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# In-construction tests show rapid smoke spread across dwellings

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**The paper discusses further proof for the use of diagnostic in-construction testing (iCT) developed by the lead author at Cardiff Metropolitan University as a framework of test methodologies for investigating incorrect installation of, missing, inappropriate or defective components within and connected to the building envelope and the fabric of new dwellings in the UK. Without rectification, these defects can affect thermal performance and thus energy efficiency and lead to increased carbon emissions than specified at the design stage. Use of iCT tests in 2014 and 2015 in collaboration with Sustainable Construction Monitoring and Research has identified a potentially far greater problem than reduced thermal performance, which may lead to complete building failure and occupant injury or death. The paper will discuss findings from three case study construction sites where during a multimethod iCT test approach, smoke spread occurred between dwellings and into means of escape in minutes, which should not before 30 min or 1 h.**

## 1. Introduction

Building fabric efficiency is central to ensuring and maximising performance: acoustic, smoke and fire spread and thermal in domestic buildings (Asdrudbali *et al*., 2015). So, limiting and decreasing carbon emissions, noise pollution and risks of smoke and fire spread between dwellings relie on a correctly designed, specified and constructed building fabric. Increasing demands in the design and construction of the fabric for the building envelope (i.e. construction components) efficiencies are driven by increasing stringent regulations and standards. Yet, there is increasing evidence of a 'performance gap' between the design aspirations and the as-built constructed building fabric, such that some new dwellings inherit inefficiencies from the construction process, which are unobserved or hidden during mandatory compliance checking (Holleron, 2014; Johnston *et al*., 2016). The presence of construction issues including defective, incorrectly fixed, missing, thermal bridging in and across construction components and, in addition, discrepancy in '*U*' values and increases in air permeability contribute to increased heat loss and carbon emissions, thereby decreasing energy and carbon efficiency (Johnston *et al*., 2016; Littlewood, 2013). Equally, building fabric weaknesses may also contribute to the overall inadequate building performance compliance for mandatory smoke and fire spread mitigation. This paper presents three case studies involving independent assessment using in-construction testing (iCT) and performance evaluation undertaken on social housing dwellings within Wales, UK (Littlewood, 2013; Littlewood and Smallwood, 2015). The paper provides further evidence to support the rationale for standardisation of diagnostic testing during the construction stages of dwellings, adding to the body of evidence for iCT developed by Cardiff Metropolitan University (Littlewood, 2013; Littlewood *et al*., 2011). By using iCT, it can reduce instances of the performance gap and its impacts upon occupant comfort, energy costs and carbon emissions by conducting thermography tests (Littlewood, 2013; Tweed and Littlewood, 2014), individual air tightness testing (Plescia and RDH, 2013), combined with smoke tests (Littlewood *et al*., 2015; Nooraei *et al*., 2013a). Furthermore, following work in collaboration with Sustainable Construction Monitoring and Research, the paper discusses that by using iCT, potential problems with compartmentation between dwellings may be identified as being potentially defective, where rapid smoke spread between dwellings occurs in minutes, rather than 30 min to 1 h, the minimum for dwellings in the UK (HM Government, 2013a). Finally, the paper introduces a 2-year research project, which began in September 2015, to further investigate developing a test method for identifying the potential problems of inadequate compartmentation and impacts on fire safety in new dwellings being constructed or recently built and occupied in the UK.

