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Fire safety risks of external living walls and implications for regulatory guidance in England

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ABSTRACT

External living walls (LWs) have aesthetic and environmental appeal, but these characteristics must not compromise fire safety. A review of legislation indicates there are no specific fire regulations or test standards for LWs in England. Furthermore, the 2013 UK Green wall guidance document (GWGD) contradicts current guidance in Approved Document B (ADB) for certain categories of buildings, yet ADB cites GWGD as “best practice”. We suggest the recommended reaction to fire testing methodology for LW systems (single burning item (SBI) EN13823/ignitability EN ISO11925-2 tests) is inappropriate for assessing their fire performance. Despite some limitations, the BS8414 full-scale test could be used to assess LW installations. While not identified in the GWGD or specifically recommended within ADB as a suitable test method for LWs, it is arguably more appropriate than reduced scale SBI testing, primarily because it accommodates full LW modules with planting, and uses a more appropriate fire size. To reduce testing costs, we propose the use of CFD fire modelling, or a modified SBI test to identify candidate LW products likely to pass BS8414 testing. Given the inherent variable nature of LWs and their associated fire properties, LW maintenance is considered essential for on-going compliance with fire safety requirements.

1. Introduction

Living walls (LWs), also known as green walls, are vertical, vegetated structures consisting of modular panels or geotextile mats, which are fixed to external building facades or internal walls. The main drivers for installing LWs are to initiate urban ecosystem services, which valorise plant selection for biodiversity, health and wellbeing, as well as air quality mitigation and improvement. These ecosystem services, which include lessening the urban heat island effect, cleaning the air, increasing biodiversity, dampening noise, decreasing flooding risk, providing a biophilic backdrop - which people require for health and wellbeing, are now becoming essential components of present and future urban living [1]. However, a potential issue of concern is the fire safety of LWs [2–5].

While the concept of LWs dates back hundreds if not thousands of years to Romans training grape vines on trellises and villa walls, the concept of a modular architectural system made up of ‘botanical bricks’ that could be built up to any height dates back to a concept developed by the American architect Stanley Hart White in the 1930s [6]. However, modern LWs are credited to French botanist Patrick Blanc who developed and installed the first successful large indoor LW at the Museum of Science and Industry in Paris in 1986 [7] and patented the concept utilising a hydroponic system with an inert medium and numerous plant species in 1988 [8]. Nevertheless, LWs are a relatively new phenomenon in the UK, becoming popular after one of the first appeared in 2006 [9,10]. What began as a novelty in mainly residential applications is now used in commercial, retail, hotel and government infrastructure projects, globally.

As styles and environmental awareness have changed, so have the design functions of LWs. There is a need and an increasing demand for boosting vegetation in our cities [11], and this has driven the interest and popularity of LWs [12]. Apart from their aesthetic benefits, these are applied to the external facades of buildings to help mitigate some of the environmental issues in built-up areas, by providing the ecosystem services that are needed to make cities healthier, more habitable and more pleasant/desirable places to live (see for example Fig. 1).

There has been a great increase in the installation of green roofs, vegetated facades and LWs across the cities of the UK and the world [1, 12,14]. The integration of ‘forests in the sky’ such as in the twin Bosco Verticale towers, by Stefano Boeri Architetti in Milan, Italy (completed

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Fig. 1. Musée du quai Branly - Green Wall by Patrick Blanc. (Photograph by Paolo Rosa licensed under CC BY-NC-ND 2.0 [13]) (www.flickr.com/photos/paolo_rosa/1349260571/, accessed 01.02.2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2014) (see Fig. 2), are lauded in terms of urban greening, which improve urban environmental conditions, in response to climate change agendas. Arup, engineers on the project, note that the design *'creates a biological habitat'* with 900 trees between 3 and 6 m high, 5000 shrubs and 11,000 floral plants, planted on terraces until the 27th floor [15],*'The plants produce oxygen and humidity and absorb* CO_2 *and dust particles thus improving the surrounding environment'* [15].

Almost every week there is an announcement in the building/architectural press of new, prestigious buildings planned with LWs. For example, the Citicape House building in London *'will be wrapped by a facade of 400,000 plants that are hoped to "capture over eight tonnes of carbon and produce six tonnes of oxygen" annually'* [16]**.** The global green walls market *'was valued at USD 213.64 billion in 2019 and is projected to reach USD 402.68 billion by 2027, growing at a CAGR* (compound annual growth rate) *of 8.2% from 2020 to 2027'* [17]**.**

While it may appear intuitive that adding vegetation containing very little readily combustible material, to the façade of a building or in the form of a sedum roof, is not a fire safety issue, nothing should be taken for granted, especially when installations may incorporate plastic planting modules, plastic water supply system components, associated support systems and with the low combustibility of the vegetation being reliant on appropriate regular LW maintenance. The fatal Grenfell Tower fire of 14 June 2017 [18], demonstrated the importance of ensuring that anything added to the external fabric of a building must not be able to support the rapid spread of fire. The tragic loss of 72 lives in the Grenfell Tower fire reinforces the need to demonstrate, using appropriate test methods, the fire performance of complex systems incorporated into the exterior fabric of buildings.

Reports of fire incidents involving LWs are comparatively rare. It is not clear if this is due to the limited number of LWs currently in existence throughout the world, or because the incidence of fire in LWs is a rare event or if LW fires are being under-reported simply because the fires that do occur are seldom of sufficient severity or perceived significance as, for example, the 2017 fire at Bligh Street Sydney [2,19]. A search of the academic literature and popular media revealed only four reported LW fire incidents since 2012, three of which were potentially significant, one in Sydney, Australia in 2012 [3] and two in London, UK in 2018 [4,5]. The little information that is available concerning these fires is reviewed in Section S1 of the Supplementary Material. Presented in Fig. 3 is a photograph of a fire in a LW situated on the 7th floor of a residential building in London [5,20,21] on 5 August 2018. The fire, believed to have started due to a discarded cigarette or match [21], spread rapidly through the dried vegetation (see Supplementary Material Section S1 (c)).

Fig. 2. Planted balconies of the Bosco Verticale. (Photograph by Andrej licensed under CC BY-NC-SA 2.0 [13]) (https://www.flickr.com/photos/truu/42869769924, Accessed 03.02.2022).

While, worldwide, there are several fire safety guidance documents, no fire standards have thus far been developed specifically addressing issues associated with LWs [22]. This is likely due to several reasons such as: LWs are a relatively recent design concept; there is a broad range of different types of vertical green systems (i.e., climbing plants, hydroponic walls, vertical LW panels, etc.), making it difficult to create a standard that addresses all aspects of each system; and new concept LW systems continue to be developed.

In the UK, the Grenfell Tower fire tragedy revealed significant shortcomings associated with regulatory guidance, fire testing and approvals of the materials used in high-rise building construction. Prior to the Grenfell Tower fire, the building fire safety regulatory guidance for England, as specified by Approved Document B (ADB) [23] made no mention of LWs or provided any specific guidance to deal with the complexities of such systems. Subsequent to, and as a result of, the Grenfell Tower fire, building fire safety regulatory guidelines for England were revised in 2019 [24] and 2020 [25]. Within the 2019/2020 edition of ADB, Volume 2, section B4 paragraph 12.7 refers to "best practice" guidance for LWs, which can be found in the 2013 publication,

Fig. 3. Living Wall fire in London in 2018 (image is reproduced from video clip on twitter by @Miss_AnitaRaj 5 August 2018 [5]).

'Fire Performance of Green Roofs and Walls', (GWGD) [26]. However, the guidance provided in this nine-year-old document does not align with current fire safety standards, or with LW systems, which have evolved considerably since 2013. For example, when the GWGD was published LDPE was the main module material for many LW products, while more recently, polypropylene is often used. In addition, new LW concepts are being developed such as low maintenance bioactive facade systems [1]. Furthermore, the following caveat is provided in the last paragraph of the conclusions to the GWGD, *'It was originally assumed that the main fire risk in green wall systems was growing media rather than the plants however the testing has also shown that the materials which* support *and contain the growing media may also contribute to flame spread. Further research is required on the different systems and should consider testing on systems populated with plants'* [26]. While this was a prudent statement back in 2013, in the intervening nine years since it was first published, it is even more valid as government regulations and guidance have not kept up with the pace of change in LW product development.

