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INVESTIGATING TIMBER BEAM BEHAVIOR IN TWO-DIMENSIONAL STANDARD FIRE EXPOSURE: A FINITE ELEMENT MODELING APPROACH

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ABSTRACT

This study explores the fire behavior of timber beams subjected to two-dimensional (2-D) standard fire exposure. This paper conducted simulation tests on eight beams of varying sizes and exposure durations to a three-sided fire. The finite element software, ANSYS, was employed to predict and analyse the fire behavior of these beams. It was found that as the size of the beam decreases, its fire behavior also diminishes, with the reduction ratio similarly decreasing. Based on main findings, it was revealed that under a temperature distribution of 945.3oC for a duration of 90 minutes, the fire data from the 60 minutes clearly indicated that the beams with dimension size 75mm×100mm×1000mm could no longer withstand the conditions. The samples were completely charred after 67 minutes and 75 minutes, respectively. The beam with dimensions 100mm×150mm×1000mm, while not entirely burned, was deemed a failure as it was nearly fully consumed by the fire. At this temperature stage, it was also observed that the beam measuring 100mm×200mm×1000mm exhibited less resilience compared to the beam of dimensions 125mm×150mm×1000mm.

Keywords:
ANSYS, Finite Element Modeling, 2-D Standard Fire, Fire Behavior, Timber Density, Mengkulang Timber

INTRODUCTION

Timber structures is one of ancient structures element with human since time immemorial. As a natural and sustainable structure material, timber has a good and great environmental property. The energy required to change over trees into wood and thus into structural timber is altogether less than that required by another structural materials, for example, steel and concrete. Concrete and steel structures are much more expensive than timber structures.

Researchers started to look for the fire behavior of timber structure in the 1960s which have created systemic research methods in 1970s. By the 1990s, a large number of researches in this field have been carried out, and leaded to great achievement. Further in the latest years since 2000s the researchers done more researches in that field (Aseeva et al., 2014).

Timber has more ability for fire than other materials such as concrete or steel. Given this information, researchers are diligently examining the fire behavior of timber (Kathinka Leikanger Friquin, 2010). It is founded that there are no enough tests have been conducted to the fire performance to the timber either for beams or for columns (Bobacz, 2008).The reasons of this lack of tests and experiments is due to many reasons such as the high cost, materials that needed to be used and the equipped place to conduct the tests and experiments needed.

Therefore, researchers have created and found out an alternative method to investigate the behavior of the timber under the fire. One of the methods is by conducting a software analysis programs to predict the performance, endurance or behavior of timber under the fire.

This research used a specimen of solid timber from Mengkulang species (Heritiera spp.) which is considered a hardwood with a normal density of 750kg/m³. It has been selected because that is widely used in Malaysia buildings and structures that made from solid timber.

This research also employed software to examine the fire performance of timber beams under two-dimensional fire exposure. The study also aimed to investigate the fire behavior of timber beams of varying sizes and exposure durations and to examine the residual cross-section of the timber beam post-fire exposure, which is crucial for design purposes.

Software Analysis

This paper utilized ANSYS software to carry out the tests on timber beams subjected to 2-D fire exposure. ANSYS is a computer-based program designed to simulate a wide range of engineering problems. It facilitates the creation of simulated models for various entities, including structures, machine components, and electronics. The primary objective of using ANSYS is to simulate or identify various properties such as strength, thermal heat, elasticity, toughness, and electromagnetism. It also aids in understanding fluid flow, temperature distribution, among other functionalities.

A study from the finite element modeling (FEM) had shown that the performance of the beam is decreasing when the load level increase and the ratio of the reduction will turn smaller. At the point when the load level is higher than 0.5, the performance of the fire is going to be very small (Bilbao et al., 2002). His finding shows that the larger the density of the material, the less the section temperature is at the similar position and more slowly the section temperature increases.

Another study stated due to the negligible differences between 1and 3 mm mesh sizes, as compared to 6 mm, it is recommended that an initial mesh size of 3 mm is used for simple heat transfer analyses in timber, to ensure accuracy while saving on computational time (Lizhong et al., 2007). Furthermore, Babrauskas in 2005 introduced a comprehensive model for analyzing the behavior of solid timber beams exposed to standard fire conditions within the framework of ANSYS software. The outcomes derived from this model exhibit a remarkable level of agreement with experimental data, demonstrating the model's efficacy in simulating the real-world behavior of timber beams under fire exposure. It was shown that not only the predicted temperature profile but the profile of the formation of char has very good agreement with the actual data.