## 2. UK approach to housing construction – fabric first

Since 2006, the UK was committed to implementing 'zero carbon' standards for all new domestic buildings by 2016, and some housing developers have focused on the building 'fabric first' approach through increased and improved insulation and reduced thermal losses by eliminating thermal bridging and increasing air tightness (Department of Communities and Local Government (DCLG), 2007; Zero Carbon Hub, 2015). The performance targets of the zero carbon standard were being implemented through progressive strengthening of the requirements of Approved Document L1A (ADL1A) 'Conservation of fuel and power in new dwellings' (ADL1A) of the UK Building Regulations, until the code for sustainable homes (CfSH) was scrapped by the UK Government in Spring 2015 (Anon, 2015a; DCLG, 2010). This included improvement in the Accredited Construction Detail specifications for mitigation against thermal losses (DCLG, 2010). Until the scrapping by the UK Government, the CfSH was a critical influencing factor in creating ever-more carbon, sustainable and environmentally efficient housing, within the 2016 zero carbon target (Anon, 2015a). Yet, to date (spring 2016), compliance within the building fabric efficiency requirements remains a 'weak area' within the Building Regulations (Cox, 2006; Littlewood and Smallwood, 2015) and undermines the UK's policy commitments. The Zero Carbon Hub Evidence Review Report (2014) identifies various issues relating to the current UK compliance methodologies and regime, which are reflected in the Standard Assessment Procedure (SAP), methodologies, processes and tools used to check compliance with UK Building Regulations, particularly Approved Document L1a governing the conservation of fuel and power in new homes in England and Wales (HM Government, 2013b; Welsh Government (WG), 2015). In that, as-built SAP assessments are often not reflective of the actual built dwelling (Johnston *et al*., 2016; Littlewood and Smallwood, 2015; Littlewood *et al*., 2014). The Zero Carbon Hub Evidence Review Report (2014) highlighted building fabric performance compliance issues including but not limited to a 'tick box' culture in recording evidence for SAP calculations, such as where compliant accredited construction details were not actually built on site.

In the UK, building control officers (local government) and approved inspectors (private) have the responsibility of approving building construction, including where accredited construction details are used (Planning Portal, 2015). However, the results presented below indicate that mandatory inspection may not always be undertaken (Littlewood and Smallwood, 2015). In addition, to short-term fixes, improvisations and poor installation of fabric due to inadequate installation guidance or design drawings may not always be followed, without understanding the impacts in achieving performance requirements assessed through air pressure testing results. The evidence-gathering (2015) sources included InnovateUK's (formerly the Technology Strategy Board) Building Performance Evaluation programme, which the authors have been involved with, one case study (Littlewood and Smallwood, 2015; Littlewood *et al*., 2014) and three case studies illustrating the key performance issues as highlighted in the Zero Carbon Hub report (2014).

## 3. Case studies

The case studies document the fabric performance testing using iCT methods first developed by Littlewood (Littlewood, 2013; Littlewood *et al*., 2011) for utilisation during the construction process and also during commissioning of the dwellings, prior to occupancy, on three separate housing developments, located in South Wales, UK. The testing was undertaken by and for the authors in conjunction with social housing developers in Wales, as part of the first authors work for Work Package Six of a European funded research project documenting the monitoring of low-carbon buildings and products in the UK between 2010 and 2013 (Littlewood, 2013; Littlewood *et al*., 2011; Nooraei *et al*., 2013a, 2013b). In addition, an independent quality assurance service was conducted by the authors as a consultancy service between 2014 and 2015 (Littlewood and Smallwood, 2015). A brief summary of each case study is given, the iCT methodologies were adopted and the results were observed before the discussion section to compare the findings. The test equipment used during the iCTs is summarised in Table 1 below.

Note that the smoke test equipment is used by many UK fire services for fire training purposes and so creates dense smoke such as in conditions in an actual building fire (albeit is it not thermally buoyant), and smoke exits the smoke generator at a temperatures of 330°C before cooling to ambient room temperatures (Concept-Smoke, 2016).

Note that due to the sensitivity of the results presented in this paper and the potential impact of inadequate compartmentation and potentially inadequate, missing or damaged cavity barriers, and the potential resulting affect on occupant safety in the likelihood of a real fire, only limited photographs of the test results were permitted to be used and published.

### 3.1 Case study one

Case study one consists of one semidetached, two-storey dwelling from 20+ affordable homes for rent and sale, designed and constructed to meet ADL1a of the 2010 Building Regulations (England and Wales) and occupied in 2013. The dwelling was of timber frame and brick-clad construction, designed to level 3+ of the CfSH. The dwelling was designed and reportedly constructed to the applicable robust construction details, with timber frame party walls. Space heating is provided by a gas condensing boiler, and internal ventilation is by way of mechanical ventilation heat recovery systems, located in the cold-roof spaces with a single vent located in the first-floor landing and all windows had passive trickle vents in the opening window frames.

| Equipment used | iCT tests |
|---|---|
| Minneapolis Blower Door | Depressure air permeability test<br>Combined pressure air permeability test/whole-dwelling smoke test |
| Micromanometer DG700 | Depressure air permeability test<br>Combined pressure air permeability test/whole-dwelling smoke test |
| Testo 511 Barometer | Depressure air permeability test<br>Combined pressure air permeability test/whole-dwelling smoke test |
| Internal and External Temperature, Testo 110 & 2 RTD Probes | Depressure air permeability test<br>Combined pressure air permeability test/whole-dwelling smoke test |
| PCE – TA 30 Anemometer | Depressure air permeability test<br>Combined pressure air permeability test/whole-dwelling smoke test |
| Energy Conservancy Software | Reporting both air permeability tests |
| Concept Turbo 4 Hybrid | Combined pressure air permeability test/whole-dwelling smoke test |

