Chapter 13

Summary and Conclusions

13.1 Summary

Focusing on the abstract response mechanism of multiple-bolt joints in timber, this work presented the derivation of MULTBOLT, a robust model that predicts the load-displacement function of multiple-bolt timber joints subjected to varying displacement histories. A computer program written in Fortran, MULTBOLT is an array of five models that are quite different in approach and nature (Figure 13.1). The core of MULTBOLT is a modified hysteresis model that is capable of describing the nonlinear hysteresis of slack systems such as multiple-bolt joints whose holes are drilled oversize. The hysteresis model is partly analytical, partly empirical in that it relies on parameter estimation from experimental results. To find the optimal parameter set that best fits the hysteresis to experimental data, a parameter estimation model was developed that searches for the optimum by use of a Genetic Algorithm. In MULTBOLT, the hysteresis model is tightly interfaced with a relatively simple, stiffness-based structural model, which accounts for the interaction of individual fasteners within a multiple-bolt joint. Brittle failure is predicted and initiated by a novel failure model. Using the conventional Tsai-Wu criterion and a newly developed, unconventional Displaced Volume Method, the failure model predicts failure based on fastener displacement only, making it a stand-alone formulation that can be easily integrated into other models. Spatial and between-member material property variation, as well as variation in slack, are introduced by a stochastic model, which, based on lengthwise stiffness correlation and probability distributions, generates material properties and slack for each run of MULTBOLT.

MULTBOLT was validated by data obtained from tests of single-shear multiple- and single-bolt joints subjected to unidirectional and cyclic displacing functions.

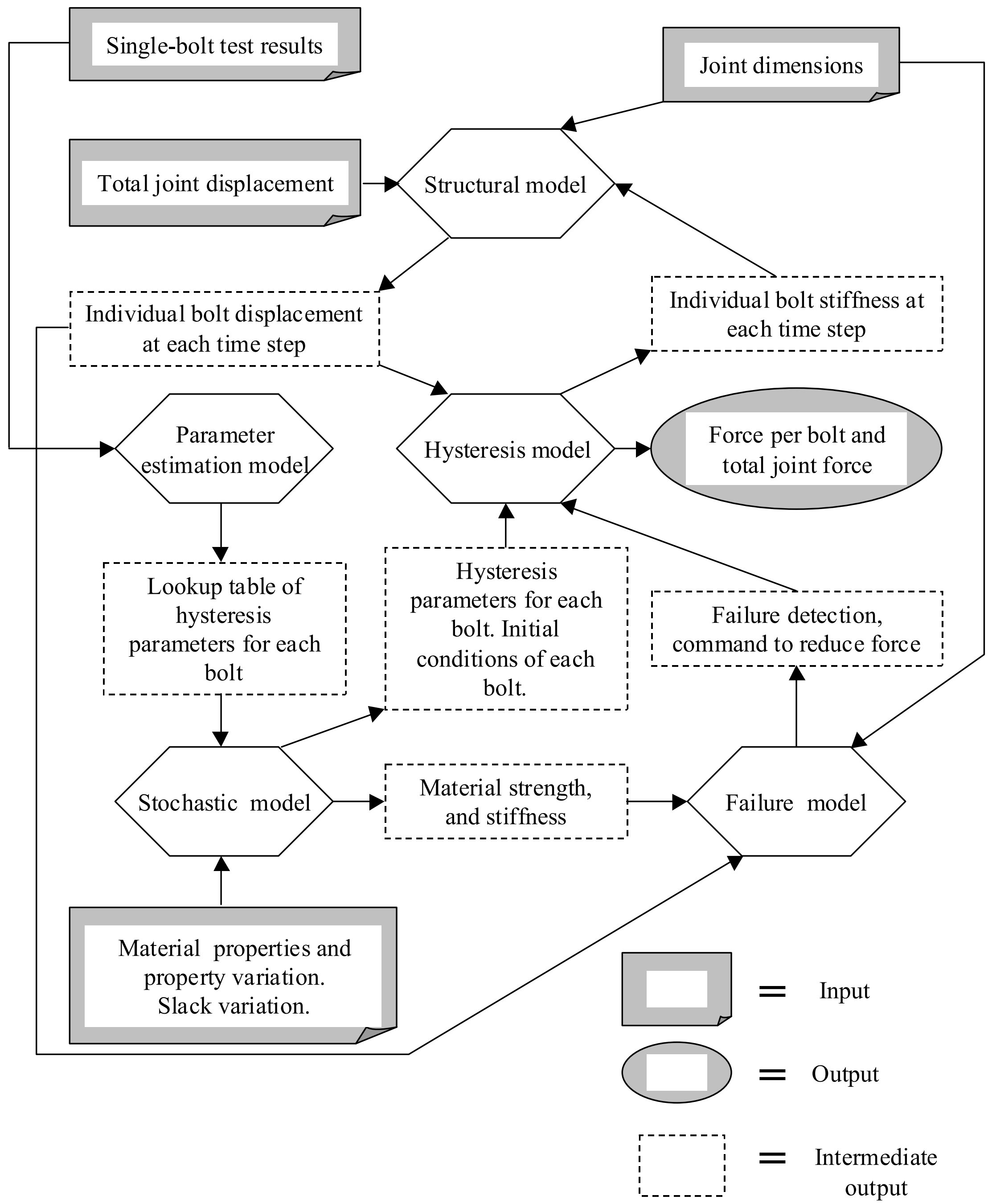

Figure 13.1: Mechanics and structure of MULTBOLT.

