Behavior of wooden based insulations at high temperatures

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Abstract

Insulation materials may give a different contribution to the fire resistance of timber frame assemblies. At present, Eurocode 5 Part 1-2 [1] provides a model for fire design of the load bearing function of timber frame assemblies with cavities completely filled with stone wool. The extension of this model for glass wool for post protection phase has been published in the European technical guideline Fire Safety in Timber Buildings [2]. Very little is known about the protection of bio-based insulation materials. Eight model scale furnace tests of floor specimens were carried out. Two different design tools to calculate the charring rate of timber frame assemblies insulated with wooden based insulations are provided. The first one is a design model for timber frame assemblies insulated with batt-type and loose fill cellulose fiber insulations. The second tool includes the functions of conductivity, specific heat and loss in mass against the temperature calibrated on the standard fire curve to implement advanced heat transfer calculations. The purpose is to give the designers two design procedures with a different level of complexity and accuracy.

Keywords: cellulose fibre insulations, timber frame assemblies, fire resistance

1. Introduction

New technologies are constantly being developed to complement current practices in creating greener structures, by reducing the overall impact of the built environment on human health and protecting occupant health. A similar concept is natural building, which is usually on a smaller scale and tends to focus on the use of natural materials that are available locally [3].
A solution commonly used to build natural buildings is the light timber frame structure with the cavity completely filled with wooden based insulation. This solution is used mostly in new buildings, however the technique can be used also for deep renovations.

The behavior of timber frame assemblies in fire is influenced by the protective properties of cladding and insulation materials. The primary protection for a timber member is given by the cladding. The charring of a timber member protected by cladding is considered the protection phase. After the fall-off of the cladding, secondary protection might be provided by insulation materials. The charring of a timber member after the fall-off of the cladding is regarded as the post-protection phase. Annex C of the current Eurocode 5 Part 1-2 [1] presents a design model that considers the contribution of stone wool. The model is extended to assemblies filled with glass wool until the failure of the claddings. The European guideline Fire Safety in Timber Buildings (FSITB) [2] includes a design model that considers the contribution of glass wool to the fire resistance during the post-protection phase. All the other insulation materials are excluded in the models described above.

The EN-standard dealing with factory made wood fiber thermal insulations for buildings refers to the performance in terms of reaction to fire and does, therefore, not provide information on fire resistance performance [4].

The model presented in the Eurocode 5 Part 1-2 was developed by König and Walleij [5]. It considers a one-dimensional charring, simplifying the residual cross section into a rectangular one, and introduces coefficients that correct the nominal charring rate to take into account the corner roundings. The greater charring depth for narrow elements is taken into account through the coefficient \( k_n \), which depends on the width of the original cross section. To transform the real charred cross section into a rectangular one, the coefficient \( k_n \) is used, based on the ratio of section modulus of the real and simplified cross-sections. The protection coefficients describe the different charring rates in the protection and post-protection phase. The coefficient \( k_2 \) considers the protection of gypsum plasterboard, while \( k_3 \) considers a greater charring rate during the post protection phase and it depends on the failure time of the fire protection.

The design model for timber frame assemblies protected with glass wool inserted in FSITB was proposed by Just [6]. It also considers charring from the lateral sides, with different starting times at the top and bottom of the side; giving the residual cross section a trapezoidal shape. This introduction was made due to a faster recession of the glass wool compared to stone wool in the fire condition.

Recent studies demonstrated that the design model included in Eurocode 5 can be used to predict the charring depth of timber members completely filled with insulations other than stone wool [7].

A lack of information and limited investigations performed have raised the necessity to develop a design model that considers the contribution of wooden based insulation materials to the protection against charring of timber members.

The purpose of this paper is to give the designers two different design procedures for calculating the charring rate. The simplest one, using calculation methods, and an advanced one, which allows implementing the cellulose fiber in heat transfer models. The aim is to achieve higher accuracy with the more advanced method.