**Table 1.** Equipment used during the air permeability tests and also the combined air permeability and whole-dwelling smoke tests

The target air permeability was 3·00 $m^3/(h.m^2)$ at 50 Pa, which meets the minimum requirements for the WG's design quality requirements (DQR) at 5 $m^3/(h.m^2)$ at 50 Pa, for dwellings being constructed using WG's social housing grant (WG, 2005). The building contractor-commissioned air test was 2·5 $m^3/(h.m^2)$ at 50 Pa recorded in April 2013. Since the construction quality had been reported to have been less than satisfactory during the construction process by the housing association, the first author and his research team were invited to conduct a series of iCT tests starting with an independent air test as part of a research project 2 weeks before occupants moved into the dwelling (Littlewood, 2013; Nooraei *et al*., 2013a).

The results of the air test was 4·5 $m^3/(h.m^2)$ at 50 Pa in May 2013, almost double that of the contractor's commissioned air test and as a result the university team conducting a combined air test/whole-dwelling smoke test, as recommended by the Building Services Research and Information Association (BSRIA, 2006) to identify unwanted air leakage pathways for remedial works before occupancy.

Within minutes, unwanted air leakage pathways were observed externally to the test house with smoke escaping from the eaves level of the roof (front and rear elevations), ground floor trickle vents that were closed in windows. In addition, smoke was seen escaping from underneath window sills and from underneath door frames (see Figures 1 and 2). These air leakage pathways indicated potential failures in product installation, such as exterior doors and windows, and faulty or damaged components such as cavity barriers and seals to exterior doors and windows.

The most significant air leakage observed from the smoke was only apparent after the neighbour in the adjoining property raised the alarm that her house was filling with smoke on the ground floor – the smoke appeared to be coming through electrical sockets on the party wall between the dwellings. This smoke spread within the adjoining dwelling was occurring within 5 min of activating the pressure test to evacuate the smoke from the test dwelling. This was a clear demonstration of potential failure in the compartmentation between the dwellings, where the party wall should have had a 30-min resistance to smoke spread and fire resistance (HM Government, 2013a). The exit passage of the smoke through the electrical sockets was thought to be due to penetration of the air permeability membrane on the party wall by inappropriately secured

**Figure 1.** Smoke escaping from non-designed air leakage pathways around and underneath one of the exterior door frames in the test flat at case study one during combined air permeability and whole-dwelling smoke test

Figure 2. Smoke escaping from non-designed air leakage pathways underneath one of the exterior window frames in the test flat at case study one during combined air permeability and whole-dwelling smoke test

'screws' in a number electrical sockets, positioned on the party. In case study one, the party wall was of a timber frame construction, which was supposed to have been built to accredited and robust construction details. Thus, the observed interdwelling air leakage pathways could pose potential acoustic, smoke/fire and thermal performance irregularities within the final constructed dwellings. With only 2 weeks before the house was due to be occupied, the housing association instructed the building contractor to repeat air permeability tests on all dwellings on this development, some of which were under occupation. The first author and his team were asked to observe the repeated air permeability test on case study one, which was only undertaken after remedial works to the party wall were investigated and completed after 6 months.

### 3.2 Case study two

Case study two was a first floor flat (one bedroom) in a two-storey block of six flats, designed and constructed to meet ADL1a of the 2010 Building Regulations (England and Wales) to be occupied in the early months of 2015. The construction was similar to case study one, timber-frame and brick-clad construction, designed to level 3+ of the CfSH. The dwellings were reportedly constructed to the applicable robust construction details including timber floors separating ground and first-floor flats with robust detail E-FT-2 to comply with Approved Document E of the UK Building Regulations (Robust Details, 2015a). Space heating is provided by a gas condensing boiler, and internal ventilation is by way of a mechanical ventilation heat recovery system, located in the cold-roof space, with a single vent located in the first-floor landing and all windows had passive trickle vents in the opening window frames.

