Glulam beam made from hydrothermally treated poplar wood with reduced moisture induced stresses

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Moisture induced stresses were studied in glulam beams, which were made from hydrothermally treated poplar (Populus deltoides) wood in the current research work to understand whether the hydrothermal wood modification can reduce those stresses or not. Wood blocks with dimensions of 6 (R) × 10 (T) × 73 (L) cm³ were cut and hydrothermally treated in a stainless steel reactor at temperatures of 140 and 160°C for a holding time of 30 min. The treated wood blocks were dried to achieve moisture content of 12%. Afterwards, the glulam beams (4-ply) were manufactured by using polyurethane (PUR) adhesive. In order to evaluate cross sectional moisture induced stresses (MISes) and bending properties of glulam beams; wood density, equilibrium moisture content (EMC) of wood, 4-point bending of the glulam beams (according to ASTM D 198-02), 3-point bending of the treated and untreated wood (according to ASTM D 143-09) and the moisture induced stresses in cross section of the glulam beams were determined. The results showed that the hydrothermal treatment reduced the cross sectional moisture induced stresses as well as relevant moisture gradients and also it caused increase of the bending strength as well as stiffness of the treated wood and the glulam beams.

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1. Introduction

Glued laminated timbers (glulam beams) are engineering materials that are generally designed for applications where they will be highly stressed under designed loads [1,2]. The moisture gradients are occurred in the wood element due to variation of the relative humidity (RH) in outdoor applications. Physical and mechanical properties of the manufactured products from the glulam beams are affected by the moisture gradients which are responsible for the internal stresses perpendicular to grain in the wood [2,3]. Moisture induced stresses (MISs) due to the moisture gradients are sometimes so significant, which can exceed the tensile strength of timbers perpendicular to grain [3]. Developing risk of the cracks in wood elements is a result of overcoming this strength, which is usually responsible for safety risks as well as serviceability problem of the timber members in the wood products [3,4]. In the timber members, the annual growth ring patterns are also affect the modulus of elasticity (MOE) of the beams. The high the MOE is obtained in the middle part of the beams where the radial direction is dominating the wood cross section. This will affect the stress distribution [5]. The tension capacity of the wood is also affected by the moisture-induced stresses to a great extent at perpendicular to the grain direction. Therefore, this phenomenon should also be taken into account during designing the structural elements in which this strength (tension perpendicular to grain) is of a great importance; e.g. for the curved and the notched glulam beams, the joints, and also vicinity of the holes [3].

Application of the treated/modified wood in manufacturing of the glulam beams might reduce the moisture gradients in the beams. There are some reports which are indicating the effects of the wood preservation/modification on the glulam beam properties.
Mechanical properties were studied in glulam beams made from ACQ preservative-treated hardwood lumbers. The results revealed that the static- and dynamic-MOE of the beams were decreased by retention increase of the ACQ preservative. However, no delaminating was determined when the beams were soaked and boiled in water [6]. There is another research report which is about structural glued laminated timber (glulam) beams and finger-jointed boards made from the thermally modified wood [7]. Bending strength as well as stiffness of the glulam beams made out of the thermally modified beech wood were also studied and the results revealed that the thermal treatment of wood increases stiffness of the glulam beams, however, there was a reduction in the bending strength of the beam [8]. Mechanical wood modification is another process that can provide increase of wood density by densification technique. Densified wood was also used to manufacture glulam beams according to the literatures [9]. Results of such research works revealed that stiffness and load bearing capacity of the manufactured glulam beams are improved due to increase of wood density during densification process. Hydrothermal treatment is also a type of wood modification process that reduces moisture absorption of wood [10]. Therefore, it could be expected that manufacturing of the glulam beams from hydrothermally treated wood might reduce moisture induced stresses in cross section of the glulam beams and increase their bending strength. Since, the moisture induced stresses as well as bending properties of the glulam beams are important properties for structural designing that should be calculated in detailed designing of the timber construction [11]. Therefore, the main objective of the current research work is to investigate the moisture induced stresses (especially) and bending properties of the glulam beams made out of the hydrothermally treated poplar wood (Populus deltoides) to understand capability of hydrothermal wood modification in reducing the stresses due to the moisture absorption.

