External walls partially filled with insulation, and the potential to "top-up" the residual cavity.

Literature Review

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Contents

Executive summary

This review found that the connecting voids in partially filled cavity walls leads to considerable variation in thermal performance. Whilst photographic records found considerable evidence of gaps in the insulation resulting from poor site practice and installation, research also shows that relatively small breaks between insulation sheets or gaps between the wall and insulation result in a thermal bypass. As the gaps and connecting voids increase air circulation, convection currents and pressure induced exchanges reduce the effectiveness of the thermal barrier. Where effective installation is possible, the topping up of partially filled cavity walls with insulation shows potential to improve the thermal performance of the wall. In the cases reviewed, the installation of blown mineral wool fill reduced variation in heat flow and increased thermal performance. By filling the voids with insulation the passage of air and thermal bypasses were restricted.

Further work should be undertaken to explore how different products, densities and fill practices affect the ability to maintain an effective thermal seal.

Introduction

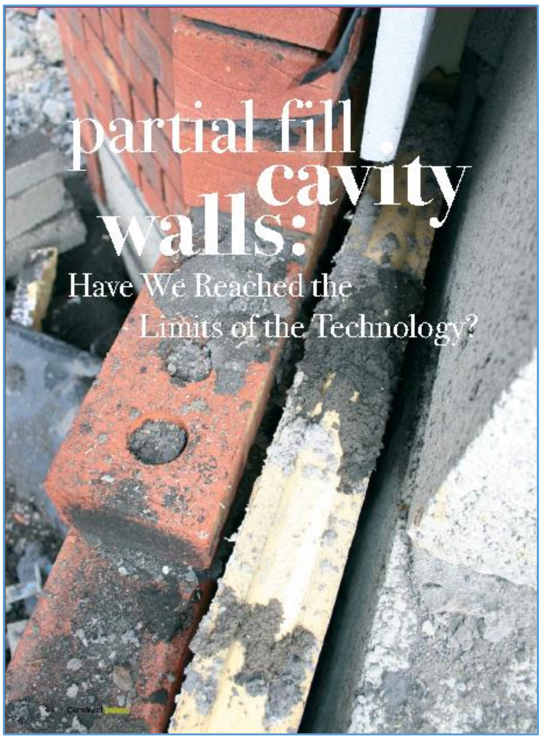

Figure 1 2014 Construct Ireland article on partial fill cavity walls

Joseph Little's (2014) article for Construct Ireland, titled "Partial fill cavity walls: Have we reached the limits of the technology?", puts forward a strong case that partially filled cavities cannot reliably meet the thermal demands for high-performing building fabrics in the UK domestic sector. The review offers a compelling critique of partially filled cavity walls, explaining their history, their popularity and aspects of their underperformance. Reasons for underperformance are listed, explained and in some cases remedies suggested; but with problems as diverse as design, subcontractor culture, site conditions, material properties and substitutions, lack of training and understanding of some quite complex heat loss mechanisms, it becomes apparent why Little has come to these conclusions. It compares partial fill to fully filled cavities and timber frame construction; and whilst thermal underperformance was observed in all 3 types of construction, the level of this was most disconcerting for partially filled masonry walls. A question that is not addressed is; what are the remedies for the >20% of dwellings, built with partially filled walls, necessary to meet the government's carbon reduction commitments and reliably ensure that effective thermal enclosures are achieved?

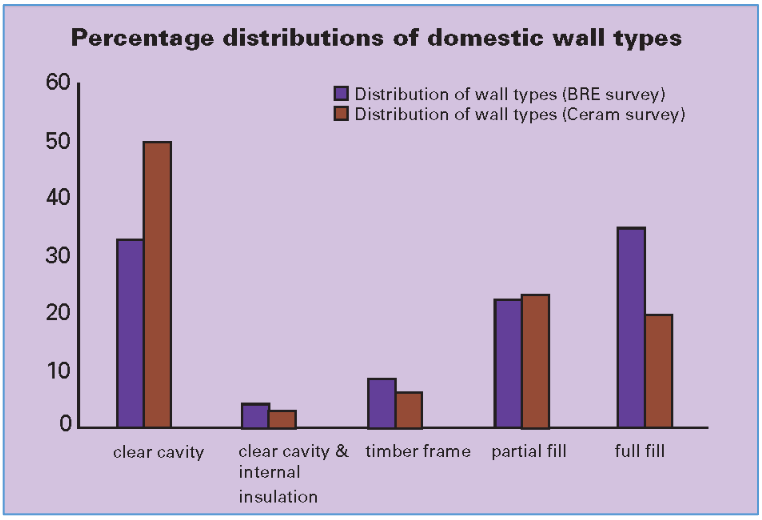

Figure 2 UK wall types distribution (Little, 2014)

Traditionally, U-value assessments of existing partially filled walls automatically assumes that the performance of the walls will be that of the regulatory target of whatever compliance model is in force at that time. Figure 3 shows an example of this from an EST/BRE report (EST, 2004). As a target figure, these U-values are going to be the maximum possible performance achievable in practice and not the mean value achieved. The vast majority of models will assume that there is no natural distribution up to these values, but everything built in these periods achieves the maximum possible theoretical thermal resistance, unaffected by workmanship issues, design errors, product substitutions, wind-washing, moisture effects, air movement effects and all the other heat transfer mechanisms and supplementary factors affecting performance discussed in this report.

1992-1998	Mainly brick/block cavity walls (with single glazing). Predominant type: facing brick; partially-filled cavity; inner leaf concrete blockwork. Effect of wall ties and mortar joints ignored.	0.45 (nominal) 0.55 (actual)
	Brick/cavity/block walls. Cavity partially filled with insulation. (Used in conjunction with double glazing to satisfy Part J.)	0.60
	Timber frame walls with 89mm studs fully filled with mineral wool quilt	0.42
1999-2002	Mainly brick/block cavity walls with insulation. Predominant technique: facing brick; partially-filled cavity; concrete block inner leaf.	0.45
	Timber frame walls with 89mm studs fully filled with mineral wool quilt insulation	0.42
2003 to present	Brick/block cavity walls with insulation. Predominant technique: facing brick, partially-filled cavity, concrete block inner leaf.	0.30
	Timber frame with variable stud depth and variable insulation materials. 140 mm studs fully filled with mineral wool is commonly used.	0.30
	Some use of insulated dry-lining	0.30

8. 1992-98
The simplest way to comply with the 1997 Technical Standards, Part J, was to construct walls with a U-value of 0.45 W/m²K and install single glazed windows. Many house builders chose to meet the regulations by opting for higher wall U-values, typically 0.60 W/m²K, coupled with double glazing.

Figure 3 Defaults U-values of existing house walls in Scotland (EST, 2004)

Whereas solid external walls and uninsulated external cavity walls are now generally thought to perform better thermally than the accepted estimated values outlined in RdSAP Appendix S (BRE/DECC 2014); insulated cavity walls, both fully filled and partially filled, are being shown to underachieve with respect to predicted values. Figure 4 shows insulated cavity walls underperforming by 29% over calculated values and 34% over typical RdSAP values. However, this report does not differentiate between different types of insulated cavity. The work, assumed that all 109 cases in this study were fully filled based on borescope observations, although also admitted that in some instances this diagnosis might not be completely correct. The report did suggest that partial ventilation of the external wall cavity would increase the U-value of the wall by 0.22 W/m^{2}K (Figure 5). It is unclear what is meant by partial ventilation as it could be assumed that most cavities are constructed with weep-holes and numerous other types of 'unintentional' ventilation. It is not fully understood what is meant by the level of partial ventilation identified and how this was measured to quantify the 0.22 W/m^{2}K figure suggested. Nevertheless, the 'partial ventilation' suggested could possibly be negated by 'topping-up' the residual cavity.

Table 1 - Summary of results and RdSAP values

Wall type	Number of cases	**Measured U-values: mean (standard deviation) W/m²K***	**Measured U-values: median W/m²K**	*Calculated U-values: mean (standard deviation), W/m²K*	*Calculated U-values: Median W/m²K*	**Typical RdSAP U-values[a] W/m²K**	Ratio of (Mean measured U-value) / (Mean calculated U-value)	Ratio of (Mean measured U-value) / (Typical RdSAP U-value)
Solid wall, standard[b]	85	**1.57 (0.32)**	**1.59**	*1.90 (0.20)*	*1.92*	**2.1**	*0.83*	*0.75*
Solid wall, non-standard[b]	33	**1.28 (0.42)**	**1.28**	*1.91 (0.49)*	*1.68*	**2.1**	*0.67*	*0.61*
Uninsulated cavity	50	**1.38 (0.30)**	**1.43**	*1.40 (0.11)*	*1.41*	**1.6**	*0.99*	*0.86*
Insulated cavity	109	**0.67 (0.23)**	**0.63**	*0.52 (0.08)*	*0.51*	**0.5**	*1.29*	*1.34*

Figure 4 Measured median U-values for insulated cavity walls exceeding both calculated U-values and typical RdSAP U-values (DECC/BRE 2014).

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There are additional uncertainties not included in Table 6 that will affect the U-value of the measured walls. For example, the unknown moisture content of the masonry at the time of the measurement. This is likely to be more marked in the calculation of the U-value for the solid and unfilled cavity walls and less so in the filled cavity walls where the insulation will dominate the thermal performance. For the unfilled cavity walls another possible uncertainty in the calculated U-value is the degree to which the cavity may be unintentionally vented. For example, the calculated U-value would normally assume an unventilated cavity. However, if the cavity were partially ventilated this could result in an increase in U-value (and hence the calculated U-value) of around 0.22 W/m²K.

Figure 5 Uncertainties surrounding U-values measured by DECC/BRE 2014, and the increase in U-value caused by a partially ventilated cavity (DECC/BRE 2014)

Indeed, most masonry external walls will show some signs of degradation over their lifetime which results in fissures developing from shrinkage, weathering, movement, wall-fixings, flora or chemical processes. BS 8208-1:1985 discusses the suitability of cavity walls for filling with thermal insulants and refers to BRE Digest 251 (BRE 1995) which categorises cracks and damage in a 5 point scale.

Category 0 (isolated and up to 1mm width) cracks are classed as negligible and have no effect on the structural integrity of the dwelling, categories 1 and 2 may also be ignored in many cases for structural purposes if movement is not progressive and weather-tightness is maintained; however, such gaps in the masonry outer leaf will affect the ventilation of the external wall cavity and could create the 'partially ventilated' condition required for the increase in U-value of 0.22 W/m^{2}K (Figure 5) to be applicable.

Performance of Partially-Filled External Walls

In-situ performance measurement

In 1990 Jan Lecompte expounded on some of his own previous work, along with other research by Kronvall (1982) and Schuyler & Solvasin (1983) which actually compared measured values of heat transfer through insulated walls with those expected through computer simulation of the details investigated (Lecompte, 1990b). The work stressed that the underperformance of the structure's measured values of heat transfer was primarily a workmanship issue rather than a problem with the insulation materials themselves. Lecompte (1990b) investigated air flow through the "inevitable" gaps around cavity insulation boards in partially-filled cavities and modelled the underperformance of them. The results showed a 158% increase in heat transfer for a 3mm gap and a 193% increase at a 10mm gap. The heat transfer was compounded further by additional gaps between the insulation board and the warm inner leaf that resulted in thermal looping and air movement by natural convection. Natural convection and convective loop heat losses in insulated wall structures had been the subject of investigation throughout the previous decade and studied in some detail by the Princeton team of Harrje, Dutt and Gadsby (Harrje *et al.*, 1985), but their work had focused on more typical American construction of insulated timber frames. Lecompte took Harrje *et al*'s theories of natural ventilation and applied them to the Northern European trend of insulating cavity masonry walls to increase their thermal resistance. The work also considered the measurements made by researchers such as Siviour, who had already identified gaps between designed and as-built thermal performance of some European houses (Siviour, 1981).

In 1994 a standard methodology for the measurement of in-situ U-values of walls was published, ISO 9869:1994 *Thermal insulation – Building Elements – In-situ measurement of thermal resistance and thermal transmittance*. The average-method, detailed in this protocol, is the method by which most of the in-situ U-value measurements reported in this document have been obtained; where the external and internal temperatures are taken and combined with the measured heat flux over an extended period to produce the in-situ U-value. However, Annex E (Heat Storage Effects) shows that this may be an unreliable method in many cases where the measurements are taken in occupied dwellings (Figure 6); and in the majority of studies found no mention is made of the correction factors necessitated in this method to transform a 3D dynamic measurement into a U-value, which is by definition (ISO 6946:2007) a steady-state value for mono-directional thermal transmittance.

That analysis assumes that the temperature profile, at the start and at the end of the test period, corresponds to that for steady state conditions at the internal and external temperature concerned. This is illustrated for a single layer uniform wall in figure E.1, line a. However, since only the internal and external temperatures, not the temperatures within the structure, are measured, the profile could be either b or c. This means that observations of the change in mean internal or external temperatures is not necessarily sufficient in itself to determine the change in heat storage.

Thus, if, for example, b applied at the start of the test and c at the end, the difference, represented by the shaded area in figure E.1, is a change in heat storage in the element that is not allowed for in correction factors of 7.2. Nevertheless it is possible to test the data for this particular effect: the first few hours of data can be discarded and the remainder re-analysed (over an integer number of days) to see whether this affects the result. If so, it is likely that the temperature profile at the original start of the test period was not typical.

The correction method also relies on reasonable estimates of the thermal mass of the various layers of the structure. Where the details of the structure are not known these estimates may not be sufficiently accurate for the criteria in 7.2 to be met. In that case the correction method cannot be assumed to provide a reliable result.

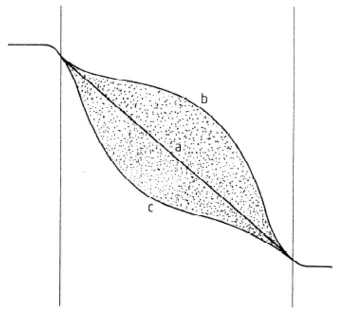


Figure E.1 — Possible temperature profiles through a building element (line "a" represents the steady state condition)

Figure 6 The effect of dynamic thermal mass effects on in-situ U-value calculation (ISO 9869:1994)

Based on this review, Doran (2001) appears to be the first to report a major UK study of as-built thermal performance of external walls. The study was limited to the use of 2 heat flux plates per property to measure the thermal performance of various construction elements in 30 different buildings, 8 of which included partially filled external cavity walls. Measurements were taken and calculations made in accordance with ISO 9864:1994 with the buildings inhabited, calculations of expected performance were calculated using ISO 6946. The large discrepancy between calculated and measured U-values for the partially filled walls was attributed solely to construction defects, rather than suggesting that the technology itself might be responsible to some measurement discrepancy. Of the 8 partially filled walls, where in-situ thermal transmittance was measured, 2 of the 3 walls which gave values closest to those calculated had potentially more airtight outer leaf constructions. For the 2 walls, one was externally rendered and the other had a double-brick outer skin, both may have provided a more airtight outer leaf, and thus might have affected the measured values, the degree of ventilation of the wall cavities was not discussed. It also recommended the possible adoption of 'Swedish-style ΔU-values' to account for some of these differences (a suggestion followed up on by Anderson (2006) and subsequent versions of ISO 6946 where ΔU-values are included in the U-value calculation method), which varied in some cases displayed by double the calculated thermal transmittance (Figure 7).