While the trend for urban greening and biophilic solutions grows, there is an existential threat to the LW industry in that potential clients may be dissuaded from installing LWs and other plant-based forms because of the perceived fire risk, along with current, imprecise legislation and guidance and inappropriate fire test methods [27]. Put simply, there are no appropriate building guidelines or fire test standards specifically designed for LWs and for LWs to continue to be used with confidence in providing the environmental benefits that they bring, the full range of risks need to be identified, quantified, and understood. Without clarification in areas of, material use, design and legislation, the industry will at best be restricted in its growth and ability to be part of the environmental solutions required in our cities or at worst, contribute to potentially unsafe living environments.

To address these issues, University of Greenwich research groups INTENT (Integrated Nature and Environment Research Group) and FSEG (Fire Safety Engineering Group) collaborated to critically review issues relating to the fire safety of external LWs and the current associated legislation and guidelines. The main aim of the review was to assess whether current building fire safety guidelines within England, and associated fire test standards, are appropriate to mitigate and minimise the risks relating to fire associated with external LWs. Understanding how the main components of external LWs (including plants and growing media), system specifications concerning construction, installation and maintenance, can be improved to develop solutions for fire safety, will benefit the industry as a whole. While much of the discussion applies equally to internal LWs and planted balconies, the focus of this paper is external LWs.

The scope of the study thus centres on the review of the recent and current situation within England regarding fire safety of LWs, to identify gaps in knowledge and the perceived inadequacies in existing fire testing regimes and to suggest improvements. The general fire characteristics of LWs are reviewed in Section 2. The current fire regulatory framework and guidance for England, including approved test methods and how they relate to LWs are presented in Section 3. Issues relating to the regulatory guidance documents and the specific LW guidance are discussed in Section 4. The appropriateness of the current fire test methods adopted by the LW industry are also assessed in this section.

Furthermore, it is suggested that a modified full-scale BS8414 fire test, would be a more appropriate test methodology for assessing the fire performance of LWs, together with a suitable method e.g., CFD modelling or mid-scale experimental test, to filter out LW systems that are unlikely to pass the full-scale assessment.

2. Living walls and fire risk

As LWs may comprise flammable materials in their construction, as well as the potential for ignition and fire in the planting and growing substrate, there are considerable challenges to understand and mitigate the risks of fire in LWs. The following discussion focusses on the diverse issues relating to LW fires.

2.1. Living walls and component materials

LWs are categorised as either passive or active in their means of purifying the air. A passive system relies on a natural exchange of air around the plants and through the substrate. An active system blows air through the substrate by mechanical means, where microbes in the substrate (soil) neutralise different pollutants. Passive systems are by far the most prevalent type of LW system used externally and there are two types of systems commonly used on external building facades. They are categorised by the type of growing system they incorporate:

1. Hydroponic based systems, which use mineral wool or felt matting where nutrients are added to the irrigation water, and
2. Soil based systems, which use manufactured soils or composts and where nutrients are added into the soil and/or are delivered within the irrigation water.

LW systems are made by various manufacturers to their own particular design specifications and so there is significant variability in materials, module design and mode of attachment. However, in broad terms, they all consist of the following key components, as illustrated in

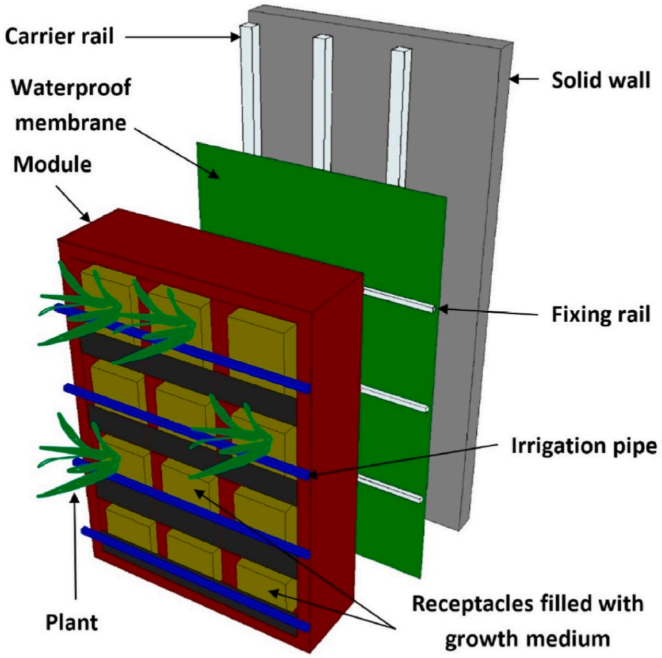


Fig. 4. Graphical depiction of the typical components compromising LW systems.

Fig. 4:

- Plants, with variations in plant species, size and quantities per square metre;
- Growing media, which is either mineral wool or felt for hydroponic systems, or a lightweight compost/organic soil for soil-based systems;
- System structure which includes:
  - a modular panel or cassette, usually with cells, troughs or pockets to hold individual plants. These are often manufactured from materials which may or may not have fire retardant additives, such as recycled plastics, recycled fabrics, or mineral wool;
  - a waterproof membrane located between the system and the building to protect the building from water ingress; and
  - a hanging system (commonly using aluminium brackets/mounts);
- Irrigation and fertigation system (commonly HDPE and LDPE pipework and polypropylene driplines); and a
- Maintenance regime, which includes both horticultural and technical/mechanical aftercare.

2.2. Living wall flammability factors

A LW is a complex system of components but at its core are the living plants. Fire, a chemical chain reaction, requires three essential components: oxygen, heat and fuel. Clearly, external LWs have an abundant source of oxygen. There are numerous potential sources of heat that can initiate a fire in a LW including accidental risks such as electrical short circuits, sparks caused by construction or maintenance nearby, indiscriminate disposal of cigarette butts etc. Other sources of heat may result from an existing fire, such as an internal building fire that exits the building via a window spill plume or an external fire originating in adjacent waste. The primary fire safety concern associated with any LW relates to the nature of the combustible fuel that may be present, including the plants and the infrastructure required to support the LW structure [27].

The LW system is comprised of many components (see Fig. 4), each of which may individually or when considered as a system contribute to the ease of ignition and fire spread. The various LW components that must be considered include:

- Individual materials - The use of combustible materials such as plants, growth media, materials such as plastics for the modules and backing layers, as well as other materials such as wood, metals, etc.
- Combination of materials - The integration of these materials into a composite LW system which may increase fire spread and severity;
- Spatial arrangement of materials – The arrangement of materials including gaps and air pockets within the system itself and the supporting structures, which may hinder or exacerbate fire spread;
- Facade design – The design across building facades, for example, where LWs abut windows or wall penetrations, can allow fire to spread from within to the LW and from the LW to the interior, hence bypassing internal fire barriers.

Other factors that can impact both ignition and fire spread include:

- LW structure and installation – The design of the system can affect fire spread;
- Defective installation – Where poor quality implementation can exacerbate fire and the spread of fire;
- Moisture levels – Moisture levels within the system growing medium and irrigation network can greatly influence flammability and fire spread;
- Maintenance – Lack of maintenance, for example the non-removal of dry matter and dry detritus (litter) can affect flammability and fire spread;
- Environmental factors – For example wind which can dry out plants and can help fire spread. Climate change is also a consideration as weather patterns change for example with higher temperatures, increased periods of drought and increases in wind velocity.

2.3. Living wall potential fire load

The potential fire load represented by LW products is one of the critical concerns impacting fire safety of tall multi-occupancy structures. The fire load is characterised by the mass of combustible materials and energy they release during combustion. Following the guidance provided by the ADB is intended to ensure that the materials used in external cladding are appropriate and provide an adequate level of fire safety. Material physical properties that impact fire performance include surface ignition temperature, heat release rate and flame spread rate under a variety of conditions. The total amount of energy that a material can release during a fire is the product of its heat of combustion and the mass of material available. The more energy released by the burning materials, so generally the larger the resulting fire.