13.2 Conclusions

Theoretical models attempt to simulate and predict mechanisms of the real world. We rely on modeling because it is often not practical to test every aspect a certain outcome, we are interested in, depends on. Models help us understand how complex systems work and influencing factors interact. It is possible to simulate parts of a system and combine several models to predict the response of the entire system (as was done in this work), which would otherwise be too complex to understand as a whole.

"The test of a model is its ability to help one understand and predict the process being modeled" (Nobel Prize winner Sharpe 1998). It is judged that the developed model satisfactorily meets these requirements. More specifically, the generated computer model enhances the understanding of the mechanics of multiple-bolt joints in timber, and yields valid predictions of joint response of two-member multiple-bolt joints. This research represents a significant step towards the simulation of structural wood components.

13.2.1 Modeling Multiple-Bolt Joints in Timber

MULTBOLT produces valid predictions for single-shear, multiple-bolt joints based on various displacement functions. Joints were tested to minimize effects cause by connection eccentricity, which allowed out-of-shear-plane forces to be neglected. Predictions are not limited to tight-fit bolts. Instead, MULTBOLT can simulate joints with holes drilled oversize. The model handles random displacement input as well as static cyclic and unidirectional displacing functions. Joint load per displacement point and brittle joint failure are accurately predicted. More specific conclusions related to the modeling process are:

- A new, fully mathematically traceable, hysteresis model could be devised that is capable of accurately tracing the force-displacement interaction of slack systems with hysteretic behavior. Slack and slack growth were related to displacement level rather than absorbed energy, which results in excellent tracing capabilities of the pinching behavior of joints containing rigid bolts and good tracing of joints with bolts yielding in Mode IV. Model fit for Mode IV yield was slightly less accurate owing to strain hardening of the fastener at larger displacements and inferior lumber used. Compared to other models, the number of hysteresis parameters necessary was significantly reduced. The widely used Livermore Solver for Ordinary Differential Equations (LSODE) was easily integrated to solve the model. Model solving is stable and convergence is achieved for smooth as well as random displacement (or loading) functions. Input functions do not have to be continuous and can be stored as a list of discrete values.

- Once properly calibrated, the hysteresis model can be used to predict the force-displacement interaction based on a wide range of input functions including random input. However, the model cannot be used to predict the response to functions that have a higher energy demand than the function used for calibration.
- The hysteresis model could be successfully interfaced with a relatively simple structural model to account for the interaction of multiple bolts in a row. A linear-stiffness-based abstraction of the joint seems sufficiently accurate to describe bolt interaction, since non-linear behavior is accounted for by the hysteresis model. The combination of non-linear hysteresis and linear stiffness model results in a very robust, relatively simple and computationally fast model that predicts force-displacement interaction of multiple-bolt joints in timber.
- A relatively novel approach, the Genetic Algorithm method (heuristic optimizer with global potential), was effectively utilized to estimate parameters for the hysteresis model. Based on the Ordinary Least Squares Criterion, the Genetic Algorithm produced sufficiently accurate hysteresis model fits to experimental data. The routine was relatively easily programmed and applied, and provides a useful tool for hysteresis model development, especially if initial parameter estimates are not available. The algorithm is extremely robust. Convergence is always achieved, even if input data contains significant noise. Parameter search consumed considerable, but still reasonable, computing resources. Much faster results may be obtained by combination with calculus-based, local optimizers. Statistical correlation was detected between hysteresis parameters that could (further tests warranted) substantially reduce the number of parameters to be estimated to only four.
- Brittle failure can be accurately predicted without the use of fracture mechanics. The newly developed method named the Displaced Volume Method in combination with the European Yield Theory, a modified Tsai-Wu failure criterion, and considerably modified stress computations based on the approach advanced by Jorissen (1998), provides an effective means of

simulating brittle failure of multiple-bolt joints in timber. The failure model predicts failure of rigid and slender fasteners alike, inserted in tight-fit or oversized holes.

13.2.2 Group Action Effect

Current group action equations recommended for design of bolted joints in the U.S.A should be revised to reflect the findings of this work, which are:

- Reversed cyclic and unidirectional group action at limit state differs substantially from group action at proportional limit (basis of NDS) and is most affected by fastener spacing. Relative drop in maximum load per fastener was determined to be greatest when the number of bolts was increased from one to two. On the other hand, an increase from 3 to 10 bolts per row produced diminishing group action. This is because the effect of member strain on group action is negligible for most joint configurations due to the high stiffness of wood parallel to the grain and inelastic load redistribution. Group action determination for multiple-bolt joints currently applied in the U.S. is based on the member strain effect.
- Bolt spacing and end distance should not be treated differently for full capacity design. Thus, minimum allowable fastener spacing for full design capacity of multiple-bolt joints should be raised to seven times fastener diameter, which is equal to the required minimum end distance.

Slack variability brought about by manufacturing tolerances is of secondary importance. This is especially true if bolt holes are drilled through both members at once because total slack per bolt is then constant. However, equal variability in spacing for both members significantly affects joint performance.

Material property variation was not found to influence capacity of unidirectionally displaced specimens in a statistically significant way. However, variation in material property does lower capacity of and increase group action of cyclically displaced multiple-bolt joints in single shear.