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Numerical Investigation on Impact of Bushfire Enhanced Wind on Building Structures

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Abstract

Most researches about bushfire and wind, individually focuses on the origins, impacts and reconstruction process which are systematically studied after a devastating event. Indeed, it can reveal a lack of research as both bushfire and wind are interrelated and subsequently referred as 'bushfire enhanced wind'. This phenomenon has long been acknowledged by researchers, however it's understanding about the different interactions and effects still remain relatively limited. Therefore, this research addresses the impacts of bushfire enhanced wind over residential structures by numerical investigation using a finite element commercial software known as Abaqus. The model first simulates the most common type of wall system (i.e. masonry: double brick) in Australia with the results presented as pressures and stress distribution. Secondly, the finite element analysis emphasises on the critical sections (i.e. wall and roof connections) when the model contains an opening (i.e. window). The outcomes generated by the finite element analysis are expected to provide valuable understanding into the fire-wind interaction and subsequently impact the Australian Standards aimed at improving structural design within bushfire prone areas.

Keywords: Bushfire, Wind, Finite element modelling, Brick masonry, Double brick connections

1. INTRODUCTION

The combined effects of bushfire enhanced wind on building structures have long been acknowledged, but unfortunately the Australian Standards: AS 3959-2009 'Construction of buildings in bushfire-prone areas', AS/NZS 1170:2:2011 'Structural design actions-Part 2: Wind actions' and AS 4055-2012 'Wind loads for housing' do not reflect that design criteria. For instance, when bushfire enhanced wind effects are considered, the factors affecting the response of the structures are the material properties (i.e. strength masonry & concrete), induced external/internal pressures and the strength of critical connections. Therefore, this paper herein presented used Abaqus to develop an accurate finite element model analysing the different impacts (i.e. strength reduction & stresses) and behaviour of building structures experiencing bushfire enhanced wind. Wherein, the main objectives of this paper are to understand and identify the critical sections within building structures, develop finite element models of Double-Brick residential structure (including opening) to analyse the pressure and stress distribution for providing design recommendations in bushfire prone areas.

Most of the previous researches investigating the complexity of fire-wind interactions on structures were limited to dangerous and costly experimental testing revealing real gaps between the Australian Standards and the actual behaviour of structures. An important factor to be considered during a bushfire enhanced wind event is the fire resistance of the construction materials used. One advantage of masonry (i.e. double brick wall) over concrete and steel structures is its ability to maintain a structural adequacy, integrity and insulation for approximately 240 minutes when equally loaded as represented in Figure 1. As a result, masonry structures (i.e. clay bricks) are typically recommended for bushfire prone areas (AS3700-2011: Standard Australia Online 2011). Similarly, wind is an essential part of the structural members design where engineers primarily focus on three of its major effects identified as: out-of-plane bending, in-plane shear and uplift (AS 4055-2012: Standard Australia Online 2012). These wind pressures can be either external or internal (due to an opening) and typically vary from 0.7 to 6.0 kPa characterising the net wind effects on the structure. Therefore, it is important to numerically analyse these correlation behaviours specially at critical locations (i.e. roof-to-wall connections) to further provide structural recommendations for bushfire prone areas. Figure 2 highlights four critical connections which will be further researched and modelled within Abaqus.

