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A new methodology for the selective measurement of building performance and safety

Littlewood, J. R.^{a*}, Alam, M.^a, Goodhew, S.^b

^aCardiff Metropolitan University, Cardiff School of Art & Design, Ecological Built Environment group, Cardiff, CF5 2YB, UK

^bUniversity of Plymouth, Environmental Building Group, Plymouth, UK

Abstract

This paper evaluates the present evidence of smoke spread due to problems in compartmentation and also reviews different test methods which can be employed to identify these problems during construction stages. Since 2010, evidence has emerged that the rapid spread of smoke occurs in and between UK buildings, including where accredited construction details and/or robust details are specified [1, 2]. It is considered that this rapid smoke spread could be due to incorrect installation, missing, inappropriate or defective components, that make up compartmentation and fire stopping within concealed spaces [1, 2, 3]. These defects can compromise the ability of compartmentation to resist fire and smoke spread between dwellings and also into any means of escape. The impact of the defects could ultimately be detrimental to occupant safety, care staff with the occupants and also fire fighters, in the event of a real fire. In 2016, fire risk assessments undertaken in buildings before occupancy (that ascertain the performance of the building with respect to fire and smoke spread in accordance with Approved Document B) of the UK Building Regulations are based upon a visual review of building design details and documentation, and also visual inspection of as-built details. However, this approach is inadequate to identify defects in the components that make up compartmentation and fire stopping details in concealed spaces [3] since, it is impossible to determine with the naked eye whether these details have been installed as designed. Littlewood and Smallwood [1, 2] have identified an urgent need to investigate the extent of these smoke spread problems within new dwellings being constructed in the UK and also the development for an appropriate compliance test which can identify issues in fire compartmentation and fire stopping and used before buildings are occupied - such as the in-construction testing (iCT) process. The paper also reviews different tests that can be employed as part of iCT methodology to identify the potential defects in fire compartmentation, and fire stops such as cavity barriers in buildings.

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* Corresponding author. Tel.: +44 (0) 29 20 41 66 76.

E-mail address: jlittlewood@cardiffmet.ac.uk

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1. Introduction

Smoke is considered as a potential threat to life of occupants and fire-fighters due to inhalation of toxic gases and disorientation due to poor visibility. Smoke can contain harmful chemicals and gases such as carbon monoxide, hydrogen cyanide, hydrogen chloride, hydrogen fluoride, carbon dioxide. The majority of dwelling fire fatalities occur due to the effects of smoke rather than the heat of fire. In 2013, 41% of fire-related deaths were caused by gas, smoke or toxic fumes in Great Britain [4]. Sometimes, smoke deposits and their resulting odour can also impact on buildings and can never be adequately removed and some buildings have had to be demolished [3]. Compartmentation in buildings is the main basis of restricting the spread of fire, smoke and toxic gases for 30 minutes to one hour, to enable the safe evacuation of occupants as set out in the UK Building Regulations Approved Document B (AD B) Volume 1 [4] for dwellings, and Volume 2 for buildings other than dwellings [5]. For hospital and health care buildings, the regulatory frameworks are the Health Technical Memorandum (HTM) 05-02 [6] and Building Bulletin 100 for educational buildings in England and Wales [7, 8]. However, defects in compartment construction or fire stopping due to incorrect installation, missing, inappropriate or defective components that make up compartmentation and fire stopping within concealed spaces [1, 2, 3] can lead to rapid spread of smoke and toxic gases into adjacent compartments, which could have tragic effects on the safety of occupants in an actual building fire.

