Light Steel Framing:

Improving the Integral Design

Aitor Amundarain[1], José L. Torero[2], Asif Usmani[3], Ahmad M. Al-Remal[4]

ABSTRACT

Light Steel Framing has been extensively used in cold climate countries due to its good thermal and structural behaviour. Improved thermal behaviour results in positive environmental impact essential for sustainable construction. This modern building technology entered the British market a few years ago and it is gaining great popularity and credibility. Heat loss reduction and tenement thermal comfort have been the main driving forces defining the design of these frames. The present study evaluates and develops the way these structures are designed. The main issue to be addressed is how striving for thermal efficiency can lead to structural weakening and poor fire performance. Thus, the main objective of this study is to establish a methodology of integral design that can lead to a better comprehensive performance. Both, experimental and computational work has been carried out in order to optimize the design of Light Steel Framing.

KEYWORDS
Light Steel Framing, Modern Methods of Construction, Sustainable Construction, Energy Efficiency, Thermal Insulation

INTRODUCTION

Energy used in dwellings accounts for about 30% of all energy consumed in the United Kingdom [DTI 2006] and a similar proportion of energy-related emissions of carbon dioxide to the atmosphere. With issues, such as global warming, energy efficiency and affordable housing that are of paramount importance in this age, efforts to address these challenges through improvement of the construction technologies is essential. By incorporating at the planning stage low-energy design elements into new build and refurbishment schemes, architects and specifiers have a unique opportunity to reduce a dwelling's energy use before construction even starts. The user aims to achieve a required indoor climate by minimising cost and energy consumption of the building.

Light Steel Framing (LSF) is a novel construction technology that has been extensively used in cold climate countries due to its good thermal and structural behaviour. This modern building technology entered the British market a few years ago and it is gaining great popularity and credibility. One of the more common concerns amongst homebuyers, architects and building specifiers when it comes to LSF is their energy efficiency. Builders framing their projects with lightweight steel desire to achieve comparable levels of insulation as those achieved with other constructive forms such as wood frames while using the same insulating materials.

[1] PhD Student, School of Engineering and Electronics, The University of Edinburgh, Edinburgh EH9 3JL, UK. Phone: +44 1316 507241, Fax: +44 1316 506554, a.amundarain@ed.ac.uk

[2] Professor, School of Engineering and Electronics, The University of Edinburgh, Edinburgh EH9 3JL, Director, BRE Centre for Fire Safety Engineering. The University of Edinburgh, Edinburgh EH9 3JL Phone: +44 1316 505723, Fax: +44 1316 506554, j.torero@ed.ac.uk

[3] Reader, School of Engineering and Electronics, The University of Edinburgh, Edinburgh EH9 3JL, UK. Phone: +44 1316 505789, Fax: +44 1316 506554, a.usmani@ed.ac.uk

[4] Structural Engineer, Powerwall Systems Limited, Lanarkshire, ML2 OEQ, UK. Phone: +44 1698 373305, Fax: +44 1698 374503, ahmad@powerwall.co.uk

Several studies have been carried out to characterize the heat transfer in steel framed wall assemblies and compared them to timber framed structures. The Canadian Sheet Steel Building Institute [CSSBI 1999] monitored the natural gas consumption of six bungalows in Toronto with the same characteristics and specifications, three of which were LSF and the rest were timber framed. They showed that the average gas consumption for the LSF homes was 7% less than for the wood framed homes. The North American Consortium for Advance Residential Building [CARB 1997] carried out a similar analysis in Maryland with bigger size properties and the results showed that the steel framed homes consumed 33% less energy than the timber framed houses.

However, there is room for potential improvements in the design of LSF external walls. The main drivers are to achieve self-containment of walls and to further increase thermal efficiency. The current tendency of the LSF industry is to transform the construction practice adopting a more off-site manufacturing approach. This gives versatility to the LSF production and consequently a reduction of a qualified work force. Thermal bridging has been identified as the main issue to be resolved for improved thermal efficiency. Thermal bridges occur due to the steel members. This causes higher rate of heat transfer by conduction through the steel framing than through other parts of the wall [J Kosny 2004]. The drive to achieve improvements in these areas could potentially result in reduced effectiveness in other aspects that are not generally considered priorities. The two main issues that require added consideration are fire and structural performance. Modifications on the LSF design have the potential to affect its behaviour under fire conditions. Although these assemblies must comply with fire British Standards [BS 476], to date, there are only a few studies on the matter [Moore 2003, M. Feng 2003 and M. Feng 2005]. The applicability of this assessment method is questionable and existing research is currently inconclusive, thus further work is needed. In addition, modifications on the LSF design have the potential to affect its structural behaviour, which needs to be evaluated.

