VALIDATING FDS AGAINST A FULL-SCALE FIRE TEST

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ABSTRACT

An investigative study was performed using the experimental data from a full-scale test on a BS8414-1:2015 [1] fire test rig in the UK. The BS8414-1:2015 test is a fire test method for external façade systems where a fire is simulated to have breached through an orifice such as a window and then spread up the external face of a building. Here, the reference test case is an assessment of an external walling system that was carried out by the British Research Establishment (BRE) and was commissioned by the UK authorities (Department for Communities and Local Government, DCLG) as part of the more comprehensive, post-incident investigation into the Grenfell Tower fire. In June of 2017, a full height fire occurred at the Grenfell Tower, a residential building in the Borough of Kensington, West London. The study here designed a model in Computational Fluid Dynamic software (Fire Dynamics Simulator (FDS 6.2.0) [2]), applying the following surface backing inputs to the FDS model; SURF BACKING='INSULATED', SURF BACKING='EXPOSED' and SURF BACKING='VOID'. The temperature profile given in the report of the original BRE-DCLG Fire Test data is replicated in FDS 6.2.0 and the different FDS input backing settings compared. The BRE-DCLG report gives temperature readings at different depths within the material, allowing a comparison in FDS with the conductive heat transfer. This project forms part of a continuing research project being conducted at the University of Leeds to computer model external fire spread in tall buildings.

1. INTRODUCTION

The use of advanced computer models for the analysis of building performance and of evacuation scenarios in tall buildings is becoming an increasingly important area of research. As the global trend for building height (and occupancy numbers) increase, a full-scale, simultaneous evacuation becomes less applicable, and a bespoke building strategy, which should offer protection to the occupants, is designed accordingly. However, when a fire has the potential to aggressively extend to the full height of a building, thereby passing the specific design features, it becomes more difficult to design and model according to the followed principles for building performance or tenability criteria [3] [4]. Potentially full height fires are occurring around the world, many with significant impact. The Grenfell Tower fire (London, UK) in June 2017 is one such example where the loss to life 72 persons was [3]. The public enquiry progresses, but it is currently accepted that a failure of the external walling system to perform as it had been designed contributed to the full height fire dynamic that was evident at this incident as with many others. The research here concentrates on the following areas. An investigation study in FDS is performed on the performance of external walling systems using experimental data from a collection of full-scale fire tests conducted at the BRE [2]. Attention is focused on the movement of heat through the external walling system and how best to manage the conductive heat flow between each material layer, in FDS.

1.1 Current Program of Research

The investigation herein forms a segment of a Post Graduate Research program being conducted at the University of Leeds in the UK. That research project aims to understand better how a fire might potentially spread up the external face of a tall building, in the external walling system or facade.
The targets for the research are summarised as follows:

- Fire testing of external walling materials, conducted at the University of Leeds, then replicate the test results in FDS 6.2.0.
- Quantify the Heat Release Rate (HRR) of a full height fire. Determining if there is a correlation between the visible flame height of a fire height fire and the heat release rate.
- Use CFD (FDS 6.2.0) to accurately model the conditions that are evident during a full height fire.
- Assess the current fire test standards for external walling systems against actual fire conditions in tall buildings.
- Design evacuation models that can be applied to the conditions of a full height fire at the building including a simultaneous evacuation of buildings not designed for such a procedure.

2. BACKGROUND

2.1 A Potentially Full Height Fire

The term Full Height Fire [3] describes a specific fire-based phenomenon. Evident in tall buildings, the fire can spread from the point of ignition to then potentially involve the full height of the building by;

I. External floor-to-floor travel.
II. Internal fire spread: ineffectual compartmentalisation.
III. Combustible external surfaces.

Typically, the fire is started or spreads to an area on the external face of the building. A common characteristic is then for the fire to spread aggressively up the external face of the building, in many cases, surpassing the fire precautions that are installed in that area.

2.2 Grenfell Tower – West London June 2017. Case Study.

Seventy-one people died, and scores of residents were forced to make an evacuation after a massive fire engulfed a residential building in West London [4]. The Grenfell Tower, a 27-storey tower block in Kensington, was the location for an incident that took place on 14 June 2017. At the time of writing this report, the public enquiry is running. The evidence available for this incident would suggest that the tower was affected by a full height fire.
Below, is what is currently known of the incident.

