



Towards a better understanding of fire performance assessment of façade systems: Current situation and a proposed new assessment framework

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ABSTRACT

This manuscript presents tools and data that serve to enable an evaluation of the risk associated with vertical fire spread on buildings. A highly detailed context to cladding fires is described to unveil the complexity and magnitude of the problem and to identify gaps of information. An engineering framework is then developed which delivers required information that fills some of those gaps and that needs to be used towards achieving quantified fire performance. The data itself has been published as a publicly available database, entitled the Cladding Materials Library (www.claddingmaterialslibrary.com.au). This data can be used to support building fire risk assessments or as the basis for more in-depth research into façade fires. This paper presents the context of the data together with the competency framework necessary for upskilling building professionals to have the capacity to implement the engineering framework.

1. Introduction

The manner in which high-rise building construction has evolved in the last two decades has resulted in the number of very large-scale building fires increasing in a dramatic way. Notable among these fires is the Shanghai fire with 58 victims and the Grenfell Tower fire with 72 victims. These fires have been documented extensively and in the majority of the cases the fast spread and ultimate magnitude of the fire is related to the manner in which the façade system was designed. Despite the numerous failures, it remains unclear how to address these complex systems to deliver a quantitative performance assessment that enables fire safety engineers to establish, in an explicit manner, an adequate fire safety strategy.

The façade system is an integral component of the fire safety strategy because the ultimate effectiveness of the strategy is strongly underpinned by the need to contain the fire to a single floor. Or, in some cases, even to a single unit. The performance and robustness of the fire safety strategy is defined by multiple layers of protection that include: detection and alarm, suppression (e.g., sprinkler) systems, smoke

management, compartmentation, egress strategy (stay-put, phased, or simultaneous ('all-out')), firefighting, and structural stability. For a building which has a stay-put evacuation strategy, the detection and alarm system are often isolated to single units, and cannot alert occupants to fire spread away from the compartment of origin. Sprinklers, if included, act as a supplementary means to reduce the probability of fire growth but cannot be relied upon as a sole means of protection. Sprinklers, as well as smoke extraction and stair pressurisation systems, will become overwhelmed once multiple floors are affected by fire. Vertical fire spread represents a failure in compartmentation, and switching to an 'all-out' evacuation strategy becomes necessary but may not be safe due to the spread of fire and smoke throughout the building. Finally, the structure will be exposed to a long duration, full building fire for which it is not designed and which threatens the life of remaining occupants and firefighters in the building. This is described in more detail by Torero [1].

The spread of fire from one floor to another compromises the entire fire safety strategy, and the layers of protection or robustness are not adequate to protect the occupants or the building. Therefore,

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establishing the capacity of a façade system to prevent external fire spread and quantification of the potential fire spread rates becomes an unavoidable calculation for the development of a holistic fire safety strategy.

The fire safety strategy defines what is adequate for a specific building [1], and in the case of a 'stay-put' strategy, adequate means no vertical fire spread. In contrast, some vertical fire spread may be permissible in cases where a fire safety strategy is driven by detection and alarm and where the evacuation strategy is prescribed as phased or 'all-out'. The maximum acceptable fire spread velocities need to be quantified and contrasted with predicted egress times. Thus, the variables that control vertical fire spread need to be distilled and assessed either through fire dynamics principles or testing. This has proven to be an extremely complex task in the case of modern façade systems.

Reducing the risk of fires migrating beyond the floor of origin is thus critical to protecting life safety and reducing potential for property damage. Research conducted in the last five decades has delivered different approaches that were deemed appropriate until the advent of novel façade systems. The most common strategies to achieve this are the use of a combination of non-combustible materials to ensure that the external envelope does not promote spread, and the design of balconies, spandrels or flame deflectors to prevent flames spreading from one storey to another. Ashton & Malhotra [2] showed for their set of experiments that a minimum of 0.91 m spandrel or 0.61 m horizontal projection would be required to prevent smoke and flames from re-entering the building. Specific dimensions have later been quantified based on the compartment characteristics of the storey below. Yokoi [3] calculated the required spandrel height or horizontal projection width based on the fuel load, compartment dimensions, opening size, and corresponding flame height. Glazing was assumed to fail at 500 °C, and so this was used as the threshold temperature for spread. The protection offered by horizontal projections has been shown to be superior to spandrels for the same dimensions [4]. Subsequent research has included 'realistic fuel' in the form of furniture and a range of internal ventilation conditions (e.g. a draught from an open door) which found larger flame lengths and would require larger spandrels [5,6] than previously predicted and that the incident heat flux to the façade is underestimated for a non-uniform fuel load [7,8]. In addition to this, any penetrations or opening have to be designed appropriately and firestops must be implemented to prevent the spread of fire. Despite the crudeness and conservative nature of many of these measures, these strategies were effective in preventing breach of vertical compartmentation.

The desire for the reduction of energy consumption became an important driver in design, resulting in the introduction of building envelopes as a practical means to reduce energy consumption. For example, the stringent targets for improving sustainability and energy efficiency for buildings in the EU [9] accelerated the already rapid changes in façade systems. Other drivers such as ease of construction, cost, aesthetics and acoustics have also emerged [10], and the continuous building envelope has become the preferred solution for retrofit and new builds [11–13].

The continuous building envelope brings an inherent problem in that it is susceptible to deformations that are very different to the structure to which it is attached. This creates the potential to render firestop arrangements ineffective, and allow penetration of the fire from a lower compartment to one above. This problem is further exacerbated by the use of specific materials, such as aluminium, to respond to other drivers such as weight reduction and ease of manufacturing. Aluminium loses all mechanical integrity by 550 °C [14] and melts at 650 °C, which are well below the temperatures of typical fires e.g., up to 1000 °C for external flames [15]. Thus, these materials represent no barrier to a fire.

The lack of quantifiable performance has also manifested itself in situations where the outcome of major external fires has not been as tragic. In these cases, the level of robustness was sufficient and the fire either did not spread, or if it did spread life safety was still ensured. In the Lacrosse fire (Melbourne, 2014), the cladding ignited due to a

balcony fire and spread rapidly upwards thus breaching vertical compartmentation [16]. The building contained an interconnected alarm system, two fire-isolated staircases that were pressurised and kept clear of smoke, a cascading (or sequential) evacuation strategy, and sprinklers installed in each apartment. These levels of robustness were sufficient to allow all occupants to evacuate with no fatalities and no serious injuries. There was nonetheless an unacceptable level of damage and led to insurance claim of 5.7 m AUD (€3.6 million) being awarded to the owner [17]. This was paid by the fire engineer (39%), building surveyor (33%), architect (25%), and the individual deemed responsible (3%, but paid by the builder). Similarly, the Address Downtown fire (Dubai, 2015) was a 63-storey building where the fire breached compartmentation and spread upwards externally. The layers of protection were capable of maintaining life safety with only 16 injuries and no fatalities but the property damage was again unacceptable and led to an insurance claim of 1.22 billion AED (€309 million) being awarded [18]. These are two of many examples where similar outcomes were observed but where the façade systems were very similar, the fire spread rates were very different and so were the life safety outcomes [1,19,20].

In summary, compartmentation provided by façade systems is critical to the fire safety strategy. The capacity of façade systems to constrain and slow the spread of a fire needs to be quantified to establish the adequacy of the fire safety strategy. Extrinsic drivers have resulted in façade systems of unknown fire performance and unpredictable fire safety outcomes. Therefore, it is essential to revisit the fundamental processes determining how a façade system supports the desired level of fire safety performance and, as a result, deliver tools that enable engineers to quantify such performance.

1.1. Current approaches to compliance and suitability

Compliance with building regulations has been the main approach used for performance assessment of novel façade systems and has generally been defined by combustibility requirements. These combustibility requirements have become the drivers behind product and system development.

Building regulations have maintained strict rules regarding the combustibility of any material used on the external surface of a building. In England and Wales, guidance in the now superseded version of Approved Document B [21] specified that external wall surfaces above 18 m should be European class B or better, and that insulation and other fillers should be of 'limited combustibility'. The European classification framework EN 13501-1 [22] involves a series of tests where the Single Burning Item test EN 13823 [23] is required to achieve a 'B' classification. No plastic material can adequately fulfil those requirements unless it is encapsulated in a non-combustible material. The strategy of encapsulation thus became a driving force for the use of combustible materials within the building envelope. Aluminium Composite Panels (ACPs) or aluminium foil covered cellular plastic insulation are perfect examples of systems where encapsulated combustibles materials are used. These systems spread widely because of their reduced cost and because they provided an effective solution to many of the required building functionalities.

The combination of an encapsulated combustible product added to a continuous, lightweight building envelope results in systems of enormous complexity and innumerable components. Many of these components have been fixed in manners that favour ease of construction [24] but do not necessarily take into consideration their performance in fire [25].

As a consequence, existing combustibility tests can no longer be used in their standardised form for these encapsulated products in a way that gives meaningful data. This is because they are designed to assess individual materials rather than composite products. Furthermore, the desired performance still needs to be established in the context of what is acceptable from the perspective of vertical fire spread.

First principle fire dynamics are therefore needed to describe vertical

fire spread. This can be done for simple configurations and over combustible materials [26] but even under these simplified conditions there is still much uncertainty on how to quantify spread rates. Complex systems that rely on encapsulation cannot be described by any of our current tools, and while several studies have attempted to do this after Grenfell [27–30] none of them has produced a well validated and sufficiently robust set of predictions. Furthermore, these studies have been calibrated against standard tests with very limited instrumentation that do not provide the necessary precision to address the accuracy of complex formulations. Finally, none of the current testing practices used to define performance of these complex systems are capable of establishing the mechanisms by which encapsulation fails, do not explicitly provide rates of fire spread [31,32] nor enable the estimation of any of the parameters that might control fire spread. These testing practices will be discussed in more detail below.

