Performance of Type X Gypsum Board on Timber to Non Standard Fire Exposure

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Abstract

Timber buildings are becoming increasingly sought after for their aesthetic and environmental appeal. Commonly, timber elements are encapsulated using multi-layered fire rated gypsum board in order to prevent the timber from contributing additional fuel load to the fire or to be approved by authorities. In recent studies performed in the last five years where non-standard fire exposures have been utilised, there have been concerns as to whether encapsulation successfully can improve the fire performance of the assembly due to board fall off or heat penetration between layers in the full duration of a non-standard fire scenario (which includes cooling phases and burn out). There has been a dearth of attention in understanding the underlying mechanisms to these documented behaviours. To address this research gap, a two-stage research program studying multi-layered and fire-rated gypsum clad stand-alone columns was undertaken by the authors in both a field and controlled laboratory study. These experiments were conducted with the purpose of understanding timber column multi-layered encapsulation performance in non-standard fires that include a natural cooling phase. In the field study, a stand-alone timber column within a large, open farm structure was encapsulated in three layers fire rated gypsum board. The fire was spot-ignited and allowed to burn until the building and the column collapsed. That experiment provided evidence that the fire rated gypsum board was not sufficient to protect this timber column, as the temperature increases under the layers of gypsum board were equivalent to the temperature increases on the exterior of the column. The second stage of the research involved four, encapsulated timber columns with localised non-standard fires (methanol pool fires exposing one face only) in controlled laboratory conditions. These tests used novel narrow-band spectrum illumination to document the underlying breakdown of the gypsum board with non-standard fire exposure and cooling phases. Results of these experiments imply that timber elements can be adequately protected from fire exposure providing that the screw spacing is strictly adhered to and redundant layers are utilised. The paper concludes with a listing of priority research areas that will advance knowledge of the performance of gypsum boards on timber in fire.

Keywords: Gypsum board, encapsulation, timber columns, gypsum fall off, narrow-band spectrum illumination, structures in cooling

Contents

1. Introduction & Motivation

Architecturally, timber structures are becoming more and more desirable worldwide. However, the combustible nature of timber makes their design very complex, as timber can contribute fuel to the fire, intensifying the smoke production and severity of the fire. Moreover, as timber chars, the member cross-sections reduce, leading to a reduction in loadbearing capacity. For these reasons, encapsulation, or covering, of timber members is seen in timber buildings globally. Many recently built timber structures have used encapsulation to cover any exposed timber, either to achieve a necessary fire resistance rating of the structural members or to be approved by authorities. Fire rated gypsum board is a popular material for encapsulation and has been used in high profile timber buildings such as the Brock Commons Building found in Vancouver, Canada [1].

While the use of gypsum board compromises many of the benefits of timber construction (such as the loss of the architectural appeal and the addition of extra materials increasing the environmental impact of the project), what is of academic interest is that previous tests have shown that fire rated gypsum board may not remain fully intact for the entire burn out time of a compartment fire. Recent tests have provided evidence that gypsum board may not effectively remain fastened to timber members during fire exposure in a compartment and fall off is largely attributed to its multiple dehydration reactions [2], screw failure, and/or discrete cracking of the boards (where studies have shown that cracks can act as pathways for heat flow) [3]. For years, research institutions have been noting the fall off of gypsum board in fire experiments [4, 5]. The compartment fire test series performed by NIST and NRCC are a recent example [6]. In those tests, researchers noted that gypsum board fall off occurred in their test configurations, with the severity of fall off ranging from only the face layer of gypsum board falling off, to up to all three layers of gypsum board falling off [6]. Edinburgh-Arup researchers [7] have also noted the fall off of gypsum board during fires in their 2.72 x 2.72 x 2.77 m timber compartments reporting that the dozens of pieces (together weighing over one hundred kilograms) of plaster board fell off during their experiments. In the literature review conducted by Brandon & Östman [8], several previously reported cases of second flashovers linked to the fall off of multiple layers of gypsum board were identified. These findings reinforce the indication that gypsum board fall off is of concern for timber structures. It should also be noted that for all of these studies, the sizes of the compartments have been approximately the size of a residential room and the bulk of the research has concerned CLT surfaces, which highlights the need for more investigation into larger compartments and various other timber-products and materials.

While the above literature is very useful information, there is a dearth of information on the fall off of gypsum board when applied to structural members such as beams and columns (whether stand-alone or as a wall system), rather than CLT surfaces such as walls and ceilings. There will be unique differences in the encapsulation techniques of beams and columns, since the members will need to be encapsulated on multiple sides and will require different methods of overlapping and connection.

The present lack of ability to predict the fire performance of protective systems, such as gypsum board, has been identified as a major obstacle in modeling the fire-structure response of timber buildings in non-standard fires [9]. So far, the bulk of the research has

focused on compartments the size of smaller rooms and on encapsulation of CLT surfaces. This has provided the motivation to the authors to examine the fire performance of stand-alone timber columns, typical of open space construction, that have been encapsulated with (multi-layered) gypsum board as subjected to non-standard fires in two stages: a field and a controlled laboratory experimental study.

The authors present results from a field study and controlled laboratory study in which stand-alone timber columns encapsulated with multi-layered fire rated (Type X) gypsum board are exposed to a steep rise in temperature (initial ramp rate faster than the standard fire) to a credible high temperature plateau (greater than 800°C) possible in a real fire. The duration of heating in the studies lasted no more than half an hour (a time suggested by the burnout time within the field study). These tests will also consider the damage to the timber after the fire is extinguished, as it has been previously reported that gypsum boards have fallen off post fire [1].

It is important to discuss that this manuscript's scope is not to define a realistic fire scenario in a real timber structure nor study its compartmentalised fire dynamic behaviour – indeed the fire scenarios illustrated herein are a few of many possible scenarios that timber structures with gypsum boards may experience. We acknowledge that other fire scenarios and fire dynamic testing can help verify or advance the fire behaviours reported herein. The value of our study is that the research can be built upon by others while illustrating novel encapsulation behaviours not entirely documented before in fire exposures, particularly where the fire exposure is of a non-standard nature with natural cooling (burn out) phase.

2. Experimental Design and Methodology

As current drivers are being considered for large open architectural spaces in construction, the authors focus their attention on stand-alone columns. The two -stage study was performed sequentially meaning the results of the field study, pilot in nature, had impacted the experimental design and methodology of the second stage of the research project, controlled laboratory tests. The first stage of the project was motivated by the construction of the Canadian Brock Commons building, a 53 m tall hybrid concrete- timber structure where columns were at times installed as stand-alone with multi-layers of gypsum board. Figure 1 illustrates an encapsulated column, representative of encapsulation systems used in existing Canadian tall timber structures. In the study herein, care was made to obtain materials representative of actual construction techniques that would be employed in tall timber buildings in Canada i.e., same manufacturers and specifications of Type X - Gypsum board available to the Canadian market. Various other gypsum technologies should be explored through future studies.

Figure 1. Encapsulation installation procedure of a stand-alone column (prior to gap sealing/wall-finishing), representative of encapsulation used in Canadian tall timber structures
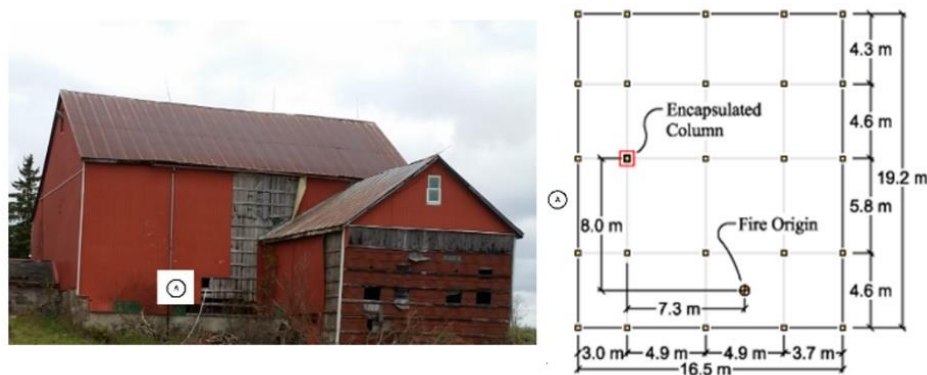
2.1 Field study

A farm structure (a timber barn) with a floor area of 317 m^2 was procured for a large-scale burn conducted in Southern Ontario through multiple partners (primarily the security and insurance industry as well as for fire-fighting training). The structure building dates to as early as 1890 – though it was not categorized as a heritage structure. The field study burn was the last procedure performed on that site that day, and therefore heavily restricted the amount of instrumentation and field preparation which was allowed, requiring certain limitations, and ultimately justifying the need for a controlled study that would follow (detailed in Section 2.2).