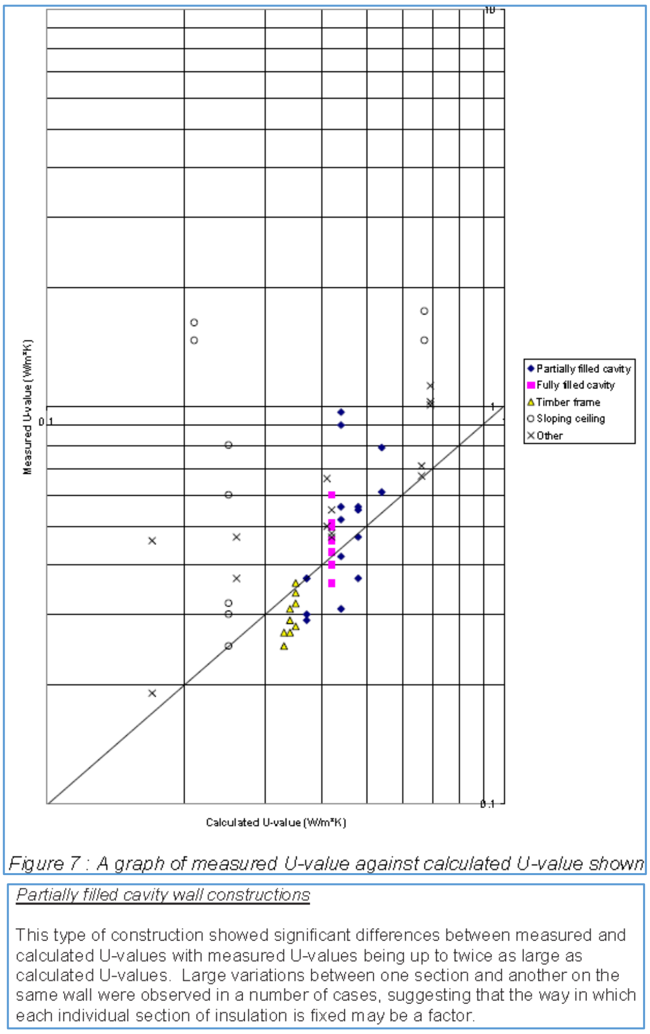


Figure 7 Comparisons of calculated vs measured partial-fill U-values (Doran 2001)

In his follow-up investigation in 2008, Doran concentrated specifically on pre- and post-fill cavity wall insulation in 70 properties using the same techniques as in 2001, but with improved surveying techniques[1] in an attempt to quantify “the realisable benefits of cavity wall insulation to existing properties” (Doran, 2008). The summary of the earlier report claimed that true U-values of partially-filled walls were only 0.1 W/m^{2}K above expected values (Figure 8). Doran mentions many additional factors which may result in higher thermal transmittance values being measured in real situations that were not included in the 2001 report, including: rain-penetration, displacement, interstitial condensation, inhomogeneous insulation materials[2], air movement, distribution of air voids, insulation installation techniques and cavity conditions prior to installation of the insulation. The issue of air movement around partial-fill boards was identified as of particular concern and suggested fitting a wind-barrier to improve performance (Figure 9).

[1] Specifically, more advanced borescope and thermal imaging techniques.
[2] Variations in material density.

U-value measurement on new dwellings

Research carried out by BRE between 1998 and 2000[Ref 1] showed that true (measured) U-values were often higher than expected, even when thermal bridging and wall ties were taken into account. The difference depended upon the type of construction. The differences between measured U-values[Ref4] and expected U-values[Ref5] were found to be as follows:

1. For internally insulated cavity walls, 0.05 W/m^2K (approx.)
2. For fully filled cavity walls, 0.05 W/m^2K (approx.)
3. For partially filled cavity walls, 0.10 W/m^2K (approx.)

[Ref 5] Bernard Carr, BRE, private communication, January 2005. It was found, through visual inspection of cavities under construction, that whereas some types of materials (eg mineral wool) can accommodate rough surfaces to some extent, semi-rigid materials are often poorly-fitting against such surfaces, and this can be especially problematic in partially-filled cavity walls.

Figure 8 Performance gap of new-build cavity walls, and why rigid-board partial-fill may underperform mineral wool (Doran, 2008)

Partially-filled cavity walls are a particular case where air movement could be particularly detrimental to thermal performance. In the case of partially-filled cavity walls, therefore, it is possible that there may be some benefit in fitting a wind barrier or breather membrane adjacent to the insulation, preferably located between the insulation and the residual cavity. Any tears or cracks appearing in the membrane during construction, should, of course, be repaired (e.g. taped) before completing the construction, but this might not always happen in practice.

Figure 9 Suggested solution to the issue of air movement around partial-fill insulation (Doran, 2008)

The Good Homes Alliance's case study of a development in Middlesbrough, for the Technology Strategy Board, illustrates the difference in the gap between expected and realised performance of 2 different types of wall construction on the same site. It involved 2 different external wall types in one multiple-dwelling construction; an internal concrete frame with a partially filled cavity with rigid board insulation with mineral wool filled timber infill panels, both shared the same brick outer leaf (GHA, 2014). Figure 10 shows the results of the in-situ U-value measurements made by the Leeds Beckett research team as part of the building performance evaluation for this development, with the level of thermal underperformance of the partially-filled sections of external wall comparing unfavourably to the closed timber panels that made up the remainder of the walls. The external wall cavity was common to both construction types; however, the partial-fill insulation is directly exposed to air movement in the external wall cavity whereas in the closed-panel timber frame sections the insulation material is shielded from it.

Table 2. Performance Gap

	Predicted	Measured [Leeds Met]
Air permeability	3 $m^3h^{-1}m^{-2}$@ 50Pa [design SAP, 2010]	5.52 $m^3h^{-1}m^{-2}$@ 50Pa
Wall [timber panel section]	0.19 W/m^2K [design SAP]	0.18-0.30 W/m^2K 0.25 W/m^2K [mean]
Wall [concrete column section]	0.21 W/m^2K [design SAP]	0.32-0.66 W/m^2K 0.42 W/m^2K [mean]
Window [kitchen & bedroom, centre-pane]	1.24 W/m^2K [design SAP]	1.33-1.54 W/m^2K 1.41 W/m^2K [mean]

Figure 10 Performance Gap table from GHA 2014, showing predicted and actual performance of the 2 main external wall types.

Hens and Roels hygrothermal study of 5 simultaneously tested walls showed different levels of thermal underperformance for partially filled and fully filled external cavity walls (Hens *et al.*, 2006). The level of reduction of thermal resistance below the calculated value was noticeably greater for both partial fill walls tested; with measured thermal resistance for the partial fill lower than that for fully filled walls at all heights measured, even though the calculated thermal resistance was greater (Figure 11).

Table 7 Calculated and measured thermal resistance

Height Cm	Wall 1 S, full fil	Wall 2 S, part. fill	Wall 3 S, part. fill	Wall 4 S, full fill	Wall 5 E, full fill
Calculated	2.90	3.05	3.05	2.90	**2.90**
Measured					
230 cm	3.19	2.82	2.04	3.19	**2.88**
160 cm	3.34	2.66	2.67	2.86	**3.29**
30 cm	2.26	1.61	1.55	2.14	**1.68**
Weighted average	**2.99**	**2.38**	**2.20**	**2.72**	2.72
Loss in %	-	22	28	6	6

Figure 11 Partially filled test walls displaying lower than expected R-values compared to fully filled test walls (Hens et al., 2006)

In Wingfield *et al.* (2009) the partially-filled external cavity walls were measured during the course of coheating test undertaken to assess the performance of a cavity party wall pre- and post-filling for a project funded by Eurisol. This study showed a range in external wall U-values throughout the period of investigation (Figure 12) that were greater than anticipated. The external walls failed to achieve the design value of 0.29 W/m^{2}K during the test (Figure 13). Only the gable wall of the end-terrace property tested displayed an average daily mean in-situ U-value that was less than double that of the design, it was suggested that this may be due to it being a large expanse of uninterrupted wall (without openings) making it easier to build. The report also measured air velocity in the external wall cavities and suggested a simplified link between measured U-value and wind speed (Figure 14) suggesting some type of wind-washing of the external walls; however, wind direction was not examined. Some deconstruction of the test houses was allowed. This revealed issues with the partial fill rigid board insulation (Figure 15) which is expounded upon in some detail in the report, and further illustrated with images from other Leeds Beckett University (formally Leeds Metropolitan University) publications.

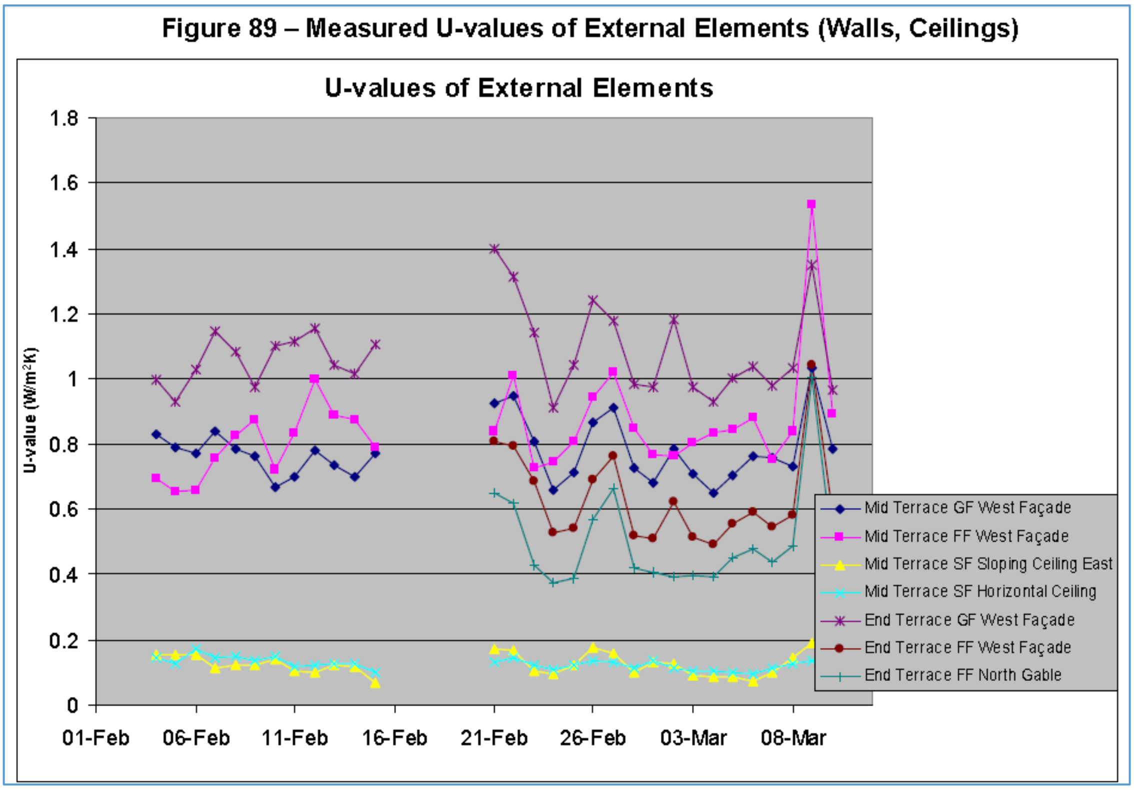


Figure 12 External wall in-situ U-value measurements from Wingfield et al., 2009

Table 25 – Mean U-values of External Elements

External Element	Mean U-value Before Filling Party Wall (W/m²K)	Mean U-value After Filling Party Wall (W/m²K)
Mid Terrace Ground Floor External Wall	0.76	0.79
Mid Terrace First Floor External Wall	0.80	0.88
Mid Terrace Sloping Ceiling	0.12	0.12
Mid Terrace Horizontal Ceiling	0.13	0.12
End Terrace Ground Floor External Wall	1.06	1.09
End Terrace First Floor External Wall	n/a	0.63
End Terrace First Floor External Gable Wall	n/a	0.50

Figure 13 External wall in-situ U-value measurements from Wingfield et al., 2009

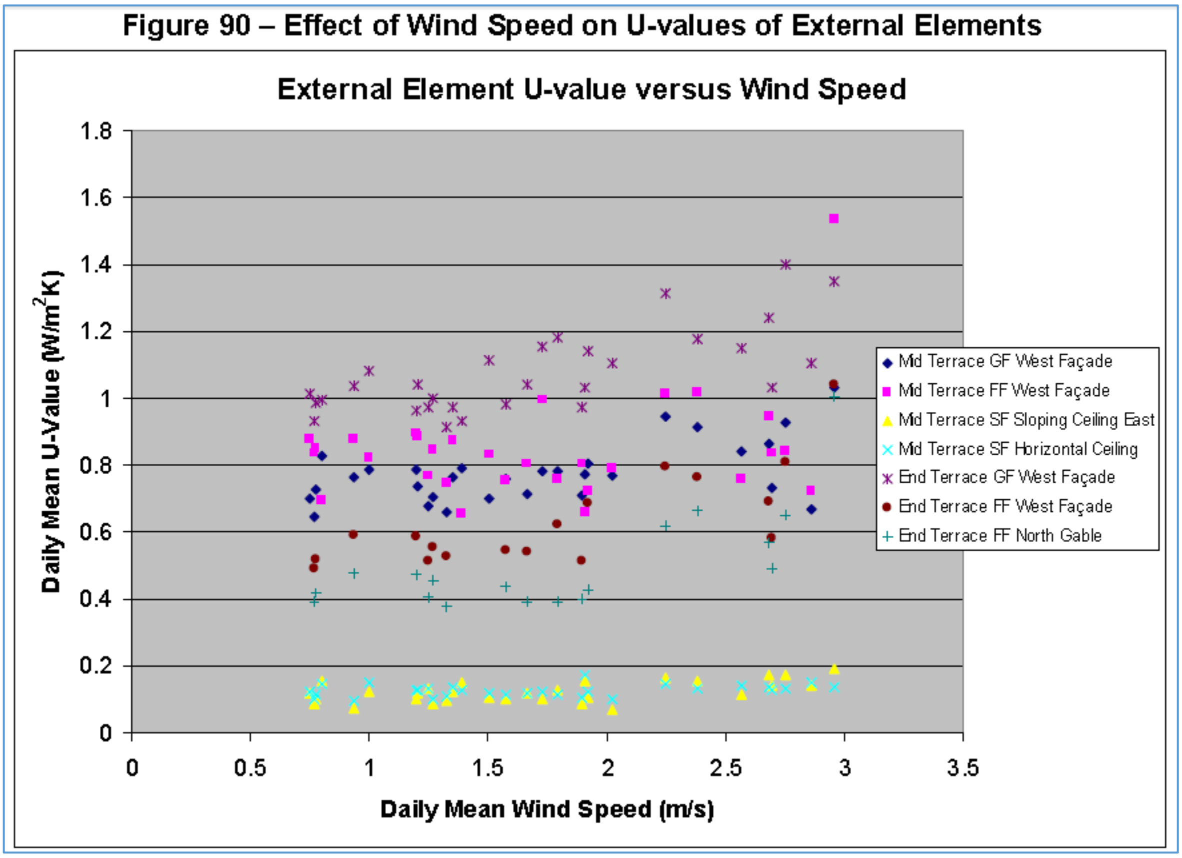


Figure 14 Effect of wind speed on the external wall in-situ U-value measurements, from Wingfield et al., 2009

Figure 15 Deconstruction allowing gaps to be seen in the partial-fill insulation, from Wingfield et al., 2009.