2.2.1 The tower geometry and construction

Grenfell Tower was built in 1974 by Kensington and Chelsea London Borough Council.
In 2016 the building underwent a period of refurbishment as part of a project to improve the housing estate [4]. The work included new exterior cladding, a replacement to the windows and the communal heating system for the building. The cladding used at the tower was a product named Celotex 5000 [5]. The lowest four levels of the building were remodelled to create seven additional homes and improvements to the shared, communal facilities. At the time of the incident in June 2017, there were 129 flats across 21 residential floors and three levels of mixed-use [4].
The flats are each located around a central core, and this acts as a protected escape route. There is a high degree of compartmentalisation between each of the flats and between the flats and the stairs. The evacuation policy which is installed at Grenfell Tower is that of most of the residential building located across the UK [7] [8]. The building is designed around a ‘stay put’ policy. The way in which a stay put policy works is that should a fire occur in a flat, the occupants of that specific flat alone would

evacuate to the central stair core and then down to ground level. The remainder of the building would stay in their dwelling. The fire alarm systems are not interlinked so the rest of the building would not necessarily be made aware of the fire-related incident. Due to the high degree of compartmentalisation between the flats and the stair, a fire in a flat would remain in the flat of origin and not affect the stairs.

Figure 1: Grenfell Tower: Soon, following the full height fire incident June 2017

The fire was seen to raise from the fourth floor to most of the northern face of the tower. From initial detection at around 0100 BST until 0130 BST the fire managed to engulf one entire face of the building, a full height fire. The fire then began to work horizontally, and by 0300 BST the two adjoining faces of the building were entirely ablaze. By around 0400 BST of that same morning, the fire had reached around the entire external face of the building. The entire external face was ablaze.

The fire service first arrived at a point where the fire involved one face and was rapidly growing. The difficulty in this situation was that the fire spread was so rapid and so vast that firefighting operations were complicated. Once a full height fire begins to take hold it is not yet known how to extinguish or contain a fire such as this. The policy for such a building was for the residents to stay put. The Fire and Rescue Service personnel were telling the occupants to stay in their dwelling. The call to evacuate the residents came at 0400 BST. The difficulty in evacuating is that the central stair core had become compromised and heat with smoke was evident throughout the building. The residents were now trapped in their dwellings and waiting for the Fire & Rescue Service to rescue them. This rapid, external fire spread through the external walling system, is a characteristic of a full height fire.

2.3 External Wall Systems. The Construction

The external walling system installed at Grenfell Tower is characteristic of many such systems around the world [6]. Metal composite claddings are typically thin section panels also known as Aluminium Composite Material (ACM). Stereotypically, they consist of two 0.5 mm thick aluminium sheets with a core material sandwiched between. The core material thickness ranges from 2 -5 mm thick. The core material is often either polyethene or a mineral filled core which typically consists of polyethene with a percentage of mineral filler. A high ratio of mineral filling provides a significant improvement in fire performance. The surface is typically coated with a fluorocarbon surface coating in a range of different colours. These panels are significantly less expensive than solid metal panels at a thickness required to achieve the same flexural stiffness.

3. METHODOLOGY

The approach of the investigation study is first to determine and extract experimental data from the selected full-scale BS8414-1 fire test conducted by the BRE-DCLG [4] in the UK. The fullscale fire test was after that simulated in FDS 6.2.0 in order to validate the CFD-software against the temperature profile collected from the full-scale testing.

Additionally, three FDS models are designed with different surface backing functions to compare the heat transfer through all aspects of the external walling system. The walling in each otherwise identical FDS model conformed to either;

- SURF BACKING='INSULATED'
- SURF BACKING='EXPOSED'
- SURF BACKING='VOID'

