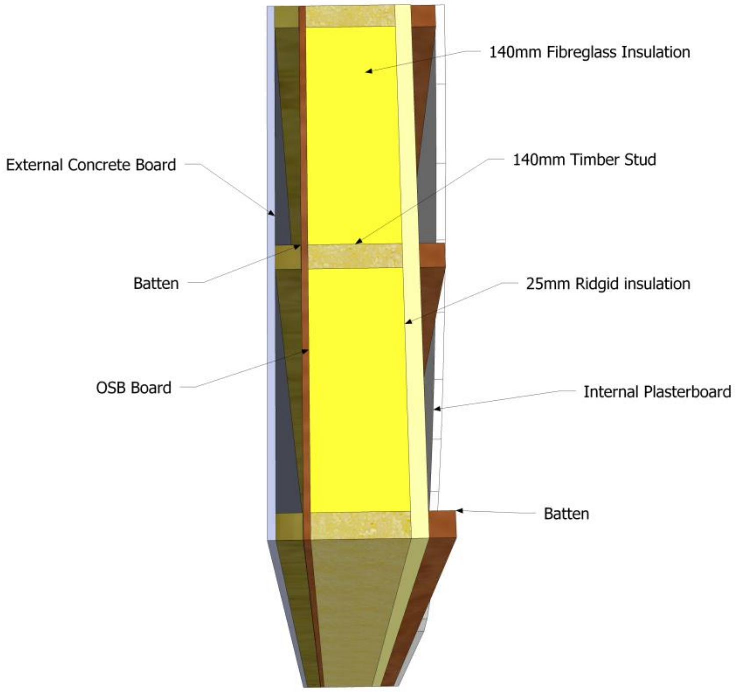

Figure 57: Section of wall showing the build-up of materials

6.1.2.3 Roof:

The roof section of Trial 1 was divided into 4 separate roof panels. For the expo show, the roof panels were not insulated and the roof was not finished externally. This reduced the weight of each panel making positioning easier. In order to support the roof, a beam was installed between wall panels 2 and 4 (Figure 56) for the expo show. This beam was made from wood and provided adequate support to the roof structure. The smaller roof panels (2, 3 and 4) were also bolted to the larger roof panel (1) to provide extra stability. Once the extension was re-erected on-site, the roof panels were bolted together in the same positions as at the expo show. The roof panels were insulated on-site and finished externally with a water proof membrane roof system.

Figure 58: Images of wall and roof panels on flat-bed truck and being lowered into position

All timber studs and joists used in walls, floors and roofs are C16 Stikka spruce cut to Canadian Lumber Standard (CLS). All timber is sourced from Irish forests. The timber was kiln dried to produce a moisture content of 14%. It is imperative to the construction process that the moisture content of the timber does not increase past 20%.

The pre-manufacture and factory assembly of Trial 1 assisted in keeping the moisture content below 20% as recommended as the timbers are kept sheltered from the elements.

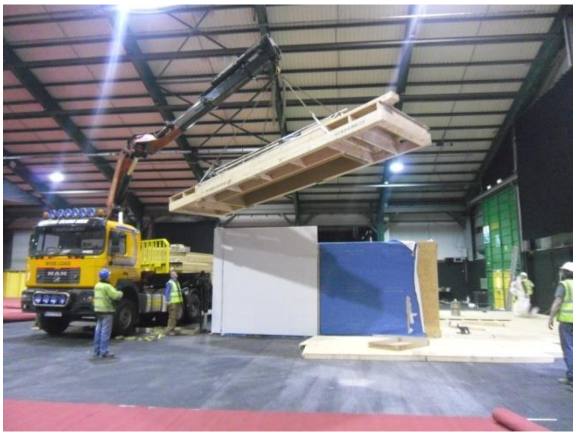

Figure 59: Images taken during the construction of the extension at the Expo show arena

6.1.2.4 Connection details:

Trial 1 was first assembled in the home expo arena (Figures 58 and 59) and because the extension was not in its final resting place, focus concentrated solely on the ease of connection between the Sherpa™ 'Type B' connectors. The Compriband tape was not used in the erection of the extension for the expo show as the structure was not permanent. Following the previous feasibility project, an addition was made to the connection detail. A single 38mm x 20mm batten was placed beside the Sherpa™ connectors, this was to ensure the connectors remained in line with each other, it also offered a means of completing a flush connection between two panels as the batten fitted neatly into the 20mm gap left by the connectors. Each wall panel had two Sherpa's™ in position, one located 400mm from the top of the panel and the second located 400mm up from the bottom.

All wall and roof panels arrived at the expo show location on the back of a flatbed truck. The truck also had a crane arm capable of lifting each panel into position. The construction sequence was straight forward; all walls were assembled as shown in Figure 56 (sequence of Wall 1 to Wall 5). The roof panels were then lifted into position in the sequence of 1 to 4.

Connecting Walls 1 and 2 together proved to be relatively simple, the Sherpa™ connectors aligned with minimal effort and Wall 2 slid into place aligning perfectly with Wall 1. The connection between wall 2 and wall 3 differed from the first connection as it was close to the corner of the large Wall 3 panel. Difficulties arose when aligning the two panels as they would not slide into each other as easy as the first connection.

The panels were separated and assessed individually. It was found that there were some dimensional differences between the adjoining faces of the wall panels. Although these differences were less than 5mm, they were still enough to prevent the connectors from joining together. A solution was provided in the shape of removing the top and bottom fixing screws from one of the Sherpa plates, this was permitted because the structure was being assembled for the expo and was not being used as a functional building. Removing both fixings allowed the SHERPA to pivot slightly in order for a smooth connection to be established.

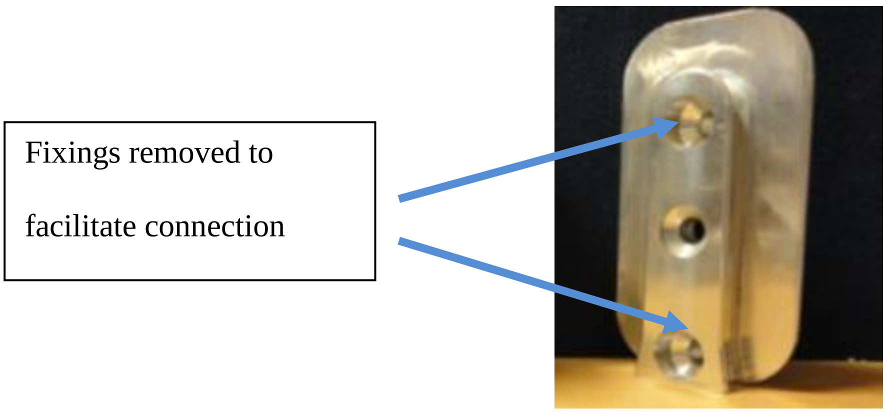

Figure 60: Image of Sherpa indicating fixing points

The difficulty in connecting Wall 2 and 3 demonstrated the 'zero tolerance' manufacturing of the Sherpa™ connectors. More accurately, the components are made to such a close tolerance that aligning them becomes problematic when there is a build-up in misalignment as successive walls are joined.

In contrast with this, the timber was not cut to the same precise tolerance and so prevented the connection becoming perfectly aligned. The connection between Wall 1 and Wall 2 proved successful because the joint was straight forward between two small wall panels. Difficulties arose in the connection of Wall 2 and 3 partly because of the size of Wall 3 and an inability to manoeuvre it with ease.

Difficulties arose again in the connection of Wall 3 to Wall 4 as once more, the connectors misaligned by millimetres preventing a clean connection. The same solution of removing the top and bottom fixings on the Sherpa™ connector was adapted and the panels slotted together with ease. The final connection of Wall 4 to Wall 5 proceeded without the need to make any adjustments to this connection, which was much like the one between Wall 1 and 2, a joint between smaller walls which could be easily adjusted during alignment. Construction of the roof panels proceeded without any hindrance as each panel slotted into the pre-designed positions with ease. In total it took 4 hours to construct the extension at the expo show arena.

6.1.3 De-construction

In order to complete the extension for the expo show, the internal layer of plaster board was skimmed and painted by the interior decorator. The plasterboard was the only material removed and disgarded during the de-construction phase. The entire extension was seperated in the reverse order to that it had been assembled in. The dis-assembly of the building took place without any damage being caused to any of the wall panels; this demonstrated a hidden potential of the connection system in terms of the ability to dis-assemble with minmal difficulty. The entire extension was then brought back to the factory in which is was pre-fabricated. Whilst in the factory, steel supporting columns were installed in Wall 2 and 4 to support the steel beam which was to be used in the assembly of the extension on-site.

6.1.3 Re-assembly

Two weeks after the disassembly of Trial 1, the wall and roof panels were once again mobilized to site. This time it was to the final resting place of the extension. As already mentioned, a concrete floor slab had been installed at the property. Due to restricted access, a mobile crane was used to drop all wall and roof panels into position (Figures 61 and 62).

Figure 61: Site at rear of property before erection of extension

The extension was erected in the exact same sequence as it had been in the RDS arena. Given the difficulties that were encountered with the connectors during the first assembly it was decided to not use the Comprband tape in the event the wall panels did not fit correctly. The joint between each panel was sealed traditionally by lapping the internal vapour barrier and external breather membrane. As with the first erection of the structure, Wall 1 and 2 connected together easily, however the joint between Wall 2 and 3 proved difficult but, with persistance, the wall panels slid into position.

Figure 62: Images of Trial 1 being installed on-site

Unlike the expo show assembly, the fixings in the Sherpa's™ were not removed and so a solid connection between the panels was maintained. Difficulty again arose when connecting Wall 3 to Wall 4 but the connection was eventually made. Once the wall structure was in place, the steel supporting beam for the roof was installed and the corresponding roof panels were dropped into place. From start to finish assembly took six hours to complete, the extra time taken, when compared to the first assembly, mostly related to the positioning and fixing of the steel element of the structure, however a significant amount of time was taken up aligning the two connections involving Wall 3 (Figure 63).

Figure 63: Image of the completed extension in position

The completion of Trial 1 demonstrated that the connection detail, although it provides a structurally solid connection between panels, has development issues in terms of the difference in accuracy between the connectors and the timber used in wall pre-fabrication. Assessing the findings of Trial 1, the following recommendations are made for Trial 2:

6.1.4 Recommendations

- Alignment of the connectors is of key importance. The next trial should ensure all connectors are set in each wall with precise alignment and will slide into each other without hindrance.

- The next project should include the Compriband strip between each joint to determine its compatibility with the connectors

Trial 2 Single storey extension

6.2 Project Background

Compared with Trial 1, Trial 2 was a relatively straight forward construction process. The project involved the pre-fabrication and construction of a one-room, single storey extension approximately 21M² in area. Unlike the previous two projects, there was no-preassembly of Trial 2 before bringing to site and so dimensions and panel positions were of utmost importance to ensure a fast construction time (refer to Figure 64).

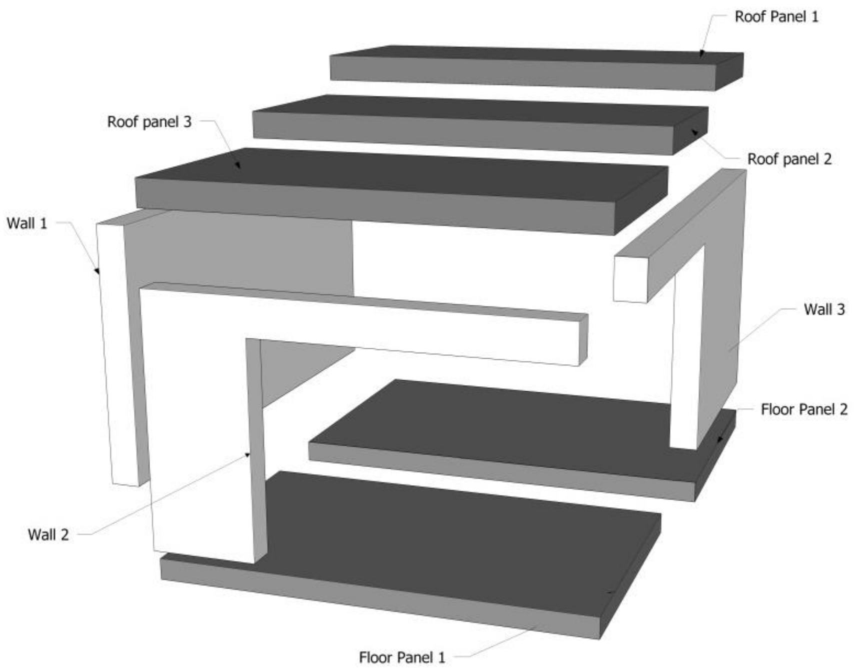

Figure 64: Exploded view of Trial 2

The existing house had recently been acquired by the project clients and they wanted to construct the extension to their new home before moving into the property. The purpose of the extension was to add more space and light to the existing living/sitting room of the house. Given that the project is roughly half of the permitted extension area ($40M^2$) it was important to the clients to utilise as much light as possible and so a large corner door/window and skylights were incorporated into the design. In conjunction with this the entire rear garden of the property was to be completely re-designed and landscaped. It was the clients wish to have this done prior to the erection of the extension leaving the extension as the final piece of the garden upgrade (refer to Figures 65 and 66).

Figure 65: Rear of house prior to extension

Figure 86 Images showing footprint of building before installation and positioning of ground floor slab

6.2.1 Construction

The on-site assembly of Trial 2 was a slight change in routine for Company A as up until now, every extension had been pre-assembled before arrival at the construction site. Once again, due to restriction of access, the entire extension was lifted into position via crane (refer to Figure 67). In total there were three wall panels and three roof panels.

Figure 67: Images showing footprint of building before installation and positioning of ground floor slab

6.2.1.1 Foundation:

Trial 2 was quite similar to the first feasibility project in regards to limited access to the rear garden. To resolve this issue it was decided by Company A to fabricate ground floor panels in the exact same manner as the feasibility project. This also helped alleviate another potential problem which was matching the floor height in the new extension to the existing finished floor level in the house. A series of pad foundations were installed at the site prior to the arrival of the floor panels. The pads were formed at a correct level accounting for the depth of the floor slab and ensuring the new floor level matched that of the old.

The floor slab was once again constructed using 225 ‘C’ section steel; however Trial 2’s ground floor was made in two sections to allow easier manoeuvering of the floor during onsite installation.

6.2.1.2 Walls

The wall build-up for Trial 2 was exactly the same as used in Trial 1, The external to internal build-up of the walls (as shown in figure 68 was; 12mm concrete board, 38mm batten, 10mm OSB board, 140mm vertical stud (containing 140mm fibreglass insulation), 25mm ridged insulation, 38mm batten, 12mm internal plasterboard.

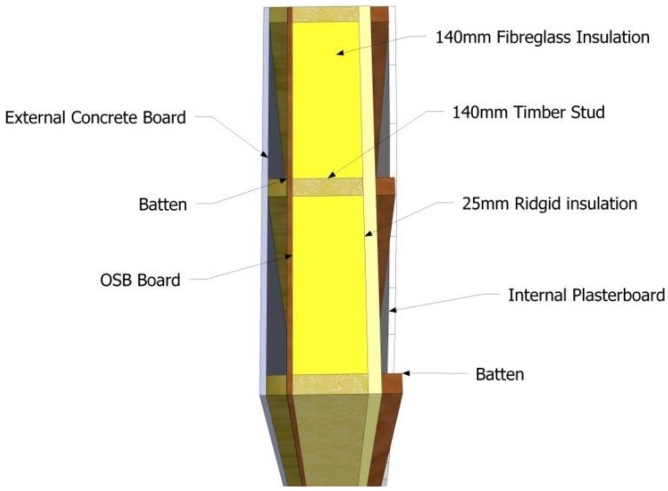

Figure 68: Section of wall showing build up

6.2.1.3 Roof

Figure 69: Images showing the fall in each roof panel and also installation of the panels on-site

The roof of Trial 2 was pre-fabricated in 3 sections. The roof spanned between Wall 1 and 3 with an overhang of 300 on the clients side of the extension. The roof was constructed with a fall already in place so all rain water would run from the left to the right side of the extension and into a designated drainage channel, also a large skylight was positioned in the roof structure to increase the light infiltration into the existing house. Once installed, the roof was finished in a zinc effect roofing material (Refer to Figure 69).

6.2.1.4 Connection Details

Although there had to be adjustments made to the connection details in Trial 1, it was decided to use the Sherpa™ 'Type B' connectors once again for Trial 2 (refer to Figure 70). Attention to detail at pre-fabrication stage was paramount to ensure the connectors would go together and not be prevented from sliding into place by slight dimensional inaccuracy. In reality, there was only one complete large joint between wall panels in the project. This was between Wall 1 and Wall 2 as the joint between Wall 2 and 3 was only above the large corner door.

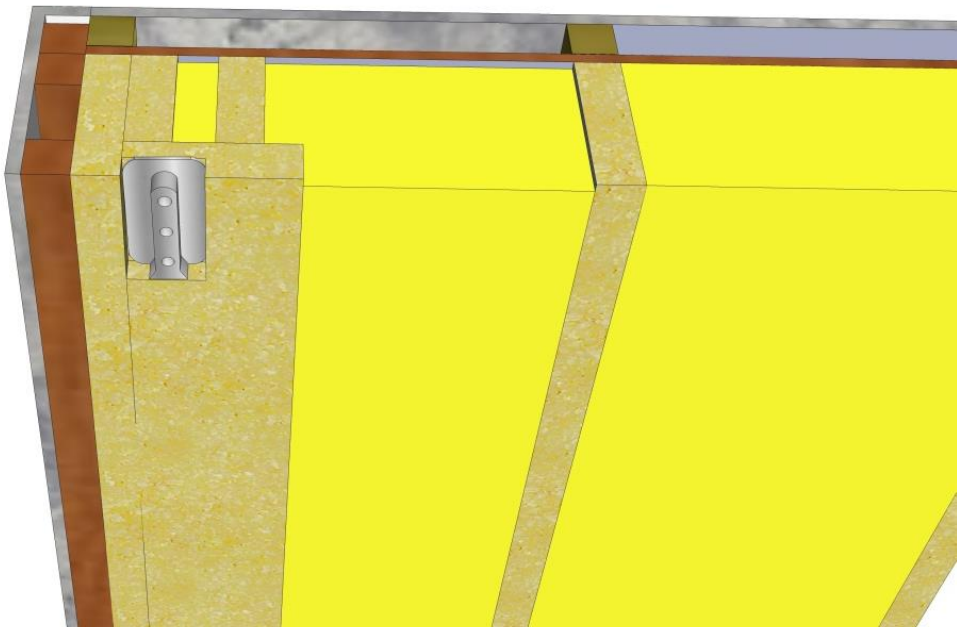

Figure 70: Detail showing the counter sunk position of the SHERPA connector

As reccomended in the previous project, the use of the Compriband tape was re-introduced to determine how suitable the tape would be for use in this connection system. The tape was also used in the joint between the extension walls and the existing house, this was in order to offer extra protection against potentail moisture intrusion at those particular joints. In terms of the joint between the wall panels, the Sherpa™ connectors were counter sunk into the vertical studs (Figure 70), this provided a close connection between both wall panel faces. In order to develop the connection detail further, the external breather membrane was wrapped around the end of each wall panel; the Compriband tape was then installed in line with the outside edge of the vertical stud as seen in Figure 71. This detail was also used when connecting Wall 1 and 3 to the existing building.