2. Material and methods

2.1. Materials

2.1.1. Wood

The wood logs were cut from two 23-year old poplar trees (Populus deltoides Bartr. Ex Marsh) grown at KoluDeh Forest Research Institute (Northern Iran, 36°33′14″N52°18′19″E). Flatsawn wood blocks were prepared in dimensions of 6 (R) × 10 (T) × 73 (L) cm³ after debarking the logs.

2.1.2. Hydrothermal treatment

The blocks were placed in a stainless steel cylinder (half filled with water) and then they were treated hydrothermally at temperatures of 140 and 160 °C for a holding time of 30 min in stainless steel cylinder. Afterwards, the treated wood blocks were initially air seasoned and then dried in a semi-pilot scale vacuum dryer at 50 °C to achieve moisture content of 12% prior to preparation of the sample glulam beams.

2.1.3. Adhesive

The polyurethane adhesive was used in current research work to mount the laminations with the following specifications as shown in Table 1.

2.2. Manufacture of glulam beams

The treated and untreated wood blocks were conditioned (RH: 52 ± 2%, T: 20 ± 3 °C) to achieve uniform moisture contents in the blocks. Pre-laminations with dimensions of 2.3 (R) × 7.4 (T) × 71 (L) cm³ were initially trimmed by a finger joint machine at both ends and then they were matched and mounted by using the PUR adhesive under a pressure of 0.6 MPa for 24 h and then, the laminations were conditioned according to ASTM D 4933-99 [12] with sodium dichromate (saturated salt) at 20 °C in glass chambers. The laminations were then planned and finished to prepare fresh surfaces prior to bonding. Afterwards, the polyurethane adhesive was applied on surfaces of the laminations as 200 g/m² (for mixture of adhesive as well as the hardener). The laminations were laid up to assemble sample glulam beams and then pressed for 24 h in a cold press under a pressure of 1 MPa. Finally, 68 glulam beams (4-ply) were manufactured with dimensions of 7.6 (H) × 7 (B) × 130 (L) cm³. The beams were conditioned in controlled glass chambers containing sodium dichromate (t: 60 days, RH: 52 ± 2%, T: 20 ± 3 °C).

2.3. Experiments

2.3.1. Density and EMC

Density and equilibrium moisture content (EMC) for both treated and untreated wood blocks were determined according to ASTM D 2395-93 [13] and ASTM D 4442-92 [14], respectively. Nine specimens (replications) were used to evaluate each parameters (density and equilibrium moisture content) for each type of the treatment level.

2.3.2. Bending test

The 4-point bending test was performed according to ASTM D 198-02 [15] using a computer-controlled Instron testing machine. Displacement increments were applied by a rate of 3.2 mm/min. Modulus of elasticity (MOE) and rupture (MOR) of the beams were calculated according to equations 1 & 2. It should also be noticed that the 3-point bending test was performed for clear cut untreated ant treated wood specimens according to ASTM D 143-09 [16] and the MOE and the MOR were also calculated according to Eqs. (3) & (4). Five specimens (replications) were used to evaluate the bending testes for each type of the treatment level.

\[ MOE = \frac{Pa}{4bh^3c} (3L^2 - 4a^2) \]  

\[ MOR = \frac{3Pa}{bh^2} \]  

\[ MOE = \frac{PdL^3}{4bh^3d_w} \]  

\[ MOR = \frac{3PL}{bh^2} \]

Where MOE is static bending modulus of the elasticity (MPa), MOR is modulus of rupture (MPa), P is load at proportional limit (N), P is maximum transverse load on beam (N), a is distance from reaction beam to nearest load point (mm), L is span of the beam (mm), b and

<table>
<thead>
<tr>
<th>Adhesive type</th>
<th>Color</th>
<th>Hardener</th>
<th>Density (g/cm³)</th>
<th>Pot life (min at 20 °C)</th>
<th>Solid content (%)</th>
<th>Application temperature (°C)</th>
<th>Thermal resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane</td>
<td>Cream</td>
<td>MDI</td>
<td>1.3</td>
<td>25</td>
<td>100</td>
<td>5–40</td>
<td>Good</td>
</tr>
</tbody>
</table>
h are width and depth of the beam (mm), c is deflection of beam between reaction and center of beam at the proportional limit (mm), \(d_{pl}\) is deflection of wood at mid-span (mm).