Although the structure was relatively empty of contents, some mixed hay, as well as small amounts of loose lumbers, books, and plastic tarps remained. The primary fuel source for the fire was therefore the exposed timber of the barn. A full structural survey and material condition assessment of the structure was conducted prior to burning. It was determined through this examination that the timber structure was decaying along the exterior frame. This well - ventilated farm structure should not to be construed as typical of any new farm or even residential/commercial structure, but its structural components do provide value as well as opportunities for assessing timber construction behaviour in high temperature exposures. The interior timber column taken under consideration was in good condition, of Oak timber species, with no evidence of rot or decay through analysis (pull out of screws, field tests for rot, etc). This column was ideal to be encapsulated to study its behaviour under fire exposure (denoted as Column 1 herein). The dimensions of the column were 230 mm x 267 mm, which was similar to the size of columns used in existing tall timber structures in Canada. It was hypothesized (and later confirmed) that the column was also unlikely to be affected by any collapsing debris surrounding it that the structure might impose (ie., it was expected the column would remain standing without debris impact for most of the duration of the test). It was also assumed that the column chosen had similar loading to surrounding columns due to the rectangular column grid. The column had no additional loading beyond service loads. Figure 2 shows the structure's condition, appearance and dimensional features illustrating the column.

Due to limited time and access to the site, the authors' research team were strictly limited to six hours of instrumentation time and site preparation. Only four of those hours were available in natural day light conditions. As a result, one load bearing timber column in the farm structure was encapsulated with three layers of fire-rated 15.9 mm Type X gypsum board. Strict allowances for screw spacing and depth of screws into the timber structure were considered and followed from CSA O86-14 standards precisely. The spacing requirements from CSA O86-14 that were followed included having a maximum screw spacing of 300 mm on centre, having each board fastened by two rows of fasteners (off set by half the row spacing), and ensuring that each fastener penetrates the wood by at least 25 mm [10]. Each layer of gypsum board was installed and screwed separately. The gypsum board installation procedure is illustrated in Figure 3 and was meant to be representative installation of existing tall timber structures. Although the authors planned to install four layers, there was only time to install three layers and therefore that number of layers would control the amount of layering seen in Stage 2 of the research program for consistency. The remainder of the farm structure was left unprotected (without encapsulation). Figure 3 provides instrumentation details of the encapsulated timber column. As shown, the column was instrumented with 16 K-Type

thermocouples (as limited by the available Data Acquisition channels) distributed on the surface of the encapsulation, between layers, and on the surface of the timber. Thermocouple leads were protected with Rockwool insulation and aluminum wrapping as they extended out of the structure. Thermocouples were not placed inside the timber, as the focus of this experiment was on the performance of the encapsulation system only (not the performance of the timber). The data acquisition unit was left a distance of 10 m from the structures exterior. Prior to the structures full collapse, safety and equipment maintenance protocol dictated that once visual indications of structural failure began (noticeable tilt of the back exterior portion of the structure), portable instrumentation was to be disconnected and salvaged – including the Data Logger. Data monitoring of the thermocouples would therefore discontinue at that indication, though video would continue until camera failure, complete collapse of the structure or to burn out. Two interior and three exterior hi-resolution cameras were set up at various locations to obtain qualitative data on the evolution and behaviour of the fire. Ignition occurred in a small sub compartment of the main farm structure, at a position 8 m by 7.3 m away from the encapsulated column. The location is labelled as the 'fire origin' in Figure 2 (approximately 10.8 m away). A member of the fire brigade used a match to ignite hay within a sub compartment of the barn. The fire was ignited in the sub compartment to ensure flashover in this region, which would then spread to the main barn. During the fire, strict safety protocols were employed by the attending fire brigade, and material recovery post fire was prohibited due to safety concerns of smoke contamination of materials. The authors were able to salvage the column's thermocouples, and these gave no indication of damage to the thermocouple cables.

Figure 2. Back side of timber farm structure (left), and atrium dimensions (right- annexes not rendered).
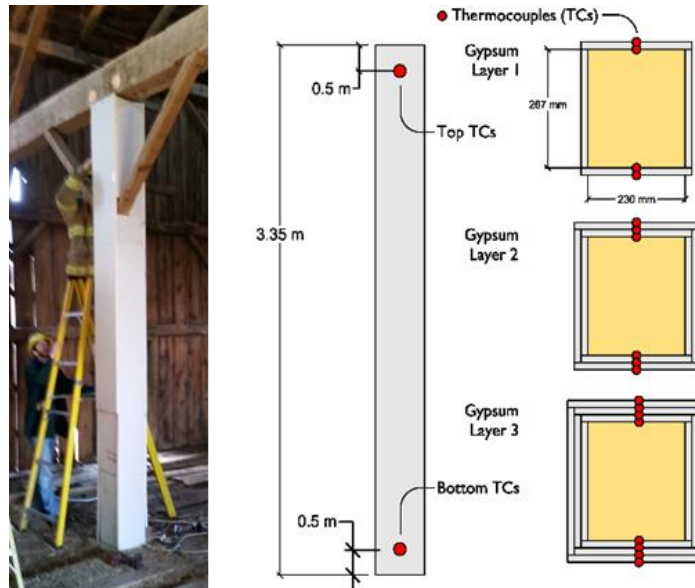
Figure 3. Field study encapsulated Column 1 during construction (left), thermocouple placement (right).

2.2 Laboratory Study

Following the field study, four units of engineered Douglas Fir Glulam fabricated in accordance to CSA O122, 16c-E Stress grade were procured. The timber was chosen as engineered stock as these units formed part of a larger study on adhesive performance in engineered timber underway by the authors and their collaborators [11, 12]. As Oak is a hard-wood, and hard-wood species are not representative of modern structural construction in Canada, the authors therefore did not replicate that species type. Dimensioning was chosen for two sizes with units at 175 x 190 x 2532 mm (denoted as Column 2 and 5) and at 175 x 228 x 2532 mm (denoted as Column 3 and 4). Dimensioning was chosen with consideration to the mechanical loading capabilities available to the authors for later research endeavors that are beyond the scope of this initial paper.

These columns were encapsulated in conformance with CSA O86 with single and multiple layers of gypsum board [12]. The encapsulation of Columns 2 and 3, like Column 1, included three layers of fire-rated 15.9 mm Type X gypsum board as defined in Section 2.1. Columns 4 and 5 were encapsulated with only one layer of this same gypsum board, in order to directly understand how much a single layer impacts the fire performance of the timber. The authors deviated slightly in application in order to specify a 'seam' (two boards side by side) in the fire exposed gypsum layer on the column at mid span for all Columns 2 to 5. This was in order to study possible heat exposure and impact of seams on the overall performance. The 'seam' only appears on the outermost layer and below the board is continuous where applicable. This would be akin to prior wall finishing and a plausible configuration. K-type thermocouples were utilised in order to provide temperature measurement at mid-span. Many thermocouples were placed in redundancy (such as the extra thermocouples located on the bottom of every beam) however thermocouples directly exposed to flame temperatures were

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unreliable in recording board surface temperature exposures as visual indicators illustrated that they detached in testing. Figures 4 and 5 show the thermocouple configurations for each column (2 to 5). The columns and screws were not finished as it was of interest to also observe the possible effects of heat transfer through the screw to the timber (worst case).