Figure 71: Image of end detail of Wall 1 before being positioned. The external breather membrane (green) is wrapped and taped on the inside of the wall (yellow) before the addition of the Compriband strip

Applying the Compriband tape in the location shown effectively means the continuation of the external membrane and also ensures the joint between the existing building and wall panels is moisture proof and airtight. The same principal can also be applied when connecting two wall panels together, for Trial 2, this could only be properly tested in the joint between Wall 1 and Wall 2. As can be seen in Figure 71, the external membrane is wrapped around to the end face of the wall before being taped into position; the Compriband tape is then applied to provide an effective seal between both breather membranes. As can be seen from Figure 72, the Sherpa™ connector is counter sunk in position at the top of the wall panel. This positional change was to effectively guide the wall and ensure that both the Sherpa™ at the top and bottom of the wall connected properly

Figure 72: Installation of Compriband tape after the external breather membrane has been taped to the end stud

One single Sherpa™ connector was installed on the much smaller connection between Wall 2 and Wall 3. As Wall 2 was the last panel to be positioned, it was paramount that all the Sherpa™ connectors joined in cohesion with each other. As Wall 2 was lowered into position, it was noted that the connectors, although perfectly aligned, were not fitting together correctly. After assessing both corner joints it was determined that the connectors simply afforded too little tolerance in the connection sequence. For ease of construction, the

Sherpa™ connector used in the smaller connection between Wall 2 and 3 was removed completely. This allowed Wall 1 and 2 to connect with minimal disruption. The connection between Wall 2 and 3 was then secured with a traditional screwed connection method

Following the completion of Trial 2 the following recommendations were put forward to improve the connection detail for trial 3:

6.2.2 Recommendations

- The Sherpa™ type B connector does not offer sufficient room to manoeuuver before a solid connection is formed. It is therefore necessary to opt for a connector which allows more movement and opportunity for alignment before the wall panels connect properly
- More emphasis should be made in future projects on the continuation of both the external breather membrane and the internal vapour barrier. These are critical elements of the detail and will be of particular importance in the development of a pre-fabricated system
- An alternative to the Compriband tape should be sought. Due to its nature, the tape can only be put in place prior to installation of each wall panel. This adds delay to the placing of each panel as the tape cannot be factory fitted.

6.3 Assessment of Trial 1 and Trial 2

After the completion of both Trial 1 and Trial 2 it had become apparent that the connection detail utilised had both positive and negative qualities. Without question the detail improved the construction capabilities of Company A and permitted the complete pre-fabrication of closed panel timber frame walls in the factory before transition to site. However, it also became apparent that the dimensional differences between the timber frame wall panels and the engineered Sherpa™ connectors were proving troublesome. This was particularly evident in Trial 2 as a connection point had to be removed in order for the project to be completed.

From the outset, Company A not only wanted to develop a method of completing closed panels before arrival to site but also wanted to ensure that this method did not add extra time to both the pre-fabrication and assembly stages of each project. The Sherpa™ connectors required very little extra work in their application to the wall panels in the factory. Production drawings given to the fabricators highlighted where each Sherpa™ piece was to be positioned on each wall. As previously highlighted in Figure 34, the factory areas marked 3 and 4 now became the areas in which extra fabrication could take place.

In Area 3, the wall panel could now be fully insulated and the internal vapour barrier could now be extended to cover the entire wall. Similarly, in Area 4, the external breather membrane could now cover the entire wall rather than being left open at both ends. Area 4 was also the point at which the Sherpa™ connectors were fixed to each panel as the panels were in the vertical position which facilitated in correct dimensioning and alignment. The ability to now fully complete each wall panel and install a connector did not add any extra time onto the fabrication of each panel. On average, it still took one hour to complete a wall panel from start to finish. This is largely because the extra times for the elements of fabrication such as the insulation were small and kept in sequence with the standard fabrication of each panel.

Prior to positioning on-site, the Compriband tape was applied to the external face of each wall joint; the tape does not expand immediately and so gave sufficient time to slide the panel into place. A mobile crane was used to ease the panel down into position and allow the Sherpa™ connectors to slide together forming a solid connection. During the construction of Trial 1 and 2 however, it was noted that the dimensional tolerances of the Sherpa™ were understandably far tighter than those for the timber and, as a result, issues began to arise when connecting larger panels together. The Sherpa™ connector has a tolerance of 0.5mm on critical dimensions, making them extremely accurate and providing a rigid connection when joined. In contrast, the timber used by the company was standard CLS Sitka Spruce which is commonly used in timber frame construction. The timber has a tolerance of +/- 3-4mm and this dimensional difference led to on-site assembly problems for both projects.

6.3.1 Trial 1 Conclusion

Trial 1 presented the unique opportunity of carrying out a complete construction, dis-assembly and re-assembly of a 40m² home extension. The connection details played a large part in terms of retaining the fabric of the building and ensuring minimal damage was caused during both construction processes. As this project was the second time of using the Sherpa™ type B connectors, there was a keen interest to see if they could function to the best of their ability during the erection of the extension at the expo show. Ultimately the details proved to be difficult to connect even with a guide batten attached to the end of each panel. As highlighted earlier, Wall 3 was the largest of all the wall panels and so was the most difficult to connect as the sheer size and weight of the wall prevented manoeuvring during positioning. This difficulty was repeated again during the erection of the extension on site. Although Wall 3 was large, future projects will contain similar size wall panels and so the incompatibility of the Sherpa's™ during Trial 1 was a concern for the progression of the detail. It is obvious that the precision of the connectors does not correlate with the level of precision used to cut the timber studs and this is a problem that will face every extension fabricated using CLS timber.

The positive outcome to be taken from Trial 1 is the execution of a complete construction, disassembly and re-assembly. The connectors allowed for an easy dis-assemble without any snags. Also a further positive is undoubtedly the time taken to construct the extension each time was relatively short including the time taken to align the connectors properly.

6.3.2 Trial 2 Conclusion

Trial 2 allowed for further development of the connection detail with particular focus being placed on the continuation of the external breather membrane in a typical closed panel timber frame build as recommended from Trial 1. This element of the detail is crucial as in order to develop a self-contained panel system, both the external membrane and internal vapour barrier must perform to the same standard at the joints in a typical project. The Compriband tape has the capabilities and the design features to ensure the continuation of an airtight and moisture proof barrier but the tape cannot be seen when the panels are joined and therefore its effectiveness cannot be fully proven. A second issue relating to the Compriband tape is the expansion time associated with the product. Once the tape is applied, it will expand from 5mm to 20mm in roughly 180 seconds. This is not an issue when the wall panels align and are completed before the tape fully expands however, in cases where the connecting of the panels is delayed due to misaligning connection pieces the tape can fully expand. This raises the issue of the tape remaining intact once the panels are connected as a visual inspection cannot be made.

The on-site assembly process of Trial 2 also provided similar connection issues as Trial 1 for Company A. The difference in dimensional accuracy between the connectors and the timber caused delays to the connection sequence of the project. Unlike Trial 1 however, the inaccuracy could not be alleviated by removing screws from the connectors. Instead, for one connection point, the entire Sherpa™ connector was removed and the wall panels were joined in the traditional nailed method.

The failure of this connection may not only be due to the Sherpa™ detail. Assessing the assembly sequence of the project suggests than rearranging the order of panel connections may have allowed the entire extension to fit correctly. As the Sherpa™ was removed from the smaller connection point between panels 2 and 3 after the installation of panel 1, assembling in the reverse order and establishing a solid connection between panels 2 and 3 first may have permitted the completion of the project without the need to remove any Sherpa™ connectors.

While connection difficulties were evident during both trials, this did not apply to all wall joints with a number of panels connecting together as designed. Although connecting each wall together in this manner took longer than the traditional approach there was no delay or extra time needed to complete the external and internal sides of the joint. With this in mind, the use of the connection system still held merit for Company A and they were still keen to pursue its application. Trial 1 and 2 had proven to be extremely insightful and worthwhile in the testing and assessment of the performance of the connection detail. Both trials gave a clear indication that the detail needed to be reassessed and potentially changed to take into account the dimensional inaccuracies between both the timber and aluminium-alloy materials.

Chapter 7

Re-development of Connection Detail

7.1 Lessons learned from using connectors

The difficulties brought to light by Trial 1 and 2 were assessed systematically after the completion of each project. Key facets of information such as workers opinions and management viewpoints were considered in analysing the problems on-site and progressing to a solution. An internal focus group was held in order to gather the opinions of all parties. The workers felt that the connection system was worthwhile in pursuing further as, where successful joints were made; they had saved time during the assembly process on-site and had also not added any time onto the manufacture of the wall panels.

Additionally, using the connectors allowed the prefabricators to complete each wall entirely on the factory floor and this, in their opinion, offered more certainty in terms of the integrity of the structure compared with carrying out the work on-site. In conjunction with this, the majority of the workforce highlighted that a looser fitting connector or one that afforded more tolerance before the point of locking should be sourced and used. Company management supported workers' opinion and expressed an interest in using connectors that allowed more movement before joining. Management also felt that the Compriband tape sealant exhibited too much variation in its positioning when installed and should be removed from the on-site connection sequence.

7.2 W8 Connector

With the viewpoints of both management and workers taken into consideration, an improvement to the connection system was sourced. After consultation with the Sherpa™

Company, the Sherpa™ 'Type B' connectors were replaced with Sherpa™ 'W8' connectors after appraising a number of different 'off the shelf' connectors available. (Refer to Fig. 73).

Although manufactured by the same company, the 'W8' connector offered more movement and tolerance before locking into position. Similar to the 'Type B' connectors, W8 connectors could be screw-fixed to each timber wall panel but with dimensions of 80mm x 65mm x 20mm deep, the W8 connectors were smaller than the connectors used on previous projects.

Figure 73: W8 connectors selected for re-development of connection detail

7.3 EPDM rubber

Removing the Compriband tape from the detail required the introduction of a robust and effective material which could maintain the same level of air-tightness and moisture proofing as the tape. An Ethylene Propylene Diene Monomer (EPDM) rubber sealant was deemed the most suitable material to use. Specifically, a self-adhesive 'D' profile EPDM strip was sourced and used as part of the connection detail. EPDM rubber is a robust material and offers excellent resistance to moisture penetration (Eriks, 2013). In terms of the connection detail, two strips of EPDM were applied with one each side of a Sherpa™ connector. This gives a compression seal when two panels were connected together.

7.4 Stud Arrangement

As a further aspect of the details use, Company A required an assessment of the thermal performance of the connection to ensure the detail performed similarly if not better between closed panels than a traditional joint. This led to additional consultation with the factory workers. They were asked how the joint could be made more thermally efficient whilst keeping its strength and accommodating the connectors. The fabricators were mostly concerned about ensuring the strength of each panel, particularly at the connection points. The insertion of additional insulation at each connection point would be the main catalyst for a reduction of thermal transmittance. Working with the fabricators, a stud layout to be used at corner joints was eventually arrived at which provided strength and support of the wall panel, accurate positioning of each connector and allowed insulation to be inserted precisely into the corners of the building. Figure 74 shows the development of the arrangement of vertical studs in the wall at a corner joint.

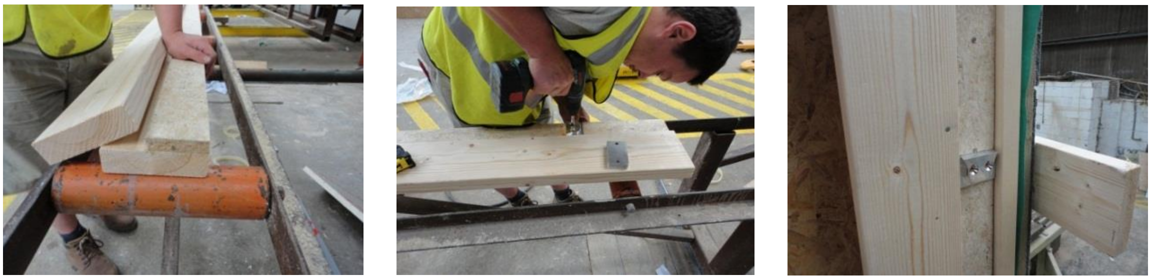

Figure 74: Images showing the new arrangement of the wall studs

The arrangement of the vertical studs was quite simple. A void or channel was created for the Sherpa™ connector by stepping two lengths of CLS timber 80mm apart. The studs were fixed in position at both the top and bottom rail ensuring a structurally stable configuration.

The Sherpa's were then supported from behind by a 20mm thick length of OSB board. The Connector and the OSB board combined resulted in a flush finish between the Sherpa™ and the end stud of the wall. Having the studs arranged in this way resulted in a void being created behind the connection point. This void could be filled with insulation to help improve the thermal performance of the detail. The channel created by the joists accommodated the connector ensuring that both were in alignment along the vertical face of the wall. At each side of the channel the EPDM rubber strips were attached which were compressed to form a seal once two panels were joined together.

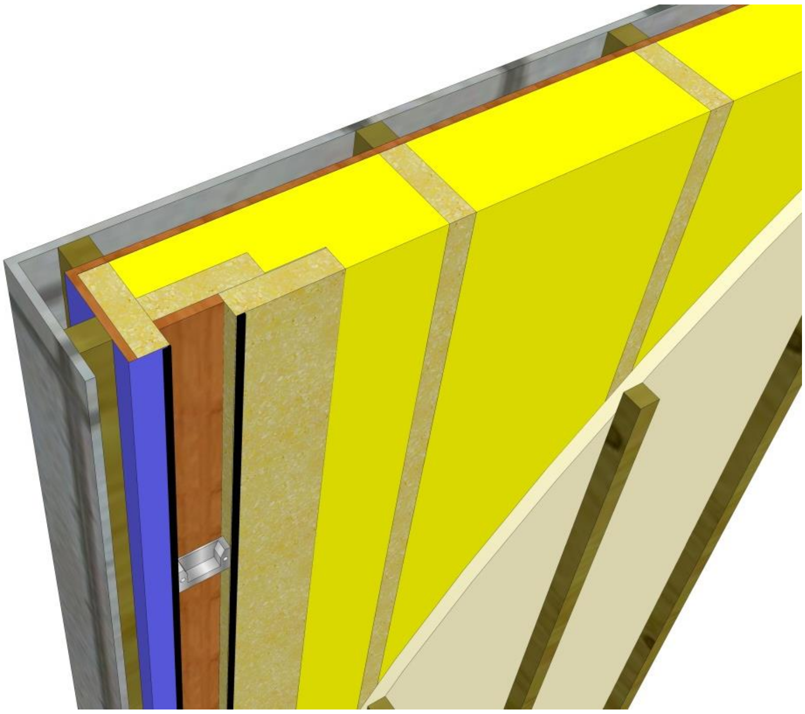

Figure 75: 3D model of stud layout of new connection

The space behind the studs can then be filled with insulation for improved thermal efficiency (refer to Figure 75).

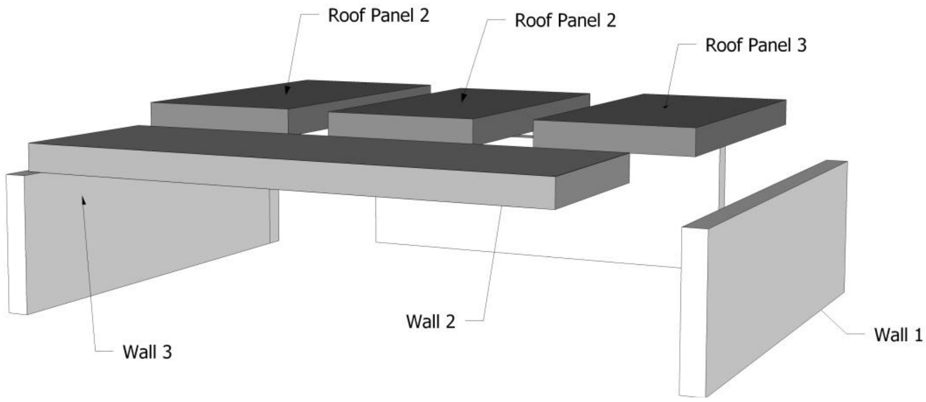

Figure 76: Exploded view of Trial 3

Constructing the panels in the factory proceeded to the same timeline as before. The simplicity of the new stud layout ensured the frame of each wall panel could be fabricated in line with the production of regular layouts. Following fabrication, OSB board, insulation and breather membranes could be applied in the same manner as the Trial 1 and 2 projects resulting in completed wall panels. As before, the Sherpa™ connectors could be attached at Stage 4 of production and the self-adhesive EPDM rubber strips could also be attached at this stage. The addition of the connectors and EPDM strips at the production stage resulted in the complete pre-manufacture of each panel taking place off-site with only the positioning and connecting of each panel to be carried out on-site.

7.5 Trial 3: Single Storey Extension

A third construction project, Trial 3, was to be used for testing the new connection detail in terms of its ease of prefabrication and assembly. The project was similar in size to Trial 1 and 2.

7.5.1 Project Background

Trial 3 involved the pre-fabrication and construction of a 40m² rear house extension. Continuing from previous projects, the extension was built using closed panel timber frame construction. The extension incorporated a living room and utility room. The extension was also designed to allow more light into the existing house and this was achieved by the inclusion of a large skylight and entrance door.

7.5.2 Construction

Similar to Trial 2, Trial 3 consisted of 3 wall panels and 3 roof panels. Before work could begin, an assembly position of the panels was agreed, as can be seen from Figure 76, Wall A was to be positioned first, then followed by Wall B and then Wall C. Once the walls were positioned, Roof Panels 1, 2, 3 and 4 were then to be positioned. All wall and roof panels were installed by crane which required an efficient assembly sequence as there was very little room at the building site. In order to reduce time spent on site, each wall and roof panel were manufactured off-site in a factory setting. The floor of the structure was the only component to be installed in-situ. Company A decided to install the floor in this manner to reduce the amount of panels required to be positioned by crane and to also to ensure a solid base and associated drainage pipe runs were in place prior to arrival of the structure. Given the limited space available at the premises, having the floor installed provided a footprint of where the building was to be positioned and gave insight into its impact on the existing house.

7.5.2.1 Foundations

Standard strip foundations were put in place before the on-site installation of the ground floor. The floor installed was a typical wooden floor with joists spanning from two outer strip foundations to a central strip foundation. Ridged insulation was then placed between the joists and the entire floor was then covered with 18mm OSB board. As already stated, the panels were lifted over the building to be positioned at the rear whilst access for workers was directly through the building.