1.2. Existing testing

Testing individual components according to combustibility tests will yield basic material information describing whether there are organic components which can oxidise and release energy but give little other indication of performance. The EN 13501-1 framework [22] specifies the ISO 1716 heat of combustion test [33] and ISO 1182 non-combustibility test [34] to assess ‘non-combustibility’ or ‘limited combustibility’. The gross heat of combustion for a sample is determined and the material is deemed to be non-combustible if it is below a certain value. The non-combustibility test consists of inserting a sample into an insulated 750 °C furnace and recording the temperature. If the temperature rises above a set threshold then the material will be deemed to have failed, and is deemed combustible. The criteria for ‘limited combustibility’ – which is to pass either of the above specified tests – does not however provide the means to assess vertical fire spread. This is because there are a number of complicated interrelated phenomena to evaluate which are not captured through a simple value of the gross heat of combustion.

‘System’ or ‘scenario’ tests have been proposed as an alternative that might provide an estimate of the ensemble consequences of all the detailed and complicated interrelated phenomena controlling fire spread. Nevertheless, it is unclear if any of these scenario tests are suitable for this purpose. One alternative has been the use of existing standard tests e.g., Single Burning Item (SBI) EN 13823 [23] as part of the EN 13501-1 framework mentioned previously. The SBI test method has been shown not to be effective for encapsulated products, where the failure modes are related to the deformation of the metal skin rather than the ignition and burning of the underlying core material [35]. The intent of these tests is to give a generalised assessment of the combustibility and flaming behaviour of materials, and they are not designed for adequately assessing mechanical deformations. The burner imposes a relatively low incident heat flux with a peak of 30–35 kW m⁻² [36] and, for many arrangements, it is not sufficient to induce this failure mode. Since the heat exposure is insufficient to create thermal deformation, the core material remains well sealed and no pyrolysis gases can escape and lead to ignition. Furthermore, oxygen diffusion to the core material is inhibited and so combustion in the core is limited. A metal skin encapsulation acts as a thermal barrier that has a high thermal inertia which reduces the rate of temperature increase and in turn increases the time taken to reach the ignition temperature of the core material. The barrier is defined with sufficient thickness to prevent ignition or failure of the material in the limited duration of the test. Foil-faced materials are protected through a combination of high reflectance reducing the absorbed heat flux, and also sealing of the core flammable material thereby preventing escape of the pyrolysis gases and reducing oxygen ingress to the core material. Encapsulation of products to protect combustible materials from ignition sources cannot be evaluated by means of these tests because the aim is no longer material performance assessment but system performance assessment. These competing

objectives lead to confusion and ultimately do not deliver the necessary information to predict fire spread.

An alternative to provide evidence of performance for these systems is to develop performance assessment strategies specifically designed for the purpose of establishing the potential for vertical fire spread. Again, the first and simplest is establishing performance by means of a ‘scenario test’ e.g., BS8414 [37] or NFPA 285 [38]. There are a large number of these test methods around the world, with different jurisdictions having a number of modifications around a common theme. The different test methods, scales, heat sources, detailing (e.g., windows and fixings) and thresholds for passing for each test method has been summarised in the literature [39,40]. Furthermore, these scenario tests have been used as a route to compliance. For example, in England and Wales the supporting document BR135 [31] stipulates pass/fail limits for tests run according to BS8414 leading to the potential interpretation that meeting the passing criterion is a sufficient route to compliance. Nevertheless, this criterion is based on a limited number of temperature measurements, and failure criteria specified at a height above the combustion chamber. There is no measurement or assessment of fire spread rates.

Part of the shortcoming of the quantitative criteria – i.e. that the temperature increase must not exceed 600 °C for 30 s within the first 15 min, among others – is that there is no justification for their basis and this information is not useful for a designer to assess the risk of fire spread. Even ignoring the limits set by BR135, the sparseness of instrumentation in BS8414 makes it impossible to assess flame spread. Thermocouples are provided at only two levels: 2.5 m and 5.0 m above the combustion chamber. With only two points, it is not possible to assess whether the flame spread is accelerating or decelerating, and thus whether it will achieve burnout or whether it may spread up the building. Furthermore, the rigid preselection of the heights may not be relevant to other specific buildings where the openings and storeys may not align to these heights. This also means that the cavity barriers are not located at representative heights for a real building as they are instead located at heights suited to achieving the best performance in the test.

Even the rationale behind the definition of the fire scenario has been questioned [41] with alternative configurations proposed as being more consistent with the thermal exposures of fully developed fires. A parallel plate configuration is proposed to significantly increase the imposed heat flux to the façade, in the order of 110 kW m⁻² and decaying over height (compared to 45–95 kW m⁻² in BS 8414). While delivering improved repeatability, the intent of the tests is to predict pass/fail in the larger 25 and 50 ft (7.6 and 15 m) room corner tests. This is based on the level of acceptable risk and corresponds to empirical limits determined by Nam & Bill [42]. These tests still lack any of the fixing details, do not include complicated window details, and remain heavily reliant on every single system being tested. Thermomechanical failure is also not evaluated as the comparatively thin panels (i.e. two panels of 550 mm width) are well fixed using rivets thereby preventing any significant deflections.

Despite this, there is only a single pre-defined prescribed scenario which is deemed to be representative of an external fire. Prescribing the fire load prevents a designer from creating a performance solution tailored to a specific building. The scenario itself assumes that the key risk is from a fire spreading upwards, with some limited lateral spread. In flame spread, concurrent (upward) flow propagates at velocities more rapid than opposed (downward or lateral). Some lateral spread was present throughout Grenfell Tower but especially significant at the architectural crown of the building due to the geometry and configuration of materials [43]. Analysis by Torero [1] shows that flaming droplets from the crown induced downward flame spread and accelerated the lateral spread across and around the building. This led to faster downward and lateral spread rates, and a larger maximum affected area. This behaviour is uncommon but also present in some other building fires, and Torero [1] provides comparison with the crown fire in the Monte Carlo Hotel & Casino (USA, 2008). Lateral and downward spread was also observed in Tamweel Tower (Dubai, 2012) and Grozny Towers

(Russia, 2013) [19]. These examples show that flaming droplets or downward spread are key risks potentially leading to large fires. However, it is not quantitatively assessed in the tests and there are no failure criteria associated with these risks.

The systems tested in 'scenario tests' include multiple interconnected components and the relative performance or contribution of each component cannot be evaluated with sparse measurements or observations. The difficulty in characterising even a single one of these components was evident from the standardised combustibility frameworks described earlier. The lack of quantified data and lack of understanding of the fire behaviour during a test means that the data can only be extrapolated to conditions very close to the exact conditions and configuration in which it was tested, and therefore does not represent an adequate assessment of performance. The tests also lack repeatability and reproducibility due to their large scale as investigated by Anderson et al. [44] and also as evident in the lack of repeatability of the exposure in tests performed by Holland et al. [45]. Furthermore, the systems are often constructed under idealised conditions in a testing laboratory, and are simplified versions of façade systems as used in real buildings. The expert witness reports of Lane and Bisby [25,43] describe the vast complexity of the façade system installed in Grenfell Tower compared to the heavily simplified versions in scenario tests.

A critical parameter is the time taken for vertical compartmentation to be breached, however, the complexity of these tests and the sensitivity on specific configurations means that this is not possible to ascertain. Furthermore, the configurations do not represent a complete system and so the results are not directly applicable to buildings as they fail to represent a real building fire scenario.

Additionally, this testing should not be used simply as a certificate of compliance but should be used as evidence to support an engineering analysis performed by a competent individual [1,31]. This has been shown not to have been the case in practice. This ultimately leads to the generation of information which may not represent a relevant fire scenario nor provide the quantified data required to assess the potential for fire spread. This is a case of a test that is problematic for two reasons, first because it does not provide any information related to the performance needs and second because its arbitrary definition makes it impossible to conduct in a repeatable or representative manner.

To add to the complexity, the exact composition and performance of different materials varies despite many times being labelled as the same product. This has added further difficulty to the process of assessment. This means that there must be some form of testing to verify the composition of a material, or otherwise it must be assumed to be the worst possible case.

1.3. Desktop studies

An alternative to 'scenario tests' is through simply using analysis i.e. desktop studies. In this case, a qualified engineer extrapolates existing testing data to write a report as proof of performance. One step further would be extrapolation or determination of performance without any test data, possibly with the aid of computer models. This has led to systems being accepted through analysis alone with inadequate support testing evidence.

The result was the widespread use of these systems until specific failures detonated extensive investigations that questioned the use of these methods. The two particularly relevant cases are the Lacrosse Building and Grenfell Tower fires which both had fires with different, but unacceptable, consequences. The investigations collated detailed information of the fire scenario, materials used and their configurations, building design, design and approval process, etc. not available in other past building fires. These investigations highlighted both that flammable systems were in wide use, and that the measures of protection were not adequate.

A multiplicity of complex failure modes have been observed including: failure of encapsulation, melting and dripping of burning

plastic material, deformation and fall-off of burning components, preferential spread through cavities and the associated failure of cavity barriers, breaches of barriers due to deformations, fire enhancement by means of heat feedback from multiple burning components, etc. None of these failure modes were anticipated by any of the existing performance assessment practices thereby casting enormous doubt on the capacity of 'desktop studies' to deliver a robust performance assessment.

