BEHAVIOUR OF FIRE-DAMAGED ENGINEERED TIMBER BEAMS

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ABSTRACT

Recently in Canada, the national building code has been amended to include mid-rise engineered timber buildings. The code also contains an allowance for Alternative Solutions, in which taller and more complex engineered timber structures may be built with sufficient research and proof of performance. For sustainable material use in infrastructure, an environmentally conscious population is motivating the employment of new engineered timber constructions. The purpose of this study is to investigate the behaviour of timber members, specifically glulam, before and after fire damage to inform future testing of large-scale engineered timber building systems. The experiments provide valuable data with regards to the post-fire performance and resiliency of mass timber. A novel Digital Image Correlation (DIC) technique using high-resolution imagery for deformation measurement through pixel movement was used for the first time, to the knowledge of the authors, in pre- and post-fire coupon specimens. The DIC analysis proved to be accurate in introductory tests on timber coupons post-heating, with the maximum difference from the traditional instrumentation being within acceptable tolerances in a separate calibration test. The accuracy decreased in the charred coupon tests, where significant scatter in strain measurement was observed, indicating possible refinement of the technology being necessary. In both coupon sets, the unburned members were recorded to have strength 18% higher than their burned counterparts. This suggests that complex failure modes occurred within the charred specimens which caused a premature failure which is investigated herein. Overall, both burned specimens exhibited significant resiliency to a severe fire exposure.

Keywords: Fire, Glulam, Timber, Char, Image Correlation, Fire Resiliency

1. INTRODUCTION

High-rise wood buildings are becoming more of a possibility in North America and specifically within Canada with new code changes and research advancements. Wood, as a structural material, is considered an exceedingly sustainable material option within the Canadian construction market. This has brought on debatable points of view within society to its fire performance and resiliency after a fire as timber is combustible. Such debate has driven a demand for timber structural research to accommodate this construction interest. In context, for the first time in Canada high rise timber construction has been in demand. A 13-storey timber building in Quebec and an 18-storey timber building in British Columbia have recently been approved. These high-rise wood buildings can use engineered mass timber such as Glulam and Cross Laminated Timber (CLT) for columns, beams, slabs and even shear walls. However, as mentioned, a concern society has with timber is fire safety. If these engineered timber building systems are to be used in Canada, the behaviour of the material during and after extreme heating must be fully understood. The purpose of the experimental program described in this study is to closely examine the behaviour of fire-damaged Glulam specimens compared to their unburned counterparts. This is in an endeavour to promote discussion into the fire resiliency of engineered timber, which is a central theme within the CSCE conference this year.

2. BACKGROUND

The fire resistance of mass timber members has been a topic of interest as of late, and many tests have been done to prove that engineered timber members can achieve and exceed code mandated fire ratings. This has predominately
have been led in Canada by the timber industry and related interest groups (see Su et al., 2014; Osborne, 2014 for details). Thus, most research has been conducted with aim to achieve quantifiable endurance ratings, rather than explore the underlying mechanisms which determine the resiliency of the material. This study investigates these mechanisms, and does not focus on traditional fire resistant ratings.

Currently in traditional conventions for timber in fire, the pyrolysis layer in fire-damaged wood beams is simply excluded in any strength calculations. It is unknown what exact mechanics the material in the pyrolysis region is experiencing. To study these mechanisms, post-fire testing may yield beneficial insight. To consider this, an accurate technology capable of measuring strain through damaged timber is necessary.

The use of traditional bonded strain gauges to measure strain and deformation in fire-damaged wood specimens is quite difficult, if not impossible, due to the degraded exterior material. Digital Image Correlation (DIC) is an innovative technique used to capture and measure deformations during experiments, the accuracy of which has been confirmed for concrete and steel at high-temperatures, in uniaxial compression and tension tests to date (see Gales et al. 2012). This technology has provided significant insight for fire damaged materials within the last two years that before this time have never been possible (Gales et al., 2016). To the knowledge of the authors, the use and therefore accuracy of the method, has not been determined for use with timber (burned or unburned) at great detail and is indeed a novel endeavour. This measurement technique allows all of the structural deformations in the member to be observed and quantified in uniaxial (one directional loading) tests. The measurement quantification will permit a discussion into the underlying mechanics and therefore possible fire resiliency of fire damaged engineered timber to inform future research.

