Chapter 1

Introduction

1.1 General

In recent years, an area of increased interest has been dynamic and reversed cyclic loading. This is attributed to the fact that more catastrophic failures occur during dynamic loading associated with natural disasters than due to gravity loads. Hurricanes Andrew (Florida) and Iniki (Hawaii) in 1992, the Loma Prieta earthquake (San Francisco) in 1989, the Northridge earthquake (Los Angeles) in 1994 and recent quakes in Turkey (1999), Taiwan (1999), India (2001) and in the Western US (2001) have raised the public's interest in and awareness of improving the engineering and reliability of structures.

As a direct result of world population growth and migration, today, more people than ever live in densely populated areas that are at risk to be shaken by earthquakes (Figures 1.1 and 1.2). Population density and building construction methods are the two main factors determining earthquake risk. While most seismologists agree that "earthquakes don't kill people, buildings do" (Nelson 2000), advances in building construction have made some inroads in increasing the safety of structures built today. However, methods to predict structural response to random dynamic excitation as experienced during earthquakes and hurricanes are still developing. Inelastic strains, random excitation in both magnitude and direction, inertia effects, construction tolerances, material property variations, intricate stress interactions, building component and system interactions etc., are just a few examples highlighting the difficulty of predicting the response to earthquake loading.

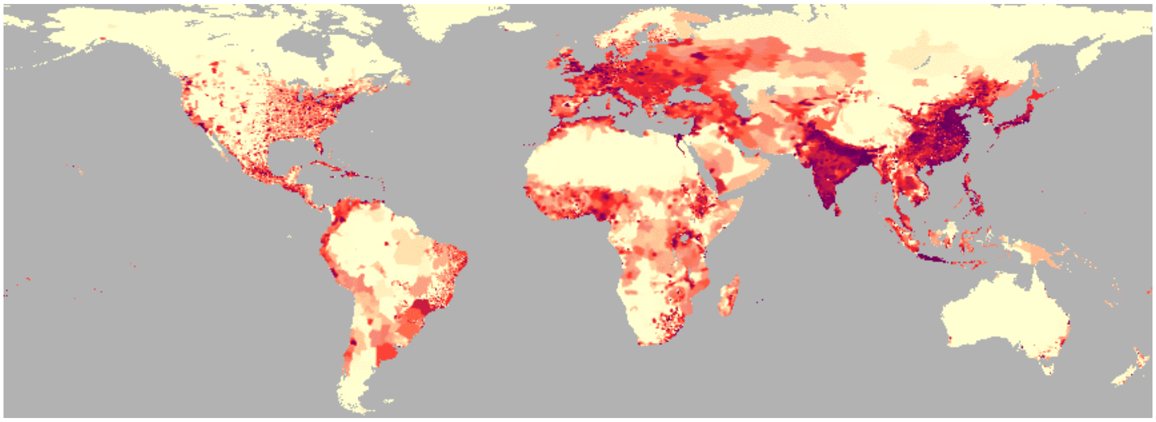

Figure 1.1: World population density (darker color = higher density) as of 1995 (from: http://www.ciesin.org/datasets/gpw/globldem.doc.html).