Wingfield *et al.* (2011) followed on from the 2009 project above, but also compared fully filled cavities and timber frame construction as well as partially filled external cavity walls. This follow-on study compared variations in measured U-values and external wall cavity temperatures with wind speeds, discrepancies between designed and measured external wall U-values and variations of U-value with temperature. Of particular interest are the 2 sites in Leeds built concurrently by the same contractor and both with partial fill rigid board insulation; extensive measurements and testing was conducted on both developments, the mean daily in-situ U-values for the partially filled external walls for the 3 test dwellings are shown in Figure 16. Whilst both the end terrace properties displayed mean in-situ U-values over 70% greater than the designed values for the external walls, the lack of a large expanse of opening-free gable wall resulted in the mean in-situ U-value for the mid-terrace property rising to three times the designed value.

Table 39 – Leeds LA1 – Closing the Loop – Nominal Predicted vs. Measured Fabric Heat Loss

		Nominal Design Data		Adjusted Data from Measurements	
Fabric Element	Area (m^2)	U-Value (W/m^{2}K)	Heat Loss (W/K)	U-Value (W/m^{2}K)	Heat Loss (W/K)
Ground floor	11.19	0.22	2.46	0.22	2.46
Floor semi-exposed	33.78	0.18	6.08	0.18	6.08
External Walls	100.33	0.29	29.10	0.54	54.18
Walls semi-exposed	3.85	0.25	0.96	0.25	0.96

Table 88 – Leeds Site B House LB1 - Nominal Predicted vs. Measured Fabric Heat Loss

		Nominal Design Data		Adjusted Data from Measurements	
Fabric Element	Area (m^2)	U-Value (W/m^{2}K)	Heat Loss (W/K)	U-Value (W/m^{2}K)	Heat Loss (W/K)
Glazing	13.25	1.80	23.84	1.80	23.84
Doors	2.10	1.50	3.15	1.50	3.15
Cavity Walls	78.53	0.29	22.77	**0.50**	**47.12**
Floor	42.08	0.22	9.26	**0.25**	**10.52**

Table 89 – Leeds Site B House LB2 - Nominal Predicted vs. Measured Fabric Heat Loss

		Nominal Design Data		Adjusted Data from Measurements	
Fabric Element	Area (m^2)	U-Value (W/m^{2}K)	Heat Loss (W/K)	U-Value (W/m^{2}K)	Heat Loss (W/K)
Glazing	13.25	1.80	23.84	1.80	23.84
Doors	2.10	1.50	3.15	1.50	3.15
Cavity Walls	34.53	0.29	10.01	**0.90**	**31.08**
Floor	42.08	0.22	9.26	**0.25**	**10.52**

Figure 16 In-situ U-values of partially filled cavity external walls measured during coheating tests (Wingfield et al., 2011)

Numerical simulation of partial fill issues

Ridouane and Bianchi (2011) used EnergyPlus and DOE2 to simulate the effects of potential faults with partially filled insulated cavities (Figure 17). Modelling a 2.44 m high wall panel, they showed that a 4” (50.8 mm) uninsulated gap at the top of the panel resulted in a 15% reduction in thermal resistance and a 2’ (609 mm) gap led to a 54% reduction in thermal resistance. Their overall conclusions was “As expected, for a partially filled cavity, a small air gap can lead to a significant reduction in resistance”, the full paper was summarised in a Building America Technical Highlight article (Ridouane & Bianchi, 2012). Parameters used included internal and external temperatures, surface emissivity, cavity aspect ratios and physical properties of the materials; the findings showed that the most significant factor affecting the thermal resistance was convection in the uninsulated cavity.

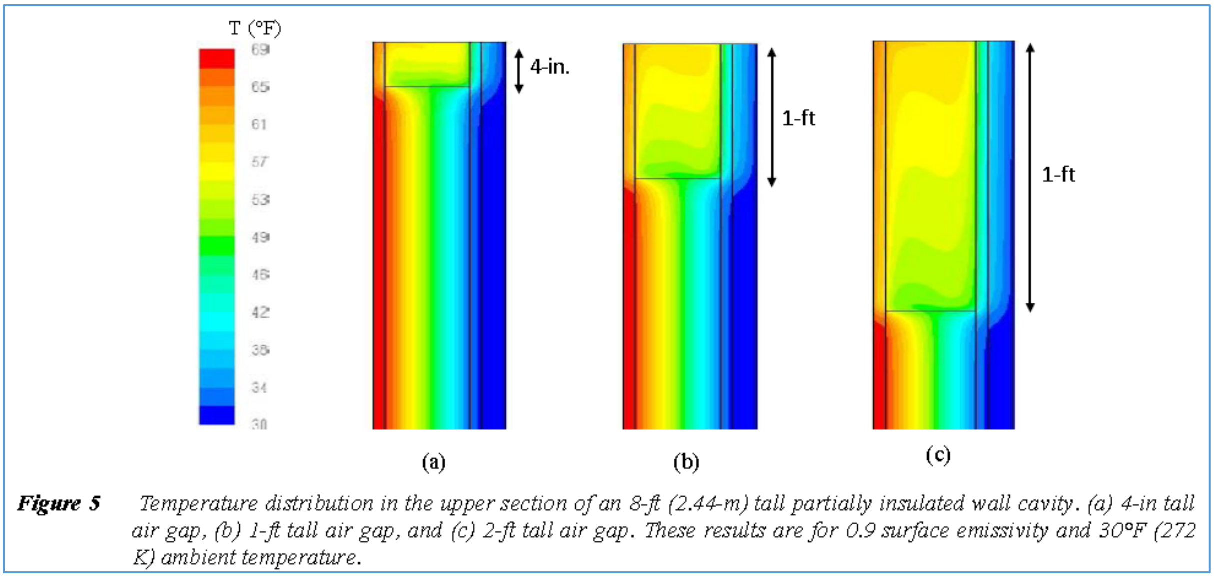


Figure 17 Simulated effect of air gaps at the top of an insulated wall panel (Ridouane & Bianchi, 2011)

Leeds Beckett University site observations

Over the past 10 years a growing portfolio of issues with partial-fill insulation has been amassed by the Leeds Beckett research team during investigations carried out on building fabric performance. Issues observed that would potentially result in deterioration of the thermal performance of the completed envelope have been observed on all sites where the construction of this insulation system has been observed; indeed, only on 2 sites has insulation installed to "best practice" actually been found. Figure 18 shows a site in Sheffield where an apartment block was being observed as part of two ODPM projects (Johnston *et al.,* 2011; Oreszczyn *et al.,* 2011); Figure 19 illustrates a site in York which was observed as part of an investigation for the Joseph Rowntree Housing Trust (Miles-Shenton *et al.,* 2010). It is noted that neither of these sites would be considered typical of mass speculative housing, as is the norm in UK domestic construction. The site in Sheffield was built by a local developer who employed their own bricklayers rather than using subcontractors, and usually constructed non-domestic buildings. The quality of construction was considered to be better than that observed on the other housing sites within these projects. In addition to the well-fitted insulation, the apartments on the Sheffield site proved to be the most airtight of the 50 dwellings tested by the Leeds Beckett research team in that particular project. The site in York comprised of 2 prototype dwellings and had a full-time site manager for the construction of just 2 houses. This micro-management approach was considered to have a direct link to the quality of management and construction. However, such a direct micro management approach to quality management was not repeated when the development went into full-scale production, and the quality of fix of the wall insulation was less consistent than that achieved with the prototype dwellings.


Figure 18 Partial-fill insulation being installed in standard brick-block masonry construction in an apartment block in Sheffield.


Figure 19 Partial-fill insulation being installed in a thin-joint masonry construction prototype house in York.

However, even with partial-fill rigid board fitted as well as in Figure 19 there can be underperformance. Figure 20 shows a detail on the same building as Figure 19 where even a small gap can cause visible and measurable change in performance. In Figure 20 the in situ U-values measured ranged from 0.18 to 0.27 W/m^{2}K (compared to a design value of 0.17 W/m^{2}K). The research illustrates that problems still do occur even when there is considerable effort placed on achieving an exemplar building.

Figure 17 The masonry prototype 1st floor rear wall (North façade), showing gaps in the insulation, heat flux sensor placement, and thermal image captured during coheating.

Figure 20 Measured discrepancy in performance due to small issues with partial-fill rigid board insulation (Miles-Shenton et al, 2010)

The vast majority of site observations made by the Leeds Beckett research team show problems with partial fill, some of which are so common they could be described as typical installation, others are less common but may have more severe consequences than just unplanned additional heat loss.

Figure 21 and Figure 22 both illustrate examples where the partial-fill insulation is not flush to the inner leaf blockwork, with examples ranging from what is typical installation to the more extreme examples of the problem. Air movement around the insulation boards will have a detrimental effect on the thermal performance of the wall (as discussed at more length later, e.g. Figure 31). Topping up the residual cavity between the insulation and the outer leaf block/brickwork would obviously increase the thermal resistance of the walls shown, but some air gaps could remain where irregular construction or obstructions prevent a more direct interface. These remaining gaps may result in the increase in R-value expected by the additional insulation not being fully achieved. In the case of some of the examples displayed in Figure 22, the thermal bridging through mortar snots may actually increase in purely relative terms. As the plane-element thermal resistance is increased by 'topping-up', the relative heat loss through mortar snots that bridge the insulation layer would naturally increase as a proportion of heat loss through the wall. How severe this effect would be could be modelled to establish whether the temperature factor (f_{Rsi})[3] would drop low enough to constitute a condensation risk in the 'topped-up' external wall.

[3] $\boldsymbol{f}_{Rsi}$ Temperature Factor, defined in ISO 13788:2012, where $\boldsymbol{f}_{Rsi}$ <0.750 there is a risk of critical surface and interstitial humidity and condensation.

Figure 21 Partial-fill boards are not positioned flush with the inner leaf blockwork

Figure 22 Partial-fill insulation affected by mortar snots

Other common examples of gaps around partial-fill insulation boards, as shown in Figure 23 and Figure 24, would prove simpler to quantify the benefits of 'topping-up' the residual cavity; where the gaps between the insulation boards and the inner leaf are minimal but areas of the inner leaf are directly exposed to the external wall cavity. In cases such as these, topping up the residual cavity with insulation would have maximum effect. Examples of this type were detected and reported on in Wingfield *et al.* (2009), where the external walls displayed daily mean in-situ U-value of more than double the theoretically obtained design values (Figure 12, Figure 13 and Figure 15).

Figure 23 Gaps between and around partial-fill insulation boards

Figure 24 Gaps around partial-fill insulation boards at openings

Figure 25, Figure 26 and Figure 27 show other commonly seen issues with partially-filled external walls where 'topping-up' the residual cavity by injecting insulation through the external leaf might not prove to be as successful as desired. Figure 25 shows a common issue with the installation of any insulation, not just partial-fill, where cavity trays prevent the insulation achieving good contact with the inner leaf, filling the residual cavity from the outside will reinforce thermal resistance on the cold side of the existing insulation, but would not solve the issue of air gaps on the warm side. Figure 26 shows another common issue with partial-fill, where the first course of insulation boards or batts only starts at dpc level or sits neatly on the first row of wall ties, rather than extending the prerequisite distance below floor insulation level. In the first case shown in Figure 26 'topping-up' would not address this problem due to the cavity tray closing off the external cavity below floor level; however, for the other two examples filling the residual cavity would also fill the uninsulated cavity below floor level and provide additional thermal resistance around the ground floor perimeter that is missing from the original construction. Figure 27 introduces further issues around cavity tray, those at lintels where insulation is often inadequate and may present problems for 'topping-up' close to the eaves junctions.

Figure 25 Issues with partial-fill insulation around cavity trays

Figure 26 Partial-fill insulation not extending below ground floor level

Figure 27 Issues with partial-fill boards at eaves, wall plates and top storey lintels

Figure 28 shows an issue which is less common than many of the other partial-fill issues mentioned previously, and rather than showing a problem illustrates a work-around another issue. In the majority of cases observed the builders would not have cut out sections of insulation to fit the partial-fill boards in close contact with the inner leaf, but instead have left gaps between the inner leaf and insulation boards where protrusions for built-in joists and RSJs extend beyond the plane of the blockwork. In the example shown in Figure 28 'topping-up' the residual cavity could prove highly successful, much more so than if the insulation board had not been adapted to limit the air gaps on the warm side of the insulation.

Figure 28 Missing/displaced insulation due to wall protrusions

Figure 29 and Figure 30 show junctions of the external wall cavity, with both adjacent external wall cavities and with party wall cavities, and illustrate how issues with the continuity of the partial-fill insulation layer arise. Small staggers in the external wall often result in no wall ties being present in the short sections of wall normal to the main façade, making it impossible to fit retaining clips to ensure contact between the insulation and inner leaf. Party wall junctions can also result in similar issues, although this is usually mitigated by the inclusion of a cavity stop sock. In both cases the 'top-up' insulation introduced to fill the residual external wall cavity would reduce the unplanned additional heat loss at these junction.

Figure 29 Staggers and other more complex junctions

Figure 30 Party wall junctions with external walls

Understanding underperformance

Hens *et al.*'s (2007) paper on brick cavity wall construction is seminal to the current understanding of how insulated cavity walls underperform, expanding on the IEA Annex 32 work on cavity walls performed by Hens, Jansens and Depraetere (Hens *et al.* 1999). It discusses the differing effects of infiltrating and exfiltrating air movement through the structure, air movement around insulation boards (Figure 31, and simplified illustratively in Figure 32), moisture effects and thermal mass harmonics; crucially, it brings all these known phenomena together and combines them with the "then" state of the art modelling techniques to define real in-situ performance in terms of a performance gap from the theoretical (Figure 33).