2. Initial response

The immediate reaction to these events resulted in numerous actions led by governments and institutions such as the fire brigades. The Lacrosse and Grenfell Tower initial fire investigations focused on the assessment of combustibility concluding that all plastic materials in these façade systems failed to meet the requirements of non- or limited-combustibility. The UK Government commissioned testing to rapidly identify whether non-combustible materials were present in the building façade. The heat of combustion was determined using ISO 1716 [33] and limits were set to determine the combustibility, as shown in Table 1. This formed the screening method, and only ACP samples were accepted. Two-thirds of samples were rejected (1503/2235) as out of scope by the end of the screening process [46] because they did not meet the required criteria.

The Insurance Council of Australia developed a similar approach intended to have broadly equivalent categories to the BRE method, and were labelled A to D. This was based on the material composition, and used polymer content to classify materials. Additional alterations have also been developed to help address the hazard posed by other flammable materials contained in a façade, such as insulation. At present, these materials are recorded but not ranked. They include expanded polystyrene (EPS), polystyrene/phenolic composites, polyurethane (PUR) and polyisocyanurate (PIR).

The method however has shortcomings. There is no evidence to support a 30% organic content cut-off (Categories B to D) as leading to no flame spread. The objective of the testing is confused because it is only adequate to identify whether a material is combustible or not (i.e. > 0% polymer content), and therefore is incapable of determining fire spread performance. The testing is not capable of delivering information of the fire performance of a material nor of a product or a complete system. It also fails to capture any of the failure mechanisms described previously, such as failure of encapsulation or melting, which would be relevant for assessing external fire spread.

There are also difficulties in accurate determination and quantification of chemical composition, and has misplaced confidence on the precision. Commonly applied chemical analytical techniques are not able to measure organic content directly, and usually infer it based on inorganic characterisation. There are biases in the techniques used to perform the analysis and the results have significant error margins, as with any measurement technique. This confusion leads to acceptance of materials with 29% polymer content but rejection at 31%. The error margins incurred when using this information to assess the potential for external fire spread will be significantly larger. This is evident from the fire spread rates collected from a limited number of real building fires by Torero [1]. Ultimately, this method gives no assessment of the fire performance even for ACP materials, and cannot be applied for any non-ACP materials.

Subsequent studies using the scenario tests reinforced the perception

Table 1
Classification of ACP samples according to the protocol commissioned by the UK government and developed by the BRE [47].

Classification	Criteria
Category 1	$\leq 3 \text{ MJ kg}^{-1}$
Category 2	$> 3 \text{ MJ kg}^{-1}$ and $\leq 35 \text{ MJ kg}^{-1}$
Category 3	$> 35 \text{ MJ kg}^{-1}$

of inadequacy associated to materials such as those in the Lacrosse building or Grenfell Tower. The UK Government commissioned a series of tests [48] containing ACPs from each of the categories (Table 1) and two types of insulation – stone wool (SW) and PIR – to be performed according to BS 8414 [37] and classified to BR135 [31]. The results confirmed inadequate performance with both tests containing the Category 3 ACP (Tests 1 and 2) and the one test with Category 2 and PIR (Test 3) all being classed as having a ‘fail’ outcome according to the limits set in BR135. A further seventh test was later performed on a Category 2 ACP and phenolic foam which was also classed as a ‘fail’.

These tests feature systems which are both simplified and idealised in a way that makes them unrepresentative of systems installed in buildings. These tests were performed as a result of the Grenfell Tower fire, and so the tests should be representative. The closest configuration is Test 1 containing category 3 (pure polyethylene) ACP and PIR insulation. From the details given – the calorific value of the ACP and the density of the PIR – it is not possible to identify the exact materials. The synthetic rubber weatherproofing membrane is not present in any of the tests, nor are a plethora of other materials including uPVC (unplasticised polyvinyl chloride), timber, XPS (extruded polystyrene), and additional combustible insulation in thin cavities. This also highlights the complexity of the actual systems containing highly convoluted arrangements and geometries. These configurations, in addition to imperfect installation, lead to the presence of thin cavities between panels and other detailing. These details could potentially elongate flame lengths because of the reduced air entrainment and can help facilitate flame spread. Lane’s expert witness report [25] highlights that there are multiple continuous thin cavities in the building details which provide pathways for fire to spread unimpeded. These are so numerous and complex that they cannot comprehensively be included in these tests, and are bespoke to individual buildings.

In the UK Government scenario tests, the ACP fixing method was riveted to create a flush straight finish, and the gap between panels was set at 20 mm. This is fundamentally different from the cassette system installed at Grenfell. The fixing details are different, and furthermore the ‘return’ detail where a length of ACP is folded at the end of panels is not included. To create folds also requires removing a portion of the aluminium skin which exposes an unprotected length of the core. The gap between panels is nominally the same, 20 mm, but the return detail forms a thin channel with ACP on either side. This geometry restricts air entrainment, causing elongated flame heights and potentially enhancing flame spread rates. The available data test from EN 13823 appears to qualitatively support this, as a riveted system achieves Euroclass B or C, which is superior to the Euroclass E of a cassette system as found by Lane’s investigation of documentation on Grenfell Tower [25]. Nevertheless, none of these studies provide a comprehensive characterisation of the parameters affecting fire spread.

Lane’s analysis further shows that the Grenfell cassette system does not match the standard cassette system detailing provided by the manufacturer [25]. This means that even when the same type of fixing method is used, the details on buildings still vary in an unknown and unpredictable manner. Thus, the riveted system as used in Test 1 is not representative of a system as installed on a real building, and does not necessarily represent a worst case scenario to be able to adequately assess the risk of external fire spread. The same logic applies to the other six tests and to other fixing methods.

Furthermore, in Grenfell the exposure of the ACP core of the cassette system immediately above the openings is hypothesised to have been a key factor in external fire spread [49]. This was unprotected, and no cavity barrier was provided immediately above the window meaning that the core would be immediately exposed to flames from a compartment fire. In the tests, there was instead a 5 mm thick aluminium profile at the top of the combustion chamber which seals and protects the cavity from the spread of smoke and flames. Additionally, an intumescent cavity barrier with a stated integrity/insulation (according to EN13501-2 [50]) of 90/30 min was added above this. The

tests only have a set duration, and this detail must fail for the fire to be able to enter the cavity, or otherwise the ACP cladding must first degrade or deform for a gap to open. The limits set in BR135 relate to the first 15 min of exposure, and so this detail is highly beneficial in providing sufficient protection to delay failure beyond this time period. None of the tests failed these classification criteria, and instead Tests 1, 2, 3 and 7 failed on a separate criterion that a test must not spread flame above the height of the rig, as assessed by visual observation. This further suggests that the limits set in BR135 are not effective, and rely on a subjective qualitative measure for success or failure.

The UK Government data is limited only to the specific individual materials used in the tests and does not include other materials of systems that could pose a risk. For example, high pressure laminates (HPL) are a distinct type of material which cannot be extrapolated from the above test results. The potential hazard of this material is evident from the Lakanal House fire (UK, 2009) with a type of HPL that led to the death of six people [51]. A further BS8414 test was therefore commissioned by the UK Government to assess a system with this material [52], although it is not officially included as part of the seven tests described above. This system contained “A1 insulation” – likely to be mineral wool based on the Euroclass and the photographs provided – and successfully passed the limits set in BR135. Despite this, there was a sudden temperature rise in the test from 400 °C up to 700–950 °C at the upper height (level 2, 5.0 m above the combustion chamber) which suggests that there was ignition and sustained burning. This occurred over a period from 25 min and 35 min, which represents burning both before and after the crib was extinguished at 30 min. This ignition late into the test further suggests that the system may have been close to failing on the “flaming above rig” criterion, where Tests 1, 2, 3 and 7 all failed. The test was performed at a separate facility from the other seven tests, and repeatability and reproducibility of the testing has already been shown to be poor. Thus, despite achieving the performance criteria in BR135 it would be difficult for a designer to use this data to confidently assess the risk of external fire spread as the crib is extinguished at a key point in the flame spread process.

This test represents a single data point in non-ACP materials and only a single type of HPL. In cladding samples taken from UK buildings, these non-ACP systems represented up to 67% and the above tests do not allow characterisation of the potential fire risk. Recognising this issue, the UK Government commissioned testing of additional non-ACP materials [53]. Testing on 28 samples – including zinc and copper composite panels, HPLs, and stone and brickslip products – was performed in an ad hoc reduced-scale rig with a wood crib fuel source broadly representative of BS8414 in terms of the imposed incident heat flux (45–75 kW m⁻²) and duration of burning (30 min). The heat exposure was intended to be sufficiently severe to induce failure mechanisms not possible using SBI. However, the tests incorporate composite products and introduce an air gap (50 mm), fixings, and joints. These attributes add extra complexity that are not trivial to characterise yet do not constitute full system behaviour.

Of these attributes, the vertical joint location represents a key weakness in a system. It provides a channel to promote vertical flame spread, and thermal expansion leads to exposure of the core in a shorter time as it is not protected by encapsulation or a coating. Despite this, its location changes from directly behind the fuel source in the worst case but in other cases is up to 0.5 m away. The impact of this is demonstrated in the testing of HPLs with different European classifications. Those with the same or superior Euroclass (C–D) and a joint directly behind the crib took 4–5 min for the fire to enter the cavity, while those with worse Euroclass (D) and a distance of 0.5 m to the joint took 11–17 min. This shorter time to enter the cavity then led to higher temperatures recorded at the top of the rig (324–366 °C compared to 267–282 °C) suggesting more likely fire spread. This was nonetheless not evaluated systematically and ultimately means that the different materials and groups of materials cannot be adequately compared as the conditions are fundamentally different. The complexity of these systems is such that it cannot

easily be extrapolated to other configurations without serious difficulty despite the fact that it is shown to impact the results.

