Effect of fire-induced damage on the uniaxial strength characteristics of solid timber: A numerical study

D.J. Hopkin*, J. El-Rimawi, T. Lennon, V.V. Silberschmidt
BRE Global, Bucknalls Lane, Garston, Watford, WD259XX, UK.

Email: HopkinD@bre.co.uk

Abstract. The advent of the structural Eurocodes has allowed civil engineers to be more creative in the design of structures exposed to fire. Rather than rely upon regulatory guidance and prescriptive methods engineers are now able to use such codes to design buildings on the basis of credible design fires rather than accepted unrealistic standard-fire time-temperature curves. Through this process safer and more efficient structural designs are achievable. The key development in enabling performance-based fire design is the emergence of validated numerical models capable of predicting the mechanical response of a whole building or sub-assemblies at elevated temperature. In such a way, efficiency savings have been achieved in the design of steel, concrete and composite structures. However, at present, due to a combination of limited fundamental research and restrictions in the UK National Annex to the timber Eurocode, the design of fire-exposed timber structures using numerical modelling techniques is not generally undertaken.

The ‘fire design’ of timber structures is covered in Eurocode 5 part 1.2 (EN 1995-1-2). In this code there is an advanced calculation annex (Annex B) intended to facilitate the implementation of numerical models in the design of fire-exposed timber structures. The properties contained in the code can, at present, only be applied to standard-fire exposure conditions. This is due to existing limitations related to the available thermal properties which are only valid for standard fire exposure. In an attempt to overcome this barrier the authors have proposed a ‘modified conductivity model’ (MCM) for determining the temperature of timber structural elements during the heating phase of non-standard fires. This is briefly outlined in this paper. In addition, in a further study, the MCM has been implemented in a coupled thermo-mechanical analysis of uniaxially loaded timber elements exposed to non-standard fires. The finite element package DIANA was adopted with plane-strain elements assuming two-dimensional heat flow. The resulting predictions of failure time for given levels of load are discussed and compared with the simplified ‘effective cross section’ method presented in EN 1995-1-2.

1. Introduction
Timber, like other structural materials such as concrete and steel, has its own Eurocode (Eurocode 5 part 1.2) for the structural fire design of buildings [1]. However, unlike other fire parts of the Eurocodes it is not widely adopted due to its inherent limitations. With the exception of a single annex, the timber Eurocode (EN 1995-1-2) is only applicable to standard-fire exposure [2]. This exposure condition describes an ever increasing time-temperature regime, typically used in the fire-
resistance testing of materials and systems. Annex A of EN 1995-1-2 gives guidance on the charring rates of initially un-protected timber members exposed to non-standard fires. In this instance these non-standard fires refer to parametric fires [3], which are a marginally more realistic means of specifying a time-temperature response, based upon the specific ventilation conditions and fire loadings of a given building/enclosure. However, in the UK the use of Annex A is prohibited by the national annex to EN 1995-1-2.

At present, in the UK (and most of Europe) timber structures are designed for fire resistance using a combination of prescriptive rules and fire-resistance testing, using the concept of fire-resistance ratings. These fire ratings are based upon standard-fire exposure and bear little relation to real fires in real buildings. There are moves towards the concept of performance-based fire design for structures, whereby a given building is designed to survive the entire duration (including cooling) of a design fire, which is dependent upon the building’s use and geometry. Much of the ability to design structures specifically for design fires (such as parametric fires) stems from the development and implementation of advanced numerical models capable of simulating multiple element interactions at elevated temperature. For this approach to be realised for large-section timber structures, then, firstly, accurate temperatures in timber sections need to be determined for non-standard fires and, secondly, the thermo-mechanical behaviour of timber needs to be further considered. This paper discusses these issues in more detail and also briefly proposes a solution to the problematic thermal physical aspects of timber behaviour in natural fires. Finally, a study highlighting how new thermo-physical models can be coupled with mechanical behaviour to implement simple simulations of timber exposed to non-standard fires, is presented.

2. Strength characteristics of solid timber
Timber, like most structural materials, undergoes some degradation in strength and stiffness at elevated temperature. However, unlike materials such as steel and concrete, this degradation for timber is over a much shorter temperature range due to its inherent combustibility. Typically, timber (both soft and hardwoods) loses all of both its strength and stiffness (regardless of grain orientation) over the temperature range of 20 to 300°C.