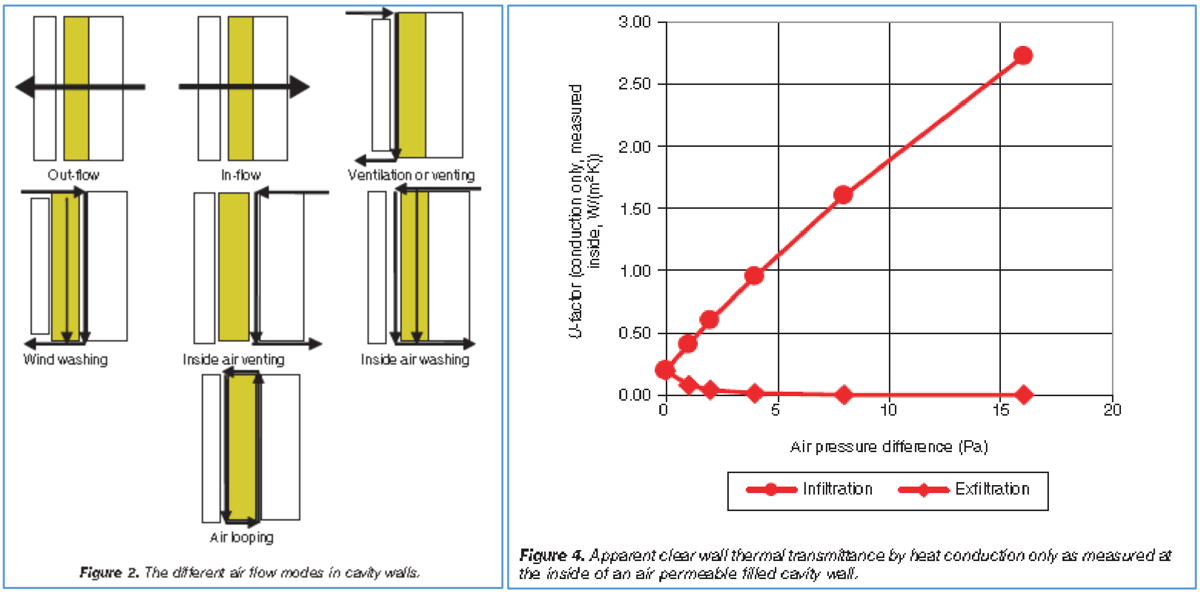
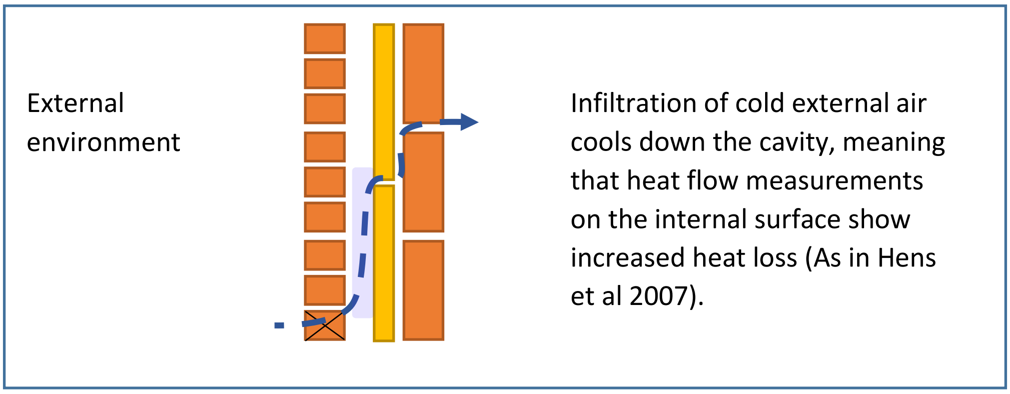


Figure 31 Effects of air movement around insulation boards within cavities and through the entire wall (Hens et al., 2007).



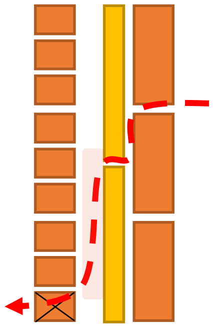


Figure 32 Effect of infiltration and exfiltration on the measurement of conductive heat flow.

Table 5. Vliet test building, effective clear wall U-values after air-tightening (a-t) the inside leaf. Combined effect of thermal looping and wind washing.

Cavity wall: veneer filled cavity inside leaf, no render Workmanship?	Fill		Intended U-value W/(m² K)	Measured U-value W/(m² K)			
				Second winter		Second winter	
				Before a-t		After a-t	
	Partial	Full		SW	NE	SW	NE
Poor		MF	0.22	0.39	0.33	0.44	0.35
Good		MF	0.22	0.21	0.21	0.22	0.22
Poor	XPS		0.21	0.86	0.86	0.94	1.03
Good	XPS		0.21	0.23	0.21	0.27	0.21
Poor		XPS	0.21	0.60	0.79	0.68	0.94
Good		XPS	0.20	0.22	0.22	0.22	0.22

Table 4. Vliet test building, effective clear wall U-values, combined effect of thermal looping, wind washing and exfiltration.

Cavity wall: veneer filled cavity inside leaf, no render Workmanship?	Fill		Intended U-value W/(m² K)	Measured U-value W/(m² K)			
				First winter		Second winter	
	Partial	Full		SW	NE	SW	NE
Poor		MF	0.22	0.37	0.32	0.39	0.33
Good		MF	0.22	0.22	0.21	0.21	0.21
Poor	XPS		0.21	0.86	0.86	0.86	0.86
Good	XPS		0.21	0.23	0.21	0.23	0.21
Poor		XPS	0.21		0.51	0.60	0.79
Good		XPS	0.20	0.21		0.22	0.22

Figure 33 In situ U-value measurements comparing different wall types (Hens et al., 2007).

Although many of the issues discussed by Hens had been presented and published prior to this, most of them had done so in isolation. In the early 1980's Siviour measured heat flows throughout insulated masonry cavity external walls and showed a discrepancy between real and theoretical values (Figure 34) as part of whole building tests (Siviour, 1981) but did not expound on the reasons for this difference. Lecompte suggested the primary cause was due to air movement around the insulation and provided models to estimate the effects (Lecompte, 1990) but only listed workmanship as the cause of these issues. Hens drew on these and other research that helped to explain that it was not just natural convection that was causing the additional heat losses and refers back to work carried out for IEA Annex 32 which examined risk analysis, calculation procedures and field measurements and suggested as many as 95% of all partially-filled cavity walls suffered from detrimental thermal transmittance above the calculated values.

Results of some measurements are shown in figure 7. An average heat flow rate of 9.8 W/m² was measured at the inner surface of the plasterboard and 7.9 W/m² on the inner surface of the insulating block. One explanation for this difference is that air flow in this cavity gives it a negative thermal resistance. The theoretical heat flow is 4.9 W/m², which means that there is an additional flow of 2.9 W/m². Measurements of temperatures through the wall show this to be because the foam insulation works far less well than predicted, corresponding to a k value of 0.08 W/mK rather than the value of 0.038 W/mK used in calculating the theoretical flow.

Figure 34 Siviour measured heat flux densities through house walls, and compared real heat loss to that calculated (Siviour, 1981)

Wingfield *et al.* (2011) measured U-values through the entire height of a 3-storey masonry-cavity town house throughout the course of a coheating test, and showed how the mean U-values varied with altitude (Figure 35). This test house was in a fairly sheltered location, so prevailing windward and leeward pressure-driven infiltration/exfiltration was much reduced compared to many of the other buildings measured. As such, the reduction in measured thermal conductance with height up the wall could be seen to support the model proposed by Hens and displayed in Figure 31; where infiltrating air will have the effect of raising the in-situ U-value, and exfiltrating air causing the opposite effect as the cooler air enters at the ground floor and warmer air leaves above the zero-point level[4], in this case somewhere just below the 2nd intermediate floor. The test house shown in Figure 35 was typical of current new-build in terms of airtightness (mean air permeability of 6.6 $m^3/(h.m^2)$ @ 50Pa), with fully-filled external wall cavities (blown mineral fibre – Rockwool Energy Saver). The cavity insulation may have increased the air resistance of the cavity and hence increased air dwell time in the cavities; if so, the effect seen in this example could be expected to be even more severe in a typical partial-fill construction, and potentially reduced by 'topping-up' the residual cavity with additional material.

[4] The zero-point level is the height above ground level at which internal and external barometric pressures are equal and the ventilation characteristic change from infiltration to exfiltration; in this study its exact altitude varied daily due to external environmental conditions.

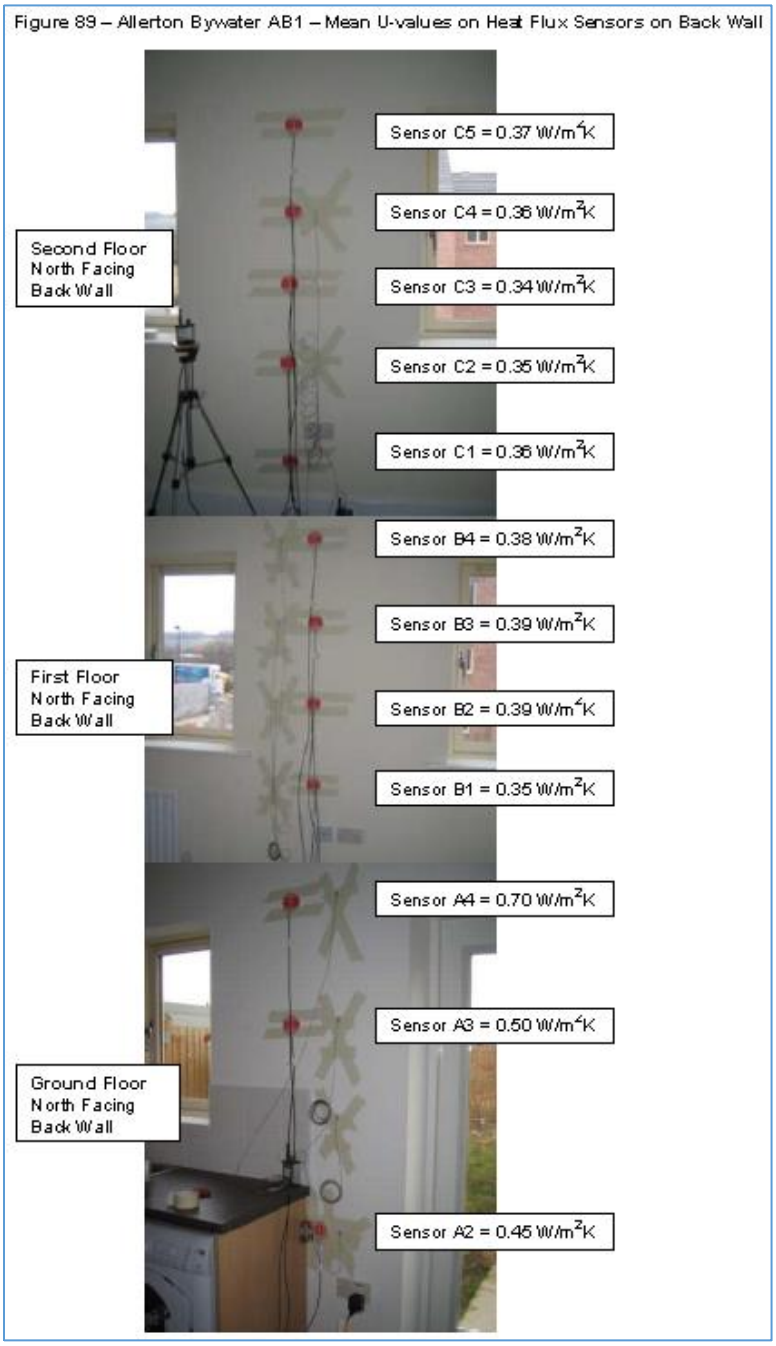


Figure 35 Effect of altitude on measured in-situ U-values (Wingfield et al., 2011)

A vast range of techniques have been employed to discuss how thermal conductivity alone is inaccurate when discussing heat loss; Vafai & Belwafa (1990), Kusuda (1977) and Bankvall (1978) all pre-date Hens (2007) and list a number of other factors that need to be considered, without applying actual values to these discrepancies in a cavity wall situation directly. Vafai and Belwafa cover changes to heat transfer through the insulation material due to moisture variations and control with an additional insulation/air interface, comparing fibreglass in fully filled and partially filled cavities; Kusuda adds to this the further complications of convection and radiation in partially filled cavities; Bankvall adds forced convection through wind washing and air movement through the insulation. All these heat transfer mechanisms occurring in partially filled cavities would be either eliminated or reduced by fully filling the residual cavity.

Increasing understanding on why and how these heat transfer mechanisms operate has occurred slowly throughout the house-building industry in general. Placing values on their effects has happened even more slowly, but is catching up. Harrje, Dutt and Gadsby's (1985) paper on convective loop heat losses affecting thermal conductivity values (Harrje *et al.,* 1985) remained pretty much disregarded by the industry until the Stamford Brook Project was undertaken by Leeds Beckett University who measured values for this effect in a masonry cavity party wall (Wingfield *et al.*, 2007; Lowe *et al.*, 2007). Since then understanding of these effects, and general acceptance of their influence into the gaps between design performance and what is achieved as-built, has grown steadily. There is a long journey from Figure 36 to Figure 37, from identifying the concept to putting informed values on actions to prevent it; but much of this work concentrates on exemplar and cutting-edge building (Figure 37 comes from the UK Passivhaus Conference, 2011), and the 20% of partially-filled walls in the UK (Figure 2) gain much less exposure even though the same laws of physics apply to them. Siddall (2011) lists how "windtight" structures need to be to counteract the effects of thermal bypassing around insulation in cavity walls that are not completely filled, whilst not aimed at partially-filled walls the principles still apply, and not many existing partially-filled external walls could be described as "windtight".

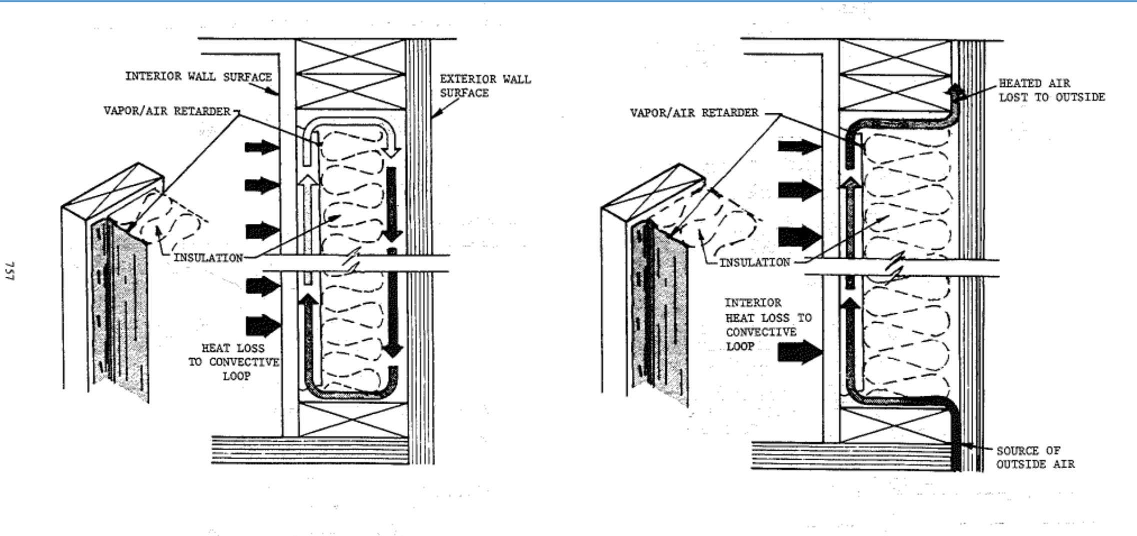


Figure 1. Closed convective loop, example of improperly insulated exterior wall

Figure 2. Open convective loop, example of exterior wall that allows airflow

Figure 36 Harrje, Dutt and Gadsby's early identification of a thermal bypass effect (Harrje et al., 1985)

Table 2

Windtightness criteria assuming a proportional relationship between the U-value and the heat loss due to windtightness

U-value W/m²K	Air Permeability (m³/(m² h) (75 Pa)	Air Permeance (m³/(m² s Pa)	Air Permeance m³/(m² h Pa)	Air Permeability (m³/(m² h) (50 Pa)
0.15	< 2.0	< 7.44×10^{-6}	< 0.027	< 1.34
0.1	< 1.34	< 4.96×10^{-6}	< 0.018	< 0.89
0.075	< 1.0	< 3.72×10^{-6}	< 0.013	< 0.67

Figure 37 Levels of wind-tightness required to limit U-value elevation in reality (Siddall, 2011)

The 2012 BBA Technical Report on air movement on the thermal performance of pitched roof constructions (BBA, 2012) showed increases in U-values of up to 80% due to air movement through building structures. Although this is based on roof construction, it illustrates measured U-values changing due to air movement (Figure 38), substantiating that this mechanism exists and raising the question of what effect air movement has on real U-values in the rest of the building fabric. BRE443 and ISO 6946:2007, the conventions for calculating U-values, both accept that air movement increases the thermal transmittance of external walls; indeed, Figure 39 specifically indicates a $_{\Delta}$U value to be appended to the calculated elemental U-value to take into account air movement around partial-fill insulation boards. Although this value is small it is not insignificant for modern, higher performance structures. Experience suggests that this figure is not regularly adopted in practice as it is an opt-in value, rather than an opt-out addition to the U-value which would need to be excluded only if it can be shown that measures will be, or have been, taken to specifically avoid these voids occurring. ISO 6946 also outlines procedures for differentiating the thermal resistance of air voids according to the ventilation of the external wall cavity, distinguishing between unventilated, slightly ventilated and well-ventilated cavities, and also acknowledges that the U-value is dynamic, quoting different heat transfer coefficients at different temperature ranges (Figure 40).

