FIRENWOOD

Improved fire design of engineered wood systems in buildings

Improved fire design model for cross-laminated timber and glulam

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1 Introduction

Adhesives state the essential prerequisite for manufacturing large timber construction elements from rigidly bonded solid wood boards of growth and processing bound limited dimensions. In the first two decades after the invention of glulam up to the 1930s, adhesives based on natural organic substances like blood and proteins were used. Such adhesives can have high dry strength but are weak when applying water or temperature. These adhesives were then replaced by synthetic ones, firstly in the early 1930s by (phenol)-resorcinol-formaldehyde (RF/PRF) adhesives and then by urea-formaldehyde (UF) adhesives. Numerous tests have shown that the boiling water resistant duroplastic RF/PRF adhesives are very stable at high temperatures up to/beyond the charring of wood (Dorn and Egner, 1967; Klippel 2014). Contrary hereto, the UF adhesives later classified in Europe as type II adhesives have significantly reduced water resistance (e.g. Raknes (1997) and are less temperature stable and fire resistant, although the latter was not communicated sufficiently. The RF-, PRF- and UF-adhesives were exclusively used up until the 1980s when the presently existing timber standards for “cold” and fire design were being developed. From the 1980s onwards, adhesives with various chemical compositions have been added to the market. Firstly the duroplastic melamine-urea-formaldehyde and pure melamine formaldehyde (MUF/MF) adhesives, followed in the mid-90s by the moisture-hardening one-component polyurethane (1C-PUR) adhesives, then followed by the emulsion-polymer isocyanate (EPI) adhesives. In order to speed up curing times, being of utmost high economic importance, significant amounts of polyvinyl acetate (PVAc) have been added to the hardeners of MUF adhesives with drawbacks on temperature stability. Each of the developed adhesives has its advantages and disadvantages regarding strength, water and/or temperature resistance, application robustness and price.

According to EN 1995-1-2:2004, chapter 3.5, the behaviour of a bond line in fire may not be considered explicitly if the bond line is made of phenol-formaldehyde and aminoplastic, Type I adhesives, according to EN 301. Regarding the general principle that adhesives shall produce joints of such strength that the integrity of the bond is maintained in the assigned fire resistance period, a footnote hints at the point that some adhesives show softening considerably below the charring temperature of wood.

2 Design model for charring of cross-laminated timber

Contrary to the present fire design specifications, the new Eurocode for fire design of timber structures (prEN 1995-1-2:2021) will contain different design scenarios and parameters depending on the behaviour of bond lines at elevated temperatures. Differences are made in the charring rates of laminated wood products after the charring has passed the bond line. Depending on the ability of the bond line to prevent the fall-off of the charred layer, the linear or step model for charring is applied. The latter model takes into account that the insulating and protecting char layer is missing, therefore enforcing an increased charring rate up to a newly developed char coal depth of 25 mm. The basic difference between the linear and the stepped design model is shown in Figure 1. A basic dilemma of the new approach to the fire resistance of bonded structural elements is, however, that at present, no commonly agreed testing and classification method for heat and fire resistance of structural wood adhesives exists in Europe. While in North America, standardized test methods and assessment procedures exist to address the stated problem.

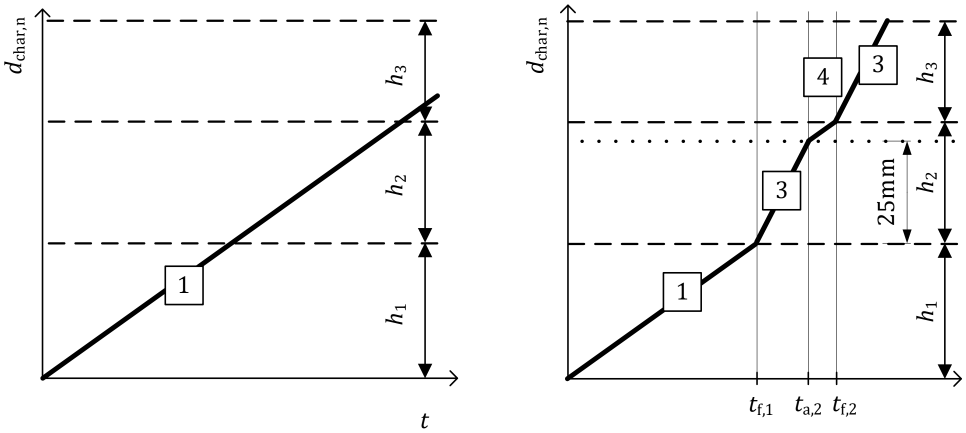

Figure 1. Linear (left) and step-model (right) for charring. Dashed lines represent the bond lines. Numbers represent different phases in charring.