Standard fire curve (ISO – 834)

ISO – 834 is the standard temperature-time curve, it is also called cellulosic curve or standard nominal fire curve (Figure 1). The curve is used to test and check the resistance of material under fire (Friquin et al., 2010). The standard fire curve is typically represented as a graph that shows how temperature within a controlled fire environment changes over time. The curve follows a specific pattern, with temperature rising at a relatively steady rate for a specified duration, usually up to a certain peak temperature. The curve is designed to mimic the thermal conditions that might occur in a real building fire.

The standard temperature-time curve is visually represented as a graph illustrating the evolution of temperature within a controlled fire environment over a specified duration. This curve adheres to a well-defined pattern, with temperature exhibiting a gradual and consistent ascent until it reaches a predetermined peak temperature. The careful orchestration of this curve is essential as it endeavors to replicate the thermal conditions that would be encountered in a real-world building fire scenario (R. , Aseeva et al., 2014; Bobacz, 2008).
The expression that used to define the standard temperature-time curve is:

$$T = T_o + 345 \log10 (8t + 1)$$

(Friquin et al., 2010)
To express about the initial furnace temperature (°C)

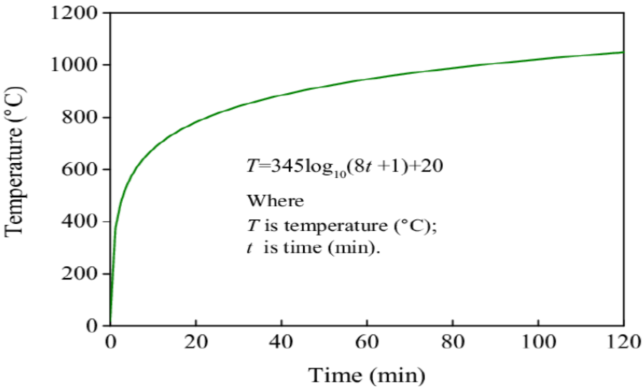

Figure 1: Standard fire temperature-time curve ISO 834 (Kathinka Leikanger Friquin, 2010)

Fire Resistance of Timber

Fire resistance evaluations of timber members are usually established by performing a full-scale test based on standards of specifications such as EC5, ISO 834, ASTM E119 or other test of similar standards (Tsai, 2010). During the fire test, the use of thermocouples helps researchers to observe and study the conditions and behaviors of timber especially during exposure to fire. Usually, thermocouples are inserted at different depths within the specified range to observe the temperature (°C) until the fire test is discontinued.

Since the timber has varied densities, it is essential to investigate its fire response, facilitating a deeper comprehension of its behavior when subjected to fire conditions. This investigation, in turn, will furnish the researcher with valuable insights into the dynamics of timber's interaction with fire. Ultimately, by leveraging the data obtained from this ongoing study, the researcher will gain a comprehensive understanding of how solid timber, specifically varying in densities characteristic of Mengkulang, performs under fire exposure, as explained through advanced software analysis.

METHODOLOGY

This section describes and discusses the methods used in this investigation whereby software analysis was carried out to examine the fire performance under the standard fire exposure of solid timber from Mengkulang. The specimens were exposed on three-sided fire exposure to the standard fire curve according to ISO 834 fire curve.

Eight models of beam from density of Mengkulang Malaysian tropical hardwood have been tested according to ISO 834 fire curve temperature. In conducting the fire performance all of the eight samples were exposed to the fire with a specified exposure period of 30 mins, 60 mins, 90 mins and 120 mins. The durations had been chosen based on the requirements of Uniform Building by Law (UBBL). In general, same experiments were carried out for each of models. The length of the beam model was constant at 1000 mm, while the dimensions of its width and depth vary, as depicted in Figure 2.

