A numerically derived modified conductivity model for softwood exposed to parametric design fires

Background, Benchmarking and Adaptation for Cooling

1 FRACTURE ENERGY AND TENSION SOFTENING

In an earlier publication the authors proposed a modified conductivity model (MCM) for softwood timber based upon the principles outlined in Konig's research and upon EN 1995-1-2 specific heat modifications proposed by Cachim and Franssen (2009). The MCM was derived using numerical calibrations of a fire load- (q_{td}) and heating rate- (r) dependent modification factor and the depths of char present in parametric design fires. In the latter case the depth of char in such fires was determined using the Annex A approach of EN 1995-1-2.

The resulting relations are shown in Tab 1. and Eqn 1.

Temperature (°C)	Conductivity (W/m K)
20	0.12
200	0.15
350	0.07
500	$0.09_{k\lambda,mod}$
800	$0.35_{k\lambda,mod}$
1200	$1.50_{k\lambda,mod}$

Temperature (°C)	Density Ratio G	Cachim and Franssen moisture modified specific heat (J/kg K)
20	1 + ω	(1210+4190 ω)/G
99	1 + ω	(1480+4190 ω)/G
99	1 + ω	(1480+114600 ω)/G
120	1.00	(2120+95500 ω)/G
120	1.00	2120/G
200	1.00	2000/G

$$k_{\lambda,\mathrm{mod}} = k_{\Gamma,\mathrm{mod}} k_{qtd,\mathrm{mod}}$$

with $k_{\Gamma,\mathrm{mod}} = 1.5\Gamma^{-0.48}$, $k_{qtd,\mathrm{mod}} = \sqrt{\frac{q_{td}}{210}}$ and $\Gamma = \frac{(O/b)^2}{(0.04/1160)^2}$,

where ω is the moisture content of timber (%), O is an opening factor ($m^{0.5}$) and b is compartment thermal inertia ($J/m^2s^{0.5}K$).

The above, when coupled with specific heat properties and appropriate densities, were found to give consistent transient depth-of-char predictions for the heating phase of a parametric fire, when compared to EN 1995-1-2 Annex A. However, from a structural-engineering view point, the definition of the depth of char in Finite Element analysis (FEA) simulations is insufficient to fully characterise the mechanical response of a member exposed to high temperatures. In timber only those temperatures below 300°C are of concern. Above this threshold the timber is charred and friable. As a result, the MCM must not only be able to place the char line correctly within a cross section, but it must also accurately simulate temperature in the intact member. This allows the sectional response to be determined using strength, stiffness and temperature relations. Given the limited number, and limitations, of experiments conducted on timber exposed to parametric fires, the authors were only able to investigate temperature development using the test data developed by Konig and Walleij (1999). The modelling conducted and the comparisons made are discussed in the section that follows.

2 BENCHMARKING AGAINST KONIG TEST DATA

At the turn of the century Konig and Walleij (1999) reported 6 experiments on timber blocks exposed to parametric fires. The experiments, as best as possible, exposed timber panels to one-dimensional heat transfer via a gas-powered furnace following parametric curves. From this it was first observed by Konig (2006) that the thermal properties present in Annex B of EN 1995-1-2 were inappropriate for use with non-standard fire exposure. The timber used in the experiments was a generic softwood with an estimated moisture content of 12% and a mean density of 420-430 kg/m³. Although Konig and Walleij (1999) attempted to follow parametric curves, this was not entirely possible due to the furnace configuration. As a result, the authors fitted EN 1991-1-2 parametric curves to the measured gas temperature-time relationships via trial and error. The resulting key parameters are noted in Tab. 2. From observation of the test data it is apparent that experiments C1 to C3 follow the standard fire curve and then cool, whilst C4 to C6 follow a different accelerated heating regime. Given this the authors decided to attempt to simulate experiments C4 to C6 as they represent an obvious deviation from the standard fire curve. In addition, as the authors' MCM was developed for the heating phase of parametric fires, only the heating phase of Konig and Walleij's (1999) experiments is considered at present.