The column was exposed to a non-standard fire, with the fire exposure from one side. Testing was performed at the University of Waterloo Fire Research Burn Hall Laboratory. These tests were performed and planned after the field study and the fire exposure was meant to be at least representative with respect to the fire duration (approximately 30 minutes), with steep initial temperature gradient seen in the field study (see Section 3. for justification on the columns heating duration). The columns were not loaded. To enhance visualization through the flames to more clearly observe the gypsum board degradation, the authors' utilised a methanol pool fire. The authors considered and evaluated other pool fire fuel types (such as acetone, kerosene etc.) but ultimately, they were obstructing the view of the specimen through the flames using the novel filming technology (which is discussed below). The methanol fire was observed to create the least amount of soot of the fuels considered. While the choice of methanol may result in different heat exposures in comparison to other fuels, the beam was partially engulfed in, and therefore exposed to, the high temperature flame gases. Thus, methanol was chosen due to the ability to make clear observations and measurements through the flame. The methanol pool fire heat exposure may be considered as a 'natural fire' due to its dependency on the specific fuel load, ventilation conditions, and materials characteristics [13]. Multiple test fires were performed by the authors using various volumes of methanol in different pan shapes to characterize and demonstrate repeatable exposures. For each 30 minute test, 14.3L of fuel in a 0.48 m (width) x 0.6 m (length) pan was needed to achieve the desired fire exposure. Expected exposure temperatures were measured 200 mm above the initial surface of the fuel. The time-temperature curves for the trial methanol fires, performed to determine the volume of methanol needed (denoted methanol 1 to 3), are shown in Figure 6. Each of the time temperature curves represents the temperature read by a single thermocouple, however the maximum difference in peak temperature recorded across the three trials was only 12°C. Localised heating to one third of the column was considered, opposed to uniform heating, as clear comparisons of undamaged and damaged locations could be made on the column and the possible propagation of flames beneath the board to unheated regions could be considered if applicable. The column was rotated as a beam, and was placed so that the bottom face of the beam was 200 mm away from the initial surface of the unburnt liquid fuel. This orientation was chosen so that the fire would reach the seam of the gypsum board, and the damage location could be controlled precisely. It is of note that while the steep gradient in temperature was possible at the initial stages of the exposure fire, it was not possible to generate the equivalent peak temperatures observed from the field study. Therefore, the laboratory tests cannot and should not be considered the same non-standard equivalency as the field test. This was an acceptable deviation, as using the other fuels with higher temperature exposures would have obscured visualization of the gypsum board surface and prohibit qualitative and quantitative observations as will be described in Section 3. Once heating was completed the columns were then monitored during a thirty minute cooling phase in order to assess if damage(s) such as cracking or further delamination of the gypsum board(s)

is exaggerated after the fire burns out. Water was not used for fire suppression in these tests, and strict environmental protocols were used for testing, and wastage disposal of materials.

Following the previous technique validation produced by Gatien et al. [14], qualitative observations and quantitative measurement during testing was performed using narrow-band spectrum illumination and image processing in order to study qualitative changes (cracking/delamination) to the gypsum board at high temperature, as well as approximate deformations and deflection of the columns during testing. The use of narrow-band spectrum illumination and matched optical filters can enhance visibility through clean burning flames [15]. Such a technique has defensibly been shown applicable in laboratory scales (flame spread testing using a LIFT for example). The technology has not yet been adapted nor defended for use in standard furnace (enclosed) fire testing (but such testing is outside the scope of this research). Verification and modification of the technology should be considered for that application in future research. The authors utilised the exact experimental and camera specifications derived from the Gatien et al. study [14] to observe the columns when exposed to the methanol fires. The lab set up included two Spectra Par 100-Watt luminaries with all blue (450 nm wavelength) Light Emitting Diodes (LEDs) to illuminate the sample (see Figure 7). A Canon EOS 5Ds Mark III DSLR camera was used to image the column specimens, this was placed 1.5 m away from the column at an angle of 17 degrees. This camera's resolution (images of 5792 x 8688 pixels) allows placement far away from the specimen during testing to maintain high resolution of the specimen, while reducing the risk of damage to the camera and lenses due to excessive heating and thermal radiation from the pool fire. The following camera settings were used due to the influence of previous research by Gatien et al. [14]: frame rate of 5 frames per second, ISO 2000, aperture f/13, shutter 1/800. A bandpass optical filter consisting of two stacked filters (HOYA Corporation B440 and Midwest Optical Systems BP470) were attached to the front of the camera's default lens. These two stacked filters provided a low-cost and effective band-pass filter at the desired frequency (450 nm). The camera was shooting at an angle, which was measured in order to translate downward and upward movement of the column in these tests into a measurable deflection. Geo-PIV RG [16] was utilised for approximating quantifiable deflection and seam deformation measurements. The technique is considered as an approximation and not a definitive calculation as the technique is not fully adaptable to a material undergoing a phase change. Gypsum boards lose their first coating (paper) layer through combustion and the application of tracking paint is therefore prohibitive. The interested reader is encouraged to read about image correlation limitations further [17].
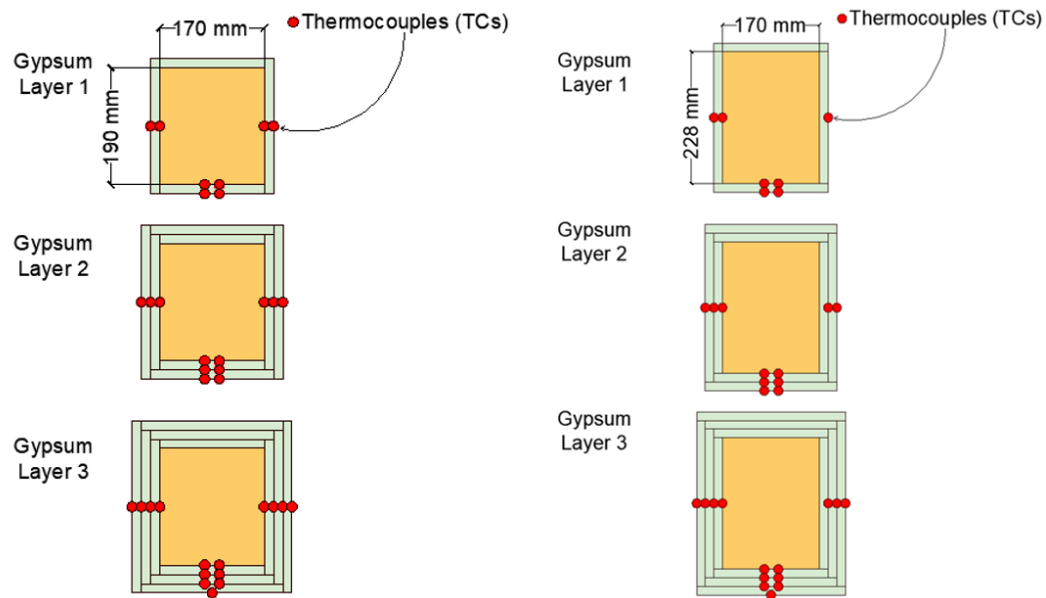
Figure 4. Laboratory encapsulated column thermocouple placement Column 2 (left) and Column 3 (right).
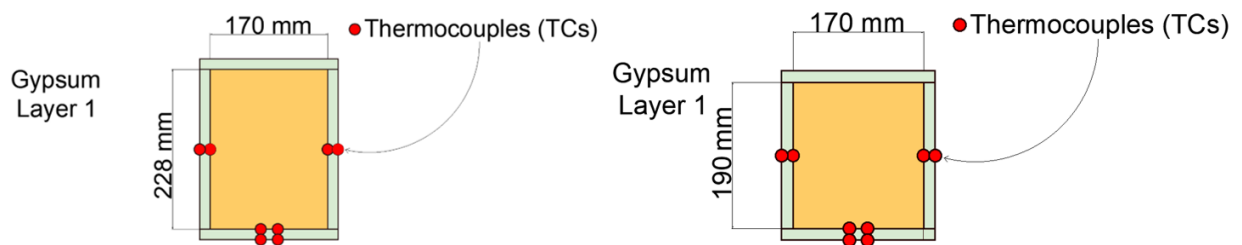
Figure 5. Laboratory encapsulated column thermocouple placement Column 4 (left) and Column 5 (right).
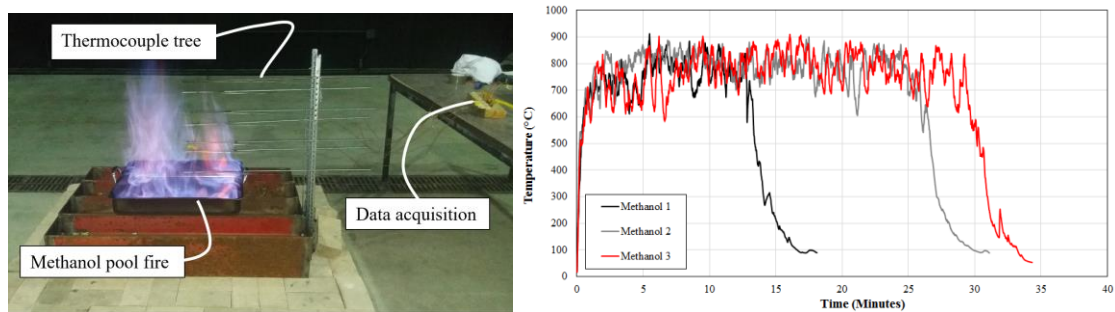
Figure 6. Characterization of methanol non-standard fire, where Methanol 1, 2, and 3 represent the trials considered in determining the volume of fuel required (h = 200 mm)