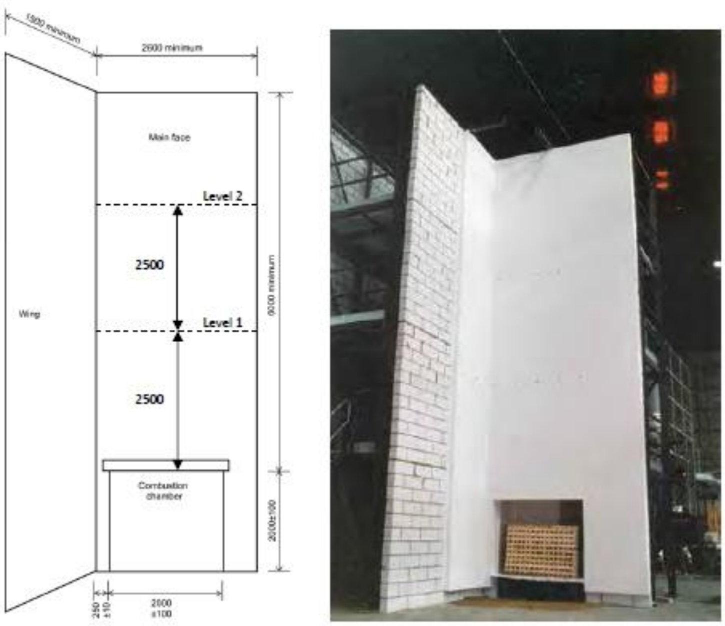

Figure 2: BRE - Post Grenfell Tower, BS8414-1 rig setup

4. EXPERIMENTAL SETUP

4.1 Testing Setup – BS8414-1:2014

BS 8414:2015 Part 1 [1]and Part 2 [7] were designed and developed by the British Research Establishment (BRE). 8414-1:2015 is a full-scale fire test for non-load bearing external cladding systems which are to be installed onto the face of an external wall. The tested is aimed at demonstrating the effects of a fire which has broken through a window. The test rig is designed into an L shaped configuration, and the rig is constructed from concrete with a substrate for installing the test material on to. The test wall extends to beyond 6m in height from the window. The main wall is at least 2.6m wide, and the adjacent wall is at least 1.5m wide. The window opening is placed at the foot of the construction and is 2m wide by 2m high. A typical fire source is a timber softwood crib of 50mm x 50mm arrangement of sticks. The crib is placed directly below the soffit of the test façade. In this arrangement, there is a heat output of 4500 MJ over 30 minutes and a peak heat release rate of 3+0.5 MW.

During the test, the temperatures are measured at the external surface of the façade and 2.5m above the window soffit (Level 1) and 5m above the window soffit (Level 2).

30 minutes after ignition, the fire source is then extinguished. Measurements continue to be taken for a total of 60 minutes or until any flaming stops. Key observations are taken to the flame spread pattern on all surfaces including any cavities. Also recorded are the extent of the burn-away or detachment of the cladding including any partial collapse.

4.1.1 Post examination for BS8414-1:2015

The material is tested once it has cooled and within 24 hours of testing for damage and delamination but not for smoke staining and the following aspects are then assessed;

- The extent of flame spread over the surface of the cladding system in both a horizontal and vertical direction.
- The extent of flame spread and damage within any intermediate layers in both a horizontal and vertical direction.

The performance criteria and for the failure of a test is defined in BR135 [8] and is as follows;

- The fire spread starts time defined as the time when the temperature measured by an external thermocouple as Level 1 exceeds 200^0C above ambient.
- A failure occurs due to external fire spread is determined when an external thermocouple at Level 2 exceeds 600^0C for at least 30 seconds within 15 minutes of the fire spread start time.
- A failure due to internal fire spread is determined when any internal thermocouple at Level 2 exceeds 600^0C above ambient temperature for at least 30 seconds within 15 minutes of the fire spread time.

4.2 Grenfell Tower Testing

Following the fire at Grenfell Tower in London on 14 June 2017, the UK Government established an independent Expert Advisory Panel to advise on an immediate measure that could be put into place to make tall buildings safer. A series of full-scale tests by BS8414-1 [2] was to be carried out as part of this recommendation.

The results of the tests are used to place the materials into a category as described in Table 1 and further described below;

Table 1: Results taken from the BRE-DCLG [3], BS8414-1 Testing of external walling systems

Report Number	Test Type	Calorific value (MJ/kg)	Category
1. B137611-1037 (DCLG test1)	Polyethylene (PE)	46.3	3
2. B137611-1037 (DCLG test2)	Polyethylene (PE)	46.3	3
3. B137611-1037 (DCLG test3)	Fire retardant Polyethylene (PE)	13.8	2
4. B137611-1037 (DCLG test4)	Fire retardant Polyethylene (PE)	13.6	2
5. B137611-1037 (DCLG test5)	Limited combustibility mineral filler	2.4	1
6. B137611-1037 (DCLG test6)	Limited combustibility mineral filler	2.3	1
7. B137611-1037 (DCLG test7)	Fire retardant Polyethylene filler	13.7	2

