

## **Implications and Proposal for Future Work**

### **14.1 General**

MULTBOLT, in its current form, is really just the tip of the iceberg. The work presented shows how completely different approaches such as empirical, analytical and mechanical modeling can be combined successfully to provide an overall model that is more powerful than the sum of its parts and, as hypothesized here, maybe even more powerful than many ‘pure’ approaches like the finite element technique or empirical modeling, for example.

### **14.2 Judgment of Utility**

The development of MULTBOLT is of instructive use as it shows one approach to modeling multiple-bolt joints in timber. Other researchers may follow, use parts of, or develop new ideas from the process presented here.

MULTBOLT’s main purpose is to trace the load-displacement function of multiple-bolt joints subjected to various displacement input. Despite the present limitations and its reliance on single-bolt joint tests, MULTBOLT provides useful predictions and allows inferences about group action behavior of single-shear multiple-bolt joints. The ultimate goal is to predict joint performance based on fundamental input properties such as bolt and joint dimensions, materials, and input function used. Based on the results presented in this work, there is high confidence that this can be accomplished. With increased versatility, MULTBOLT will become a useful tool for designers and scientists alike, with which new joint configurations may be found and joint dimensions may be optimized.

### **14.3 Possible Improvements**

No single model completely represents real situations. By their very definition, models rely on a set of assumptions that, be they realistic or not, help approximate and often simplify processes in the real world. Therefore, every model prediction contains errors – MULTBOLT is no exception to that rule. There is one aspect, where the current version of MULTBOLT is very close to reality, however. The model developed here constitutes Version 1.0 and as with most other well-known software packages, updated, improved versions of MULTBOLT (i.e. Version

1.1, 1.2, etc.) are to be expected in order to not break with the tradition of upgrading. Possible improvements of MULTBOLT are discussed next.

More validation tests should be conducted to establish MULTBOLT's validity to a wider range of cases. This will also help explain the relatively large error in absorbed energy predictions. Additional validation tests should also allow cross-validation, improved calibration, and provide more in-depth information on prediction errors.

MULTBOLT exhibited some difficulties predicting variation in slack at small displacements. The slack function in the modified hysteresis model may have to be altered to rectify this problem. Along the same lines, the solver LSODE produced significant numerical noise at large displacements if the input function was monotonic. Numeric noise is a function of the error control used. A better error control mechanism may be devised that reduces noise development.

As a result of a limited number of single-bolt joint tests conducted, hysteresis parameters are currently not stochastically generated if material properties are varied. Rather, discrete values that are a specified fraction of standard deviation away from their mean are selected from a lookup table, which limits the variability that can be simulated during uncertainty analysis.

The Failure model should be modified to account for changing yield modes within a joint. More specifically, the "Yield Mode Evolution Hypothesis", as devised from experimental results, should be incorporated, which will increase MULTBOLT's versatility and most likely accuracy, since yield modes are predicted rather than input by the user. Also, a method should be developed to include peak stresses perpendicular to the grain without significantly altering the current approach to modeling failure.

Parameter estimation presently takes up significant computing power. It is therefore important that the number of parameters be reduced by statistical modeling, which implies that more single-bolt tests should be conducted. Eventually, hysteresis parameters should not have to be estimated from experimental data, but it ought to be possible to predict them derived from basic joint properties. In general, however, there is room for improvement regarding curve fitting by Genetic Algorithms. As already mentioned in Chapter 6, the application of Genetic Algorithms is both an art and a science. An optimally adjusted Genetic Algorithm takes many trial runs and much experimentation. An entire study could be devoted to improving the algorithm written for this work. Furthermore, a calculus based optimizer may be combined with the Genetic Algorithm to speed up the estimation process.