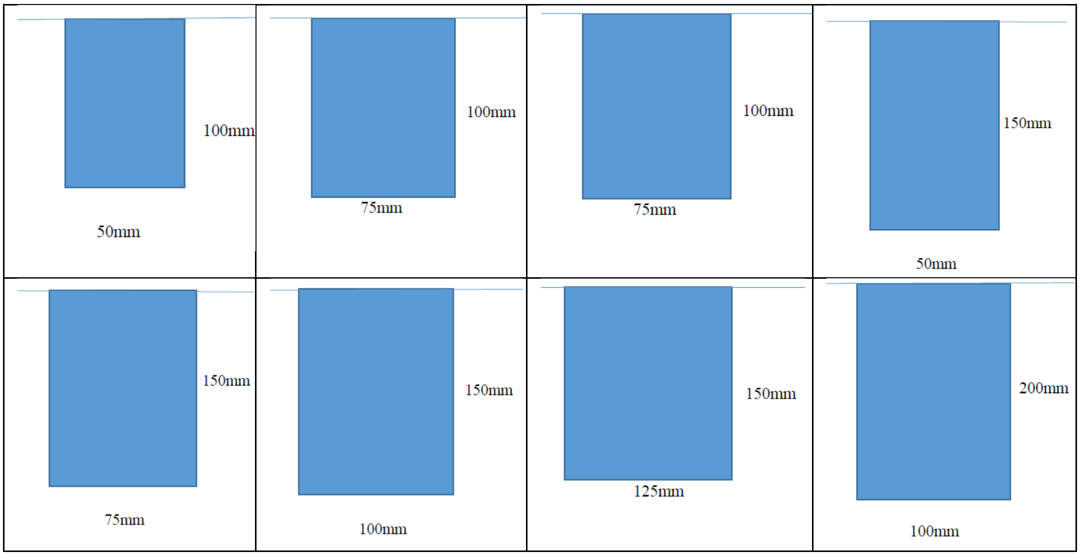

Figure 2: Models of beam size

Steps to Use ANSYS Software Analysis

In order to use ANSYS software analysis for heat transfer it was very important to know how to use the software. The general steps below are going to show how to use the software to determine the heat transfer in a timber beam model:

1. The ANSYS Workbench is downloaded and installed prior running the application.
2. The Engineering data is selected, before choosing the material used for the simulation.
3. After the material is chosen, find the materials needed in the library.
4. Then, the thermal conductivity and density of the selected material is identified.
5. Following that, the element is draw by selecting the geometry icon as shown in the Figure 3.
6. Model icon is selected to start the ANSYS mechanical and key in the required data.
7. After the ANSYS mechanical is started, select solid for the solid design element followed by meshing. The maximum meshing of 20mm was used in this study (maximum allowed meshing for ANSYS student version).
8. The button "solve" is click to run the meshing input on the design element.
9. After that, the steady thermal icon will appear.
10. Heat flux and convection was chosen from the list in the "insert" button followed by inserting the required data. Then, the "solve" button is click to run the input data.
11. Lastly, the "model icon" is clicked to re-open the ANSYS mechanical followed by "right click" on the "transient thermal" icon.
12. Then heat flux, convection, and the temperature parameters are chosen from the list under the "insert" icon. The data is inserted accordingly and press the "solve" icon to get the results as shown in Figure 3.

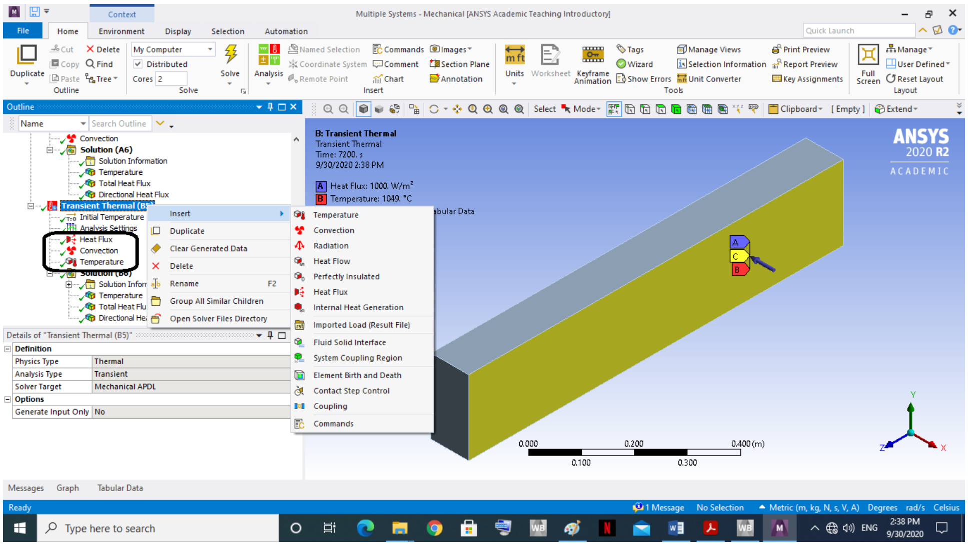

Figure 3: ANSYS mechanical page.

Mesh refinement was applied uniformly across all beams, with a prescribed mesh size of 20 millimeters (mm) due the student version of the software, which prevent the utilization of mesh sizes smaller than 20mm for beam elements. Steady-state thermal applied as well on the beam to express the weather temperature which have been applied with a value of 20℃ with a constant time. Transient thermal has been applied after that to express the increasing on the temperature with time. Standard curve for temperature and time (ISO 834) have been used to express the time and temperature. The temperature has been applied in a three-sides on the beam in order to find the fire performance of the beam under fire from three-sided fire exposure.