7.5.2.2 Walls

The build-up of the external walls was the same as used in Trial 1 and Trial 2. The external to internal build-up of the walls (as shown in Figure 77) was; 12mm concrete board, 38mm batten, 10mm OSB board, 140mm vertical stud (containing 140mm fibreglass insulation), 25mm ridged insulation, 38mm batten and 12mm internal plasterboard. The total U-Value of the wall was 0.21W/m²K

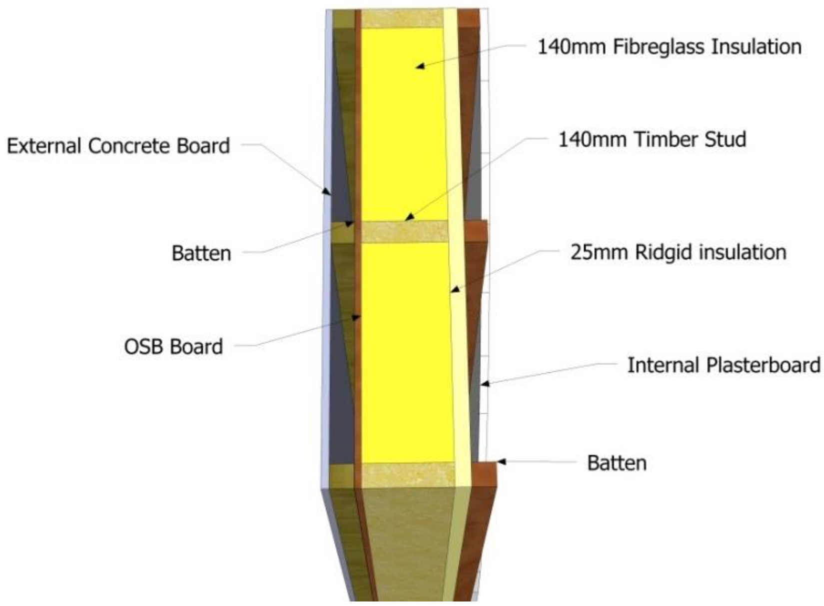

Figure 77: Section of wall build-up

7.5.2.3 Roof

The Trial 3 roof consisted of 4 sections with one of the roof panels containing a large skylight. The panels rested on the external walls with a steel support spanning across the building for extra stability. Insulation was inserted into the roof after assembly of the extension.

7.5.2.4 Sequence of installation

Given the cramped conditions at the front of the house and at the rear, the positioning of the crane was extremely important. Correct positioning ensured that the crane could lift panels off a flatbed truck into position on site. The cranes position was also important in ensuring no damage was done to the surrounding buildings, both by the panels and by the crane itself. Before lifting commenced, the area of existing wall where wall panels A and C would join the house had to be prepared. A self-adhesive bitumous tape was attached to the wall to provide a clean joint. A self-adhesive EPDM rubber 'D' seal was then applied to the bitumous tape in order to achieve an effective air and moisture seal between the old and new building (Figure 78). The external side of this joint was then plastered as part of the external finish and the internal joint was covered with the internal vapour membrane, plasterboard and then skimmed.

Figure 78: Bituminous layer with EPDM sealant between new and old building

7.5.2.5 Wall 1 to Wall 2 Connection

Wall 1 was lifted into position first. Strong winds prevented the panel from being lifted and positioned quickly. However, after careful direction, the panel was slotted neatly into its position. The panel was then squared and levelled before being fixed to the existing external wall. Wall 2 was then lifted and swung into position for alignment with Wall 1. Wall 1 contained the revised arrangement of the Stud layout and Sherpa™ 'W8' connector and Wall 2 contained the matching 'W8' connector. Wall 2 was positioned above wall one and slowly lowered to allow both Sherpa's™ to connect. The connector located at the bottom of the wall fitted together with relative ease and, after some minor adjusting of both wall panels by the assembly crew, the top connector also aligned and a solid connection was established between both panels. The precision of the joint is not to be underrated as the positioning of the Sherpa's™ both in the vertical and horizontal planes was carried out with less than 1mm tolerance. The 'W8' connectors offered much more movement during assembly when compared with the previously used 'Type B' connector. A visual inspection of the EPDM strips could be maintained right up to the point of connection due to the tolerance allowed by the W8 connector, this ensures a continuous vapour barrier was maintained between both wall panels. (Refer to Figure 79).

7.5.2.6 Wall 2 to Wall 3 Connection

The connection detail between Wall 2 and Wall 3 was originally designed to be the exactly as the Wall 1 to Wall 2 connection. However, an error in calculating the length of wall 3 resulted in the panel being unable to fit properly on the pre-installed floor. As a result, the connection detail between panel B and C had to be altered. The connecting end of Wall 3 was cut in order to fit around Wall 2, as a consequence to this, the Sherpa™ connectors and EPDM Rubbers were not used. After this adjustment Wall 3 fitted perfectly between Wall 2 and the existing building and completed the wall section of the extension. After the positioning of the walls, the roof sections were dropped into place to complete the buildings structure. Due to the cramped conditions, turbulent weather and necessary readjustment to the structure, the assembly time of Trial 3 took 5 hours.

Figure 79: Image of connector and EPDM rubber strips in position prior to joining Wall 1 and 2

7.6 Assessment of Trial 3

The W8 connectors offered more movement before a solid connection was formed and so it was expected that the panels would fit together with greater ease than in previous projects. Site assembly of Trial 3 was successful in terms of achieving an accurate alignment and joining of the Sherpa™ 'W8' connectors. Time and care was taken when craning each wall into position in order to ensure the connectors fitted together and the EPDM rubbers remained intact. The extra tolerance afforded by the new connectors made the positioning of each wall easier before becoming locked in place. This allowed small adjustments to be made to the position of each wall while the walls were held millimetres above their final resting places. This was not the case with the previous connectors which led to their on-site adjustment. The extra tolerance provided by the connectors also benefitted the appraisal of the EPDM rubbers as a visual inspection of their location and condition could be made up to the point of the connectors locking together.

Although the re-developed Sherpa™ connection only took place at one connection point in Trial 3, the feasibility and functionality in its application were evident. The ease of use and seamless incorporation in both manufacturing and assembly demonstrated the connection detail was a success and has the potential to be adopted by Company A into its whole stream assembly process.

Chapter 8

Thermal Performance Assessment of Connection detail

Company A were satisfied from the perspective of ease of assembly with the arrangement and layout of the connection detail as it was applied in Trial 3. However, in order to accurately and thoroughly assess the detail, it was necessary to evaluate both the thermal and structural performance of the connection between two closed panel timber frame walls. This resulted in the need to carry out live testing and computer simulations of the connection detail. The simulations of the tests related to the assessment of the detail using thermal evaluation software and the live testing related to structural integrity tests under laboratory conditions.

8.1 Thermal Assessment

The thermals assessment of the application of the connection detail followed two strands of assessment; firstly, a thermo-graphic survey and secondly, a computer simulated thermal performance of the connection detail. Given the fact that all four construction projects were private projects, access to each project in order to carry out a thermo-graphic survey was restrictive. Ultimately access could only be gained to Trial 1 and Trial 2 which utilised the initial 'Type B' connector. Access could not be gained to Trial 3 and so a thermo-graphic survey of the re-developed connection detail could not be carried out.

8.1.1 Thermal performance of buildings

A thermo-graphic survey studies the thermal performance of a building. In simple terms; it is the highlighting of any thermal bridges or air leakages in a building which are contributing to a loss of heat and energy. When there is a temperature difference between the inside and outside of a building, heat flows through walls, doors, windows and through any gaps in the fabric of the structure. The resistance to such heat flow is dependent on the materials used to construct the building. Materials such as concrete and brick offer poor resistance to heat flow and so require to be used in tandem with insulation. Timber and mineral fibre offer better resistance, however materials that can trap pockets of air in their fabric are better insulators.

Air layers are an important consideration in a thermo-graphic survey. Where there is little or no air movement, a still layer of air adjacent to the structure acts as in insulator. This layer of air is known as the boundary layer and can cause differences in surface temperatures during a thermo-graphic survey. In cases where there is wind movement, such as when surveying the outside of a building, the boundary layer is diminished leaving the building surface at an ambient temperature. Thermal imaging can detect faults or variations in the conductivity of many components in buildings; however both skill and knowledge are needed to properly assess surveys and to differentiate between various material layers.

8.2 The Thermographic survey

A thermographic survey of a building is carried out by using an infra-red camera. There are two basic methods used to carry out a survey, they are:

8.2.1 Qualitative approach:

This form of survey is the most common and is ideal for finding and observing hidden details such as missing insulation or the location of pipes/wiring within a structural component

(Hart, 1991). The surveyor (or thermographer) uses real time footage to offer assumptions and recommendations in respect of any potential problems uncovered. The qualitative method of survey can be regarded as being a simple approach, as once the survey is completed it is very difficult to compile further results as parameters and temperature references are not set.

8.2.2 Quantitative approach:

A quantitative thermo-graphic survey is more stringent and detailed when compared with the qualitative method. Surface temperature calculations are based on the thermal image and necessary analytical parameters relevant to the building and conditions. Often, the results of a quantitative survey are calculated in a laboratory and not in the field (Hart, 1991). Correct calibration of the infra-red camera is carried out by the inclusion of an object of known emissivity and temperature. The temperature of surrounding surfaces can then be calculated based on this standard.

8.2.3 Air Leakage

A large advantage of thermographic surveying is the ability to identify air leakage paths in the structure of a building. Airtight testing via a pressure test is the most reliable way of identifying the rate of an air leakage, however a thermal image can indicate the exact locations of the leakages and because of this, both methods complement each other. (Pearson, 2002)

In the construction of a typical dwelling, it is very important that a reasonable level of air tightness is achieved (Stoppard, 2012). Air tightness is a key factor in low energy buildings. Failure to properly design and factor air tight capabilities in construction can have disastrous effects on the energy conservation capabilities of a dwelling. Insufficient air tight qualities result in the loss of warm air through a building's fabric; this reduces or, in some cases, completely removes the benefit of insulation (Stoppard, 2012). Air tightness is 50% dependent on design and 50% on construction quality. Both aspects go hand in hand as one is dependent on the other (Antonelli, 2006). Part L of the Irish building regulations deals specifically with the conservation of fuel and energy for dwellings. The document outlines the air permeability for new dwellings to be $7m^3/hr/m^2$ (TGD, 2007). Currently the passive house requirement of 0.6 air changes per hour at 50 Pa pressure is the highest air tightness standard in construction (McLeod, Tilford, and Mead, 2011). The passive house requirement is an indication of the level of airtightness that can be achieved in domestic construction providing there is correct design and more importantly, standards for achieving installation.
Currently in the Irish construction industry, an air tight layer is incorporated into dwelling construction. In the instance of block or masonry constructed dwellings, the air tight layer is the internal plaster finish. This is an effective form of air tightness provided there are no gaps in the completed render (Antonelli, 2006).

Ineffective airtightness in a typical dwelling results in draughts and the constant movement of air as warm air is more buoyant than colder air infiltrating the building. As this warm air rises, it increases the pressure inside the building which in turn forces air out of gaps or holes in the building envelope (Stoppard, 2012). There are a number of areas in typical house construction where air leakage can occur; they are outlined as follows;

- Joints around components (e.g. windows set within walls)
- Gaps between one element and another (e.g. wall to floor interface)
- Gaps around services passing through the construction
- Building materials that are permeable (e.g. unpainted lightweight block work) (Jaggs, 2012)

While all the highlighted areas are a concern in appropriately designing an air tight barrier, the second point; gaps between one element and another will be the particular area in which the thermal surveys focus on. Undoubtedly, improved airtightness leads to a greater thermal performance.

8.2.4 Survey conditions

There are a number of conditions which should be adhered to when carrying out a thermo-graphic survey:

- Temperature difference across the building fabric to be greater than 10°C
- Internal air to ambient air temperature difference to be greater than 5°C for the last twenty four hours before survey
- External air temperature to be within +/- 3°C for duration of survey and for previous hour
- External air temperature to be within +/- 10°C for the preceding twenty-four hours
- Necessary surfaces are to be free from direct solar radiation for at least one hour
- No precipitation prior to or during the survey

- All building surfaces to be inspected are dry
- Wind speed to be less than 10m/s (UKTA, 2007)

8.2.5 Thermo-graphic survey of Trial 1 and Trial 2

Thermo-graphic Surveys can be carried out externally or internally. An external survey is useful for an overview of the thermal performance of a building, however attention must be given to the wind speed as this can affect the surface temperature of a building (Pearson, 2011). An effective thermal reading is ideally made when the difference in temperature between the inside of a building and the outside is 10˚C. Further to this, there should be no precipitation and wind speed should not exceed 5 m/s. In the UK and Ireland, it is difficult to find suitable testing conditions in the months of May to September, the best time to carry out a thermo-graphic survey is during the winter months preferably during a cold, cloudy, dry still night. Internal surveys are the most common and do not have to factor in wind speed, because of this they are more effective at identifying anomalies (Pearson 2011). A qualitative approach was adopted in the thermo-graphic surveys of both Trial 1 and 2. Each survey was carried out at night in order to ensure there was a distinct difference between the internal and external temperatures.

8.2.6 Equipment

The same equipment was used for both surveys. The thermal camera used was a mid-market camera with limited ability, but was sufficient for identifying areas of thermal anomaly and potential air leakage paths in the building fabric. A hand-held temperature gauge was also used to record the internal and external temperatures. The temperature gauge also had a probe sensor which was used to record the surface temperature of the building.

8.2.7 Trial 1 Thermal Survey

Figure 80 shows data relating to the thermal survey of Trial 1. This data could be used to determine the thermal performance of the building.

Weather Condition	Wind/rain
Internal air temperature	18.8˚C
Internal Surface temperature	20.7 ˚C
External air temperature	9.5 ˚C
External surface temperature	9.3 ˚C
Total wall area	65.455 m

Figure 80: Data recorded at the thermal survey of Trial 1

8.2.8 The Thermal index:

The thermal index or TI (sometimes referred to as the temperature factor) is used to assess the risk of surface condensation under steady state conditions. The use of the TI allows surveys to show areas where there is a risk of condensation or mould growth under design conditions (UKTA, 2007). TI is given in Equation 1 and is a dimensionless parameter and can be applied to both internal and external surveys.

Equation 1: Thermal Index (internal)

TI (Thermal Index) = $T_{si} – T_e / T_i - T_e$

T_{si} = Internal surface temperature

T_e = External air temperature

T_i = Internal air temperature

For Trial 1, the internal Thermal index is:

(20.7 – 9.5) / (18.8 – 9.5) = 1.2

For external surveys:

Equation 2: Thermal Index (external)

$$T_{se} – T_{i)} / (T_i – T_{e)}$$

T_{se} = Internal surface temperature

T_e = External air temperature

T_i = Internal air temperature

For Trial 1 External Thermal Index:

(20.7 – 18.8) / (18.8 – 9.5) = .228

An internal TI value would typically be 0.75 whereas an external TI value would typically be 0.9. This value is higher than that of an internal survey because the external face of a building is exposed to more air movement. The Thermal index is a useful calculation for determining anomalies or potential defects. A TI value of below 0.75 or above 0.9 for internal and external TI's respectively is an indication of a serious thermal defect in the structure of a building and can lead to condensation or mould growth (Ward, 2006). Trial 1 performed satisfactorily in both of these calculations

8.2.10 Thermal Images

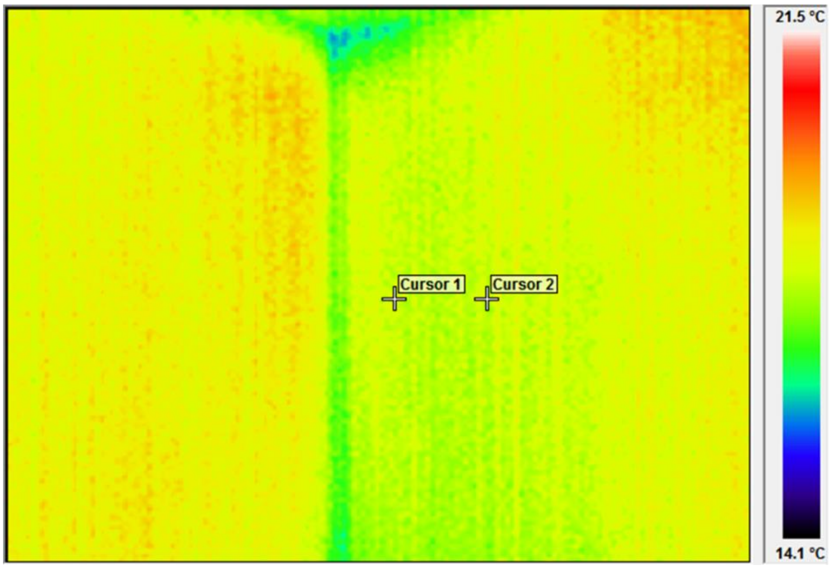

Figure 81: Thermal image of Trial 1

Figure 81 shows an image taken during the thermo-graphic survey of Trial 3. The image was taken of a corner of the extension where the Sherpa™ 'Type B' connector was used to join two wall panels together. As can be seen in the image, the corner joint emitted a colder reading than that of the walls around it. However, when assessing the temperature of this joint it was seen on the temperature gauge to have a reading of approximately 17 °C which is not a cause for concern. The blue colour shown in the very top corner of the joint is an indication that there was more thermal conductivity occurring at this point but, comparing the reading to the temperature gauge, shows that this area had a reading of 15-16 °C which was not a thermal failure.

Figure 82 shows a second thermal image taken of Trial 1. The image was taken at a straight joint between two wall panels in the extension. As with the previous image, the wall panels were joined together using the Sherpa™ 'Type B' connectors. The joint in the wall was located at the point marked 'Curser 1' and, as can be seen, there was no deviation in temperature reading on the wall at this point. This indicates that the connection had produced an airtight and thermally efficient joint between both panels. The green area to the right of the point marked ‘Curser 2’ was a return wall coming towards the camera.

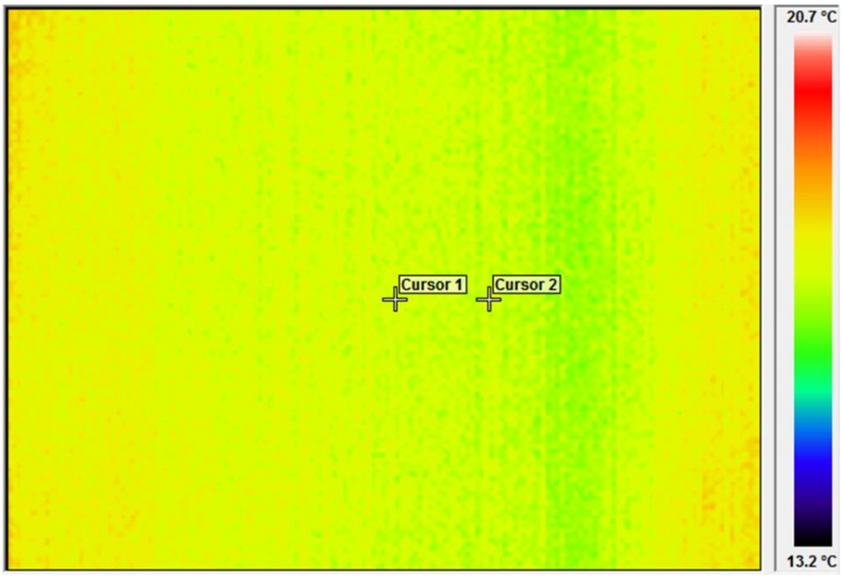

Figure 82: Second thermal image of Trial 1

8.2.11 Analysis of Trial 1 Thermal Survey

Although slightly limited by the quality of the thermal imaging camera, the thermal survey of Trial 1 established that the connection detail, using the ‘Type B’ Sherpa™ connector, offered satisfactory continuity regarding the thermal readings of the internal walls. Deviations in temperature were recorded at external corner joints; however the temperature difference did not significantly differ from the temperature of the rest of the walls. More importantly, there was no evidence of any significant thermal bridges in the assembly of the walls or in their connection points.