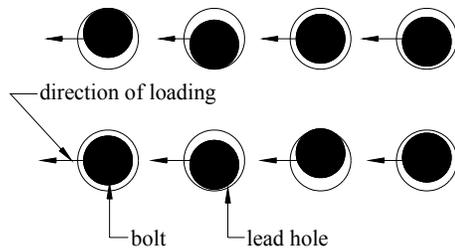
MULTBOLT does not yet feature a graphical user interface, which may make the program tedious to use for other users. The design of an easy-to-use and comprehensive interface to MULTBOLT provides a significant improvement to its utility.

#### 14.4 Suggested Extensions

One of the most important extensions to MULTBOLT is the development of a stochastic hysteresis parameter model. This implies that more single-bolt tests under cyclic loading need to be conducted until a covariance matrix with high confidence can be established, which may be a rather comprehensive project. But once parameters can be stochastically generated, MULTBOLT becomes much more generic and will be able to simulate the response of a wide variety of multiple-bolt joints.

Another valuable addition is the inclusion of bolt-row interaction. For the most general case, predictions should be possible with fasteners placed virtually anywhere in the joint. That is, bolts are not restricted to be arranged in rows and columns. However, this, by itself, may be a complex problem to tackle. It is widely suspected that fastener location tolerances normal to the applied load due to misdrilled and oversized holes may introduce perpendicular-to-grain stresses, which may cause premature failure. Bolt misalignment perpendicular to the applied load caused by hole oversize and its influence on joint performance has not been quantified to date (Figure 14.1). Hence, the stochastic modeling of tolerances normal to displacing direction may shed light on the mechanics of fastener interaction perpendicular to loading and may provide important insight into the response of multiple-bolt joints.

Misalignment perpendicular to load



Misalignment parallel to load

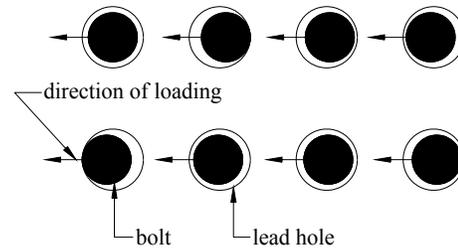


Figure 14.1: Two-dimensional misalignment of fasteners due to oversized holes.

Moments and forces brought about by asymmetry were completely ignored in the derivation of MULTBOLT. It would be of value to investigate the effects of asymmetry on joint response. Yield and failure modes may be affected by deformations out of the shear plane.

Not so much an extension but an additional validation for MULTBOLT, predictions and their validity of rapidly changing displacement input, which triggers inertia effects should be studied.

The ultimate plan is the creation of a modular program that can be continuously expanded. The models developed in MULTBOLT are programmed as individual modules that are interfaced with the main program. For example an additional module could contain a hysteresis model for small diameter fasteners such as nails. MULTBOLT itself could be integrated into a structural analysis program.

## **14.5 General Suggested Research Needs**

### **14.5.1 Extension of the Yield Theory**

The European Yield Theory for bolted wood connections has gained wide acceptance in recent years attributed to its closed form, simplicity, and accuracy. The model predicts joint capacity for unidirectionally strained joints but it does not relate capacity or any other loading state to joint displacement. A method to determine deflection related properties of bolted joints in timber with a single equation, based on the proven and commonly accepted Yield Theory, would be an important contribution to the field of timber engineering.

### **14.5.2 Investigation of Real Stress Distributions by Full-Field Strain Measurements**

Surface strain measurements may yield useful information regarding the stress distribution around a pin-loaded hole and the stress interaction between multiple pin loaded holes in timber, which to date has not been determined experimentally.

Strain gages, dial gages, string pots, and linear differential transducers have been used extensively to measure deformation. Most of these methods are used to measure strain at a point or over a very limited area. Strain gages mounted on any surface measure the average strain experienced by the gages along their length. Hence, strain gages are really best suited for point measurements of strain rather than field measurements. Associated with the finite dimension of strain gages, reinforcement effects, the difficulty of attaching and wiring a large number of gages, and the high cost of using multiple gages, the resolution obtainable of full field strain measured using strain gages is moderate at best. The digital image correlation technique, however, is a very

versatile method that has been used by numerous researchers to detect in-plane deformation in areas ranging from rigid body mechanics to fluid mechanics to biomechanics and fracture mechanics and maybe a useful tool to investigate surface stresses around pin-loaded holes.

