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Numerical Investigation of the Impact of Bushfire-Enhanced Wind Profiles on Structures

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Abstract

It has long been known that extreme bushfire circumstances are always associated with violent winds. There has been a wealth of research devoted to investigating the effect of wind on bushfire spread, but only recently is attention being paid to the enhancement wind by fire and the subsequent impact on buildings. Previous studies have focused on building blocks with simple configurations, however, building structures in reality can be quite complex. This research examines the effects of bushfire-enhanced wind on a typical structural configuration, that is, a building with openings. The computational fluid dynamics approach was employed to reveal pressure distributions, wind velocity, and temperature profiles. The numerical simulations also revealed an interior flow within the building, which is believed to have been caused by the stack effect. Consequently, fire-generated wind pressure loading on the building is different to that on a building with no opening. The analytical information obtained will assist in research on structural response during intense bushfire, furthering the development of relevant standards for better protection of building structures against bushfire attacks.

Keywords: Buoyancy, Bushfire, Wind, Computational fluid dynamics (CFD), Stack effect

1. Introduction

Bushfire is a type of natural disaster that is heavily influenced by a range of environmental factors that combine to create catastrophic conditions. Bushfire affects vast populations across the world, particularly within Australia, which is recognised globally as the most fire-prone continent on Earth (Bryant 2008). Wind is another significant environmental aspect that can have a detrimental impact on modern infrastructure. It has long been known that wind and bushfire interact to form more aggressive bushfire conditions, however there appears to be severe lack of research regarding their combined properties. The destructive nature of a bushfire event should therefore not be solely attributed to apparent bushfire attack mechanisms such as flame contact, radiant heat and ember attack that are identified in the relevant standard (AS3959–2009).

Several extreme cases of bushfire have highlighted the significance of the need to fully understand the phenomenon of fire-generated wind, such as the 2009 Victorian Bushfires which claimed the lives of 173 people and in excess of 4,500 structures (Mannakkara and Wilkinson 2013). It was indicated by Lambert (2010) that excessive quantities of wind were being drawn to the base of the bushfires to replace the displaced air, creating increased pressure conditions great enough to prise main structural components (mainly roofs) from their fixtures. As a consequence, structures were left unprotected from flame and ember attack, which ignited buildings from within the interior. Furthermore, the 2003 Canberra Bushfires which killed 4 people and destroyed approximately 500 houses was another instance of intense bushfire-enhanced wind damage. According to McRae *et al.* (2013), the intense bushfires coupled with extreme winds resulted in a powerful pyro-convective atmospheric event, which essentially formed a 'fire tornado', the first ever recorded in Australia.

Earlier research attentions to bushfire-wind structure interactions were reported in the works by He *et al.* (2011) and Kwok *et al.* (2012), followed by Ly (2012). Their studies focused on a simple intact building block and demonstrated significant variations in pressure distributions that could have more detrimental effects on the building structure than the wind that is not affected by bushfires.

It has been identified through various research projects that ember attack, rather than radiant heat or flame exposure, is the primary cause of building ignition during and after a bushfire event *(Whittaker et al.* 2013). However, embers by themselves do not pose much threat to buildings, it is the wind damage that creates opportunities for embers to attack. Furthermore, a partially damaged structure could be subjected to even greater wind generated pressure load, hence greater devastation. The objective of the current study is to investigate bushfire-enhanced wind effects on a structure with partial damage that is represented by an opening in the windward wall. The results of this study will play a critical role in future structural response analysis projects aimed at improving stability and protection for buildings during bushfire-enhanced wind scenarios, such as the research conducted by Camille *et al.* (2017).

2. Numerical Simulation

The numerical investigation presented within this research has been conducted from a computational fluid dynamics (CFD) approach to examine to the effects of bushfire-enhanced wind on a building structure containing an opening. The software program used to undertake this investigation is the Fire Dynamics Simulator 6 (FDS), which has been developed by the National Institute of Standards and Technology (NIST), USA (McGrattan *et al.* 2013). The program is designed to model fire-driven fluid flow, particularly for heat and/or smoke transfer from fires. It numerically calculates a form of the Navier-Stokes equations to resolve turbulent flow using the large eddy simulation (LES) scheme.