In 2016, fire risk assessments undertaken in buildings before occupancy that ascertain the performance of the building with respect to fire and smoke spread in accordance with AD B of the UK Building Regulations are based upon a visual review of building design details and documentation, and also visual inspection of as-built details. However, due to the hidden nature of these details, this approach is inadequate to identify defects in the components that make up compartmentation and fire stopping details in concealed spaces [1, 2, 3]. Littlewood and Smallwood [1, 2] have identified an urgent need to investigate the extent of these smoke spread problems within new dwellings being constructed in the UK and also the development for an appropriate compliance test which can detect issues in fire compartmentation and fire stopping before buildings are occupied - as a refinement to the in-construction testing (iCT) process. This paper discusses the present evidence of potential problems with fire compartmentation between dwellings, which has led to rapid smoke spread between dwellings in less than minimum time frames required for dwellings, as set out in the UK Building Regulations. Further, the paper reviews different tests that can be employed as part of iCT methodology to identify the potential defects in fire compartmentation, and fire stops such as cavity barriers in buildings.

2. Review of existing evidence and case studies related to smoke spread in dwellings

The Zero Carbon Hub in their Thermal Bridge Guide [9] and Builders Book [10] illustrate errors in workmanship and construction site practices within the UK for the installation of insulation in exterior walls, ground floors and intermediate floors, party walls and in roof spaces, and this includes where accredited and robust details are specified. Furthermore, the errors that were discovered in workmanship also included incorrect fitting of components through insulation, such as ducting, indicate that mandatory inspection may not always be undertaken. Short term fixes, improvisations and poor installation of fabric due to inadequate installation guidance or design drawings may not always be followed and this leads to unintended consequences without understanding the impacts in achieving performance requirements assessed through air pressure testing and acoustic testing. One of the findings around air tightness from Innovate UK's Building Performance Evaluation programme was that 30% of dwellings monitored did not meet the reported post construction air permeability values when tested during the BPE programme [11]. An unwanted air leakage pathway is not just a problem which impacts upon thermal performance, it could also have effects on acoustic performance through unwanted airborne sound; and smoke/fire performance, since unwanted air leakage through compartmentation could mean that the minimum 30 minute/60 minute smoke/fire resistance is breached. However, links between the three main building performance areas: thermal, sound and smoke/fire yet, needs to be established.

In 2010, the Department for Communities and Local Government (DCLG) reported on the investigation of real

fires in existing dwellings and revealed that in some incidents compartmentation could not resist the spread of smoke into adjacent dwellings, or through concealed voids [12]. In 2013, a fire in a multi-storey care home, which was built in 2001 led to a high profile UK court case in 2015; where a housing association combined with the Sussex Fire Service successfully sued a building contractor for their failure to construct adequate compartmentation between flats in a care home [13]. The fire burnt rapidly (in less than 30 minutes) between flats horizontally and into the roof space vertically and it was proven that because the compartmentation failed to contain the smoke and fire spread for one hour, the fire service were prevented the time needed to tackle the blaze and evacuate the occupants before rapid fire engulfed the building across the six storeys, and over 30 people had injuries as a result of the fire and smoke spread. A study conducted by the UK's Building Research Establishment (BRE) on fires reported to the DCLG between 2003 and 2013 in different types of buildings [3,14] revealed that 32% of investigated fires had issues of fire spread either defects in construction details such as missing or inadequate fire stopping at junctions of compartment wall with the roof missing and inadequate cavity barriers, holes in the cavity barriers, poorly fitted cavity barrier and service ducts passing through compartment walls were not fire stopped. In some cases, simple regulatory requirements of AD B had not been correctly met by contractors and were never identified by the building control authorities. In the majority of cases, the main issues identified were voids in roof compartmentation and problems in cavity barriers, i.e. concealed spaces [14]. These findings correlate with the outcomes of the case studies from Littlewood and Smallwood [1, 2].