The parameters evaluated above also highlight the difficulty in extracting useable quantitative information from these tests. The instrumentation is denser than in large-scale tests but interrelated phenomena progress simultaneously. The tests are concurrently attempting to evaluate the ability of the material to act as a barrier, the potential for fire spread on the exterior of cladding, the intensity of a cavity fire, and the potential failure as a result of a cavity fire. The composite nature of the ACP adds complexity in the heat transfer mechanisms, melting behaviour, thermomechanical deformation and possible delamination. Additional difficulty is that one event depends on another. For example, the cavity fire will be dependent on the time taken for the cladding barrier to fail and for the flames to penetrate through. If penetration times are long, then an active cavity fire cannot be evaluated effectively because the test will terminate partway through the process due to the arbitrary time limits.

The reports compare the available parameters to a series of ‘calibration’ tests involving three types of ACP each tested with two trials, for a total of six tests. The vertical joint location is not kept consistent between the different types of materials, with 0.5 m for ACP A2, 0.25–0.5 m for ACP FR, and 0 m for ACP PE. The different vertical joint location in the two ACP FR tests led to ignition of the cavity near the end of one test but not the other, which again illustrates the influence of vertical joint location. These tests are therefore not well suited to be calibration tests. Furthermore, there is no experiment for an inert wall or product and instead modelling is relied upon to provide a baseline. The reports use these calibration tests to conclude that no other material represents the same level of hazard as pure PE core ACPs. However, they otherwise make little to no definitive conclusions on the relative performance of other materials, whether they would constitute acceptable performance, and under what other conditions there could be acceptable performance. This therefore does not provide designers with the information that they need to evaluate non-ACP products or product systems.

The combination of the lack of repeatability, simultaneous evaluation of multiple interrelated phenomena, lack of a complete system, sensitivity on the configuration, comparison to highly flammable materials and the lack of satisfactory data, all make it impossible to adequately use this information to assess the hazard of any materials or systems from the results of these tests. It is also important to repeat that exact material composition can alter the outcome and in none of these cases was this fully characterised.

2.1. Outcome and implemented methods

Despite the weaknesses of the information available, what followed these assessments was the immediate removal of façade systems in many countries and widespread review of the existing systems with the objective of identifying systems that represented an unacceptable level of risk. As an example, in the audit of non-conforming building products in Queensland (Australia) there were almost 15 000 buildings registered for investigation and 76% were found to not have flammable cladding with no further assessment needed [54]. In Victoria, further along the audit process, they identified 72 buildings with extreme risk and 409 with high risk as of July 2019 [55], and in the UK, 455 high-rise residential or publicly-owned buildings are affected [56].

The costs associated with remediation of large numbers of buildings are substantial. To deal with the crisis, Victoria (Australia) has set aside \$600 million AUD (€360 million) [57], and the total cost has been estimated [58] as \$250 million to \$1.6 billion AUD (€150 million to €950 million). In England (UK), a fund of £600 million (€690 million) was announced for high-rise residential buildings with high risk ACP systems [59], and a further £1 billion (€1.15 billion) for non-ACP systems [59]. The National Housing Federation (NHF) in the UK have estimated that the total cost of remediation may be more than £10 billion (€11.5 billion) [60]. These estimates are very similar for other

countries.

The methodologies used for assessment have been proven not to be robust and have left many gaps and contradictions. Buildings such as the Neo 200 building (Melbourne, Australia) were deemed of low or moderate risk but nevertheless have sustained large fires. Despite this, the same methods are still being used.

Furthermore, instead of developing new and more appropriate methods of assessment, attempts are still being made to iterate around the existing methods suggesting that they can be further simplified. Studies have attempted to demonstrate that the scenario tests can be scaled down and still provide adequate results [61]. The fire exposure is also scaled down, imposing 40 kW m^{-2} [62] to the façade which is only slightly higher than the peak exposure in SBI [36] described earlier. As with the BS8414 tests commissioned by the UK Government, the system was highly simplified and does not capture critical aspects leading to failure of the system. None of the measurements – including the addition of a calorimeter to measure heat release rate – allow separation of the various materials or component contributions. Assumptions are instead based on the difference in measurements from the nine different systems tested. The tests are not able to discriminate between any of the non-ACP PE systems in any meaningful way. Nonetheless, these scaled down tests are still being provided as evidence to demonstrate that combustible insulation has very limited impact of fire spread [61].

In contrast, other researchers have established that these conclusions are inadequate and the methods are not appropriate [63]. They cite that the constructions tested do not match real buildings in terms of the location of cavity barriers and height of storeys, the lack of window and other penetration details, that pass/fail criteria are not appropriate for the wide range of building types, and that all data should be publicly available. They propose that a new method needs to be developed based on quantified scientific means with improved repeatability and reproducibility. Scenario tests intend to provide a representation of reality but require enormous characterisation to allow extrapolation [25]. Thus, most tests are conducted with systems that are idealised and are by no means a representation of the systems implemented in buildings and therefore do not represent reality. Lane [25] details 15 discrepancies between Grenfell Tower and the BS8414 report provided by the insulation manufacturer. This not only highlights the level of characterisation required, but also that these discrepancies arise due to the idealised nature of the tests which ultimately makes them neither representative nor useful.

Finally, a decision making tool – NFPA EFFECT [64] – has been developed that uses expert opinion to enable performance assessment and decision making in matters pertaining to fire safety of façade systems. Users are able to input details of a building and will receive a corresponding risk rating. However, there is no evidence given to support the rating, and there is no way to understand the basis for how the rating is generated. For example, a different rating will be given depending on whether the wall cavity size is greater than or <75 mm. This is an arbitrary limit based on the expert judgement of the panel of developers, and cannot be interrogated in any way. The tool has been rarely used to aid decision making and authorities have shown no interest in adopting it. The lack of uptake of such a tool represents clear evidence of the current lack of confidence in expert opinion.

3. The current situation

The conclusion of all the work conducted post-Grenfell demonstrated that the existing tools and testing practices are inadequate for the assessment of the performance of modern façade systems. None of the existing tools can reproduce the different phenomena observed, in particular the strongly coupled thermomechanical behaviour that results in deformations, rupture, and complex interactions between combustible and non-combustible materials. Existing standard testing methodologies have proven incapable of delivering adequate, relevant or sufficient information for performance assessment of systems, and

'scenario' tests are not only too complex, lack adequate instrumentation and are too sensitive to construction detailing but more fundamentally cannot recreate the desired conditions or deliver the necessary information for design.

The overall outcome of the aftermath of the Grenfell Tower fire has reinforced the already existing perception that there is an intrinsic problem in the manner in which the construction industry is addressing fire safety [65,66] and the need for a new path. The Warren Centre reports [67] and the Grenfell Phase One report [68] have introduced competency as a new aspect of the problem. The complexity of these systems is such that none of the stakeholders have the necessary skills to address their fire safety. Furthermore, presumptions of competency have been proven flawed with accreditation and certification systems rendered completely inadequate. This was highlighted in Phase One of the Grenfell Inquiry which was focused on the cause and spread of the fire, and the response of the London Fire Brigade. The Phase One report [68] concluded that, despite the well-recognised scenario, firefighters were not able to establish the risk through inspection, could not quantify the hazard during the events, and were not able to implement a response strategy that was effective at fulfilling their obligations to reduce the loss of life.

The complete lack of confidence in our capacity to assess performance has resulted in complete bans on all combustible materials used in façade systems in numerous countries around the world. These bans have been accompanied by other extreme measures like the incorporation of sprinklers in all residential buildings above 11 m (UK) and the introduction of stringent management structures [69]. The cost associated to these measures is very significant, and has created unnecessary challenges for many industries, for example, the timber industry.

The conclusion is that there is a need to generate the underpinning knowledge necessary to properly assess the performance of these systems. The previous sections have reviewed the past and current efforts to understand the problem to emphasise the shortcomings of the current approaches but mainly to determine the appropriate fire safety objectives as well as to extract the information needed to be able to demonstrate – in a quantitative manner – that those objectives have been attained.

The framework proposed thus focuses on two physical phenomena deemed of relevance to the fire safety strategy, (a) the characterisation of the no-fire spread condition and (b) the quantification of fire spread rates. Therefore, for the framework to be able to address the integrity of the performance assessment process, it needs to include the following components:

- (i) Characterisation of all combustible materials for identification purposes
- (ii) Characterisation of all materials to quantitatively determine all properties associated to their combustibility
- (iii) Characterisation of material performance by implementation of bespoke testing and adequate diagnostics
- (iv) Integration of material performance within a framework that enables characterisation of product system performance
- (v) Implementation of calculation methodologies that can enable the incorporation of the product system performance into the assessment of the overall performance of the fire safety strategy
- (vi) Definition and implementation of a competency framework that delivers the certified professionals that have the necessary competencies to conduct an overall performance assessment of the fire safety strategy for buildings with complex building envelopes.

4. Engineering framework

A robust engineering framework has been developed by The University of Queensland in partnership with the Queensland Government to provide the means to evaluate the potential for external fire spread.

This includes the components (i)–(v) described immediately above, to identify materials on buildings, characterise them in a meaningful way to help address building performance, and underpinned by the required competence (vi). The backbone of this framework is a publicly available flammability database, the Cladding Materials Library (<https://claddingmaterialslibrary.com.au> [70]), which contains the underpinning knowledge required to assess façade system performance. All of the test methods used are commonly available to ensure that others are easily able to implement the framework, without the need for highly specialist equipment. This also ensures that existing tools and models can be readily applied.

This paper does not explicitly review the theory associated to the no-fire spread or the calculation of fire spread rates. There is a vast body of literature that describes the different parameters required and, given the many differences between systems or buildings, it will be pointless to create a calculation framework. This is why, instead, this paper introduces a competency framework that should deliver competent professionals capable of using the existing literature and the parameters quantified here for the purposes of a proper risk assessment.