8.2.12 Trial 2 Thermal survey

A thermal survey was also carried out on the extension building assembled in Trial 2. Figure 83 details a range of data recorded at the survey:

Weather Condition	Dry
Internal air temperature	24˚C
Internal Surface temperature	22 ˚C
External air temperature	11.6 ˚C
External surface temperature	12.5 ˚C
Total wall area	43.195m²

Figure 83: Data recorded at thermal Survey of Trial 2

As with the Trial 1 data, the Internal Thermal Index of Trial 2 could be established as:

(22 – 11.6) / (24 – 11.6) = .83

And the External Thermal Index as:

(22 – 24.6) / (24.6 – 11.6) = 0.2

Both were within their respective limits resulting in an overall satisfactory thermal performance of Trial 2.

8.2.13 Thermal Images

A number of thermal images were taken of Trial 2. Particular attention was focused on the two external corner joints of the building. During the course of construction, there was difficulty in aligning and assembling the walls resulting in one of the Sherpa™ connectors being removed. This left the project with one external corner joined using Sherpa™ connectors and the other external corner joint using standard screwing. Figure 84 shows a thermal image taken of the corner which contained the Sherpa™ connectors. The lines of both where the ceiling meets the walls and where the walls meet each other can clearly be seen at a different temperature compared with the rest of the wall area.

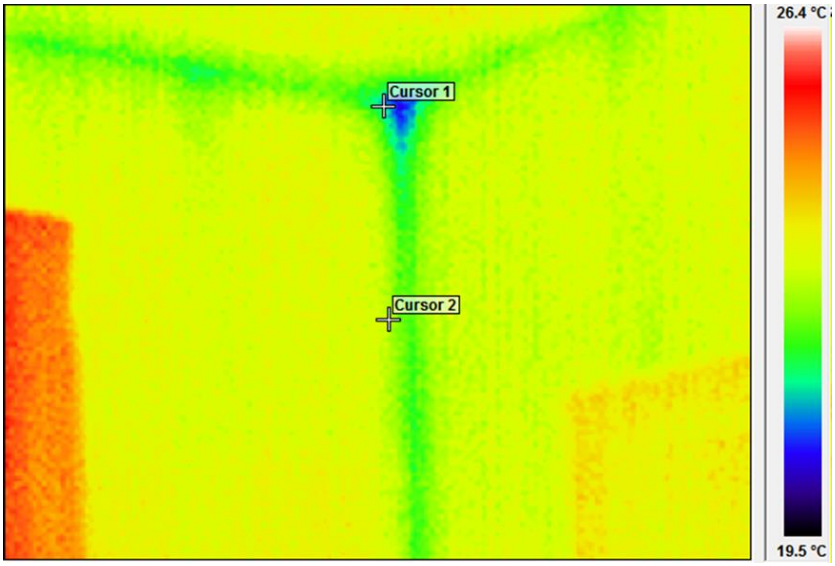

Figure 84: Thermal image of Trial 2 showing corner joint with Sherpa™ connector

When compared with the temperature scale it can be seen that the greener shading of the corner joint is approximately 2 °C colder than the main wall area and this small deviation in temperature is not an indication of a thermal bridge in the structure. The blue area, visible on the right at the point of where the ceiling and wall meet, is evidently colder than the main wall area; however the difference in temperature is approximately 3 °C which again does not point to a significant thermal bridge at this point.

In contrast to the corner joined together using the Sherpa™ connector, the opposite corner of the extension project was also thermally assessed. Figure 85 shows the thermal image taken of this corner joint.

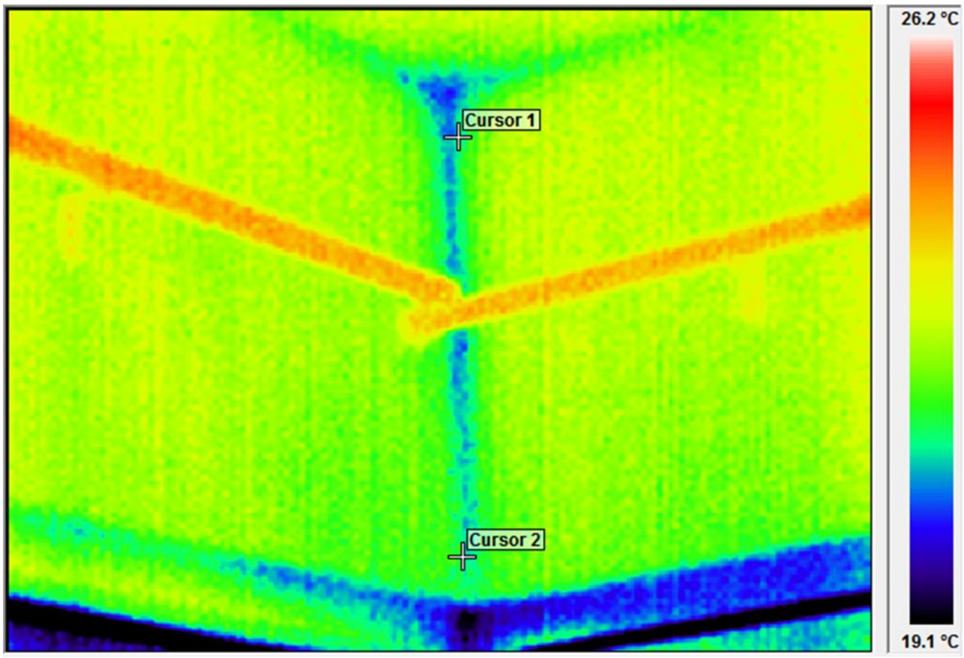

Figure 85: Second thermal image of Trial 2; Corner joint without a Sherpa™ connector

Although the temperature range as indicated by the temperature gauge is relatively the same as the first image, there is a clear difference of temperature at the corner joint of the walls. This temperature difference is minor at approximately 3 °C to 4 °C. However, unlike the previous image where the drop in temperature could only be seen at the very top of the corner joint, Figure 85 shows a continuous temperature difference right along the corner joint. This temperature difference is once again negligible and does not indicate a substantial thermal bridge.

8.2.14 Analysis of Trial 2 thermal survey

The thermal survey of Trial 2 gave further insight in to the capabilities of the Sherpa™ connectors in terms of the thermal performance of the building. The removal of the connection system from one corner joint during construction allowed for a thermal image comparison to be made between a Sherpa™ joined corner and a standard screw connected corner. Although the Sherpa™ used in Trial 2 is the 'Type B' connector and not the revised 'W8' connector, it can be seen from the images that the Sherpa™ connector offers a tighter, more thermally sound connection. The low tolerance level of movement between the Sherpa's™ results in a very close connection between both closed panel timber frame walls, The Compriband tape used in the connection detail adds further to the joint quality by expanding and creating an airtight barrier within the connection detail. In contrast to this, Figure 85 shows the corner connection which was joined by traditional screw fixings and a clear line of temperature difference can be seen along the corner joint indicating that the screw fixings do not offer as close or as tight a connection between two wall panels as the Sherpa™ connectors.

8.2.15 Thermal survey conclusion

Thermo-graphic surveys offer an unparalleled means of observing the true thermal behaviour of a building. The development of infrared technology over the years has led to better survey equipment and more accurate testing. Results of a survey, either positive or negative can be used to further evaluate construction methods and details. Given the large emphasis on reducing energy consumption in both domestic and commercial buildings, thermography has the potential to allow anomalies such as thermal bridges to be discovered and identified earlier in the construction process. The changing of construction details to eliminate such defects will have a lasting effect and will allow various construction processes to evolve with sustainability in mind.

8.3 Simulated Thermal Evaluation

Carrying out the thermal surveys of both Trial 1 and 2 established that the Connection detail offered improved levels of thermal efficiency when compared with standard screw fixed joints. However, a more detailed assessment of the thermal performance of the connection detail throughout all 4 projects was needed. It was essential to explore and evaluate the performance of the connection detail under simulated conditions in order to assess its suitability within the structure of a building.

8.3.1 Feasibility project results

A THERM assessment of a joint between two wall panels used on the initial feasibility project was carried out. As already described, two types of wall layout using 100mm studding and 140mm studding were used in the completion of the project. A Sherpa™ 'Type B' connector was used in the connection detail for both types of wall. Figure 86 shows the simulated thermal assessment of the wall containing the 100mm studding. The THERM assessment of the wall highlighted the loss of heat through the wall structure. There is typically a higher level of heat loss at specific points along the wall such as where the vertical studs are located however; the layers of insulation dissipate this rate of loss.

Figure 86 shows a section of the THERM simulation for the feasibility project. The stud on the left-hand side of the picture shows increased levels of thermal conductivity when compared with the areas between the studs. The double stud on the right-hand side of the

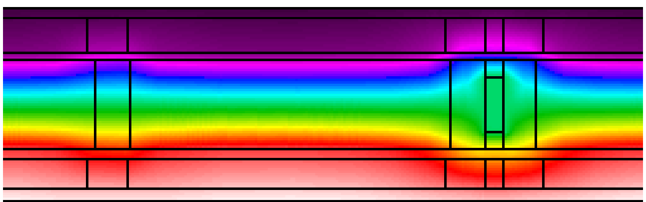

Figure 86: Close-up of normal stud and connection point between walls of feasibility project

picture is the connection between both walls with the Sherpa™ connector shown in the centre. As can be seen, there is much more thermal activity at this point when compared with a standard stud. This is largely to do with the high level of thermal conductivity of aluminium alloy compared with timber. The thickness of the wall assists in the level of thermal transmittance from inside to outside as a 100mm stud layout is not commonly used. It also should be noted that this wall was installed against an existing external wall of a neighbouring property and so was not exposed to the elements.

Figure 87 shows the simulated infrared thermal assessment of the 140mm stud wall used in the feasibility project. As indicated, there is an internal temperature of 19.6 °C and an external temperature of -5 °C. The Sherpa™ connector was located in the centre of the wall juncture. There was much less thermal transmittance through the Sherpa™ connection point when compared with the other 100mm stud wall used in the project. This is mainly due to the increased thickness of insulation and the surrounding of the Sherpa™ by the timber studding.

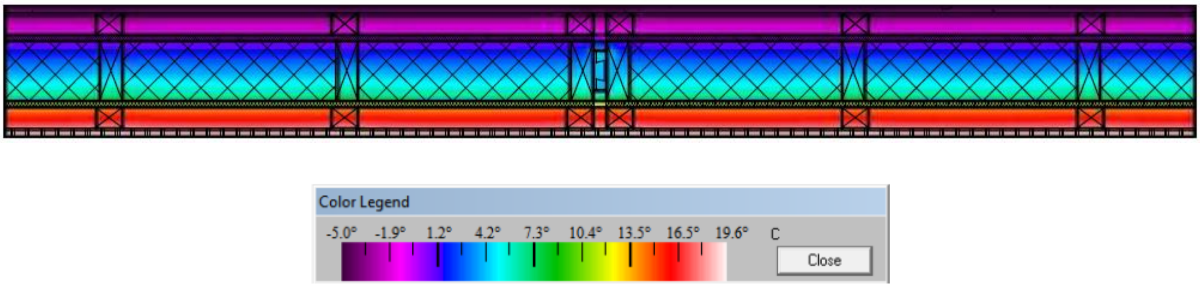

Figure 87: Simulated thermal infrared assessment of 140mm stud wall used in the feasibility project

8.3.2 THERM Assessment of Trial 1

A simulated thermal assessment was carried out on Trial 1. During the prefabrication and construction of this project, a timber batten was installed alongside the Sherpa™ connector for alignment purposes. As can be seen in Figure 88, an assessment of an entire wall, including a corner detail was made showing the level of thermal transmittance through the external wall when there was an internal temperature of 19.6 °C and an external temperature of -5 °C.

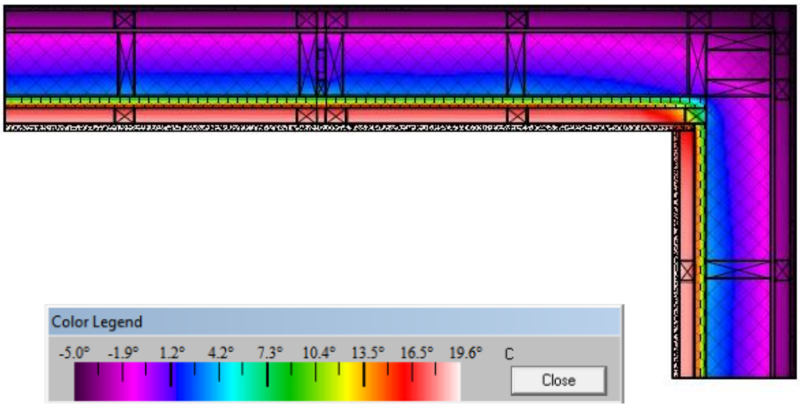

Figure 88: THERM infrared simulation of Trial 1 connection point

The thermal behaviour of the wall at the Sherpa™ connector is quite similar to that in the previous feasibility project. The inclusion of a guide batten beside the Sherpa™ on the internal side offers more resistance to thermal transmittance. However, there is a slight deviation at the point of the Sherpa™ connector. It is also important to note the thermal transmittance at the external corner of the wall assembly. The stud layout shown at the external corner in figure 88 is typical of a standard corner detail and, as can be seen in the image, there is an increase in the level of thermal activity at this point. This is common in all buildings as external corners are deemed the most thermally inefficient points of a structure (BSI, 2012). The thermal performance of the external corner layout of Trial 1 had added significance as both Trial 2 and 3 had corner connection points. This allows for a comparison to be made between the thermal performances of both junctions.

8.3.3 THERM assessment of Trial 2

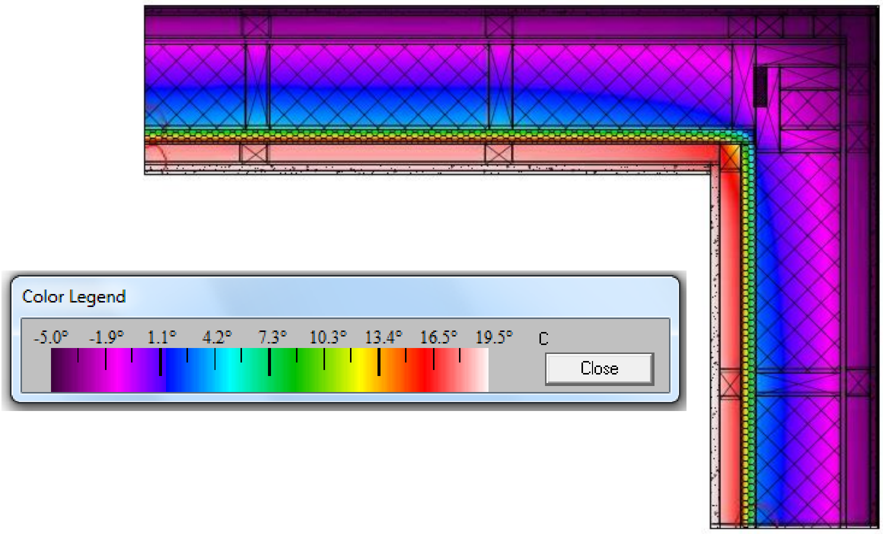

Figure 89: Thermal infrared simulation of Trial 2 with corner connection point

The layout of Trial 2 required a change in the assembly process compared with Trial 1. Instead of a straight connection between panels as in previous projects, a corner connection point was adopted. As previously documented, the Sherpa™ 'Type B' connector was used in the assembly of the project and this is highlighted by the black rectangular shape in Figure 89. The layout of the connection point ensured that the Sherpa™ connector was countersunk in the timber stud of the walls thus helping to reduce the overall thermal conductivity of the connector. As can be seen from Figure 89, an internal temperature of 19.5 °C and an external temperature of -5 °C were applied. The level of conductivity across the corner connection point was similar to the standard layout associated with Trial 1. There was deviation around the Sherpa™ but a clear thermal bridge was not evident.

8.3.4 THERM assessment of Trial 3

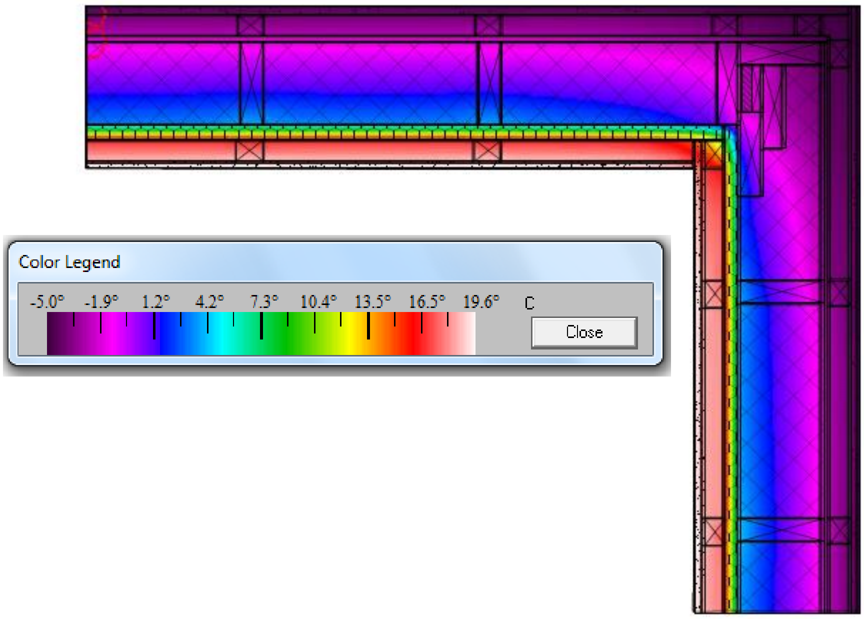

Figure 90: Simulated infrared thermal assessment of Trial 3 corner connection with 'W8' connector

Trial 3 used a corner connection system in its on-site assembly. The connection detail used in the project was a change in design to the previous projects as a new Sherpa™ connector and stud layout was applied. The thermal assessment as shown in Figure 90 indicates that the level of thermal activity at the corner junction is in line with the levels of thermal conductivity at standard corner layouts. With an internal temperature of 19.6 °C and an external temperature of -5 °C the connection point was assessed in the same conditions as the previous trials. The use of the 'W8' connector offered less of surface area when compared with the previous 'Type B' connector and the application of extra insulation behind the connection point also helped to alleviate the level of thermal conductivity.

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8.3.5 Direct comparison between connection points

The thermal simulation offered by the LBNL software gave visual indications of the levels of thermal conductivity through the building materials, however for more conclusive evidence of the performance of the connection points, a separate strand of the software was utilised. By calculating the thermal conductivity of each material in the wall assembly, the software was capable of giving a temperature reading using isotherms or points within each wall. This is the most efficient way of defining the success of the new connection layout.

8.3.6 Temperature Isotherms

As the simulated temperature in all four THERM assessments were essentially the same (19.5 °C internal and -5 °C external), similar temperature isotherms ran throughout each assessment.