3. EXPERIMENTAL METHODOLOGY

To accomplish the research objectives laid out and inform future research endeavours by the authors and others in engineered timber studies for fire resiliency, a series of axial compression coupon tests were completed for this study. First, a small, unaltered Glulam timber square section was loaded axially in compression within the elastic deformation range. The specimen was equipped with a 60 mm bonded strain gauge as well as recorded with the DIC technique as a calibration test. Strain and deformation were measured and compared to traditional measurement technology to determine the accuracy of the DIC method with timber. An image showing the camera setup during a test is shown in Figure 1.

![Figure 1: Test setup for one specimen axial compression test showing the camera setup for DIC data acquisition.](image-url)
Two sets of default sized solid Glulam stub columns were then also examined in uniaxial compression. Each set was comprised of three unique specimens. The three specimens were: an unaltered control specimen, a burned specimen heated under standard fire exposure of one hour (Standards Council of Canada, 2014), and a manually-reduced cross section (by mechanical carving) where material was carved away to the effective depth of the burned specimen (discussed later). The cross-sections of the specimens were square with dimensions of 180 mm and 228 mm respectively, chosen for their availability as common stock sizes. A summary of the axial-compression test series can be seen below in Table 1. All specimens had a stable pre-fire exposure moisture content of less than 6%.

<table>
<thead>
<tr>
<th>Series</th>
<th>Specimen Preparation</th>
<th>Specimen</th>
<th>Caliberation</th>
<th>180 mm*</th>
<th>1</th>
<th>Burned</th>
<th>2</th>
<th>Carved</th>
<th>3</th>
<th>Unaltered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burned</td>
<td>228 mm*</td>
<td>2</td>
<td>Carved</td>
<td>3</td>
<td>Unaltered</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

*Measurement denotes the default size prior to any material modification whether through heat or manual carving.

### 3.1 Specimen Preparation

To prepare the specimens for post-fire axial testing, three phases were involved to condition them for testing.

#### 3.1.1 Fire Exposure

The first phase was to burn one specimen from each of the sets in a furnace at the Carleton University fire lab. The furnace is approximately a 2.5 m squared space with a height of 2 m. Additional glulam members were in the furnace at the time of the fire, however; these are a focus of future studies beyond the scope of this current study. The Glulam sections were burned under the standard CAN/ULC-S101 (2014) fire curve shown in Figure 2 (Standards Council of Canada, 2014).

![Figure 2: Time-temperature curve of furnace during burn, with the standard curve as the dashed line](image)

The furnace burners are manually controlled by an operator, so care was taken to ensure the time-temperature curve in the furnace averaged around the standard fire curve accordingly to the allowable averaged graph area tolerances permitted by the standard. After one hour, the burners were extinguished but the Glulam in the furnace was allowed to self-extinguish for an additional hour. The temperature in the furnace during this decay phase is seen in Figure 3. Rarely are timber specimens studied in this phase, however, this better represents the conditions as would be seen in a real compartment fire exposure where materials are often left to burn out (self-extinguish). In this manner the fire
exposure experienced for these timber members is much more severe than would be expected with a regular one hour fire exposure. Timber charring should be expected in the decay phase. After the one hour of decay time, the furnace door was opened and any timber that was still smoldering was extinguished. This temperature was at an ambient gas phase where it was felt that the gas temperature was no longer contributing to promoting severe charring.

![Temperature-time curve of furnace during decay phase](image)

Figure 3: Time-temperature curve of furnace during decay phase

3.1.2 Char Depth Quantification

During a fire timber undergoes a highly complicated phase change, where the material turns to a porous carbon layer. This layer is considered an insulator against heat penetration to more interior timber, but is highly complicated with its function and degree of effect on the mechanical properties of timber.

After the fire damaged specimens were cooled completely, the char depth on each one was quantified. This was achieved by constructing a frame of the original outer dimensions and measuring the depth that a prodding dowel penetrated in from the outer face. These measurements were done on each face of the specimen at intervals of two centimeters. The apparatus used to quantify the char layer depth is shown in Figure 4. At every point, one centimeter of extra depth was added to the penetration depth to conservatively account for the “zero-strength layer”, as it is defined as seven millimeters in Eurocode 5 (European Committee for Standardization 2004).