The framework for the library contains two testing protocols. A series of experimental methodologies termed the **detailed testing protocol** is used to determine the complete material properties, thermal properties, and fire performance for a given cladding material. This includes chemical composition; thermal degradation; gross heat of combustion; critical heat flux for flaming ignition; ignition temperature; total heat transfer coefficient at ignition; apparent thermal inertia; time to ignition and residual mass as a function of incident heat flux; heat release rate and mass as a function of time and incident heat flux; effective heat of combustion; and critical heat flux for flame spread and flame spread parameter for both horizontal and vertical orientations. The database currently contains 27 materials and new materials can be added at any time, ensuring that it is futureproof. This number of materials has already been shown to be effective for fire risk assessment in Queensland, and contains materials relevant to other regions and climates. Data is essential in the development, verification and validation of more advanced models currently unavailable to fire engineers, and fundamental towards understanding the interactions of different materials in a system. This database delivers components (ii) and (iii) summarised at the end of the previous section, in a way that they can be incorporated as part of calculations for a system and building described in components (iv) and (v). This protocol requires samples in the region of $1 \times 1 \text{ m}^2$ and consists of:

- (a) Chemical composition quantification
- (b) Thermal decomposition of a material
- (c) Gross heat of combustion
- (d) Ignitability measurements
- (e) Burning behaviour
- (f) Flame spread characteristics

It would be prohibitively expensive for building owners to run detailed flammability testing for all materials on all buildings. Instead, the framework features a **screening testing protocol** where materials on a building are identified with samples of dimensions 10–100 mm. There are only a finite number of cladding materials possible, and this obtains a unique fingerprint for each material. This is then used to cross-reference the database, and find whether the same material already exists. If it does, then the flammability data from the database can be used directly without having to run expensive and time-consuming flammability testing. If not, then the testing can be performed, or other decisions can be taken to decide on how to characterise the fire risk. Alternatively, the decision may be made to simply remove the cladding, at substantial cost. This delivers component (i) detailed in the previous section. This protocol requires samples of approximately 10–100 mm diameter and consists of:

- A. Chemical composition quantification
- B. Thermal decomposition of a material

The **competency framework** is delivered through the development of two Continuous Professional Development (CPD) courses. The first of these ensures that fire engineers have the skills and competency to able to design and assess buildings containing extremely complex flammable façade systems. A second course is also specified for other building professionals to ensure that they also understand key considerations in regards to external fire spread. This ensures that professionals with the necessary skills are delivered and can perform fire risk assessments competently. This delivers the final component (vi) detailed in the previous section.

This whole process enables fire engineers to be able to confidently perform quantified fire risk assessments for buildings with flammable claddings. An abridged version of the framework is described in the following sections. In response to calls for increased transparency and the availability of test reports, all the data is publicly available free of charge, and a number of supporting guidance documents comprehensively describe the background [71], testing methods [72], sensitivity [73] and use of the Library [74].

4.1. Tools & data – The cladding materials Library

The process to use the Library is shown in Fig. 1 and is as follows:

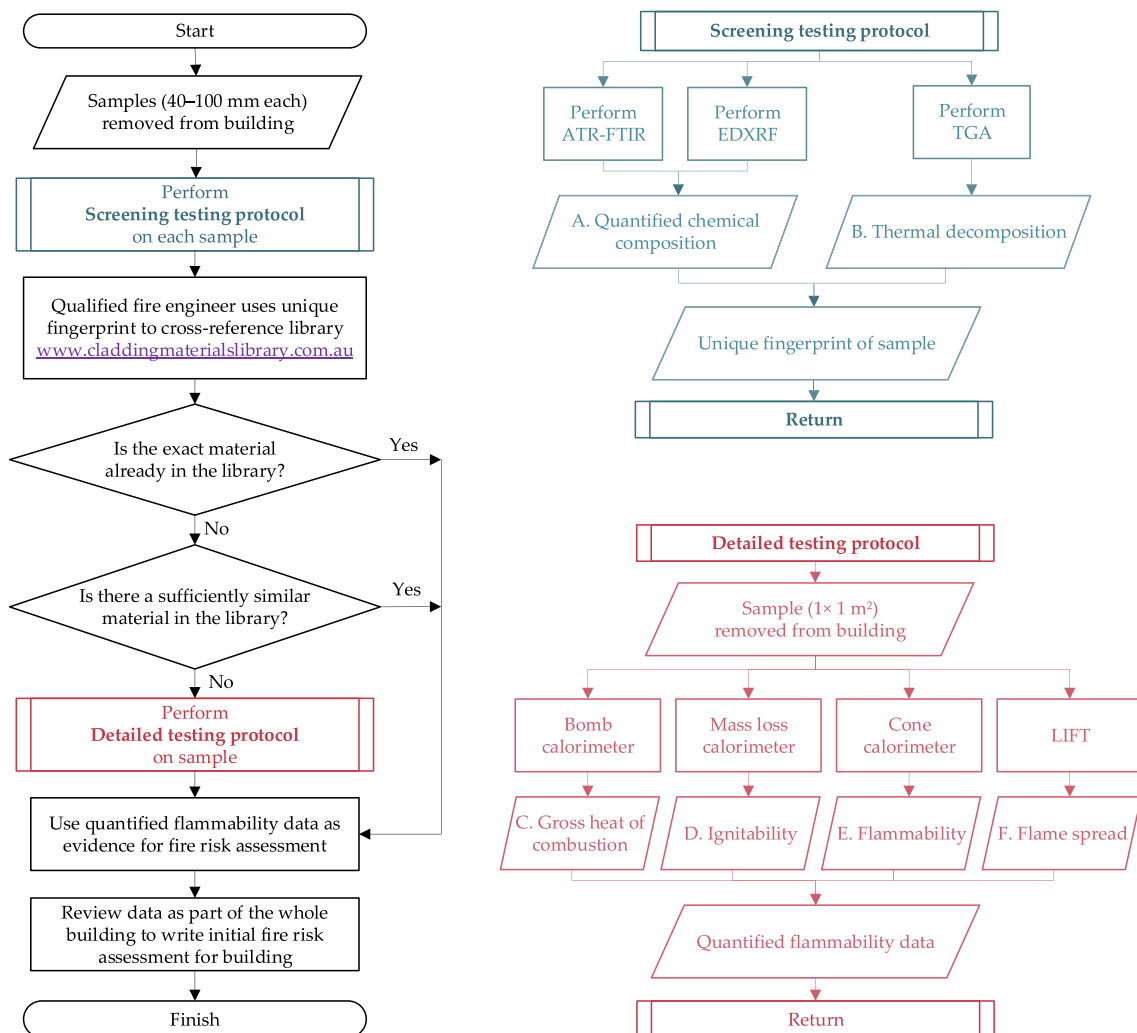


Fig. 1. Process for using data from the Cladding Materials Library.

1. Remove a number of samples from the building as required. Guidance for how many and their locations is available [75]. A sample from each unique material or panel should be taken, and more samples should be taken for taller buildings, larger cladding areas or high-risk buildings such as hospitals.
2. Perform the screening testing protocol to obtain the unique fingerprint associated with a material to be able to cross-reference it with the database.
3. A competent fire safety engineer should identify whether there is an identical material in the Cladding Materials Library [70]. If there is, then the flammability data from the Library can be used for that sample without the engineer having run their own tests to determine the flammability. Details on the required competencies for engineers are described in Section 4.2.1.
4. If there is no identical material, then there are still options that remain:
 - a. Perform a detailed testing protocol to obtain the needed flammability data.
 - b. Exercise best judgement to identify whether the data from another similar material can be used, erring on the side of caution and taking suitable responsibility for the decision [76]. The complexity of fire risk means that the same criteria cannot be used for every material, and the engineer will need to use their judgement and competence to make an appropriate assessment.
5. Alternatively, identify the relevant fire scenario and conduct a large-scale fire test for that building-specific façade system, materials,

geometry, and detailing. It should be noted that this option is far more expensive and requires a huge amount of material to be removed from a building (e.g. approx. 25 m² for BS 8414 [37]) and is only relevant for one specific scenario as tested.

6. If none of these options are feasible, then the material represents an unknown risk and appropriate action must be taken. This may require the entirety of the cladding to be removed as soon as possible, and temporary mitigation measures to be in place until this is achieved.
7. Repeat all the steps above for each sample on the building.
8. Review and investigate the fire safety strategy of the building and write a quantified fire risk assessment specific to that building. This should take into consideration not only the materials but also the response of the overall façade system and the response of the building in the event of a cladding fire.

This process addresses the initial investigation required for a building to assess the relative fire risk of its cladding material. Fire engineers can use this to answer the following questions and make decisions:

- Does this building contain flammable cladding which will overwhelm the fire safety strategy of the building?
- Is remediation required? If so, in what form? Specification should include both long-term and interim measures.
- Is more data required to be able to make a more complete assessment?

4.1.1. Sample preparation

In general, the intent of this framework is to extract fundamental material properties of the core. Every effort is then ensuring that the testing is able to extract representative and relevant properties. As such,

materials containing encapsulation – e.g. metal skins on aluminium composite panels or steel facings on sandwich panels – had this removed so that the core material properties could be determined. Small-scale experimental methods are often not designed for composites or products with heterogeneous composition, as reviewed in detail previously in Section 1.2. As a result, using these test methods on materials for which they were not designed or intended gives little useful information, and do not aid a building assessment. Full sample preparation details are given in the guidance documents [72] with the express intent that other researchers and practitioners should be able to replicate the results without any issue. Sensitivity studies are also available [73].

4.1.2. Testing protocol components

Both the screening and detailed testing protocols are comprised of a number of testing methods or objectives. These have been labelled Parts A to F. The testing conditions are summarised in Table 2 and brief descriptions of the methodologies are given in the bullet points below.