**Figure 7.** Specimen, apparatus, camera and LED light locations

3. Results and Discussion

3.1 Field study

The performance of Column 1 was evaluated primarily through examination of the temperatures reported by the thermocouples and through recorded video footage as plotted and illustrated in Figures 8 to 11. In the plots shown in Figures 8 to 10 below, Gypsum Layer 1 refers to the thermocouple under one layer of gypsum, Gypsum Layer 2 under the second layer, and Gypsum Layer 3 is between the inner most gypsum layer and the timber column itself. Gas temperature refers to the temperature measured by a thermocouple placed on the outer most layer of gypsum board at the top and bottom of the column on both sides. Fire side refers to the side of the column facing the room of fire origin, and the non-fire side refers to the opposite side of the column (not facing the room of fire origin). While cameras were placed throughout the interior and exterior of the farm structure, the thick flames and smoke made it difficult to see the column within the structure and, in particular the gypsum board encapsulation after the initial period. While it is beyond the scope of this manuscript to discuss the resulting fire dynamics, in brevity temperatures were only recorded at the column location, and the thermocouples were manually terminated by the authors as structural collapse was considered possible and the data acquisition unit had to be retrieved. The structure eventually collapsed approximately 30 minutes beyond the steep temperature rise. It is not possible to deduce temperatures beyond when the thermocouples were taken off line.

From Figures 8 to 10, it is seen that the gas temperatures away from the column rise sharply at 20 minutes after ignition when the fire exposure spreads to the column's location (Figure 10). Within two minutes, rapid heating occurs, and all of the temperatures beneath each layer of gypsum board rise quickly above 1000°C. This behaviour can suggest several aspects relating to cracking of the board, and sealing effect – where fall off of (all) the gypsum board layers is ruled out, as discussed below.

With respect to cracking of the board, once the flames had spread to the location of the column, the gypsum board only delayed the rise in temperature by a minute or two where excessive cracking (without fall off) of all of the board could have occurred, thereby allowing heat penetration into the column. Since the temperature at the surface of the timber appeared to be delayed in heating by only a couple of minutes, there is some evidence that the gypsum board may not be performing as desired. A second hypothesis considers that the gypsum may have had a gap in sealing along the length of the column allowing heat penetration between

the layers. From Figure 9, which focuses only on times around the sudden temperature rise (plotting scales between 22 and 24 minutes), it is seen that the gas temperature rises first, followed by the thermocouple covered by one layer of gypsum, then two layers, and finally the thermocouple at the face of the timber rises in temperature last. These hypotheses suggest that the gypsum board had probably not fallen off at this point as is visually confirmed in Figure 12, and instead hot gases were able to penetrate between layers through an unconfirmed mechanism (at this point). It can be clearly shown that at least one layer of the gypsum board seems to be fastened to the column despite the rise in temperature measured in all layers of the field study – it is therefore doubtful that the simultaneous rise in temperature in all layers was observed because all layers fell off. The exact mechanism cannot be determined without examining the column itself in-situ. Post-fire in-situ investigation was prohibited by the fire department in attendance due to concerns for smoke exposure and its contamination to the materials. In any case, these results suggest that the gypsum board was not successful in functioning fully to burn-out of the fire – at least in terms of performance objectives where heat transfer is concerned. This particular field study therefore justifies additional investigations being required to determine the true influences from board cracking, sealing and fall off in controlled tests performed at laboratory scale.
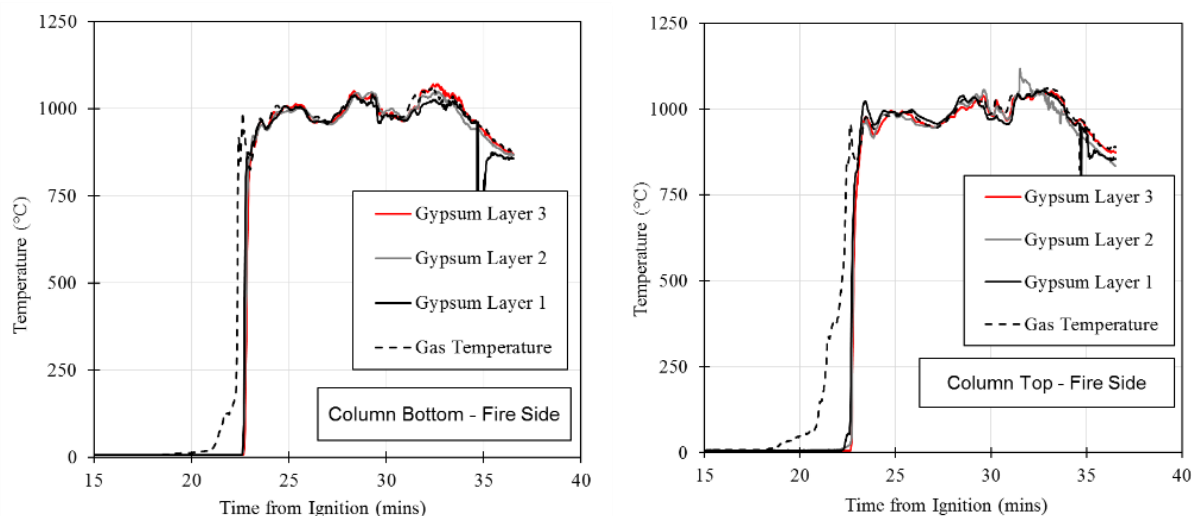
Figure 8. Fire side temperatures measured at (left) the top of the Column 1, and (right) the bottom of the Column 1 (t= 0 ignition)
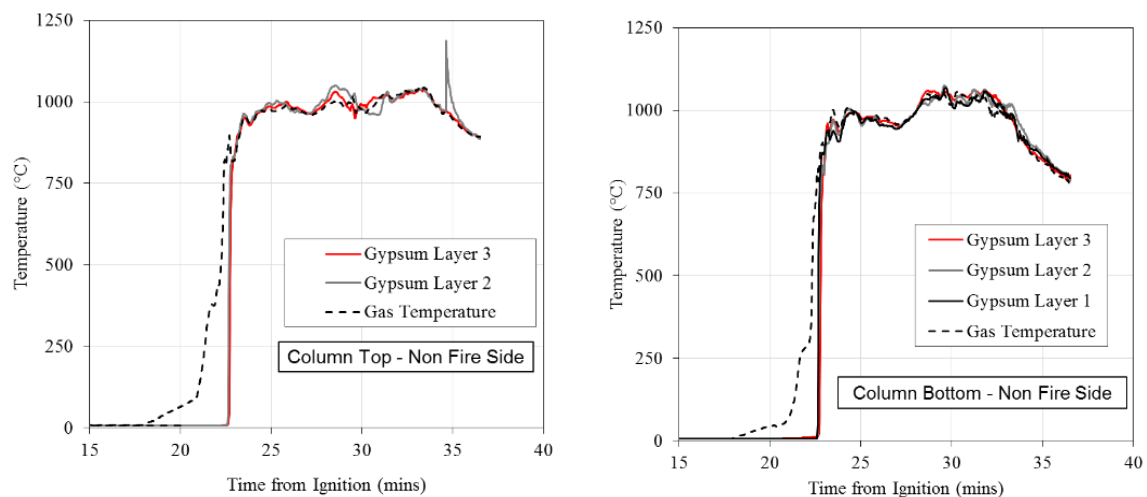
Figure 9. Non-Fire Side temperatures measured at (left) the top of the Column 1 and, (right) the bottom of the Column 1
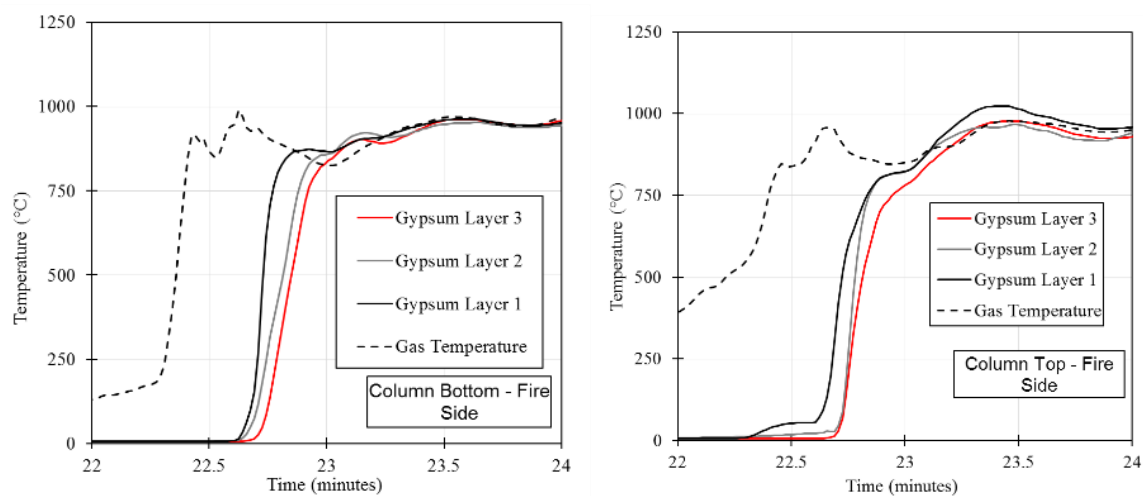
Figure 10. Scale magnified of fire side temperatures measured at, (left) the top of the Column 1, and (right) the bottom of the Column 1 (t= 0 ignition)