Many textbooks and reference documents for timber in fire have collated various strength and stiffness retention factors using numerous classical studies [4-17]. These have been summarised in Figures 1 to 3 for tensile strength, compressive strength and elastic modulus, respectively. In all instances the study of Konig & Walleij [11] is also shown as these properties are codified in EN 1995-1-2.

3. Overview of the modified conductivity model for timber
The design of timber structures for non-standard fire conditions is not simple since only limited test data exists on temperature development within timber structural elements under these conditions. In addition, as timber is an organic material, the thermo-physical properties are complex and depend on a number of factors. The complex phenomena present in heated timber elements are difficult to model explicitly and, hence, to date ‘effective properties’ are often defined. Such properties implicitly account for the effects of complex behaviour, such as the flow of pyrolosis gases and water vapour, through calibration against known temperatures, in limited experimental configurations. Konig [11] has been instrumental in initiating such a process for timber and has calibrated ‘effective’ thermal properties for standard fire exposure conditions.

These properties form the basis of the advanced calculation models contained in Annex B of EN 1995-1-2. However, additional studies by Konig [18] proved (both experimentally and numerically) that those properties exhibited very conservative predictions of char depth when applied to non-standard (parametric) fire conditions with heating rates in excess of that for the standard-fire curve.
Similarly, the properties from the code were shown to result in un-conservative predictions of timber temperature and depth of char for heating rates lower than that for the standard-fire curve. As a
result, EN 1995-1-2 explicitly states that the thermal properties present in Annex B should only be adopted for standard-fire exposure and not parametric fire exposure.

![Figure 3- Elastic modulus reduction in softwood exposed to elevated temperature (Parallel to the grain)](image)

Konig [18] previously proposed that consistency between parametric charring measurements in experiments and computational predictions could be achieved via subtle modifications to the conductivity-temperature relationships proposed in Annex B of EN 1995-1-2, for standard-fire exposure. Konig [18] noted that only those properties in excess of 350°C should be modified as they represent the ‘effective’ properties of the char layer. It is phenomena in this area which appears to be influenced by heating rate, such as ‘reverse cooling pyrolysis flows’, cracking and ablation [18]. Although Konig [18] made the observation that the thermal properties present in Annex B of EC5-1-2 were not appropriate for parametric fire applications and that better agreement could be seen through adaptation of the char-layer conductivity, no follow-on research has been conducted to quantify necessary modification of the char-layer conductivity.

In recognition of the above limitations the authors proposed a modified-conductivity model for solid timber [19], which introduces its dependence on both heating rate ($\Gamma$) and fire-load density ($q_{td}$) via a modification factor $k_{\Gamma, mod}$, thus making it possible to simulate the temperature development in timber members exposed to natural fires. The modifications proposed are outlined in Table 1 and the equation that follows describing $k_{\Gamma, mod}$. Additional information can be found elsewhere [19].

### 4. Numerical study

Currently, the most common procedure for the fire design of timber structures is the residual cross section method, which is popular due to its simplicity. It accounts for reduction in load-bearing capacity, caused by a fire, through consideration of the depth of char ($d_{ch}$) and depth of pyrolysis layer (often referred to as a zero-strength layer, $d_0$) as a function of time. The depth of char is most commonly calculated for standard-fire exposure and is based on charring rates (often denoted as $\beta$).
Table 1- Proposed conductivity model modification for softwood

| Temperature (°C) | Conductivity (W/m.K) |
|------------------|-----------------------|
| 20               | 0.12                  |
| 200              | 0.15                  |
| 350              | 0.07                  |
| 500              | 0.09k\_mod            |
| 800              | 0.35k\_mod            |
| 1200             | 1.50k\_mod            |

\[ k_{\text{mod}} = k_{\Gamma,\text{mod}} k_{qtd,\text{mod}} \]  

(Equation 1)

\[ k_{\Gamma,\text{mod}} = 1.5 \Gamma^{-0.48} \]

\[ k_{qtd,\text{mod}} = \sqrt{\frac{q_{td}}{210}} \]

Where: \( O \)- Opening factor (m\(^{0.5}\)), \( b \)- Compartment thermal inertia (J/m\(^2\)s\(^{0.5}\)K) and \( q_{td} \)- Fire load density related to the total area of the enclosure (MJ/m\(^2\)).

