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The impact of assumed fracture energy on the fire performance of timber beams

A Numerical Study

1 FRACTURE ENERGY AND TENSION SOFTENING

The fracture energy of timber, more specifically softwoods, is an area well researched at ambient temperature. Many textbooks give fracture energies for different cracking modes, which are shown to be highly dependent upon density (Thelandersson & Larsen 2003). Larson & Gustafsson (1990/91) give one such correlation for notched timber members subject to bending, where:

$$G_f = 1.07p - 162 \qquad (1)$$

where G_f is fracture energy (Nm/m²) and is density in kg/m³.

For typical softwood this gives fracture energies ranging from 160-480 Nm/m² for mixed mode cracking. However, little, if anything, is known about the fracture energy of timber or other brittle materials at elevated temperature.

The numerical mechanical modelling of timber at elevated temperature is rare. To date, simplified models are often adopted using spreadsheets and sectional analysis tools (Konig & Walleij 2000, Schmid, et al. 2010). As a result of such an approach, it is not necessary to define fracture energy as timber in tension can be treated as a perfectly brittle material.

However, such an approach cannot be adopted in more general FEA computations as this may lead to numerical instability. To this end, tension softening regimes are often defined to describe the descending branch of a materials constitutive relation (See figure 1). The definition of such behaviour requires either knowledge of fracture energy (i.e. the integral of the deformation stress curve) or ultimate crack strain, i.e. the strain at which all crack stress has vanished.

In the DIANA FEA package it is possible to define a number of tension-softening relationships based upon fracture energy, crack bandwidth and/or ultimate crack strain. To investigate the impact of these parameters, a parametric study was designed to study the behaviour of simply supported beams, loaded to different utilisation levels, under standard fire exposure. To undertake the study, it has been necessary to make a number of modifications to DIANA in order to extend characterisation of the behaviour of timber.

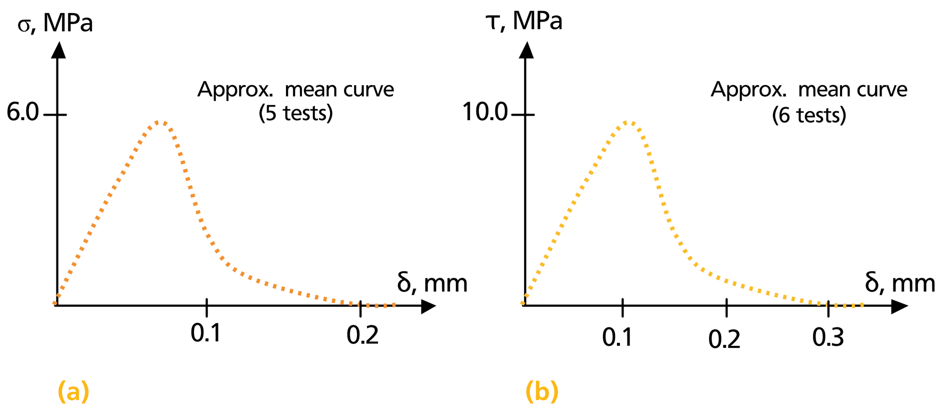

Fig. 1 Indicative fracture behaviour of timber in (a) tension and (b) shear (displacement vs. stress) after Thelanderson and Larsen (2003)

2 PARAMETRIC STUDY DESIGN AND MODELLING APPROACH

In DIANA the tension softening relations of a material can be described either via fracture energy or ultimate crack strain. Both of these parameters can be specified as a function of temperature. DIANA offers linear, exponential or Hordyk tension-softening regimes, which describe the stress-strain relations of an open crack (see figure 2). More information on the tension softening regimes can be found in Manie (2010).

In the parametric study conducted, both of the above were adopted to investigate the apparent failure time of a simple timber beam exposed to fire (ISO834) from below and subject to varying degrees of load level (via a mid-span point load). A simple bi-linear model describes the plasticity behaviour of timber in compression as part of a total strain-based crack model incorporating the above. The beam is modelled as continuum using second-order quad plane-stress elements.

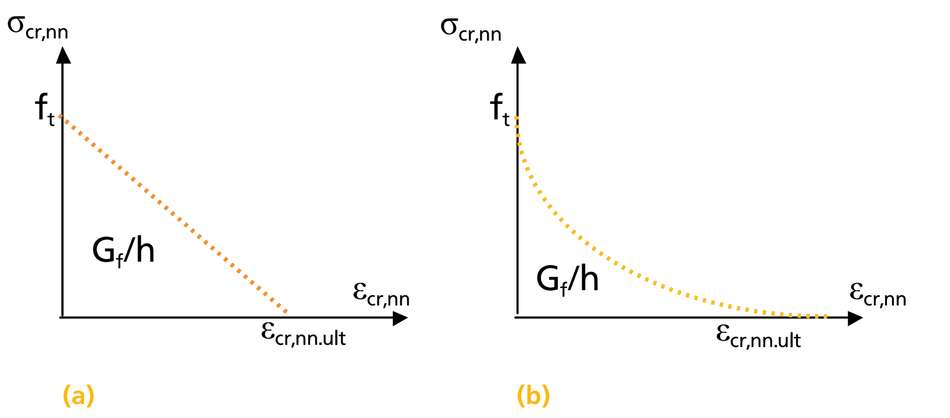

Fig. 2 Tension-softening relationships available in DIANA (Manie 2010):- linear (a) and Hordyk (b)