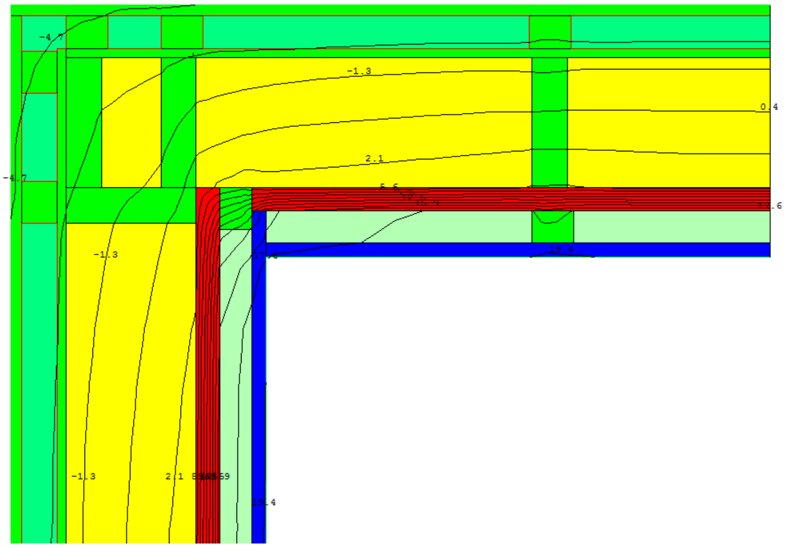

Figure 91: Screen shot of standard timber frame corner joint with temperature isotherms

Figure 91shows a standard timber frame corner detail. As can be seen in the image, the temperature decreased through the various materials that make up the wall structure. Importantly, the temperature at the vertical studs of the wall at the corner point was given as 0.4 °C. From this point inwards, the temperature steadily increased until the simulated set temperature was achieved. Figure 91, set a standard thermal behaviour model of a closed panel timber frame wall. The application of both the 'Type B' and W8 Sherpa™ connector were assessed against this to determine their success.

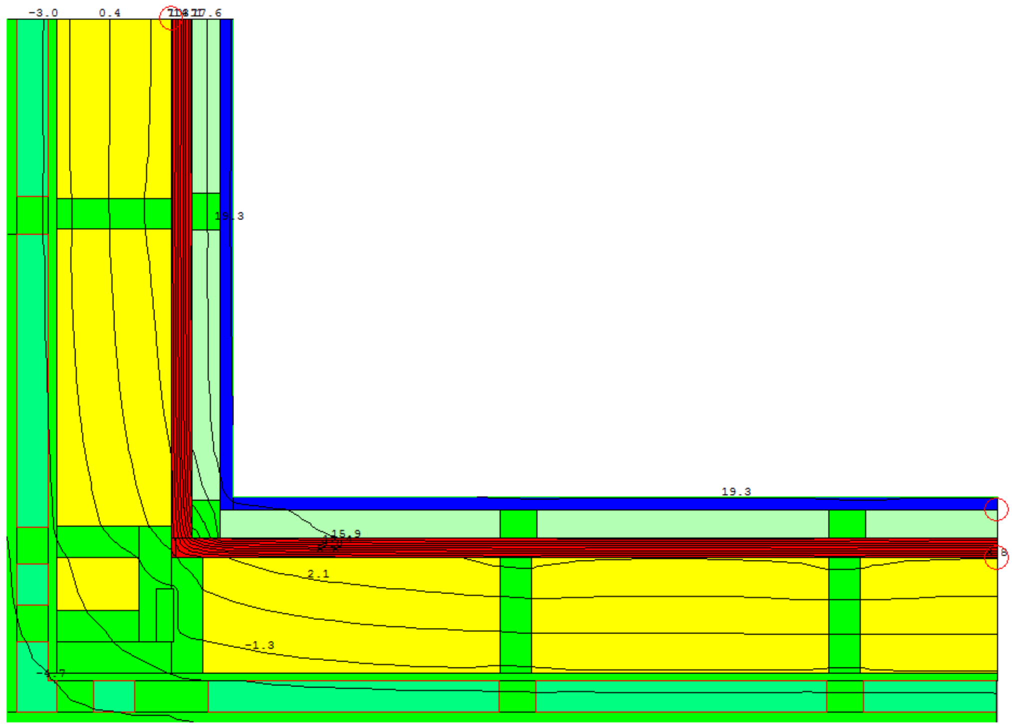

Figure 92: Screen shot of Trial 2 'Type B' corner joint with temperature isotherms

Carrying out the same temperature assessment of Trial 2 showed that the overall rate of temperature change through the wall did not alter significantly. Figure 92 shows the temperature of the vertical studs contained in the wall stayed at 0.4 °C. However, there was a noticeable adjustment in the temperature isotherm marked -1.3°C as, rather than running through the wall structure in a standard arc formation, the isotherm deviated and stepped around the position of the Sherpa™ indicating the higher level of conductivity of the connector when compared with the surrounding timber. The rate of thermal transmittance between the internal and external temperatures was slightly increased in the Trial 2 detail. The temperature isotherms encroached on the materials contained within the wall fractionally earlier when compared with a standard connection layout.

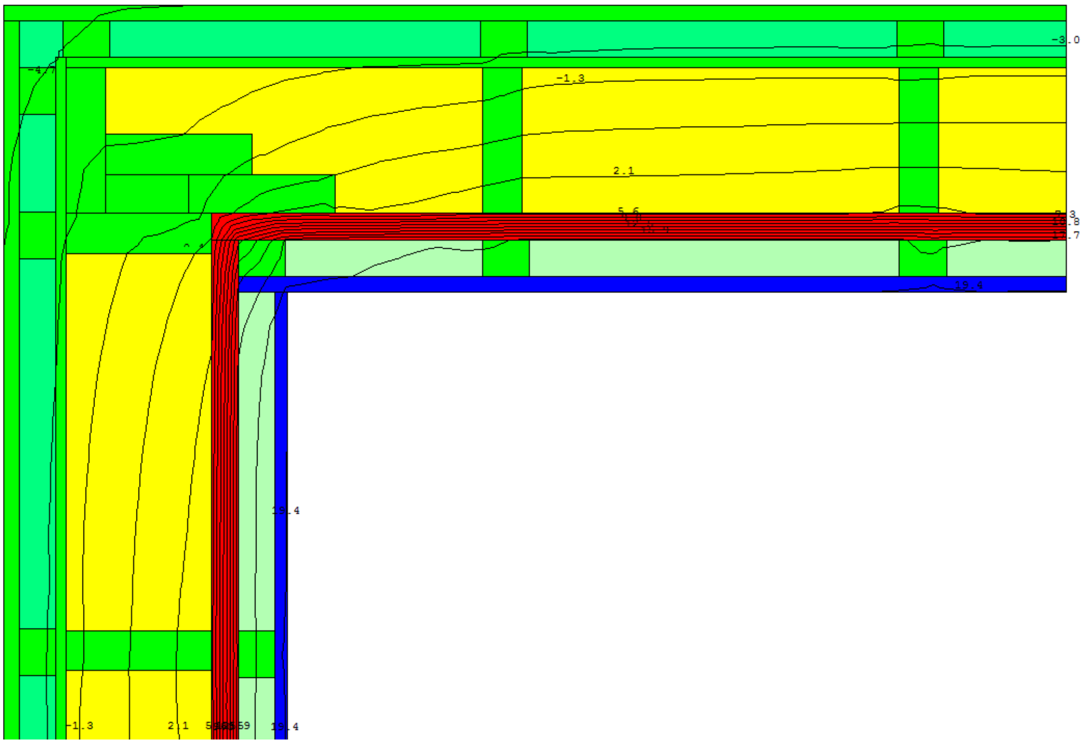

Figure 93: Screen shot of Trial 3 connection point using W8 connector

Figure 93 shows the layout of the connection point used in Trial 3. As with the previous assessments, there was a gradual reduction of temperature across the wall and its components. Examining the detail and the associated temperature isotherms, it can be seen that the temperature of the timber remained at -0.4 °C. This corresponds with both the standard method of corner connection and the use of the Sherpa™ connector as shown in the previous assessments. A further similarity with the Trial 2 assessment was the deviation of the 1.3 °C temperature isotherm. This was not as pronounced in the case of Trial 3 but did show evidence of the thermal conductivity difference between the timber and the aluminium-alloy connector. As with the Trial 2 detail, comparing the Trial 3 detail with the initial standard corner joint indicated that it did not perform to the same level. However, the difference was negligible as the temperature isotherms in both instances were very similar with millimetres in the difference of their locations.

8.3.7 Simulated Thermal assessment conclusion

The use of the LBNL software gave a greater insight into the thermal behaviour of each connection point assessed. From the outset, the main aim of the thermal evaluation was to determine if the new connection detail and the steps involved in its progression to use could result in a similar or improved thermal characteristics at the connection detail. The initial infrared thermal assessment indicated that the straight wall connections used in the initial feasibility project and in Trial 1 showed signs of thermal transmittance. Although not significant, the level of transmittance was more than would occur at a regular stud connection. This is largely due to the high conductivity factor of the aluminium-alloy. For the corner connections, the infrared assessments showed no sign of thermal bridges in the structure of each wall due to the inclusion of the aluminium alloy Sherpa™ connector.

The thermal assessment of Trial 1 also incorporated the thermal conductivity levels which are indicative of a standard corner detail in a closed panel timber frame structure. Assessing the corner detail in terms of the thermal conductivity levels is essential when comparing the performance of both Sherpa™ connected corner details. Initially comparing the Sherpa™ 'Type B' connected corner of Trial 2 demonstrated that, although the temperature isotherms did not radically change, they did deviate around the connector, increasing the thermal conductivity level of the wall slightly. The comparison of the Sherpa™ 'W8' connector used in the connection of Trial 3 also resulted in a slight deviation of the temperature isotherms around the location of the connector; however this was not as pronounced as in Trial 2 and was most likely due to the smaller connector size and increased amount of timber covering.

In conjunction with the actual thermal images taken of Trial 1 and Trial 2, the use of the THERM software offers a unique insight into the thermal behaviour of the closed panel timber frame structures in question. The software allowed for a concise and factual synopsis of the thermal behaviour of each connection point when subjected to set temperature conditions. The analysis of the connection points ultimately proved that, from a thermal performance point of view, the tried and tested methods of connection are marginally superior. However, the difference is negligible, particularly in the assessment of the connection detail developed for use in Trial 3. The isotherm analysis of Trial 3 when compared with a standard connection detail indicates that thermal conductivity in the wall structure did minimally increase; however this deviation took place in the load-bearing facet of the wall, at the vertical studs and infill insulation. The internal rigid insulation and plasterboard areas were unchanged and maintained a constant temperature with no breaches or thermal bridges.

Chapter 9

Comparison of Fixings from the Structural Tests

9.1 Test Environment

Both the test for compressive strength and racking strength were carried out in laboratory conditions using a number of test instruments commonly applied during structural testing. The compressive force needed in both test formats was supplied by a hydraulic bottle jack. The jack was capable of applying a force of 50kN which was more than the anticipated fail loading of the test pieces, though the maximum stroke of the jack could be reached before failure. The jack was also a hand-operated version requiring the application of consistent pressure during the course of each test. A pressure recorder was connected to the hydraulic jack during each test. The recorder measured the amount of force applied to the test pieces during each test and relayed the data to a computer programme. The movement of the wall panels during testing was measured using a deflection gauge. This is a movement sensitive instrument which was placed in contact with the timber before each test started. The deflection gauge took readings every second and relayed the amount of movement to the same computer programme as that for the hydraulic jack; both sets of data were then recorded simultaneously for analysis. The use of a large testing rig was an essential factor for both test formats. The rig used in both instances can be seen in Figure 94. It consisted of a steel, square framed structure with an open sided platform onto which the test pieces could be placed. As can be seen in Figure 94, the steel frame is robust and offers a means of placing both the test pieces and the hydraulic bottle jack most efficiently to determine the structural integrity of the panels.

Figure 94: Steel framed testing rig

9.2 Test 1A: Compressive strength of a timber frame corner joint

9.2.1 Background to test selection and positioning

To truly assess the potential benefits that the Sherpa connectors could bring to the assembly of closed panel timber frame walls, it was necessary to determine their strength when compared with traditional screw fixing. As previously highlighted, once panels were positioned on site they were connected together using standard 8mm x 80mm screws and the screws were fixed at various points along the joining vertical studs at each panel until a solid connection was formed. In order to assess if the Sherpa connection detail equalled or improved the traditional method, it was necessary to carry out a direct compression test for each alternative and to compare the findings.

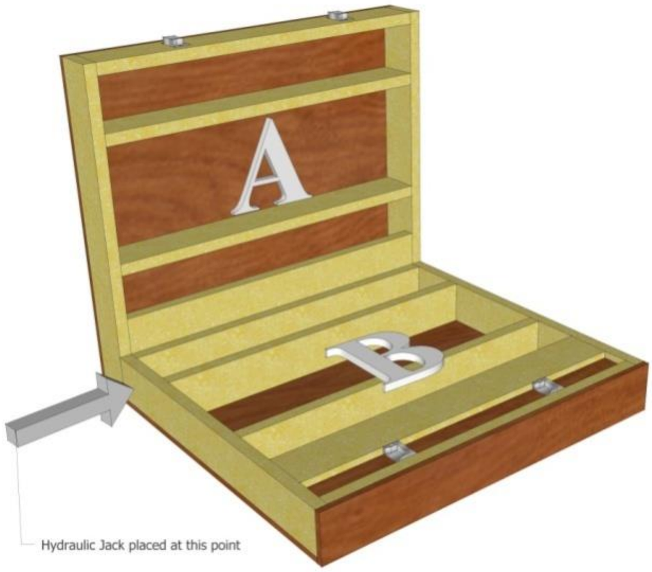

Figure 95: Panel position for test 1

Assessing the size of the timber frame walls and the available testing equipment, it was essential that the positioning of the test pieces allowed the most accurate and comparable data to be extracted from each test. After considering different layout options, it was decided that two wall panels were to be connected in a corner joint position and laid horizontally on the test rig. The layout of the test pieces can be seen in Figure 95. The wall labelled 'A' was braced to the test rig using steel infill pieces. This allowed only wall 'B' to move during the test process giving a simple and concise measurement of the structural strength of each connection method. The hydraulic jack was placed in contact with wall panel 'B' directly over the corner joint as shown in Figure 95. The displacement gauge was installed at the other end of panel 'B' to measure the distance panel 'B' moved. Each compression test was intended to determine the maximum force (kN) applied to the test piece before failure and the amount of deflection or separation that occurred during testing.

9.2.2 Test 1A – Compressive strength of a screw fixed corner joint

The first compressive test was carried out on a screw fixed corner joint. A total of 5 screws were fixed in alternating positions along the joint between both panels. Both the Hydraulic jack and displacement gauge were positioned and calibrated before the test began.

9.2.3 Visual Inspection during Test

During the course of test 1A, a constant visual inspection of the test pieces was maintained. During the test it was noted that both panels remained intact; however, movement could clearly be seen at both ends of the panels indicating that the screws had not suddenly sheared or given way but had moved from their original position. As the pressure from the hydraulic jack increased, the screws began to pivot and become embedded in the timber. The screwed corner joint did not suddenly fail during the course of the test and, as the hydraulic jack reached its full stroke, the test had to be concluded. A visual inspection of the wall panels post-testing showed that significant movement had occurred between both panels whilst leaving them intact. The screws used to connect the panels together had moved during the testing; however all five screw heads remained visible on panel 'B' indicating that the screws had pulled away from panel 'A' but the panels had not separated. The extent of the movement can be seen in both images of the test panels shown in Figure

Figure 96: Images taken of test 1A after test completion

9.2.4 Data Analysis of Test 1A

Data recorded from both the hydraulic jack and the movement gauge was correlated on a spread sheet which is represented by the graph shown in Figure 97. As indicated, the force applied to the test panels rose steadily until a release of this pressure occurred at a deflection point of 39mm corresponding to a load of 20.69 kN of pressure applied. This plot is typically associated with the failure of a securing screw. However; as the screws were still visible and had not sheared and the panels were still connected it may be attributed to a release of pressure brought about by a drop in friction between the two wall panels as they were initially abutted to each other. This is further supported by the graph indicating a rise in force after the initial fall. As outlined in the graph there was a steady rise in pressure during the initial 20mm of deflection. This virtually constant rise is a measure of the stiffness of the connection and is the optimal data to be compared with test 1B. A maximum pressure of 20.99kN was imposed on the test panels at a deflection of 43.5mm into the test. From this point, the pressure loading decreased steadily until the hydraulic jack reached its limit. The connection between the two panels did not fail completely; however as indicated in Figure 94, Panel ‘B’ moved significantly during the course of the test.

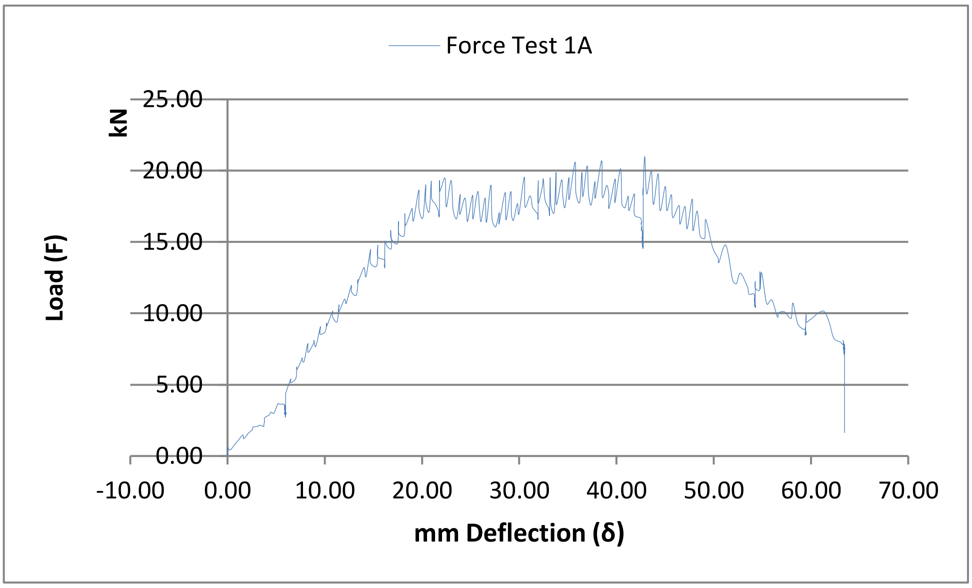

Figure 97: Test 1A Force displacement graph

Movement of this panel remained uniform during the early stages of the test with a momentary plateau arresting this movement at 38.99mm. This corresponds to the fall in pressure at the same time as that indicated in Figure 97. Movement again rose as a result of the increased loading on the test panels until the hydraulic jack reached its limit with a total movement of 63.49mm imposed on wall panel 'B' (Refer to Figure 97).