Littlewood and Smallwood [1, 2] identified construction defects leading to potential failure of compartmentation and cavity barriers in different case studies across South Wales, UK, identifying air leakage pathways in dwellings between 2013 and 2015. In one case study, the dwellings were timber frame construction, and the exterior walls included a cavity and brick cladding. Unusual observations were seen during the implementation of the in-construction air permeability testing combined with smoke (iCT:at_s) test on a two-storey house [2]. In addition, to observing unwanted air leakage from faulty window and door seals the researchers also discovered rapid smoke spread into an adjoining dwelling, through an electrical socket in the party wall [2]. In undertaking a pre-survey of this house some weeks prior to the test on the day, in which the building contractor commissioned air tightness tester had undertaken a test, they observed an invalid sealing of an electrical socket on the party wall (separating wall between dwellings). This party wall was designed with a 30 minute smoke/fire resistance, but the compartmentation appeared to fail in less than five minutes, as identified by the occupant in the house where the smoke appeared through the electrical socket on the party wall in the adjacent dwelling. The apparent failure in compartmentation was limited to the party wall. However, this research also identified weaknesses in the UK's compliance methodology for air permeability testing as part of Approved Document L (AD L) [15] of the England and Wales Building Regulations. In that, there is very little auditing of this testing procedure to ensure that it is conducted in accordance with ATTMA TSL1 [16]. One of the reasons researchers from Cardiff Metropolitan University were asked to perform the iCT:at_s was that the housing association were sceptical of the workmanship observed during the construction of the house and at such were concerned that relatively low design air permeability design target of $3\text{m}^3/(\text{h}\cdot\text{m}^2)\text{@}50$ Pascal (Pa) could be achieved; and were more concerned when a post construction air permeability of $2.5\text{m}^3/(\text{h}\cdot\text{m}^2)\text{@}50$ Pa was reported.

In 2014, and as part of an Innovate UK/housing association funded building performance evaluation (BPE) project, an example of potential falsified design documentation was found in relation to the air permeability of one of the test dwellings recorded in the standard assessment procedure worksheet, which has an effect on the EPC rating [1, 2, 17]. The design air permeability was $5\text{m}^3/(\text{h}\cdot\text{m}^2)\text{@}50$ Pa, and $4.8\text{m}^3/(\text{h}\cdot\text{m}^2)\text{@}50$ Pa was recorded within the SAP documentation from the test. However, during the BPE study both a depressure and pressure test were undertaken and the air permeability recorded was $8.8\text{m}^3/(\text{h}\cdot\text{m}^2)\text{@}50$ Pa, almost twice that had which been reported in 2010. It is almost certain that the original air permeability test was not undertaken or that an invalid test was undertaken. However, the test certificate was not lodged at the local Building Control Office, in itself non-compliant with AD L of the then England and Wales Building Regulations. The unwanted air leakage was found to be a void behind the dwelling heating system installed on the ground floor of the house, which passed through both floor voids and into the roof space without any capping to prevent heat loss, sound transmission or more importantly spread of smoke or fire; and this void did not appear on any drawing or construction detail. In this particular property the occupants found it difficult to maintain comfortable internal temperatures within the dwelling during the heating period between 2013 and 2014 [17]. Another example, of where it is likely that the building control officer did not inspect this aspect of the work before completion.

In another case study building, which was of a timber frame construction with exterior brick cladding, smoke appeared to be coming through electrical sockets on the party wall between the dwellings, so a breach in the horizontal compartmentation [2]. A second example of smoke spread between the dwellings in a different case study (also timber frame construction, but with an exterior render finish upon blockwork) was at the eaves level in the roof space [1, 2]. This had examples of breaches in vertical compartmentation upwards from dwelling to roof space, and also horizontal through fire stopping from one roof space to another, and then vertically downwards into an adjacent flat below the breached roof space. There were also breaches in the vertical compartmentation downward and horizontally through the exterior wall and porch roof at the ground floor level (where the test dwelling was at first floor level directly above the breach). Furthermore, there were breaches in ducting through the compartmentation horizontally (around the boiler flue outlet to the external environment) and vertically/horizontally where the smoke was found to be escaping through an extractor fan mounted on the exterior wall, in a bathroom, in a dwelling diagonally below the test flat. The final case study was of a UK traditional outer brick, cavity and inner block exterior wall (with thin bed mortar system) where there were breaches in vertical and horizontal compartmentation from a test dwelling (on the first floor with one floor below and one above). The breaches in vertical compartmentation affected dwellings above, and then above this into the roof space, and also below into another dwelling on the upper storey and into the roof space above. The horizontal breaches in compartmentation also affected fire stops in the cavity with dwellings affected on the same floor. Finally the breaches in ducting in compartmentation including ceiling light fittings and boiler flues in the exterior walls [1, 2].