This paper focuses is embedded within a study to define an integrated design methodology that includes all aspects. Nevertheless, in this particular study focus is given only to the assessment of the tools used to determine the thermal efficiency and fire performance of LSF external walls.

LSF Thermal Efficiency and Fire Performance

LSF is a building technique based around vertical structural members called studs, which provide axial load-bearing capacity and stiffness to the structure. The studs are connected together by trusses or noggins in order to enhance structural resistance and control lateral deformation of the whole structure. The empty space left around the steel frame is usually filled up with thermal, acoustic and fire resistant insulation and finally covered by various sheathing materials. Figure 1 shows a sketch of a LSF external wall. The existence of a drainable cavity in external walls is necessary [NHBC Standards] to take away any content of water that could have been accumulated within the wall due to diverse factors such as condensation, infiltration, etc... LSF constructions have usually been completed with brick work in the outer side of the external walls.

The popularity of LSF assemblies is increasing because they provide the following advantages:
- *Lower cost*. LSF walls are light weighted compared to other assemblies, hence saving on foundation and handling costs. Steel prices are very stable. Steel is 100% recyclable and does not rot, nor allow growth of mildew. Design life is long and maintenance is rarely required.
- *Ease and quality of construction*. Manufacturer-controlled material properties eliminate grading and site quality checks. Geometry is very accurate. Members are cut to size with pre-punched assembly and service holes. Due to steel's uniformity and stability in dimension, there is little chance for gaps to form as a result of shrinking or warping. This will reduce the likelihood of air infiltration.
- *Stability and strength*. Steel is dimensionally stable which greatly reduces the need for movement joints. Strength of the assembly does not normally degrade with time.

These assemblies are being used as load bearing external walls, non-load bearing infill walls and partition walls in low rise buildings (up to a maximum of six storeys). However, and due to improvements in the way LSF is designed and its self containment they are being incorporated in high rise constructions as infill and partition walls. Complete buildings, including roof and floor members, have also been successfully built with LSF members in a similar manner to timber framed construction.

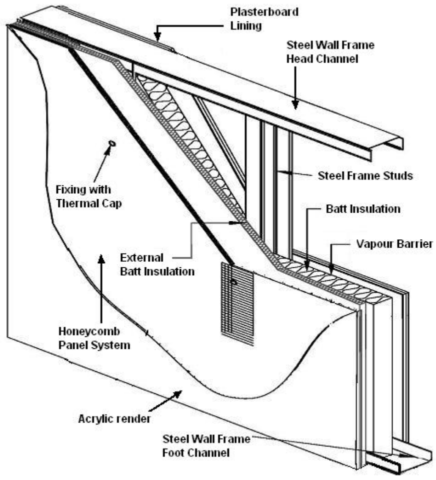

Figure 1: LSF External Self Contained Walling System

The walls and their insulating value contribute to the overall energy performance of a home and represent approximately 25% of the total heat lost [Action21 2006]. This value might vary depending on the source of information selected.

Thermal insulation of the building envelope is characterised by the U-Value (i.e. the Thermal transmittance). U-Value is a measure of how much heat will pass through one square metre of a structure when the air temperatures on either side differ by one degree. U-Values are expressed in units of Watts per square metre per degree of temperature difference (W/m^2K). Lower U-Values signify better levels of insulation. Current building regulations [BRE&W 2006] are meant to make buildings more energy efficient and tackle climate change. In order to comply with the mandatory standard, target U-value methods can be used in design of the building fabric. These methods limit the U-value for external walls in new dwellings to 0.30 W/m^2K, which applies to LSF. This value is likely to be reduced in the near future in order to converge with international requirements (Kyoto protocol 1997).

The current trend is to push further the way LSF structures are designed in order to achieve heat loss reduction. However, any modifications on the LSF design have the potential to affect, not only its structural behaviour, but also its behaviour under fire conditions. While structural behaviour has been extensively studied, fire behaviour is hardly understood.