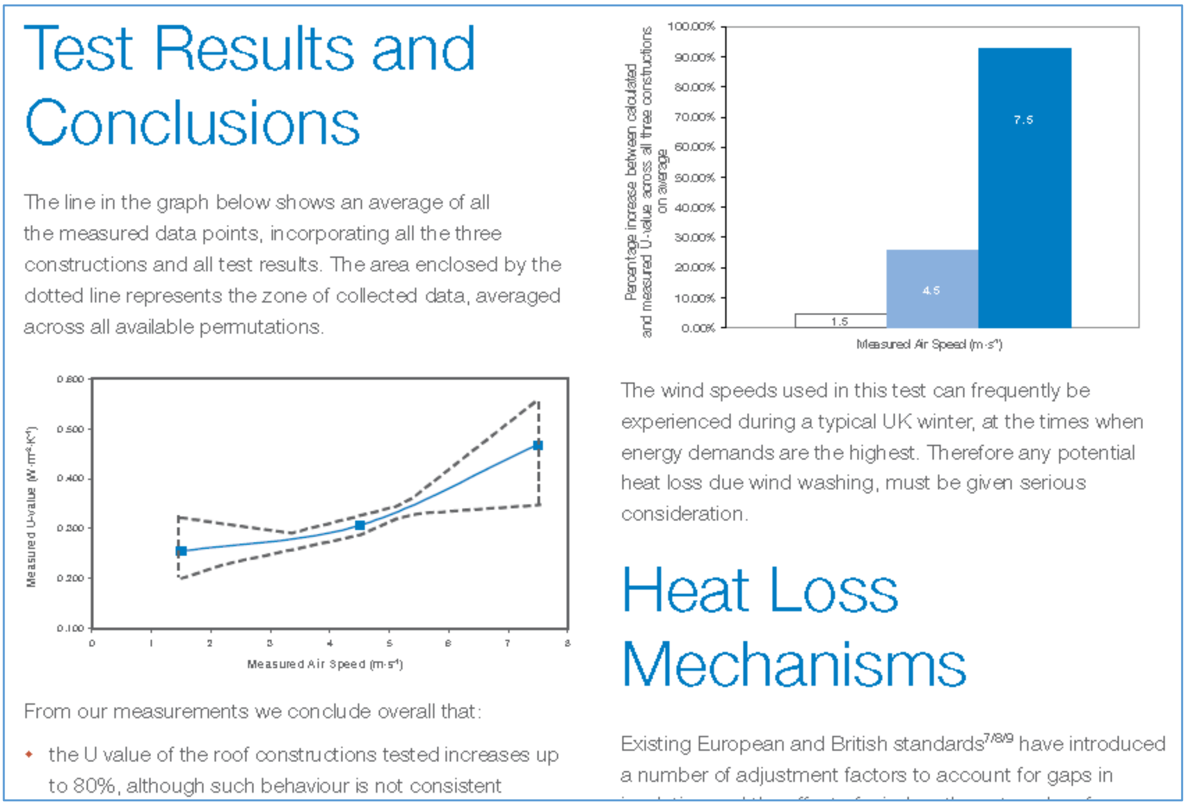


Figure 38 Effect of air movement on measured U-values of roof structures (BBA, 2012)

4.9.1 Corrections due to air gaps

Annex D of BS EN ISO 6946 recognises three levels of correction for air gaps in an insulation layer. The levels are:

Level 0 $\Delta U = 0.00$
There must be no gaps exceeding 5 mm width penetrating the insulation layer. This applies for double layer insulation, and for single layer boards with lapped or sealed joints or with dimensional tolerances such that no gap will exceed 5 mm.

Level 1 $\Delta U = 0.01$
A correction for air gaps is needed if:
- the sum of the length or width tolerance and the dimensional stability of the insulation boards is more than 5 mm, or
- the squareness tolerance of the insulation boards, batts or slabs is more than 5 mm.

Level 2 $\Delta U = 0.04$
Air gaps as in Level 1, and also air circulation possible on the warm side of the insulation layer. It applies, for example, to partial cavity fill with insulation boards if the boards are not affixed to the inner leaf.

Figure 39 Correction to U-value due to air gaps in the insulation layer from BRE443 (Anderson, 2006)

Table B.1 — Convective heat transfer coefficient for temperature difference $\Delta T \leqslant 5$ K

Direction of heat flow	h_a [a] W/(m²·K)
Horizontal	1,25
Upwards	1,95
Downwards	$0,12 \times d^{-0,44}$
[a] Or, if larger, 0,025/d.	

Table B.2 — Convective heat transfer coefficient for temperature difference $\Delta T > 5$ K

Direction of heat flow	h_a [a] W/(m²·K)
Horizontal	$0,73 \times (\Delta T)^{1/3}$
Upwards	$1,14 \times (\Delta T)^{1/3}$
Downwards	$0,09 \times (\Delta T)^{0,187} d^{-0,44}$
[a] Or, if larger, 0,025/d.	

Figure 40 Convective heat transfer coefficient for airspaces (ISO 6946:2007, Appendix B)

Residual Cavity Top-Up

Case studies & examples

Figure 5 (DECC/BRE, 2014) claimed that a partially ventilated cavity could increase the U-value of a cavity external wall by 0.22 W/m^{2}K, so “topping-up” the partial-fill residual cavity could substantially reduce this and have a marked effect even prior to the consideration of the reduction in thermal conductance, due to the installation of additional insulation. The actual case studies where any such pre- and post-intervention measurements have been performed were not forthcoming through the usual sources.

Wingfield *et al.* (2011) conducted a study where the investigation included measurement of U-values of the external walls of a site in Leeds where the 50mm partial fill rigid board in a 100mm cavity was topped up with blown mineral fibre to fill the residual 50mm cavities by a CIGA registered installer. Two attached dwellings were tested, an end terrace house (LB1 in Figure 41) had the residual cavity filled with Knauf Supafil 40 (target density 18 kg/m^3, actual density 21.5 kg/m^3), the attached mid terrace house (LB2 in Figure 41) with Rockwool Energy Saver (target density 48 kg/m^3, actual density 56.9 kg/m^3)[5]. Coheating tests before and after the intervention were used to quantify the results in terms of the change in whole dwelling heat loss. Issues such as incomplete filling behind cavity trays were highlighted, but in general the reduction in thermal transmittance of the external walls was significant, much greater than the theoretical gain from a drop in external wall U-value from 0.29 W/m^{2}K to 0.26 W/m^{2}K. The post-intervention improvements in thermal performance measured in both dwellings appear similar, suggesting that the density of the product used to top-up the residual cavity was not the determining factor in achieving the results shown below.

Figure 41 compares the reduction in whole house before (Phase 2) and after (Phase 3) the filling of the residual cavity which is much greater than expected, suggesting that some of the issues raised with partial-fill insulation mentioned earlier are being compensated for. Table 1 shows the benefits of ‘topping-up’ the insulation to be 10 and 20 times more effective than the expected calculated reduction in heat loss coefficient. Figure 42 lists all the 23 heat flux plate locations on the external walls in house LB1 throughout the coheating test periods and shows the calculated daily mean U-values from these; again these show a greater improvement than the theoretical calculation suggests. The thermal image provided in Figure 43 shows that there are still issues remaining with the gable wall even after the filling of the residual cavity (in this case an issue with cavity trays as shown in Figure 25).

[5] The actual density values are based on the amount of material injected divided by the assumed residual cavity volume, based on cavity measurements at drill holes and assuming no areas of missing partial fill.

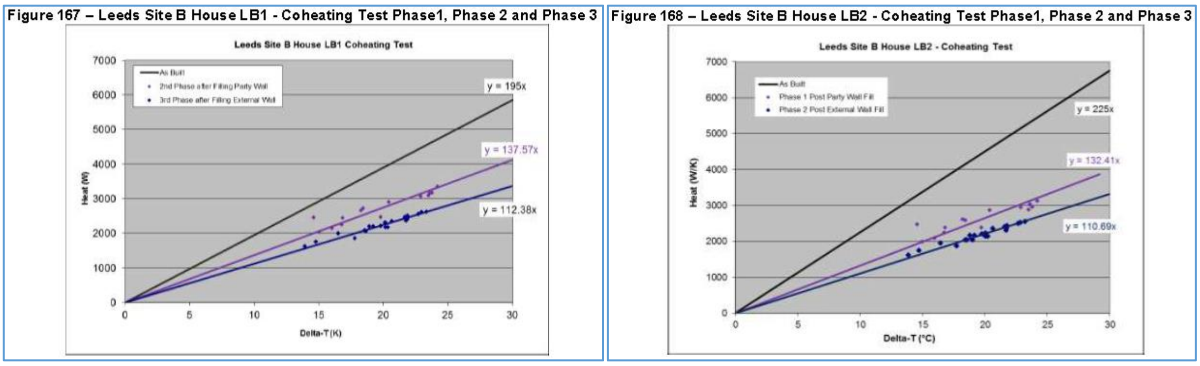


Table 82 – Leeds Site B House LB1 – Summary of Heat Loss Coefficients

Condition of Test House during Coheating Test	Heat Loss Coefficient (W/K)			
	Predicted	Measured	Difference Measured vs. Predicted	Measured Difference after Intervention
Phase 1 - As Built	105.9	195.0	+89.1	n/a
Phase 2 - Party Wall Filled	106.0	137.6	+31.6	-57.4
Phase 3 - External Wall Filled	102.8	112.4	+9.6	-25.2

Table 83 – Leeds Site B House LB2 – Summary of Heat Loss Coefficients

Condition of Test House during Coheating Test	Heat Loss Coefficient (W/K)			
	Predicted	Measured	Difference Measured vs. Predicted	Measured Difference after Intervention
Phase 1 - As Built	88.3	225.0	+136.7	n/a
Phase 2 - Party Wall Filled	88.4	132.4	+44.0	-92.6
Phase 3 - External Wall Filled	89.6	110.7	+21.1	-21.7

Figure 41 Coheating test results before and after residual cavity top-up of 2 Leeds houses (Wingfield et al., 2011)

Table 1 Expected and actual drop in heat loss coefficient as a result of topping up the residual cavity (from Wingfield et al., 2011)

House	Expected decrease in wall U-value	External wall area	Expected drop in heat loss coefficient	Actual drop in heat loss coefficient
LB1	0.03 W/m²K	78.53 m²	2.36 W/K	25.2 W/K
LB2	0.03 W/m²K	34.53 m²	1.04 W/K	21.7 W/K

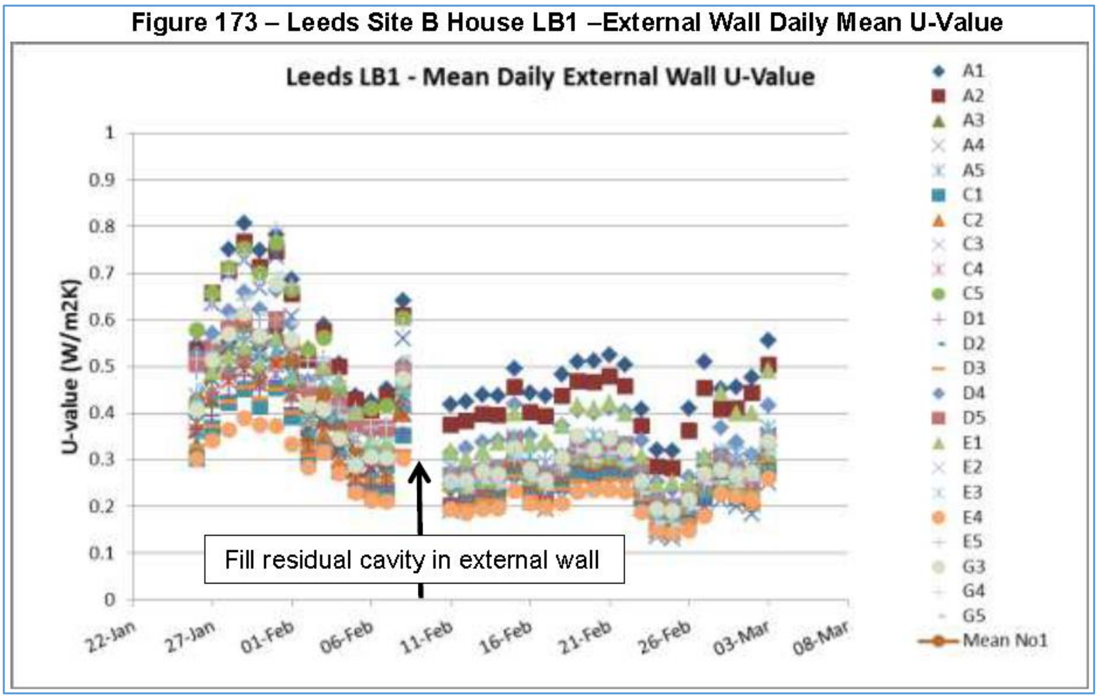


Figure 42 Mean daily in-situ U-values before and after residual cavity top-up (Wingfield et al., 2011)

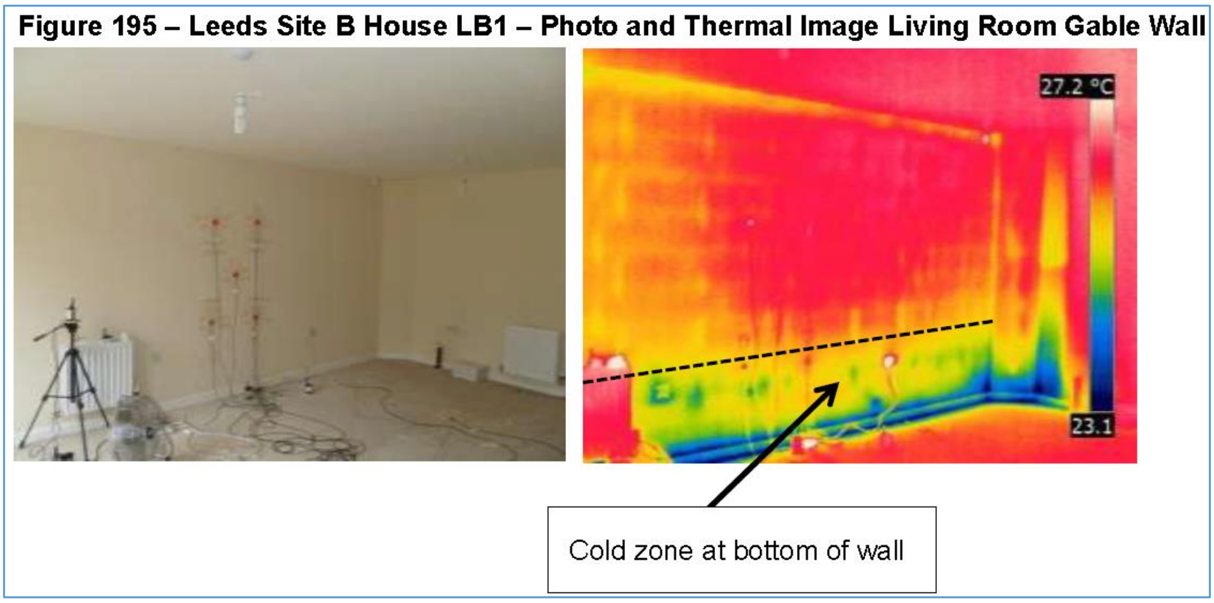


Figure 43 Post-'top-up' thermal image of the external gable wall (Wingfield et al., 2011)

If the value of 0.22 W/m^{2}K suggested in DECC/BRE 2014 (Figure 5) for a ventilated wall cavity is added to the partial-fill design value of 0.29 W/m^{2}K for these properties, the resultant wall U-value would be what was measured on the gable wall (0.50 W/m^{2}K in Figure 16). Filling the residual cavity would remove this 0.22 W/m^{2}K, as a filled cavity is essentially unventilated, bringing the expected decrease in wall value from "topping-up" to 0.25 W/m^{2}K. Table 2 shows the expected drop in heat loss coefficient using these revised expected improvements in wall U-value, which is much closer to the actual improvements in whole house heat loss values measured.

