Adaptation of fea codes to simulate the heating and cooling process of timber structures exposed to fire

Mechanical Behaviour

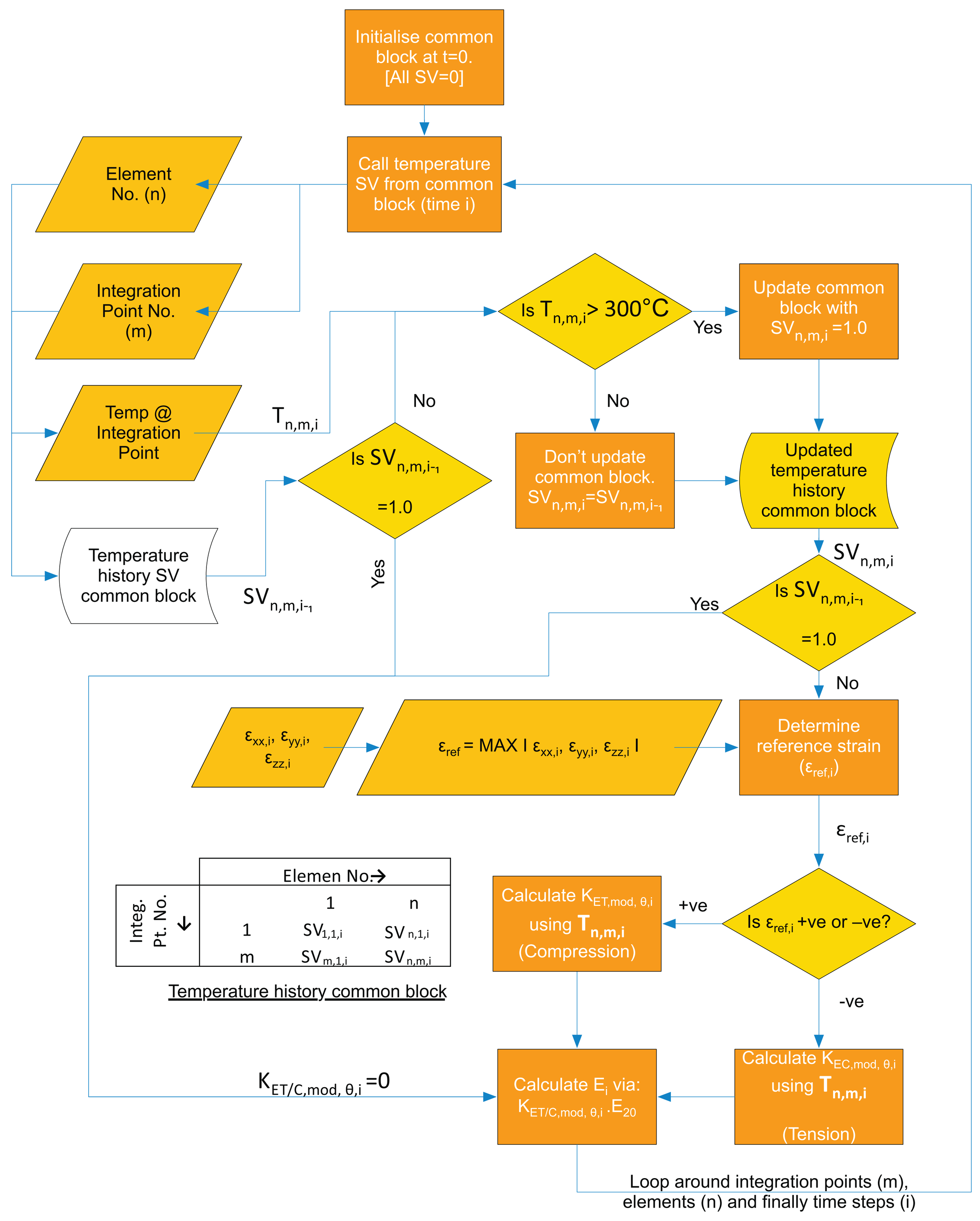
1 MODELLING FIRE-EXPOSED TIMBER STRUCTURES

The modelling of timber exposed to fires has largely focussed upon temperature development either in unprotected large-section or light-weight gypsum-lined structures. The mechanical modelling of timber exposed to fire is a recent endeavour instigated by Thomas (1997) followed subsequently by König & Walleij (2000). However, to date this mechanical modelling has been the domain of adhoc codes and spreadsheet programmes due to complexities in timber behaviour at elevated temperature. This poster presents a number of developments made to enable researchers to use general finite element codes in the analysis of fire exposed timber structures.