EXPERIMENTAL AND COMPUTATIONAL TOOLS

Assessing thermal efficiency and fire performance can be done using a number of protocols. Some of these are standardized others are ad hoc. Standard tests generally require real scale assemblies as well as complex methodologies, thus many times it is useful to rely on small scale ad hoc tests and modelling to understand the general trends, before resorting to large scale tests.

The experimental data is used to define the behaviour and subsequently performance can be extrapolated to the desired scenarios. High performance software packages such as ABAQUS, ANSYS or TRISCO can be used for this purpose. However, there are other commercial programs such as HEAT2 and HEAT3 which are easier to use and can be effectively applied for the purpose of the present calculations. The computational simulations require a good definition of the geometry analyzed and of the materials and their thermal properties. On top of that, specific boundary and initial conditions need to be specified. The test methods used will be described as follows.

Guarded Hot Box

The main apparatus used to experimentally determine the thermal transmittance (U-Value) of any system including LSF is the Guarded Hot-box. A series of tests were conducted using one of these boxes that satisfy closely the criteria given by British Standards [BS 874]. The Guarded Hot Box consists of two chambers, a hot and a cold one. A representative test sample is sandwiched between these chambers and the objective is that heat will flow from one chamber to the other only through the sample. This allows precise quantification of the heat flux. Figure 1 shows a schematic of the arrangement and details of the theoretical background and dimensions can be found in the standard.

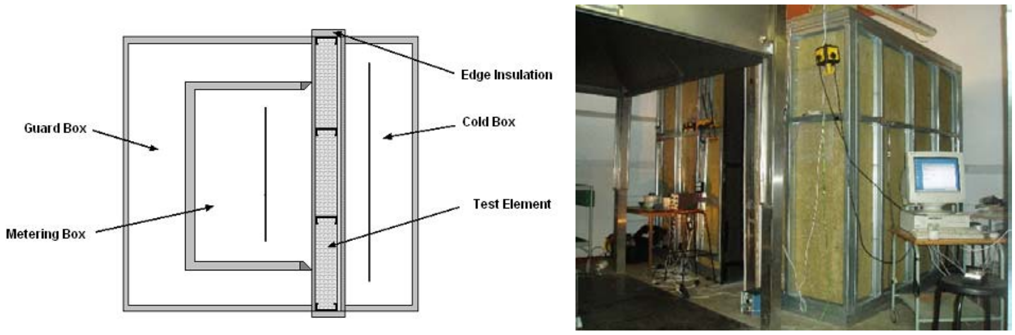

Figure 2: Guarded Box a) Schematic b) Actual

The hot chamber comprises an inner box (metering box) surrounded by a larger box (guard box). The metering box has an area of 1.2 m by 1.2 m and the guard box area is 2.4 m by 2.4 m. Both boxes are heavily insulated and have environmental control to minimise heat flow. The objective is to isolate the metering box so that all heat flowing will be through the sample. A PID controller based upon the measured temperature difference over the metering box walls, controls the environment in the guard box. Inside the metering box there is a baffle to allow proper definition of the radiation fields inside the enclosure. The cold box has the same area as the guard box and is kept at a constant ambient temperature. The metering box is kept at a constant temperature of 48ºC. A total of 64 type T thermocouples connected to 8 different data loggers are used to record the temperatures in every test. Six AC fans circulate the air in the guard box and three variable speed DC fans allow the control of the air velocity within the metering volume. Temperature homogenization is achieved in the cold box by using three AC fans that circulate the air around it and put it in contact with the cooling system. The cooling system consists of a spiral tube through which temperature controlled water is introduced. Two 1000W tubular heaters are used to provide the heat necessary to keep the temperature at the appropriate values.

Preliminary Low Heating

Conceptual designs are firstly assessed by subjecting a test sample to the effect of low external radiation produced by a tubular heater (similar heating levels as those of the hot box). The boundary conditions imposed are the temperature in the exposed face and natural ventilation is allowed around the test element. Internal temperatures are mapped and recorded. Infra red thermography was also used to establish temperature differences between different areas of the assembly. The camera was a FLIR Thermacam P60, with a detector Focal Plane Array (FPA) uncooled microbolometer, temperature range -40°C to +120°C. This camera translates emissions within the 7.5 μm – 13 μm into temperatures. The camera was set to an emmisivity of 0.96 therefore the temperatures can not be considered the real ones of the back face. Nevertheless, temperature differences can be clearly established showing hotter and colder areas (see Figure 3).