The target air permeability was $4{\cdot}00\,m^3/(h.m^2)$ at 50 Pa. The authors undertook an independent air test on one of the dwellings in November 2014, a first-floor mid-terrace flat, with a measured air permeability of $5{\cdot}74\,m^3/(h.m^2)$ at 50 Pa, which was lower than the final contractor's air testers determined air permeability of $5{\cdot}93\,m^3/(h.m^2)$ at 50 Pa. The difference between the two reported air permeabilities is observed to potentially result from further completion and sealing of potential air pathways in the building fabric, both internally and externally, although still observed to be incomplete during the test undertaken by the authors. Before the authors conducted their air test, they observed the contractor's commissioned air test and a number of discrepancies in the methodologies employed by the contactor's tester appeared to contradict those set out in The Air Tightness Testing and Measurement Association's Technical Standard L1 Measuring Air Permeability of Building Envelopes (Dwellings) October 2010 issue (ATTMA, 2010). The discrepancies appeared to be

- non-verification on-test of the building dimensions derived from the supplied construction drawings and calculated off-site, and the tester used an uncertainty value of '2%' within the software program for building dimensions to calculate the air permeability from the air test results for all observed plots tested, without validation of the uncertainty
- incomplete measurement of external and internal environmental conditions
- incomplete external building fabric such that the test results are not representative of its final completed state
- none and/or incorrect and/or inappropriate sealing of potential pathways was observed prior to and/or during the air tests conducted on tested plots.

Taken together, the observed non-compliance by the contractor's air tester with ATTMA TSL1 (ATTMA, 2010) air testing procedures could potentially invalidate all the (observed) air tightness tests conducted at the development. The reported observations also have implications for potential compliance with ADL1a of the UK Building Regulations and associated certification. It also raises questions of energy and carbon efficiency of the constructed building fabric.

Because of the observed anomalies and also the air permeability being worse than the design target, a combined air tightness test (following the pressurised methodology) and whole-dwelling smoke test were conducted by the authors. Unwanted air leakage pathways were observed externally to the test flat with smoke escaping from eaves level of the roof (front and rear elevations), a ground floor porch roof and exterior door reveal (one storey below the test flat) and also the boiler flue outlet. Since the designed air permeability target was quite high at 6·0 $m^3/(h.m^2)$ at 50 Pa, it is expected that there would be a number of air leakage pathways from the dwelling; however, these should not be from areas that indicate potential issues with incomplete work described above.

Of notable concern was that within minutes of starting the combined air permeability/whole-dwelling smoke test, smoke was observed to be present within the loft space of the adjacent first floor flat and also in the bathroom of the adjacent ground floor flat by way of the wall mounted extractor fan unit. These results indicate potential problems with the horizontal and also vertical compartmentation, that is the fire separation between these three dwellings, which means they may not comply with Approved Document B, Volume 1 (2010) of the Building Regulations (England and Wales). Also, they may not comply with ADL1a or ADE.

Note that in the UK there are mandatory tests required to demonstrate compliance with ADL1a for thermal performance with an air permeability test and with ADE for acoustic performance. Yet, there is no mandatory test for ADB Volume 1 for demonstrating that compartmentation and fire separation provide 1-h fire and smoke spread resistance.

The smoke spread between loft spaces within the concealed roof areas corresponds with findings from a BRE study considering lessons learned from real fires and the results of poor compartmentation between 2003 and 2013 in the UK (Shipp *et al.*, 2016). The BRE study found that there is often concealed fire spread in roof voids, presenting life risk to both occupants and fire fighters, and may cause widespread damage to buildings, where some buildings may have to be demolished because they cannot be adequately repaired. The BRE study found failures of inadequate compartmentation; inadequate, missing or damaged cavity barriers; lack of stopping between walls and roof covering and ducts passing through compartment wall not fire stopped (ibid).

The results were reported (by way of the housing association client) to the local government building control office, whom refused to revisit the dwellings having already issued the fire safety certificate, which appears to have based on the specification of accredited and robust details but potentially not site visits during construction. Even though, the findings of the combined air test/smoke test could have implications with respect to both the tested dwelling and the associated dwellings within the same block of dwellings in terms of meeting the necessary building standard requirements for certification. Without a revisit by the certifying officer for ADB, the housing association had no comeback with the building contractor, since there is no mandatory requirement to demonstrate compliance with the 1-h prevention of smoke spread between dwellings – a potential serious safety flaw in fire safety in the UK.