2.3.3. Moisture induced strains and moisture content in glulam beam's cross sections

Thirty specimens (Fig. 1a) were sawn from the manufactured beams and immediately wrapped in plastic foils to avoid any exposure to climate changes. Subsequently, all the specimens conditioned in a standard climate before test. The test program involved two climate variations namely wetting and drying (as summarized in Table 2) to simulate any effects of climate changes producing moisture gradients and subsequent stresses in the beams. For wetting step, the conditioned specimens were seasoned in a climate chamber with 50% RH and thereafter exposed to RH 90% (4). For drying step, the specimens were initially exposed to RH 90% and thereafter exposed to RH 50% (4). Each wetting and drying steps were lasted up to 20 days (Table 2). The application of single instead of cyclic climate changes was selected, because annual changes in RH are generally more significant than daily changes (4). The destructive measurement were undertaken after 20 days of wetting and drying, respectively. Fig. 1 illustrates the experimental procedure for the wetting analysis, schematically. After conditioning step, 36 black dots (as measuring points) were marked on both sides of each specimen (on upper and lower surfaces of each specimen as shown in Fig. 1b) and the initial lengths (\(L_1\)) between two dots marked on the specimen’s depth (height) were measured. According to Angst and Malo [4], the prepared specimens were moisture sealed on four sides by means of water proof silicon varnish to prohibit one-dimensional moisture transportation perpendicular to the grain (Fig. 1a). The specimens were exposed to a climate change, which induced moisture gradients and caused strains (expansion or shrinkage) of the specimens (Fig. 1b). These strains were measured by recording the distances between the dots after exposure to RH (wetting or drying) in the same manner as initially done according to Eq. (5) [4].

\[
\varepsilon_{RS} = \frac{L_2 - L_1}{L_1}
\]

Where \(\varepsilon_{RS}\) is the restrained strain (mm/mm), \(L_2\) is the length between two dots after exposure to 90% RH (mm), \(L_1\) is the length between two dots after exposure to 65% RH (mm).

Moisture contents of slices were measured by oven dry method (approx. 103 °C, 24 h) according to Eq. (6).

\[
MC = \frac{(M_1 - M_2)/M_2 \times 100}{M_2}
\]

Where MC is moisture content (%); \(M_1\) is slice weight before oven drying (g); \(M_2\) is slice weight after oven drying (g).

2.3.4. Modulus of elasticity and moisture induced stresses in glulam beam’s cross sections

After cutting each glulam specimen into 6 slices (dimensions of 76 × 50 × 7 mm³) with a band saw [4] as shown in Fig. 1c; MOE of the slices were also determined by a 3-point bending test (Fig. 2) according to Eq. (7). During bending test of each slice, the rate of loading was 0.5 mm/min.

\[
MOE = \frac{p_{pl} b h^3}{4 h^3 d_{pl}}
\]

Where MOE is static bending modulus of elasticity (MPa), \(P_{pl}\) is load at proportional limit (N), \(l\) is span (mm), \(b\) is width (mm), \(h\) is height (mm) and \(d_{pl}\) is deflection of slice at proportional limit (mm).

Finally, moisture induced stresses of each slice were also calculated according to Eq. (8).

\[
MIS = \varepsilon_{RS} \times MOE
\]

Where MIS is moisture induced stress (MPa), \(\varepsilon_{RS}\) is the restrained strain (mm/mm); MOE is the static modulus of elasticity (MPa).

3. Results and discussion

3.1. Density and equilibrium moisture content

The density as well as the equilibrium moisture content (EMC) values of the treated and the untreated wood blocks before bonding are given in Table 3. As indicated, the density values were increased by raise of the treatment temperature. While, the EMC values affected reversely and reduced due to the hydrothermal treatment. Increasing the density with the treatment temperature is in agreement with previous works [10,17–19]. According to the reports it could be expressed that any increase of the density in treated wood is related to cell wall collapses during the hydrothermal treatments.