Figure 11. Pre heating view of compartment prior to fire ignition (left), atmosphere of compartment when fire spreads to column (right)

Figure 12. Images of Column 1 during field test (left) prior to structural collapse (right) post flashover event

3.2 Laboratory Study

3.2.1 Thermocouple Results

The performance of the timber columns (2 through 5) within the laboratory study were evaluated first through examination of the temperatures reported by the thermocouples as plotted in Figures 13 to 16. In these plots shown, for Columns 2 and 3, Gypsum Layer 1 refers to the thermocouple under one layer of gypsum, Gypsum Layer 2 under the second layer, and Gypsum Layer 3 is between the inner most gypsum layer and the timber columns themselves. Where Columns 4 and 5 have only one layer for consistency it is called Layer 1. Exposed surface and Gas temperatures were unreliable measures in these tests as the thermocouples appeared to delaminate visually from the surface during testing. For the thermocouples underneath at least one layer of gypsum, it could not be entirely verified whether the thermocouple was measuring the gas temperature immediately below the surface of the column, or if the temperature was being measured on the surface of the gypsum which was lower. However, as exact quantities of fuel are given as well as burning rates of the fuel (burn rate of approximately 0.5 L/min) it is possible for the interested practitioner to characterize the exposure if they wish to utilise the results for modelling or replication purposes (which are beyond the scope of this paper). Careful examination of fire dynamics text book literature provides information on repeatability and quantification of heat exposure from pool fires [18].

The fire side of the columns were installed with two thermocouples mid span each denoted A and B respectively, where the fire side is the side of the columns facing the pool fire (the bottom of the column). Thermocouples on the vertical sides of the columns (perpendicular to the fire side) are denoted as C and D. On sides C and D the thermocouples were not installed in replicate as channels in the Data Acquisition were limited.

Figures 17 to 19 are provided to place the temperature profiles into context. Column 2 has a noticeable increase in temperature during the heating portion of the test, increasing to

temperatures of 70$\mathring{0}$C and 35$\mathring{0}$C between the 1st and 2nd gypsum board layer. It is not unexpected that the temperatures do not measure the same between them, on forensic post-fire examination it was observed that these thermocouples were located in the region that coincided with charred zone of the timber. Whereas in Column 3, which showed no temperature incline in the temperatures recorded by the thermocouples, examination post-fire showed that these thermocouples were installed away from this charred zone on the second gypsum layer as observed in Figures 17 and 18. This behaviour gives credence that the fire exposure between the first and second boards likely occurred at an isolated location near the seam, resulting in a localized charred area and not along the full length of the column, as it was only a localised fire exposure. The results seem to verify the temperature measurement trends and hypothesis observed in the field study that indicated temperature rise through penetration between the gypsum layers. In the controlled case, however, the temperatures measured beyond the second layer of gypsum board did not exhibit a spike increase in temperature. Temperatures do discretely rise as expected with duration. The penetration of heating in these tests is likely due to the larger seam opening in the first gypsum layer which correlates to a partial delamination of the gypsum board as tracked through narrow spectrum and image filtration technologies (sometimes called blue light technology). Column 2 illustrates a potential fall off (peel away) of the board in progress as the heating duration halted seen in Figure 20. The post-test examination of Columns 4 and 5 reveals the extent of char damage below the board. Figure 15 reveals that ignition of the Column 4 had occurred during the cooling phase of the tests manifesting as a smouldering fire under the side boards away from the fire. Once the boards were removed after 30 minutes of cooling, the fire was damped out with light amounts of water. Excessive smoking also occurred for these columns post heating phase confirming a small self-sustaining (without additional application of heat) fire. Figure 19 illustrates that Column 4 developed a 25mm deep crack running along the entirety of the heated zone beyond the charred zone which was not present during the installation of the gypsum boards pre testing. Figure 16 does not show evidence of a fire event on the side boards of the column, though analysis after the test revealed thermocouples C and D for column 5 were not in the charred region of the column.