3. Refinement of in-Construction testing (iCT) methodology for smoke spread across compartmentation

Littlewood developed the iCT methodology with the assistance of Goodhew (both authors of this paper) and in collaboration with a Social Housing Group, for assessing building performance and specifically defects from workmanship issues affecting construction quality and ultimately thermal performance [1, 2, 17]. iCT was developed with a three step process (pre-test, on-test, post-test) using thermography for application during the construction process, so that any problems that were identified could be rectified before completion of the building and occupation. In 2013, Littlewood developed the iCT process further to include air permeability testing combined with whole dwelling smoke tests iCT:at_s, also to be used during the construction phase, with the same benefit over post construction testing [1, 2]. In engaging with the Welsh Fire Industry in 2016 it is found that there is no requirement for demonstrating compliance with Approved Document B in terms of adequate compartmentation, fire stops, or ducting through compartmentation for actual buildings, during the construction phase or existing buildings already occupied; this is determined by visual inspection alone by private Fire Engineers or the Public Fire Service [1, 2, 18] as part of building risk assessment. This visual inspection method is insufficient to identify defects in construction details which cannot be seen by naked eye as shown by [1, 2]. Therefore, a non-destructive compliance test method is necessary to assess the performance of building compartmentation.

For smoke spread testing, the iCT methodology has used domestic air permeability test equipment operated as a pressure test (at 35Pa) and combined with cold smoke (Figure 1a) to identify air leakage paths and defects in compartmentation. Currently, iCT for smoke spread uses water based cold smoke which is a mixture of purified de-ionised water and glycol or glycerol as smoke fluid for creating cold smoke (Figure 1b). Glycol smoke starts to layer at 35-45°C while glycerol smoke at 50-60°C [19]. The iCT process involves fully filling a dwelling with the cold smoke, and then activating the blower door pressure test (Fig 1c). Smoke is then filmed with digital video cameras as it escapes from adjoining dwellings (vertically and horizontal) and also observed through a sense of smell, if it is not visible depending on the concentration in the adjoining dwellings, circulation routes for means of escape and also the roof space. The use of cold smoke testing is a useful test method, which may be representative of conditions of very small fire sizes where buoyancy effect of the fire heat will be negligible and smoke will follow the existing air circulation paths. However, cold smoke tests do not reproduce the real conditions of smoke, as in a real sizeable fire situation, where temperature of the smoke is similar to the fire and movement of smoke will be affected by buoyancy forces due to density difference between hot gases in smoke and ambient air, as well as the air expansion forces generated by heat from the fire. These initial tests were conducted at 35 Pa, which is much less than that will build up in real fire situations. Van den Brink [20] experimentally found that within a minute of fire ignition, in a fire test room size of 3.6m × 2.4m × 2.4m (length × width × height) peak pressure of 172 Pa was reached. Van den Brink [20] also

concluded that in practical building fire situations pressure will exceed 64 Pa. Hence, the iCT:at_s testing methodology requires testing at pressure higher than 35 Pa to replicate the behaviour of smoke spread of smoke in real fire conditions.