The parameters selected for use in the framework are quantifiable, repeatable and reproducible, and provide the means to evaluate material performance. The extraction of these properties is known to be apparatus or environment dependent but this is still sufficient to assess the relative hazard of each material, especially given the huge variation in upward flame spread e.g. as shown in the data collated by Torero [1]. A review of material property flammability and their application to models is described by Bal [77] and scaling up is reviewed by Torero [78]. Key novelties added by the proposed framework are (a) a robust means of material identification, through the screening testing protocol, and (b) the addition of upward flame spread through modifying a commonly available apparatus. This enables engineers to estimate the relative hazard of each cladding material.

This cross-referencing of the screening protocol to the library data is a critical novel component of the framework that enables building

Table 2
Summary of testing parameters and outputs for parts of the framework.

Framework part	Apparatus	Samples and dimensions	Testing conditions	Outputs
A1. Compound identification	ATR-FTIR	1 sample 15 × 5 × 0.5 mm ³	32 scans/locations 3 locations 4 cm ⁻¹ spectral resolution	Material components (qualitative)
A2. Elemental quantification A (combined)	EDXRF	1 sample 40 mm diameter	Vacuum, standardless method. Ranges: 20 kV – 50s ; 40 kV – 50s ; 50 kV – 100s	Elemental composition (quantitative)
B. Thermal decomposition	TGA/STA	2 samples 10.3 ± 0.4 mg unless otherwise noted 5.2 ± 0.3 mg for wool insulation or sarking 2.5 ± 0.2 mg for foam insulation 1.0 ± 0.1 mg for adhesives	1 test in air; 1 test in N ₂ 50–800 °C 20 °C min ⁻¹ 150 ml min ⁻¹ purge flow 50 µl Al ₂ O ₃ crucibles, no lid	Chemical composition (quantitative) Mass as a function of temperature, <i>m</i> Derivative mass as a function of temperature, <i>dm/dT</i>
C. Bomb calorimetry	Bomb calorimeter	3 samples <1.0 g	Pure oxygen environment	Gross heat of combustion, Δ <i>H_c</i>
D. Ignitability	Mass loss calorimeter	As many samples as needed 100 × 100 mm ²	No ignition within 900s <i>q_{cr}^{''}</i> defined as value halfway ignition and no ignition	Critical heat flux for flaming ignition, <i>q_{cr}^{''}</i> Ignition temperature, <i>T_{ig}</i> Total heat transfer coefficient at ignition, <i>h_T</i>
E. Burning behaviour	Cone calorimeter	6 samples total – 2 samples per incident heat flux, <i>q_{inc}^{''}</i> 100 × 100 mm ²	<i>q_{inc}^{''}</i> = 35, 50, and 60 kW m ⁻² (80 kW m ⁻² was also provided in some cases) Mesh grid in place (25 mm spacing) with retainer frame	Apparent thermal inertia, <i>kρc</i> Effective heat of combustion, Δ <i>h_{c,eff}</i> Heat release as a function of time, <i>q^{''}</i> Mass as a function of time, <i>m</i> Peak heat release rate, <i>q_p^{''}</i> Time to ignition, <i>t_{ig}</i> Mass residue, <i>m_f</i> Total heat released, <i>E_t</i>
F. Flame spread	LIFT	4 samples (2 horizontal and 2 vertical) 600 × 100 mm ²	<i>q_{inc}^{''}</i> = <i>q_{cr}^{''}</i> + 5 kW m ⁻² Preheating time until sample reached thermal equilibrium	Critical heat flux for flame spread, <i>q_{0,s}^{''}</i> Flame spread parameter, <i>Φ</i> Flame velocity as a function of heat flux, <i>V_s</i> Inverse root flame velocity as a function of heat flux, <i>V_s^{-1/2}</i>

owners and engineers to run a limited number of small tests but gain access to a fuller suite of flammability data. This provides the needed flammability data to assess the fire risk associated with upward flame spread. Thus, the chemical composition provided by the screening protocol in itself does not provide the means to perform a fire risk assessment. The chemical composition should only be used to reference the database, and then the flammability data should be used to evaluate the potential for external fire spread. There are some situations where this is not the case e.g., the identification of purely inorganic materials where no further testing is needed or useful. The building fire risk assessment should still consider other risks or possible modes of fire spread.

- **Chemical composition (Part A)** – The chemical composition is an accurate determination of the constituent components of a sample and helps oversimplification into categories such as “ACP FR” (where FR is fire retardant) or “HPL”. A number of chemical analytical techniques can be combined to determine the composition and there is no correct way to obtain this data. For the framework development, qualitative compound identification using ATR-FTIR (Attenuated Total Reflectance Fourier Transform Infrared spectroscopy) according to ASTM E1252 [79] was paired with quantitative elemental identification using EDXRF (Energy Dispersive X-Ray Fluorescence spectrometry) according to ASTM D6247 [80]. The combination of these two techniques enables the accurate identification and quantification of the different components in a sample. This represents one half of the screening protocol. It should be strongly emphasised that the sole purpose is to identify materials to cross-reference with the library, and that the chemical composition alone is not an assessment of material flammability. This should also be remembered when considering the precision of error margins, and a $\pm 1\%$ change in the chemical composition will have no perceptible effect on vertical fire spread on a full building.
- **Thermal degradation (B)** – Thermogravimetric analysis (TGA) or simultaneous thermogravimetric analysis (STA) according to ASTM E1131 [81] provides thermal decomposition of the material as a function of temperature. TGA could be used as a sole means of material identification but the presence of overlapping reactions in complex materials results in difficulty of accurate identification of materials. This data is an additional step in the screening protocol to aid material identification, to improve robustness, and to prevent gaming the system. The lattermost was heavily criticised in construction industry inquiries [65,66]. This also provides some quantified data which can be used by a practicing engineer in an initial assessment, for example, an indication of a possible pyrolysis or ignition temperature based on analysis of the chemical reactions.
- **Bomb calorimetry (C)** – The first component of the detailed testing protocol is the determination of the gross heat of combustion using a bomb calorimeter according to ISO 1716 [33]. This gives an upper-bound limit on the amount of energy that a material can release and can aid in the hazard assessment of the sample. However, it does not inform on the rate at which the heat is released, or on the ignition behaviour of a material.
- **Ignitability (D)** – The critical heat flux can be determined using a mass loss calorimeter according to the process described in ISO 5660: Annex H [82] but without calorimetry. This measures the minimum amount of energy required to ignite a sample – the critical heat flux for flaming ignition – which enables calculation of the ignition temperature [72] according to the classic ignition theory for flaming solids [83] as well as the total heat transfer coefficient at ignition. The ignition temperature can then be used as a means to classify materials according to their ignitability. The risk of ignition is particularly relevant to vertical flame spread, as materials which ignite readily will also cause rapid flame spread. Furthermore, those with a low critical heat flux are more ignitable and thus may represent a greater hazard.

- **Burning behaviour (E)** – The heat release rate and mass loss of a material are critical in evaluating its fire hazard and are some of the most commonly used metrics in fire safety engineering. Standardised data and metrics can be obtained according to ISO 5660 [82]. The use of three radiant heat fluxes for each material also allows determination of the apparent thermal inertia [83] which indicates how rapidly the temperature of a material rises when exposed to a heat source. This enables evaluation of the fire risk associated with cladding materials, and the scale is sufficient that the relative effectiveness of fire retardants and inorganic fillers will be evident. The burning rate is ultimately a critical parameter in vertical flame spread given the direct relationship between flame height and material heat release rate [84].
- **Flame spread (F)** – An empirical flame spread correlation can be obtained using a reduced-scale [85] LIFT (Lateral Ignition and Flamespread Test) apparatus designed in principle with the procedures described in ASTM E1321 [86] and ISO 5658 [87]. A flame spread parameter is calculated which allows assessment of the relative flame spread performance of materials. To obtain the best results, the research methodology from the original literature [88–90] was adopted. As such, there were significant deviations from the standards referenced above [86,87] which are described in detail [72]. Testing was also performed in the vertical orientation to give an assessment of the potential for vertical flame spread. The conditions in vertical orientation change and the flame length overlaps the pyrolysis region which rapidly increases the rate of pyrolysis upstream and thus leads to much larger flame spread velocities. Further analysis will be required in future to correctly utilise this data in a quantitative manner. Flame spread analysis requires input from the other preceding sections. The critical heat flux for flaming ignition is required in order to set the incident heat flux to the sample, as described above. The thermal inertia, ignition temperature, and total heat transfer coefficient at ignition are also required for the calculation of the flame spread parameter.

4.1.3. Initial version of the library

An initial version of the database has been published based on an audit of all publicly-owned buildings in Queensland, Australia. There were 1,095 samples taken from approximately 57 buildings or sites, and a total of approximately 9,221 tests were performed. The samples were taken from all external layers of the building fabric, including underlying insulation and weatherproof membranes. This technique also means that non-ACP outermost cladding layers were captured, such as wood-based materials or polycarbonate façades. The challenges from assessing external wall assemblies are not only limited to ACPs and are instead dictated by both material and system performance.

A total of 88 unique different cladding materials were identified. From these, 20 representative materials were selected to perform the full detailed testing protocol and further determine their heat of combustion, ignition behaviour, heat release, and flame spread characteristics. This number of materials was based on the available time and budget with the possibility of new materials to be added after the conclusion of the initial project. Materials were also selected to have relevance to other climates and construction methods across the world to ensure immediate applicability. Of the 1,095 samples screened, 584 samples had an exact corresponding detailed testing entry in the library. A further 278 samples corresponded to materials that do not require detailed flammability testing, for example, metallic sheets or largely inorganic mineral wools which do not ignite. In total, this means that 79% of samples had exact corresponding entries from the initial library alone.