#### **14.5.3 Quantification of Real Fastener Deformation by Ultrasonic Pulse-Echo Real Time Measurements**

Briefly introduced in Chapter 10, the ultrasonic pulse-echo inspection technique may be a promising method to measure plastic hinge formation and location without the need to use instrumented bolts or X-ray technology. Furthermore, joints can be loaded to failure, which is currently not feasible with bolts instrumented with strain gages. The true, real time deformation of bolts under cyclic loading has not been measured and may establish new guidance for joint modeling. The current pulse-echo inspection technique does not allow real-time measurements. But owing to ever increasing computing power, the method may be extended in the future.

#### **14.5.4 Moisture Content Effects**

The response of multiple-bolt joints may be substantially altered at different member moisture contents. Increase in moisture content adversely affects most material properties of lumber (Table 14.1). For example, a considerable drop in stiffness most likely changes load distribution among fasteners. It is suspected that multiple-bolt joints fail at lower loads (or displacements) if moisture content is higher but test data that substantiate that claim are hard to find. Furthermore, the effect of swelling and shrinking as moisture content changes, may induce tensile stresses perpendicular to the grain, especially in joints with tight-fit bolts in multiple rows.

Table 14.1: Approximate relative increase of selected material properties of wood per percent decrease of moisture content (Faherty and Williamson 1999).

Property	% increase per 1% decrease in moisture content
Modulus of elasticity	2
Tension strength parallel	4
Compression strength parallel	6
Tension strength perpendicular	1.5
Compression perpendicular	5.5
Shear parallel	3

### 14.5.5 Time Effects

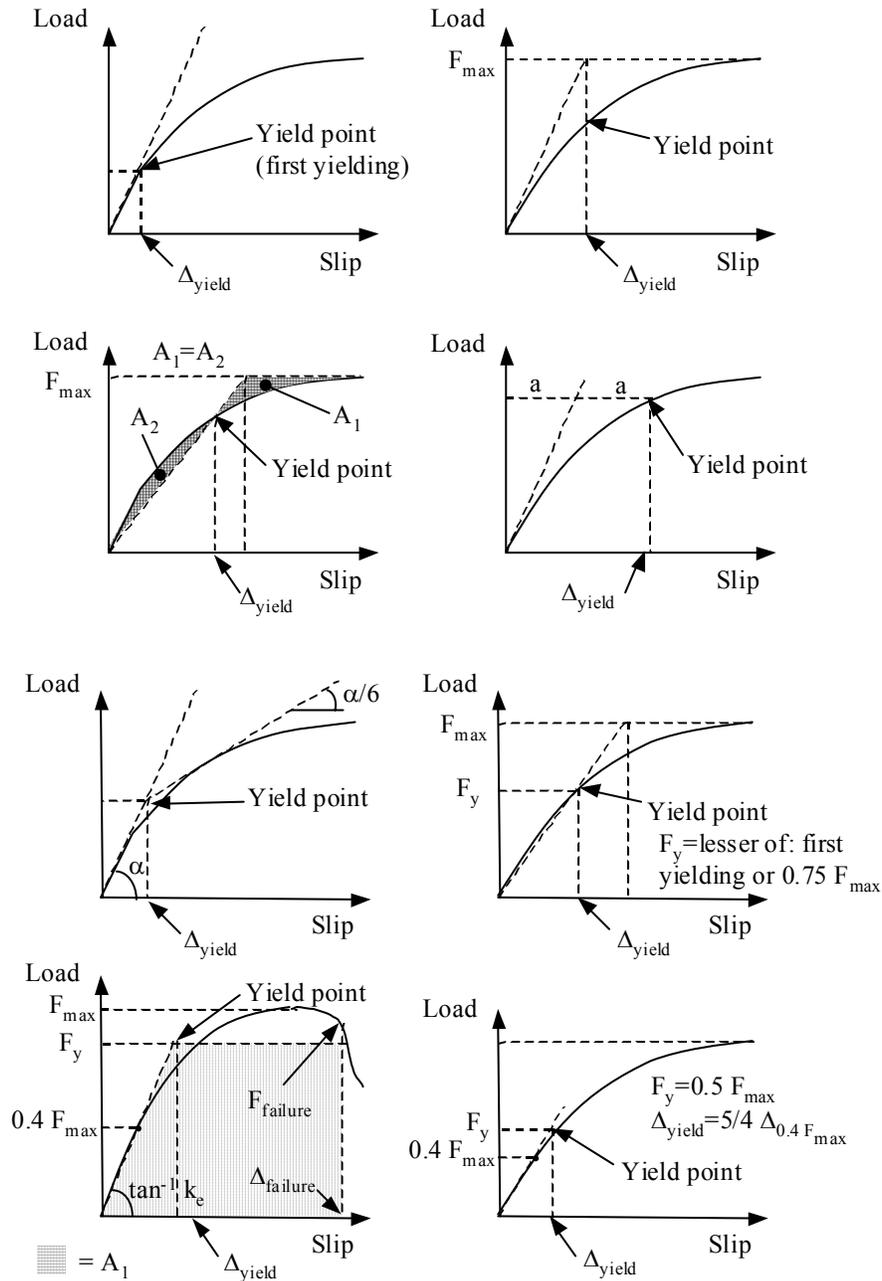
Wood is a rheological material that relaxes and creeps over time if subjected to stresses. Although they are mostly undesired properties for other applications, creep and relaxation may actually reduce the group action effect of multiple-bolt joints due to load redistribution over time.