The code assumes such charring rates are independent of both density and moisture content of timber. However, studies have shown [20] that they are consistent with a timber moisture content of 12% and an initial density of 450 kg/m\(^3\). The zero-strength layer (\( d_s \)) is nominally 7 mm, as defined by the code. The concept of the zero-strength exists to simplify the effective strengths of an infinite number of timber layers at various temperatures located between the char line (typically defined by the 300°C isotherm), where timber has no apparent strength, and the ambient (typically 20°C) isotherm, where timber retains all of its cold-design strength.

The EN 1995-1-2 residual cross-section method has its benefits, namely that it is simple and can be applied to both standard and parametric fire exposure. However, the method is limited to isolated members without consideration of the beneficial aspects of behaviors present when entire structures are subject to fire. The adoption of coupled thermo-mechanical whole-timber building models is potentially a much more efficient way to design fire-exposed timber buildings, especially when natural fires are considered. For this to be realised, the aforementioned modified-conductivity model must be coupled with mechanical behavior (with associated strength and stiffness reduction with increasing temperature). Before more complex behaviors associated with bending, biaxial bending and buckling are considered, it is first appropriate to observe how uniaxially loaded members behave when exposed to fires, both standard and natural. The ability of the MCM to be adopted in performance-based fire designs is measured by comparing the predicted failure times of uniaxially loaded timber members using both FEA simulations and simple empirical calculation models (reduced cross-section method) contained in BS EN 1995-1-2. Once this step has been taken it will be possible in future research to explore the potential for whole-building design using coupled thermo-mechanical modeling and the authors proposed MCM [19].

4.1. Modelling approach

To assess the applicability of the proposed MCM in the design of timber structures exposed to natural fires, it is necessary to confirm that simulations give results consistent with simple examples, for which solutions are well defined. A simple case of a 200 mm wide vertical wall member, of unit length, heated on both sides by a nominal fire, is considered. The fire follows a time-temperature response corresponding to either the standard fire curve [2] or a defined parametric fire [3]. As noted previously the ‘standard fire curve’ refers to the heating regime a furnace would typically follow in a fire resistance test. This fire curve describes an ever increasing gas temperature with time. In reality
fires have a finite life governed by available fuel. One simple representation of ‘real fires’ are parametric curves which include a cooling phase.

Using the residual cross-section method in section 4.2.2 of EN 1995-1-2 it is possible to determine when a uniaxially loaded timber member will fail under well-defined fire conditions. Conversely, it is also possible to determine the applied load required for a timber member to fail at a pre-determined time. The following is a simple example of this process for a timber member loaded in compression and exposed to the standard fire curve. The target failure time ($t_f$) is 30 minutes:

**Step 1:** Determine depth of char after 30 minutes- From EN 1995-1-2 table 3.1:

$$ \beta_0 = 0.65 \text{ mm/ min } \quad d_{ch} = 30 \text{ min} \times 0.65 \text{ mm/ min} = 19.5 \text{ mm}$$

**Step 2:** Determine reduced cross-section width:

$$ b = 200 - 2(d_{ch} + d_0) = 200 - 2(19.5 + 7 \text{ mm}) = 147 \text{ mm}$$

**Step 3:** Determine limiting load:

$$ P_{\text{max}} = A\sigma_c = bl\sigma_c = (147 \times 1000) \times 21.25 = 3123750 \text{ N}$$

This principal of determining a limiting load for a fire resistance can also be applied to timber tension members using the grade strength [21] of the given timber element. Similarly, the standard-fire charring rate can be substituted with that of the EN 1995-1-2 Annex A to determine failure times/loads for timber members exposed to natural fires. These limiting loads form the applied load in an FEA simulation and the apparent failure time is noted, thus giving a means of benchmarking empirical and simulated results. This modeling process and concept is discussed in detail below.