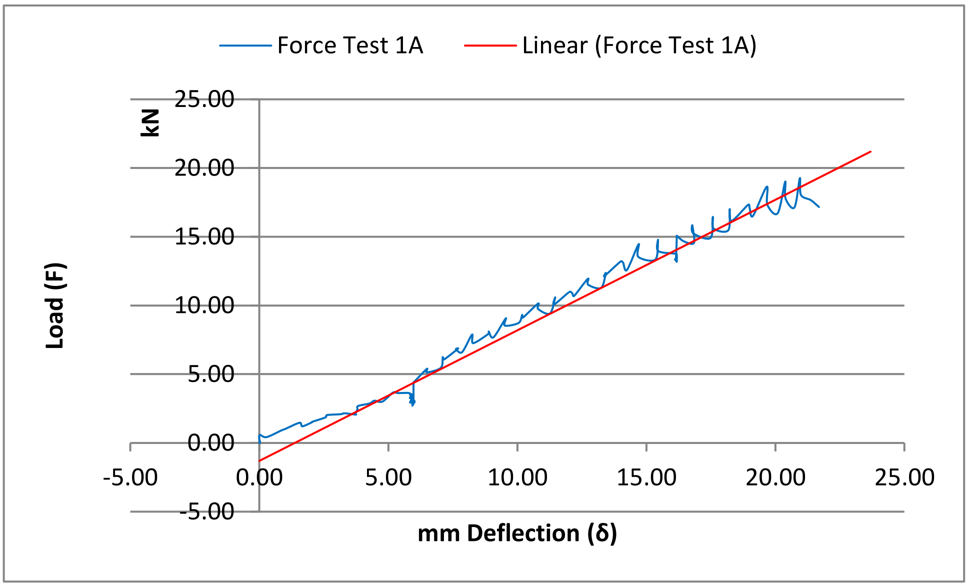

Figure 98: Force displacement graph showing stiffness of screw-fixed connection

Figure 98 depicts data relating to the first 20mm of deflection during test 1A and the corresponding loading imposed on the test piece. A linear trend line is also included to show the stiffness of the joint during the test process. From figure 98 it can be seen that the stiffness of the screw fixed joint prior to separation was approximately (22.5 - 6.5) / 15 = 1.07 kN/mm

9.2.5 Test 1A Conclusion

Test 1A established the strength offered by a standard screw-fixed connection between two wall panels. The test pieces behaved as expected under the compressive load with over 60mm of movement recorded laterally between both panels. The behaviour of the screw fixings during the test is important to note. As anticipated the position of the screws changed as more force was added to the test panels. Rather than shear or break, the screws moved within the timber. Although the walls did not separate during the test, both graphs indicate that pressure and movement would have continued to rise if the hydraulic jack had a longer reach. This would have seen the eventual dis-lodging of the screws and separation of wall panel 'B' from panel 'A'. The force displacement graphs associated with test 1A were compared with those provided by test 1B in order to ascertain a comparison with the robustness of the Sherpa connection detail.

9.3 Test 1B - Compressive strength of Sherpa detail at corner joint

Test 1B was carried out directly after test 1A. As all the wall panels had the same dimensions, the test rig and associated equipment did not have to be altered as the new test panels were lifted into place by hand. Similarly, as with the previous test, the wall panels were pre-joined with the vertical panel labelled panel 'A' and held in position on the rig to prevent movement. Two Sherpa Connectors were used in the connection detail between both panels. The EPDM rubber was omitted as it was considered to have minimal influence on the structural integrity of the joint. Each connector piece was held in place using two 8mm x 80mm Sherpa™ specified screws. The hydraulic jack and displacement gauge were once again positioned at either end of Panel 'B' to record the respective force and movement achieved during the test.

9.3.1 Visual Inspection during Testing

A visual inspection of the test panels was maintained throughout the test procedure. In the early stages of the test, the vertical, restrained panel ‘A’ moved slightly but did not influence any of the test equipment and so the test continued. Much like Test 1A, movement between the two panels could clearly be seen and this is shown in Figure 96. In conjunction with this, there was also clear evidence of movement at the point of both Sherpa connection pieces contained in the wall joint. A small gap formed between the test panels allowing visual confirmation that the connectors, although remaining intact, had begun to pivot and become embedded in the CLS timber as can be seen in Figure 99. This was similar to the screw fixings becoming embedded in Test 1A. Both panels remained entirely intact throughout Test 1B and the connection detail did not give way or fail during the course of testing.

Figure 99: The left image shows pivoting Sherpa connector and the right image shows the range of movement of panel 'B' during test

9.3.2 Data Analysis of test 1B

Data relating to Test 1B is represented in Figure 100 by a force displacement diagram. In terms of the structural strength of the Sherpa™ connector, it is evident from the graph that the detail out performs the standard screw fixed connection method. A steady rise in compression can be seen on the graph until the test pieces reach a deflection point of 14.9mm and a force of 12.75 kN. It is not known exactly what caused this dip in pressure but from this point onwards the strength and rigidity of the detail did not diminish. The force applied to the test pieces rose continuously until a force of 32.76 kN was reached at a deflection point of 50.1mm. As in Test 1A, this is the point at which the hydraulic jack reached its limit and this, combined with the visual inspection of the test pieces, resulted in the end of the test.

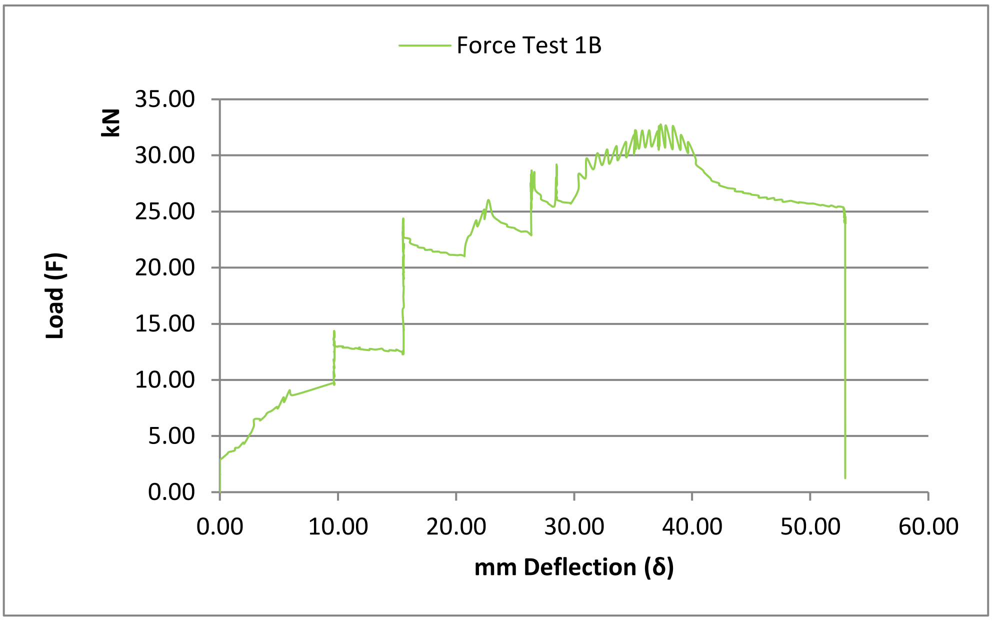

Figure 100: Force Displacement graph of Test 1B

An assessment of the data relating to the movement of panel 'B' during the test shows that the panel moved a total of 53mm. This represents the full stroke of the test apparatus. The movement of the panel remained at a steady rate with apparent dwells in displacement during the course of the test which were clearly indicative of systemic errors which did not affect the overall gradient of the load / displacement plot. Similar to the force displacement test for the screwed joint, the maximum stroke of the hydraulic jack was reached before the wall panels sheared or failed. However, the connection had shown sufficient structural robustness up to this point. The stiffness of the joint using Sherpa fixings was approximately (33 – 2.75) / 25 = 1.25 kN/mm

9.3.3 Test 1B Conclusion

As a stand-alone assessment of the strength of the Sherpa connectors in a typical timber frame construction joint, Test 1B provided a comprehensive insight into the behaviour of the connectors under high compressive loading. During the course of the test, the connectors pivoted and began to embed themselves in both test panels; however this provided more grip within the joint and allowed a compressive force of 32.76kN to be applied. Based on the overall movement of wall panel ‘B’ and the movement of the Sherpa’s, the wall panels would have eventually become separated had the hydraulic jack had a longer reach. However, it is inconclusive as to what would have failed first, the wall panels or connectors, though it could be anticipated that the screws holding the connectors would be torn from the timber.

9.4 Comparison of Test 1A and 1B

The results put forward by each test clearly highlight the superior strength offered by the Sherpa™ connection detail. In total, the Sherpa connection absorbed 11.77kN of extra force when compared to the standard screw fixed method and this figure would have been higher had there been a longer stroke on the hydraulic jack had a longer stroke. As referred to in the analysis of Test 1A, the screws holding the test panels together did not shear but did move inside the timber end studs of each panel. Similarly, the Sherpa™ connectors also pivoted from their original position but this did not detract from the strength of the joint.

In physical terms; the Test 1A result of 20.99kN can be considered as a datum for comparing the strength of the joint in each test. Subtracting that force from the maximum force applied in Test 1B (32.76kN) gives a differential of 11.77kN. The percentage strength difference is expressed as follows: 11.77/20.99 * 100/1 = 56.07% Therefore, the Sherpa connection detail appeared to exhibit 56% greater load bearing capacity in compression when compared with a standard screw fixed connection.

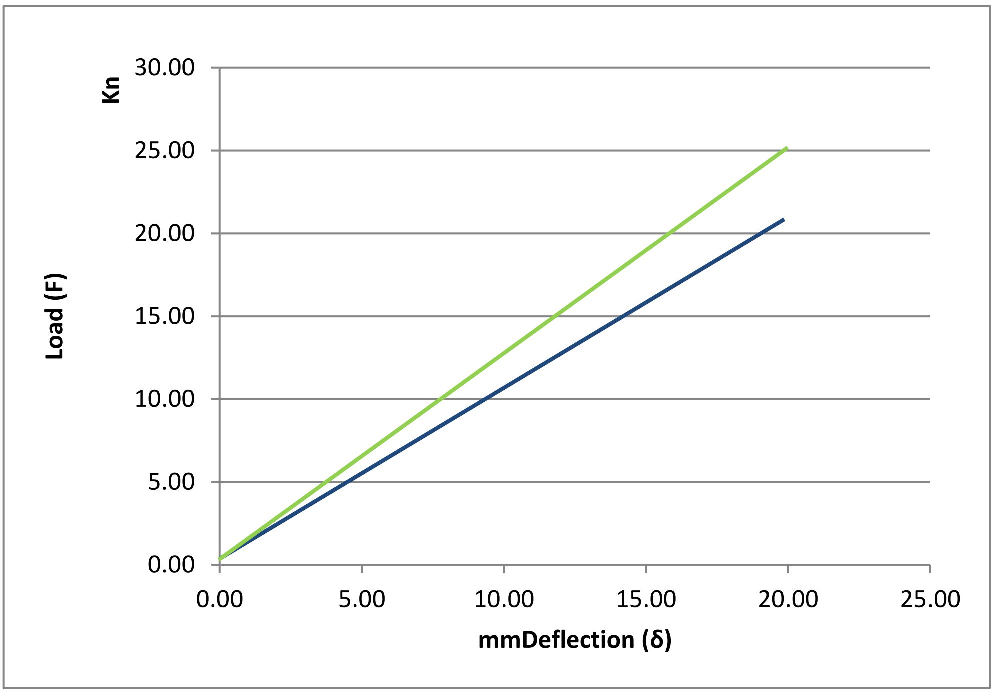

Figure 101: Force displacement graphs showing difference in stiffness of Test 1A (1.25kN/mm) and Test 1B (1.07kN/mm)

It is also worth noting that the Sherpa™ connection detail withstood considerably more compressive force than the screw connected detail further highlighting the connector's strength and resistance to movement. The screw fixed panels remained in closer contact during testing as the pivoting of the Sherpa™ connectors opened a slight gap between both panels in test 1B. Under a stronger test force, this would inevitably result in both walls detaching from each other or structural failure of both end studs. It is unlikely that such conditions would be replicated in a typical timber frame building. However, the test was the most efficient and accurate method available of determining the structural integrity of the new connection detail under compressive loading. A further comparative test was undertaken to evaluate the lateral or 'racking' strength of the detail.

9.5 Test 2: Lateral (Racking) strength of straight wall connection

9.5.1 Background to test selection and positioning

As already shown in Test 1, comparing the strength of typical joint details between wall panels is the main focus of the test phases. Having completed a corner joint comparison, attention then turned to a comparison between two walls which were joined together side by side. Testing the strength of the connection details in this wall arrangement establishes the lateral or 'racking' strength of both the walls and the connection between them. As previously described, racking is a common force applied to timber frame structures during their assembled lifetime. The timber sheathing applied to the external side of a timber frame building offers resistance to this force and, when a number of panels are joined in unison, resistance is increased. Therefore a test layout had to be designed to allow adequate testing of the racking strength of a typical screw-fixed connection and a connection using the Sherpa™ connectors.

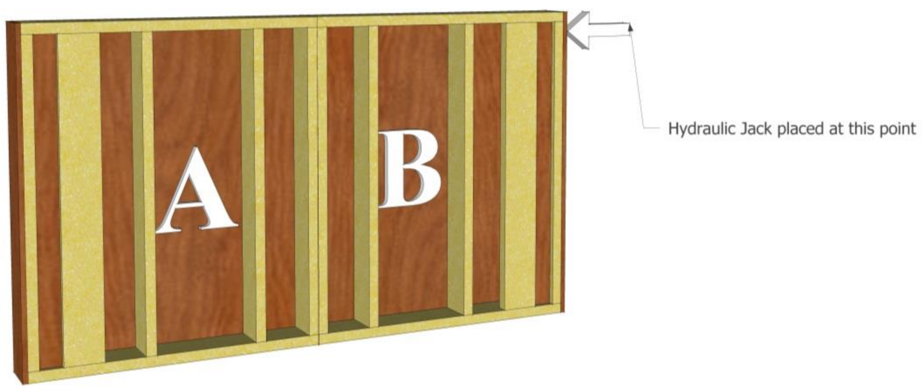

Figure 102: Panel position for Test 2

As shown in Figure 102, the panels were arranged vertically in the test rig. The Hydraulic jack was positioned at the top right hand corner of panel B in order to replicate the lateral forces applied to a timber frame structure in use. The displacement gauge was placed in contact with Wall A on its upper left-hand corner. Two tests were carried out, Test 2A and Test 2B. Test 2A assessed the lateral strength of a screw-fixed connection between the timber frame walls whilst Test 2B assessed the lateral strength of a Sherpa™ based connection. In both tests, Panel A was restrained at the bottom left hand corner by using steel wedges. A larger hydraulic jack, to be held in a fixed position was placed on the rig just above the upper right hand corner of Panel B. This would be used to prevent Panel B from lifting during the test process. Similar to Test 1, each test was established to determine the maximum force (kN) applied to the test piece before failure, the stiffness of the joints under a racking load and the amount of deflection or separation that occurred during testing.

9.5.2 Test 2A: Lateral (Racking) strength of a screw-fixed straight wall connection

Wall panels A and B were set up in the testing rig as previously described. A total of six 8mm x 80mm screws were used to join the panels together in a typical timber frame construction fashion. Once the hydraulic jack and displacement gauge had been connected to the computer and calibrated, the test began.

9.5.3 Visual inspection of Test 2A

As the pressure on the test panels increased, it became clear that an accurate measurement of the strength of the screws under a lateral force would prove to be difficult as the panels did not deflect linearly under loading. At a force of 10 kN, the top left hand corner of Panel A began to deflect outwards as depicted in Figure 103. This drew the panel away from the displacement gauge, and twisted the screw-fixed joint between both panels

Figure 103: Movement of test panels during Test 2A

With both panels moving away from the test rig, an accurate measurement of the pressure exerted by the hydraulic jack could not be obtained. In order to keep the panels in position during testing it was decided that the bottom rail of each wall panel would be bolted down to the test rig. As shown in Figure 104, 10mm bolts were used to secure both panels in position. Once in place, the hydraulic jack and displacement gauge were recalibrated and the test began again. Although the bolts provided more stability than in the first test, the panels again began to deflect away from the test rig in the same direction as indicated in Figure 103. Further securing of the test panels was needed in order to prevent this movement.

After considering the options, it was decided that steel guide rails would be the best solution to the problem as the number of degrees of freedom in the test needed to be minimised. The guide rails were bolted onto the wall behind the test rig with two vertical pieces draped either side of the test panels. The function of the guide rails was to allow the panels to move in a straight line without deflection and without influencing the outcome of the test. The position of the guiderails can be seen in Figure 104.

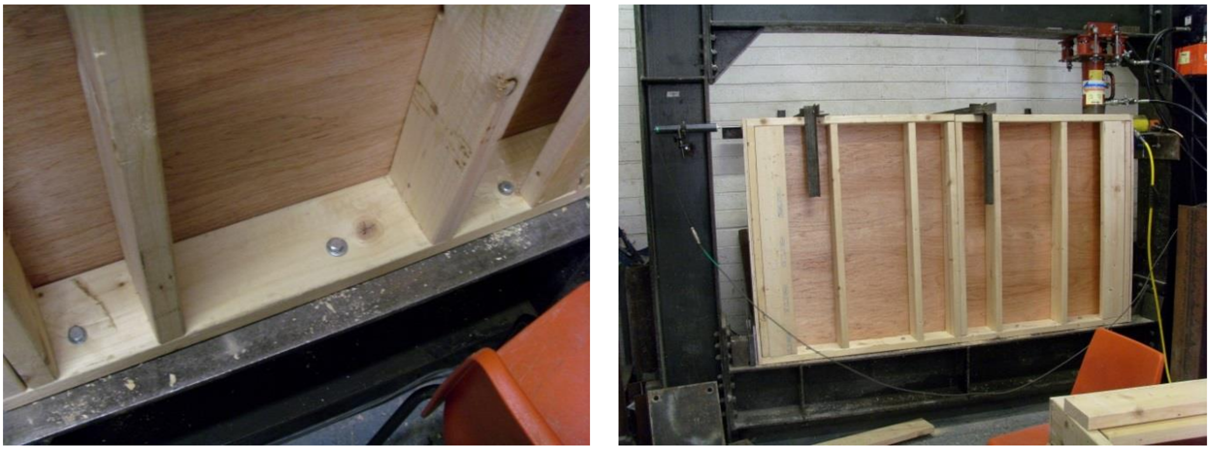

Figure 104: Images showing bolting of wall panels to test rig and guide rails to prevent movement during testing

With the panels bolted and the guide rails in place, a third attempt was made at carrying out Test 2A. Both means of restraint ensured the panels remained inline during the course of the test. A visual inspection was maintained throughout the test. As the pressure from the hydraulic jack increased, minimal signs of movement could be seen at the point of contact between the two wall panels. However, clear signs of movement could be seen across both wall panels as all vertical stud members began to slant and gaps began to appear between the studs and the horizontal top and bottom rails of each panel. This movement and separation of the members became more and more pronounced as the testing continued. The test concluded once the hydraulic jack had come to the end of its stroke. The extent of the damage induced in the test can be seen in Figure 105 as both test panels exhibited signs of twisting and separation during the lateral strength test.