Where:

1. Category 1. This means that the result is in line with the requirements for a material of limited combustibility (calorific potential <3 MJ/kg).
2. Category 2. This means that the results do not meet the requirements of Category 1 but that it does have some fire-retardant properties (calorific potential > 3 MJ/kg and <35 MJ/kg).
3. Category 3. This means that the result does not achieve the requirements of Category 1 or Category 2 and that it has no flame retardant properties (calorific potential >35 MJ/kg

Furthermore, the advice given by the Department for Communities, and Local Government [2]offers the view that a cladding material which is given either Category 2 or Category 3 in the screening test would not meet the requirements for limited combustibility set out in Approved Document B guidance.

5. FDS SET-UP

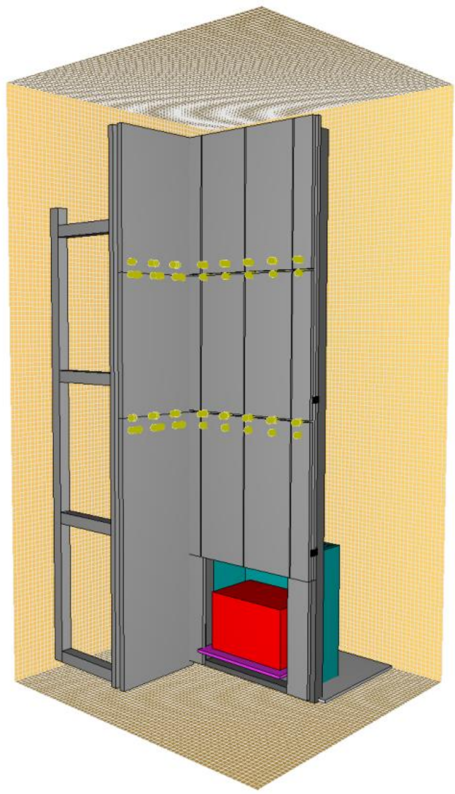

Figure 3: Three-dimensional representation of FDS model

The model in FDS was built using the geometry corresponding to the set-up used for the BRE-DCLG-1 testing. The three-dimensional image for the reference test in FDS is shown in Fig.3

A key aspect when designing the FDS model is that the original test data has thermocouples to the external face of the test rig and in the cavity behind the cladding and the rear insulation. Therefore, to accurately replicate the model, it is critical that the heat flux to these areas be also correct.

5.1 The Design Fire

A surface of obstruction was given a Heat Release Rate Per Unit Area (HRRPUA), and this, combined with the ramping factors of FDS gave the curve of Heat Release Rate.

In the BS8414-1:2015 [1] test, the wooden crib is designed to generate 4700 MJ of energy over the 30-minute duration with a peak heat release rate of 3000kW+/- 500W.

This gives an HRRPUA of 2000 kW/m^2. [10]

The fire reaction was set to match that of a pine wood fire; this includes the heat of combustion is set to 1.45E4 kJ/kg. This is in keeping with the stoichiometric reaction for wood.

5.1.1 Measurement devices

At points in the FDS model, corresponding in geometry to the original BRE test rig set up, temperature measuring devices are installed into the FDS simulation to be able to collect the temperature profile. Default input thermocouples are installed at 2.5m above the combustion chamber for Level 1 and a further 2.5m above Level 1, creating Level 2. The devices are also placed 50mm apart from each other to create a spread across the testing rig. See Fig 3. Also, at the same location within the FDS model, further measurements devices of:

- Adiabatic surface temperature (T_{AST})
- Convective heat flux ($\dot{q}_c^{"}$)
- Wall temperature (^{0}C)
- Back wall temperature (^{0}C)
- Inside wall temperature (^{0}C)

The additional devices are to first gauge the heat flux performance of the external walling system during the fire testing. Secondly, the temperature of the original BRE-DCLG fire test was taken from the external aspect of the wall, from inside the cavity between the external face the insulation and in the insulation its self. The additional devices allow for a more thorough temperature assessment of the obstruction.