Table 2 Expected and actual drop in heat loss coefficient as a result of topping up the residual cavity using additional 0.22 W/m^{2}K for a ventilated cavity (from Wingfield et al., 2011 & DECC/BRE 2014)

House	Expected decrease in wall U-value	External wall area	Expected drop in heat loss coefficient	Actual drop in heat loss coefficient
LB1	0.25 W/m^{2}K	78.53 m^2	19.63 W/K	25.2 W/K
LB2	0.25 W/m^{2}K	34.53 m^2	8.63 W/K	21.7 W/K

Another interesting outcome of topping-up the residual cavity from Wingfield *et al.* (2011) was the effect of external temperature on the measured in-situ U-value. Figure 44 plots the calculated apparent daily mean U-values of the external gable wall against daily average temperature for both the original wall (Phase 2) and the topped up wall (Phase 3). The original partially filled wall appears to deteriorate (in terms of thermal resistance) at an increased rate compared to the topped-up external wall as the external temperature decreases; with the difference between the two phases increasing as the external temperature falls – the exact time when the better performance would be most beneficial.

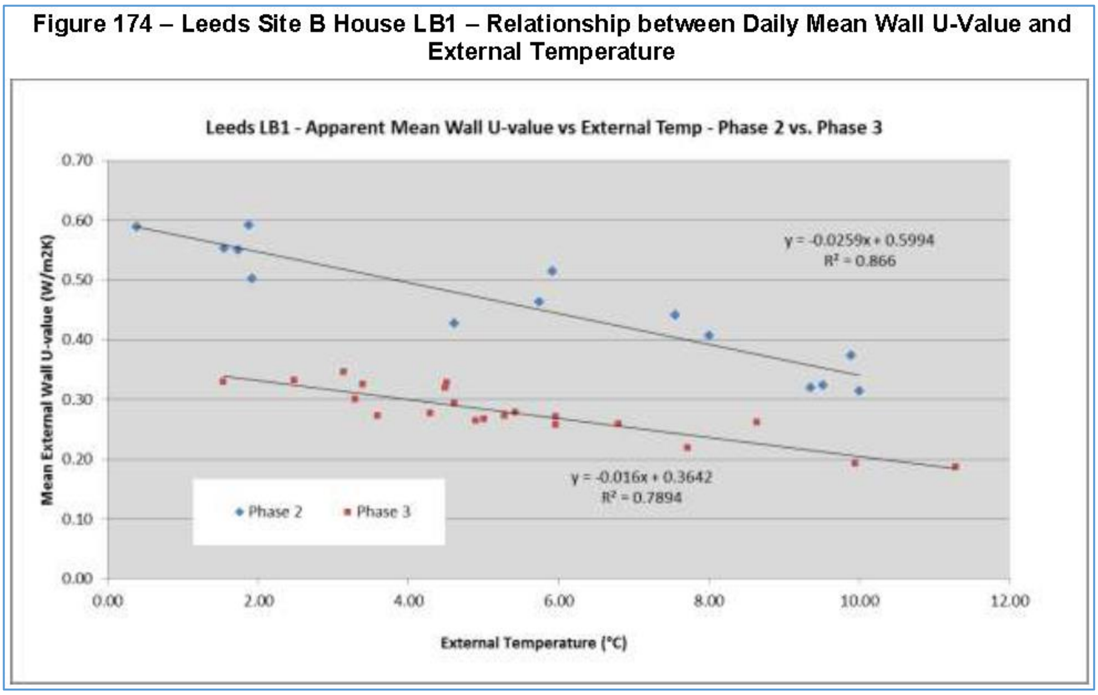
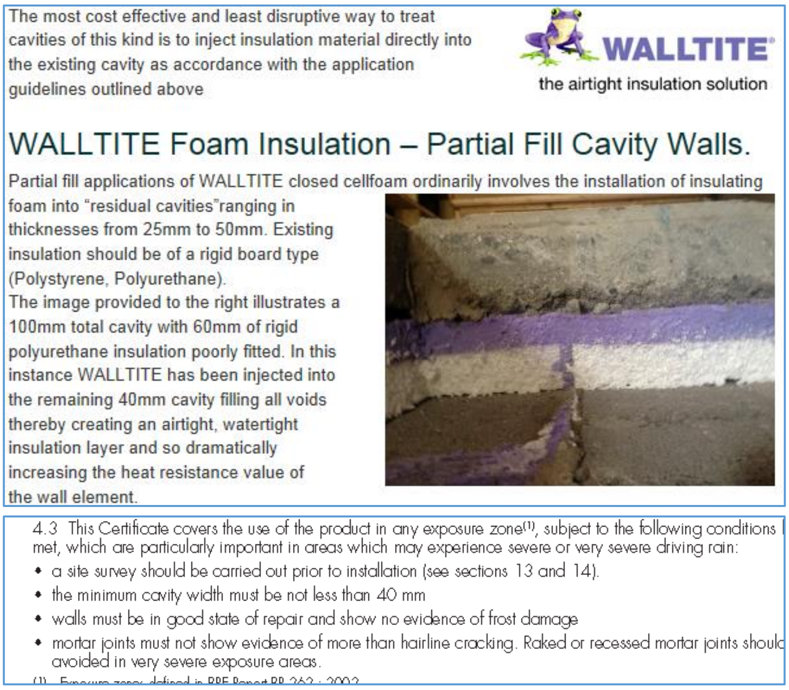


Figure 44 Variation of mean daily in-situ U-value with daily average external temperature, before (Phase 2) and after (Phase 3) residual cavity top-up (Wingfield et al., 2011)

Ireland appears to be where a number of case studies of "topping-up" the partial-fill residual cavities have been reported, although with limited technical detail. Figure 45 describes such a case study (http://www.warmncosyhomes.ie) and claims partial-fill residual cavities from 25 to 50 mm can be 'topped-up', but the associated BBA certification states that the minimum cavity must be no less than 40 mm. However, no measurements of performance are included in the published study to confirm the claimed improvements in post-intervention thermal performance.


The most cost effective and least disruptive way to treat cavities of this kind is to inject insulation material directly into the existing cavity as accordance with the application guidelines outlined above

WALLTITE
the airtight insulation solution

WALLTITE Foam Insulation – Partial Fill Cavity Walls.

Partial fill applications of WALLTITE closed cellfoam ordinarily involves the installation of insulating foam into "residual cavities"ranging in thicknesses from 25mm to 50mm. Existing insulation should be of a rigid board type (Polystyrene, Polyurethane).
The image provided to the right illustrates a 100mm total cavity with 60mm of rigid polyurethane insulation poorly fitted. In this instance WALLTITE has been injected into the remaining 40mm cavity filling all voids thereby creating an airtight, watertight insulation layer and so dramatically increasing the heat resistance value of the wall element.

4.3 This Certificate covers the use of the product in any exposure zone(1), subject to the following conditions met, which are particularly important in areas which may experience severe or very severe driving rain:
- a site survey should be carried out prior to installation (see sections 13 and 14).
- the minimum cavity width must be not less than 40 mm
- walls must be in good state of repair and show no evidence of frost damage
- mortar joints must not show evidence of more than hairline cracking. Raked or recessed mortar joints should avoided in very severe exposure areas.

Figure 45 'Top-up' case study from Walltite and extract from BBA 13/5002

Energystore Ltd, Co Down have also published a case study on their web site of a top-up of partial fill rigid board with poly-bead which appears fairly inconclusive (Figure 46) and much more detailed document '*A preliminary investigation into Cavity Wall Insulation in Northern Ireland*' which provides technical advice on 'topping-up' residual cavities and is illustrated by another case study (Energystore, 2014). Figure 46 shows the analysis of before and after performance undertaken using questionable thermography, where the thermal images appear to be manipulated in an attempt to show a difference where there is none obvious. In this case study 50mm partial-fill board was topped-up with grey ESP bonded bead to fill the 100mm cavity "in line with BBA standards" but again no actual measurements of performance are included in the case study. Figure 47 and Figure 48 are taken from the longer more detailed document, which provides some confusing summary advice (Figure 47 shows what appears to be contradictory statements regarding BBA approval of 'topping-up' on the same page) along with other more considered and better sourced information (Figure 48), illustrated with an additional case study, again, without measurement.

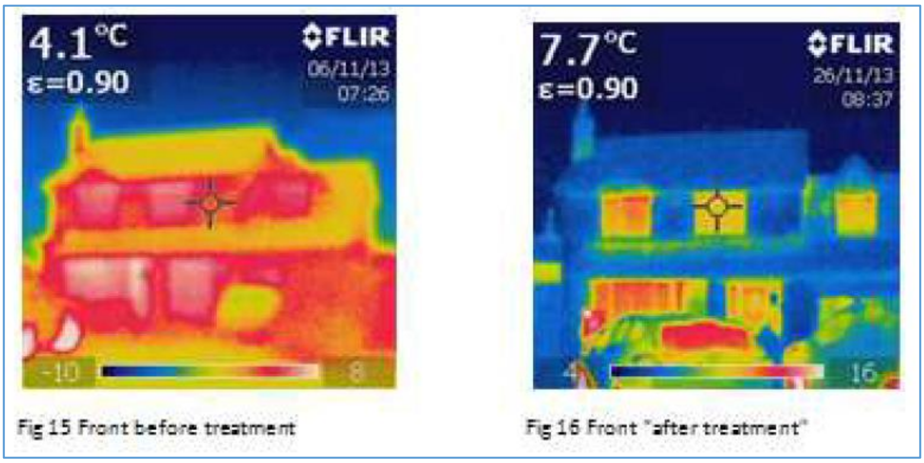


Figure 46 Thermal images of a partial-fill 'top-up' from http://www.energystoreltd.com/?page_id=5299

Partial Fill to Full Fill

Cavities that were built with rigid or semi-rigid board fixed to the inner leaf during construction can now be upgraded with BBA approval to a full fill cavity using bonded bead. The property will therefore benefit from higher levels of thermal insulation. This can also be used to eradicate issues of damp and mould in houses with only partially filled cavities.

Due to the complexity of the process, the quality of the survey is deemed critical and is required to be at a level over and above that carried out for conventional installations.

Insulation Top Ups

The topping up of any cavity wall insulation is not certified by BBA and should not be carried out. Where fibre has slumped, foam has disintegrated or bead has come out during building alterations there is no suitable system to "top up".

Topping up existing cavity wall insulation will render void any CIGA guarantee and could lead to additional problems relating to damp and mould.

Figure 47 General advice for partial to full fill top-up (Energystore, 2014. p.16)

Partial fill solution

What is partial fill?

Partial fill was the preferred option to improve thermal performance when building regulations required insulation post 1980.

Partial fill cavity insulation is only achievable during construction of the external walling. Partial fill must be rigid or semi-rigid to be fixed to the inner leaf.

Why original partial fill underperforms

Fundamentally the effectiveness of CWI depends not only on the 'theoretical' properties of the insulating material but also on the 'real life' manner of installation and the environmental conditions that the material is exposed to. Voids and gaps are major issues with insulation board and partially filled insulation board and are often the result of poor workmanship onsite.

In their publication: *Cavity Walls with high insulation quality: Performance prediction using calculation procedures and field testing, IBEPA 1999*, Hens and Janssens refer to studies of partially filled cavity walls in Belgium where it was observed in a very high proportion (about 95%) of cases that the partial fill was not pressed against the inner leaf of the wall. Gaps occurring at corners allowed for air to circulate around the insulation.

Another study of partially filled cavity walls showed that the U-value can be altered substantially when air is able to circulate in the cavity around partial filled board.

In: *The influence of natural convection on the thermal quality of insulated cavity construction. Building Research and Practice, CIB, 1990*, Lecompte reported that where there is a gap of 10mm at the top, bottom and sides of insulation board the U-value can rise by over 90% leading to a near doubling of the wall's U-value.

The industry BBA approved partial fill solution

Cavities that were built with rigid or semi-rigid board fixed to the inner leaf during construction can now be upgraded with BBA approval to a full fill cavity using high performance grey bonded bead.

The hard to heat or cold house will therefore benefit from higher levels of thermal insulation.

Thermal imaging showing heat loss through a void

This system can also be used to eradicate issues of damp and mould in houses with only partially filled cavities.

Due to the complexity of the process, the quality of the survey is deemed critical and BBA require the survey to be at a level over and above that carried out for conventional or standard installations with three boroscope inspections of the cavity required for each elevation. These physical boroscope inspections enable the trained surveyors to ensure that only properties suitable for this system are upgraded. Thermal imaging can also be used when necessary to identify voids or gaps.

Not only is the survey more complex than that for a standard cavity fill but there are additional install requirements to ensure adequacy of fill and to ensure that the existing board is not damaged in any way.

Where the board is poorly fitted (usually by a bricklayer) and gaps are present this allows cold air to circulate around the insulation

38 Cavity Wall Insulation in Northern ireland

Figure 48 More specific advice for partial to full fill top-up (Energystore, 2014)

The introduction of insulation, whether as a "topping up" of a partially filled cavity or directly into an uninsulated cavity, can have a marked impact on performance. The introduction of blown insulation into a previously unfilled party wall visually demonstrates the impact that filling the cavity can have. Figure 49 (Gorse *et al.,* 2014) shows a party wall cavity in an existing dwelling, previously unfilled, which offers limited and variable resistance to the passage of heat. The measured heat flux into the wall demonstrates inconsistency in thermal performance across a relatively small section of party wall, which appears to be communicating directly with the external wall cavity. As the external conditions impacting on the wall change, and thus the conditions in the attached external wall cavity change, a large degree of variance in the party wall can be seen. Notably, once the party wall is filled with insulation the thermal resistance is improved for each section of the wall, there is also a greater degree of consistency in thermal performance across the wall and the impact of external conditions on the thermal resistance is significantly reduced.