Currently, the k_3 value in prEN1995-1-2:2021 for CLT, GLT and GLVL is always 2 for horizontal members. In reality, the value for these elements may vary, e.g., the value may exist somewhere between 1 and 2, and further research is needed to evaluate whether the value could be calculated for each adhesive separately. For example, the k_3 value for vertical linear members can be taken as 1,3, as shown in Figure 2.

The next formulas represent charring phases depending on whether the bond line integrity of surface bondings is maintained or not maintained during the fire exposure, respectively, as seen in Figure 1.

Phase 1 and 4 $\beta_n = k_n \cdot \beta_0$

Phase 3 $\beta_n = k_3 \cdot k_n \cdot \beta_0$

Horizontal	**Vertical**	
	first layer	other layers
2	2	1,3

Figure 2. Post-protection factor k_3 for linear timber members made of CLT and GLVL (prEN 1995-1-2:2022).

In order to close the mentioned knowledge gap, hereinafter reported research work has been performed jointly within the frame essentially in an ERA-Net Forest Value project FIRENWOOD by research partners RISE Sweden / Norway, Tallinn University of Technology, Materials Testing Institute of University Stuttgart and Technical University of Munich. The presented research work and findings focus on testing and analysis of charring scenarios of glulam beams built up from boards with well-known properties (densities, MOE) and bond lines made of various adhesives approved for structural applications.

3 Design model for charring of glued laminated timber

The fire tests of this study showed that glulam beams with well-known wood properties and bond lines made of various adhesives approved for structural applications had different final charring depths in 90 minutes of standard fire exposure. That indicates the need for a choice between linear or stepped charring models on the fire-exposed sides depending on charring direction and bond line integrity.

Project Team of EN 1995-1-2 have proposed that the bond line integrity may be assumed as maintained for phenol-formaldehyde Type I adhesives according to EN 301. For other adhesives, there are no conclusions according to adhesive family. The bond line integrity should be assessed by testing. There are a comparative charring rate method proposed in prEN 1995-1-2:2021 and small-scale methods under development in FIRENWOOD project, and new temperature resistance classifications developed within the frame of CEN/TC 193/SC1).

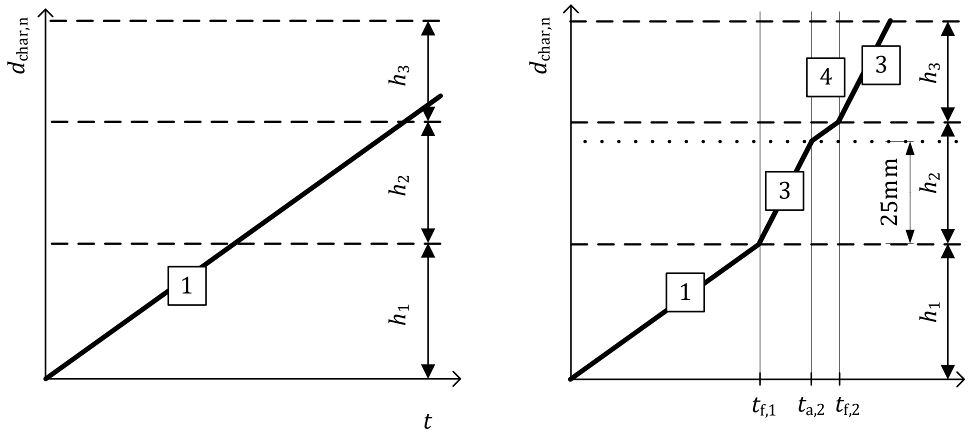

Figure 3. Linear (left) and step-model (right) for charring. Dashed lines represent the bond lines.