The cross section and axonometric view results of each beam is recorded in a different time (30mins, 60mins and 90mins). The simulation results of the tests have been recorded to differentiate between them and to find the most suitable beam that can survive longer under fire to enhance the safety of the buildings in the future.

RESULTS AND DISCUSSION

30 mins fire exposure

The results obtained from the heat transfer simulation, in conjunction with the empirical data gathered during a 30-minute fire exposure, yielded valuable insights into the structural performance of the beams under such conditions. Figure 4- Figure 11 below shows the beams after exposing it to the fire for 30-minute fire exposure.

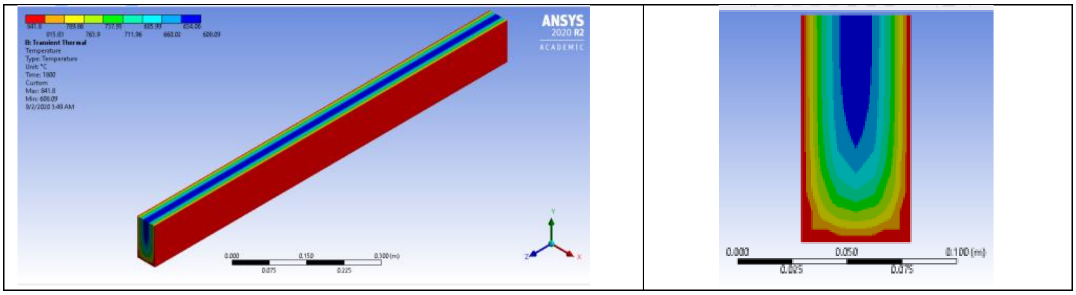

Figure 4: Temperature distribution of the timber beam size 50mm×100mm×1000mm

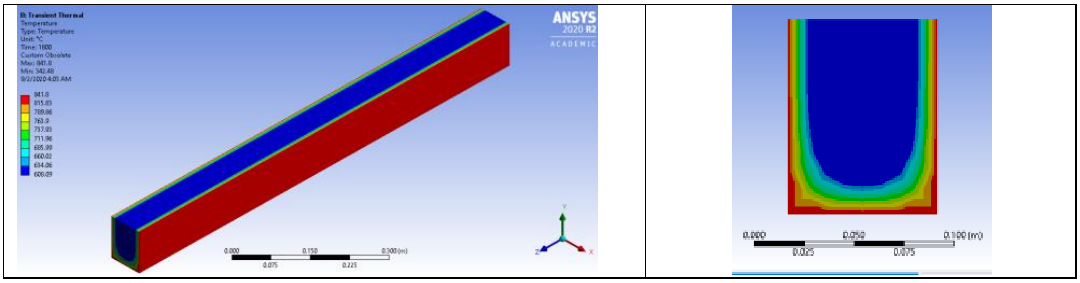

Figure 5: Temperature distribution of the timber beam size 75mm×100mm×1000mm

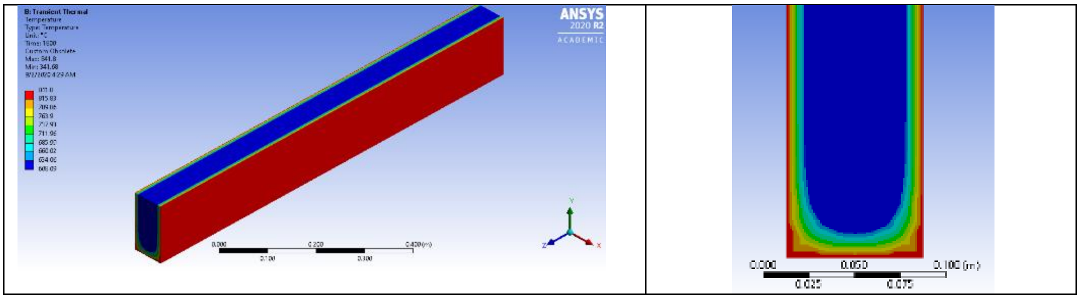