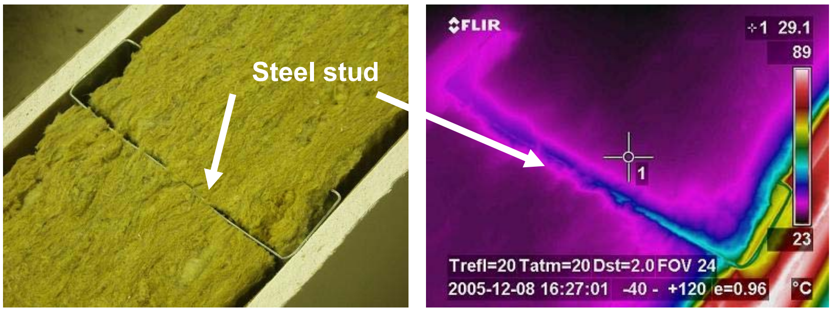

Figure 3: Characterization of LSF Thermal Bridge a) Test Specimen b) Thermography

High Radiation Panel (Fire Test)

This experiment is used to establish the performance of LSF under heat fluxes typical of fire. The nature of this test is similar to the preliminary low heating experiment explained above. The difference lies in the severity of the heat flux imposed over the test element. The heat fluxes established for fire conditions range between 7-60 kW/m^2. The heating element used for this experiment is a ceramic radiant panel with no enclosure fuelled by a mixture of propane and air, which is shown in figure 4. Due to its nature, the heat flux from the heating element is constant. The heat flux reaching the exposed face of the test element could be varied either by altering the distance from the panel to the sample or by changing the flow of propane. Following the high radiation tests preliminary conclusions about fire performance can be drawn and predictions can be made of the behaviour of a specimen subjected to British Standard [BS 476]. The translation from the current tests to the larger scale BS 476 and to realistic fire behaviour is achieved with the aid of computational models.


Figure 4: High Radiation Panel and Representative test Sample

SOME CONCEPTUAL DESIGNS

The previous tools have been applied to some conceptual designs and they have proved to be adequate. Based on the conclusions drawn, a methodology for the development of new LSF designs can be established.

Self contained external walls

In order to achieve self containment of external walls, the external layer of brickwork has been substituted by an aluminium honeycomb to which glass fibre skins are bonded using epoxy resins. Honeycomb panels are developed from space technology where very high tensile, compressive and impact resistance is required in an extremely lightweight durable panel. Different approaches have been considered in order to create a drainable cavity. The original approach was the use of foam insulating channels (such as phenolic foam, EPS, etc…) between the steel frame and the external honeycomb. The second approach was based on creating a drainable honeycomb panel by drilling holes through the aluminium matrix and substituting the foam insulating channels for batt insulation, which perform better under fire conditions. Figure 5 shows a comparison of the outcome obtained from applying the preliminary low heating experiment to both of the approaches mentioned. The EPS channel approach has shown not only an inferior thermal efficiency but a poor fire performance due to the low melting point of the channels. Because of that, only the drainable cavity approach was tested on the guarded hot box.

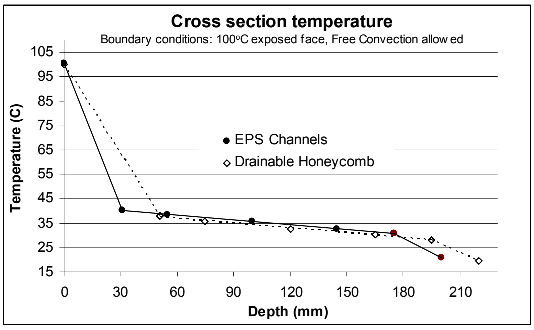

Figure 5: Temperature comparison from preliminary low heating experiment

The hot box experiment was carried out with prototypes of a walling system comprising a drainable honeycomb panel and the following characteristics. 140 mm and 1 mm thick C section steel frame, two sheets of plasterboard internal lining, mineral wool internal insulation, polythene vapour barrier, breather membrane, mineral wool external insulation, drainable honeycomb panel and acrylic render, which corresponds to the one in figure 1. The experiments allowed obtaining U-Values for different variants of the design and optimising the choice of insulation. All U values obtained where below 0.3 W/m^2K, which satisfy the current regulation. It was also demonstrated that the measured values closely matched the computational simulations. An important observation was that significant reduction of the U-value could be achieved by varying the insulation density.