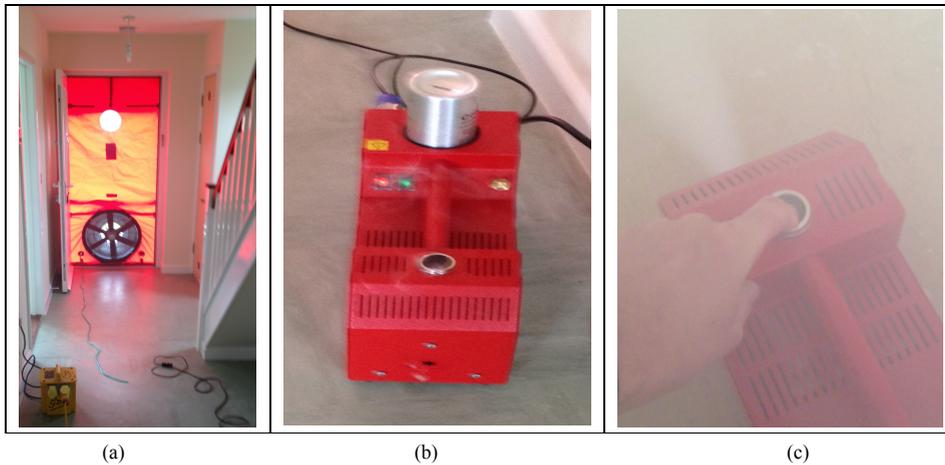


Fig. 1. (a) Blower door setup for pressure test (b) Cold smoke generator (c): Smoke generation with water based oil

One potential method that is being explored is heating the water based cold smoke by mixing it with hot air generated by a space heater, in a vertical tube, replicating a ‘chimney’. However, one limitation of using water based smoke is that there is significantly low temperature resistance i.e. 35°C to 50°C and at increasing temperatures cold smoke starts to evaporate and disappear. This challenge can be overcome by using - mineral oil based smoke, which can resist temperatures up to 200°C [19]. Heating of oil based smoke can be achieved by using controlled alcohol fires, such as in a hot smoke test. Hot smoke tests are currently undertaken to test smoke control systems, such as smoke management systems in enclosed spaces of large volumes. For example, shopping centre atrium [21], tunnels [22], airports [23] underground car parks, exhibition halls and railway stations [24]. Hot smoke tests can produce thermally buoyant smoke using controlled alcohol fires directly beneath the smoke, where the smoke is generated with pyrotechnic smoke generators and this test has also been adopted in Australian National Standard ANS 4391:1999 [25]. Hot smoke tests require careful control of the fire source and the hot smoke to avoid damage to building materials. In hot smoke testing temperatures at ceiling height of a building is required to be less than 55°C, to avoid activation of sprinkler systems [26] and damage to plastic components in buildings, such as PVC cables with a melting point - between 75°C and 110°C. Therefore, this test does not replicate the smoke temperature conditions as in real fire situation in buildings where temperatures are more than 600°C in the vicinity of fire flame and is greater than 100°C at the ceiling height [26]. Also, building contractors and developers may not be in support of carrying out hot smoke testing with controlled alcohol fires due to potential increase in building insurance costs associated with naked flames on a live construction site where there may be flammable materials present on site. Therefore, researchers at Cardiff Metropolitan University are exploring how to generate thermally buoyant smoke, which can simulate real fire conditions without any risk to buildings. Such non-destructive testing should have more acceptability in the UK construction industry. Risks associated with controlled fires can be eliminated by using the space heater as a source of heat to produce thermally buoyant smoke. Figure 2 (a) shows the setup for heating water based cold smoke with the help of electrical heater and chimney [19]. Figure 2 (b) shows the use of oil based cold smoke heated with a propane heater and being directed vertically, using deflector plate [19].

An alternative to heating smoke with electrical or propane heaters could be to use inert helium gas mixed with commercially available smoke generators, which could create buoyancy as helium is of a lower density to air and therefore there should be no need for employing heating apparatus. The approach with helium has been used for testing venting systems in airplanes [27, 28] and simulating the visibility in cockpits in fire emergencies [29]. So the Cardiff Metropolitan University team are exploring how to adapt Helium smoke tests to be used in their iCT:at_s for building