4.1.1. Geometry Meshing. As noted previously, the simulated specimen represents a wall of width 200 mm, heated from both sides. Utilising a plane-strain formulation and symmetry, it was possible to simplify the model geometry extensively. The wall is purposely short in height to ensure failure is a result of squashing and not instability/buckling. Simulations were conducted on walls (of unit length) loaded both in uniaxial tension and compression. The density of mesh adopted was governed by the heat transfer analysis conducted prior to the mechanical analysis. As such a graded mesh was adopted which is denser at heated boundaries relative to the centre of the timber specimens. More dense meshes were trialled and were shown to result in nominal differences relative to the mesh adopted.

4.1.2. Thermal material properties. The thermal properties adopted fall into two categories, namely boundary/interface properties and thermo-physical material properties. The boundary properties determine the net heat flow into a structure and describe convective and radiative heat transfer. Convection coefficients of 25 and 35 W/m² K were adopted for standard and parametric fire exposure. A constant emissivity of 0.7 was assumed throughout. The thermo-physical properties of solid timber are taken from Annex B of EN 1995-1-2 for standard fire exposure (Figure 4), with modifications for natural fires, as set out in section 3, where appropriate.

4.1.3. Mechanical material properties and models. Given the findings of the literature review, it is apparent that timber is ductile in compression and brittle in tension. As a result, plasticity models should be defined for simulations of compression. Similarly, for elements loaded in tension smeared cracking models were implemented, with tension softening for improved numerical stability. Class 16 timber is assumed throughout, giving 80% fractile compressive and tensile strengths of 21.25 N/mm² and 12.5 N/mm² respectively. Tension softening is assumed to occur over a maximum crack strain of 0.5%. Crack initiation is assumed to occur when the principal tensile stress exceeds the defined tensile strength. The onset of plasticity is determined using the Von Mises yield criteria [22].
4.1.4. Constraints and boundary conditions. The creation of a perfectly uniaxial loaded member heated from one side is challenging. To achieve only pure vertical displacements the concept of ‘tyings’ was adopted in DIANA, whereby degrees of freedom were tied together with corresponded resulting displacements. For the purpose of the simulations presented in this paper all degrees of freedom were tied to corresponding horizontally adjacent symmetry-line nodes. This ensured that edge degrees of freedom displace by the same amount as nodes located on the axis of symmetry. In addition, vertical constraints were introduced at the base of the wall, and the horizontal displacement of all nodes was restrained.

![Figure 4 - Conductivity and specific heat of softwood from EN 1995-1-2 [1]](image)

4.1.5. Thermal & mechanical loading. Mechanical loading was derived on a case-by-case basis using the concept shown previously in the three-stage example. Applied loadings and target failure times are summarised in the Table 2. Initial calibration trials were conducted for standard-fire exposure (Runs 1 to 8 C/T), where the thermal and mechanical aspects of timber behaviour are well defined in BS EN 1995-1-2. Those simulations were conducted to establish the robustness of the proposed geometry and material model arrangement before simulations of timber specimens exposed to parametric fires were conducted. The construction of a parametric fire curve is not included herein, however guidance can be found in EN 1991-1-2 [3] using the parameters outlined in Table 2. In Table 2 $q_{td}$ refers to the surface averaged fire load density in MJ/m$^2$.

5. Results

The simulations outlined in Table 2 are split into two categories: standard-fire and parametric fire simulations. In each case the assumed failure time is compared with the target failure time according to calculations conducted using section 4.2.2 of BS EN 1995-1-2. Failure in the simulation of the timber members is determined via either a deflection rate tending towards infinity or a lack of convergence for ductile and brittle failure modes respectively. In the latter case the stresses immediately before numerical instability were inspected to confirm the simulation was approaching failure. In addition to a comparison of the failure times of various cases, the concept of the zero-strength layer (adopted in the reduced cross-section method of EN 1995-1-2) was also investigated. In the simulation results presented the apparent zero-strength layer is determined as follows:

Step 1: Determine area required to resist the applied load using ambient temperature strengths, i.e.

$$\frac{P_c}{\sigma_{c,20^\circ C}} = A_{req} \quad \text{similarly} \quad \frac{P_t}{\sigma_{t,20^\circ C}} = A_{req}.$$  

Step 2: Determine depth of char ($d_{ch}$) from simulations by approximating the position of the 300°C isotherm as the position of the char line.