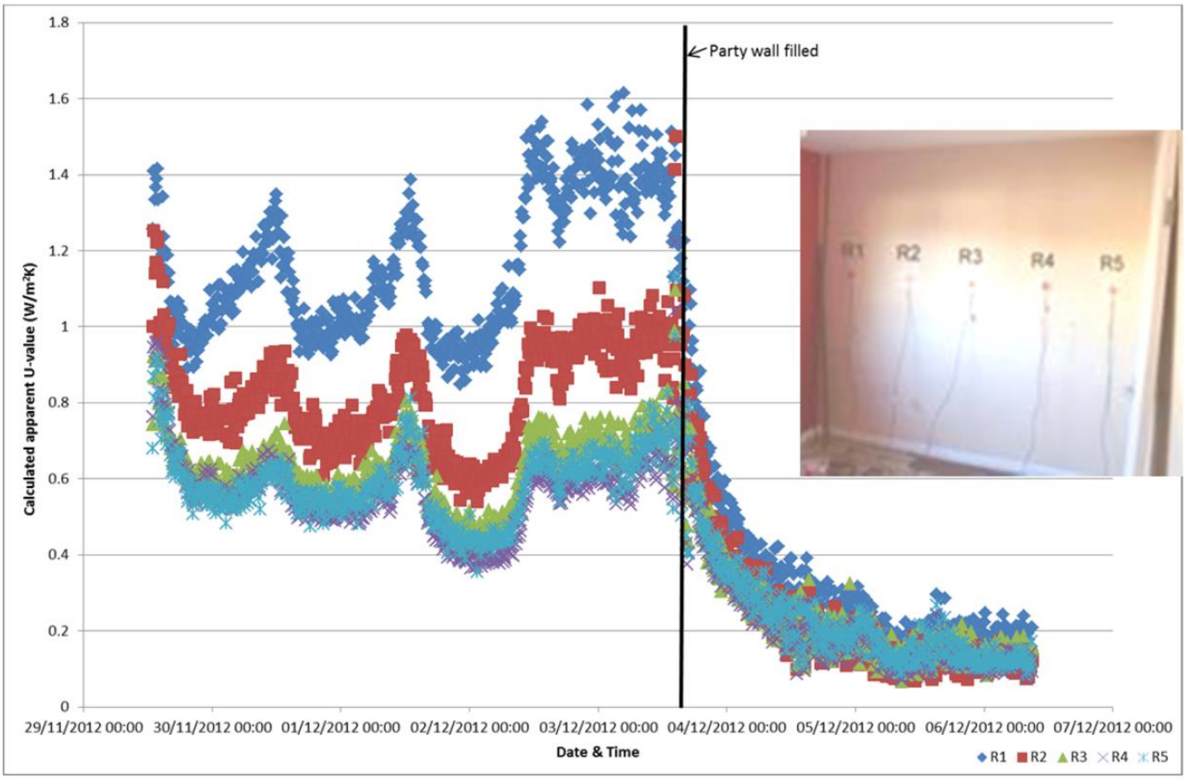


Figure 49 An unfilled cavity party wall exhibiting characteristic signs of thermal bypass and air movement, the full-fill intervention creates a fabric that controls movement and significantly reduces heat loss (Gorse et al., 2014)

Advice and Certification

Whilst the Energystore "top-up" shown in Figure 46 states that it is installed "in line with BBA standards" there does appear to be some inconsistencies with the information provided on the relevant BBA certification. For example, BBA 07/4414 2014 Energystore Cavity Wall Insulation and BBA 11/4867 2013 Instabead Cavity Wall Insulation both approve the filling of residual cavities down to 40 mm with polystyrene bead insulation (Figure 50 and Figure 51), whilst BBA 09/4630 2009 Supabead Cavity Wall Insulation does not for what appears to essentially be the same product. BBA 09/4630 2009 Supabead Cavity Wall Insulation and BBA 88/2033 2014 Supafil 40 Cavity Wall Insulation are also very similar to each other in terms of being limited to a 50 mm minimum cavity width and applicable design considerations, even though they are different products. The BBA themselves have a document on their web site entitled "*Functional description of testing injected cavity wall insulation into a partially filled cavity*"[6] which outlines a test procedure based on a 3 m x 2.8 m test box set up to represent a worst case scenario, with a fairly stringent set of criteria that need to be addressed for the filling of any residual cavity in order to gain their approval. Conversely, others avoid recommendations for the topping up of a partially filled cavity of any width, choosing to

[6] http://www.bbacerts.co.uk/wp-content/uploads/2014/07/Functional-description-of-testing-injected-cavity-wall-insulation-into-a-partially-filled-cavity.pdf

advise that other methods would be more appropriate, such as the advice provided by EST 2010 (Figure 52).

Partial fill — residual cavities[1]

4.7 This Certificate covers the use of the product for topping up of residual cavities in partial fill installations, subject to the following conditions being met:

- prior to installation, a site survey is carried out by a BBA Approved Assessor (see section 14)
- the existing built-in insulation in the cavity is one of the following:
  - mineral wool (MW) batts
  - expanded polystyrene (EPS) boards
  - foil-faced polyisocyanurate (PIR), polyurethane (PUR) or phenolic (PF) boards
- the minimum residual cavity width is not less than 40 mm
- installation is carried out by a BBA Approved Installer, trained to work on this type of installation
- all other conditions in section 4.3 are met.

(1) Partial fill installations relate to existing constructions where insulation, in the form of batts or boards, has previously been built into a wall and there is a residual cavity.

Figure 50 Section from the Design Consideration Section of BBA 07/4414 2014

Partial filling — residual cavities[1]

4.7 This Certificate covers the use of the products for the topping up of residual cavities in partial fill installations, subject to the following conditions being met.

- prior to installation, a site survey is carried out by a BBA Approved Assessor (see section 14)
- the existing built-in insulation in the cavity is one of the following:
  - mineral wool (MW) batts
  - expanded polystyrene (EPS) boards
  - foil faced polyisocyanurate (PIR), polyurethane (PUR) or phenolic (PF) boards
- the minimum residual cavity width is not less than 50 mm for InstaBead and InstaBead Diamond and 40 mm for InstaBead Carbon Saver
- installation is carried out by a BBA Approved Installer, trained to work on this type of installation
- all other conditions in section 4.3 are met.

(1) Partial fill installations relate to existing constructions where insulation, in the form of batts or boards, has previously been built into a wall and there is a residual cavity.

Figure 51 Section from the Design Consideration Section of BBA 11/4867 2013

(ii) Suitability

Most masonry cavity walls can be filled with insulation, especially those under 12 metres in height built after 1930. There are also systems available for buildings up to or over 25 metres in height and a few even taller buildings have been successfully cavity-filled following suitable assessment.

Almost all of the systems on the market are approved for use in all parts of the UK. However, they assume that the outer leaf is built for local exposure conditions so that rainwater penetration is minimal.

Where cavity walls are not suitable for cavity insulation, for example when there is only a partial cavity, they can be treated in the same way as solid walls and have internal insulation installed.

(iii) Benefits of cavity wall insulation

Cavity wall insulation can significantly reduce heat loss through the wall. Performance depends on the existing construction as well as the properties of the insulating material used. Table 6 shows the improved thermal performance achieved with various insulation materials.

Figure 52 Advise that partially filled cavities are unsuitable for topping-up (EST, 2010)

Other insulation manufacturers appear to offer advice which is, understandably, suited towards their own products rather than addressing the issue directly; in some cases suggesting remedies which may solve one problem but create additional issues. For example, Celotex suggest that existing partially-filled cavities should not be topped up but instead their PL4000 plasterboard laminate applied internally is their recommended solution (Celotex, 2013). However, as we have observed in practise (DECC “Green-Deal-Go-Early” project, Leeds Beckett University unpublished), even following the recommended installation guidelines (Figure 53) could leave the intermediate floor void without additional insulation creating a significant thermal bridge and potential condensation risk. Fully filling the residual cavity would not increase the thermal bridging at the intermediate floor perimeter, reducing the risk of mould growth rather than potentially increasing it.

Installation guidelines

Installation guidelines for internal lining systems using direct bonding

- Ensure that existing walls are permeable. Strip any gloss paint or vinyl wallpaper.
- Use the Celotex Insulation Saw to cut the 1200mm x 2400mm Celotex PL4000 boards to fit the floor-to-ceiling height of the room.
- Ensure a continuous seal at skirting, ceiling level and at openings by applying a continuous band of gypsum adhesive. Gypsum adhesive at perimeter edges can be replaced with thin timber battens.
- Apply further dabs of gypsum adhesive. This should be in accordance with the adhesive manufacturer's instructions.
- Align sheets against the dabs and secure into correct position.
- Once the dabs are set, it is recommended that

Installation guidelines for internal lining systems using mechanical fixings

- Ensure that existing walls are permeable. Strip any gloss paint or vinyl wallpaper.
- Use the Celotex Insulation Saw to cut the 1200mm x 2400mm Celotex PL4000 boards to fit the floor-to-ceiling height of the room.
- Secure Celotex PL4000 with suitable mechanical fixings. Fixing details should be in accordance with the fixing manufacturer's instructions.
- Joints between the boards must be tightly butted, taped and jointed using appropriate tape and jointing material to create the VCL.
- Line window and door reveals as for direct bonding technique in adjacent column.

Installation guidelines for internal lining systems using mechanical fixings to timber

Figure 53 Installation guidelines for Celotex PL4000 (Celotex, 2013)

Iwaszkiewicz (2010) conducted a desk-study that looked at the potential for 'topping-up' residual cavities of partially filled external walls. In his 2010 report *Hard to Fill Cavity Walls in Domestic Dwellings* Iwaszkiewicz lists partial-fill in the 'hard to treat' category, and acknowledged that although the original partial-fill may not perform as well as expected this may or may not produce the expected gains for the 'topped-up' solution (Figure 54). Potential savings might be elevated due to issues in the original partial-fill being resolved, or alternatively potential savings may be limited by existing problems with the original partial-fill causing residing issues in the 'topped-up' solution. The report also provides limited technical advice (drawings from Appendix B are shown in Figure 55), but also raises many issues with the 'top-up' of partial fill such as surveying adequately, ancillary costs, moisture penetration and slumping/displacement of the original partial-fill. The work supplies lists of issues to consider for each type of hard-to-treat cavity with the notable exception of partially filled cavity walls.

The baseline performance of the wall constructions being considered in this study are shown below and their U-value ranges from 0.464W/m2K to 2.457W/m2K. The value of 0.464W/m2K for partial fill assumes that it has been installed ideally i.e. retained permanently against the inner leaf of a cavity and in a continuous manner with no gaps in insulation. If the installation were poorer in practice then the predicted savings shown for retro-fitting partial fill cavities would be higher than described below.

Partial filled	Where insulation had previously been installed to a fraction of the cavity width by design or otherwise and may have even sloped away from its intended location on the inner face of the cavity over time. Any newly introduced insulation material would need to be able to fully fill the remaining spaces without unintentionally becoming a cause of unpredictable locations of damp penetration e.g. where condensation builds up after running down the sloping insulation

Figure 54 Issues relating to the success of 'topping-up' partially filled 'hard to treat cavities' (Iwaszkiewicz 2010)

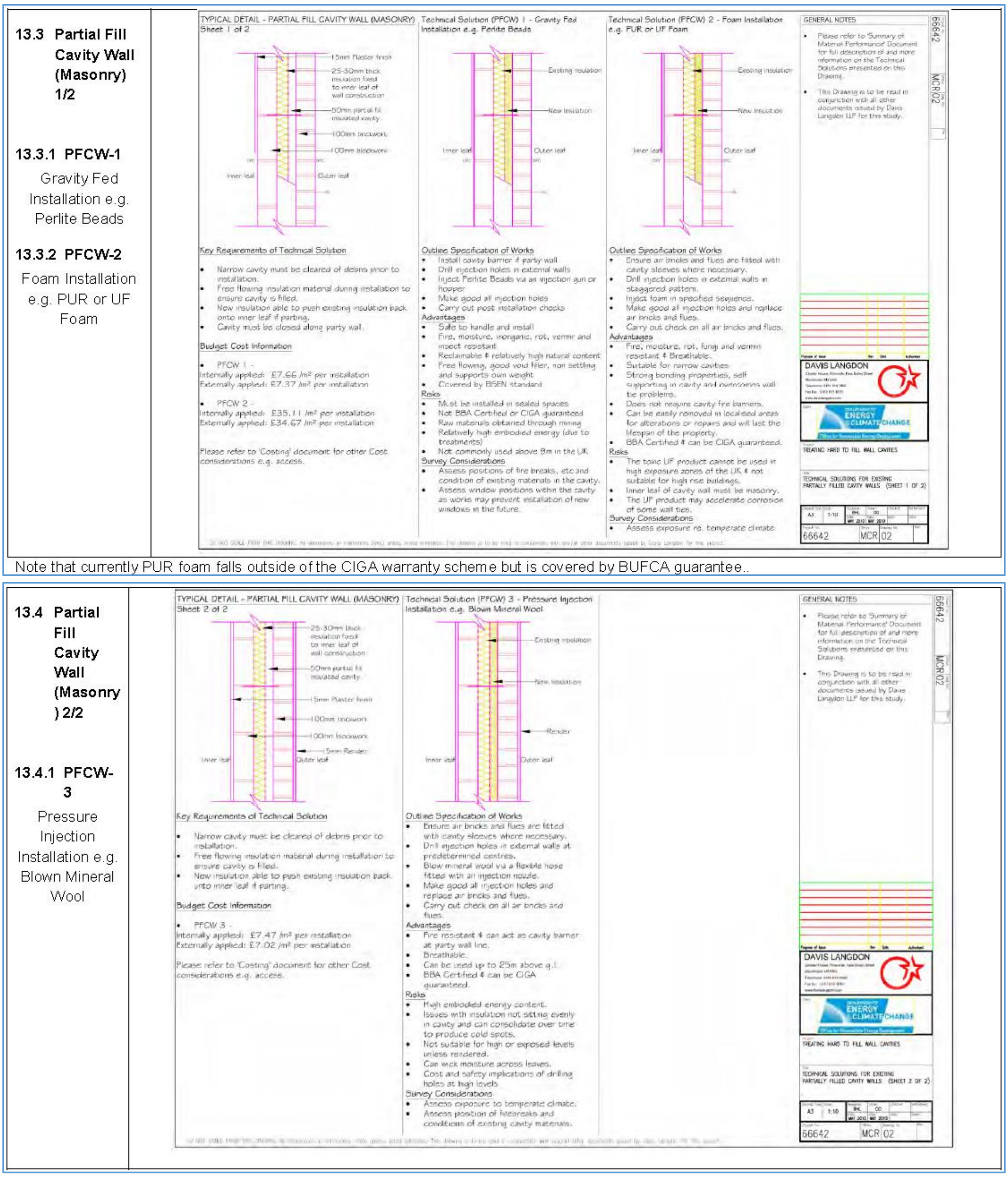


Figure 55 Technical advice for the 'top-up' of partially filled 'hard to treat cavities' (Iwaszkiewicz 2010)

Potential market

Thompson (2012) used the English Housing Survey 2008, Scottish House Condition Survey 2009 and Living in Wales 2008 to calculate an estimated number of partial-fill cavity walls in the UK. It estimated U-vales for partial-fill walls at 0.464 W/m^{2}K and filled ones at 0.36W/m^{2}K. The work is based on DECC 2010 English House Condition Survey work by the Energy Savings Trust, using NHER Plan Assessor to provide some estimates for potential CO_2 savings of selected property archetypes. It also refers to Doran (2001) to use an as-built error of 0.10 W/m^{2}K for partially filled cavity walls for the difference between estimated and actual thermal performance. Without providing a total number of partially-filled dwellings in the UK it estimated between 560,000 to 840,000 partial-fill walls as "Type 3: non-standard cavities – not fillable" due to a variety of issues.