For LW modules, Polypropylene (PP) is a common module panel material. It has a heat of combustion of ~44.6 MJ/kg, which is as high as that for polyethylene (PE) (43.3 MJ/kg), the core material of the aluminium composite (ACM) panel cladding which made a significant contribution to the Grenfell Tower fire [18]. The thickness of the PE core of the ACM panel was 3 mm and so the mass of PE per unit area of cladding at the Grenfell Tower was approximately 2.91 kg/m^2 [18]. One of the five reviewed LW products listed in Table 2 contained 3.80 kg/m^2 of PP, thus a construction module of this LW material has 34% more potential fire load per square metre than the ACM used in the cladding involved in the Grenfell Tower fire and furthermore, unlike the ACM has no fire resisting surface layer. The heat release rate (HRR) of a combustible material strongly influences fire spread. The larger the HRR, the more rapidly the fire can spread. When exposed to an external heat flux of 50 kW/m^2, PP reaches its peak HRR of approximately 1900 kW/m^2 in approximately 180 s while fire-retarded PP has a peak HRR of approximately 1600 kW/m^2 after approximately 170 s [28]. An ACM panel with a PE core requires approximately 190 s to reach its peak HRR of approximately 1300 kW/m^2 [29]. Thus, the peak HRR of PP is at least 23% larger than the ACM panel while both materials reach their peak

HRR in approximately the same time. As a result, we can expect that PP may support similar fire spread rates, if not slightly larger, than an ACM panel. As the PP LW module described above contains 34% more potential fire load, per square metre, than the ACM panel, and both PP and the ACM panel support similar fire spread rates, it could be argued that a fire over the LW module constructed from PP has the potential to spread as rapidly as the Grenfell Tower fire.

Unfortunately, to date, there has been little research concerning the flammability properties of plant species used in LWs. One exception is the work of Dahanayake et al. [30], who conducted cone calorimeter experiments for three plant species used in LWs, namely: Hedera helix, Peperomia obtusifolia and Aglaonema commutatum. When the plants were fresh (moist) and green, no ignition was observed for all three species. Hedera helix started to ignite once the moisture content (i.e., the mass ratio of water to dry plants), reduced from 326% to 243%, when exposed to a constant heat flux of 50 kW/m^2. For Hedera helix, the peak Heat Release Rate (HRR) (for a specimen 300 mm high weighing 30 g when fresh (moist)) was 3 kW/m^2 but when dry, this increased to 200 kW/m^2 producing a total heat release of 10 MJ/m^2 (see Supplementary Material Section S2 for details). Combustibility data for these three LW plant species support the view that maintenance of LWs is critical to ensure that plants are kept moist and that dry plant material is removed, thus making it more difficult for the plants to ignite and reducing the total heat release potential. Furthermore, the risk of fire in LWs can be reduced by selecting plants with low peak HRRs and low total heat releases.

In contrast to plants used in LWs, plant flammability is an area of significant research interest in regions where wildfires are prevalent e.g., California, the western provinces of Canada, Southern France, Portugal, Greece and Victoria and New South Wales, Australia. Transferrable knowledge relating to flammability of domestic garden plants in fire prone WUI (Wildland Urban Interface) regions is particularly useful [31–33]. This relates to the impact, on fire spread, of: moisture levels in leaves and woody stems; aromatic oils, waxes and resins; seed heads and grass-like leaves; and the placement of plants in proximity to each other (for example, to act as a 'fire-break' in a design mix). This assists in the selection of plants that are relatively fire-resistant and to identify, and hence avoid, plants that are fire-hazardous (See Supplementary Material Section S2).

Flammability of the growth media is even less understood and requires more research. Mineral wool for example, is fire resistant and insulating, however the material may experience bacterial/algal growth and dried-out biofilms could constitute or add to the fire risk. Soil is unlikely to contribute directly to flame spread however this depends on the amount of organic content of the growing media and its moisture content and whether other materials such as peat or fertilizer is included. Maintenance is carried out either by the LW supplier or independently by agents of the client. Maintenance includes key operations at various times of the year such as pruning. Pruning plants at timely intervals may be required to manage fire risk. Understanding the combustibility of LW materials is a key focus for LW manufacturers however, this alone is insufficient. How LWs behave when ignited, with respect to their location on the building façade and relative to environmental factors such as wind and the degree of wetness is also of importance and is poorly understood.

Furthermore, as LWs grow in popularity and number, consideration must also be given to combustibility and flame spread characteristics associated with dead and dying LWs. As the number of healthy LWs increase, we can also expect the number of dead LWs to increase – indeed there is growing evidence of this in London [8,34,35].

3. Current fire safety practice and regulatory framework for England associated with living walls

In England, the current (i.e., at the time of writing, July 2022) statutory building fire guidance [25] only makes passing reference to fire safety issues associated with LWs by referencing the GWGD. Furthermore, there are currently no fire test standards specifically developed for LWs. As a result, the building industry, LW manufacturers and planning authorities must interpret how existing regulations, guidance and fire test standards apply to fire safety standards for LWs. The appropriate regulatory and guidance documents for England include:

- Building Regulations 2010, Part B Fire Safety [36];
- Approved Document B (ADB), Fire Safety, Volume 2 Buildings other than Dwellings, 2010, revised 2019 [24], 2020 [25] and 2022 [37]. The 2022 revisions [37] took effect in December 2022 [38];
- Fire Performance of Green Roofs and Walls, 2013 [26] (referred to as the 2013 guidance in this paper);
- Reaction to fire tests: Single burning item test (SBI) EN 13823 [39], and ignitability testEN ISO 11925-2 [40]; fire performance of non-loadbearing external cladding systems BS8414-1 [41] and BS8414-2 [42];
- Fire Classification: BS EN 13501–1:2018 [43], Fire classification of construction products and building elements.

3.1. Regulatory and guidance requirements for living walls in England

The section of the building regulations for England dealing specifically with fire safety is Part B and consists of five sub-parts, B1 dealing with fire alarms and means of escape to B5 dealing with firefighter access [36]. Section B4 of the regulations is entitled 'External Fire Spread' and simply states [36]:

1. The external walls of the building shall adequately resist the spread of fire over the walls and from one building to another, having regard to the height, use and position of the building.
2. The roof of the building shall adequately resist the spread of fire over the roof and from one building to another, having regard to the use and position of the building.

The regulation simply requires that the external walls will 'adequately resist the spread of fire'. While the intent is clear and straightforward, it does not state how the intent can or should be achieved nor does it specify what is or is not adequate. At best, the regulations vaguely specify the performance required by a compliant design. Along with the regulations there are a series of approved documents (AD) that provide general statutory guidance on how specific aspects of building design and construction can comply with the building regulations. However, the AD are not legally binding; rather, they present the expectation of the Secretary of State concerning the standards required for compliance with the building regulations, and the standard methods that can be used to achieve these.

Thus, within the regulatory framework for fire safety in England, engineers can demonstrate compliance with the regulatory requirements (i.e., Part B) by adopting the prescriptive solution suggested by the AD associated with part B i.e., Approved Document B (i.e., ADB). At the time of the Grenfell Tower fire, the ADB (i.e., ADB 2013) did not specifically address fire safety issues associated with LWs [23].

The so-called "best practice" guidance for LWs can be found in the GWGD [26]. This document recommends that LWs should adhere to the combustibility requirements as specified in ADB 2013 [23]. The combustibility requirements within ADB 2013 are dependent on intended building use (e.g., assembly, recreational, residential, etc), building height, with 18 m being a critical height, and façade distance from a boundary, with 1 m being a critical distance. There were essentially three classes of building use identified, that are intended to cover all building uses, these are, 'any building', 'assembly or recreation' and 'any building other than assembly or recreation'. As a result, there are five different building categories and associated combustibility requirements identified (See Diagram 40 [23]). Our focus in this paper, is on building use restricted to residential or office buildings, which come under the ADB 2013 use definitions of 'buildings not used for assembly/recreation' and 'any building'. For brevity, we define buildings less than 18 m high with a façade more than 1 m from the boundary, as Type 1, and buildings greater than 18 m high with a façade less than 1 m from the boundary, as Type 2. Thus, one example of combustibility category relevant to residential or office buildings within ADB 2013 is, 'buildings not used for assembly/recreation purposes' that are Type 1, while another example of building category is described as 'any building' that are Type 2 (see Table 1). Within the GWGD these requirements are interpreted as, LWs can be installed on facades of Type 1 residential or office buildings without restriction as there are no special requirements for these buildings in ADB 2013. For the other four building categories identified in ADB 2013 there is some constraint on LW combustibility requirements. For example, for Type 2 residential or office buildings the GWGD recommends that LWs must be demonstrated to be of 'limited combustibility' (see Table 1). Post Grenfell, the ADB was revised in 2019 (ADB 2019) [24] and 2020 (ADB 2020) [25]. The revised ADB makes explicit reference to the GWGD in paragraph 12.7, identifying it as "best practice". The ADB was amended again in 2022 (ADB 2022) [37] with reference to the GWGD as "best practice" moved to paragraph 12.8. ADB 2022 came into force from December 2022 [38].