Step 3: Determine residual cross section area ($A_{fail}$) at failure:

$$A_{fail} = (b - (2d_{ch})) \times l, \quad \text{where} \quad l = 1000 \text{ mm}.$$
### Table 2- Overview of numerical study

| Run number | Fire   | \( \Gamma \) | \( q_{td} \) | \( t_f \) (min) | \( P_C \) (kN) | \( P_T \) (kN) |
|------------|--------|---------------|---------------|----------------|---------------|---------------|
| 1          | C/T    | Standard      | N/A           | 15             | 18063         | 10625         |
| 2          | C/T    | Standard      | N/A           | 30             | 15617         | 9187          |
| 3          | C/T    | Standard      | N/A           | 45             | 13545         | 7968          |
| 4          | C/T    | Standard      | N/A           | 60             | 11473         | 6750          |
| 5          | C/T    | Standard      | N/A           | 75             | 9401          | 5531          |
| 6          | C/T    | Standard      | N/A           | 90             | 7330          | 4312          |
| 7          | C/T    | Standard      | N/A           | 105            | 5258          | 3093          |
| 8          | C/T    | Standard      | N/A           | 120            | 3186          | 1875          |
| 9          | C/T    | Parametric    | 6.83          | 210            | 11690         | 6877          |
| 10         | C/T    | Parametric    | 8.93          | 210            | 12557         | 7387          |
| 11         | C/T    | Parametric    | 12.15         | 210            | 13356         | 7857          |
| 12         | C/T    | Parametric    | 17.49         | 210            | 14276         | 8398          |
| 13         | C/T    | Parametric    | 27.34         | 210            | 15191         | 8937          |
| 14         | C/T    | Parametric    | 12.34         | 280            | 11166         | 6569          |
| 15         | C/T    | Parametric    | 16.12         | 280            | 12080         | 7106          |
| 16         | C/T    | Parametric    | 21.94         | 280            | 13040         | 7671          |
| 17         | C/T    | Parametric    | 31.59         | 280            | 13981         | 8225          |
| 18         | C/T    | Parametric    | 49.34         | 280            | 15039         | 8847          |
| 19         | C/T    | Parametric    | 3.54          | 150            | 12411         | 7300          |
| 20         | C/T    | Parametric    | 4.63          | 150            | 13072         | 7690          |
| 21         | C/T    | Parametric    | 6.30          | 150            | 13800         | 8118          |
| 22         | C/T    | Parametric    | 9.07          | 150            | 14537         | 8551          |
| 23         | C/T    | Parametric    | 14.17         | 150            | 15411         | 9066          |

Step 4: Determine zero-strength layer depth \( (d_0) \) simply as:

\[
d_0 = \frac{1}{2} \left( \frac{A_{reg} - A_{fail}}{l} \right).
\]

The use of the above simple formulae allowed the authors to determine the validity of the zero-strength layers published in EN 1995-1-2 for standard fire exposure, whilst also allowing the assessment of their suitability for natural (parametric) fire exposure conditions.

The results of the numerical simulations outlined in Table 2 for standard-fire exposure (cases 1-8) are shown in Figures 5a and b. The first of these figures plots computed failure times (from FEA simulations) against target failure times, for which corresponding loads were derived with the reduced cross-section method. The second figure plots the apparent zero-strength layer depth versus failure time for members loaded in compression (C) and tension (T). Additionally, the size of zero-strength layer given in EN 1995-1-2 is also included for comparison. Similarly, Figures 6a and b give the same results for parametric fire exposure (cases 9-23).

### 6. Discussion

The results presented in Section 5.1 highlight that both the reduced cross-section method and the advanced calculation properties (included in Annex B of EN 1995-1-2) give consistent predictions of failure time for simple tension and compression members exposed to standard fires. Generally, apart from very low failure times, the variations fall within 10%.
The deviations apparent at low failure times are explained by the significant difference in depth of char when simplified charring rate concepts and advanced heat transfer models are compared. The former case assumes charring starts instantaneously, whilst the latter case is more realistic and simulates a short time delay in the onset of charring.