![Fig. 1. Experimental procedure for determining moisture induced strains [4].](image-url)
The moisture absorption (EMC) could be suppressed due to growth in the cellulose crystallinity and reduction of the amorphous regions in the cellulose microfibrils, as well as reduction of free hydroxyl groups in the cellulose microfibrils during the hydrothermal treatment [20,21].

### 3.2. Bending strength

The results of the bending test for the treated and untreated glulam beams are presented in Fig. 3. It was revealed that the MOE and the MOR were increased in both wood and beams due to the hydrothermal treatment. As shown in Fig. 3, both bending strength parameters are increasing as the treatment temperature raises.

Mohebby et al. [19] reported that less moisture absorption and increased wood density are the most important reasons for increase of the MOE in the treated wood and the glulam beams made out of the treated wood. The high the MOE values indicates that the material is not easy to be distorted under bending load and it has a high rigidity [22] also, the high the MOR values indicates the maximum load that the material can be tolerate during bending test [2,22]. Water molecules perform as plasticizer in texture of wood material. These noticed conclusion is also confirmed by the results shown in Fig. 4. As hydrothermally treated wood becomes less hygroscopic [10]; therefore tendency for distortion (deflection) is reduced under the load (Fig. 4a). Displacement of the beams is reduced due to the hydrothermal treatment and increase of the treatment temperature. Also, displacement of slices during 3-point bending was shown in Fig. 4b.

Any different behaviors the treated beams in comparison with the untreated one is shown in Fig. 5. It has indicated that the treated beams required more loads to break; while it was less for the untreated one. The brittle behavior of the treated beams could also be understood in comparison with the untreated one. Because, the treated beam are immediately broken; while the untreated poplar beams are still tolerating bending load.

There are some reports indicating that mild thermal treatment of wood leads to a 5% increase in MOE [23]. Recently, improvement of flexural behavior of glulam timber beams reinforced with FRP cords has also been assessed by other authors [24]. Cleavages between lignin and hemicelluloses, re-orientation of the lignin polymer as well as condensation reactions in lignin structure along with formation of new cross-linking due to the thermal treatment might be the reasons for MOR increase in the treated wood [25]. During the thermal wood modification, less stiff polymers such as hemicelluloses are extracted from the wood cell walls [20] and crystalline cellulose, which is a stiff polymer, is also increased due to the thermal treatment [26]. Both polymers are responsible for the stiffness increasing of the treated wood [27]. It is well known that changes of hemicelluloses play key roles in the strength properties of wood heated at high temperatures [28].

### 3.3. Assessment of failure modes

Failures are the most important mechanical properties during the bending tests that they should be typically assessed during the tests [29]. It was revealed that brittle failure were occurred during the bending tests (Fig. 6). Similarly, this behavior was also understood in bending load-deflection curves as shown in Fig. 5. It is well known that the wood become brittle after the hydrothermal treatment. Therefore, it could be concluded that this phenomenon might be responsible for brittle failures in the glulam beams.
beams. Brittleness of the treated wood during thermal wood modification process was also reported in previous works [30].

3.4. Moisture induced strains and moisture content in glulam beam’s cross sections

Moisture gradient as well as correlated moisture induced strains in glulam cross sections are presented in Fig. 7 for wetting and drying steps. Each point on the graphs are related to each slices of the beams. It was revealed that curves for wetting and drying are in reverse situation of each other. The restrained stresses are following the moisture variations in the beams for correlated wetting or drying steps. As shown, inner slices of the beams gained less moisture and strains in wetting step and reversely more moisture for drying steps (Fig. 7). Similar behaviors were earlier also reported in other research works as well [4]. As shown here, any increase of the treatment temperature is responsible for reduction of the moisture contents in slices (after wetting and drying stages) as well as the final gradients (Fig. 7a,b). The moisture induced strains are also affected by the hydrothermal treatment. As shown in Fig. 7c,d, the large the strains were occurred in the untreated glulam beam’s cross sections; while the less the strains were occurred in the treated ones. In the untreated glulam beams, the strains as well as the moisture gradients are larger in comparison with the treated ones. As expected, the curves are typically symmetric and the large gradients in the moisture profiles provided considerable gradients in the restrained strains of the glulam beam’s cross sections. Current results are also comparable with previous works [3,4]. Less hygroscopic property of the treated wood is the main reason for the less moisture absorption and correlated strains reduction during the moisture exposure. In both treated and untreated glulam beam’s cross sections, the innermost slices exhibit mainly radial wood and the outermost slices exhibit mainly tangential wood. In addition to the moisture gradients, it is well known that the tangential swelling is typically more than that of the radial swelling. Therefore strains due to the swelling at outermost slices should be greater than that of the innermost slices.