2.1. Domain Modelling and Boundary Conditions

The domain for the FDS modelling is a three-dimensional rectangular prism with *XYZ* dimensions of 73 m × 30 m × 24 m as shown in Figure 1. This domain layout has been based upon previous studies by He *et al.* (2011), Kwok *et al.* (2012) and Ly (2012). The domain parameters have been verified within the aforementioned studies, which focused on a 6 m × 6 m × 6 m building block with no opening known as the Silsoe cube (Richards *et al.* 2001). The mesh sizing applied to the domain is 0.1667 m × 0.25 m × 0.15 m. The bushfire front is 3 m in width in the *X*-direction, and extends across the domain in the *Y*-direction at a height of *Z*=0 m. The origin of the coordinate is set at the base of the building block which is placed at the centre plane across the transverse direction. The wall of the block has a thickness of 0.26 m and a roof thickness of 0.2 m in accordance with works conducted by Camille *et al.* (2017).

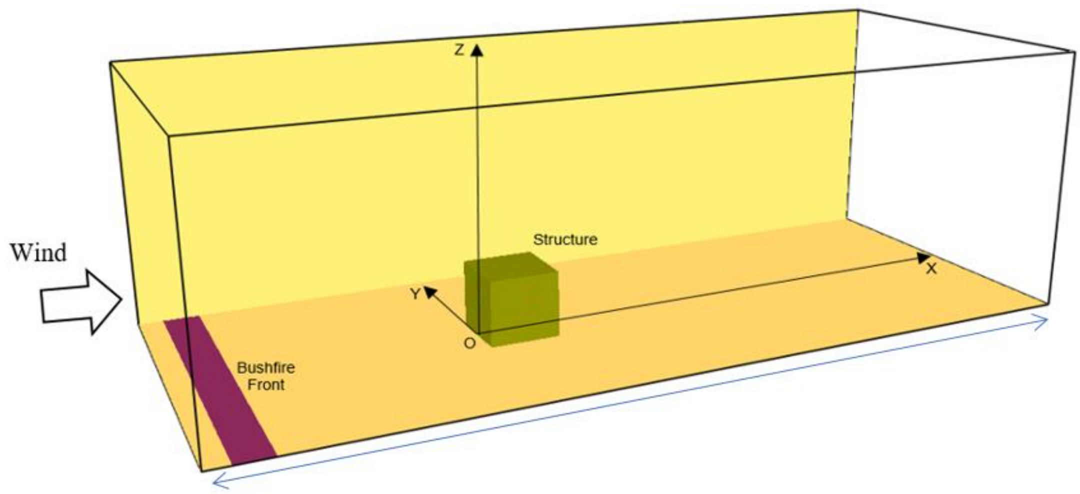
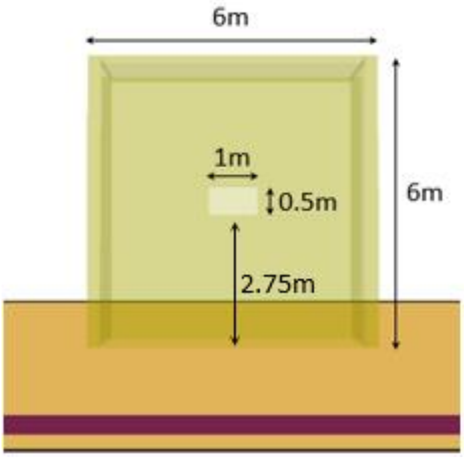


Figure 1. Layout of computation domain.