3.2. *Current test methods adopted for living wall products*

Wall materials are classified in terms of their reaction to fire performance in accordance with BS EN 13501-1: 2018 [43] as follows:

Combustibility: A1 – F (A1 is the highest level of performance: non-combustible);

Smoke propagation: s1 – s3 (s1 is the highest level of performance, producing little or no smoke while s3 represents no limitation on smoke production);

Flaming droplets and particles: d0 – d2 (d0 is the highest level of performance, producing no droplets while d2 represents no limitation on droplet production).

The standard references five European test methods for conducting reaction to fire tests, which are used to determine the different classes (See Table S2 in Supplementary Material for the test methods). The SBI test (EN 13823 [39]) and the ignitability test (EN ISO 11925–2:2010 [40]), as identified by the standard, are currently used to assess the fire performance of products developed by the LW industry (for example see Refs. [26,44–48]). The SBI test is an intermediate-scale fire test representing an internal corner formed with two faces of product, 1.5 m high with 1.0 m and 0.5 m wide surfaces. The fire source used in the test is a 30 kW propane burner. The SBI test is one of the tests required to assess building products used in the construction of walls for Euro classification from A2 to D. The single-flame test or ignitability test is designed to determine the ignitability of a product by directly exposing a vertically oriented sample to a 'small-flame' (with a flame height of 20 mm). It is one of the tests required to assess building products for Euro classification B to D. To determine a product's reaction to fire rating within the product classes B to D, the European classification protocol requires that the product be subjected to both the SBI and ignitability tests. However, only the ignitability test is required for European classification E, while untested materials are automatically given classification F. Other test protocols are required to demonstrate compliance with the A class rating (see Supplementary Material Table S2).

3.3. *The full-scale BS8414 cladding fire test*

As an alternative to the prescriptive requirements specified in the ADB, a performance approach to demonstrate that façade materials are satisfactory and meet the requirements of regulation B4 is available (see paragraph 12.5 of ADB 2013, paragraph 12.3b of ADB 2019 and ADB 2022 [37]). This involves meeting the performance criteria given in BRE report BR 135 [49] for external walls using data from the full-scale fire test described in BS8414–1:2002 [50]. BR135 specifies a range of pass/fail criteria based on internal and external façade temperatures and flaming height. The BS8414–1:2002 test protocol was superseded by BS8414–1:2015 [51] and further amended as BS8414–1:2015+A12017 [52], which is referenced in the updated current version of ADB (ADB 2020 [25]) and in ADB 2022.

The BS8414 test [52] attempts to treat the building façade as a complex system taking into consideration how each component of the façade system reacts to a representative fire threat. The test deals with representative large panels of façade materials (including cavity barriers) subjected to a realistic fire assault intended to represent the conditions of a post flash-over spill plume. This full-scale test represents an external building corner formed by two faces at least 8.0 m high with 1.5 m (wing) and 2.6 m (main face) wide surfaces. The fire chamber is represented by a 2.0 m wide by 2.0 m high chamber in the main face and the fire source is a wood crib producing 3 MW peak output and 4500 MJ over 30 min. The test is intended to represent the action of a fire

Table 1
Changing definition of external wall fire performance in UK guidance documents, GWGD and ADB.

Building use (ADB definition)	Type		Guide	Required Fire Performance
	Critical Height (m)	Location of Boundary (m)		
Residential or office (Building other than recreation or assembly)	Type 1 <18 m	>1 m	GWGD 2013 and ADB 2013	No restriction
Residential or office (Any building)	Type 2 >18 m	<1 m	GWGD 2013	Limited combustibility stated in GWGD but European Class B or National Class 0 based on Diagram 40.
Residential or office (Any building)	Type 2 >18 m	<1 m	ADB 2013	European Class B or National Class 0 according to Diagram 40.
Residential or office (Any other building)	Type 1 <18 m	>1 m	ADB 2020	No restriction
Office (Any other building)	Type 1 <18 m	>1 m	ADB 2022	No restriction
Office (Any other building)	Type 2 >18 m	<1 m	ADB 2020 and 2022	European Class B
Residential (Relevant buildings)	Type 3 >18 m	Any distance	ADB 2020 and 2022	European Class A2
Residential (All residential PG1 and PG2)	Type 4 >11 m	Any distance	ADB 2020 and 2022	European Class A2
Residential (All residential PG1 and PG2)	Type 5 <11 m	>1 m	ADB 2022	No restriction

Table 2
Summary of living wall product SBI and Ignitability tests and results.

Country Date	System Type	Module thickness excluding plants (m)	Nature of Plant sample	Moisture	Installation to wall	Component material for ignitibility test	Results
UK 1 2020 [44]	Compost (with plants)	0.105	Test 1: plants were untrimmed. Test 2: plants were cut back to 0.08 m. Test 3: plants were cut back to the compost.	The module was fully saturated. 45% moisture mass (excluding the water in the plants) for the whole system.	Modules fixed to aluminium framework mounted on the wall.	Polypropylene	B s2 d0 (in all three cases)
UK 2 2017 [45]	Hydroponic (with and without plants)	0.062	Test 1: plants were untrimmed. Test 2: plants were cut back to 0.08 m. Test3: unplanted.	The stone wool fibre insulation was saturated with 70% moisture content.	The backing module board was fixed to the wall.	Polypropylene and stone wool	B s3, d2 (in all three cases)
ES 1 2017 [46]	Compost (with plants)	–	Information not provided, but images available in the test report suggest that the plants were untrimmed.	The module is reported to be 'wet'. Further data not provided.	There is no gap between the samples and the backing board.	Fytotextile (product name)	B s2 d0
NL 1 2017 [47]	Compost (with plants)	0.105	Information not provided.	14% moisture mass (excluding the water in the plants) for the whole system.	Information not available.	Expanded polypropylene and ethyl vinyl acetate	C s3, d0
NL 2 2014 [48]	Hydroponic (with plants)	0.065	Information not provided, but images available in the test report suggest that the plants were untrimmed.	27% moisture mass (excluding the water in the plants) for the whole system.	There is a 0.03 m air gap between the panel and the backing board.	Flexipanels (product name)	B s2 d0

impinging on the external surfaces of the façade and on the lower edge of the façade at an opening to the fire compartment (e.g., compartment window). This type of fire can occur as the result of an external fire in close proximity to the building envelope, such as fires involving general waste or malicious fire setting or as the consequence of a fire developing to flashover within a building and breaking out from the room of origin through a window opening or doorway.

While the BS8414 test protocol was updated in 2020 [41], ADB 2020 and ADB 2022 do not refer to the updated test protocol. To the authors' best knowledge, the BS8414 test has not been used to assess LW systems, or at least there are no publicly available reports describing such applications.

4. Implications and discussion

4.1. *Approved document B and living wall guidance*

As stated above, the GWGD recommends, based on ADB 2013, that for Type 2 residential or office buildings (i.e., use type 'any building'), that LWs must be demonstrated to be of 'limited combustibility'. According to ADB 2013, this suggests that the material components of the LW must comply with European Class A2 or better (see table A7 of ADB 2013). However, the GWGD also states that LWs must comply with the requirements as specified in Diagram 40 of ADB 2013. According to this diagram, to comply, the LW must satisfy 'National Class 0 or European Class B', suggesting that Class 0 and Class B are equivalent. However, by definition Class B materials are not of 'limited combustibility'. This confusion is compounded as within ADB 2013, National Class 0 has several conflicting definitions e.g., in addition to the Diagram 40 statement, Appendix A, paragraph 13 states, 'The highest National product performance classification for lining materials is Class 0. This is achieved if a material or the surface of a composite product is either, (a) composed throughout of materials of Limited Combustibility, etc'. Nevertheless, while the GWGD clearly states that LW materials should be of 'limited combustibility' for Type 2 buildings, this was generally taken to mean, Class B by the industry referring to Diagram 40. As a result, the interpretation of Diagram 40 is disputed by many fire safety specialists. It is further noted that terms used in the GWGD to define the fire performance of LWs such as "Class 0" and "Limited Combustibility" are no longer used or defined within the updated ADB [25], further adding to potential confusion.