3.2.2 Qualitative Results using Narrow Spectrum and Image Filtration

The innovative use of narrow spectrum and image filtration technologies allows the authors to qualitatively observe the surface deformation behaviour, such as that described above of the exposed first layer of gypsum board in Column 2 and 3 tests. Table 1 and 2 illustrate an arbitrarily chosen surface feature taken on the fire exposed side near a screw on the first layer of gypsum board for each laboratory test. As the gypsum board heats up, a web of discrete fine cracks form on the board on Column 3 immediately after the rapid temperature rise. This does not seem to affect heat transfer at the location of measurement. Note that in Column 2, this phenomenon appears absent along the surface; instead, Column 2 demonstrates a larger crack opening along the surface and partial delamination as previously discussed. Figure 21 illustrates that cracking patterns tend to exaggerate during the cooling process, a phenomena that seemed apparent with any large gypsum board crack opening for all columns. While visually these features appear to be detrimental to the performance of the column, it
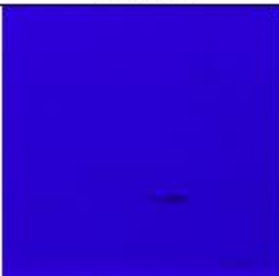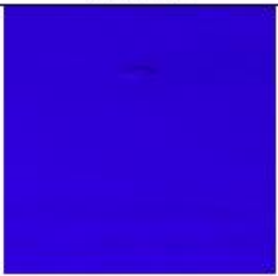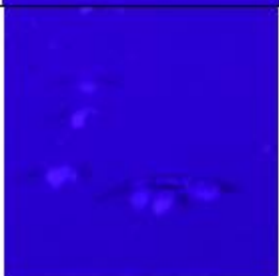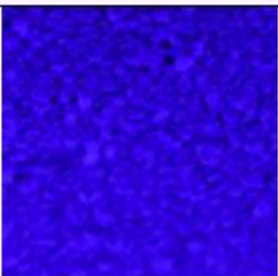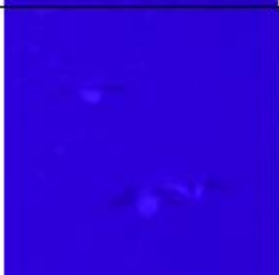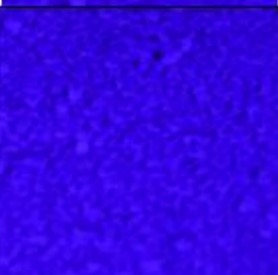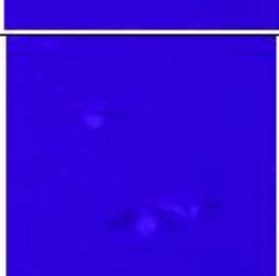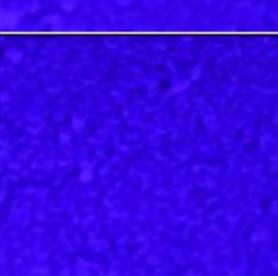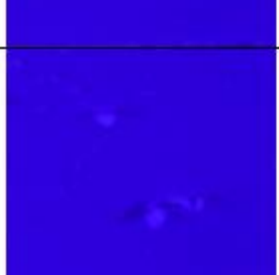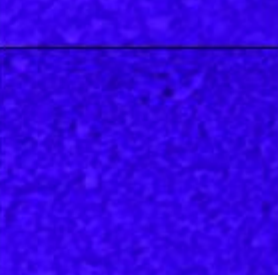
should be noted that the second and third layers of gypsum upon removal during post heating assessment illustrate no visible damage. However, columns 4 and 5 with only 1 layer of board illustrate maximum charring depths of 25 and 15 mm respectively spanning a length of 41 and 29 cm respectively for a maximum 1cm seam opening during the test. While the metallic screws utilised were hypothesized to have potential to transmit heat to the timber below the board, it was observed upon extraction of the screws outside central charred locations that no evidence of localised charring was present in the timber screw holes for post-test evaluation for all tests. A longer heating duration should be explored to test the amount of potential heat penetration into the timber column through the screws. But overall these remained fixed for the duration of all Column 2 to 5 tests.
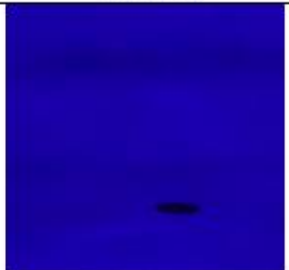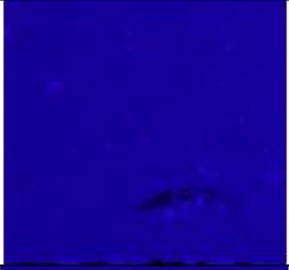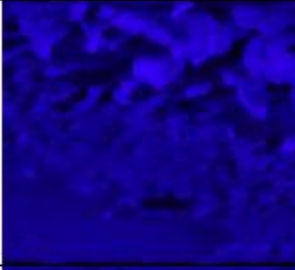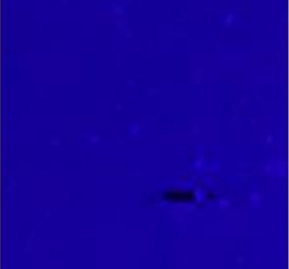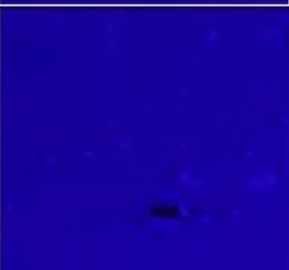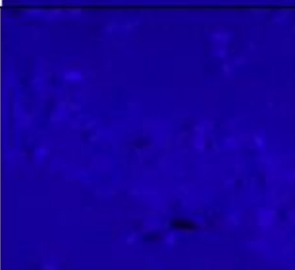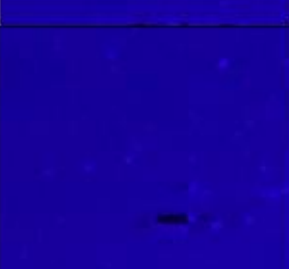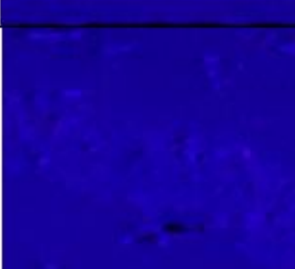
In addition to the gypsum degradation, it was very apparent during the tests that columns 2 and 3 began to bow toward the fire, and upon cooling restored away from the fire. A timber beam unencapsulated tends to bow away from the fire due to dehydration effects. As the timber is protected from the heat it is not dehydrating in these tests, and dehydration is not the driver for the reaction. The bowing behaviour is likely due to a fibre expansion mechanism on the column, as a result of expansion that all layers of the gypsum board are experiencing prior to dehydration dominating the board and timber behaviour (a sign of a short duration fire). Whether this type of heating would induce second order effects on a column would be an appropriate future modelling endeavour. Columns 4 and 5 illustrated negligible bowing behaviour but an expected upward camber at test conclusion. The columns in consideration were not loaded at the time of testing. The addition of an applied load may cause the columns to bow further towards the fire than was observed in this study- this effect could be explored in future research, and particularly in model validation.

Table 3 quantifies the exact deflections and seam opening measurements taken from the image analysis. Figure 22 illustrates the measured fall off behaviour with respect to temperature of Column 2. It is supported by the narrow band spectrum illumination technology that fall off/delamination behaviour is driven predominately by the dehydration of the board (100∘C) to when fall off of the board will initiate and is not linked to a specific temperature. Seam openings exaggerated in size during the cooling phase and were substantially large for penetration of air to the surface of the timber, particularly if the board began to peel away from the columns as seen in these tests.