Figure 6: Temperature distribution of the timber beam size 50mm×150mm×1000mm

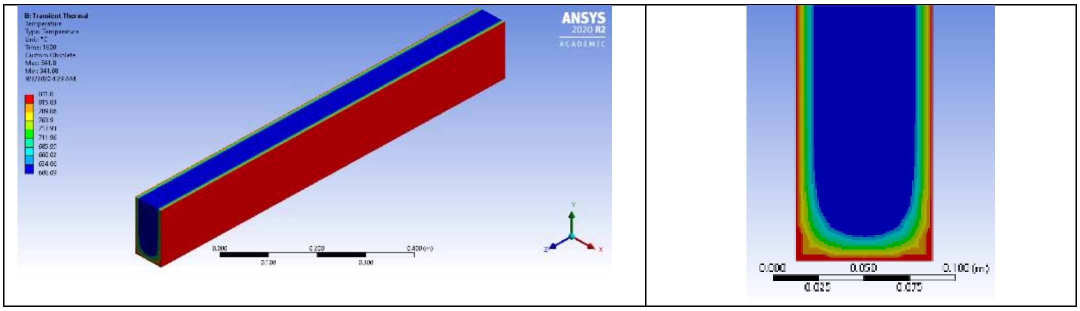

Figure 7: Temperature distribution of the timber beam size 75mm×150mm×1000mm

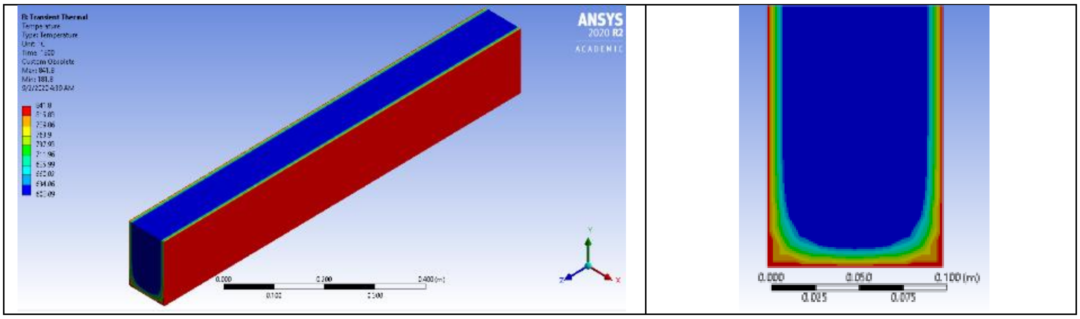

Figure 8: Temperature distribution of the timber beam size 100mm×150mm×1000mm

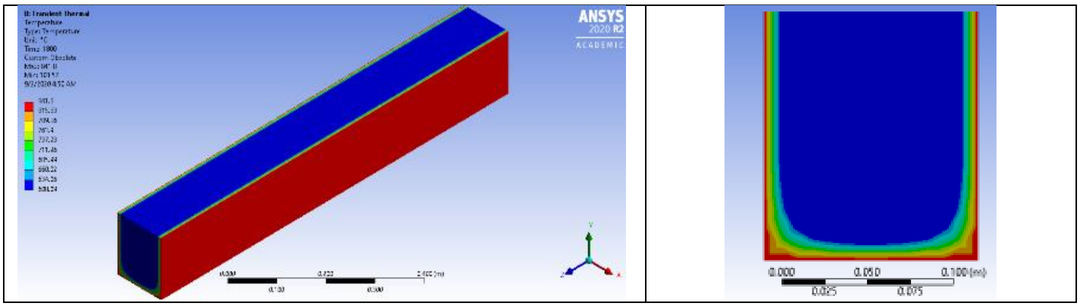

Figure 9: Temperature distribution of the timber beam size 125mm×150mm×1000mm

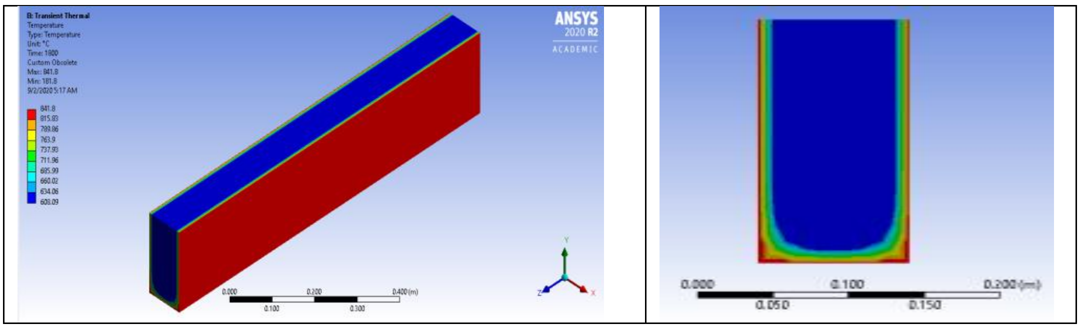

Figure 10: Temperature distribution of the timber beam size 100mm×200mm×1000mm

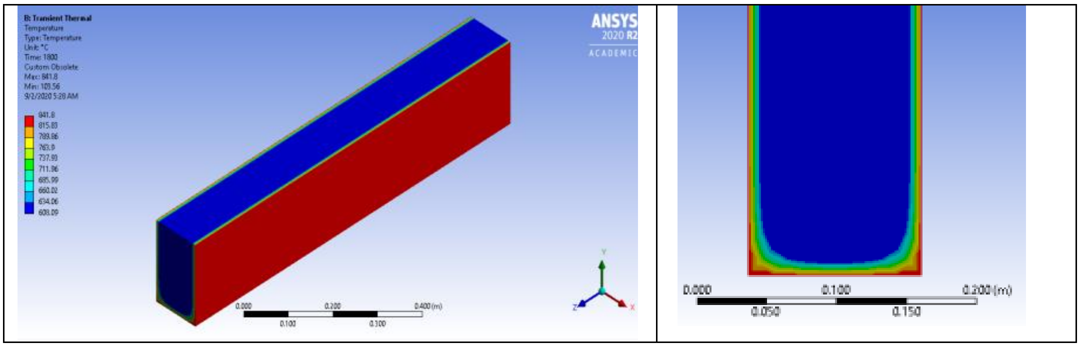

Figure 11: Temperature distribution of the timber beam size 150mm×200mm×1000mm

Notably, it was evident that none of the beams had undergone complete combustion within this timeframe. This outcome can be attributed to the limited duration of heat exposure experienced by the beams during the fire event as supported by Nelson Pine, 2003 & White et al., 2013. The primary reason for the beams' survival and lack of total burnout can be traced back to the thermal dynamics at play. The temperature distribution across the beams remained below critical levels during the 30-minute timeframe. Specifically, the recorded temperature distribution reached a maximum of 841.8ºC. This temperature observation was consistent with the established temperature-time curve outlined in the ISO 834 standard (Frangi et al., 2008). These findings underscore the significance of fire resistance measures in structural design and construction. The ability of the beams to withstand a 30-minute fire event without catastrophic failure showcases the effectiveness of timber fire-resistant properties and adherence to regulatory standards.

60 mins fire exposure

The subsequent figures (Figure 12-19) visually document the state of the beams after enduring a 60-minute exposure to fire. These images offer a comprehensive portrayal of the structural changes, damage, or resilience exhibited by the beams under the influence of intense heat and flames.