5.1.2 Layered materials in FDS

If an obstruction in FDS is one cell in thickness or less with gas cells on both sides, applying the attribute BACKING='EXPOSED', then FDS calculates the heat conduction through the entire thickness of the obstruction [2], and it uses the gas phase temperature and heat flux on the front and back sides for boundary conditions.

To match the configuration of the external walling system, layered material is used in FDS for the obstructions that become the external walling systems. The set-up for the wall is shown in Table 2. A difficulty in FDS is that the model is reacting first with the outer aluminium layer, slowing pyrolysis. Therefore, the material properties of the front face were altered to match that of polyethylene as this was found allow the propagation of the fire up the external face.

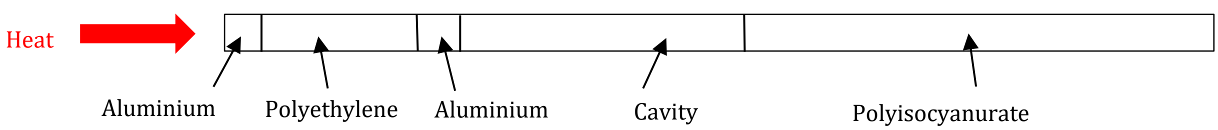

Figure 4: Cross section of the external walling system with materials

Table 2: External walling material as configured in FDS

Material composition	Thickness (mm)	Ratio
Walling system front face		
Aluminium	0.5mm	1.0
Polyethylene (PE)	3.0mm	1.0
Aluminium	0.5mm	1.0
Walling system rear aspect		
Air	50mm	
Polyisocyanurate	70mm	1.0
Total material thickness	**70 mm**	

Therefore; the thickness of the defined obstruction in FDS (the cladding) determines that the cell size need be more than 0.08m and the D*/δx ratio of 2 gives a cell size of 0.08m. The input parameters are described in Table 3.

Table 3: Mesh sizes and geometry in the FDS model

Grid size (m)	Domain size (m)	Total number of cells	Mesh resolution D*/δx
0.08	5.5 x 10.2 x 5.0	552,069	2

5.1.3 Conduction through an obstruction

To measure the passage of heat through the external walling system; the arrangement in FDS needed to include a set-up that would facilitate heat passing from the front face and reaching through to the back wall. FDS only performs a transient, one-dimensional aim of heat transfer [10]. For most fire simulation situations, this is a computationally fast and appropriate approximation.
The convective heat flux is given by Equation 1.

$$\dot{q}_c'' = h(T_g - T_w) \qquad \text{Equation 1}$$

Where:
h = convective heat transfer
T_g= gas temperature
T_w= surface wall temperature

The radiative heat flux here is a function of radiation intensity and the geometry of the obstruction. Where the radiation shape is unity, the radiative heat flux is given by Equation 2.

$$\dot{q}_r'' = \varepsilon\sigma(T_w^4 - T_a^4) \qquad \text{Equation 2}$$

Where:
ε= emissivity
σ= Stefan-Boltzmann constant (5.670x10-8 W/m²·K⁴)
T_w= wall temperature
T_a= ambient temperature

For steady-state heat conduction through a uniform material with no internal heat generation, the convective heat flux is given by Equation 3.

$$\dot{q}_{conduction}'' = \frac{-k}{thick}(T_{back} - T_{front}) \qquad \text{Equation 3}$$

Where:
k= conductivity
$thick$= thickness of the material
T_{back}= wall temperature (back)
T_{front}= wall temperature (front)

Equations 1,2 & 3 (above) are used here to calculate the balance of energy at the surface of the obstruction used in the FDS model for the external walling system [10].
In FDS, the back side of the surface can have three boundary input conditions.

1. Insulated. There is no heat loss from the rear of the material.
2. Void. The obstruction is open to ambient conditions with radiative and convective heat fluxes removing heat.
3. Exposed. Heating the front of one surface would result in raising the temperature of second, parallel surface. However, the “Exposed” option is only valid for obstructions that are less than or equal to one cell thick.

An FDS Model was designed to run each of the three input settings. Each model was identical, except for the Surface/Surface Props which was changed for each.