	C4	C5	C6
q_{td} (MJ/m²)	93.8	109.4	114.6
r (-)	2.7	3.0	4.5

Using these parameters it is possible to determine the appropriate values of $k_{\lambda,mod}$ for each test thus yielding modified conductivity properties.

As the moisture content was estimated as 12% by Konig & Walleij (1999) then the specific heat relationship from EN 1995-1-2 can be adopted without modification. Using the gas temperature measured in each experiment as a boundary condition, coupled with boundary coefficients of ε = 0.7 and α = 35 W/m² K, the one-dimensional heat flow was simulated using TNO DIANA. In all instances first-order quad elements with dimensions of 0.5 mm were adopted. Temperatures at depths of 0, 6, 18, 30, 42 and 54 mm, denoted 1, 2, 3, 4, 5 and 6, respectively, were measured by Konig & Walleij (1999). Therefore, temperatures for corresponding nodes are used as output in DIANA (Manie 2010). In addition, simulations were conducted with unmodified conductivity properties as per EN 1995-1-2 for comparison. Plots of the resulting temperature development are shown in Figure 1(a-c).

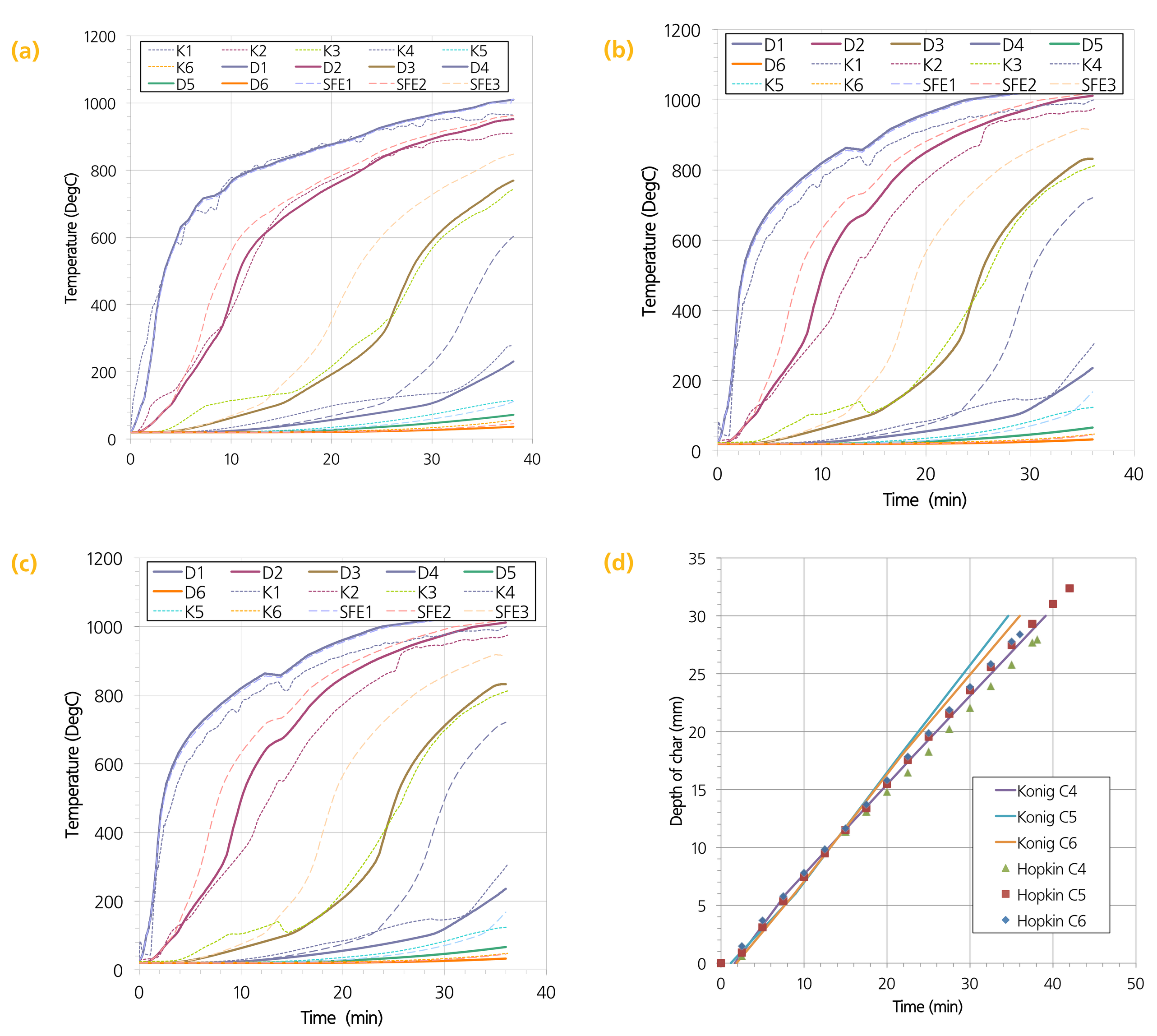

Fig. 1 (a-c) Temperature development, comparison of MCM (D), Konig (K) and EN 1995-1-2 (SFE) simulations/experiments; (d) Transient depth of char- simulation (Hopkin) versus experiment (Konig)

3 EXTENSIONS TO COOLING TIMBER

Given that the MCM was developed for the heating phase of parametric fires (i.e. up to t0), its applicability in the cooling phase of fire development is uncertain. To verify its applicability further benchmarking was conducted against Annex A of EN 1995-1-2 by conducting simulations with the proposed conductivity changes and a fully defined parametric fire (inclusive of cooling). An example finding is shown in Figure 2.