2. Methodology

The contribution to fire resistance of timber frame assemblies given by three different wooden based insulations was studied by means of model scale furnace tests. The specimens consisted of timber beams and the applied insulation materials. The insulation materials involved in this investigation are cellulose fiber in loose fill type in its original composition (OF), the same loose fill cellulose fiber impregnated to improve fire resistance (FF) and cellulose fiber in batt-type (BF).

Furthermore, a series of thermal simulations by means of SAFIR (v2014a1) were carried out.

2.1. Model scale furnace tests

Eight specimens of timber frame assemblies were tested in horizontal position in a cubic meter furnace following the standard fire curve according to ISO 834 [8] (Table I). The specimens consisted of a timber beam the sides of
which were protected by insulation as a portion of a floor (Figure 1 a). The external dimensions of the specimens were 80 x 100 cm.

The timber beam cross section chosen was 45 x 145 mm. The fire side of the tested assembly was protected by 15 mm thick gypsum plasterboard Type F. A specimen insulated by loose fill cellulose fiber for each treatment was also tested protected by 12.5 mm thick gypsum plasterboard. Two specimens, one for each loose fill insulation, were tested without cladding.

On the unexposed side particle board with the thickness of 19 mm was used in all the tests. In order to obtain comparable results for the post-protection phase among the insulation materials, the fall-off of the gypsum plasterboard was imposed during some tests. This was done by releasing the special fastening system.

Different techniques were adopted to prevent the fall-off of the insulation materials when the failure of the cladding occurs and for the unprotected specimens. BF was glued on the particle board by means of fluid sodium silicate based glue. The loose fill insulations were held in place by a chicken net (Figure 1 b). Thermocouples were embedded on the timber beam and insulation material at different depths to follow the charring scenario. The expected duration of the tests was 60 minutes; in some tests the specimen was removed earlier due to the start of charring of the particle board.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Insulation material</th>
<th>Cladding</th>
<th>Fall-off of cladding (min)</th>
<th>Duration of test (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OF</td>
<td>GrF, 15 mm</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>OF</td>
<td>GrA, 12.5 mm</td>
<td>NO</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>OF</td>
<td>GrF, 15 mm</td>
<td>NO</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>OF</td>
<td>NO</td>
<td>-.</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>FF</td>
<td>GrA, 12.5 mm</td>
<td>NO</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>FF</td>
<td>GrF, 15 mm</td>
<td>NO</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>FF</td>
<td>NO</td>
<td>-.</td>
<td>23</td>
</tr>
<tr>
<td>8</td>
<td>BF</td>
<td>GrF, 15 mm</td>
<td>45</td>
<td>60</td>
</tr>
</tbody>
</table>

At the end of the tests for each beam the instrumented and the minimum residual cross sections were collected.

2.2. Thermal simulations

Thermal simulations were conducted by means of SAFIR software. It uses finite element method for thermal and structural analysis. Test configurations 3, 4, 6 and 7 were simulated with SAFIR.

Fig. 1. (a) Example of specimen tested in furnace; (b) specimen insulated with loose fill cellulose fiber and chicken net applied.
The simulation software uses thermal conductivity, specific heat, density and surface coefficients as input. Therefore, it is imperative to use effective input values. These can be found with some certainty either by separate testing or calibrating them to fit furnace test data. The latter approach was used here.

The calibration of input parameters is a multi-step process. For more widespread materials, a literature survey could be enough to find the necessary properties. The data for wooden based insulations is scarce. Hence, a mathematical approach was taken. As a preliminary, some test data was gathered from thermo-gravimetric analysis and transient plane source methods [9]. This was taken as the known starting point for the calibrated curves and extrapolated at first using analogy with mineral wools to obtain a starting curve for calibration.

The next step was calibration using mathematical methods for curve fitting. This was done by iterative approximation using MATLAB. For a detailed description of the calibration procedure and the code developed, see [10]. Different setups were then simulated with calibrated input curves obtained from the same tests. The results were compared and the safest input parameters declared as effective. The input parameters obtained from different setups were also compared.