The full Fire Rating Test [BS 476] for an external fire was executed for the EPS channel configuration described above. The criteria that determined the failure after 38 minutes of structure exposure was loadbearing capacity. Special attention is paid to this failure mechanism because it will allow defining the mechanisms that lead to failure. However, the rest of possible failure criteria are also assessed. The temperature on the exposed flange has been selected as the critical value for failure. By running High Radiation Panel experiments, the external heat flux evolution imposed by the furnace over the test element can be approximated. This heat flux evolution is then applied over any other configuration, bearing in mind the effect that the insulating properties of the test sample are going to have over the heat flux imposed. The drainable honeycomb approach has given a much better performance. Even though the full test has not been terminated, a fire rating exceeding 60 minutes is expected.

Thermal bridge reduction

Any further means of improving the thermal efficiency of LSF external walls keeping its self containment properties begins by reducing the existing thermal bridge. There are several approaches in this respect [J Kosny 2004], which recommend insulating sheathing, steel stud web modification, steel stud flange modification, spacers to reduce contact area between the steel studs and exterior sheathing, reflective surfaces to improve thermal resistance of air space, local foam insulation for studs and a combination of foam/steel studs. Before any effort is made to reduce the thermal bridge, this needs to be characterized. The following figures show the temperature distribution throughout a test element comprising a 140 mm C-shaped steel stud, 120 mm mineral wool internal batt insulation, covered with one internal and external plasterboard lining on both sides, which correspond to figure 3. A constant temperature of 100ºC has been imposed in the exposed face until reaching steady state conditions.

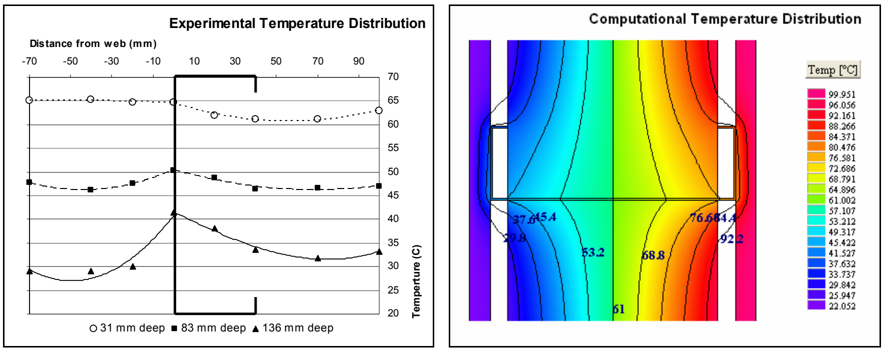

Figure 6: Thermal Bridge Characterization a) Experimental b) Computational

The partial symmetry shown by figure 6a is due to the lateral heating imposed from the web of the stud towards the batt insulation. That figure also shows that the heat reaching the hotter flange does not flow perpendicularly to the wall. It is conducted through the hotter flange, along the web and to the unexposed flange. This flange produces backward heating of the mineral wool contained between the flanges. By using local foam insulation for studs and a combination of foam/steel studs, this heat will be kept within the steel section, improving its thermal performance.

Steel stud modification

One of the most efficient techniques to reduce the thermal bridge is the modification of the steel stud by the production of straight slots [T Hoglund & H Burstrand 1998, N R Elhajj 2002]. However, this has an important impact in the structural and fire performance. This was initially ignored for the purpose of examining the various options but it will be very much in the forefront when choosing the best option. Extensive computational simulations and experimental work has been carried out in order to get initial conclusions. Each of the configurations simulated represents an effect to be evaluated, such as the slot length, spacing between slots, effect of staggering the columns and the reduction of slotted columns.

The approximation used to evaluate the effect of the slot arrangement involves steel removal from the web. This has been kept constant (3% and 5%) in all the different configurations analyzed. However, in practical applications there is no steel expected to be removed from the web and the slots are created by a punching process to form internal web stiffeners giving more strength to the assembly. The next figures show the preliminary results obtained from the analysis of a prototype containing both a slotted stud (7 columns of slots, 3mm wide, 70 mm and a separation of 30 mm, 3% of steel removed) and a non-slotted stud for comparison. The studs are hold by a metal frame and comprise 120 mm mineral wool internal batt insulation, covered with one plasterboard sheet on both sides.