Table 1. Surface texture during heating and cooling

Column 2	Test Time (min)	Column 3
	0 (heating)	
	10 (heating)	
	30 (transition from heating to cooling)	
	40 (cooling)	
	60 (cooling)	

Table 2. Surface texture during heating and cooling

| Column 4	Test Time (min)	Column 5
	0 (heating)	
	10 (heating)	
	30 (transition from heating to cooling)	
	40 (cooling)	
	60 (cooling)	

Table 3. Deflection and Seam opening measurements

Column	Max deflection - heating (mm)	Max seam opening - heating (mm)	Max deflection - cooling (mm)	Max seam opening- cooling (mm)
Column 2	- [1]	105 [1]	- [1]	118 [1]
Column 3	12	6	6	9
Column 4	4	6	-4 [2]	9
Column 5	6	2	-1 [2]	6

[1] – Seam includes opening that developed from peel away of gypsum board, it was not possible to take a total deflection with the peel away present on the column
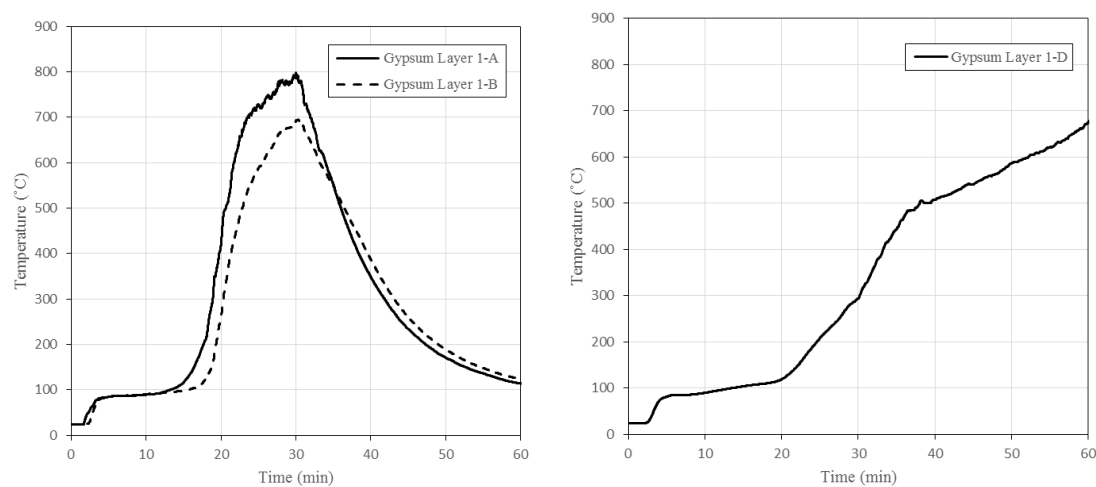
[2] - Upward camber of the beam
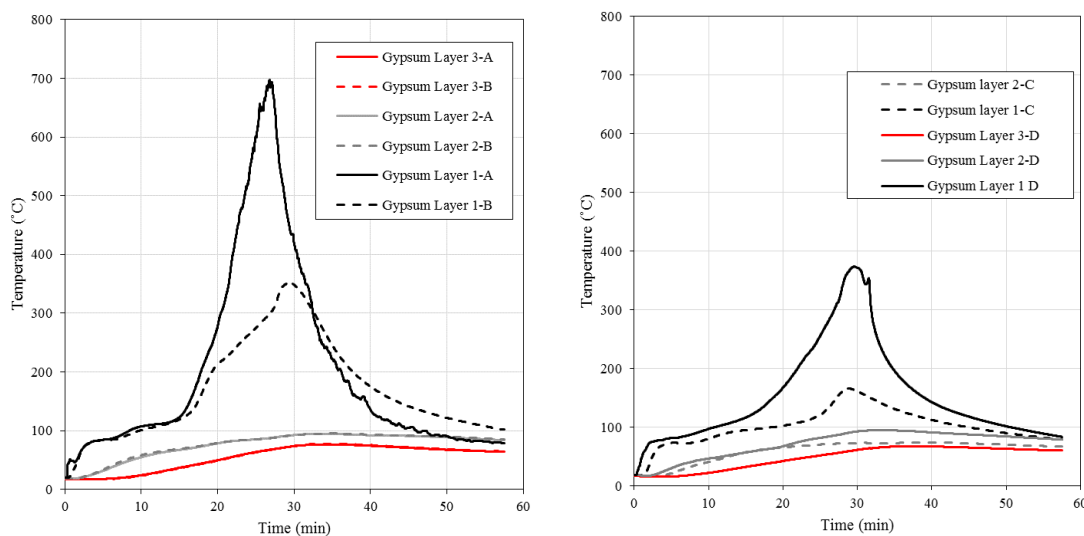
Figure 13. Recorded temperatures between the gypsum board layers for Column 2 (175x190x2532) (Note: TC 3C was not installed properly)
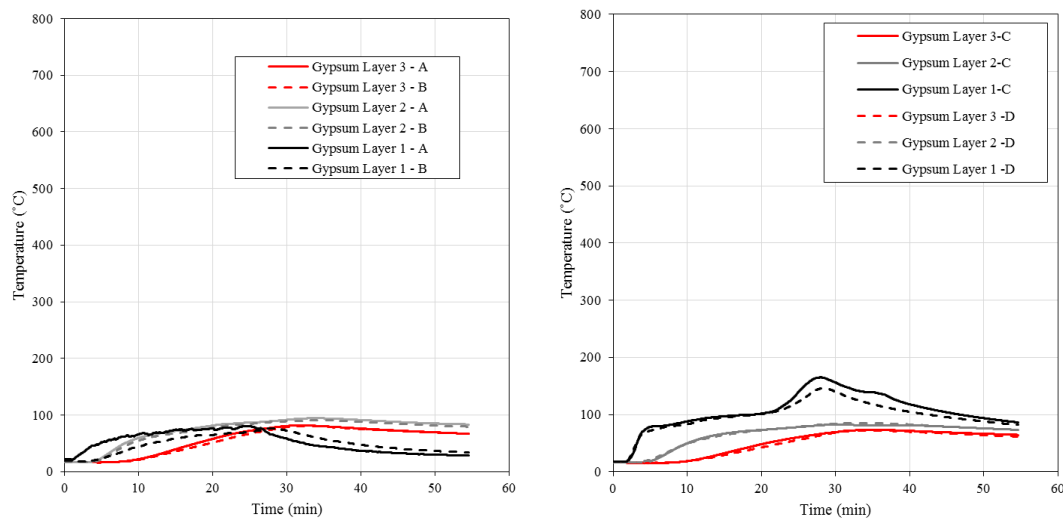
**Figure 14.** Recorded temperatures between the gypsum board layers for Column 3 (175x228x2532)

Figure 15. Recorded temperatures between the first and second gypsum board layers for Column 4 (175x228x2532) (Note: TC 1C was not installed properly)

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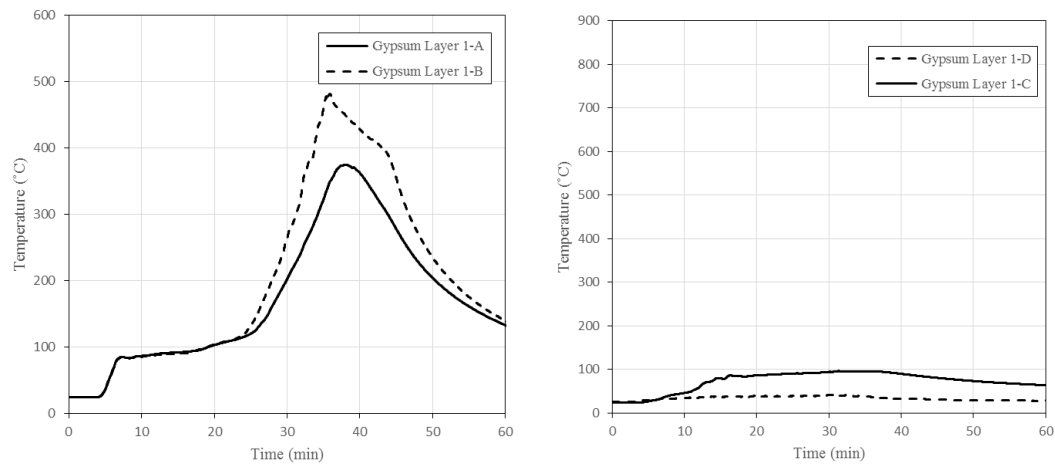
Figure 16. Recorded temperatures between the gypsum board layers for Column 5 (175x190x2532)