3. Results

Residual cross-sections of timber beams from specimens protected by different wooden based insulation materials are shown in Figure 2. It is possible to observe similar shapes in residual cross-section of the beams protected by loose fill cellulose fiber original (OF) and fire protected (FF). In the other case, a different residual cross-section shape was observed.

![Fig. 2. (a) Residual cross section of timber beam from specimen insulated with loose fill cellulose fibre; (b) insulated with impregnated cellulose fiber; (c) insulated with cellulose fiber batt-type](image)

The geometric properties of the residual cross sections were obtained from the negative pictures of the residual cross sections by means of AutoCAD. The residual moment of inertia ratio is plotted against the charring depth ratio (Figure 3 a).

König [5] defines the coefficient $k_s$ on unprotected members. In this study two unprotected specimens are present, one for each insulation material studied (see Table I). The coefficient $k_s$ was calculated as

$$k_s = \frac{\beta_m}{\beta_0,EC5}$$

where $\beta_m$ is the charring rate in the middle of the narrow side, $\beta_0$ is the charring rate for one-dimensional charring of initially unprotected wood according to Eurocode 5 [1]. The two specimens that were tested unprotected had a beam width of 45 mm. The $k_s$ factors resulted for OF and FF are 1,49 and 1,40 respectively.
Post protection factors ($k_3$) are compared with fall-off times of claddings (Figure 3b). The coefficients $k_3$ were calculated by dividing the charring rate in post protection phase ($k_3$) by the one dimensional charring rate ($\beta_0$) for the cross-section factor according to Eurocode 5 ($k_{s,EC5}$) as

$$k_3 = \frac{\beta_3}{k_{s,EC5}} \cdot \beta_{0,EC5}$$

(2)

![Graph](image)

Fig. 3. (a) Reduction of moment of inertia versus charring depth ratio; (b) $k_3$ factors

It is shown on Figure 3a that the relation between $d_{\text{char}}/h$ and $J_f/J$ for Test 1 is between the line of $k_n = 1,5$ and $k_n = 1,7$. Observing this relation for other test results it can be seen that the data are more spread. The $k_s$ factor obtained for both insulations slightly differs from the value proposed in the Eurocode 5 for stone wool.

![Graph](image)

Fig. 4. (a) Temperature against time measured at 145 mm in Test 4 (OF); (b) temperature against time measured at 145 mm in Test 7 (FF)
The temperatures measured by thermocouples placed behind the insulation (at 145 mm depth) middle width of the cavity were used to calibrate the thermal properties. Temperatures against the time are plotted in the Figure 4.

4. Discussions

The results of this study indicate that the protection given by OF and FF is different in tests protected with 12.5 mm gypsum plasterboard, Type A (GtA). Comparing the Test 1 and the Test 8 it can be seen that specimen insulated with OF accomplished greater residual moments compared with the one insulated with BF. Furthermore, the scatter of the residual moments of inertia in the beam protected with BF is greater compared to the beams insulated with loose fill insulations.

It can be observed that the same charring depth on the narrow side can give two different moments of inertia, for example in Tests 3 and 4, as well as in Tests 5 and 6. This inconsistency related to the reduction of moment of inertia may be due to a two-dimensional charring behavior. This result can be explained by the fact that the unprotected tests (4 and 7) were stopped quite early, before the lateral sides had completely charred. At a certain point in the longer tests, these insulation materials lost their ability to protect the lateral sides of the beam from charring. At that point the start of charring on the lateral sides takes place at a different charring rate compared to the narrow side. For that reason the factor \(k_n\) applied on the narrow side may not be capable to correlate the charring depth with the residual section modulus. This observation further supports the idea to introduce a design model that considers charring from three sides [11][12].

Studying the calibrated input curves, it became apparent that there is a significant difference in the result of loose fill and batt type insulations, but within these categories, the parameters showed good similarity. The FF and OF loose fiber insulations differed most significantly in thermal conductivity. Specific heat and loss in mass curves were obtained from the OF type insulation and generalized for FF as well.