Iwaszkiewicz (2010) also based figures on the English Housing Condition Survey (2007) and estimated potential CO_2 savings achievable from topping-up the residual cavities, combining these with potential costs of performing the work. Using SAP2006 as a calculation tool for estimating CO_2 savings and values, Iwaszkiewicz suggested that the 'top-up' market could save up to 163,000 tonnes of CO_2 annually and be worth up to £3.4 bn, based on 2010 prices, (Figure 56).

- In addition there is a category of walls that the English House Condition Survey describes as "filled" but that have a remaining cavity. There are in the order of 1.6 to 2.4m such "partially filled" cavities in Great Britain. The potential annual CO2 savings in filling these are in the range of 22,000 to 33,000 tonnes/annum assuming a take up of 20%, 109,000 to 163,000 tonnes/annum for full 100% take up and 54,000 to 81,000 tonnes/annum if CERT underperformance and comfort factors are applied and if 100% of potential population of cavities are filled.

Other Dwellings (Partial fill only)	Population	Annual CO2 saving - allowing for 20% application of solutions (Tonnes/annum)	Annual CO2 saving - allowing for 100% application of solutions (Tonnes/annum)	Annual CERT CO2 saving – If CERT underperformance & comfort factors are applied and if 100% of potential is filled. (Tonnes/annum)
Partial Fill	1.6 million - 2.4 million	22,000 - 33,000	109,000 - 163,000	**54,000 - 82,000**

- The estimated costs of filling both categories of wall cavities (excluding filling of party wall cavities) at current (mid 2010) prices are as follows:

	Dwellings	20% uptake	100% uptake*
	No.	£m	£m
Hard to Fill	3.9-5.8m	£1,103-1,660	£5,530-8,300
Partial Fill	1.6-2.4m	£450-680	£2,265-3,400

Figure 56 Estimates of number of partially filled cavities that could be 'topped-up' and filling costs (Iwaszkiewicz, 2010)

Laine (2012) independently expands on the numbers of homes listed in the report above based on later DECC and NHBC figures, and although the numbers come from a more limited dataset the percentage of each construction type with partially filled cavities is shown to be fairly consistent. Figure 57 shows partial-fill construction still comprising around a third of all low-rise traditional build in 2011, and also over 10% of UK timber frame construction utilising partially-filled cavities to improve the thermal resistance of the walls. The *Consumer Focus* document also criticises the Green Deal for its use of rdSAP design based performance assumptions. The work notes in particular the lack of pressure to overwrite the default values with evidence-provided values. The use of such values has led to an over-estimation of the performance of insulated cavity walls, in general, by assuming design/target U-values are always achieved in practice. The trend in new build houses shown in Figure 57 will mean more dwellings continuing to add to the underperforming partial fill existing building stock, as listed in Iwaszkiewicz (2010) and Thompson (2012) above, for some years to come.

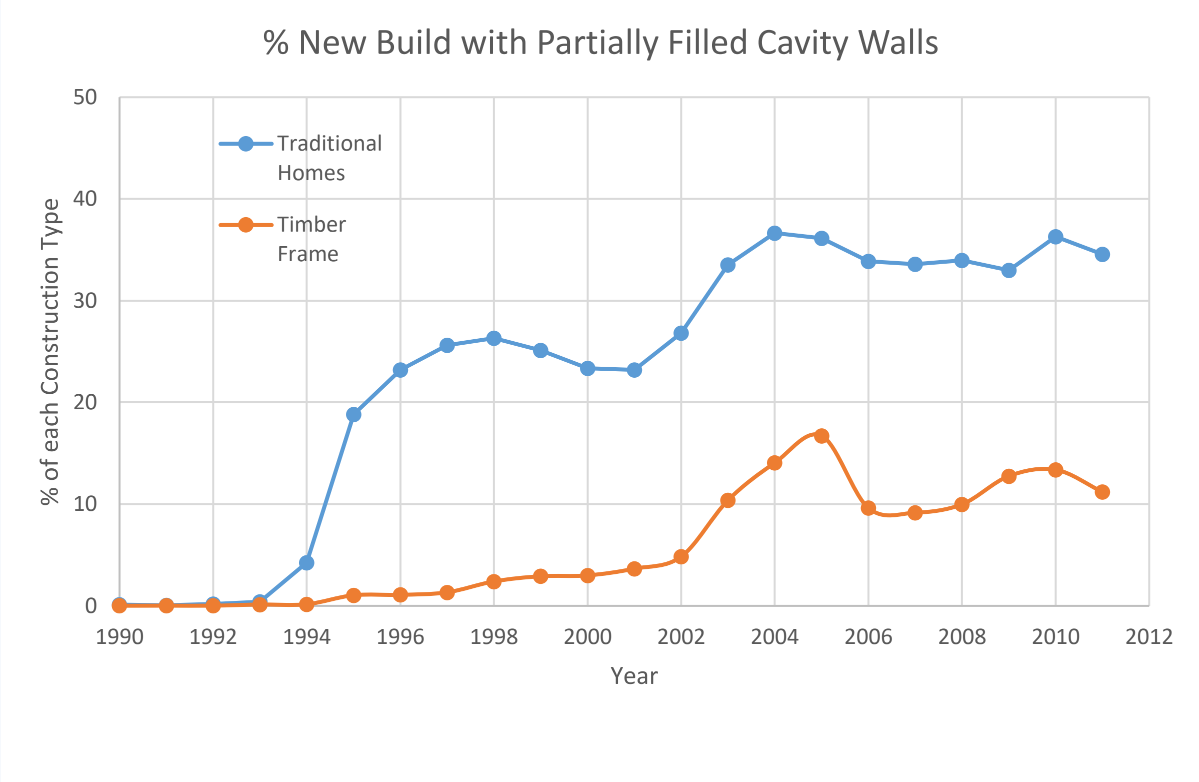


Figure 57 Percentage of new build with partially filled cavity walls (from Laine, 2012)

In addition to the “topping-up” of partially filled external wall cavities, there is also a potential market for the “topping-up” of partially filled party walls. A number of Robust Details show party wall cavities partially filled, including: E-WM-8 (Figure 58), E-WM-14, E-WM-15, and all steel frame robust details. The party wall bypass heat loss mechanism described in Lowe *et al.* (2007) would still be operational in these structures, although for the property with the attached partial fill insulation this would be somewhat mitigated. Filling the residual cavities here would reduce or eliminate any existing bypass heat loss mechanism from the property with the un-insulated party wall.

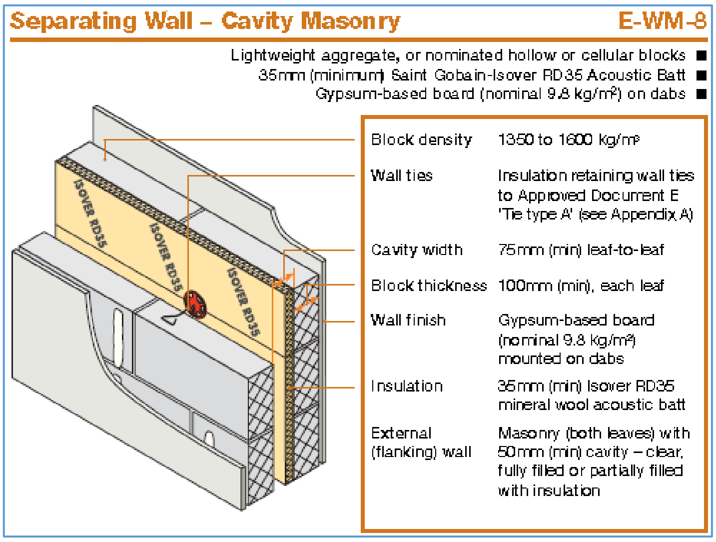


Figure 58 Partially filled party wall detail (Robust Details, 2015) allowing the party wall heat loss mechanism to operate from the un-insulated side and raising the potential for the potential number of partially filled walls suitable for residual cavity ‘top-up’.

Conclusion

The review has identified a number of recurring themes affecting cavity partial fill wall construction. However, of first consideration is the degree of variation between the studies and, whilst comparison is made, it is important to note some of the differences in research methodology will inevitably impact on the results.

Each study that assesses the thermal properties of partial fill cavity must be considered on their own merit. Some studies are limited by both the equipment and methodology used. The work reported here has shown that many studies use one or two heat flux sensors to measure heat flow through plane elements. By limiting the number of measurement points the ability to capture and recognise anomalies and inconsistent behaviour is reduced. Where studies have used multiple measurement points, the results show that partial fill cavities have variable performance across, what may be considered plane elements. In the few studies that have topped-up the remaining cavity with insulation the results have shown improved performance and less variability across the plane element. The reduced variance in most cases is attributable to the filling of voids and possibly the additional force of the fill pushing the existing boards to assume closer proximity to the internal face of the wall, further reducing gaps. Further work needs to be undertaken to determine how different partial fill materials respond to different fill patterns and densities.

Where studies attempt to measure heat exchange under occupied or dynamic conditions, the factors that impact heat flow through the wall need further consideration. Dynamic internal conditions are likely to lead to a more variable temperature distribution within the wall fabric resulting in greater variation in the measurements taken on the internal and external surface. While access to properties in the field may be limited, sometimes with measurements undertaken in occupied buildings, the degree to which a building can be controlled should considered when assessing the reliability of the findings.

The dynamic response of a wall is of interest especially when considering thermal capacity, lag and response under different conditions, but at this point in time, work shows that measurement under quasi-steady state internal conditions offers more reliable test conditions (Bauwens, 2015), and provides a more appropriate comparison with calculated U-values by eliminating thermal mass harmonics and reducing other significant variables. Further work should be undertaken to explore the thermal capacity and lag of partial fill and fullly filled cavities under both quasi-steady state and dynamic conditions.

The consistent theme running through this review is the degree with which the interconnecting air paths offer the potential for thermal bypass and reduced thermal resistance of the partially insulated cavity wall. By design (weep-holes) and through practice (gaps in construction) the air within open cavities cannot assumed to be still. Furthermore, when the conditions are excited by heat or internal / external pressure differences convection currents and air circulation takes place within the fabric. Experimental work has shown that very small gaps, less than 5mm, will result in a deviation from expected performance, and gaps or openings larger than this lead to highly changeable thermal behaviour. The early research undertaken provides examples of air exchanges in cavity that can result in the heat flow being more than twice that expected. Further work in the field would be of benefit to explore the heat exchanges during changeable conditions, such as high winds and fluctuating moisture levels.

The partial fill cavity, in its current construction form, offers a conduit for heat exchange and bypass into, out of, around and thought the external envelope. A topped up and filled cavity shows potential to reduce the heat exchange, as found in the few cases tested.

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Appendix

Examples of practice and possible remedies

	Issue identified	**Potential to remedy**
Effective seal	Most of the partially filled cavity walls reported and studied did not provide an effective seal.	The top-up of partially filled cavities can significantly dampen or provide an effective thermal barrier where there is adequate access to fill remaining cavity. The filling and sealing of narrow cavities requires consideration of fill product and condition and characteristic of partially filled consider. In all circumstances a survey should be undertaken. Further work is required to asses building type and fabric conditions that benefit from such an upgrade.
Inconsistent performance: Air infiltration	Due to the different levels of air infiltration and exfiltration, thermal performance often varies across the plane element. The cooling and heating affect is dependent on the internal and external temperature; the focus of most studies is where the internal environment is warmer than that of the external environment, thus in most studies infiltration will result in cold air entering the fabric and exfiltration with warm internal air passing through the fabric. The air exchanges, whether recognised as infiltration (cold external air cooling the wall) or exfiltration (internal air warming the wall) are sources of thermal bypass and would normally benefit from remedial installation of insulation to seal the cavity.	Dependent on width of cavity and technology applied, research results suggest that performance would be improved. Obstructed areas may still present paths that may require remedial attention. Both exchanges of air could are considered problematic. The infiltration of cold air increases heat exchange and reduces the ability to control internal environments. Exfiltration of warm moist air could lead to interstitial condensation as the air cools and gives up water it cannot hold. The addition of water within the fabric may also increase thermal conductivity.

Inconstant performance: poorly placed insulation	Gaps, irregularities, cracks, ill-fitting insulation, cuts and overlapping of boards, can all contribute to underperformance. Significant evidence exists of the potential for bypass in such situations.	Where there is sufficient access and irregularities and the gaps can be filled, the degree that such deficiencies continue to influence thermal exchanges may be reduced. Further work should be undertaken to explore the degree that insulation fill can remedy construction defects.
Bypass links to neighbouring elements and properties.	Thermal exchanges between elements and properties can carry both warm and cold air. The passage of warm high humidity air into cold parts of the building is risky. Tests on some properties has found that smoke can pass from one property to another. Ineffective seals between properties has implications for both thermal and fire	Full fill external wall, party walls and any connecting cavity between properties to reduce air exchanges influenced by differential pressure. Further testing required.
Construction fault	Much of the evidence of underperformance found documents the misplacement, poor alignment and inadequate fixing of insulation within plane elements. The photographic evidences shows this is largely a result of site practice. A better understanding of site based instalment requirements, supervision processes and potential consequences for malpractice is required.	Site personnel must have a basic understanding of how insulation works. The link between poor alignment and gaps in the insulation and failure to achieve thermal performance should be understood. Ownership and responsibility installation needs to be achieved and neglect targeted. Evidence based supervision, meta and geo-tagging of photographic records to demonstrate quality of installation should become mandatory and part of a buildings construction, maintenance and performance manual.
Ageing and deterioration of external cavity walls	Both wall structures and any insulation contained within will suffer some deterioration over time.	Shrinkage, settlement, weathering and chemical decay of masonry outer leaves should be addressed for air and weather tightness, not just for structural issues.

	Cracks and fissures in external walls are only deemed problematic should they represent a structural defect, however, even small gaps will increase air movement in external wall cavities.	Topping up a partially filled external wall cavity with additional insulation should make the thermal performance of the wall more robust to the natural deterioration of the masonry outer leaf.
Design	Failure to adequately specify and detail assembly. Many junctions and details are not fully designed and specified. The responsibility for installation then remains with site based personnel.	Provide full details and specifications. Where junctions are difficult to model they will be difficult to build. Care should be taken to produce detailed interface information and product assemblies.