### 14.5.6 Validation and Standardization of Testing Protocols and Data Analysis

As of this writing, no commonly agreed upon standardized cyclic testing protocol for connections in timber has been advanced. Many current draft standards rely on unidirectional displacement controlled tests to calibrate the protocol for a certain joint configuration. Based on experiences gained in the present research, monotonic calibration requires a relatively large number of tests due to the high variability of failure displacements. The limited number of tests conducted in this work, left the experimenter with much guesswork.

Many practical questions as to the use of cyclic protocols remain unanswered. For example, what are the effects of using the same cyclic protocol, if results of changes in joint configurations are of interest, versus the use of adjusted protocols, by means of monotonic tests, for each configuration? How sensitive is the choice of the protocol to the final result? The answer to that question determines the number of monotonic tests to be conducted. That is, does it matter if the estimated failure displacement from monotonic tests lies within 10, 20, or 50 percent of true value? Since it is desired to subject the specimen to similar energy demands as during earthquakes or high wind events, it may be useful to provide the experimenter with guidelines as to what maximum energy demands should be. A more general concern is how measured performance based on triangular cyclic displacing protocols compares with performance using true earthquake records.

Data analysis of cyclic and unidirectional tests should be a straight forward, clearly defined tool, which assists in making inferences about the obtained data. Instead, it is a much debated, contentious, and at the same time controversial area. Anyone who follows the scientific literature soon realizes that there are probably almost as many definitions as there are studies of what constitutes the yield point of wood structures (Figure 14.2), which may partly explain the latest and much needed shift to capacity-based design. Clear definitions for other property computations, namely ductility, stiffness of slack systems, failure, etc. are also lacking.



Area under curve from 0 to  $\Delta_{failure} = A_2$   $A_1 = A_2$

$$F_y = \frac{-\Delta_{failure} \pm \sqrt{\Delta_{failure}^2 - \frac{2A_2}{k_e}}}{-\frac{1}{k_e}}$$

Figure 14.2: Various definitions of yield for timber structures and systems as reported in the literature (adopted in part from Foliente 1996).