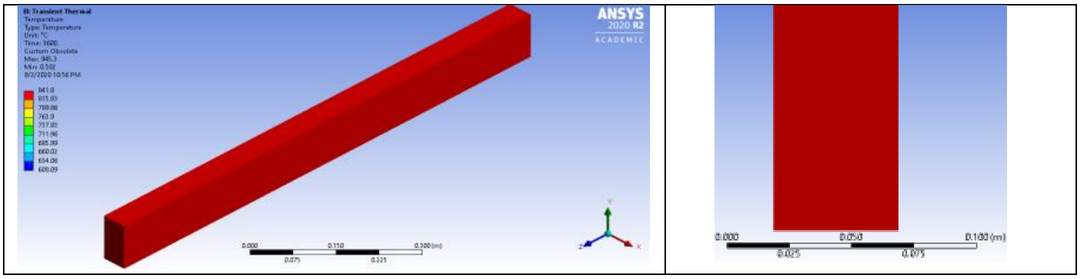

Figure 12: Temperature distribution of the timber beam size 50mm×100mm×1000mm

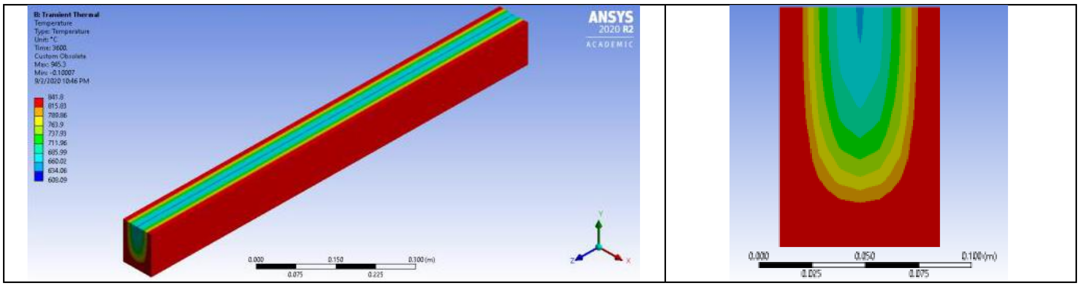

Figure 13: Temperature distribution of the timber beam size 75mm×100mm×1000mm

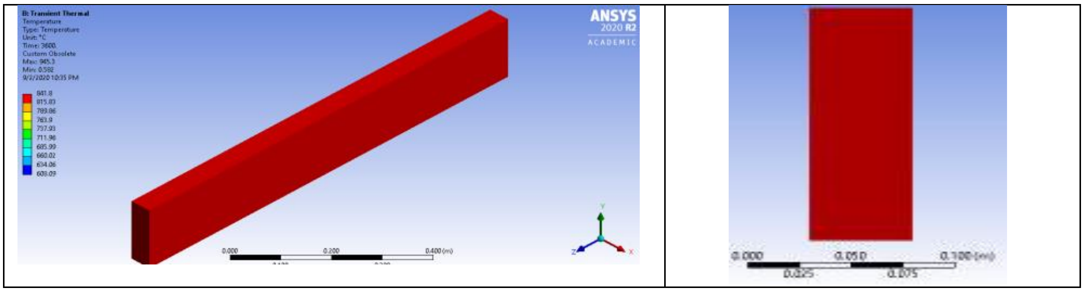

Figure 14: Temperature distribution of the timber beam size 50mm×150mm×1000mm

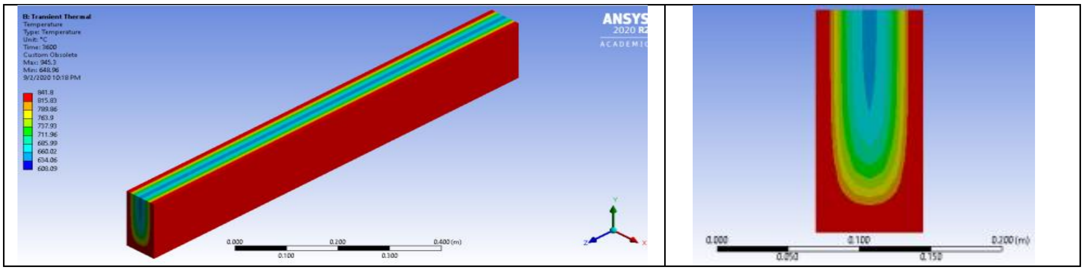
Figure 15: Temperature distribution of the timber beam size 75mm×150mm×1000mm

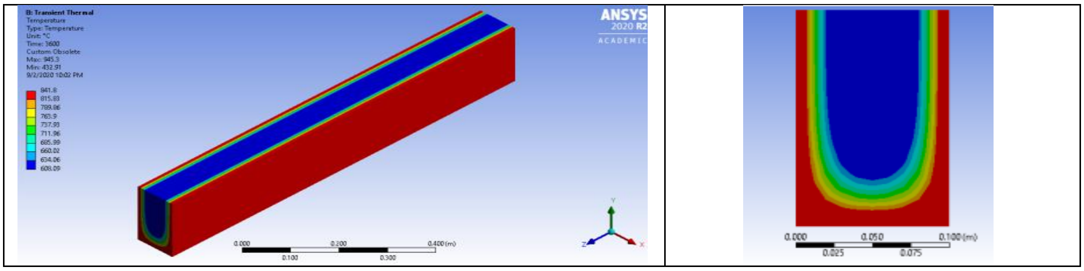
Figure 16: Temperature distribution of the timber beam size 100mm×150mm×1000mm