5.1.4 Transient conditions

To verify the transient heat condition calculation, the transient, one-dimensional heat conduction into a semi-infinite solid equation is used. This solution will be valid while the rear surface remains at the initial temperature. This can be seen in Equation 4.

$$T(x,t) = T_0 + (T_i - T_0)\mathrm{erf}(\frac{x}{2\sqrt{\alpha t}}) \qquad \text{Equation 4}$$

$$\alpha = \frac{k}{\rho c}$$

Where:
T_0= boundary surface temperature
T_i= initial temperature

If the surface is exposed to constant heat flux, the solution is given by Equation 5

$$T(x,t) = T_i + \frac{2\dot{q}''\sqrt{\alpha t/\pi}}{A}\exp\left(\frac{-x^2}{4\alpha t}\right) - \frac{\dot{q}''x}{A}(1 - \mathrm{erf}(\frac{x}{2\sqrt{\alpha t}}) \qquad \text{Equation 5}$$

6. RESULTS

In this section, the critical results from the simulation performed as described in the FDS setup are presented.

6.1 Grenfell Tower – DCLG Test 1 Polyethylene

For the comparison study, the experimental results are taken from the BRE-DCLG-1, Polyethylene cladding core test [3]. Thermocouple readings from the original tests are used to form a temperature profile. Also, observations were made and recorded during the original test, a summary of which are in Table 4.

Table 4: Observations from the BRE-DCLG commissioned testing of the polyethene cladding

Parameter	The result of the Grenfell Test
Start Temperature (T_s)	18.4
Start Time (t_s)	130 seconds after crib ignition
Peak temperature/time at Level 2, External	813.9^{0}C at 390 seconds after t_s
Peak temperature/time at Level 2, Cavity	410^{0}C at 380 seconds after t_s
Peak temperature/time at Level 2, Insulation	218^{0}C at 380 seconds after t_s

Here, BRE-DCLG Test 1, was terminated at 390 seconds after t_s and did not run for the full 1800 seconds as prescribed in BS8414-1. The reason for the stoppage was that the threshold of the test parameters was surpassed. Level 2, centre-line, external thermocouple (1029-C) was at more than 600^{0}C for more than 30 seconds, thus failing the test.

6.1.1 Temperature Comparison BRE Test Results with FDS Model – External Temperature

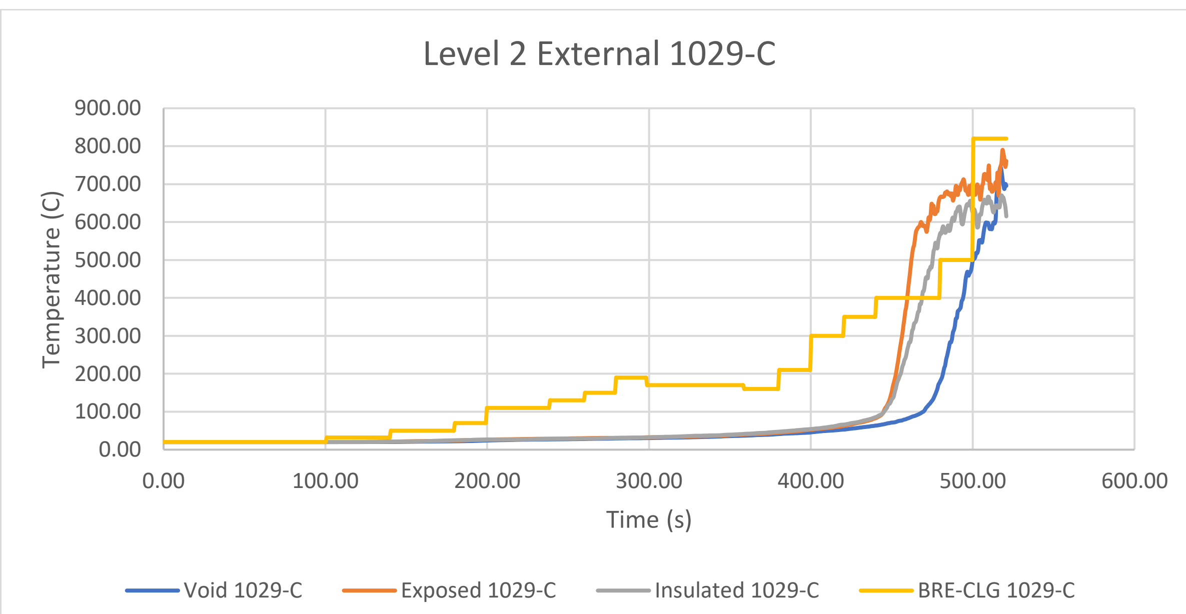

Figure 4: BRE-DCLG-1 test data. An external thermocouple at Level 2 in comparison with FDS models

A comparison of the temperature data received from thermocouple 1029-C (centre-line, external, Level 2) during the BRE-DCLG Test case and the simulated thermometers in FDS are presented in Figure 4. A good agreement is in order between the test data and the FDS models.