![Char depth quantification apparatus](image)

Figure 4: Char depth quantification apparatus. The image on the left depicts the frame from above, where the specimen is held in place by a dowel at the base and was later secured with a cross-rod at the top. The figure on the right shows an elevation of the apparatus, and illustrates how the dowel was used to measure the char depth.
The char depth at each point for the two charred members can be seen in Figure 5 (a) through (d), where the upper and lower bounds of the horizontal axis represent the original dimension. To prepare the unburned, manually-reduced cross-section specimens, an average char depth was calculated. The carved stub column from each of the sets was then cut with a band saw to replicate the average cross-section of the charred beams.

Figure 5: Char depth measurements for north-south and east-west axes of burned specimens

3.1.3 Painting

Digital Image Correlation (DIC) software analyses the deformation of the specimen in question through a series of high-resolution photographs. It does this by tracking user-predefined patches of pixels from one photo to the next by finding the identical regions in each image. In this paper’s context the GeoPIV 8 software (White et al., 2003) was utilised as it is considered one of the most validated DIC software utilised for fire damaged material testing in literature (Gales et al., 2016). For this reason, the subjected specimens must be painted with a speckle pattern as defined therein; the unique textured pattern allows the GeoPIV 8 software to differentiate between different regions. The change in location of each patch and their relative change between each other are then used to infer the strain and deformation imposed on the specimen, measured in pixel per pixel, and the technique is accurate to 0.1 of a pixel (Gales et al. 2012; White et al., 2003). The carved (reduced cross-section) replica specimens and the unaltered specimens in each set were painted with a speckle pattern, but the charred members were hypothesized to have enough variance in the
surface texture for the software to differentiate without painting. Not utilising paint has been known to decrease accuracy slightly for the technology as the authors have found in previous studies (Gales et al., 2016). The final result from preparations of all six specimens (less the calibration test), including the mass loss of the burned specimens can be seen in Table 2.

3.2 Experimental Testing Programme

After all specimen preparations were complete, each stub column was tested under axial compression. The tests were done with a loading rate of 0.305 mm per minute, as specified in ASTM D143 (American Society for Testing and Materials, 2007). Photos were taken with a digital single-lens reflex high resolution camera at three second intervals during each test. The DIC software GeoPIV 8 was then used to analyse the behaviour of each coupon post-test. As aforementioned, a non-destructive calibration test was also run to ensure the DIC method would work with accuracy for timber. The test used a 60 mm bonded strain gauge which was applied to the calibration coupon before testing. The strain in the member was measured using the strain gauge and the DIC method in parallel at the same location on the specimen so the results could be compared. The maximum difference in measured strains between the second DIC analysis and the bonded strain gauge was 0.000121 pixels per pixel (px/px), which corresponds to only 0.16 pixels. This is very close to the quoted accuracy of 0.1 pixels (Gales et al. 2012). For context, a one-millimeter length on the specimen was equal to about 10 pixels. The resulting properties from each of the specimen tests are displayed in Table 2, Section 4 discusses the results in greater detail. The ultimate capacity of the control coupons was not reached in some cases. Instead, the specimens were loaded close to the capacity of the load actuator and held at the maximum load for ten minutes. The stresses and strains tabulated in parentheses for the control specimens are the maximums experienced. Additionally, the correlation in the charred data was not conclusive enough to extrapolate a value for the modulus of elasticity.

<table>
<thead>
<tr>
<th>Table 2: Summary of Specimen Properties</th>
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<tr>
<td>180 mm Coupon</td>
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<tr>
<td>Charred</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>Effective Area (mm²)</td>
</tr>
<tr>
<td>Maximum Load (kN)</td>
</tr>
<tr>
<td>Predicted Max. Load (kN)</td>
</tr>
<tr>
<td>Ultimate Stress (MPa)</td>
</tr>
<tr>
<td>Ultimate Strain (px/px)</td>
</tr>
<tr>
<td>Modulus of Elasticity (MPa)</td>
</tr>
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</table>

4. EXPERIMENTAL RESULTS

As can be seen in Table 2, the stresses reached in the coupons are much higher than the manufacturer quoted compression strength of 33 MPa (Nordic Wood Structures, 2015). This is most likely due to the small size of the coupons, so there were no reductions in the actual strength of the members for size effect and defects. The control member strengths were so large that the failure stress could not be achieved by the test apparatus, so the specimens were simply loaded close to the capacity of the actuator which is 1700 kN. The control coupons were then held at this...
load for ten minutes, to observe if any evidence of plastic and time-dependent behaviour was present. The strain behaviour observed in all members is seen in Figure 6 (a) and (b).