3.5. Modulus of elasticity and moisture induced stresses in glulam beam’s cross sections

The modulus of elasticity (MOE) as well as the moisture induced stress (MIS) values are shown in Fig. 8 for wetting and drying steps. It was revealed that the MOE curves are similarly following the MC curves for both steps of wetting and drying (Fig. 8 a,b). However, the moisture induced stresses are following reversely the MOE curves and similarly the MC curves (Fig. 8 c,d). It means that the increase of the moisture gradients in the glulam beam are followed by reduction in MOE and increase in MIS. It was also revealed that the MOE was increased as the treatment temperature raises. The MOE values in both treated as well as the untreated glulam beams are small at the outermost slices; while the large the MOE was measured in the innermost slices (Fig. 8 a,b). The main reason for this phenomenon is probably low tendency of the innermost slices to water absorption (especially in the case of treated glulam beam’s cross sections). The MIS values are also affected in the beams due to the hydrothermal treatment. As shown in Fig. 8 c,d the large the MIS values are indicated in the untreated glulam beams and the lesser ones in the hydrothermally treated samples. The MIS values was also reduced as the treatment temperatures was increased.
Mohebby et al. [19] reported less moisture absorption as well as increased wood density in the hydrothermally treated wood. They also expressed that reduction of the moisture contents as well as increase of the density are the main reasons for increase of the MOE. Therefore, it could also be concluded that the main reasons for reduction of the moisture induced stresses in the cross section.

Fig. 7. Moisture gradients in glulam beams after wetting (a) and drying (b); restrained strains after wetting (c) and drying (d) steps. The symbols are mean values of the slices.

Fig. 8. Gradients of modulus of elasticity MOE in glulam beams after wetting (a) and drying (b); and moisture induced stresses (MIS) after wetting (c) and drying (d) steps. The symbols are mean values of the slices.
of the treated glulam beams are less moisture absorption as well as subsequent less restraints in the treated wood. Gereke et al. [31] analyzed the dimensional stability and moisture induced stresses of cross laminated timbers made from thermally treated beech timber and they also reported that less hygroscopic properties of the treated wood are the main reasons to improve dimensional stability and reduction in moisture induced stresses of the manufactured cross laminated timbers.

Correlations between the moisture content (MC) as well as the moisture induced stress (MIS) in the glulam beam's cross sections are also presented in Fig. 9. As shown, the less the MIS was obtained in the treated beams; while the high the MIS was for the untreated samples for both cases of drying and wetting steps. The current results were also confirmed that the MIS is affected by hydrothermal treatment.

4. Conclusion

The current research work was planned to study any effects of the hydrothermal treatment on moisture induced stresses in glulam beams. According to the findings, the following results could be concluded:

- The moisture induced stresses in glulam beam's cross sections depend on not only the moisture content and relevant strains distribution but also the MOE distribution.
- Moisture induced stresses are also correlated with the moisture changes in the beams. Anyhow, less stresses are occurred in the hydrothermally treated beams.
- Relationship between the moisture content and moisture induced stress in the glulam beam's cross sections is meaningful.
- The hydrothermal treatment affects the moisture gradients in the glulam beams. Any increase of the treatment temperature reduces the moisture contents as well as the relevant gradients in the glulam beams.
- The moisture induced strains and the relevant gradients are also reduced due to the hydrothermal treatment in the glulam beams.
- The bending properties (MOE and MOR) of the glulam beams increased due to the hydrothermal treatment.

References


Fig. 9. Relationship between the moisture content and moisture induced stress in hydrothermally treated glulam beam after wetting (a) and drying (b).