2 USRYOU - A SUBROUTINE FOR DETERMINING MOE OF TIMBER IN FIRE

DIANA offers a number of subroutine options for customising the analyses performed. One such subroutine (USS) is the USRYOU option, which allows users to return MOE based upon a number of inputs, including integration point strain and temperature. The authors have developed a USRYOU USS for determining the Modulus of Elasticity (MOE) of timber exposed to both heating and cooling.

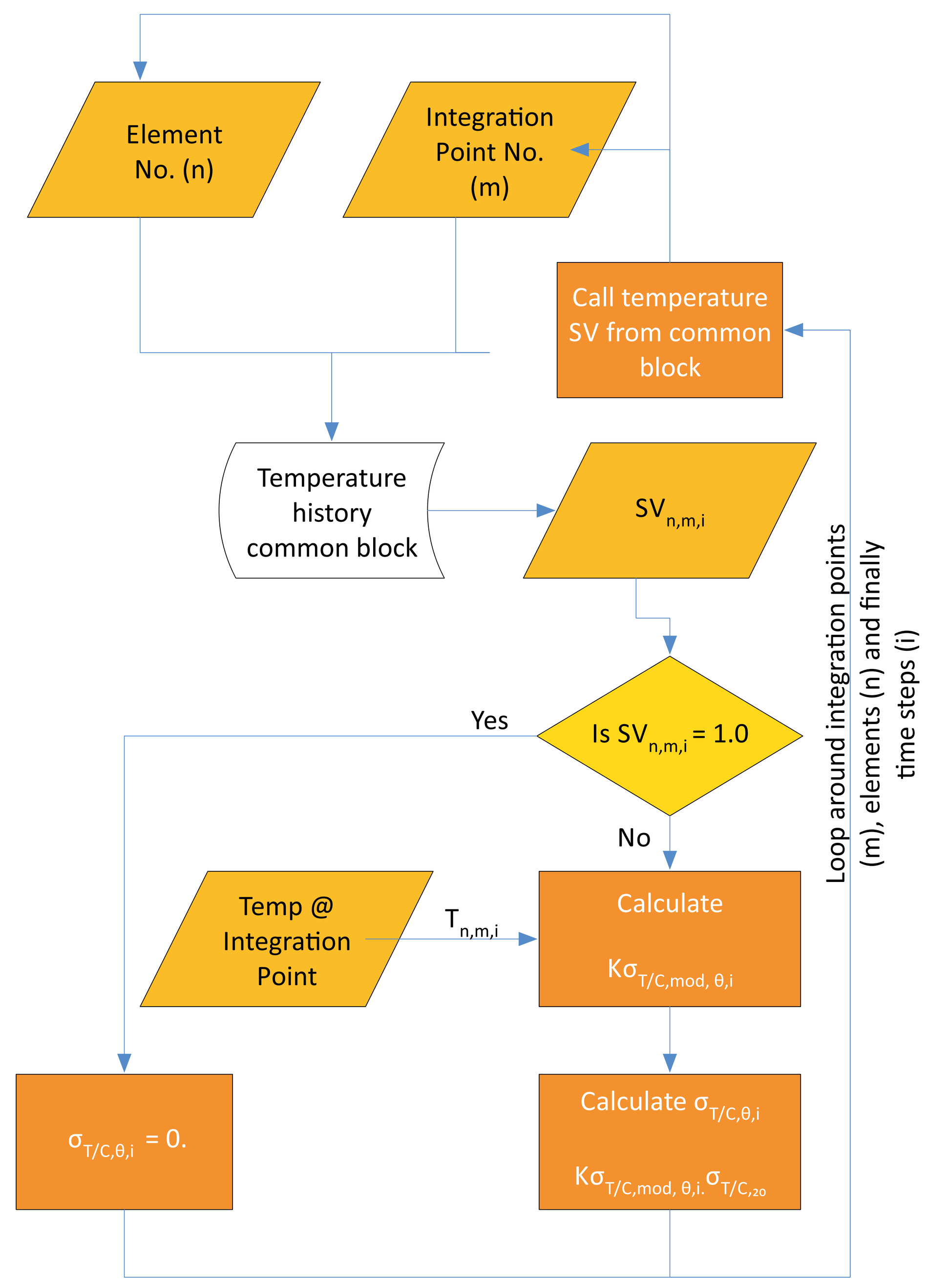
Firstly, integration point and element numbers are called from the program along with temperature at the given integration point. Temperature history of elements is recorded via a common block, which determines whether the temperature of the timber (a) exceeded the charring temperature of 300°C, (b) exceeded the moisture evaporation temperature of 100°C, or (c) below 100°C, that is, timber neither charred nor suffered moisture evaporation. Based on this, the temperature-history common block is updated incrementally, which allows state history to be recorded. The latter allows for a number of hypotheses to be investigated, which will be discussed in section 4.