The regulatory requirement concerning LWs is further confused by the 2019 [24] and 2020 [25] updates to ADB. Within the ADB, the definition of building use was defined using seven purpose groups (PG) including 'Residential dwellings' e.g., flats, (PG 1); 'Residential institutional and residential other' e.g., establishments where people sleep in the premises (PG 2); 'Offices' (PG 3), etc. In the updated ADB, for the purposes of allocating a fire performance category, these PG are collapsed into three categories of building usage defined as, 'relevant buildings' according to Regulation 7(4) i.e., buildings containing one or more dwellings; an institution; or a room for residential purposes (excluding a room in a hostel, hotel or boarding house) of at least 18 m in height [25], 'assembly and recreation' and 'any other building'. As a result, there are now 10 categories of reaction to fire performance of external surfaces (see table 12.1 [25]). In this categorisation, residential buildings over 18 m in height, fall in the building type 'relevant buildings' while office buildings and residential buildings under 18 m in height, fall in the building type 'any other building', thus the performance of residential and office buildings are defined separately. Furthermore, for residential buildings greater than 18 m high (i.e., 'Relevant buildings'), the façade distance to the boundary wall is no longer considered relevant and so the specified fire performance of the façade does not depend on this parameter. We refer to this updated definition of Type 2 buildings as Type 3 (see Table 1).

As already stated, ADB 2019 makes explicit reference to the GWGD however, the recommendations within GWGD are based on ADB 2013, making specific reference to the specifications within (the disputed) Diagram 40 of ADB 2013, which has been deleted from the updated ADB [24]. Furthermore, the guidance in ADB 2019/2020 concerning acceptable materials for residential and office buildings now differentiates between these two building types. External surfaces of residential buildings over 18 m in height (i.e., 'Relevant buildings'), must satisfy European Class A2 or better irrespective of distance to the boundary while office buildings must satisfy European Class B or better if the boundary is less than 1 m away (see Table 12.1 and paragraph 12.11 in ADB 2020 and Table 1). Another conflict between the requirements of ADB 2019/2020 and those of the GWGD is that the updated ADB no longer considers the distance to the boundary as relevant for residential buildings over 18 m in height while it is still relevant for office buildings, see Table 1. For other types of buildings, such as assembly or recreation, the requirements specify that the façade materials must satisfy the less onerous minimum requirements of European Class B or C depending on building height and distance from the boundary. However, for Type 1 residential and office buildings, the requirements specified in ADB 2019/2020 are identical to those of ADB 2013 (see Table 1).

Thus, for residential and office Type 1 buildings, the current ADB 2019/2020 and ADB 2013 and hence GWGD are consistent in their guidance and permit the implementation of LWs, without restriction. However, according to the updated ADB, residential Type 3 buildings must ensure that all wall materials (comprising all the components of the LW system including the growing media and plants) must be compliant with Class A2 s1, d0 or better (see Table 1). This is a more demanding requirement than specified in ADB 2013, which according to (the disputed) Diagram 40 required National Class 0 or European Class B. However, depending on interpretation of the recommendations of the GWGD, these may be consistent with the requirements of ADB 2019/2020. This essentially means that all components of the LW must consist of non-combustible materials (A1/A2) and produce little or no smoke (s1) and no droplets (d0). In contrast, the requirements for office Type 2 buildings, within ADB 2019/2020 are consistent with those of ADB 2013 and the GWGD and permit the use of materials satisfying European Class B or better (see Table 1). It is noted that based on the clear requirements of ADB 2019/2020, it is likely to exclude the use of most current LW technology in many residential buildings within England. For example, adherence to this guidance would mean that the 40 m tall planting at One Central Park Sydney [53,54], a residual apartment tower, would not be possible in England, unless it could be demonstrated to satisfy Class A2 or better.

As part of the 2022 amendment to the ADB [37], additional building types from the PG definitions are introduced into the fire performance categorisation resulting in four types of building usage. The additional building usage type combines PG1 and PG2 to define an 'All residential dwellings' building type. Furthermore, for the 'All residential dwelling' building type, a new critical height of 11 m is introduced. As a result, there are now 14 categories of reaction to fire performance of external surfaces in ADB 2022 (see table 12.1 [37]). For brevity, we define Type 4 buildings to be greater than 11 m in height irrespective of the façade distance to the boundary and Type 5 buildings to be less than 11 m in height with the façade greater than 1 m from the boundary. According to ADB 2022, for Type 4 'All residential dwelling' buildings, all wall materials (presumably comprising all the components of the LW system including the growing media and plants) must be compliant with Class A2 s1, d0 or better (see Table 12.1 in ADB 2022 and Table 1). In addition, paragraph 12.8 of ADB 2022 refers to the GWGD as best practice for LWs; however, it also states that where Regulation 7(2) applies i.e., for residential buildings over 18 m in height (see paragraph 12.15 in ADB 2022), ADB 2022 takes precedence. While this statement clarifies the apparent contradiction between the GWGD (which specifies that the fire performance of LWs must be Class B or better for residential buildings over 18 m) and the ADB for residential buildings over 18 m in height, the additional critical height creates a new discrepancy between the GWGD and the ADB for residential buildings between 11 m and 18 m in height and where the boundary is more than 1 m from the façade i.e., Type 4 buildings. According to the GWGD these residential buildings have no specific fire performance specified, but according to ADB 2022, the façade for these residential buildings must have a fire performance of at least A2 (see Table 1).

Finally, another contradiction between the GWGD and ADB occurs if LWs are considered to be insulation products, as suggested by Fox et al. [55]. If so, then according to ADB 2020 (i.e., the current ADB) [25], irrespective of building type, LW materials are required to be Class A2 or better.

Thus, the GWGD bases its recommendations on confusing, defunct and superseded concepts (Diagram 40, Class 0 and Limited Combustibility) from ADB 2013 (see Table 1). Furthermore, changes to the ADB (2019/2020) and ADB 2022, mean that the GWGD is misleading and confusing and urgently requires updating. In its current form, its inclusion in the updated and forthcoming ADB is likely to lead to confusion amongst the LW industry, fire engineers and regulators.

4.2. *Appropriateness of fire test methods for wet living wall systems*

Although the updated ADB [25,37] refers to the GWGD, specific fire test standards appropriate for LW products are not identified. As a result, it is assumed that currently available test standards used for the assessment of common wall materials, such as BS476 part 6 and BS 476 part 7, as described in the ADB are appropriate for application to the components of LWs.

These test protocols use small samples with sizes of 0.05 m^2 and 0.24 m^2 respectively. While these tests may be suitable for individual solid materials and components used in LW modules and support systems, the small sample size cannot take into consideration variation in foliage and growth medium. As a result, they are inappropriate as a fire risk assessment for a LW system.

Within the GWGD, the SBI test (EN 13823) is used to quantify the fire performance of LW systems. The LW industry has also adopted this test protocol to characterise their products. Prior to the Grenfell Tower fire and even more so post Grenfell, manufacturers of LWs appreciated that the risk of fire was a concern for developers and designers and as a result many of them have initiated some form of fire testing of their products. The results from fire tests of five different LW products produced by five leading LW companies in three European countries were available for review (note, the names of the manufacturers and their products have been redacted from the cited references [44–48]. These tests were carried out using the SBI test (EN 13823) [39] for the whole system and the ignitability test [40] for solid components. The results are classified based on the European classification criteria [43]. Presented in Table 2 is a summary of the test specifications and main results from the five tests.

In reviewing the test results presented in Table 2 it is important to note the limitations of the test method when applied to test specimens consisting of living plants, growth media and associated support structures, in particular:

- The standard SBI test requires that specimen surfaces are flat or regularly corrugated with a thickness of no more than 0.2 m. These requirements cannot always be satisfied due to variability of plant material in random combinations with regard to quantity, size, form and moisture levels;
- The tested sample may not be representative of the original LW module as the plants are usually trimmed to fit in the test facility;
- SBI test specimens must be conditioned to a temperature of 23 ± 2 ^{O}C and a relative humidity of 50 ± 5%, in order to achieve either a constant mass, or for a fixed time period. These test conditions cannot be met by LW components as plants continue to grow and the wall modules must be wet.
- Test results will be dependent on the level of moisture within the module (plants, growth medium and support structure). As such,

moisture levels will be dependent on the nature of the particular product tested and so cannot be standardised as a predetermined test requirement [27]. However, to avoid potential biasing of test results, the moisture level tested should be representative of the minimum levels expected for the installation and this should be specified as a condition for the achieved product test performance;
- A gap between the modules and support wall and any barriers is highly likely to impact fire development. However, this is not specified in the SBI test standard; and
- The fire source in the SBI test is only 30 kW. This relatively small heat source may be inappropriate for assessing the fire performance of LW organic matter under wet conditions. One issue is that in real fires, with much larger fire sources, the organic components of the LW are likely to be rapidly dried and as a result its ignition and burning characteristics will be considerably altered.