### 3.3 Case study three

The test dwelling was a two-person, one-bedroom, first-floor flat, with two flats per storey, over three storeys, and there was an adjoining block of a further six flats in the same configuration. The two blocks were separated by a party wall. The dwellings were developed by a UK house builder for a housing association under a section 106 agreement (Local Government Association, 2015).

The terrace block was constructed using traditional brick-block construction, with concrete base ground-floor and concrete beam and block intermediate floors, built to robust details including E-WM-20 for the party walls (Robust Details, 2015b). Access to each block of six flats, including the test dwelling, was gained by way of a common staircase forming the central area within the terrace block. Each pair of flats shared a party wall, extending from the shared landing. There is also a shared party wall to the rear of the dwellings with the second terrace block which forms the residential block. The dwellings consisted of an entrance hallway/interconnecting passageway with a kitchen/lounge, bedroom and bathroom. Space heating is provided by a gas condensing boiler and internal ventilation by way of a continuous running vortice mechanical system with local extract fans within the bedroom and kitchen of the dwellings. Trickle vents in the windows and a wall-mounted dryer vent in the kitchen were observed in the test flat. On each landing, there were cupboards housing the electrical and gas meters for flats on that floor and the corresponding gas and electrical inlets.

The design air permeability of the dwelling was 4·70 $m^3/(h.m^2)$ at a pressure of 50 Pa, the contractor's air tester determined an air permeability of 4·59 $m^3/(h.m^2)$, in November 2014. Observations of the contractor's air tightness tests were conducted by one of the authors in November 2014, in the test flat and also other flats within the same block, which illustrated a number of considerable discrepancies in the air test methodologies, contradicting those set out in ATTMA TSL1 (ATTMA, 2010)

- electrical sockets and ventilation extract ducts in the majority of rooms completely sealed to the walls during tests (see Figure 3 with branding greyed out and Figure 4)
- temporary sealing of holes (some larger than the size of a fist) within the seperating walls between flats and means of escape corridor during tests.

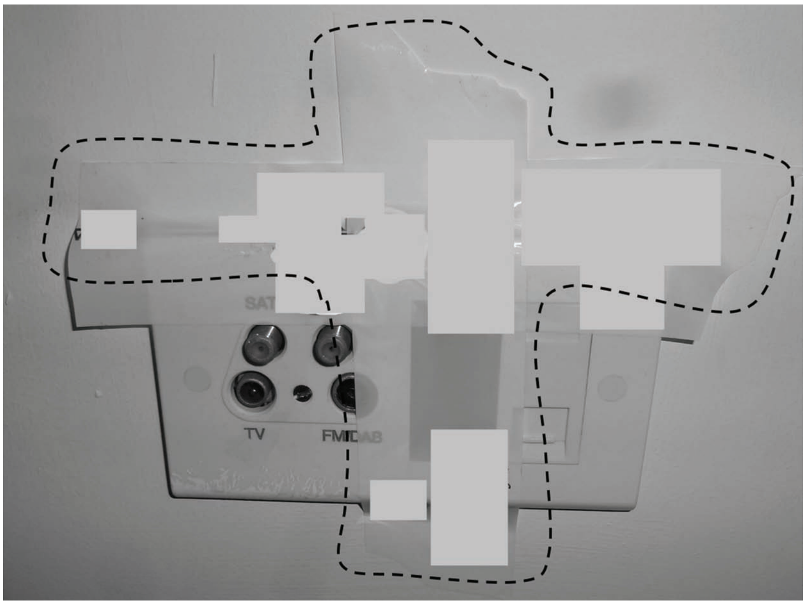


**Figure 3.** Observed temporary sealing of electrical socket to an internal partition at case study three test site (not the test flat) not permitted under the air test methodology set out in ATTMA TSL1 (ATTMA, 2010)

Thus, the authors conducted an independent air test in December 2014, with an air permeability of $4{\cdot}92\,m^3/(h.m^2)$ at 50 Pa, marginally failing the target design air permeability of $4{\cdot}70\,m^3/(h.m^2)$, although still passing the WG's DQR benchmark of $\leq 5{\cdot}0\,m^3/(h.m^2)$.

Like the previous case studies, due to the observed anomalies and also the air permeability being worse than the design target, a combined air tightness test (following the pressurised methodology) and whole-dwelling smoke test were conducted.