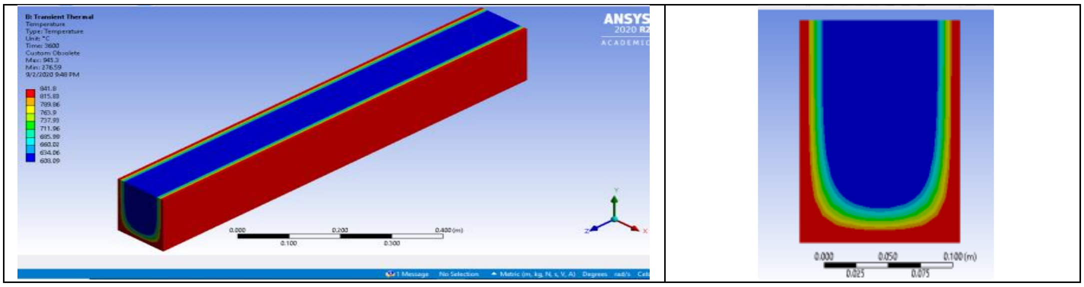

Figure 17: Temperature distribution of the timber beam size 125mm×150mm×1000mm

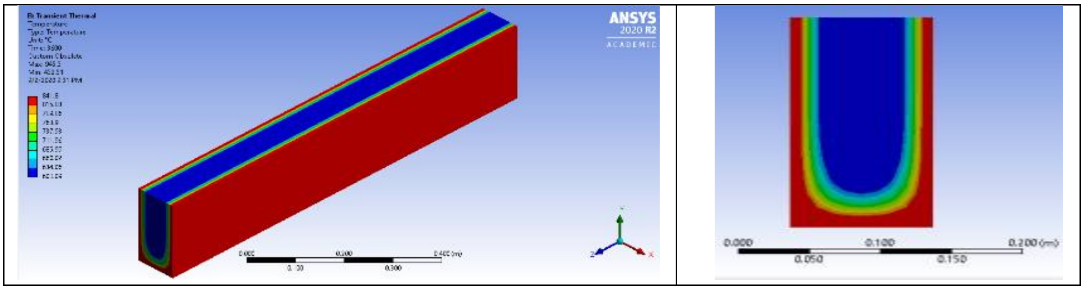

Figure 18: Temperature distribution of the timber beam size 100mm×200mm×1000mm

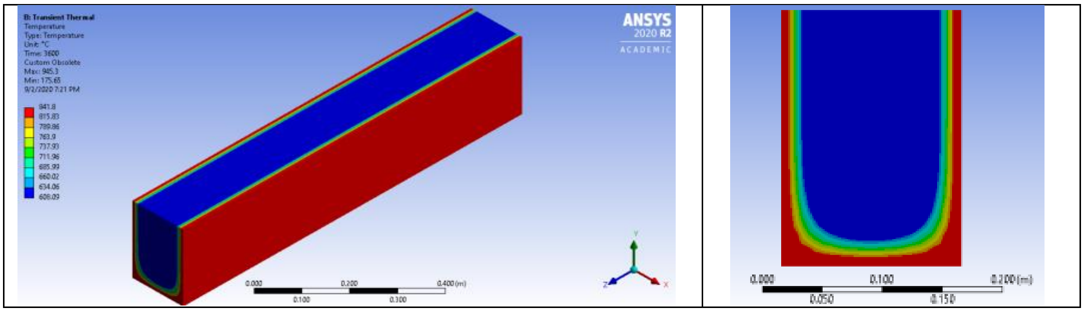

Figure 19: Temperature distribution of the timber beam size 150mm×200mm×1000mm

In the context of a 60-minute fire exposure, where the maximum temperature distribution reached 945.3°C, notable structural responses were observed among the beams under investigation. Several beams exhibited varying degrees of failure, with some succumbing to complete combustion while others displayed partial burnout. Specifically, considering the dimensions of the beam (50mm×100mm×1000mm), it became evident that this beam had completely burned by the 45-minute mark. Conversely, the beam with dimensions (75mm×100mm×1000mm) did not experience total burnout, but it reached a critical stage of degradation that would be classified as failure due to substantial heat-induced damage. Similarly, the beam (50mm×150mm×1000mm) exhibited complete burnout after 50 minutes of fire exposure. This finding is consistent with findings of previous study (R. Aseeva et al., 2014; Babrauskas et al., 2005; Wells et al., 2018).

The beam (75mm×150mm×1000mm) also neared total combustion, although its condition was slightly better compared to the (75mm×100mm×1000mm) counterpart. Notably, the remaining beams remained structurally sound and withstood the fire exposure, exhibiting no signs of significant damage or failure. These observations underscore the varying fire resistance capabilities of beams with different dimensions, shedding light on the critical threshold for structural failure in fire scenarios, which is essential for informing structural design and safety standards (Daud et al., 2015; Fahrni et al., 2017).

CONCLUSION

The findings and subsequent analysis within this research substantiate the acceptability and comparability of utilizing software for experimental testing purposes. Notably, the study explores the structural integrity of beams subjected to three-sided fire exposure and investigates the evolving cross-sectional characteristics of these beams in response to varying durations and temperatures of fire exposure. The software employed for this investigation was the student version of ANSYS, which, while a valuable tool, is associated with certain limitations, particularly in terms of result outputs and input data parameters. It is important to emphasize that this research has diligently adhered to the constraints imposed by the software, utilizing the maximum allowable input data to ensure comprehensive and accurate results within the software's capabilities.

One of the primary objectives of this research was to ascertain the performance and resilience of beams in a fire scenario, specifically the beams' ability to withstand three-sided fire exposure. The utilization of software facilitated the virtual experimentation necessary to investigate this phenomenon. The results obtained from this simulation-based approach provide valuable insights into the behavior of structural elements under fire conditions, contributing to the broader understanding of fire resistance in construction and engineering.

However, it is essential to acknowledge that while software simulations offer numerous advantages, the software inherently possess limitations stemming from their computational constraints and simplifications. Researchers must operate within these confines to ensure the validity and applicability of their findings. Nevertheless, within these boundaries, the study successfully achieved its objectives, offering valuable data and knowledge that can inform future research endeavors and practical applications within the field of structural engineering and fire safety.

AUTHOR BIOGRAPHY

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