While the SBI test is an appropriate test protocol for conventional wall materials and has been applied by the LW industry, it is not ideal for assessing the wet LW system. Indeed, for the reasons identified above, it is even questionable if a living product, such as a plant species, can be classified under the European classes of reaction to fire performance. Abley et al. [27] suggest that assessing LW systems using the SBI test while including succulent plants and irrigated growing medium is an abuse of the small-scale tests in BS EN 13501-1 as the moisture effectively protects combustible components. They recommend simply testing the module and backing layer, excluding plants, growth medium and all moisture [27]. However, this then would not be testing the complex system that is intended to be installed. Clearly, moisture levels will tend to improve the fire performance of the system (both in testing and in reality), and plants may have a negative (i.e., worse fire performance) impact while growth medium may have a negative or positive (i.e., improved fire performance) impact. It is thus preferred to test a representative minimum acceptable condition of the installed system (see Section 4.4).

However, if the test concept is to be applied to LW materials, the protocol will need to be adapted to address issues associated with critical factors such as: the appropriateness of test specimen, size, surface requirements and conditioning requirements, module moisture levels, ignition source fire size, degree of plant dryness and module installation etc.

It is also questionable if the ignitibility test is suitable for the assessment of entire LW modules. The ignitibility test method requires the flame source to be in direct contact with the specimens so that the flame spread can be measured across the material. The apparatus used to hold the specimen for testing requires the specimen to be no more than 0.25 m high, 0.09 m wide and maximum 0.06 m thick. These dimensions are smaller than common LW modules. Thus, if this approach is to be meaningfully applied to LW modules, the test protocol must be adapted to highlight that the test is restricted to components used in the construction of LW products, not the entire modules and excluding the plants.

It is also worth noting that according to the results presented in Table 2, none of the LW options tested would satisfy the requirements of ADB 2020 for Type 3 (or ADB 2022 for Type 3 or Type 4) residential buildings. Prior to the December 2022 release of ADB 2022, if we were to apply the recommendations of the GWGD, deciding which options are acceptable is complex as there are many permutations depending on interpretation of the guidance (i.e., Class B or limited combustibility), building height and distance to the boundary and GWGD recommendations may conflict with those from ADB 2020. However, from December 2022 this will be clearer, at least for Type 3 residential buildings as for these buildings the ADB 2022 guidance takes priority. As these buildings require a façade fire performance of A2 or better (see Table 1), once again none of the LW options (in Table 2) would be considered acceptable. However, for residential buildings between 11 m and 18 m in height, with a boundary greater than 1 m away, all the LW options would be acceptable based on the guidance of GWGD or ADB 2013 or ADB 2022 (as ADB 2022 identifies GWGD as best practice document). This clearly contradicts the requirements of ADB 2022 for non-LW façade construction.

Together with the SBI test, the single-flame test (ignitability test), EN ISO 11925–2:2010 [40] has been widely used to assess LW components prior to 2020 (see Table 2). However, as the ignitability test is inappropriate for assessing materials with a classification of A2 (or better), it is not suitable for assessing LW products intended for use in buildings over 18 m in height that require materials to be of limited combustibility i.e., Class A2 (or better). Rather than using the single-flame test, potential LW materials should be assessed using either the test method EN ISO 1182 or EN ISO 1716 as specified in the fire classification standard for construction products and building materials [43] or BS 476-11 suggested in ADB 2020 [25] to determine if they are equivalent to Class A2.

4.3. Appropriateness of the BS8414 test protocol for assessing living wall fire performance

ADB 2013 introduced the concept of the full-scale fire test protocol described in BS8414 [50] to assess the fire performance of exterior wall components using criteria provided by BR135 [49]. The test protocol was updated in 2015 [51] and 2017 [52] and again in 2020 [41]. However, in the current ADB (ADB 2020), the superseded 2017 test protocol is referenced.

Post Grenfell fire, a number of concerns associated with the appropriateness of the BS8414 test method have been raised, including [56]:

- inconsistency of the fire source;
- lack of construction details in the certification report;
- effect of the different construction details between the test and actual installations;
- appropriateness of the pass-failure criteria.

Some of these issues have been addressed in the 2020 version of the test methodology as described in BS8414 2020 [41]. A significant change relating to the specimen concerns the detailed installation requirements for cavity barriers such that the tested system is fully representative of the end use design in terms of the distance between cavity barriers. Another critical change to the test apparatus relates to the height of the main wall. This has been increased from at least 8 m to at least 9.7 m. In addition, previously the pass/fail assessment was partially based on external and cavity temperature measurements at two levels, Level 1 and Level 2, at 2.5 m and 5.0 m respectively above the combustion chamber. A third temperature measurement location, Level 3 (7.5 m above the combustion chamber) has been included in the test protocol. Furthermore, the sections of the test report concerning post-test examinations have been expanded. For the test report, more detailed information is required such as the involvement of test specimen selection by the test laboratory, the construction details (especially for the cavity barrier), mechanical response behaviour of components of the cladding system in fire, etc. Even with the changes to BS8414 2020, the pass/fail criteria detailed in BR135 were not updated, suggesting a more stringent and representative experimental set-up could be tested using the existing criteria.

While not specifically mentioned in ADB 2020, ADB 2022 or in GWGD, as a test protocol for LW systems, the BS8414 test could be used to assess LW installations and is arguably more appropriate than the reduced-scale SBI test. This is primarily due to the large LW module size that can be accommodated by the BS8414 test compared to the smaller SBI test and also the more appropriate fire source (2.5–3.5 MW) used. Nevertheless, when applied to LWs, the BS8414 test is not without its issues, suffering from many of the concerns identified for the SBI test (see Section 4.2). In addition, the BS8414 test suffers from a range of additional issues, such as the experimental inconsistency of the fire resulting from the prescribed wood crib (varying by at least a factor of two), the lack of glazing units, vents or other wall penetrations to demonstrate the interaction of the façade fire with critical building components. It also does not specify the extent of cavity barrier deployment or control ambient ventilation, and does not restrict falling debris or molten/burning droplets. Furthermore, the current pass/fail criteria suggested by BR135 is questionable as it does not attempt to grade performance and at the very least should be updated so that it addresses the new test specification. Another issue of concern is that it is unclear how the BS8414 test and the pass/fail criteria relate to life safety implications for occupants within the building. Furthermore, the potential benefits offered by the BS8414 test compared to the SBI test come at significantly higher financial costs and convenience due to the smaller number of facilities that can undertake a BS8414 test.

To reduce costs associated with assessing LW systems using the full-scale BS8414 test, it may be appropriate to utilise the SBI test methodology (see Section 4.2) as a screening test prior to undertaking a test of the proposed full LW system. The SBI test could be used to assess the LW system with a prescribed simple delay time criterion (e.g., 14 days without water), or just defined as the LW structure with dry growth medium, but excluding the plants and irrigation. If this proved acceptable, the entire system could then be tested using the BS8414 methodology, including the proposed plants and with representative moisture levels.

4.4. Issues of structure, moisture content and maintenance

When specifying external LWs, in addition to the building fire regulations and guidelines, issues associated with LW structure integrity, plant flammability factors, the fire load, the testing conditions and the maintenance etc., must be considered. Here we discuss key issues associated with fire testing conditions and LW maintenance, while issues associated with plant flammability and structural integrity, are discussed in the Supplementary Material (see Sections S2 and S4, respectively).

As already stated, the ignition and fire spread characteristics of LW products can be strongly influenced by the moisture content within the module and the dryness of the plants. Thus, for the fire testing of LW products to be meaningful, it is essential that the tested samples are representative of the products as they have been installed and are likely to be maintained. Furthermore, unlike standard building materials, the fire characteristics of LW products can be strongly dependent on environmental conditions, and as they involve living components, the state of health of the plants. Thus, without appropriate maintenance and care, over time the state and hence fire characteristics of the LW may change, and hence be unrepresentative of what was tested. For example, LWs using man-made substrates (such as rock-wool or insulation) rather than compost or soil, require an almost constant irrigation supply containing nutrients to sustain the plants (i.e., hydroponic systems). If the irrigation should fail, even for just a couple of days, the entire planting is susceptible to drying out and failing [57].