Using the recorded temperature history the stress state may be investigated. The strains in the local element co-ordinates are called from DIANA. The dominant integration point strain is determined, which is then used to evaluate MOE appropriate to temperature and the strain state. For example, if ε_{xx} is found to be the largest element strain and the strain is compressive, the MOE is returned, based upon EN 1995-1-2 (BSI 2004) compression reduction factors (KEC) and element temperature. The converse case would be adopted if ε_{xx} was found to be tensile. In this instance reduction factors are defined as KET. This process is shown diagrammatically in Figure 1.

3 USRCST/TST- A SUBROUTINE FOR DETERMINING COMPRESSIVE/ TENSILE STRENGTH OF TIMBER

Two more USSs, namely USRCST and USRTST, are available in DIANA for determining the tensile and compressive strength, respectively. These routines in particular are for implementation with Total Strain Based constitutive models, which are discussed in a supporting paper (Hopkin et al. 2011). The routines utilise the temperature-history common block initialised in the above USRYOU routine to calculate tensile and compressive strength using EN 1995-1-2 reduction factors. The element number and integration point number are used to reference allocated memory slots, where temperature state variables are stored. Compressive and tensile strengths (limiting stresses) are passed to DIANA for implementation in the adopted Total Strain Based Constitutive model. This process is shown in a flow diagram in Figure 2.



4 THE USE OF TEMPERATURE STATE VARIABLES IN THE COOLING DOWN PHASE

When the temperature reaches a certain limit within a timber section its moisture content will be completely lost through evaporation. As the section's temperature increases, charring of certain parts may also occur. The charred timber will not contribute to the strength and stiffness of the section. Clearly, this damage is irreversible. However, little is known about the strength and stiffness of the remaining un-charred part of the section and how the section behaves during cooling down. To study this, the concept of temperature history state variables (SVs) has been introduced. This allows for a number of hypotheses to be investigated.

- **Hypothesis 1-** During cooling down, undamaged timber recovers none of its strength or stiffness. This would be the case if temperature changes during the cooling phase are ignored. In this case, the maximum temperature reached during heating up governs the behaviour during cooling.
- **Hypothesis 2-** It could be argued that moisture lost during the heating phase cannot be regained during cooling down. This means that strength and stiffness of timber whose temperature, upon heating, did not exceed 100°C will be fully recovered to that appropriate to its temperature during cooling down. However, timber heated beyond 100°C, but not charred, may recover its strength and stiffness but only up to the maximum value applicable to dry moisture-free timber. The latter condition implies that reduction factors corresponding to 100°C should remain applicable even when timber temperature drops below this limit.
- **Hypothesis 3-** While cooling down, all non-charred timber will recover the entire strength and stiffness appropriate to its temperature. This implies that loss of moisture during heating had no effect on the recovered properties. Clearly, this approach may be implausible as it suggests the return of moisture into the timber during cooling.

The implications for these three hypotheses can be observed through a number of simple numerical tests on single quad elements or simply supported beams. This testing process is discussed in the following section.