The analysis is conducted as a staggered thermo-mechanical model whereby second-order structural elements are converted to first-order flow elements. Thermal and boundary properties are as per EN 1995-1-2 and EN 1991-1-2, respectively (BSI 2002/2004). Grade C30 timber is assumed throughout with a characteristic density of 300 kg/m³. Tensile strength is derived according to Thunnel (1941) assuming 80% fractile strength. The Modulus of Elasticity (MOE) as a function of temperature is determined using a subroutine proposed by Hopkin et al. (2011).

Timber beams 150 mm deep and 2 m long are subject to different utilisation ratios of 25, 50, 75 and 90%. The required loads to achieve such utilisation levels are derived using the reduced cross section method set out in EN 1995-1-2 for standard fire exposure. Target 'failure times' are also derived using this method. Where a "mixed" fracture energy is referenced, this implies an increasing fracture energy with temperatures as per figure 3.

The mixed fracture energy concept is introduced as a potential solution to numerical instability. Large strains can develop in the char zone of a beam, which contributes little to the mechanical resistance yet may govern the termination time of a simulation, should the total strain at the extreme char fibres exceed that of the ultimate crack strain. The application of a single large fracture energy for all temperatures (i.e. 5000Nm/m² for all temperatures) may overpredict the load-carrying capacity of a timber beam and, as such, it is important to maintain realistic fracture energy values for uncharred timber.

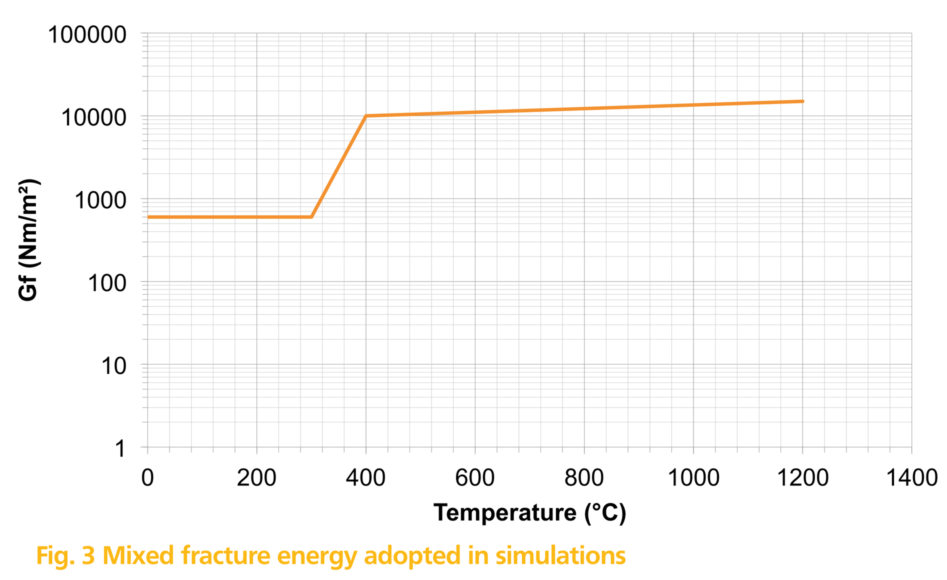

Fig. 3 Mixed fracture energy adopted in simulations

Group No.	Utilisation (%)	Fracture energy (Nm/m²)	Tension softening	Target failure time (min)
1 (A-E)	25	600 (A), 1000 (B) 2000 (C), 5000 (D), Mixed (E)	Linear	66 (3960s)
2 (A-E)			Hordyk	
3 (A-E)	50		Linear	34 (2040s)
4 (A-E)			Hordyk	
5 (A-E)	75		Linear	13.5 (810s)
6 (A-E)			Hordyk	
7 (A-E)	90		Linear	5 (300s)
8 (A-E)			Hordyk	

Simulation failure is crudely taken as the last converged step. It is recognised that such a termination can be brought about due to numerical instability and not a physical failure. However, where fractures develop without alternative means of load redistribution, it is highly likely that failure is due to a violation of the stress-strain relationship for the material and thus can be considered as a 'true failure'. This is particularly the case for instances where large fracture energy values, and thus large ultimate crack strains, are specified for the char layer, i.e. the mixed case.