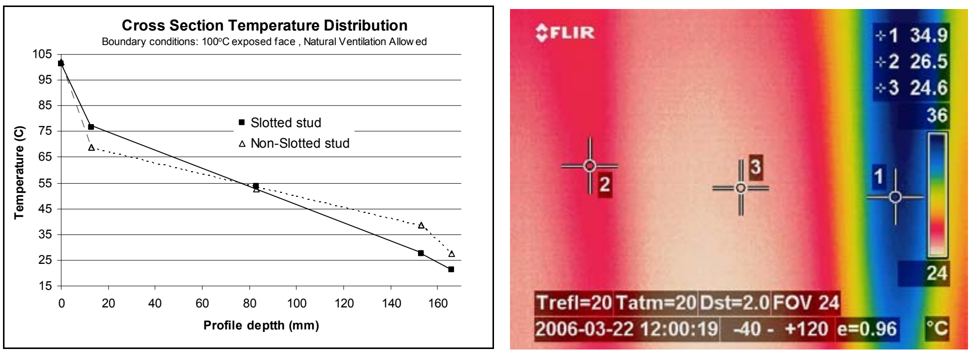

Figure 7: Steel Stud Modification a) Experimental b) Thermography

Figure 7b shows qualitatively the temperature in three different points by using thermography. Point 1 corresponds to the plasterboard over the non-slotted stud flange, point 2 to the plasterboard over the non-slotted stud and point 3 to the plasterboard over the batt insulation. Figure 7a shows the temperature distribution through the cross section on steady state conditions and proves that the slotted stud approach is an option to be considered.

CONCLUSIONS

Preliminary conclusions have been drawn in all the aspects analyzed. However, more robust computational simulations are expected to give a better understanding of the thermal efficiency and fire performance of LSF. It has also been identified the need to incorporate structural aspects in the subsequent analysis.

The experimental tools have proved to be adequate. The results obtained from them are within the error bar expected. However, further improvement of their capabilities will lead to more precise results. This will simplify and improve the coupling with the computational outcome.

The initial conceptual designs explained before are being analyzed, developed and implemented. New ideas are currently being incorporated in the design process. It is expected that in the near future, the total acceptance of this technology will be a fact that will contribute to a global CO_2 emission reduction, keeping high levels of fire safety.

REFERENCES

BRE&W. Building Regulations for England and Wales 2006. *Part L. Conservation of fuel and Power*

British Standard BS 476:2004: *Fire tests on building materials and structures*

British Standard BS 874:1973: *Methods for determining thermal insulating properties with definitions of thermal insulating terms*

Canadian Sheet Steel Building Institute (1999). *Lightweight Steel Framing Technical Bulletin.* Volume 5, Number 1.

Consortium for Advance Residential Building (1997). *Case Study, Dearbought Townhouses,* Frederick, Maryland, USA.

D B Moore, T Lennon (2003). *Fire safety of light steel framed houses.* BRE Milestone no. 202-999

DTI. Department of Trade and Industry. *Energy Consumption in the United Kingdom, Final energy consumption by final user 1970 to 2004.* (2006)

Jan Kosny, Jeffrey E. Christian , and André O. Desjarlais. *Improving Energy Performance of Steel Stud Walls, Steel Framing Can Perform As Well As Wood.* Oak Ridge National Laboratory, Buildings Technology Centre, USA.

M. Feng and Y.C. Wang. *An analysis of the structural behaviour of axially loaded full-scale cold-formed thin-walled steel structural panels tested under fire conditions.* Thin-Walled Structures, Volume 43, Issue 2, February-February 2005, Pages 291-332

M. Feng, Y. C. Wang and J. M. Davies. *Structural behaviour of cold-formed thin-walled short steel channel columns at elevated temperatures. Part 1: experiments*. Thin-Walled Structures, Volume 41, Issue 6, June 2003, Pages 543-570

Nader R. Elhajj. (2002) *Developemnt of Cost-Effective, Energy-Efficient Steel Framing. Thermal Performance of Slit-Web Steel Wall Stud.* NAHB Research Center, USA

NHBC Standards*. National House-Building Council. 2006 Technical Standars.* Chapters 6.9 and 6.10

T. Hoglund, H. Burstrand. *Slotted steel studs to reduce thermal bridges in insulated walls.* Thin-Walled Structures 32 (1998) 81–109

Warwick District Action 21. Sustainable_construction. Existing_buildings 2006. Available from: http://www.action21.co.uk