However, current fire test protocols, such as the SBI test, when applied to LW products, do not require the moisture content of the test sample or the health (dryness) of the plants to be specified [39]. While some SBI test results for LW modules have reported moisture levels, for example values of between 14% and 70% have been reported in some test literature (see Table 2), it is not a specific requirement of the SBI testing protocol. In another example test report, the documentation simply described the moisture content of the sample as ‘wet’. It is also not required by the test protocol to state that test results may be dependent on sample moisture conditions and state of the plants. While moisture levels required for a healthy LW are likely to be specific to the type of plants incorporated within the module and module design (i.e., product specific), it should be a requirement of the test (not optional) to clearly specify (quantify) the moisture content of the system tested. Similarly, it should be a requirement of the test protocol to state, not only the type of plants tested, but also their condition at the time of testing. While not stated in the test reports described in Tables 2 and it is assumed that all the testing involved healthy plants in prime condition. At the very least, specifying these conditions as part of the test protocol will improve the repeatability of test results. In addition, when manufacturers quote the fire performance of their LW products based on fire test data, they should also state the moisture and plant state conditions under which the data was collected and the corresponding conditions expected for their products in normal use with appropriate maintenance.

Furthermore, rather than testing a LW in its expected optimal state, for the test result to be of practical relevance, the state (including moisture levels) of the tested module and growth medium, should reflect that of the minimum acceptable condition in practice. Similarly, the tested plants should be reflective of the minimum acceptable plant condition. In this way test results identify the expected performance of the maximum degraded LW system which is still considered acceptable. If a LW installation deteriorates below the state of tested conditions, it should no longer be assumed compliant. As a result, further testing of the degraded system would be necessary to determine if the degraded state is still considered compliant or remedial actions may be necessary, either to reinstate the condition of the LW above the minimum or replace it.

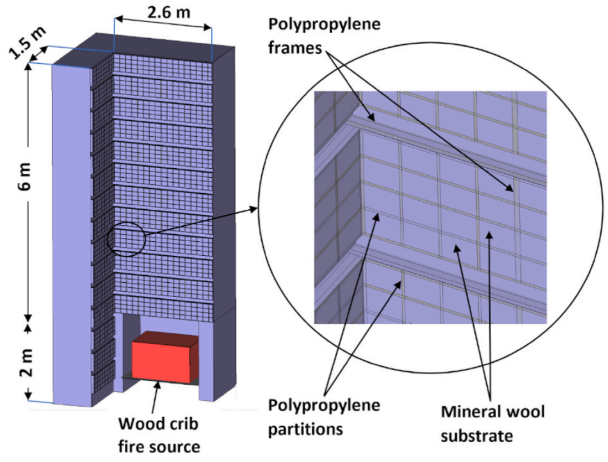
Thus, as a condition of fire safety compliance, the LW installation must be supported by regular monitoring and maintenance to ensure that both the plant health and the moisture level comply with or exceed that of the tested state and that plants do not dry out. This means that automated watering systems should be able to accommodate changes in climatic and environmental conditions. Furthermore, the installation should be designed to cope with temporary interruptions to the water supply. Regular maintenance of LWs is also essential to ensure that dead plants are regularly replaced, and that growth of the living components (including root bulk) is controlled and kept within tested conditions [27]. Thus, maintenance of LWs should not be considered as a desirable option but as a necessity to satisfy fire safety compliance.

4.5. Potential for CFD fire simulation of living wall systems

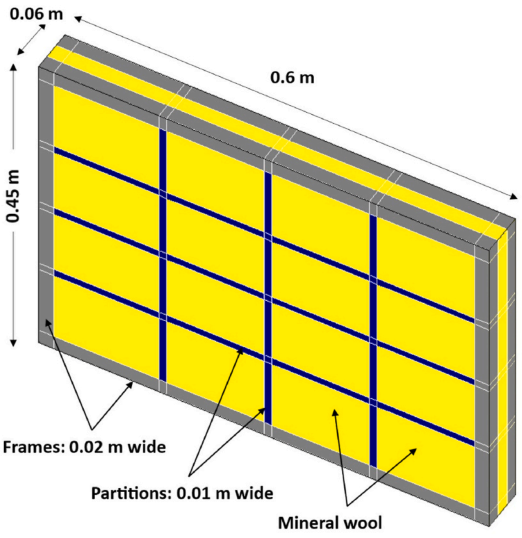
Compared with expensive full-scale fire experiments, Computational Fluid Dynamics (CFD) based fire simulation [58–61] offers an attractive potential route to investigate the fire performance of LW systems. CFD fire models have been used to simulate large-scale cladding wall fires [62] and have been able to reproduce a polyurethane wall fire incident [63]. In a recent numerical study, Dahanayake et al. [64] simulated fire development in a LW located in an underground corridor. As part of the study, the ignition and heat release rate (HRR) characteristics of three different plant species under various plant moisture states were quantified using cone calorimeter tests. The plant species, which are commonly used in LWs, were Hedera Helix, Peperomia Obtusifolia and Aglaonema Commutatum. The CFD simulations used this HRR data to demonstrate that the fire risk increases gradually as the plants dry out as well as the importance of plant selection. The study also highlights the importance of proper maintenance of vegetation to manage the fire risk and keep it at an acceptable level. While informative, Dahanayake’s modelling only considered the burning of plants, ignoring the:

- burning of plastic modules in common LW systems;
- module support systems;
- irrigation system; and
- physical structure of LW systems.

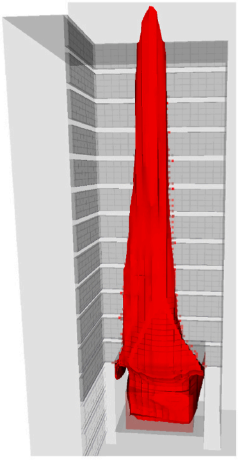
The SMARTFIRE CFD fire simulation software [65] has recently been used to simulate the BS8414 full-scale fire test protocol [66], to numerically assess the fire risk posed by wall claddings. The model represents a full size BS8414 setup, with a fire chamber containing a calibrated fire source that represents the appropriate fire curve for the wooden crib used in the tests. The outer wall material properties and



(a)LW test assembly



(b) LW module detail



(c) Simulated fire in LW assembly

Fig. 5. BS8414 fire simulation of hypothetical LW system, (a) LW assembly excluding plants; (b) LW planting module construction detail; (c) Simulated LW fire showing flame envelope at 330 s.

cavity gap for the setup can be configured as required to represent/include a range of cladding components, panels, insulation and cavity fire barriers, as required to evaluate a specific cladding wall installation (see Supplementary Material Fig. S3 for a representation of the BS8414 solution domain for an ACM cladding system within the SMARTFIRE CFD software). The model has the capability to predict fire development within the cladding system and potential failures according to the requirements of BR135 (see Supplementary Material Fig. S4 for an example of the predicted state of the fire progress at the predicted time of ACM failure). This ability to configure the simulation as required provides a potential platform for examining the fire characteristics of LW products (see Fig. 5). Presented here for demonstration purposes is a simulation of a fire (see Fig. 5) in a hypothetical LW assembly (Fig. 5a). The modules in the hypothetical LW assembly (see Fig. 5b) are formed of a polypropylene structure with mineral wool as the hydroponic substrate. A module is 0.6 m wide by 0.45 m high and 0.06 m deep. The module is made up of a polypropylene frame 0.02 m wide on the face of the four sides. Each module consists of 16 boxes (4 × 4) made up of a polypropylene mesh (0.01 m wide) filled with mineral wool (see Fig. 5b). A total of 78 modules are installed with 48 on the main wall and 30 on the wing wall (see Fig. 5a). The modules are flush to the external solid wall and so there is no cavity between the module and wall. While there are no left and right-side gaps between the modules, a module gap of 0.1 m is assumed between upper and lower modules within this hypothetical LW assembly. A 0.02 m wide polypropylene strip is placed on the front and back of the exposed top and bottom edges of the module (see Fig. 5b). Therefore, as seen in Fig. 5b, only the exposed polypropylene module frames (front, bottom, top) and the polypropylene partitions (front) are combustible. For demonstration purposes the following simplifications were used in the model:

- No plants are included;
- The modules and mineral wool filler are dry;
- No irrigation system is involved;
- The polypropylene material forming the planting modules, does not contain any fire-retardant material;
- The back of the modules attaches directly to the wall (fixtures are not modelled);
- Potential failure of the module structure is not considered.