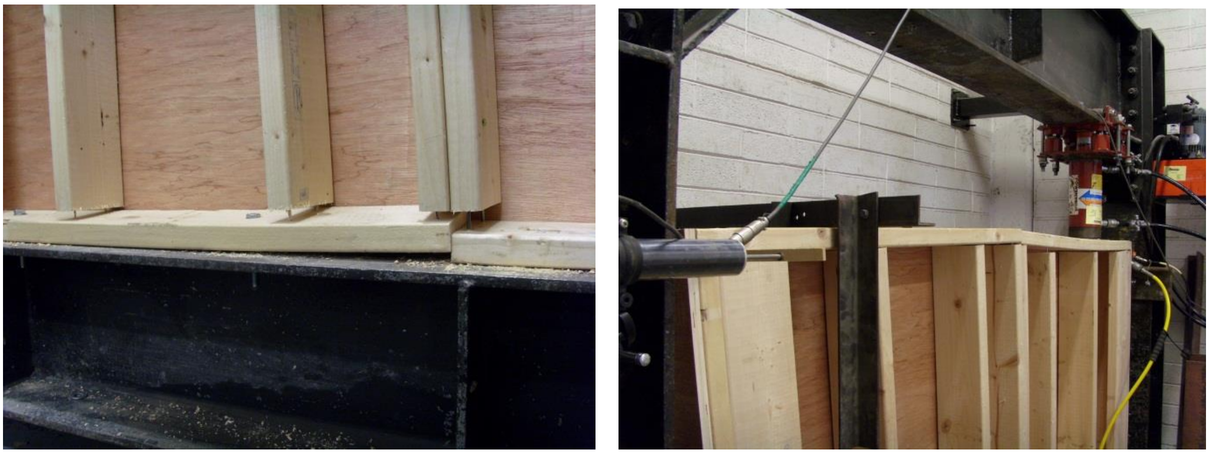

Figure 105: Images showing separating and distortion of panels after Test 2A was carried out

9.5.4 Data Analysis of Test 2A

As in both Test 1A and 1B, data relating to the amount of force (kN) exerted and the overall movement of the test panels was recorded and correlated. The results are shown in Figure 107. In terms of the lateral strength graph, the force applied by the hydraulic jack steadily grew until it reached a maximum force of 15.89kN with a corresponding displacement of 28.8mm. At this point the test panels did not fail but had significantly weakened. At a displacement value of 38.87mm, the hydraulic jack was at the end of its stroke. However, the graph indicates that a sustained period of pressure is imposed on the test panels from this time until the hydraulic jack is released.

In terms of the data relating to the movement of the test panels during the course of Test 2A, the movement corresponded with the load data as the movement increased with the amount of pressure exerted on the panels until a total displacement of 38.87mm was recorded. This distance is indicative of the distortion of the panels as seen in the images in Figure 106.

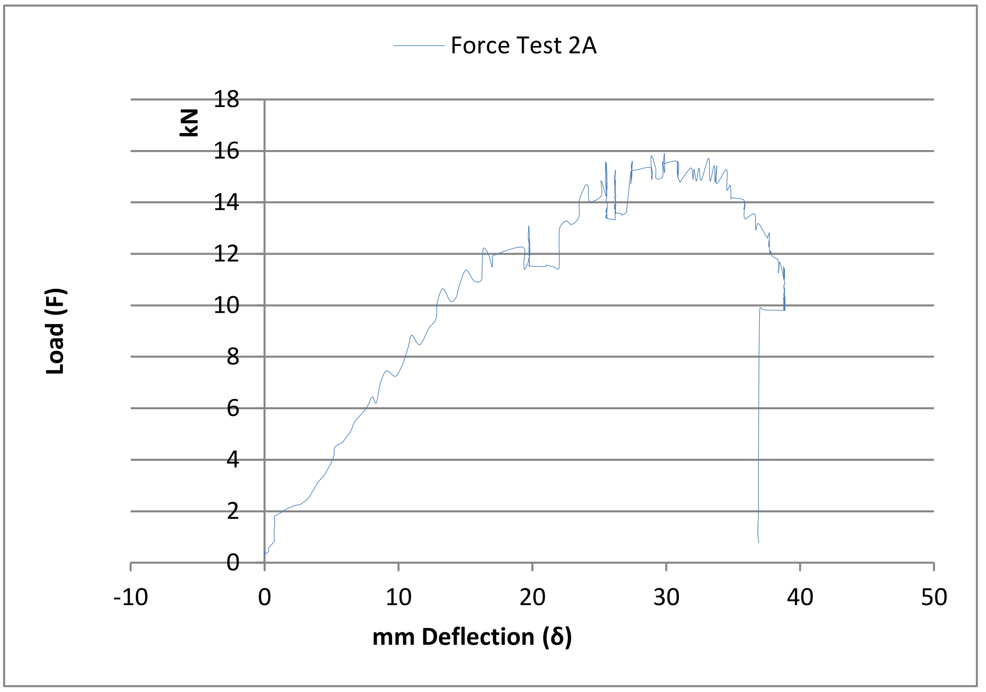

Figure 106: Force displacement graph of Test 2A

As indicated in Figure 107, the first 20mm of deflection during test 2A is represented by a linear trend line. This line indicates a steady increase in both loading and deflection and will be used for comparison with the Sherpa™ connection in test 2B. The racking stiffness of the screw fixed panels is approximately 12 / 16.25 = 0.74 kN /mm.

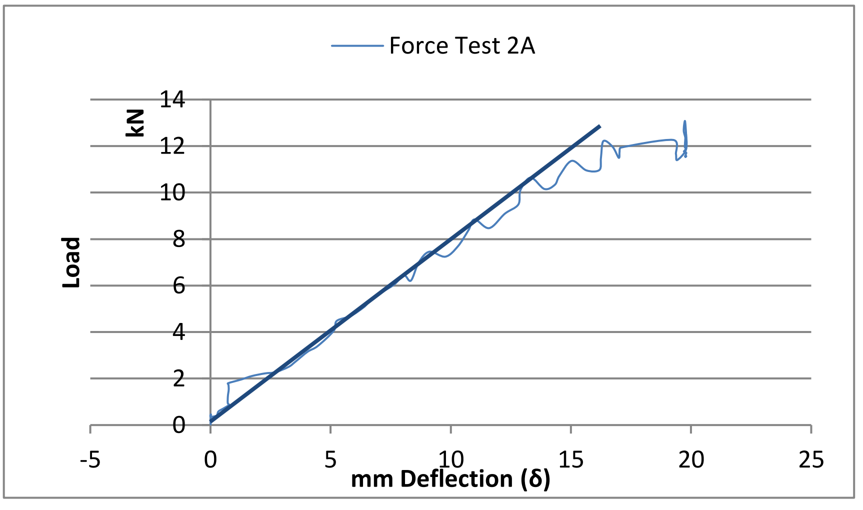

Figure 107: First 20mm of deflection during test 2A

9.5.5 Test 2A conclusion

Test 2A established the racking strength of a standard screw-fixed connection between two timber frame panels. The force displacement data is a clear indication of the integrity and rigidity of the screw connection between the test panels and the limit of their performance. Combining the data with the visible damage across both Panel A and B indicates that if the hydraulic jack had a longer reach, the panels would have eventually separated and collapsed. A visual inspection of the screws after the test showed that, as was the case in Test 1A, the screws had moved inside the timber studs and were now inclined rather than in the horizontal position that they were originally positioned in. Given the separation and distorting of the panels members around the joint, the connection would offer little racking strength other than in the connection.

9.5.6 Test 2B: Lateral (Racking) strength of a Sherpa™ fixed straight wall connection

Test 2B was carried out using the same rig set up as Test 2A. This saved a lot of preparation time as the experience of the previous test meant that both panels required bolting down to the test rig frame and the application of the same guiderails in order to constrain the panels to move in one plane. The Sherpa™ connectors were installed on each panel end. In order to maintain a visual inspection of the connectors, they were not countersunk into the timber and instead left proud of each panel end. The panels were lifted onto the rig by hand and joined. After the panels had been bolted and the guide rails applied, the displacement gauge and hydraulic jack were calibrated and the test began.

9.5.7 Visual inspection of Test 2B

Having both test panels restrained in the same way as Test 2A, ensured that the force and movement of the test panels acted in a linear fashion in the test rig. During the course of the test, the expected distortion of the panels took place as the vertical stud members slowly slanted away from the direction of the force being applied by the hydraulic jack. Small gaps began to appear between the horizontal and vertical members of each panel (Figure 106). However, these were not as pronounced as in test 2A. The position of the displacement gauge had to be adjusted during the test causing the sensitive node of the instrument to project forward before being repositioned on the test panels. As with Test 2A, the test concluded when the hydraulic jack had fully extended. Visually, the test panels had not failed or become badly damaged. (Refer to Figure 108).

Figure 108: Images showing damage to test panels after the completion of Test 2B

9.5.8 Data Analysis of Test 2B

Initially a load of approximately 4.6 kN was recorded for no displacement and this is clearly a false reading due to an apparent error in the computer recording of load data. However, thereafter an approximately linear load / displacement relationship resulted. From Figure 110 it can be seen that the stiffness of this structure when configured to represent racking is approximately (13.2 – 4.6) / 10 = 0.86 kN /mm. It is therefore apparent that the racking stiffness of the Sherpa set-up is superior to the screw jointed set-up. During the course of the test, the force applied to the test panels grew steadily until a maximum force of 15.45kn was imposed. This can be seen in the force displacement graph illustrated in Figure 109 and corresponded to a deflection point of 11.64mm.

During the course of the test the force applied to both test panels grew steadily until a maximum force of 15.45kn was imposed. This can be seen in the force displacement graph illustrated in Figure 109 and occurred at a deflection point of 11.64mm. As with test 2A, this was also the point at which the hydraulic jack had fully extended. Following this, the test panels withstood a steady average force of 13.42kN before the hydraulic jack was released. In the initial stages of the test a short dip in pressure can be seen at a deflection point of 8.83mm, this was due to the bottom right corner of Panel A lifting slightly causing a momentary release of pressure however, the Sherpa™ connectors remained intact and testing continued.

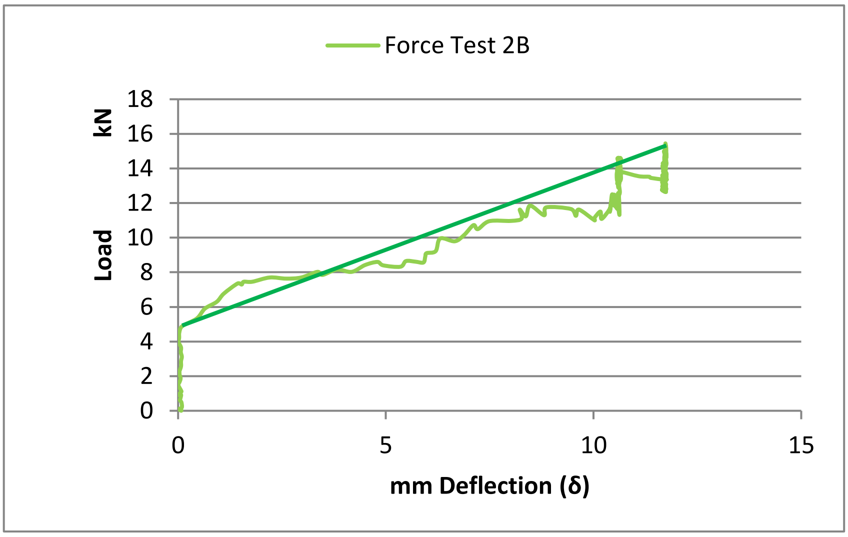

Figure 109: Test 2B force displacement graph

The movement of the test panels during the course of Test 2B can be seen Figure 110. The distance moved by the test panels increased as more force was applied during the test; however, movement was ultimately significantly less than in Test 2A. As shown in the graph, the measurement gauge records a maximum movement of 11.76mm. This distance is maintained during the time between the hydraulic jack coming to the end of its reach and the release of the jack.

9.5.9 Test 2B Conclusion

In order to adequately sum up the results from both tests, comparisons between both methods of connecting the test panels must be made, as was the case with Test 1A and 1B. A comparison between the racking stiffness showed that the Sherpa connector provided the most rigid joint (0.86 kN /mm by comparison with 0.74 kN / mm). This gives a clear indication of the difference in the physical characteristics of the two connection methods. Loading differed minimally in the two tests but the deflection of the Sherpa joint was considerably smaller. Test 2A exhibited a maximum force of 15.89kN and Test 2B gave a maximum force of 15.45kN. As already alluded to, the maximum deflection of Test 2A was 38.87mm. This was substantially more movement than occurred in Test 2B which gave a maximum deflection of 11.76mm. The difference of 27.11mm indicates the ability of the Sherpa™ connected panels to provide a more rigid structure during the lateral force testing.

In contrasting the results for force in both Test 2A and 2B, the displacement data relating to the tests can be presented in terms of a percentage improvement in the displacement of the panels using the connector given by:

$$27.11/38.87 * 100/1 = 69.74\%$$

The equation uses the difference between both test results to determine that there was approximately 70% more movement under a lateral force when connecting wall panels together by traditional screw-fixing than with the Sherpa™ connectors. This result is all the more noteworthy when the similar compressive force values are considered. As there was .44kN difference in the tests, the loading in both instances could be taken as equal in each case. From this point of view there is a large difference in the structural integrity of both tests. The screw-fixed approach resulted in much more movement across both panels and at the point of contact. As indicated, separation and damage to both panels was clearly visible during and after Test 2A.

9.5.10 Comparison of Test 2A and 2B

In order to adequately sum up the results from both tests, comparisons between both methods of connecting the test panels must be made, as was the case with Test 1A and 1B. A comparison between the stiffness of each joint is illustrated in Figure 112 as the force displacement results of both Test 2A and 2B are compared on one graph. This gives a clear indication of the difference in deflection between the two connection methods. However, there is little difference in the loading applied in each test. Test 2A exhibited a maximum force of 15.89kN and Test 2B gave a maximum force of 15.45kN. As already alluded to, the maximum deflection of Test 2A is 38.87mm this was substantially more movement when compared with Test 2B which gave a maximum deflection of 11.76mm. The difference of 27.11mm indicates the ability of the Sherpa™ connected panels to remain more rigid during the lateral force testing.

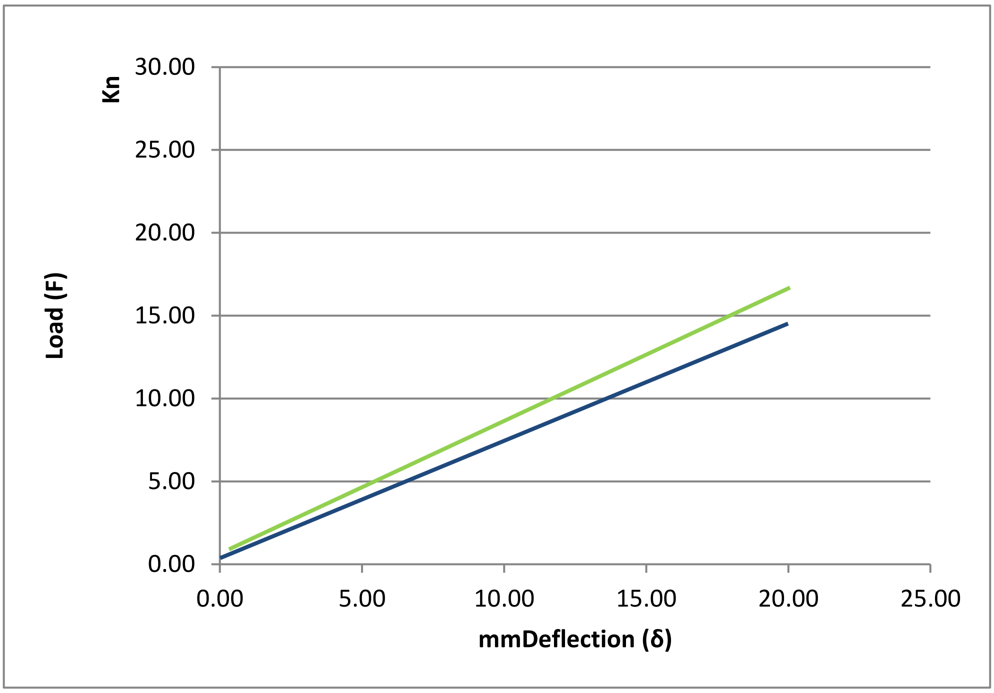

Figure 110: Force displacement graphs showing difference in stiffness of Test 2A (0.74 kN/mm) and Test 2B (0.86 kN/mm)

Although there is a difference between the stiffness measurements, this difference does not clearly represent the higher performance of the Sherpa™ connector.

The Sherpa connector exhibited continued strength despite the limited stroke of the hydraulic jack which prevented further readings during testing. It is evident the Sherpa™ connection is unquestionably superior from a structural integrity and robustness perspective.

Although the screws used to connect the panels did not shear or give way, they did move inside both end studs allowing for more movement across both test pieces. Damage was also clearly visible to both panels during the course of Test 2B. However; this was not as pronounced as in the case of Test 2A. In contrast with the screw fixings, the Sherpa™ connectors did not move or become dislodged during the course of testing. It was noted in Test 1B that the connectors pivoted during compression and began to enter the vertical timber studs during the test. This was not the case in Test 2B as the connectors remained rigid and vertical relative to the studs of both panels.

The lateral or racking tests carried out on both the screw-fixed and Sherpa™ connected test panels yielded encouraging results. In a typical timber frame building, racking strength and resistance to this force is key in maintaining structural strength and integrity. As in the case of Tests 1A and 1B, the test set-up was aimed at replicating a high loading situation in terms of the forces applied to the test panels. With this in mind however, the panels and connections are still required to perform to resist typical loading and a clear assessment of both connection methods needed to be assessed. As a further emphasis on the strength of each connection, the sheathing material used in each test case was 20mm plywood which offered more strength across each panel and ensured that the strength of the connection was the main focus of both tests. The lateral strength test proved that the Sherpa™ connectors are capable of withstanding greater forces than were ultimately achieved during testing. This is evident, due to the limited stroke of the testing equipment. The screw-fixed connection displayed adequate strength. However, as the data shows, more force and displacement would have resulted in the failure of the test panels at lower loads than for the Sherpa connectors.

Both the compressive strength and lateral force tests demonstrate the superior strength of the Sherpa™ connectors when compared with standard screw-fixed wall panels. In both cases, the connectors out-perform the screw-fixings and demonstrate their strength and resistance to movement. The results shown indicate that connecting wall panels using Sherpa™ connectors provides more rigid and stronger connections both in corner joints; with a 56% stronger connection offering 16.5% less movement under a compressive force and under a racking force where a significant difference can also be seen in the strength of the panels as the Sherpa™ connectors offer 70% less movement when subjected to the same lateral force. The results of both tests are significant in supporting the upgrading of traditional connection techniques in closed panel timber frame walls.

Chapter 10

Conclusion

The culmination of the development, trialling, thermal and structural testing of a new connection detail satisfies the overall aim of this research project. This aim was:-

To develop an innovative, viable method of connecting closed panel timber frame walls and assessing if this method can improve the energy and structural performance of a timber frame building when compared with existing assembly practices.

The overall aim is supported by research into specific objectives which have delivered outcomes and results that have shaped the research project and allowed conclusions, recommendations and suggestions for further research to be identified. Research and insight into the specific objectives are discussed in Sections 10.1 to 10.4

10.1 To Research and Document Current Timber Frame Construction Practice

From the outset, the research was designed to explore alternative methods of connecting closed panels whilst offering improved thermal and structural capabilities. In order to truly assess the application of a new approach or addition to timber frame construction, it was necessary to research past construction practices and changes in the methods and means of this construction process over time. Domestic construction using timber has been in existence for centuries across the globe. This can be seen in the integration of the industrial revolution in timber frame construction practice particularly in the United States of America at the turn of the nineteenth century. In this instance the improvement in timber frame construction came just at the right time as it satisfied the needs of the day's society.

Following this, the balloon system of timber framing progressed to the platform method ensuring safer and more rigid buildings. This again demonstrates the changeable and adaptable nature of timber frame construction.