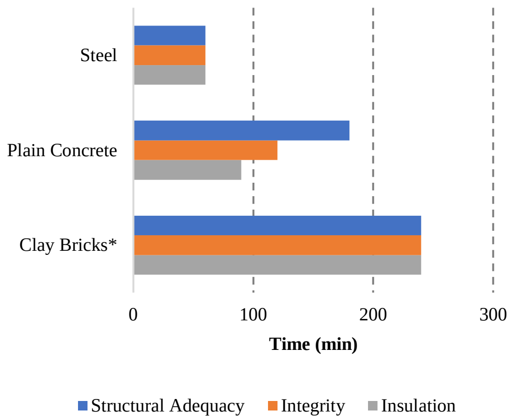

Figure 1: Fire resistance levels of construction materials

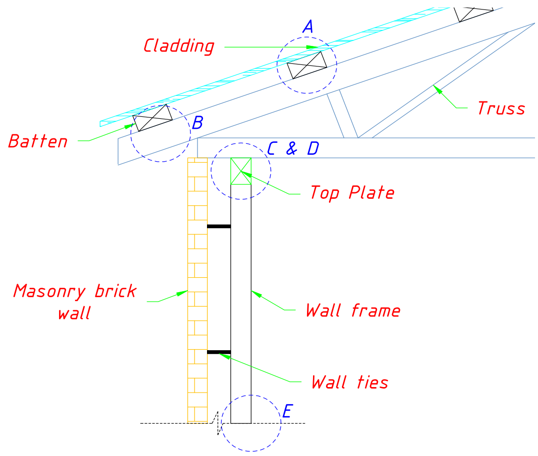

Figure 2: Cladding-to-batten (A), batten-to-truss (B), truss-to-top plate (C), top plate-to-wall frame (D) and wall-to-foundation (E)

2. FINITE ELEMENT MODEL

2.1 General

The numerical investigation herein presented used the finite element software Abaqus to simulate the interaction of bushfire enhanced wind on building structures and their connections to an exposure of 9MW/m (fire-front) and a 9.52m/s wind. These effects are represented in terms of forces and material properties reduction affecting the behaviour of the double brick walls and the concrete roof. Therefore, to achieve accurate results from the finite element analysis, these crucial components must be thoroughly researched and their mechanical properties precisely imputed towards the generation of a three-dimensional model.

2.2 Concrete

The models mainly consist of load bearing double brick walls supporting a concrete roof, wherein the behaviour of concrete in compression is assumed to be linear up to 40% of its strength (f'_c). Exceeding that stress, a non-linear behaviour is observed for which the stress-strain relationship of concrete in compression can be expressed using Equation 1 (Carreira & Chu 1985).

$$\sigma_c = \frac{f'_c.\gamma.(\varepsilon_c/\varepsilon'_c)}{\gamma - 1 + (\varepsilon_c/\varepsilon'_c)} \qquad (1)$$

where $\gamma = \left|\frac{f'_c}{32.4}\right|^3 + 1.55$ $\qquad \varepsilon'_c = 0.002$ (peak strain)

f'_c = Compressive strength, ε_c = Strain of the curve, γ = Dimensionless material parameter

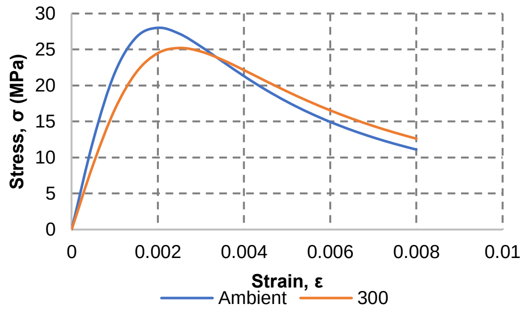

Figure 3: Stress-strain relationship of concrete at elevated temperature (Carreira & Chu 1985; Kodur 2014)

In addition, it is essential to simulate the performance of concrete when exposed to elevated temperatures (i.e. 300°C), as it usually experience a compressive strength reduction of approximately 10% (Kodur 2014). As result, the stress-strain relationship of the concrete roof imputed within Abaqus is illustrated in Figure 3.

2.3 BRICK MASONRY

In order to provide an efficient numerical analysis, the research herein presented has adopted the macro-numerical approach simplifying the masonry unit, mortar and unit-mortar interface to one homogenous element. As a result, the masonry stress-strain curve can be expressed by Equation 2 which has provided a good fit to numerous past experiments (Kaushik, Rai & Jain 2007).

$$\frac{f_m}{f'_m} = \left(2 * \frac{\varepsilon_m}{\varepsilon'_m}\right) - \left(\frac{\varepsilon_m}{\varepsilon'_m}\right)^2 \quad (2)$$

where $\varepsilon'_m = 0.0018$ (peak strain at ambient temperature)

f_m = strength (stress) of masonry unit

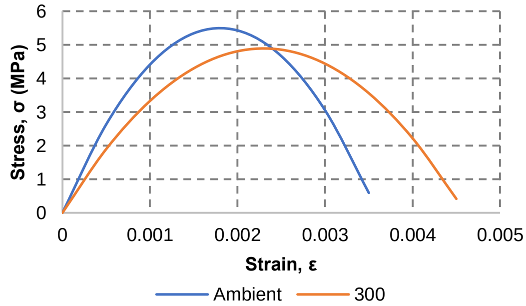

Figure 4: Stress-strain relationship of clay bricks at elevated temperature (Russo & Sciarretta 2013)