From Figure 5, unwanted air leakage pathways were observed externally from the test flat escaping from the kitchen tumble dryer vent and mechanical ventilation vent installed within the exterior wall, the bathroom mechanical ventilation vent installed in the ceiling and in the exterior wall. The vents (not the boiler) were temporarily sealed in accordance with ATTMA TSL1 2010; thus, the escaping smoke could indicate that the ventilation and boiler vents were not installed correctly through the exterior wall or that they were potentially faulty (see Figure 5). In addition, although the gas boiler was deactivated and is supposed to be a sealed system, smoke was seen escaping from the flue of this boiler and also that of the boiler in the flat below (see Figure 5). Furthermore, in the block of flats where the test flat was located, smoke was present in the roof space (two storeys above the test flat) and seen to be escaping when the loft hatch in the top floor corridor was opened; the meter cupboards on each floor where smoke was seen to be escaping at the ceiling level; the corridors (leading to the corridor window automatically opening) and also four of the other five flats. The smoke was present in these locations within a matter of minutes. In the adjoining block of flats, smoke was present in four out of the six flats, and in the other two flats, the odour of the smoke was present. In the flats where smoke was present, it was observed to be entering the flats from underneath the windows, and thus, it appeared from within the cavity wall, indicating a potential breach of the fire compartmentation between flats, through the party wall between the block of flats and within the structural integrity of the exterior walls. Similar to the case studies of real fires reviewed by the BRE study (Shipp *et al*., 2016), there may also have been damaged/missing/inadequate cavity barriers in the compartment wall.

In both blocks of flats, a number of smoke alarms were not sounding, or the siren was sounding intermittently. These results suggest that there were potential serious problems with the fire compartmentation and separation between the properties (horizontally and vertically) and may mean the minimum requirements for AB, Volume 1 – fire separation and compartmentation and fire safety associated with the means of escape are potentially not met. Like the previous case studies, the observed interdwelling rapid air leakage pathways could pose potentially acoustic, fire/smoke and thermal performance irregularities within the final constructed dwellings and may be derived from a number of factors either individually and/or together including potential failure in the building control officer to attend site during installation of construction components to prevent fire/smoke spread, potential failure or incorrect in design

**Figure 4.** Observed temporary sealing around an mechanical extract duct and to an exterior wall at the case study three test site (not the test flat) not permitted under the air test methodology set out in ATTMA TSL1 (ATTMA, 2010)

detailing, potential incorrect execution of construction details and potential incorrect or faulty installed building components. The findings of the combined air test/smoke test could have implications with respect to both the tested dwelling and the associated dwellings within the two blocks of adjoining flats.

Similarly to case study two, a representative from the housing association reported the results to the building control fire officer, whom refused to revisit the dwellings having already issued the fire safety certificate. The building developer however undertook remedial works between December 2014 and January 2015 and undertook their own commissioned combined air permeability/smoke tests, which were observed by the authors and the housing association in January and February 2015. Similar rapid smoke spread between dwellings was observed, even after remedial works.

Also, similarly to case study two, the housing association had no comeback with the building developer, since there is no mandatory requirement to demonstrate compliance with the

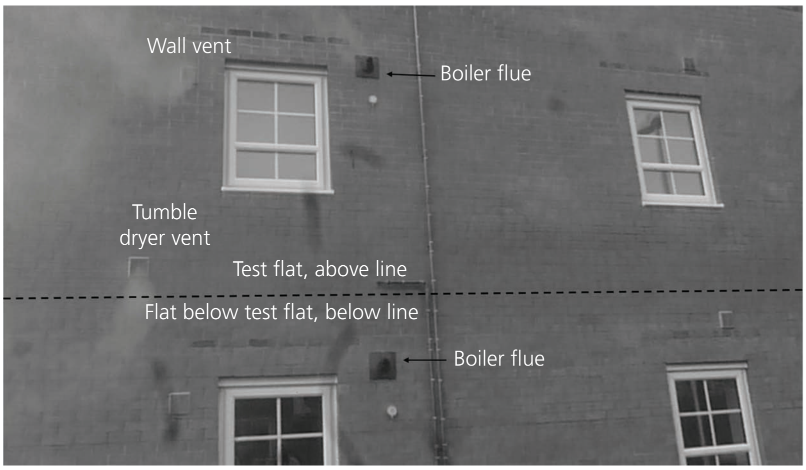


**Figure 5.** Smoke escaping from non-designed air leakage pathways from mechanical and non-mechanical ventilation ducts, the boiler outlet duct in the exterior wall of the test flat and also the boiler outlet duct in the exterior wall of the flat below the test flat at case study three during a combined air permeability and whole-dwelling smoke test

30-min/1-h prevention of smoke spread between dwellings – a potential serious safety flaw in fire safety in the UK and also suggesting that updates need to be made to ADB, Volume 1.