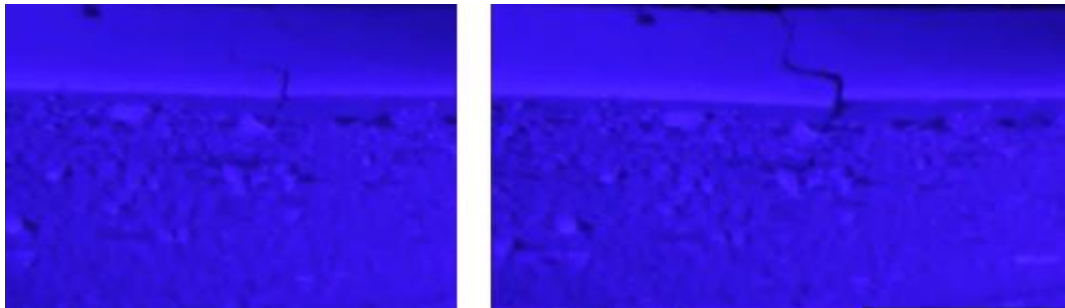**Figure 17.** Post-fire 'seam' opening in Column 3
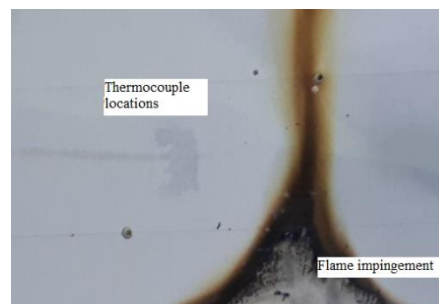
**Figure 18.** Flame impingement after fire of Column 3

Figure 19. (left) Post-test condition of Columns 4 and 5 (right) post-fire cracking of Column 4 (note Columns 2 and 3 showed no signs of char damage)

Figure 20. Delamination and cracking action of Gypsum Board at seam Column 2 during heating

Figure 21. Crack opening after heating in Column 3 (left at end of heating, right at end of cooling)
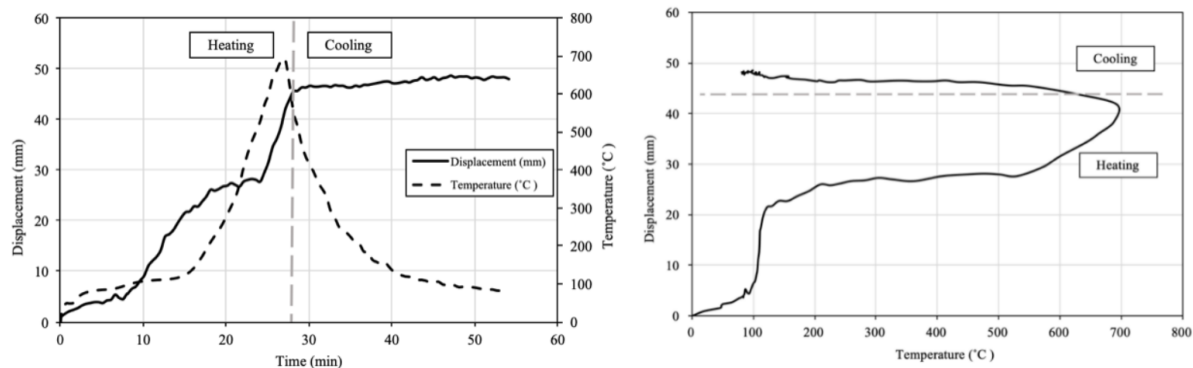
Figure 22. Peel away of soffit gypsum board in Column 2 with respect to time and temperature (temperatures are those recorded by Gypsum Layer 1-A)

4. Conclusions and Future Work

The performance of the five encapsulated columns has raised several important design considerations and insights into future studies. On the basis of all tests, it appears that the presence of multiple layers of Type X gypsum boards alone cannot always be successful at significantly delaying a rise in temperature at the surface of the timber column. One layer of board seemed ineffective where charring depths were near 25 mm for 30 minutes of direct non-standard fire exposure with a maximum charred region of over 40 cm in length for a seam opening of approximately 1 cm. The reasoning for these temperature rises and charring behaviours appears to be caused by the junctions of the gypsum boards, causing a seam on the

column. Each seam grew upwards of 1 cm during the tests allowing heat to penetrate below the layers, where one layer is used, prompting ignition of the timber beneath the board lasting well into the cooling phase.

From laboratory experiments, it seems evident that by installing three layers, redundancy can be provided, implying that timber elements can be adequately protected from fire exposure providing that screw spacing is strictly adhered to and redundant layers are utilised. In the field study, there is potential that even if the gypsum board is installed in accordance to current standards, all layers may still not survive burn out in a realistic fire scenario. In the laboratory study, which innovatively applied narrow spectrum illumination technology, discrete and large quantifiable cracking patterns in the gypsum board may exaggerate in the cooling process. Cracking mechanisms appeared not responsible for heat penetration within the column. Delamination is possible at low heating times. Testing confirmed that cracking that occurs during heating exaggerates during cooling, and this behaviour gives credence to the fall off of gypsum boards during the burn out phase of testing.

In both the field study and the laboratory study, the rise in temperatures occurs at a rate higher than the standard fire, indicating that the time-varying heat fluxes that the columns were exposed to in this study were higher than those considered by standard fire testing – at least in initial heating phases. Furthermore, in this study, the gypsum boards began to fail (by peeling away from the timber) at lower temperatures than would be anticipated if the assembly were exposed to standard fire exposure. This result may support the notion that the temperature may have less of an impact on the fall off of gypsum board, than the dehydration (or rate of dehydration) of the board from high incident heat flux. Further testing is needed for verification, which may potentially consider heating timber encapsulated with gypsum board at varying heat fluxes, but these preliminary results align with previous studies on other materials (such as intumescent paints) which have shown differences in material degradation and failure mechanisms to be tied to the rate of heating [19]. Moreover, significant opening of the seams of the gypsum board layers was occurring throughout the cooling phases of testing (Figure 22). This effect may not have been observed if only the heating phase of a fire were monitored, reinforcing the need for non-standard fire testing.

The results of the laboratory study closely looked at both the heating and cooling phases of fire exposure. While many cracks were initially formed in the heating phase of the test, many of these cracks became larger as the gypsum board cooled. This could potentially indicate that gypsum board encapsulation continues to be susceptible to fall off, even after the heating of the gypsum boards has stopped.

While it can be argued that seams will be finished after the construction process completes, there is still reliance on these boards for the construction process at times, and the gap opening that is developing in these tests supports that such a sealant may not remain in place. This will require further study. For the purposes of this study, the seams are used to explain potential behaviours. Based on the testing and evaluation of this experimental program the following areas of research are advised by the authors to build upon this work:

- Equivalent tests of two layered gypsum be conducted to understand both seaming and deflection mechanisms;
- Modelling to evaluate whether localised heating may induce significant second order effects of the timber;

- Other manufacturer's gypsum boards be studied for their performance in non-standard fires;
- Narrow spectrum technology be adapted for standard fire testing for comparison;
- Narrow spectrum technology be enhanced for use with furnace testing, such that furnace tests of encapsulation assemblies following nonstandard curves may eventually be observed;
- Longer duration tests to the point where all layers undergo dehydration and the dehydration processes are more closely studied;
- Study of the use of realistic fires in realistic compartments of timber structures to understand the realistic fire exposure on a timber assembly;
- Include two columns where no gypsum protection is added so that an estimated equivalent char depth relation to a standardized fire exposure can be determined from the non-standard exposure;
- Digital image correlation for strain and deflection should be further validated with narrow band spectrum (blue light) technology; and
- Investigating coupled fire strategies where the boards may be pre-wetted with a sprinkler system before fire exposure.

To begin to address these components the authors have provided preliminary analysis of the fire dynamics of this structure [20], however further work is required on representative structures built in practice.

Acknowledgements

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