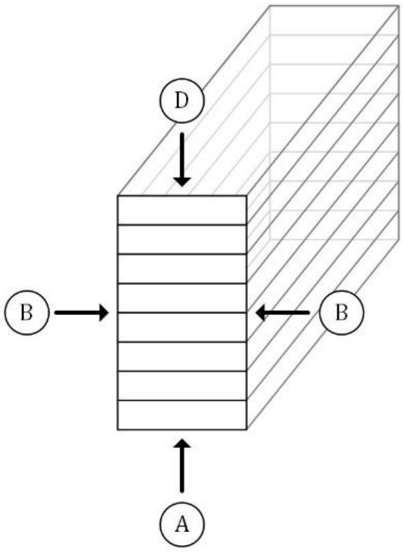

Figure 4. Charring directions for glulam beam (prEN 1995-1-2:2021).

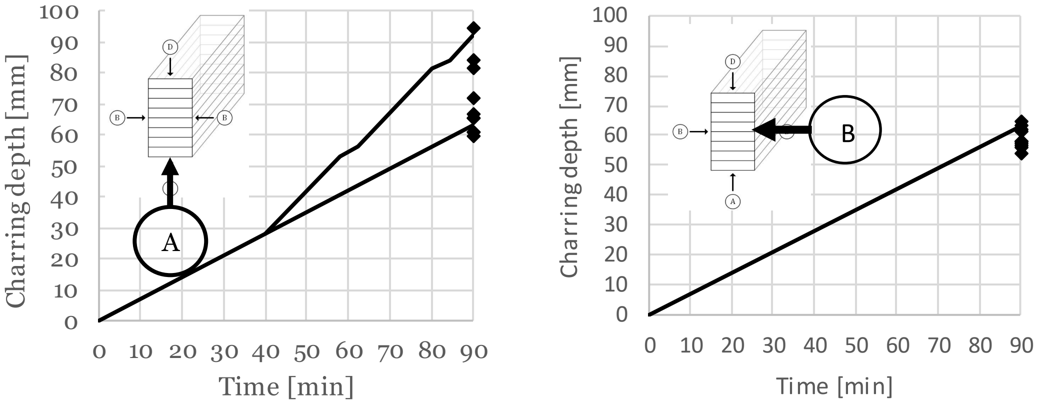

Figure 5. Charring in direction A (left), and direction B (right).

The next formulas represent charring phases depending on whether the bond line integrity of surface bondings is maintained or not maintained during the fire exposure, respectively, as seen in Figure 3.

Phase 1 and 4 $$\beta_n = k_n \cdot \beta_0$$

Phase 3 $$\beta_n = k_3 \cdot k_n \cdot \beta_0$$

The black dots in Figure 5 represent the test results from this research. The lines represent the proposed design models for charring (linear and stepped models).

A stepped model for charring shall be applied for charring from direction A (see Figure 4) in the case when bond line integrity is not fulfilled. However, the stepped model with k_3=2 is rather conservative for many adhesives that were tested in glulam beams.

Further research is needed to evaluate the exact value for each adhesive family.

For charring direction A, when bond line integrity is maintained and charring direction B and D in all cases, the linear charring model should be applied.

Lamella thickness and bond line integrity of face bond will be necessary parameters for fire design of glulam beams according to prEN 1995-1-2:2021 in the case where bond line integrity is not maintained.

The charring scenarios influenced by bond line integrity in a fire can also be predicted by small-scale test methods. The work with the small-scale methods is ongoing at MPA Stuttgart, Tallinn University of Technology and RISE.

4 Summary

The fire tests done within this project showed that not all adhesives approved for structural use today have the same fire resistance properties. Therefore, it is important to distinguish between adhesives that are more durable in fires and adhesives that are less durable in fires. When the bond line integrity is not maintained, the protective char layer covering the next lamella falls off, and the lamella starts charring at a faster rate. To take this phenomenon into account, the stepped model of charring is introduced for adhesives that demonstrate this behaviour.

The stepped model should be considered for both cross-laminated timber and glued laminated timber when the bond line integrity is not maintained. The linear model can be used when the bond line integrity is maintained.

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