5 SUBROUTINE TESTING AND IMPLEMENTATION

The testing of the USSs was conducted at a number of different scales. Firstly, trials of hypotheses 1–3 were conducted using single first-order quad elements uniformly heated and cooled down, and subject either to a compressive or tensile strain. In these trials, only the USRYOU subroutine is implemented so that non-linear elastic solutions can be sought without either cracking or plasticity. Resulting strain-temperature plots are shown in figure 3 for all three hypotheses. A constant load was applied throughout. In such trials it is not possible to indicate permanent charring damage as it would result in numerical instability. Thus, the maximum applied temperature was 210°C. Tensile and Compressive loads of identical magnitude were applied to allow for the difference in MOE degradation with temperature for different strain states to be checked. However, only one set of results (compressive) is shown as the other indicated the same pattern.

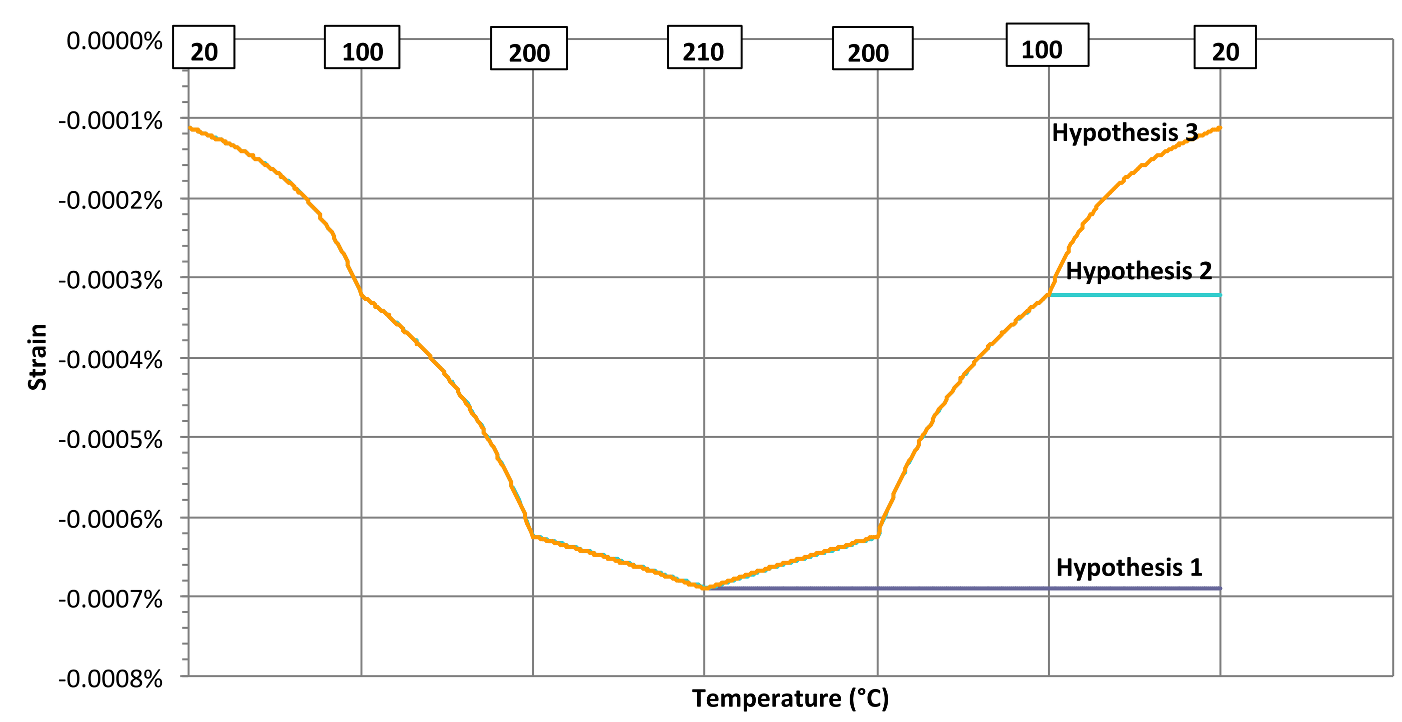
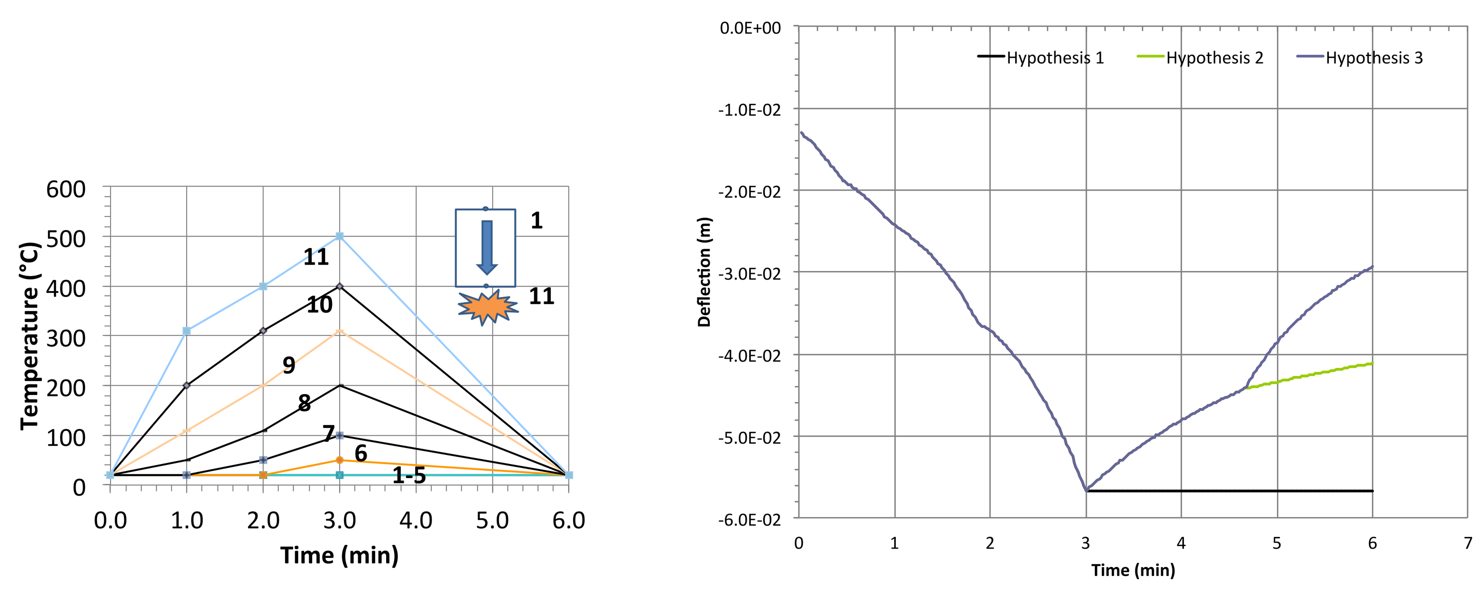