Similar to concrete's mechanical behaviour, the masonry bricks experienced a strength reduction of 11% when exposed to a bushfire temperature of 300°C corresponding to the peak measurement at the surface of the walls. Figure 4 summaries the deformation of clay bricks within the finite element model through its stress-strain relationship.

2.4 MESH, BOUNDARY & LOADING CONDITIONS

Three-dimensional solid elements commonly abbreviated to C3D8R were used to model the double brick walls and the roof as shown in Figure 5. That specific element uses the Continuum solid element, 3-Degree of freedom as well as 8 nodes with Reduced integration to efficiently reduce computational time and enhanced the convergence towards accurate results. For the boundary condition, the bottom edge of the double brick walls (highlighted in red) were set to 'encastre' simulating a fixed connection to the ground.

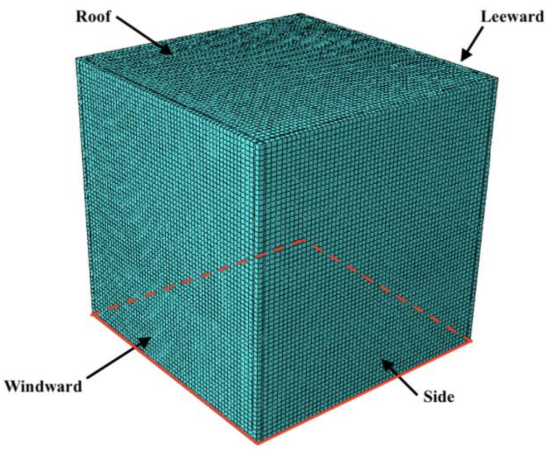

Figure 5: Finite Element Model of a Silsoe cube

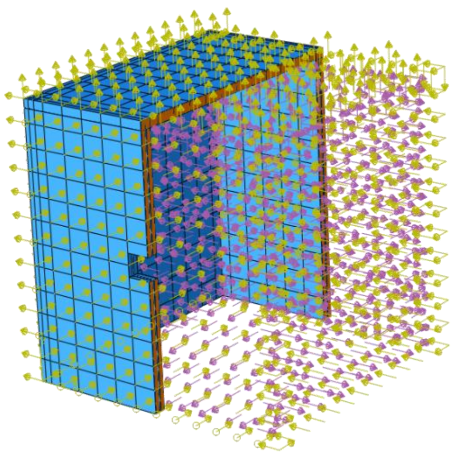

Figure 6: Finite Element Model with all the forces

Additionally, all the loads applied towards the Abaqus model were generated from a Fire Dynamics Simulator (FDS) analysis conducted by Baker (2017), wherein the surfaces on both the external and internal walls of the Silsoe cube were exposed to the effects of a typical 9MW/m bushfire and 9.52m/s wind. The loading conditions herein described involve two cases of which the first one simulates the exposure of the surfaces to the maximum positive and/or negative pressures. On the other hand, case two precisely followed the FDS simulation in terms of average pressure on every single side. However, two cases include the simulation of the model under both the influence of opening and no opening expose to either fire or no fire. Figure 6 represents the internal and external forces acting on both the walls and roof due to the presence of an opening being 1m wide and 0.5m high.

3. RESULTS & DISCUSSION

3.1 OVERVIEW

The results generated from the finite element analysis herein presented summarised the fire-wind interaction onto a building structure and its connections. Eight Abaqus models were analysed for the following scenarios focusing on the maximum/minimum stresses, forces, pressures and critical connections:

1. No opening subjected to only wind effects of 9.52m/s;
2. No opening structure exposed to a 9MW/m fire front and a 9.52m/s wind;
3. Windward wall opening (1m wide and 0.5m high) affected only by a 9.52m/s wind.
4. Windward wall opening (1m wide and 0.5m high) exposed to a 9MW/m fire front and a 9.52m/s wind.