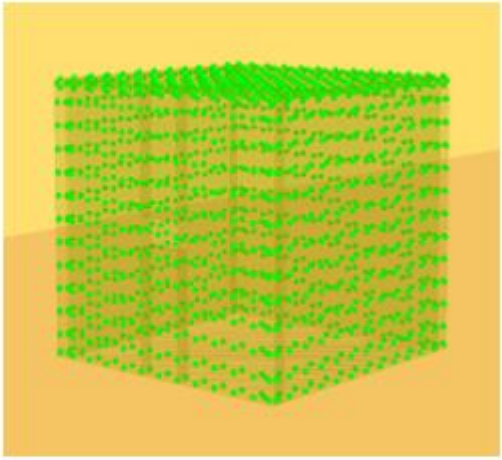
The following boundary conditions were set in order to achieve the most accurate simulation for the investigated scenario. The domain essentially forms an open roof tunnel, whereby wind travels from the left (X= –25m) boundary across the domain to the exit point at X=48 m. The velocity profile at the entrance follows a power function (He *et al.* 2011). The boundaries at Y= –15 m and Y=15 m are specified as slip surfaces. The ground at Z=0 m is a no-slip surface and the top at Z=24 m is specified as in the open condition.

2.2. Windward Wall Opening and the Simulation Output Point Distribution

A window opening is specified at the centre of the windward wall of the building block. The dimension of the window opening was a control parameter in the simulation. Figure 2 below illustrates the location of the opening when the dimension is set at 1 m × 0.5 m. Also identified in Figure 2 are the pressure output points which record the relative pressure acting on the interior and exterior surfaces of the structure. They are equally spaced at 0.5 m across and down the face in a 13 by 13-point grid.



(a)



(b)

Figure 2. (a) windward wall opening dimensions and location and (b) pressure output points (green dots) over the exterior and interior surfaces of the structure.

3. Results & Discussions

The numerical investigation of this research was based upon a number of scenarios in which the opening configuration was altered to examine the role of the opening for structural response studies. The presence of the bushfire was also altered. Two control scenarios containing no opening in the windward face, one with fire and the other without fire, were established as reference cases for comparisons with the investigations by He *et al.* (2011) and Ly (2012). Both of these scenarios were also reproduced without a bushfire front to highlight the significance of the fire-generated wind. A summary of the simulation scenarios is given in Table 1 below.

Table 1. Summary of the simulation scenarios.

Scenario number	Bushfire intensity (MW/m)	Opening size, $h \times w$ (m × m)
1	0	0 × 0
2	9	0 × 0
3	0	0.5 × 1
4	9	0.5 × 1
5	0	1 × 2
6	9	1 × 2

The following parameters were employed as the input across all six scenarios based on the aforementioned studies, the wind velocity has been referenced as an average value taken from the field testing on the Silsoe cube conducted by Richards *et al.* (2001);

- Building Block Dimensions, $L \times W \times H$ = 6 m × 6 m × 6 m;
- Characteristic Wind Velocity, u_r = 9.52 m/s;
- Bushfire Front Intensity, Q_m = 9 MW/m;
- Simulation Running Time, t = 50 s

He *et al.* (2011) also investigated the velocity profile across the domain for the simulation, concluding that it takes approximately 20 seconds for the flow field to establish a quasi-steady state. Therefore, the data averages presented throughout this research are based upon the average values for the quasi-steady period, which in all cases is the range between 20 and 50 seconds.

3.1. Opening Configuration Comparison

An analysis comparing each scenario regarding the pressure coefficient C_p acting on the exterior and interior vertical centreline (Y=0 m) of the structure was conducted to verify the output data from the simulations. Figure 3 below shows the predicted C_p distributions for all six scenarios. The non-dimensional distance parameter S^* is defined by $S^*=s/L$, where s is the distance measured from the base of the block and L is the characteristic length of the building block (=6 m).