The initial list of 20 materials was composed of:

- 11 ACPs with varying performance including: 1 predominantly inorganic material, 2 with aluminium sheet geometries bonded by adhesive, 2 predominantly polyethylene-core, 2 with primarily Al-

based FR, 3 with primarily Mg-based FR, and 1 cellulose/phenolic composite;

- 2 remaining cellulosic-based materials including: 1 phenolic/cellulose composite with FR and 1 primarily cellulose-based material;
- 6 insulation materials including: 2 PIR foams, 1 PHF (phenolic) foam, 1 PUR foam, 1 EPS foam, and 1 polyester fibre insulation (PET);
- 1 sarking (weatherproofing membrane) consisting of glass fibre reinforced polypropylene with Al backing.

Stone wool and glass wool insulation were screened and had their heat of combustion determined as part of the detailed testing protocol. The materials did not ignite, and there was little value from further testing.

An initial assessment of these materials and the trends in their behaviour has been performed [91]. ACPs with the same polymer content were shown not to have the same fire performance, as reflected by a 75% increase in peak heat release rate for the same polymer content. This evidence directly contradicts the assumptions made in the existing frameworks described in Section 2 and similar assumptions regarding gross heat of combustion as an indicator of fire performance. Application of a simple upward flame spread model combining ignitability and flammability [84] showed that aromatic materials, including HPLs, have a huge range of performance. Those with high phenol resin content were ranked as least likely to propagate spread, while those with higher wood fibre content would behave in-line with typical cellulose-based charring solids. The model illustrated the stark differences in behaviour between distinct insulations, and that sarking and thin film ACPs (i.e. samples where aluminium profiles are held together by <1.0 mm resin) can yield flame spread, which has not been assessed anywhere else. This forms the basis for additional in-depth analysis. Furthermore, detailed analysis is required to fully assess the fire risk of vertical fire spread for all these materials, especially as part of a system.

Since the completion of the project, a further 7 materials have been tested through the private sector, comprising 3 further ACPs with primarily Mg-based FR, 1 further PUR foam insulation, 1 WPC (wood polymer composite), 1 GFRP (glass fibre reinforced polymer composite), and 1 GFRP epoxy adhesive. There are a large number of Mg-based FR ACPs in the database as the FR is obtained through mining natural minerals and thus subject to large amounts of impurities and differences in composition [73]. The fire performance must then subsequently be characterised to enable adequate assessment of their fire risk. The main Al-based FR, aluminium hydroxide, can instead be commercially manufactured through the Bayer process which consistently produces a purer material (99%) and has near insignificant variation in composition [73]. The addition of the new materials demonstrates that using fire performance as the metric is futureproof, and enables new or innovative materials to be included and can be assessed using the same framework without modification.

4.2. Education and competency – CPD courses

4.2.1. Fire safety engineering professionals

The complexity of the engineering framework requires upskilling building professionals, and thus two CPD courses were developed to achieve this. The first is designed for practicing fire safety engineering professionals and aims to give them the skills and tools to tackle the cladding fire crisis. Participants must have an accredited engineering degree, be a fire safety engineering practitioner with demonstrated experience, or either be registered as a professional engineer or otherwise capable of becoming one. The pathways for becoming a fire safety engineer have been defined [92] as:

- (i) Through formal education and achieving an accredited Fire Safety Engineering degree, later complemented by on the job experience under the guidance of a suitably qualified competent individual.

- (ii) Alternatively, exclusively through on the job experience working on projects to gain the skills and knowledge necessary, and again with appropriate mentorship and supervision.

The extent of this modern problem and the frequency of recent events suggests that many engineers have not been adequately equipped. The complexity of façade systems cannot be underestimated. As such, it is necessary to complement their existing skills or knowledge through additional training. This enables the engineers to be able to use the data output from the database outlined in the previous sections. A five-day full-time CPD was designed to help achieve this and runs annually. It consists of seven modules with the associated learning objectives:

1. Analysis of the fire strategy of a building (4 h) – How to describe the fire safety strategy of a building with respect to external fire spread
2. Fundamentals of vertical flame spread (7 h) – How to analyse the fundamental fluid mechanics, thermodynamics and fire science which drive upward flame spread
3. Review of professionalism and the design process (2 h) – Taking responsibility and how to effectively implement fire safety systems as part of a prescriptive design
4. Curtain wall systems and structural mechanics (1 h) – How to approach different building types and their relevance to external flame spread and how to analyse thermomechanical behaviour in common systems to assess potential for fire spread
5. Cladding Materials Library and laboratory sessions (7 h) – How to use the Cladding Materials Library and correctly interpret the data
6. Reformulation of the fire safety strategy (11 h) – How to create holistic fire safety solutions which connect the fundamental fire behaviour, the complexity of façade systems, and the fire safety strategy
7. Examination (3 h)

It should be noted that the course simply contains robust knowledge which is readily accepted by the community. Whilst it is radical in changing how engineers approach the problem, the solutions themselves are not controversial and do not utilise cutting edge untested research knowledge, for example, the use of advanced modelling of façades is not advocated. The course is nonetheless extremely challenging and is fitting to the difficulty of designing highly complex buildings. Attendance to the course does not guarantee passing, and once complete the engineer should only work within their knowledge and skill level.

4.2.2. Other relevant building stakeholders

A second, less in-depth CPD course was developed to upskill other relevant building professionals and stakeholders who may encounter flammable cladding. The cladding crisis has impacted the whole construction industry including – among others – certifiers, architects, building owners, insurers, builders, contractors, manufacturers, regulators, and other engineers. Firefighters and emergency service workers may also be included in this group.

Those involved in cladding work must understand the limits of their capabilities. For example, an architect should not be responsible for a complex performance-based fire engineering design which they do not understand, and they should not make any unsupervised changes without consultation and approval of someone sufficiently competent. The upskilling of building stakeholders ensures that the information and decisions delivered by fire engineers do not have to be excessively diluted or simplified to be understood. They will also hold sufficient baseline knowledge to identify key hazards e.g. understanding the complexity and risk that flammable cladding adds to a building.

A two-day full-time CPD course was developed for these building stakeholders in partnership with the Queensland Government – Department of Housing and Public Works. There are four modules in the course, where the final two modules act as a basic introduction to fire

safety engineering:

1. Legislative process and requirements – 4 h (delivered by Queensland Government): Interpret the legislative requirements including deciphering the available pathways and identify compliance pathways and the process to consistent routes of product selection, application and approval
2. Interim risk management, referral requirements and process – 4 h (delivered by QFES, the Queensland Fire & Emergency Services): Understand the role of input from the emergency services
3. Fire safety strategies, fire dynamics, and external wall systems – 4 h (delivered by The University of Queensland): Understand basic fire safety principles and considerations in regards to external fire spread
4. Material behaviour, the Cladding Materials Library, and application of data – 4 h (delivered by The University of Queensland) Interpret materials procedures, and protocols relevant to external wall assemblies and apply the legislative requirements for external wall assemblies, including provisional requirements

4.3. Application

4.3.1. Implementation in Queensland

To demonstrate how the framework can be successfully implemented, the process followed in Queensland is outlined in the bullet points below and in Fig. 2. This successful implementation in Queensland also demonstrates the robustness of the framework. Each step has a significant number of technicalities, caveats and intricacies [75] but the information provided here should be sufficient to understand the general process.

The process begins with all buildings undergoing Checklist Part 1 and at each subsequent step the number of buildings being investigated can be narrowed down. Documentation must all be registered with the Government to be stored centrally. This includes record of the building, the owner, any professionals who complete any part of the checklist, and all the required information detailed below. Evidence is required that the individual engaged is competent and able to perform the job, and this varies between each profession. This is a means to improve the quality of documentation on buildings.

- **Part 1 – identify possible flammable cladding:** The first objective is to identify whether a building has any possibility of external fire spread whatsoever. If this possibility exists, then the building must then progress to Checklist Part 2 (and 3) for an investigation and analysis of the materials and the building fire safety strategy. If there is any doubt about whether there is the possibility of external fire spread, then the building must also progress to the next stage. Of the 15 000 buildings in Part 1, approximately one quarter progressed to Part 2 [54]. The person required to perform this work is the building owner, but they may wish to contract the work to a building professional who has more knowledge on materials and on the Checklist process. The regulator has the power to investigate buildings at will

and the answers must be truthful otherwise the owner risks prosecution. The owner – or a designated subcontractor – must specify the function of the building (e.g. hotel, school, etc.), the number of storeys, the total floor area, and the materials present by visual inspection.

- **Part 2 – extent and nature of flammable cladding:** A more thorough investigation is performed, and buildings containing materials of uncertain composition may be confirmed as flammable or not flammable. A registered and competent building professional is required to perform this Part. The professional must state whether there are combustible materials using visual inspection, reviewing building documents, checking possible product substitute, and preliminary sample testing can be performed to aid assessment. Materials with definite (or still uncertain) possibility of vertical fire spread will progress to Part 3.
- **Part 3 – quantified fire risk assessment of building:** The final objective is to provide an initial fire risk assessment for the building supported by quantified performance. All the relevant evidence must be collected, and the assessment must take into consideration the entire fire safety strategy of the building and not only consider the cladding in isolation. The framework detailed in this manuscript supports the assessment performed in this Part and enables estimation of the response of the building. This work may only be performed by a registered and competent fire safety engineering professional. The fire engineer must verify whether an existing performance solution exists, deliver the quantified fire risk assessment of the building and provide evidence to support this, specify whether remediation work is required, and specify whether interim risk mitigation measures are required before remediation is completed.