The early temperature indication of the test data is however not picked up in any of the FDS models, and only the Exposed-FDS model goes on to reach a temperature close to that of the original test.

6.1.2 Temperature comparison BRE Test Results with FDS Model – Cavity Measurements

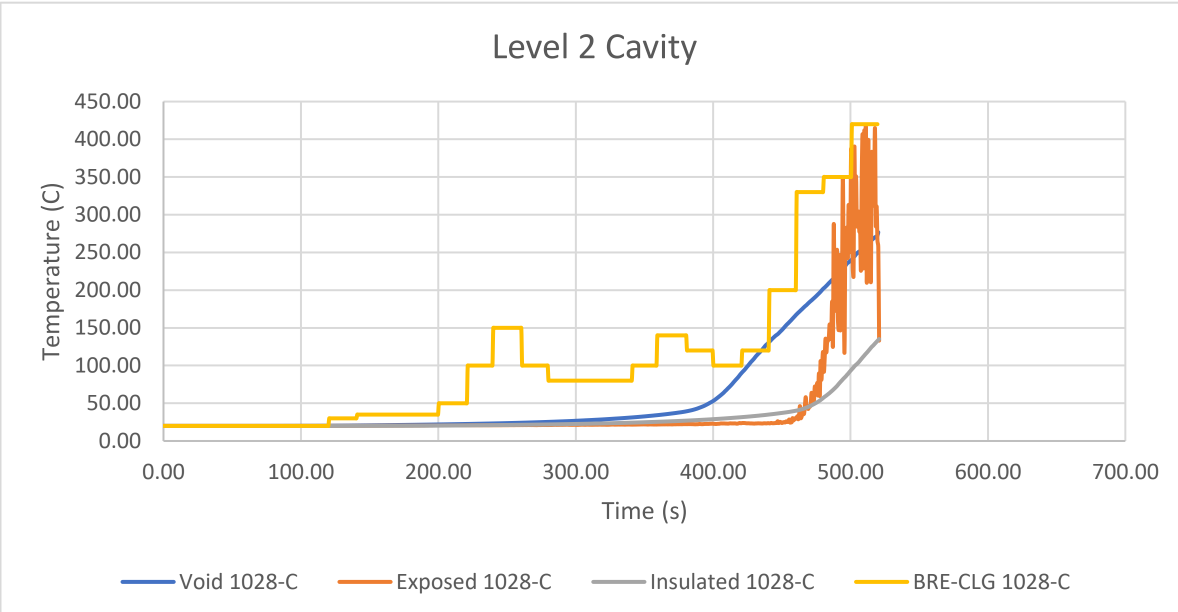

Figure 5: BRE-DCLG-1 test data. Cavity thermocouple at Level 2 in comparison with FDS models

A comparison of the temperature data received from thermocouple 1028-C (centre-line, cavity, Level 2) during the BRE -DCLG test case and the and the simulated thermometers in FDS are presented in Figure 5. The agreement is less so, between the test data and both the Exposed-FDS and Void-FDS models. Again, the Insulated-FDS model is not well matched to the original test data.
Here, both the Exposed-FDS model and Void-FDS model are in partial alignment. However, there is in the region of 100^{0}C difference between those FDS models and the BRE-DCLG test data.