3.1 An engineered approach to design for cooling

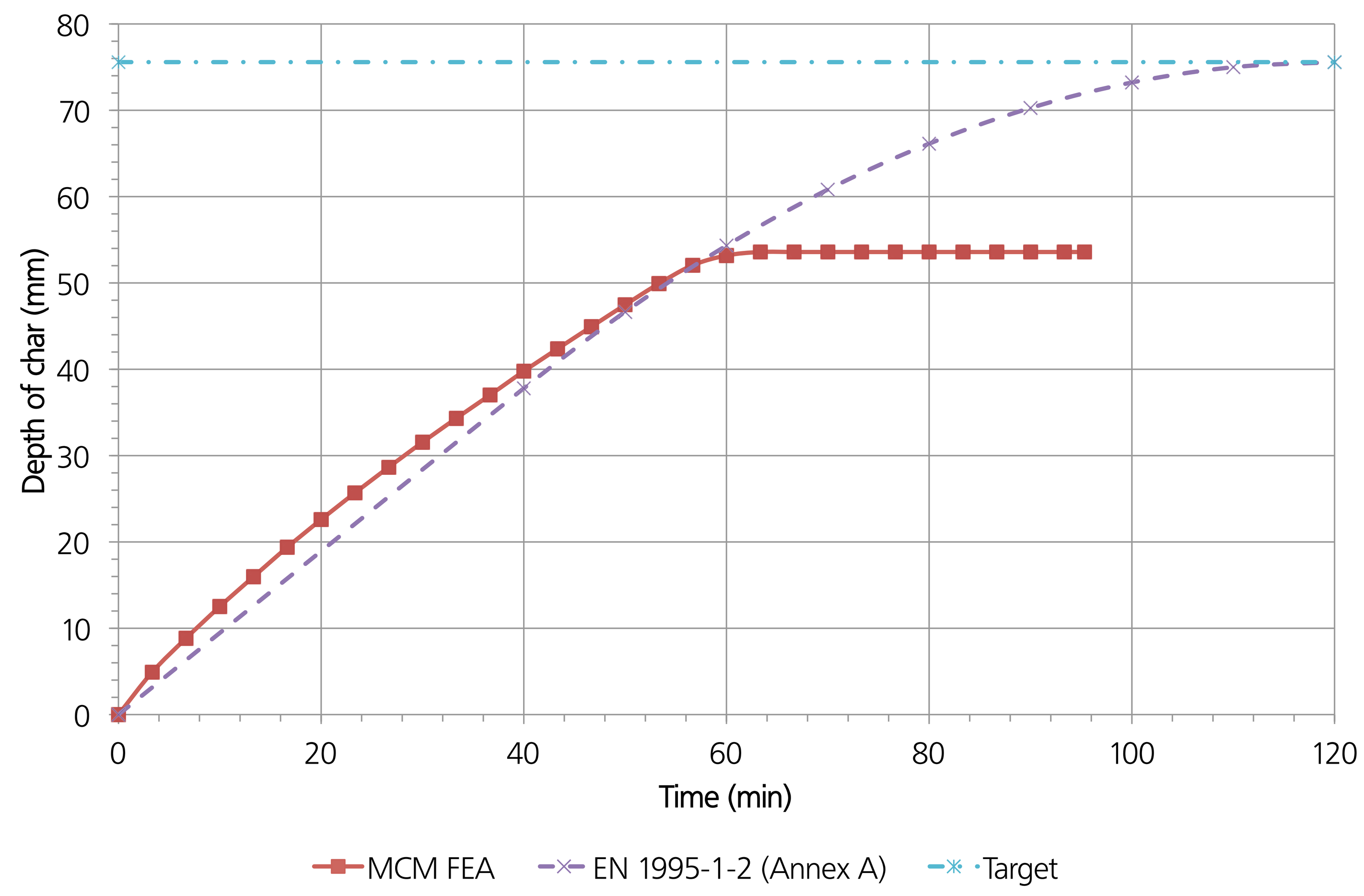

Fig. 2 Comparison of FEA, MCM and EN 1995-1-2 calculation of depth of char

Since charring is a dominant phenomenon, and that transient effects and thermal expansion of timber appear to have little bearing on behaviour in fires, it becomes less important to accurately simulate temperature and char development as a function of time.

By definition, performance-based design is a process whereby a structure is designed to survive the entire duration of a fire, and, in crude terms, the resulting building has infinite fire resistance. It follows that to design a timber member for such an event, it is only necessary to determine the maximum depth of char (at the end of cooling) and the maximum temperature apparent in any undamaged residual timber. This process is semi-independent of time.

Further numerical calibrations performed by the authors showed that, via a slight modification to the fire load-dependent term (kqtd,mod) in the MCM, the total depth of char can be determined accurately using FEA simulation. The calculated char depth is inclusive of the additional char that develops during cooling. The modified term is given by:

$$k_{qtd,\mathrm{mod}} = \sqrt{\frac{4.q_{td}}{210}}$$

This simple modification yields the following relationships between depth of char and time for different parametric fire exposures, see Figure 3. In all instances qtd=210 MJ/m2:

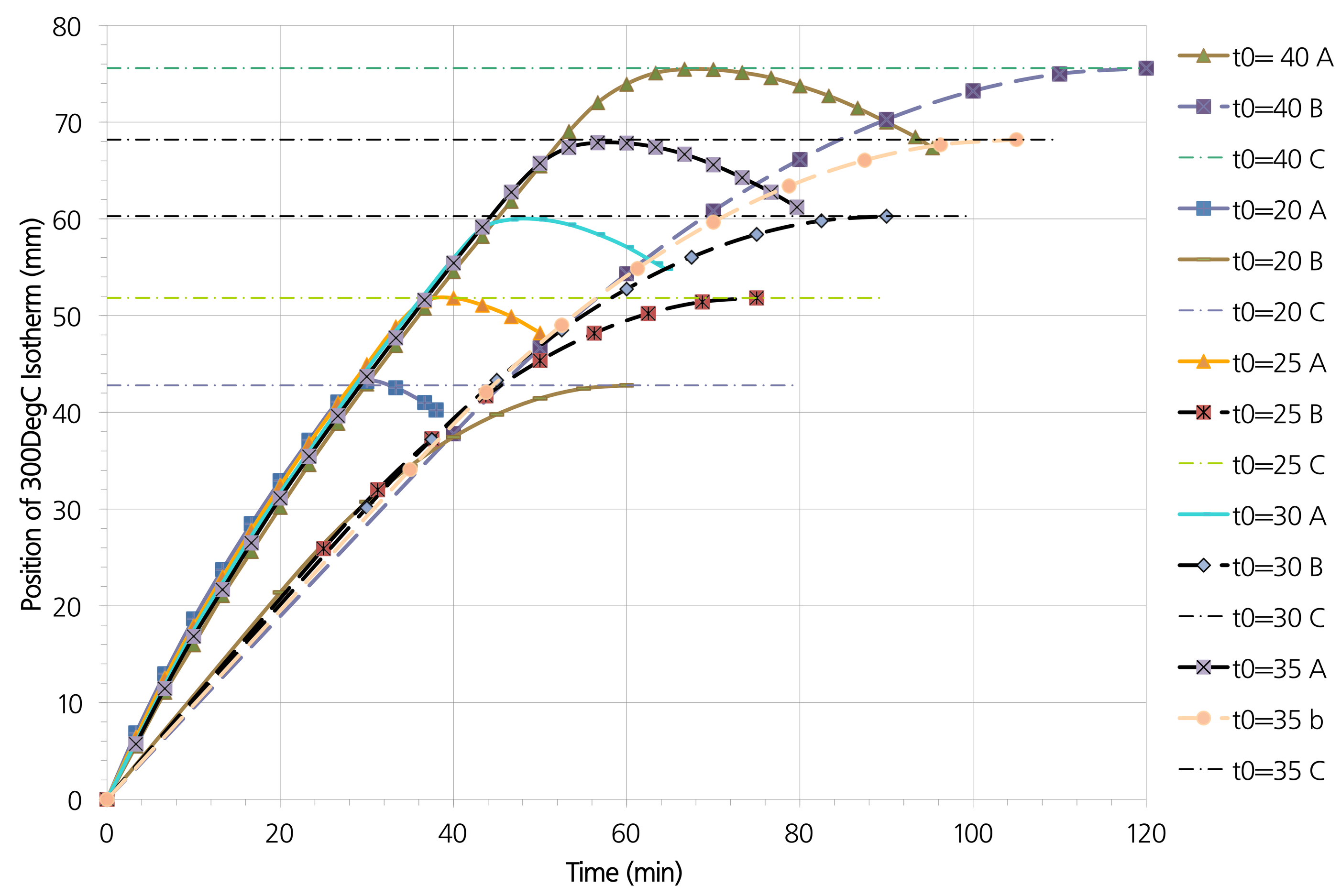

Fig. 3 Position of 300°C isotherm using modified kqtd,mod (A) and EN 1995-1-2 Annex A (B). Target depth of char shown as (C).

Figure 3 shows that in all instances the maximum depth of char determined via simulation is consistent with the Eurocode approach. As a result, although in transient terms the depth of char is inconsistent, the residual cross-section determined in both cases at the end of the fire is identical. From a scientific view point the method proposed does not accurately simulate the physical complexities that occur in timber on cooling. However, this is also the case for the many empirical methods contained in EN 1995-1-2. To gauge the applicability of such an approach, determining the charring depths alone is not sufficient. It must also be shown that ultimate temperature development in uncharred timber is compatible with that apparent in reality. To verify this, further benchmarking will be conducted against the test data of Konig and Walleij (1999).

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