It is apparent from observing Figure 5b that significant differences exist between the codified zero-strength layer and that determined by the authors using numerical simulations. For both compression and tension simulations, the zero-strength layer exceeds that proposed in EN 1995-1-2 after approximately 45 and 15 minutes, respectively. Much of EN 1995-1-2 is empirical; however the
concept of the zero strength layer was derived numerically based upon simulations of flexural members [23]. Hence, the applicability of the EN 1995-1-2 concept of a 7-mm zero-strength layer for uniaxially loaded members is questionable as noted in other studies [23].

The results in Section 5.2 indicate that the MCM proposed by the authors can be implemented in coupled thermo-mechanical analyses of timber exposed to the heating phase of parametric fires. Comparison of predicted failure times using FEA simulations are benchmarked against target failure times using the reduced cross-section method, indicating very favorable correlation. This is particularly apparent for uniaxial tension members. Much like for standard-fire exposure, the determined depths of a zero-strength layer are inconsistent with those proposed in EN 1995-1-2. As a result it is clear that the equations for the zero-strength layer in EN 1995-1-2 should be modified not only for parametric fires, but also for cases where members are not loaded in flexure. It is, however, apparent that there appears, particularly for parametric fires, to be a linear relationship between the zero-strength layer depth and failure time.

7. Conclusion
This paper has presented a demonstration of the implementation of a MCM proposed by the authors in coupled thermo-mechanical analyses. Encouragingly, although the cases studied are relatively simple, the failure times noted in simulations are in agreement with those determined using the empirical equations in EN 1995-1-2. Interestingly, it has been determined that, for uniaxially loaded members, the zero-strength layer presented in EN 1995-1-2 may not be sufficient for both standard and parametric fire exposure and is derived from simulations of flexural members [23] using the advanced calculation properties outlined in Annex B.

References
[1] BSI, 2004. BS EN 1995-1-2, London.
[2] ISO, 1999. ISO 834-1:1999, Geneva.
[3] BSI, 2002. BS EN 1991-1-2, London.
[4] SCHaffer, E.L., 1973. ASTM J. Testing Evaluation, 1(4), 319-329.
[5] OSTMAN, B., 1985. Wood Sci Technol, 19, 103-106.
[6] KNUDSON, R.M. and SCHNIEWIND, A.P., 1975. Forest Products J, 25(2).
[7] LAU, P.W.C. and BARRETT, J.D., 1997. Proceedings of the 4th Int. symposium on fire safety science. Australia: Melbourne.
[8] GLOS, P. and HENRICI, D., 1991. Munich: Institut für Holzforschung der Universität München.
[9] SCHAFFER, E.L., 1984. Structural Fire Design: Wood. FFL 450. Madison: Forest products lab.
[10] THOMAS, G., 1997. Thesis. New Zealand: University of Canterbury Press.
[11] KONIG, J. and WALLEIJ, L., 2000. IO001001. Stockholm: SP Tratek.
[12] GERHARDS, C.C., 1982. Wood Fibre Sci, 14(1), 4-36.
[13] KOLLMAN, F., 1951. Meddelande 22. Stockholm: Svenska Traforskningsintitutet.
[14] NYMAN, C., 1980. VTT forest products No.6. Helsinki: Technical Research Centre of Finland.
[15] PREUSser, R., 1968. Holztechnologie, 9(4), 229-231.
[16] YOUNG, S.A., 1996. Internal report for CESARE. Melbourne: Victoria University.
[17] YOUNG, S.A., 2000. PhD thesis. Melbourne: Victoria University of Technology.
[18] KONIG, J., 2006. Fire Mater, 30(2), 51-63.
[19] HOPKIN, D., et al. 2010. J. Construct Building Mater. doi: 10.1016/j.conbuildmat.2010.12.002.
[20] CACHIM, P.B. and FRANSSEN, J.M., 2009. Fire Mater, 33(3), 129-143.
[21] BSI, 2003. BS EN 338:2003, London.
[22] MANIE, J., 2010. DIANA User's Manual. 9.4 edn. Delft: TNO.
[23] KONIG, J., 2005. Fire Mater, 29(3), 147-163.