In the smaller coupon (see Figure 6(a)), just after 400 seconds, the beginning of some plastic and time-dependent behaviour is observed. This is when the constant loading was sustained, but additional strain was still recorded. This may indicate that the coupon was close to failure at the applied sustained load. In Figure 6(b), at around 1400 seconds when the constant loading began, there is no additional strain observed. There is therefore no evidence to suggest that the larger coupon was not near failure at the sustained load, which can also be concluded by the much lower stress level that the large coupon was experiencing at that maximum.

![Figure 6: Strain versus time graphs for the three specimens in each series](image)

The failure mechanisms of the stub columns were very subtle. In each case, cracking was observed in the top and bottom faces of the specimens between radial layers of the wood or between laminates themselves. The cracking between laminates was observed more often in the charred specimens, as the Glulam adhesive would have been degraded from the fire. This is an important implication when considering the post–fire resiliency of engineered timber structures and has not been studied with great detail as of yet. In this case it appears to have a significant impact on the remaining strength of engineered timber.

In both sets of coupons, the ultimate strength reached by the carved specimens was about 18% higher than that of the charred specimens. This is arguably a small difference. It is the opinion of the authors that it may be indicative of the role which the degraded timber adhesive is playing in the mechanics of the timber after a fire – however it must be considered that the accuracy of the carved layer may have contributed. It is possible that more of the underlying timber
is damaged than was originally believed and the effective cross-section of the charred specimens should be further reduced. Further study will investigate this difference.

Although a conclusive modulus of elasticity for the smaller charred specimen was not found, the trends indicated a much higher value than that of the unburned specimens. In both sets, the burned members were observed to have a higher stiffness than their unburned counterparts. The modulus of elasticity was determined in each case by a linear trend in the stress-strain diagrams of each specimen. In most cases (except for the 181 mm charred coupon), the strength of the correlation for the modulus of elasticity trend line was greater than an R^2 of 0.95. The scatter in the charred coupons strain data is most likely a result of the char not deforming at the same rate as the sound timber beneath it. It is possible that sections of char which had separated from each other were moving independently, depending on the connection to the un-damaged wood beneath.

5. DISCUSSION AND PRELIMINARY CONCLUSIONS

The Digital Image Correlation software proved to be quite accurate from the calibration test, in which the greatest error was found to be 0.16 pixels. The results for members with no char were much more conclusive than the charred coupons. It is recommended to run further analyses of the strain on the charred members in different areas, and to take an average of those strains to converge on a more accurate curve. A further study may also be conducted where tracking paint is applied to char layers to help improve the measurement of the deformation. If the char is brittle and of very little strength however, this may not aid, and further study will be required.

The unburned wood coupons had a strength that was about 18% greater than the burned ones in both coupon sets. In all cases, the strengths recorded were higher than the manufacturer quoted strength in compression parallel to the grain. Additionally, the stiffness of the burned members was found to be much greater than that of the non-fire-damaged ones. This increase could not be fully quantified due to the significant scatter in the charred coupon stress-strain curves.

Overall, despite the significant fire exposure induced on all specimens, it was seen that the remaining reserve strength capacity of fire damaged timber Glulam coupons was of significant strength and reserve capacity despite its more complicated manufacturing process involving engineered adhesive additives. This was seen by comparing the carved and burned specimens. While still different they had a number of similar characteristics in strength. In fact, the ultimate stress reached by the charred coupons was still higher than the quoted strength from the manufacturer. Additionally, the failure mechanisms involved were far from violent. As the specimens, burned or unburned, approached their failure small cracks began to form as warning. When failure was finally reached, many laminate layers within the specimens maintained integrity while the load began to drop slowly and steadily. Further research, as is indeed planed by the authors, should help enlighten the subject on the fire resiliency of engineered timber. In Canada we should expect a growing need for more information as we make these buildings even more complex.

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REFERENCES