Similarly, case 2 investigate the same fire, wind and opening arrangement, yet based on the average FDS results compared to case 1 which consider the highest positive/negative effects.

3.2 SCENARIO 1

Figures 7 and 8 below represent the stress distribution under wind actions with no reduction in materials properties. The numerical analysis revealed that the average pressures resulting from the wind actions on both cases were negative indicating a suction effect. In accordance with the Australian Standards: AS 4055:2012 'Wind Loads for Housing', this structural response is expected where only the windward wall experienced positive external pressures with roof corner and wall edges being critical.

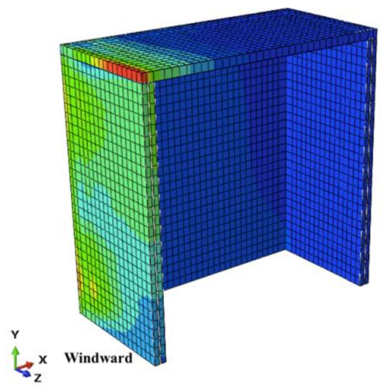

Figure 7: Stress distribution of the Abaqus model with no opening under wind actions (Case 1)

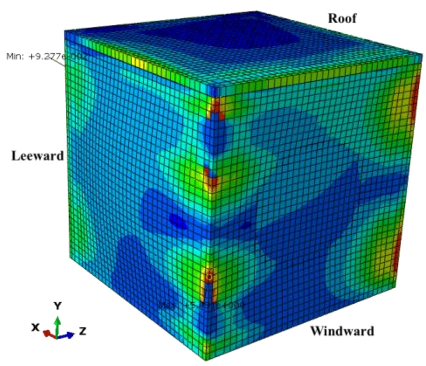

Figure 8: Stress distribution of the Abaqus model with no opening under wind actions (Case 2)

3.3 SCENARIO 2

The stress distribution for both the fire and wind effects are highlighted in Figures 9 and 10. For this second scenario with the addition of fire, it was observed that the critical sections were situated on the windward side with the wall edges and roof-to-wall connections initially failing. In terms of average external pressures, both cases mainly experienced positive pressure due to the fire surrounding the structure.

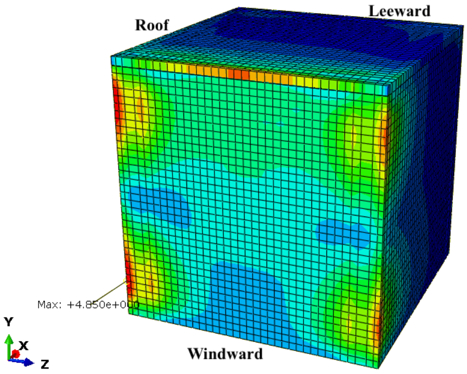

Figure 9: Stress distribution of the Abaqus model with no opening under fire and wind effects (Case 1)

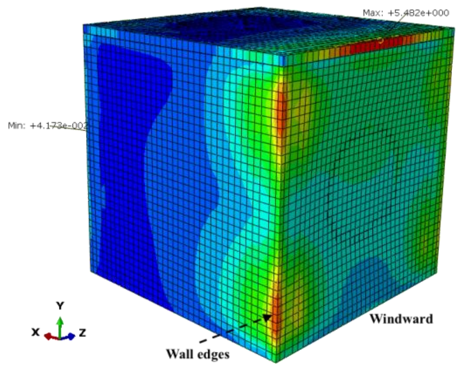

Figure 10: Stress distribution of the Abaqus model with no opening under fire and wind effects (Case 2)

3.3 SCENARIO 3

The stress distribution under wind actions only is represented in Figure 11 and 12. In both cases, the wall corners and roof edges experienced significant deformation on the windward side as justified in the Australian Standards: AS 4055:2012 ‘Wind Loads for Housing’. However, when subjected to the average wind pressures (Case 2), the finite element model displayed a critical stress at the roof-to-wall connection on the left-side wall describing a higher wind actions on that side of the structure.