Assessing the practice of timber frame construction used in today's construction industry resulted in a detailed analysis of the entire timber process including structure and chemical composition of wood, manufacturing methods and defects common to wood frame buildings in use. Looking at each of these areas in detail verifies that, unlike steel and concrete, timber is a living structural element. It is a renewable crop which is expertly and scientifically converted into a useable construction material. The level of skill involved in the conversion process was witnessed first-hand at the Glennon Brothers timber processing plant. It is the unique manner in which timber is processed and used that sets it apart from other materials. Timber is naturally strong in both compression and tension and if treated correctly has the capability to last as long as any concrete or steel structures.

As highlighted throughout the research project, construction practice is now focused on a widespread carbon footprint reduction. In terms of timber frame construction, open panel timber framing is still the most common in Ireland. However, closed panel timber framing offers more certainty in its application as internal components such as insulation are never exposed to weather ensuring their effectiveness in use. The open panel format results in a quicker prefabrication time as panels are not required to be insulated or completed in a factory.

The factory assembly basis of closed panel timber framing allows for more accuracy both in terms of structural layout and the quantity of materials used in each project. As demonstrated by Company A, the constant flow of panels through the factory ensures that each work station is competent in its fabrication task thus reducing material damage and ensuring a maintained rate of manufacture. Assessing the development of timber framing through time and up to its current standards clearly shows that closed panel timber framing is merely a small step up from open panel methods. For a country such as Ireland which is prone to wind and rain, constructing and fabricating on-site using the open panel method is a risk as exposure to the elements may lead to the degradation of internal components.

This is significantly reduced in the case of closed panel timber framing. Interestingly however, a critical element of the assembly in both methods takes place on-site. This is the completion of the internal vapour barrier and external breather membrane. From assessing both methods of timber frame construction, it is clear that the closed panel option is the future of timber framing in Ireland and possibly further afield. Closed panel offers a solid platform for the continuous development and upgrading of the sustainable capabilities of timber frame construction which is essential in today's construction industry. Although the primary focus of this research project centres on the development and integration of an improved connection method, it is important to note the significance of applying the connection methodology to the timber frame industry. Regardless of the sustainable advances made in the steel and concrete industries, the strength, workability and renewable aspects of timber, place it above any benefits offered by the respective man-made construction materials. Timber has shown it delivers a unique benefit of being one of the most basic and dated materials used in construction but yet it can be continually adapted and used alongside newer technologies and engineering options. Because of these factors, closed panel timber frame construction is not only certain to continue to improve in the construction industry but may become the predominant technique as sustainable construction becomes more standard than desirable.

10.2 To Improve Existing Methods of Closed Panel Connection

The impetus for the research is the upgrading of the current method of connection used between two closed wall panels. The development of a connection system which removed the necessity of open ended panels and provided a solid, reliable connection was a unique challenge. A further aspect to be taken into consideration was the application of a new connection method whilst maintaining the tried and tested pre-fabrication process of Company A and not disrupting panel production. In order to offer an improved method of on-site panel connection, a conscious decision was made to look for an 'off-the-shelf' connection method which could be applied to timber frame construction. The Sherpa™ 'Type B' connector suited the dimensions of the timber used in closed panel assembly and was used in conjunction with Compriband tape.

The feasibility project was the first instance in which the connection detail was applied on a live construction project and hence this application was novel in terms of construction research. Trial 1 provided an interesting and challenging backdrop to a standard home extension. There is no doubt that the Sherpa™ connectors were beneficial in the disassembly process of this building. Their use not only ensured that the building could be disassembled efficiently but also allowed the building to remain free from damage. This was a huge benefit when taking both the performance of the Sherpa's™ and the assembly process of Trial 1 into consideration.

In order to remove the issue of the connectors misaligning in the assembly process, the connection points for Trial 2 were repositioned at the very top of each wall panel. In theory, this would result in a more visible connection and more tolerance in terms of aligning the walls. Although the inability of the connectors to work efficiently on Trial 2 ultimately resulted in the replacement of the Sherpa™ 'Type B' connector in the development of the connection detail, a positive outcome of Trial 2 was the integration of both the vapour and breather membranes and the connection detail. The wrapping of the membranes around the ends of the panels and subsequent sealing with the Compriband tape demonstrated that a self-contained closed panel could be achieved.

When re-assessing the connection detail, the input of both Company A's workers and management was key in the re-development of a connection method that would be viable in both the manufacture and assembly of each wall panel. Although a new Sherpa™ connector was sourced and used, the connection detail changed completely from the one initially used in the first projects. Workers' opinion and assessment of the first detail was crucial in developing a second one that would work and satisfy the requirement of both management and workers alike.

Replacing the Compriband tape with the EPDM 'D' profile rubber sealant offered more confidence in the airtight and moisture proof seal. The EPDM could be applied in the factory rather than on site and, unlike the Compriband tape, did not expand or change shape allowing assembly to proceed as normal.

In striving to develop an improved connection detail, the most relevant and realistic methods of connection were used. This specifically relates to the Sherpa™ connectors as there layout and design are intended for use in the timber industry. Adopting the connectors for use in between closed panel's had not been attempted before in the timber frame industry and because of this, there was a lack of readily available results or instances with which any findings could be compared. As a result of this, the systematic assessment of the detail through a series of trials was essential in the development of a viable method. Through the series of trials, both positive and negative aspects of the connection detail became clear. Changes were made to facilitate the close tolerances associated with the Sherpa™ 'Type B' connectors in an attempt to make them viable for mainstream use by Company A.

Arriving at the connection layout used in Trial 3 required the input and focus from company management, prefabricators and assembly crew. The development of this connection system satisfied the pre-determined objective as from a technical viewpoint a new and unprecedented connection system had been developed and successfully deployed in a live construction project. The construction of Trial 3 using the developed connection detail was however, the first step in the overall assessment of the detail as a thermal and structural analysis was essential in fully defining its capability and potential within the industry.

10.3 Thermal assessment of connection detail

As already alluded to, the development of a physical connection detail that worked effectively during the assembly process was the key aspect of the research project. However, to further reinforce the use of the detail as a mainstream solution for Company A, it was necessary to assess the thermal performance of the connection method and compare it with existing connection practices. A two tiered assessment of the thermal performance of the detail was carried out. The first was the assessment of the previous details used in Trial 1 and Trial 2 using a thermal imaging camera. The inability to gain access to carry out a thermal survey of the revised detail as used in Trial 3 prompted the necessity of a second method of thermal performance assessment. The use of THERM software allowed for a concise analysis and greater insight into the behaviour of heat and thermal transmittance across each completed structure.

The thermal imaging assessments of both Trial 1 and 2 highlight the potential of the initially used Sherpa™ 'Type B' connection. Undoubtedly the connectors, due to their rigid fitting and excellent strength, provided a compressed connection between the wall panels resulting in improved airtightness along each junction. This is particularly evident in Trial 2 as a direct comparison between two corner joints constructed in the project provides visual evidence that the Sherpa™ connected junction delivers a closer, more airtight connection than a standard screw-fixed connection. Although the temperature difference between both cases is relatively small and not a cause for concern, a more detailed investigation into the thermal behaviour at each junction was necessary. The use of the THERM software satisfied this requirement and provided a clearer and more accurate method of measuring the standard, developed and re-designed connection details.

Comparing the standard corner connection layout for a timber frame structure with the detail used in Trial 1 and 2 indicates that the materials used in the build-up of each connection ultimately provide the internal wall surface of each dwelling with a standard temperature. However, the penetration of thermal activity into the wall from the external surface is greater in the detail using the Sherpa™ 'Type B' connector. This is in direct contrast to the thermal survey carried out in Trial 2 which showed less conductivity at the Sherpa™ connected corner when compared with the screw-fixed corner. The thermal images taken at the completed project are more useful in determining the airtight capabilities of the connection whereas the simulated results of the thermal activity across the wall are possibly more accurate with regard to indicating the sustained thermal performance of the structure.

This is further supported by the thermographic assessment of Trial 1which was also an inhabited, live building and demonstrated no thermal or airtight failures at the junctions of the wall panels where the Sherpa™ connections had been used. The THERM analysis of the wall junctions using the Sherpa™ 'Type B' connection indicated that the detail layout did not perform to the same standards as a typical screw fixed stud arrangement but the difference in performance was minimal.

Under THERM assessment, the re-designed Trial 3 connection detail using the Sherpa™ 'W8' connectors did perform better than the 'Type B' details used in Trial 1 and 2. The detail did not perform to the same thermal standards as a typical screw-fixed connection but the difference in performance was marginal. This indicates that the re-designed detail, with the extra layer of insulation at the outer-most corner offers an improvement on the original Sherpa™ connector and has the added capability of providing a more-airtight connection between two closed panel timber frame walls.

Although the detail did not equal or better the standard connection method, the ease of assembly, erection and the thermo-graphic evidence of a more-airtight connection when in place, supports the adoption of the improved connection method over a standard detail. Taking all of these factors into consideration, the refined connection detail as used in Trial 3 provided a satisfactory thermal performance and also had the capability of being adapted and used in mainstream closed panel timber frame construction.

10.4 Structural assessment of new detail

In terms of the compressive strength of the detail, the testing clearly showed the improvement in the strength of the joint between two test panels. The resulting 56% increase in the compressive strength of the Sherpa™ detail when compared with a standard screw fixed connection indicates the potential for the connection detail to be used in favour of standard screw-fixing in a mainstream capacity. This is further supported by an equally assertive result in relation to the structural stiffness of the panels. The Sherpa™ fixed connection exhibited a stiffness of 1.25 kN/mm compared to the stiffness of a standard screw-fixed connection (1.07 kN/mm). The superior performance of the Sherpa™ connection is clearly presented in these findings and this is further supported by the racking strength tests of both methods of panel fixing. As previously mentioned, the layout and execution of the compressive strength test was in effect a ‘worst case scenario’ which is not likely to be repeated in a typical timber frame construction environment. However, the test was the most suitable method of assessing the detail’s compressive strength and structural stiffness against a screw-fixed connection and in the confines of a closed panel timber frame wall joint.

The lateral or racking strength test was applied to the connection detail in order to assess the strength of the connection under lateral loading. Although both sets of test panels were capable of withstanding the total pressure exerted by the bottle jack at its full stroke, the test panels connected together using the Sherpa™ ‘W8’ connectors exhibited superior structural stiffness with a result of 0.86 kN/mm. By comparison with this, the standard screw-fixed connection had a structural stiffness of 0.74 kN/mm. This is a clear indication of the extra rigidity and reliability provided by the developed connection detail in comparison with a standard screw fixing.

The structural assessment tests were rigorous in their examination of the connection detail. Constructing live projects using a developing connection method outlined that there was potential for the Sherpa™ connectors to work.

The testing has proven that both the connection layout and the Sherpa™ connectors themselves offer significant structural improvement over the standard screw fixed method. The stiffness of each joint is a crucial factor in the overall structural integrity of a completed building. The structural testing, highlighting the improved joint stiffness satisfied the main objective of this element of the research; the detail is superior to the screw fixed option in both tests which further promotes the possibility of Company A using the detail as a permanent replacement.

10.5 Research question

Both the compressive and lateral strength test demonstrated the connection details emphatic improvement on the existing connection method. This, in conjunction with the thermal performance of the connection detail offers a viable solution to the overall research question of the project. The chain of development which led to the arrival at the prescribed connection detail was necessary as it depicted a trialling period used to assess the viability of employing pre-manufactured aluminium connectors to improve an existing connection method. The arrival at the viable connection detail and method was in no doubt as a result of the previous connector trials. As equally important was the input from company management and workforce and the belief that the connection detail was a positive step and could be applied in practical situations. The supportive thermal and structural analysis further reinforced this belief and the development and application of the functional detail that integrated with the factory fabrication and on-site completion process was made a reality.

10.6 Recommendations:

The research highlighted in this project is an initial attempt to resolve the stated problem and the steps taken to offer a remedy and develop a solution. Arriving at a satisfactorily connection detail is essentially the first step in solving the broader needs of the company to improve timber frame construction techniques. Implementing the connection detail into the prefabrication routine of company A is the next step of the issue resolution.

For this to become a reality it is recommended that:

- The connection detail is used in a limited number of future projects by Company A to truly assess its performance and ease of use.

- An integrated project delivery programme is created by the company with the adoption of Building Information Modelling incorporated into each design. By using this system within the company each project could be meticulously planned with the location of all connection points pre-determined at the design stage. This will then filter into the design drawing stage, prefabrication and onto site assembly. This is essential in the avoidance of on-site miss-matches in the connection sequence of a particular project.

10.7 Limitations to the research

Throughout the research process, numerous limitations and hindrances were encountered. As Company A were a commercial company the application of the connectors, particularly during the three trial projects was relegated in importance to the need for job completion. This was particularly relevant to the assembly process and sequence used in the projects. In Trial 2 in particular, the removal of the Sherpa™ connector was requested by Company A on the basis that it was slowing down project completion.

In terms of the thermal analysis of the connection detail, the use of the THERM software provided a comprehensive source in which the thermal performance of each wall structure could be compared and contrasted. This is however one method of carrying out this thermal evaluation and a limitation of the research was the availability of time to carry out more detailed thermal evaluations of the performance of the final connection detail and its comparison with a standard screw-fixed connection. The thermal surveys of completed buildings were carried out to assess the performance of the connection detail in a completed project. One obvious limitation on the research in this instance was the prevention of entry into the completed Trial 3 to carry out a thermal survey of the finalised detail in use. In addition to this, a top of the range thermal imaging camera would have been preferred for use on the thermal surveys.

The structural testing of the connection detail provided few limitation as a complete comparison was enabled between the two different connection types. Alongside the structural evaluation it was hoped that a practical test could be carried out to test the airtight capabilities of the EPDM rubber strips in the final connection detail. However, time did not permit this.

Although there were limitations to the research, Company A provided flexibility and coherence in allowing the research to be carried out on live projects and allowed the research to run its course. This ultimately resulted in the successful development of the connection detail.

10.8 Further Research

On completion of this research project and taking into account the conclusions that have been put forward, there are a number of areas for further research:

10.8.1 The overall implementation of the new connection detail into Company A

Undoubtedly the detail would be introduced on a trial basis for a number of initial projects and spread across all projects eventually. Before that point can be reached however, an assessment of the details would have to be correlated after each initial project. This would take into account opinions and experiences from management, prefabrication workers and assembly workers as to how the detail is performing and if any further changes need to be made as it becomes more frequently used by the company.

10.8.2 Further strength testing of the connection detail from a practical view point

As already alluded to, the compressive and lateral strength of the connection detail has been assessed. Both structural tests carried out were extreme in nature, fatigue testing over a length of time would provide a deeper assessment of the detail and give an indication of its performance over time and in keeping with the stresses and strains imposed on the connection if it was used in a typical domestic timber frame construction. A comparison of this data with data collected from an identical fatigue test carried out on a standard screw fix connection would further inform the case to adopt the new connection detail in closed panel timber frame construction.

10.8.3 Assessing the optimal wall make-up for use with the connection detail

As highlighted in this research project, there is a large focus on the reduction of energy used in standard domestic construction. The Chapter 3 descriptions of the many materials and combinations of use within a timber frame project give a perspective of how detailed and scientific each wall make-up is. Further research in this area would help to establish the optimal wall make-up for integration into Company A and for use with the new connection detail. There is no doubt that materials and construction methods will continuously evolve however, a functioning connection system in conjunction with an energy efficient wall design will provide a complete consumer package for future construction.

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Appendix A

Interview with Brendan Farrell, Operations manager at Glennon Brothers timber processing plant, Longford, Co Longford 08/03/2013

What is the preparation process for freshly received timber?

We receive roughly 10 truckloads or 300m^3 of dimensioned lumber from our conversion factory located in Fermoy, Co Cork. Once received, the timber is stacked by a machine which inserts separator sticks in preparation for the kiln drying procedure. We have a total of 7 kilns here, usually there are a minimum of 4 in operation at any one time. Our boiler system here at the plant is self-sufficient and burns waste timber and sawdust.

What is the most common species process by the plant?

90% of the timber we process is Stika Spruce which 5% Norway spruce and the remaining 5% is Larch. All three timbers are very common in appearance and are easy to dry dimension and treat.

What method of log conversion is most used?

In our Fermoy plant, the machinery is state of the art and a band saw system is used to convert logs into usable dimensioned lumber. Chippers are also used in the Fermoy plant to remove bark and branches before conversion; this waste material is collected and recycled, usually for agricultural purposes.

What is the typical process of drying and dimensioning timber in the Longford factory?

In a usual week, timber that is received on a Monday morning is processed and stacked in our drying kilns. The timber is typically removed after two days but this time frame largely depends on the level of moisture contained in the timber. Our aim is to reduce the moisture content of the timber down to 18%; this is to allow for eventual moisture regain when the timber is removed from the kiln. Once removed, the timber is processed through our dimensioning and testing section of the factory, this takes one day and after the timber is either shipped untreated or goes to our pressure treatment section of the factory, this adds another day to the process so a batch of timber that is required to be pressure treated usually takes one week to pass through our factory, non-treated timber, such as fencing posts, take roughly four days.

How are the timbers dimensioned and tested?

This is a fully automatic process but is preceded by human input. As the timber is taken from the kiln to the dimension stage each row of timber is checked for moisture content by one of our workers, this is recorded in a log book for our records. This is also the first stage of a visual inspection as any blatantly obvious defects are removed. Following this, the timbers are individually fed to our planer via a conveyor system. Each timber is planed to the correct dimension as it passes through a large automated planer. This machine uses rotating plane heads to cut the timber to size along its length. Depending on the size and quantity of timber required, the planer heads can be changed and used to grade other timber sizes such as battens.

Are quality checks applied? If so, what ones? How often?

Directly after the automated process every timber passes through a strength grading machine which automatically applies a stress test to each timber. The machine rejects any timbers which do not meet the strength standards. After this the timber is stacked into pallets ready for shipping. A visual inspection is also made at this point and any timbers which are visibly defective are removed by hand. This is in keeping with standards outlined by TRADA as 10% of timber can be removed after visual inspection. Once the timber is planed, graded and has passed a further visual inspection a stamp is applied to show the timbers classification, grading, batch number and a 'CE' mark which is new addition to the grading process and is required by BM TRADA EN14081-1

After seasoning, how is the timber dimensioned?

Timber is dimensioned when it passes through the planning machine. When dried, the timber has shrunk to 2 to 3 mm below its required size. Once out of the drying process, air and moisture will enter the timber causing it to swell to its required size. The entire timber will never conform to a uniform size as there will always be between 2 – 4mm deviations along its edges.

What is the % of output going to the Irish Market?

Currently 25% of our processed timber goes to the Irish market

What is the % of output being exported?

75% of or processed timber is being exported to the UK and France

Is there a pressure treatment facility at the factory?

Yes, we have two treatment facilities; the first is a standard evacuated cylinder for pressure treatment of standard dimensioned lumber. Our cylinder is approximately 10 metres in length which allows us to fit a large amount of timber for every pressure treatment. It takes roughly 1 hour and 20 minutes to carry out a full treatment process. The pressure treatment process is fully automated with a technician on hand to monitor progress and operation of the cylinder. In this process the timber is coated with a preservative known as Osmose Naturewood AC 500. This impregnates the timber to a satisfactory depth. This is mostly used on timber that will be exposed at all times to weather conditions such as fencing timber of external battens. In the case of Standard CLS timber, it is treated with a different preservative known as Protim Clearchoice E406. This preservative is applied to the timber in a low pressure evacuated cylinder which follows the same routine as the high pressure cylinder but the preservative does not impregnate the timber to the same degree.