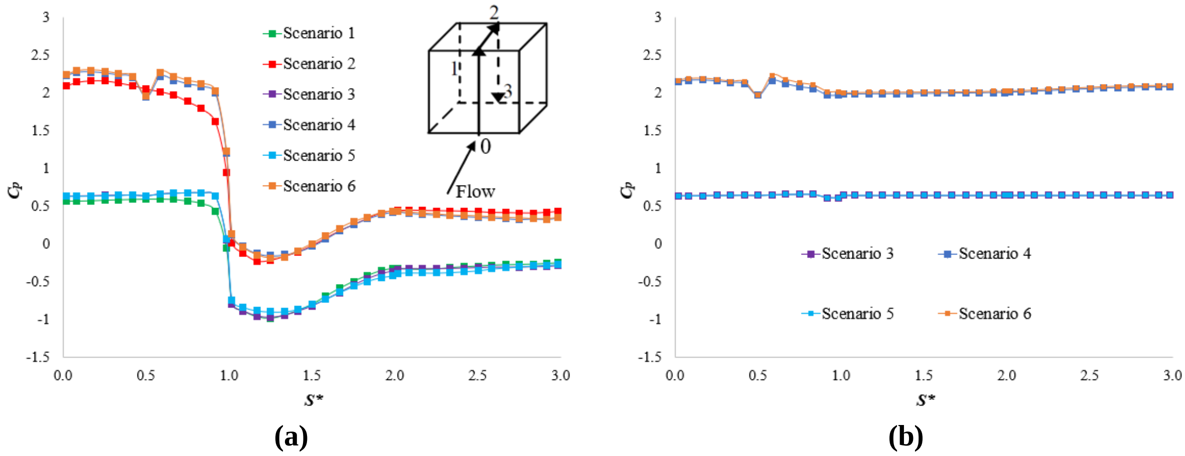


Figure 3. Pressure coefficient variation along the centreline of (a) exterior and (b) interior of the building.

As it can be seen from Figure 3(a), several key points can be drawn from the results. Firstly, the C_p distribution for Scenario 1 (no opening, no fire) appears to be in accordance with that produced by Ly (2012). Only minor discrepancies exist between C_p distributions of Scenario 1 and Scenario 3 (0.5 m × 1 m opening, no fire). When the fire of 9 MW/m intensity is introduced, the entire distribution curves are shifted upwards significantly. The exterior C_p variation on the structure is not affected by the sizing of the opening. It is apparent that the bushfire contributes significantly to the pressure on the structure with increase of approximately 350%.

A similar upwards shift is evident in the interior C_p in Figure 3(b), where the curves for the scenarios with bushfire are increased significantly compared to the scenarios without bushfire. The similar nature of the data values for Scenarios 3 and 4 and Scenarios 5 and 6 indicate that the size of the windward wall opening does not significantly alter the interior C_p and is therefore considered negligible. The data from the interior C_p distributions appears to confirm that the wind entering through the single opening pressurises the interior of the structure and the C_p is therefore constant throughout the building.

3.2. Temperature Variance

One difference between ordinary wind and bushfire affected wind is that the latter has a much higher temperature and poses additional attack to building structures. Figure 4 shows the predicted temperature planar distribution across the domain at *Y*=0 m and at time of *t* = 40 s. The flow immediately in contact with the building façade is estimated to have reached the temperature range of approximately 300-320°C. It can be seen that a minor portion of the temperature profile is entering the building through the opening at approximately 100°C. This provides more evidence for the velocity flow phenomenon inside the structure, as air with a higher temperature is more buoyant, which may be the main driving force causing the fluid flow within the building.