3 FINDINGS

Without supporting experimental data the authors have chosen to measure the relative impact of fracture energy on 'failure' time by comparing simulation termination times with predicted failure times using the reduced cross-section method of EN 1995-1-2. Results are divided by tension-softening regime and as such plots of apparent simulation failure time and EN 1995-1-2-derived failure time are shown for linear and Hordyk tension-softening regimes in figures 4 and 5, respectively.

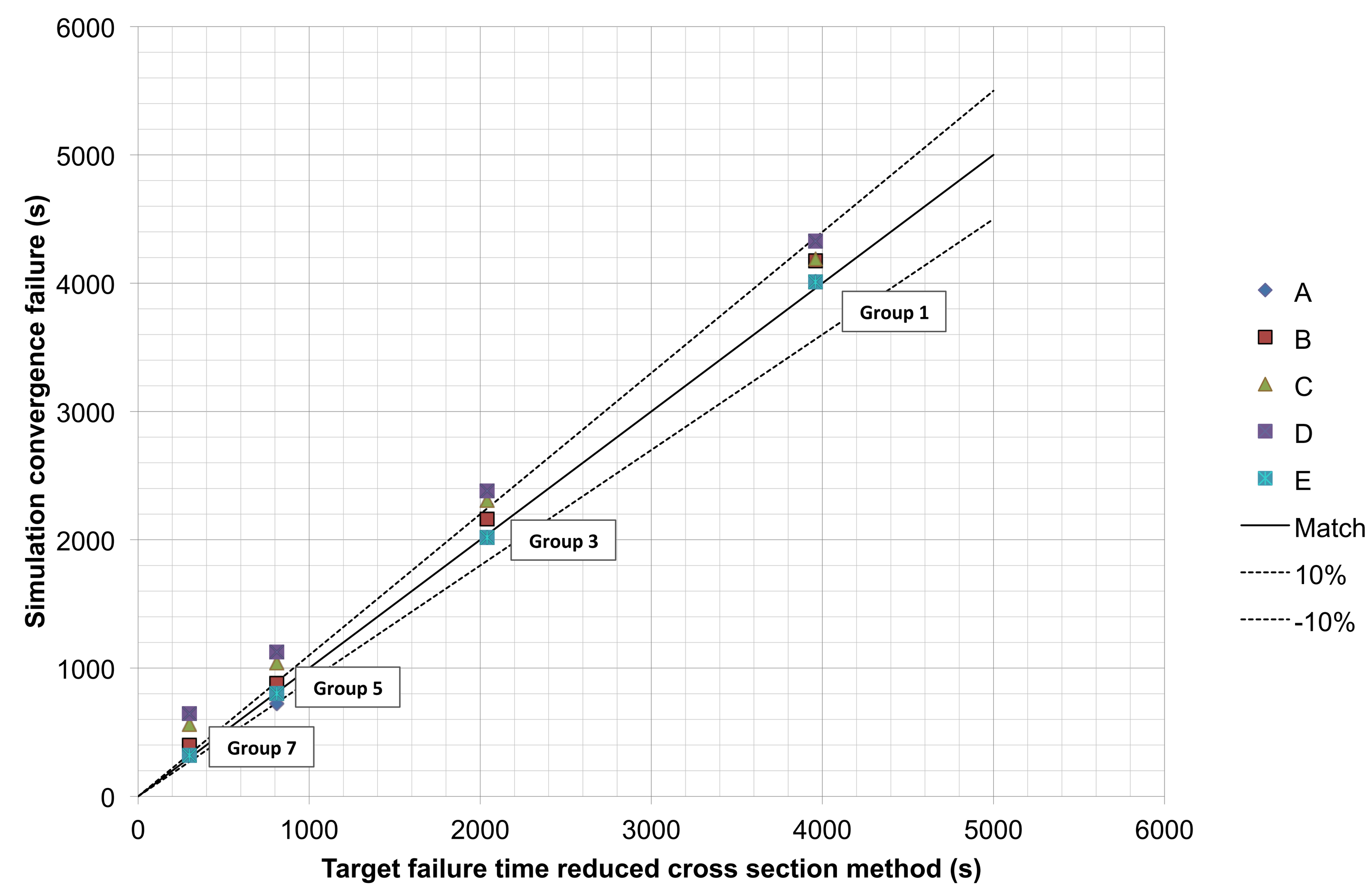

Fig. 4 Simulation termination time vs. predicted failure time from EN 1995-1-2 (linear tension softening)