6.1.3 Temperature comparison BRE Test Results with FDS Model – Insulation Measurements

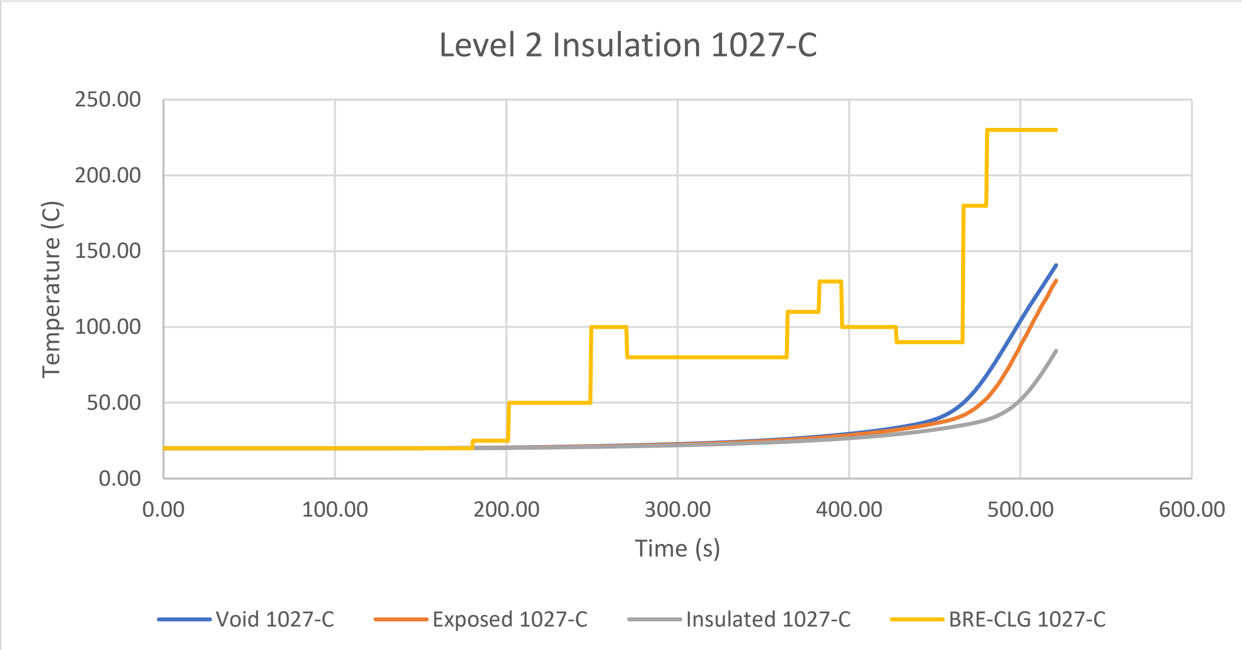

Figure 6: BRE-DCLG-1 test data. Insulation thermocouple at Level 2 in comparison with FDS models

A comparison of the temperature data received from thermocouple 1027-C (centre-line, insulation Level 2) during the BRE-DCLG Test case and the simulated thermometers in FDS are presented in Figure 6. There is a lesser agreement in order between the test data and both the Exposed-FDS and Void-FDS models here. There is the potential for greater error when measuring the insulation as the location of the thermocouple in the original test is not precisely known. The Insulated-FDS model is not well matched to the original test data.

7. CONCLUSION & DISCUSION

In this paper, the results of BS8141-1:2015 fire testing were analysed and reproduced in an FDS model. The input data was taken from the BRE-DCLG fire test of external walling systems which was commissioned during the inquiry of the Grenfell Tower fire, London 2017. Three FDS models, each with different input setting for the surface backing were designed.

The FDS model was used to compare the different methods of heat transfer through a substantial obstruction, the walling system.

Fire spread rate, surface temperature, mass loss rate and heat release rate were analysed. The main conclusions are as follows:

First, there is a good relationship between the Void-FDS model and the Exposed-FDS model. The external thermocouple test result is also in proper alignment with the Void-FDS and Exposed-FDS models.

Secondly, there is less relationship between the test data for the Insulation and the Cavity measurements. The exact location of a thermocouple within a solid insulation object is more difficult to duplicate in a post-test, FDS model and a small change in location may have a significant impact on the result.

Thirdly, during the original test and evident in full height fire incidents, the aluminium layer of the cladding delaminates and exposes the more reactive core. This is difficult to replicate in FDS. Here,

the properties of the front face of the cladding material are changed to match that of polyethylene. Further investigation may provide different methods for replicating the delamination.
Finally, the SURF BACKING='INSULATION' input is not suitable for replicating the results of the original fire test.

The research project is continuing, and the next stages of the project may add further accuracy to the model. In the short term, the aims are as follows:

I. Cladding core and insulation materials are to be tested in the cone calorimeter at the University of Leeds.
II. The ramping features of the model are to be adjusted to replicate the early heat indications from the test data.
III. All the BRE-DCLG tests with the differing configurations, are to be replicated in FDS Models.

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