Fig. 3 Single-element implementation of USRYOU subroutine: temperature-strain plots for a constant nominal load

The second element of USS testing is concerned with the behaviour of simply supported beams subject to a temperature gradient. A beam was modelled simply in DIANA using a number of first-order 2D beam elements. Temperatures were specified at 11 integration points through the cross section of beam elements. Integration point distribution was according to a Simpson integration scheme. The adopted temperature profiles are shown in Figure 4a. The legend indicates fire from below with 11 integration points numbered from the top down. The temperatures applied are fictitious temperatures and serve only to demonstrate implementation of the USS. The modelled beam is 4 m in length and has a 100 mm x 250 mm cross-section. The beam is subject to a nominal load of 5 kN/m. The development of deflection upon heating, followed by cooling can be seen in Figure 4b. In this case, the beam temperature developed beyond 300°C. Therefore, permanent deformation due to charring was apparent, including the case with full un-charred timber strength recovery (hypothesis 3).



(a) (b)

Fig. 4 Beam implementation of USRYOU and USRCST/TST subroutines: (a) Temperature profiles at integration points (b) Deflection–time plots.

In relation to the strength and stiffness recovery of timber upon cooling, experimental evidence suggests that the first two hypotheses may be more realistic (Lennon et al. 2010 & Hopkin et al. 2010). In the many experiments conducted by BRE on timber structures over the last decade, there appears to be little evidence to suggest any strength or stiffness recovery in timber structures exposed to fire, upon cooling.

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