Following on from Checklist Part 3, a building will have undergone an initial investigation and identified potential remediation. The investigation may find that the strategy or building was sound, and that it is safe with no further work required. In other cases, it will be necessary to improve the safety through risk mitigation efforts. The development of long-term solutions may require additional testing, research, and analysis to form a more detailed and complete fire risk assessment for the building.

4.3.2. Example usage of data from the Library

In Section 3 previously, the required components of a framework to adequately assess buildings were summarised in a bulleted list labelled (i)–(vi). The Cladding Material Library represents parts (i)–(iii), and the process outlined below describes how the quantified material data can be used to provide evidence for risk assessments of external fire spread on buildings. While the framework is open-ended, some suggestions are given here for some possible ways that the data can be used at present.

The performance assessment of any product, whether it is through the Cladding Materials Library or any other means, needs to first take into consideration the requirements of the fire safety strategy. Different approaches towards the fire safe design of tall buildings will impose

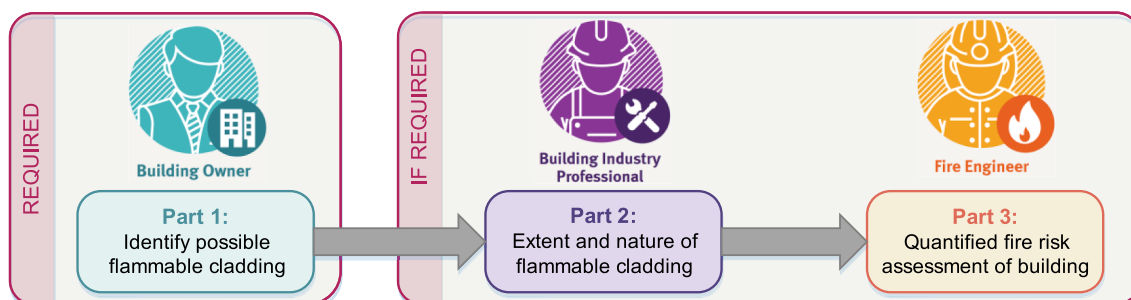


Fig. 2. Illustration of the different parts and parties involved. Adapted and reproduced with permission from the Queensland Government – Department of Housing and Public Works.

different requirements for the products, with some strategies requiring the ‘no vertical fire spread’ conditions while others allowing for ‘bounded’ fire spread rates. Given the specific building requirements then the results from the library can be used in different ways.

Materials can then be classified according to their relative performance from the bench-scale data. This may be based on the ignition data, burning behaviour, the flame spread characteristics, or any combination of these.

The simplest method to achieve this would be through correlating the performance to existing large-scale data. For example, by identifying materials in the library which have corresponding large-scale data, and then using these as benchmarks. A material in question could be identified as better, the same, or worse (based on the classification above) when compared with a benchmarked material. From this, a competent engineer can understand whether a material is liable to support flame spread and provides a rough quantification of fire spread rates and make decisions based on this.

For this, there needs to be the large-scale data available. Two sources of this would be comparison with a database of real fires, or through existing large-scale test data. The level of data available from real fires, including material identification, tends to be severely limited by available information and its detail and reliability. Flame spread rates for various buildings have been estimated by Torero [1] with substantial uncertainty margins. This may serve as an estimate for the flame spread rate in a real building for a given material, but clear justification will have to be given for why a specific value was selected.

The main sources of large-scale test data are the UK Government-BRE BS8414 tests following the Grenfell Tower fire [48] and the FM Global 4880 tests [41]. Both test series focus predominantly on ACP and insulation combinations, with one or two examples of HPLs. Other large-scale data may be available in journals [62,93] but the limited results presented in these publications may not be adequate to make a comparison. In each case, the assessment should be based on the performance of the materials and the system as interpreted by a competent engineer.

More fundamental approaches that can be used to assess the performance of the materials could be according to heat release as is given by McLaggan et al. [91]. Using the linear flame height approximate developed by Saito et al. [84], the heat release rate can be directly correlated to fire spread rates. A more explicit quantification of vertical fire spread has also been shown to be possible when adding the results of the upward flame spread experiments [94]. Needless to say, these extrapolations do not include all relevant physical phenomena, and therefore they are complex in their interpretation and require very conservative application.

A simple approach is to establish products which would clearly violate the goals defined by the fire safety strategy by concluding that they will lead to fire spread that monotonically increases with scale attaining unacceptable values within the scale of the present tests.

Given that these relative classifications are still based on bench-scale data, they most likely will not provide precise real building behaviour. Thus, conservative interpretation will still be needed.

5. Discussion

5.1. Current solutions using the framework

The database represents a tool which forms a useful component of an engineer’s toolkit. At present, knowledge of the fire behaviour of complex flammable façade systems is extremely poor. The approach promoted in this framework is the use of quantified evidence and the use of competent professional judgement.

This means, based on current knowledge, that the possible solutions using the database are still highly conservative and are not simply a pathway for implementation of innovative materials or systems. The use of the Library is not merely justification to use combustible materials

where desired. When compared with prescriptive options, the solutions will often appear similar and will lead to the use of non-combustible materials. The key points here are:

1. The solutions are backed up by quantified fire performance evidence and are not based on seemingly arbitrary limits which may change over time and are only relevant for some materials in some circumstances.
2. The framework keeps the door open for being able to safely develop façade solutions using novel products which do not currently fit within existing classification systems in the future. As knowledge progresses, the ability to design safe quantified wall systems will also improve. New materials and new systems will be able to be incorporated, which would not otherwise be possible.

5.2. Terminology – material, product, and system

In this paper, *material* refers to a single element which does not include any encapsulation. For ACPs, this refers to the core, and the metal skin is removed (Fig. 3). A *product* refers to a composite element which may contain multiple components, for example, the ACP with both the core and the bonded metal skins would be considered a product. Finally, a *system* is a collection of products (or materials) which may be combined in a number of ways. These systems would also typically include weatherproof membranes, fastenings and fixings, and connection to a substrate or structure. For clarity, these are not shown in Fig. 3. The term ‘external wall assembly’ is also sometimes used to mean system. The Library focuses on ‘material’ scale to provide an upperbound solution to the problem, and additional work is required to investigate product and system scales more thoroughly.

6. Conclusions

- The Cladding Materials Library framework provides quantified flammability data as the underpinning knowledge required by engineers to estimate upperbound values for external fire spread rates in buildings with flammable claddings. Testing provides rapid and reliable identification of materials, and the data is used to support a quantified fire risk assessment of a building. The data includes chemical composition, thermal degradation, heat of combustion,

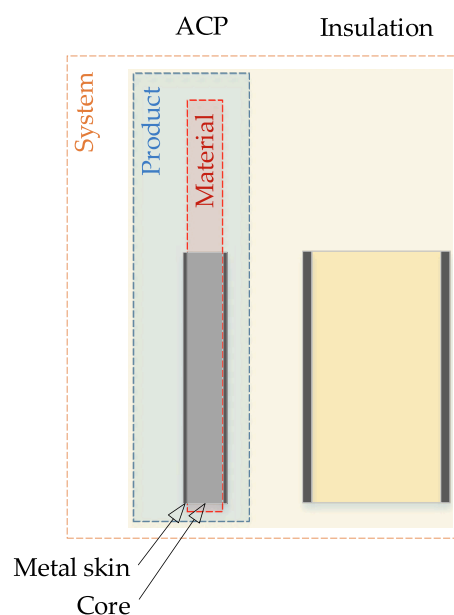


Fig. 3. Diagram showing the use of terminology in a façade system. The insulation is not fully annotated.

ignitability characteristics, flammability and burning behaviour parameters and a determination of the flame spread parameter.

- Compliance testing and compliance-based frameworks are not suitable for evaluating product systems. They cannot cope with the extremely high levels of complexity in façade systems, are not futureproof, and the performance of *products* cannot be ascertained through misapplication of *material* testing. This is especially problematic in a modern, ever changing world where new materials and systems are constantly developed which do not fit into rigid frameworks. Performance-based solutions in these cases are a must and the only viable pathway for complex buildings.
- The screening protocol defined in the Cladding Materials Library delivers a rapid cost-effective means to assess the flammability of building samples through cross-referencing with the flammability database. Documentation in existing buildings is not adequate and this screening protocol is required to satisfactorily identify materials and avoid this issue.
- Upskilling of the industry is critical in delivering adequate solutions. Without this, building professionals cannot understand the fire safety considerations of external wall assemblies, and practicing fire engineers often lack the expertise to confidently design for external fire spread. The framework can only be applied where the industry is sufficiently trained and competent.
- The Cladding Materials Library is a tool which has great benefits but has limitations. It is not a means to automatically fix the cladding crisis. It provides the basis to make informed decisions, and acts as the foundation for a ground-up approach to understanding façade fire spread. Engineers must still exercise their best judgement and use it as a tool to enhance their decision-making.
- This framework philosophically acts as an exemplar for how fire safety engineering can be executed. The quantity and configurations of materials are known, as well as their fundamental material properties and fire performance over a range of conditions. This is conceptually similar to the approach proposed by Emmons [76] and can be applied to non-cladding cases.

CRediT authorship contribution statement

M.S. McLaggan: Conceptualization, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration. **J.P. Hidalgo:** Conceptualization, Methodology, Software, Formal analysis, Resources, Data curation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **A.F. Osorio:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Funding acquisition. **M.T. Heitzmann:** Conceptualization, Methodology, Validation, Formal analysis, Supervision, Funding acquisition. **J. Carrascal:** Validation, Resources, Investigation, Supervision. **D. Lange:** Conceptualization, Methodology, Funding acquisition. **C. Maluk:** Conceptualization, Methodology, Funding acquisition. **J.L. Torero:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.conbuildmat.2021.124301>.

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