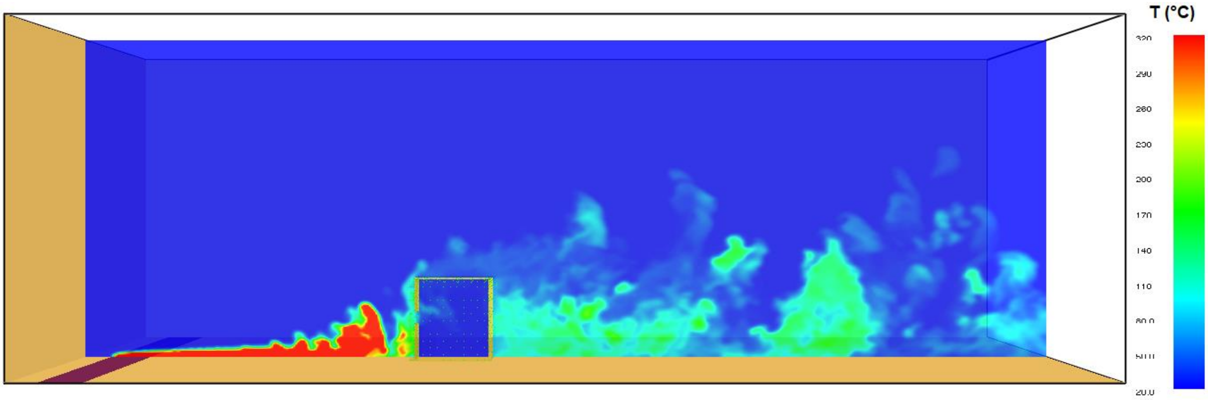
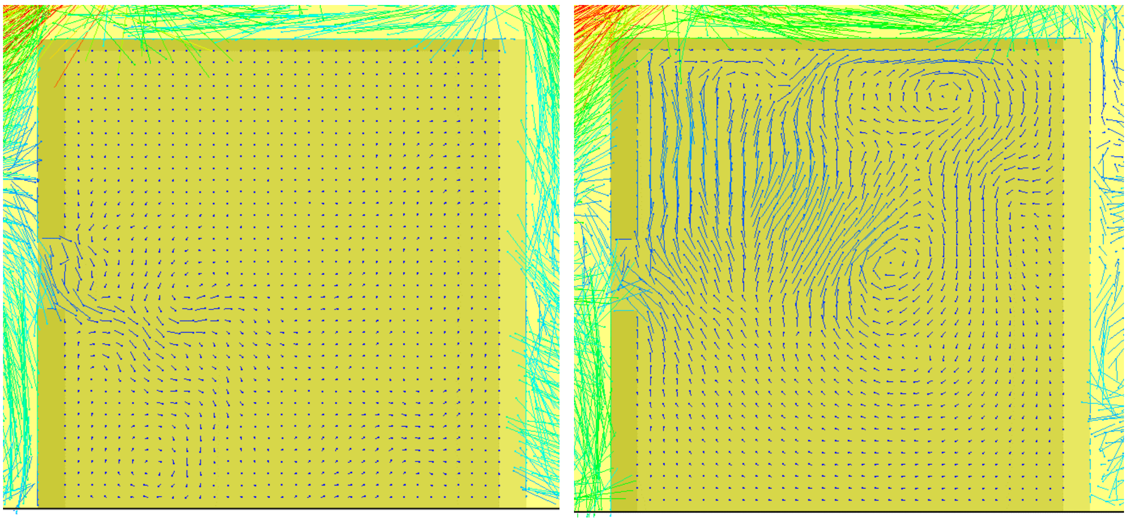


Figure 4. Temperature distribution across the domain (*Y*=0 m) in Scenario 6 at *t* = 40 s.

3.3. Evidence of Interior Flow

The expected to allow the attainment of pressure equilibrium between the exterior and interior of the building block. However, the temperature differential between the exterior and interior helped the creation of the stack effect (Klote and Milke 2002) which induced a counter-current flow phenomenon at the opening. Figure 5 compares two simulations with the 1 m × 2 m opening, (a) is from Scenario 5 with no bushfire effect and (b) is from Scenario 6 with 9 MW/m bushfire intensity. It is evident that the temperature from the bushfire is the main factor behind this flow.



(a) (b)

Figure 5. Interior flow within the structure with a 1×2 m opening (a) no fire; and (b) with fire.

4. Conclusion and Further Research

It has been confirmed through the numerical simulations that the fire-generated wind pressure loading acting on the structure with an opening is vastly different to a similar structure with no opening. The numerical simulations revealed that fire-enhanced winds can induce severe pressure loading conditions that have the potential to ultimately cause structural failure during a bushfire event. Furthermore, the numerical investigation revealed a distinctive phenomenon of the fire-driven fluid flow within the building enclosure. The key parameter that controls this interior flow is the temperature difference between the exterior and interior of the enclosure. Although there is adequate evidence provided to suggest this interior flow phenomenon is occurring, a greater depth of study is required to determine the major contributing factor. Future research focusing on various independent parameters such as bushfire front intensity and the characteristic wind velocity would provide explanations to distinguish the main cause of the internal flow.

The results of this report can be used in future research to determine the structural response of the building block to support developments within the bushfire protection field. Other future investigations for this work include modifying the positions of the opening(s), as this research focused solely on openings in the windward wall. In conclusion, further investigation is required to confirm the interior flow within the building structure, although substantial evidence has been provided.

6. Acknowledgement

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