CONSTITUTIVE MODEL FOR WOOD BASED ON CONTINUUM DAMAGE MECHANICS

Carmen Sandhaas¹, Jan-Willem van de Kuilen²

ABSTRACT: Based on the theory of continuum damage mechanics (CDM), a 3D constitutive model was developed that allows for a holistic approach for timber models. With one single material model, simultaneous ductile and brittle behaviour of wood can be simulated and the failure modes can be identified. To validate the model, tension, compression and embedment tests were modelled applying the developed constitutive model. Not only softwoods were used, but also European and tropical hardwoods. The predictive quality of the constitutive model was assessed by comparing load-slip curves and failure modes of the test specimens with the numerical results. Good agreements were found and brittle behaviour with stable crack growth could be predicted. The developed material model proved to be a valid approach to improve the prediction quality of numerical models and to identify failure modes.

KEYWORDS: 3D constitutive model wood, continuum damage mechanics (CDM), finite element method

1 INTRODUCTION

Wood and timber connections are difficult to model. Apart from heterogeneity, two other main material-specific issues lead to numerical problems: anisotropy with different strength in tension and compression and ductile and brittle failure modes occurring simultaneously. Within the framework of continuum damage mechanics (CDM), a general approach combining the above mentioned issues in one single material model was developed. This developed constitutive model can be used to predict material behaviour and embedment tests.

2 FAILURE MODES

Classical theory of plasticity is generally based on single-surface failure criteria that are not able to identify failure modes as the material starts yielding/failing in all material directions once the failure criterion is exceeded. Examples are the wide-spread Hill [1] or Hoffman [2] criteria. Therefore, in order to recognise failure modes, the single-surface was divided; different failure criteria were assigned to stress components that were valid only for the respective stress-strain quadrants. For instance, in a FE model, the stress component \( \sigma_L \) in every integration point is controlled. If \( \sigma_L \) is smaller than zero and bigger than the chosen compression strength parallel-to-grain, then the material starts to fail. Splitting in the LT-plane on the other hand is caused by stress components \( \sigma_R, \sigma_{LT}, \) and \( \sigma_{RT}. \) For a complete 3D description of wood as an orthotropic material, eight failure criteria were defined.

3 CONTINUUM DAMAGE MECHANICS

CDM is a nonlinear elastic approach where the nonlinear behaviour is obtained by modifying the stiffness matrix. CDM can be implemented in an incremental-iterative FE framework. The stress increments are calculated from strain increments having a variable stiffness matrix. Therefore and as opposed to classical plasticity, the unloading in damage mechanics is following the secant stiffness and not following the elastic stiffness. Damage variables \( d_i, 0 \leq d \leq 1, \) are determined and inserted into the fundamental Hooke equation as follows:

\[
\sigma_{ij} = (1 - d_{ij}) D_{ijkl} \varepsilon_{kl}
\]

If \( d_{ij}=0, \) no damage is present; if \( d_{ij}=1, \) the material has failed.

Nine damage variables were defined to represent the 3D behaviour of wood. Failure criteria in compression triggered ductile stress-strain behaviour where the damage variable followed a elastic-perfectly plastic law. The failure criteria for tension and shear instead led to a elastic-perfectly brittle stress-strain relationship as illustrated in Figure 1. Figure 2 shows the flow diagram of the developed CDM material subroutine.

¹ Carmen Sandhaas, Timber Structures and Wood Technology, Delft University of Technology, Stevinweg 1, 2628 CN Delft, the Netherlands. Email: c.sandhaas@tudelft.nl
² Jan-Willem G van de Kuilen, Holzforschung München, Technical University Munich, Winzererstrasse 45, 80797 München, Germany. Email: vandekuilen@wzw.tum.de
4 MODEL VALIDATION

The developed material model was programmed in a user subroutine UMAT and inserted into the commercial FE software ABAQUS®. Different model validations were carried out among which compression on a cube with different angles to the grain. The needed mean material properties were derived from characteristic values for strength classes valid for the used wood species. Fracture energies however were not readily available and judgements based on test results for softwoods were made. Figure 3 shows the modelling results using the developed UMAT.

Compression parallel- and perpendicular-to-grain showed elastic-perfectly plastic behaviour as implemented whereas for 22.5° and 45°, brittle behaviour due to the influence of the brittle shear damage laws could be observed. This can be confirmed with test results. Also embedment models were developed whose outcomes could be verified with tests taken from literature [3]. Figure 4 and Figure 5 show exemplarily the modelling outcomes of embedment models in comparison with test results. In Figure 4, damage due to compression parallel-to-grain directly underneath the dowel of a spruce (Picea abies) specimen can be clearly seen. Figure 5 shows load-slip graphs of azobé (Lophira alata) specimens in overlap with the modelling result. The stiffness prediction is good. However, the model failed too early.

5 CONCLUSIONS

A promising holistic constitutive model for the material wood could be developed that can identify failure modes and combine simultaneous ductile and brittle failures within one model. First modelling results were satisfying in terms on stiffness and load carrying capacity. However, the model is not yet ductile enough. This should improve considerably by choosing different fracture mechanics properties. The next step is to apply the constitutive model for connection modelling.

REFERENCES