## 4. Discussion

The three case studies demonstrate the identified issues within the reported performance gap between the design intentions and the actual constructed as-built building fabric, including limits of current diagnostic testing regime used to verify the construction of design intents (Zero Carbon Hub, 2014). The testing that does occur 'at best' during the 2nd fix phase of construction provides commercial pressures to ensure that the required outcomes for compliance are met. As a result of these pressures, issues of inconsistencies in test guidelines and methodologies and the interpretation of data coupled with short-term fixes and improvisations on site contribute potentially to the long-term building fabric failures and inadequate performance.

On-site quality assurance issues impact significantly on the construction processes in the delivery of accredited and robust construction details necessary to meet the required building fabric design intents. These may include variability in construction processes between site contractors and trades, failures in on-site management systems in procurement, installation and construction supervision and work scheduling undermining previous phase work compliances. Off-site, there could be limitations in the robustness of third-party verification and enforcement of the required compliances with regulations and standards, themselves proving to be inadequate in meeting the demands of delivering effective building fabrics that perform to the required energy efficiencies and low-carbon intents. Furthermore, when local government and private building control officers receive documentation that indicates that robust and accredited construction details will be used, perhaps they reduce their site inspections to observe and verify compliance from installation of these details, because the act of using approved and accredited details should mean that completed dwellings comply with ADL1a and ADE. However, the BRE study (Shipp *et al.*, 2016) suggests otherwise in the context of ensuring that buildings comply with ADB, since their review of real fires between 2003 and 2013 has indicated 106 had concealed fire spread that should not have occurred if there had been adequate compartmentation, adequate fire stopping for ducting and between compartment wall and roof covering and adequate cavity barriers. All items that should be inspected by local government and private building control officers.

Overall the 'performance gap' is best described as a 'knowledge gap' between off-site designers and on-site constructors and within both the policy makers and administrators, including local government and private building control officers (Littlewood and Smallwood, 2015). The cost in not addressing this knowledge gap not only is observed in the weaknesses of constructed building fabrics to increase energy efficiencies and reduce carbon emissions, but also has both operation and associated fiscal impacts for both the owners and occupants of these dwellings, and potential safety impacts for occupants.

Perhaps the greatest catalyst to the change is that the observed potential failures in the building fabric have the potential to make the occupation of these dwellings unsafe due to smoke and fire penetration and failure in compartmentation, cavity barriers and fire stopping. This is contrary to any certification, with potential regulatory implications if such constructed building fabric failures were proven to be a contributing factor. Indeed, in 2015, there has been a high-profile UK court case where a UK housing association is suing a building contractor for failure in compartmentation between flats in a care home, where a fire burnt rapidly between flats and into the roof space on the building, which was constructed in 2001 (Twinch, 2013; Wilson, 2015). The housing association with the Sussex Fire Service is claiming that because the compartmentation failed to contain the smoke and fire spread for 1 h, the fire service was prevented from tackling the blaze before rapid fire engulfed the building across the six storeys (Wilson, 2015). Furthermore, the Chief Fire Officers Association in 2015 reported they are collating incidents of fires involving timber-frame construction, since more housing associations are using this construction method more frequently (Williams, 2015). Indeed, a fire destroyed a timber-frame building of 120 flats in June 2015, managed by a property services organisation and required 100 firefighters to tackle the blaze where 40 homes will require rebuilding (ibid). Indeed, the BRE study (Shipp *et al.*, 2016) illustrates that in some cases, because the deposits and odour caused by smoke spread in real fires can never be adequately removed, sometimes such buildings have had to be demolished.

Thus, without a mandatory test, such as an iCT using air tightness testing combined with whole-dwelling smoke tests (or a development of this test procedures) to demonstrate non-compliance with ADB Volume 1, the results observed in the case studies discussed within this paper and those illustrated by Shipp *et al.* (2016), Williams (2015) and Wilson (2015) may occur in every dwelling that has been built in the UK with robust and accredited construction details, particularly those where building control officers have used these details to approved compliance and thus limit their site inspections when the details are constructed.