When comparing results from simulations of different test setups with the input curves obtained from the same tests, it was concluded that unprotected tests yield the safest results. Hence, the calibrated thermal properties developed from unprotected test configurations are declared as effective.

5. Design tools

5.1. Design model for timber frame assemblies

A universal design method to calculate the contribution to fire resistance of timber frame assemblies given by different insulation materials was already presented by the authors of this paper [11]. This model considers the start of charring on the lateral sides during the post-protection phase. This assumption was introduced to take into account the effect of the corner roundings bypassing factor \(k_n\). The charring rate during the protection phase is calculated as:

\[
\beta_{1,n} = \beta_0 \cdot k_2 \cdot k_2
\]  

where

\(\beta_0\) is the one-dimensional charring rate (0.65 mm/min)

\(k_2\) is the cross-section factor

\(k_2\) is the insulation factor of the cladding according to Eurocode 5

The charring rate during the post-protection phase is considered from three sides and for the narrow side is calculated as:

\[
\beta_{1,n} = \beta_0 \cdot k_s \cdot k_{3,1}
\]  

where

\(k_{3,1}\) is the post-protection factor for the narrow sides, given as

\[
k_{3,1} = 1 + \frac{2}{475} t_f
\]  

for cellulose fibre loose fill type (OF)
\[ k_{3,1} = 1 + \frac{1}{32} t_f \]  \text{for cellulose fibre batt-type (BF)} \tag{4}

\( t_f \) is time of the failure of the cladding

The charring rate during the post-protection phase for the lateral side is calculated as:
\[ \beta_{2,n} = \beta_0 \cdot k_{3,2} \]  \tag{5}

where

\( k_{3,2} \) is the post-protection factor for the lateral sides, given as

\[ k_{3,2} = 0.84 \]  \text{for cellulose fibre loose fill type (OF)}
\[ k_{3,2} = 1.39 \]  \text{for cellulose batt-type (BF)}

The start of charring from the lateral side is assumed when the cladding has fallen off. The post-protection phase coefficients were calibrated in order to compensate the residual section modulus at 60 minutes.

Fig. 5. (a) Design model for timber frame assemblies; (b) example of charring rates according to the two-dimensional charring model for a timber element (45 mm x 145 mm) insulated with loose fill insulation (OF)

5.2. Effective thermal properties of wooden based insulation materials

The thermal properties developed for loose fill cellulose fiber insulations are shown in the Figure 6. Two different functions of thermal conductivity against the temperature are proposed for the different types of loose fill cellulose fiber insulation (OF and FF). Common functions for specific heat, as well as loss in density, against the temperature are proposed for both original and impregnated loose fill type cellulose fiber. These can be used in advanced thermal calculations performed with suitable finite element software.
6. Conclusions

The main goal of the current study was to provide different methods to predict the charring of timber frame assemblies insulated with wooden based fibers. The investigation has identified equations for a design model and functions for implementation in advanced thermal calculations. Furthermore, this research extends the knowledge in the field of fire resistance of bio-based building products.

The assumption that the lateral sides start to burn when the fall-off of the cladding occurs is conservative. More research on this issue is required in order to describe the performance more accurately. Moreover, this study has shown a different value of $k_s$ compared to the ones proposed for stone wool in the Eurocode 5. Further studies are already planned in order to provide an equation of $k_s$ factor for cellulose fiber.
In order to investigate various configurations, a parametric analysis could be carried out by means of numerical simulations using the functions proposed.

Besides the design model, a parallel study is concentrated on developing qualification methodology to describe the contribution of different insulation materials to the fire resistance of timber frame assemblies. The qualification methodology has to be linked to the design model presented in this paper.

More broadly, research is also needed to determine the chemical reactions that take place in the cellulose fiber during the fire. The knowledge of any key phenomena would give the calibrations a stronger basis and help increase their accuracy.

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References

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