Within the limitations of the above assumptions, the demonstration simulation shows that the fire rapidly spreads to the top of the wall by 330 s from crib fire ignition (see Fig. 5c). As a result, using the pass/fail criteria of BR135, the hypothetical LW structure (without plants and moisture) is likely to fail a BS8414 fire test.

While CFD fire models have the potential to assess the development and propagation of fires in LW installations, there are a number of challenges that need to be addressed before this can become a practical reality:

1. A significant challenge concerns modelling the change in moisture levels within plants and growth media during a fire. This includes evaporation due to thermal radiation and elevated temperatures (e.g., in the hot thermal plume rising above the fire and impacting the plants above the fire). The impact of the irrigation system during the fire will also need to be considered.
2. A significant concern in LW fires is the collapse of the modules holding the plants and growth medium. Predicting the collapse is a significant challenge. The mass density per unit area of a LW can be very high, some manufacturers quote as much as 40 kg/m^2. The frames/panels of LW modules are commonly constructed of plastic, such as polypropylene. With the increase of internal temperature, the rigidity of plastics will decrease and eventually melt; the melting point of polypropylene is only 130–171 ^{O}C. Thus, in a fire there is a high risk of component shedding or complete collapse for LW systems exposed to fires. This poses a risk to people at ground level as

well as a risk of downward propagation by flaming droplets/burning material (as seen in the Grenfell Tower fire [18] and the Lakanal house fire [67]).

3. A modelling challenge involves the integration of the plant fire model, module fire model and the moisture model into to a complete simulation environment using existing general fire spread models for solid fuel, such as that used in the BS8414 simulation.
4. Finally, for the CFD predictions to be representative, experimental data is essential to characterise the performance of plants, growth medium and modules, to assist in the development of the required sub-models and to calibrate the models. Given the variety of available plants, and the need to characterise their performance under a variety of moisture levels and radiative fluxes, this is a significant task. However, most of the required data can be collected from small-scale and medium-scale fire tests [30] (see Supplementary Material Section S2). As demonstrated by Dahanayake et al. [64], this can be achieved through the systematic and strategic selection of plants and other components. Data from large-scale fire tests, for example BS8414 scale test, are also required for model validation purposes. However, there are a number of issues concerning the data collection that need to be considered.
    - **Selection of representative plants:** The range of plants used in LW products is large. It is impractical to attempt to collect fire data for each individual type of plant that can be used in LW products. Furthermore, the overall fire performance of a collection of plants is likely to be different to the sum total of the individual performance of each plant. Therefore, one possible approach is to collect fire performance data for the combined system of plants used within the LW installation, rather than individual components.
    - **What fire data should be collected?** There are many different types of fire performance data can be collected in a fire test. Among them are temperature, flame height, flame spread rate, radiation fluxes, heat release rate, etc. However, ignition characteristics, flame spread rate and heat release rate are probably the most important properties to consider.
    - **Interpretation of collected fire data:** Compared with characterising the fundamental fire properties of conventional building materials, when assessing living plants, these properties will be dependent on a range of additional factors such as moisture levels with the substrate, plant dryness, growth stage of the plants, height of the plants, etc. As suggested in Section 4.4, fire data will need to be specified for a specific plant/substrate state and so a given combination of plants may have a range of fire performance data dependent on their specific state. To simplify the process, data associated with a minimum acceptable plant state should be considered. Furthermore, even for a specified state, the burning characteristics of living plants may be dependent on specific plant arrangements as well as individual plant and planting characteristics, thereby introducing a degree of randomness into the process making test repeatability difficult. Thus, several sets of fire testing of given combinations of plants and specified states may be necessary to identify representative ranges of fundamental fire characteristics.

However, the advantage of using suitably validated CFD fire modelling is that candidate LW configurations can be pre-tested using the modelling approach. This will reduce the number of full-scale experiments required by eliminating configurations that are determined as unlikely to pass. Only configurations that have a good chance of meeting the pass/fail criteria would go onto full-scale testing. Given the current capabilities of CFD fire modelling, as a first approach, modelling could be restricted to LW systems excluding plants and moisture - as suggested for SBI testing (see Section 4.3). However, unlike the mid-scale SBI testing, CFD modelling would have the advantage of investigating full-scale LW implementations. Furthermore, the CFD modelling can be adapted to consider other factors which are likely to be of importance but are not currently catered for in full-scale testing. This could include issues such as adapting the geometry to consider windows and the risk of fire spread back into the building from an external LW fire.

4.6. Living walls and external fire suppression systems

Finally, in situations where the fire risk associated with planned external LW is considered high, it may be worth considering the possibility of external fire suppression systems as a means of mitigating the risk. While a significant financial and technical challenge, the use of deluge or alternatively localised water-based fire suppression systems may be feasible. Such a system would attempt to extinguish or control the fire within the planting system at a very early stage of fire development (and so also require a means of automatic fire detection within the LW) or to protect the façade or building penetrations to prevent fire ingress. It may also be feasible to extend the design of the irrigation system to include fire suppression.

5. Conclusions

While there may be environmental, aesthetic and psychological drivers for LWs, these cannot override the fundamental need to ensure that building fire safety is not compromised or forced into second place. The hard lessons learnt from the Grenfell Tower fire demand that fire safety considerations override all other factors. To explore fire safety issues associated with LWs, this paper reviewed the legislation, guidance and testing protocols in England and reported on previous LW fires. While there are thankfully few reported LW fires to date, LWs are a relatively recent development and as their popularity and number increases, so too does the expected frequency of fires in LW installations. Furthermore, although the identified fire safety issues are of international interest, the regulatory issues identified are limited to England as an exemplar of a worldwide and potentially systemic problem.

Review of the legislative environment for England suggests a woefully confused and misleading set of recommendations. The UK LW guidance document (GWGD), published in 2013, bases its recommendations on the defunct and disputed Diagram 40 from ADB 2013, makes use of terms such as ‘Class 0’ and ‘limited combustibility’ that are no longer in regulatory use and suggests that LW installations must satisfy Class B requirements for particular building types. While the 2020 (and 2022) version of ADB, which cites the GWGD as “best practice”, suggests that LW installations in the same category of building must satisfy Class A2 or better. The inclusion of the GWGD in the 2020 and 2022 versions of ADB, is likely to lead to confusion amongst the LW industry, fire engineers and regulators. It is thus essential that the GWGD is updated as a matter of priority or removed from future updated versions of the ADB.

Perhaps of greater concern is the appropriateness of the test methodologies currently suggested in both the GWGD and the ADB for assessing the reaction to fire of LW installations i.e., the single burn item test (SBI) EN 13823, and the ignitability test EN ISO 11925-2. While both methods are appropriate for conventional building materials, their suitability for assessing fire performance of large, moist, highly non-homogenous LW specimens is questionable. It is even questionable if a living product, such as a plant species, can be classified under the European classes of reaction to fire performance.

While not specifically identified as a suitable test method for LW systems within GWGD and ADB, the BS8414 test is appliable to LW installations and addresses many of the shortcomings identified for the reduced-scale tests. However, to date LW systems have not been assessed using BS8414, possibly due to significantly higher financial costs. To reduce costs associated with full-scale testing, it is proposed that CFD fire modelling could be used to identify candidate LW products likely to pass BS8414 testing. While CFD fire models have the potential to assess the propagation of fires in complete LW systems, there are several modelling and data challenges that need to be addressed before this can become a practical reality. As an alternative, it was suggested that the intermediate scale SBI test or CFD modelling could be used to pre-assess dry LW support systems including dry growth medium, but excluding plants.

However, regardless of which test methods are used to assess the fire performance of LW systems, it is essential to address the issue that LW systems are fundamentally different to conventional building materials. The fire performance of the LW may change over time and be dependent on environmental conditions as it comprises ‘living’ components. This raises two issues specific to LWs. The first concerns what state of development and condition should the LW tested specimen represent? Rather than representing the state of the LW in optimal conditions (i.e., minimal fire risk), it is suggested that the condition of the tested specimen should be representative of the minimum acceptable state expected for the installation (i.e., maximum reasonable fire risk) and this should be specified as a condition for the achieved product test performance. The other related issue concerns maintenance of the LW – addressing both the horticultural and systems features of the LW. Without regular maintenance the condition of the LW cannot be guaranteed to at least meet the minimum condition tested. Thus, continuous maintenance of the LW must be a condition of compliance and appropriate maintenance schedules specified to ensure that the state of the LW is sufficient to maintain the required fire performance.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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