Finally, following the reporting of the tests results in the case studies above, the social housing providers have enhanced their development site inspections. In addition in case study three to co-funding (with the contractor) the replacement of the existing fire alarm system with that of a double-knock fire alarm system in the case study three flats, this type of system will be specified on all its other new development sites (Littlewood and Smallwood, 2015).

## 5. Further work

In July 2015, the first author was awarded a 2-year Research and Enterprise Investment Fund (REIF) grant by Cardiff Metropolitan

University to work in collaboration with a housing association and the University of Plymouth. The 2-year REIF grant is funding the collection of further data from the construction process and performance of dwellings specific to any technical issues related to the implementation of design details, construction quality and the execution of construction details for compartmentation between dwellings horizontally through walls and vertically through floors and ceilings. The data collection will include observation of compliance tests for air permeability, and also the research team undertaking combined air permeability tests with whole-dwelling smoke tests and also in conjunction with thermography. The whole-dwelling smoke tests will involve the refinement of the iCT methodology and the implementation of the smoke-testing process using heated and hotter smoke than that which has been generated by the smoke equipment documented in the three case studies in this paper. Furthermore, the work will involve interaction with the Welsh Fire Service and their safety teams. The data will be analysed to correlate any links between actual occupant injury or death in dwelling fires and the construction methods (including accredited and robust details) for compartmentation and also any relationship with performance compliance containing smoke and fire spread for 1 h between dwellings, and in comparison with the findings of Shipp *et al*.'s (2016) study. In addition, data will be compared with the air permeability test certificates lodged by Building Control Offices in the UK. The project commenced in September 2015, and the evidence and results gathered will be disseminated and presented through the Perceptual Experience Laboratory (PEL) at Cardiff Metropolitan University in order to try and give as close as is possible the experience of what it is like to be in a fire – during the early stages with smoke spread. By using PEL, it could be useful for understanding how dwelling occupants react in a fire, for example where smoke passes through electrical sockets at eye level when people are in bed or through ventilation ducts in the ceiling, and thus how best to design means of escape and showcase the actual problems of inadequate compartmentation (Anon, 2015b).

In addition, the research will be presenting findings at UK academic, industry and professional body workshops and conferences to a variety of stakeholders. To date, this has included the Community Housing Cymru's (CHC) Fire Safety group meeting (CHC, 2015) and also the Chartered Institute of Architectural Technologists Design Futures Reflecting and Projecting conference (Allwinkle, 2016), both in December 2015. It is hoped that the findings from this research can assist housing developers and building contractors to identify appropriate construction detailing to ensure compliance with UK Approved Documents, particularly ADL1a and ADB. Furthermore, the findings may inform the WG on a requirement for a mandatory test method (during construction) to demonstrate compliance with the 30/60-min prevention of smoke and fire spread between dwellings, as part of ADB Volume 1, thus ultimately reducing the destruction of buildings and also limiting risks and injury to occupants, such as were found at a care home in the UK in 2013, where 30 residents were evacuated when fire broke out in one flat and rapidly spread to neighbouring properties horizontally and vertically, due to fire containment not being within 60 min (Wilson, 2015).

## 6. Conclusions

The discussion, results and analysis in this paper provide evidence suggesting that compartmentation between dwellings to prevent the spread of smoke and fire is potentially not working in the UK. In the event of a real fire in the dwellings, there is a substantial chance that the occupants would be injured, if not killed. The results from three case studies using iCT developed by the authors also highlight the potential inadequacy of statutory sign-off for Approved Document B and L and also of the irregularities that occur with mandatory air tightness tests and lead to incorrect test certification. Thus, it is concluded that more evidence should be collected on the reported irregularities and the potential for a mandatory iCT test to demonstrate compliance with compartmentation and Approved Document B for preventing smoke and fire spread up to 30/60 min. Finally, a two-research project, which started in September 2015, is also discussed, which is in collaboration with a major developer and regeneration organisation in Wales and two Universities, that sets out to explore some of these questions and collect further evidence on the risks of potential smoke and fire spread between dwellings and to trial the use of iCT methods with heated smoke. This paper is important for building surveyors, design professionals, housing associations and housing developers, building control surveyors, building contractors, fire officers, local authorities, the DCLG and the WG.

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