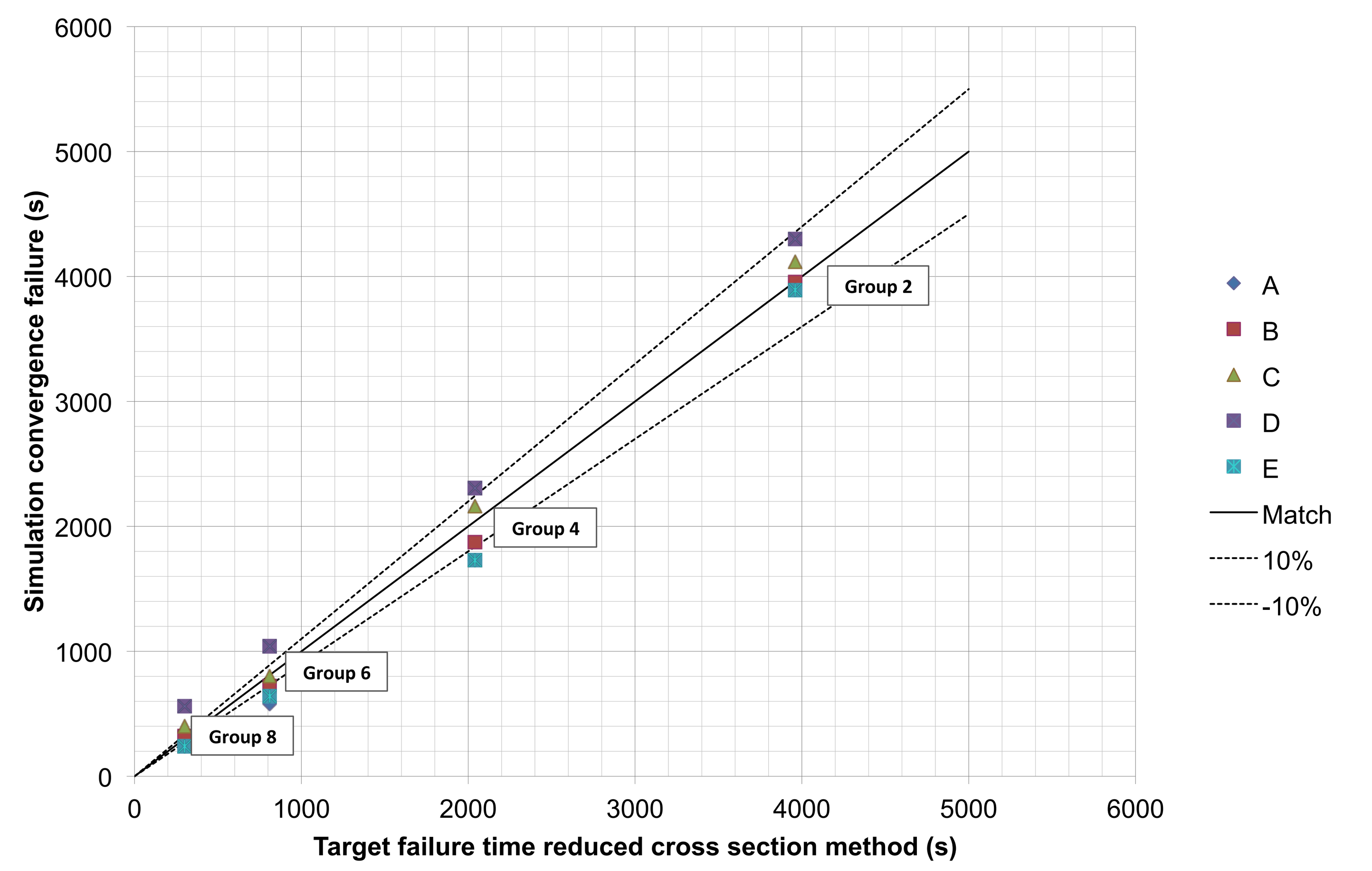

Fig. 5 Simulation termination time vs. predicted failure time from EN 1995-1-2 (Hordyk tension softening)

4 SUMMARY

Figures 4 and 5 demonstrate that the assumed fracture energy has an important influence on the simulation termination time when a timber beam is exposed to fire from below and is subject to different levels of load. The larger the fracture energy, the more ductile a structural member behaves as crack stress is dissipated over a much larger crack strain.

In numerical simulations the incorrect input of fracture energy can result in overall reductions in tensile strength as the values specified should be sufficient for the full tension-softening regime to be defined. In DIANA the limiting tensile strength is dependent upon the tension softening regime, fracture energy, MOE and crack bandwidth. Where small crack bandwidths and fracture energies are introduced, reductions in tensile strength can occur, which impact heavily upon apparent 'failure time'. This behaviour was found to be more critical when Hordyk tension softening is adopted over Linear.

For the purposes of modelling timber beams exposed to fire it has been found that linear tension softening is adequate. A mixed fracture-energy approach (i.e. increasing Gf with temperature) can ensure that numerical instability does not develop in the char zone, where strains are high, whilst also giving realistic strength characteristics and brittleness behaviour in the undamaged residual cross section.

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