applications, to create buyout smoke at ambient temperature conditions within buildings. Helium testing has been evaluated for a multi-compartment building configuration through modelling, and results showed that the Helium smoke test achieved similar levels of smoke layer height as that of hot smoke test, but the Helium smoke plume moved faster to upper floors than hot smoke without Helium [30]. This effect needs further investigation as the performance of building compartmentation is always evaluated with respect to time, in that it should resist the passage of smoke, fire and toxic gases for between 30 and 60 minutes in the UK, dependent upon floor height from external ground level. The main drawback of using the Helium smoke method is the high cost of Helium. However, this cost may be justified due to the safe nature of the test compared to hot smoke or heated smoke tests. Heating Helium gas before mixing with cold smoke and air is one method to reduce the ratio of the Helium in the air/smoke mixture, whilst producing buoyant smoke with the same apparent temperatures as in a real building fire with a higher ratio of Helium in mixture [31]. Other types of non-destructive testing such as thermal imaging, acoustic testing and indoor air quality testing could also be used indirectly to identify the fire or smoke spread in buildings, which the Cardiff Metropolitan team are investigating. This may be possible by establishing a correlation between the parameters of air permeability, acoustic test, thermal imaging, indoor air quality and smoke test. Results of mandatory tests, such as acoustic tests and air permeability tests may identify inadequate fire and smoke performance of a building and indicate whether further investigation using smoke test will be required.

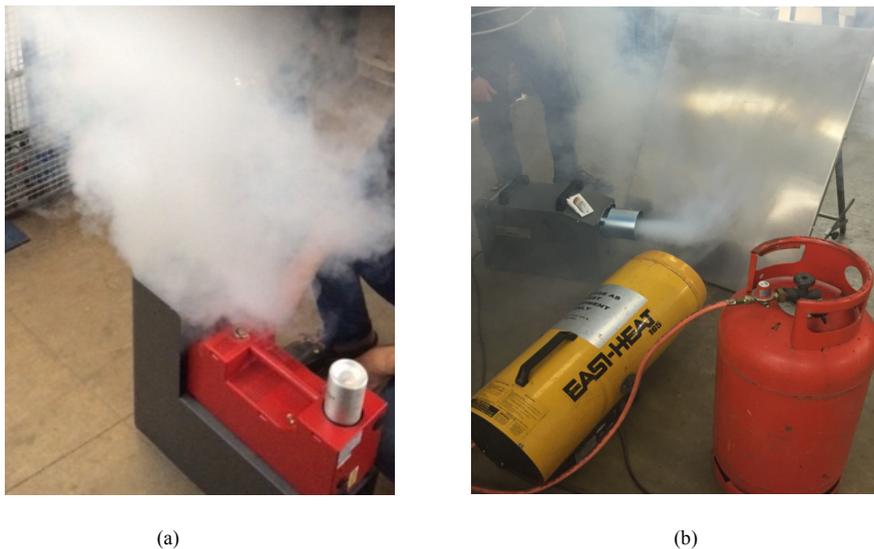


Fig. 2. Heated smoke testing apparatus being trialled (a) water based cold smoke heated with electrical space heater (b) oil based smoke heated with propane gas heater [19].

4. Discussion

The evidence and case studies discussed in this paper clearly show the potential problems individually and combined of inadequate compartmentation, fire stops and ducting through compartmentation and fire stops within buildings in the UK. In each case study, smoke spread across compartmentation was observed under five minutes and more than 50% of dwellings were affected. Of notable concern in addition to the inadequate construction quality is the potential impact upon the occupants should there be a real fire, in that in all these cases studies, full fire evacuation strategies were specified, which rely upon 30 minute and 60 minute smoke/fire resistance to enable occupants to escape safely and for the fire service to tackle the fire. The smoke test results appear to demonstrate that in a real fire, these evacuation strategies may not give adequate time for occupants to escape safely as set out in AD B of the Building Regulations. AD B of the Building Regulations only provides guidance to meet the fire/smoke performance in buildings and there is no requirement of performing a compliance test as is in the case of Approved Document L (AD L) for energy efficiency (air permeability test) and Approved Document E (AD E) [32] for acoustic performance (air