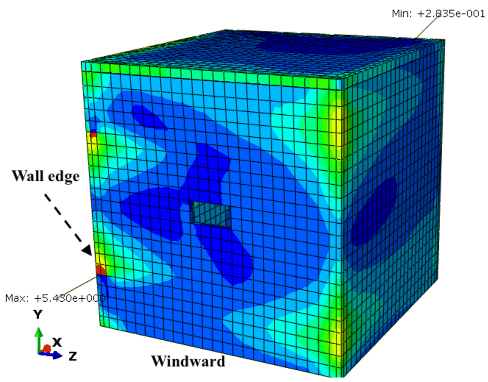

Figure 11: Stress distribution of the Abaqus model with windward opening under wind actions (Case 1)

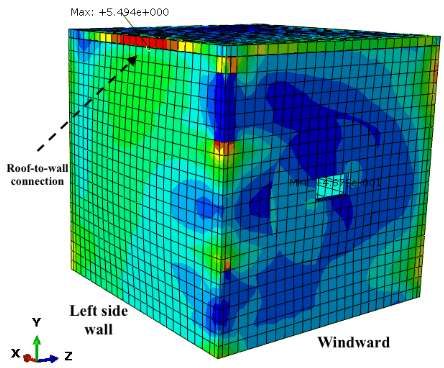

Figure 12: Stress distribution of the Abaqus model with windward opening under wind actions (Case 2)

3.3 SCENARIO 4

Figure 13 and 14 represent the stress distribution under the interaction of fire and wind which produced a reduction in materials properties and an increase in pressures due to the elevated temperatures. These last finite element models also represent the bushfire enhanced wind interaction with opening (1m wide and 0.5m high) and are considered to generate the most realistic effects a structure will endure.

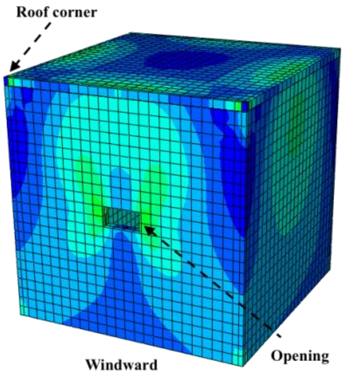

Figure 13: Stress distribution of the Abaqus model with windward opening under fire and wind effects (case 1)

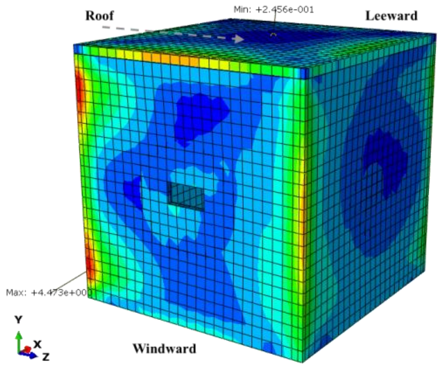

Figure 14: Stress distribution of the Abaqus model with windward opening under fire and wind effects (case 2)

This increase in pressure validate the accuracy of the finite element models which conformed to the pressure law as the temperature increases.

4. CONCLUSIONS

This paper discusses eight different bushfires enhanced wind scenarios and their effects towards buildings structures. The reasonable accurate finite element models have been developed to interpret the influence of fire and wind both individually and in combination, wherein the materials deterioration have been taken into account. Subsequently, the finite element analyses conducted on eight models include two cases and four possible scenarios from which the following conclusions were achieved:

- The effects of fire tend to reduce the peak stress experienced by the building, implying a strength reduction capacity of the structure;
- The presence of opening induced a drastic change in the net pressures configuration as the internal pressures may in certain circumstances resist or facilitate the failure of the structure;
- In specific arrangement, Case 2 which uses the average FDS pressures has been identified as the critical loading case inducing the highest stresses throughout the connections;
- The interaction of bushfire, wind and opening generated the worst situation as structures are exposed to elevated temperatures as well as high internal and external pressures. The pressure difference may vary by ± 50 to 130%.

5. FURTHER STUDY

Further research into the following areas will be conducted to improve the accuracy and understanding of bushfire enhanced wind effects:

- Perform finite element modelling for roof-to-wall and wall edges connections;
- Perform a time-dependant finite element analysis to evaluate different combinations of varying pressures.

6. ACKNOWLEDGEMENT

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