borne and impact sound insulation test). However, even with stringent regulations governing acoustic and thermal performance and compliance tests to be conducted before buildings are occupied there has been for a number of years in the UK evidence of the performance gap (discrepancy between the measured and the theoretical energy performance) [9, 10, 11]. Defects in the construction are one of the reasons for a performance gap between the design aspirations and the as-built constructed buildings [33, 34]. The presence of construction defects 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 and thereby, decreasing energy and carbon efficiency [1, 11]. Without a mandatory compliance test for smoke/fire performance there is no way of knowing the impact upon compartmentation, as fire risk assessments are suitability of compartmentation are entirely based on visual inspections, often by the private sector where officers are commissioned by the building contractors and not the client. With evidence indicating that air permeability tests are undertaken that do not follow required protocols, this could also mean that defects that affect air permeability also affect smoke and fire performance and are largely unseen [35].

Thus, there is a need to develop a compliance test before commissioning new buildings and to ascertain the safety of occupants in case of smoke and fire spread in real building fires. At Cardiff Metropolitan University the research team is developing a test as part of iCT methodology that could be used to show the effectiveness of building compartmentation without causing any damage to the buildings. For this purpose different methods of generating thermally buoyant smoke are being considered which can be suitable for testing building compartmentation.

Compliance tests for energy efficiency, sound insulation and fire/smoke spread involve high cost and resources. New iCT methodology could be employed to develop correlations between energy efficiency, acoustic performance and fire/smoke resistance of a building leading to develop single building performance measurement. The major benefits of using single building performance measurements to indicate possible compliance for other related areas of a building's operation offers a less costly and therefore possibly more widespread take up of compliance testing. This in turn could provide society with higher performance buildings that genuinely meet the standards set by current Building Regulations. This research has applicability in other countries, particularly where multi-storey buildings are used for residential accommodation and where most of the risks of rapid smoke spread has been observed when conducting iCT:at_s tests. Bearing in mind the current juxtaposition between the measurements taken of diesel cars and their emissions performance on the road, it would be good to see some genuine relationships between design predictions and the as-built performance of homes and workplaces [36].

5. Future Work

One of the major contributions that a combined or inferred measurement can offer is a reduction of time and expense expended to achieve an end result that is equivalent to a series of other measurements. This research intends to undertake a series of carefully scheduled measurements on real buildings noting where one measurement can, with appropriate justification, infer a level of compliance for other stipulated areas of building performance. Where focused acoustics or thermal imaging measurement (UK regulations Part E or L) may offer tangible indicators that buildings may also be compliant/deficient for spread of smoke (UK regulations Part B). The film recorded results of the testing are to be presented in Cardiff Metropolitan University's Perceptual Experience Laboratory to determine the emotive responses of occupants, professionals engaged in the inspection of fire prevention measures and the fire service to gauge their response from identified compartmentation problems and thus evacuation strategies; and the industrial partners to showcase the work and problems identified [37].

6. Conclusion

Evidence shown in different cases studies and fire investigation reports revealed that compartmentation and cavity barriers are inadequate in resisting the spread of smoke and fire, most likely due to problems of incorrect installation, defects due to poor quality of workmanship and weaknesses of design. Currently, effectiveness of compartmentation against smoke/ fire spread in buildings relies only upon the visual inspection and design and drawing information assessed by the building control or fire services authorities. However, this approach is inadequate to identify the real

details of construction problems in building compartmentation. Thus, development of compliance tests which can identify issues of fire and smoke spread through compartmentation during construction stages is important. The compliance test could also be included in risk assessments of all building types including dwellings, care homes, hospitals and schools to prove the resistance of compartmentation against the spread of smoke for specified period of time. The test method needs to be safe to perform without any risks to buildings and accepted by developers, constructors, local councils and fire services authorities. Heated smoke and Helium smoke tests are being investigated to safely identify smoke/fire spread issues in compartmentation and cavity barriers in buildings as part of combined ICT methodology.

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