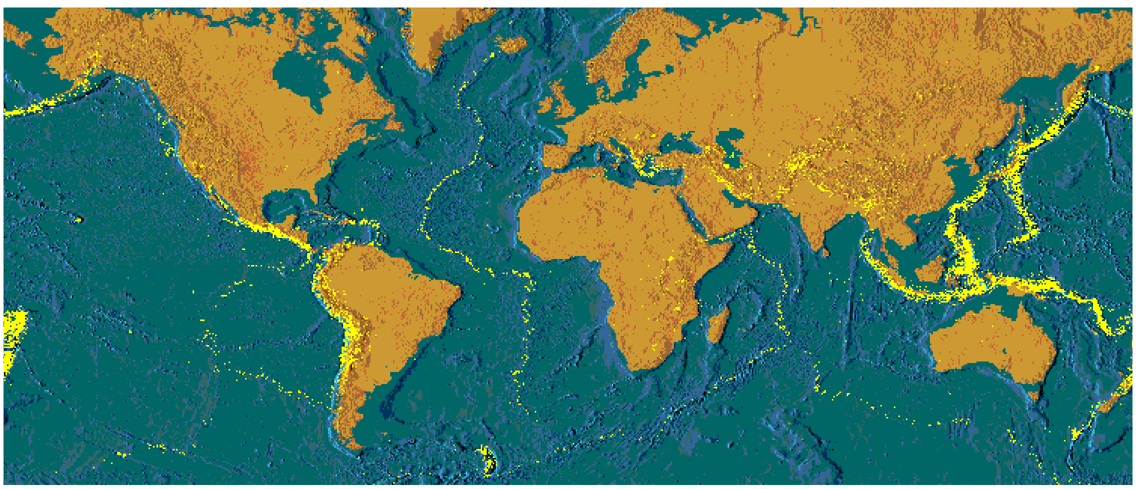

Figure 1.2: World earthquake activity of magnitude 4.5 and higher within the last three years (from: http://www.letus.northwestern.edu/projects/esp/ phaseC/datamaps/relief&eqdatamap.html)

In North America, wood has been the material of choice for residential construction due to its renewability, low cost, superior strength-to-weight ratio, high degree of versatility, and its natural beauty. Because of its high strength and low weight, wood offers many options to cover space efficiently, even for commercial buildings as testified by innovative structures around the world such as the Tacoma Dome in Tacoma, Washington, U.S.A, the ice-ring dome in Davos, Switzerland, and the recent symbolic timber structure of the World Expo 2000 in Hanover, Germany, just to name a few. Associated with enduring world population growth and the allied quest for cheaper, more efficient housings, especially in third world countries, and attributed to tighter energy regulations and pollution restrictions in the world's richest nations, the number of wood structures built around the world is projected to increase far into the future.

1.2 Reversed Cyclic Loading and Dowel Type Joints

To satisfy the growing demand for housing in the future, timber structures need to become more reliable in terms of performance, safer regarding resistance to natural disasters such as earthquakes, and more efficient in terms of amount of material consumed. This requires that the performance and response of each structural component as well as its interaction with other components in the structure be thoroughly understood and accurately predicted. Unfortunately, this cannot be claimed for many elements used in wood construction today.

One of the most important elements of a timber structure is the connector. In fact, it is well established that the overall response of a wooden structure is a function of the performance of its connectors. This is not surprising since, as a consequence of the brittle failure characteristic of wood in tension, and the much more ductile failure of steel, modern buildings are engineered such that elastic and inelastic deformations and eventually failure occur in the connection rather than the wood members. Except for a few traditional heavy timber structures, metal connectors have mostly displaced wood-to-wood connections. Based on simplicity, ease of use, and effectiveness, metal dowel-type fasteners in particular, such as nails, screws and bolts, are a principal connector used in modern engineered timber structures. Although easily installed, bolts are extremely complex regarding the response mechanism to various loading, mainly inherent to the anisotropic and variable characteristics of the surrounding wood. For example, while the mechanics of a single-bolt joint are complex enough to require comprehensive three dimensional finite element analysis to predict stresses (see Patton Mallory 1996), the response of an array of bolts in a joint is even more complex and far from being completely understood and predictable.

Constituting the simplest loading condition and joint configuration, single-bolt joints tested under unidirectional loading have attracted much research. Much information on bolts available today is hence based on single-bolt connections subjected to unidirectional displacing functions. Past research, however, demonstrated that the behavior of single-bolt joints cannot be extrapolated to predict the response of multiple-bolt configurations. This is especially true for stiffer bolts, which cause stress concentrations that may reach material strength and prematurely fail a joint.

During construction, it is good practice to drill bolt holes oversize to facilitate joint assembly and to prevent splitting attributed to moisture related dimensional changes. Bolt hole oversize is defined as hole diameter less fastener diameter. Required hole oversize may vary substantially depending on building code regulations (Table 1.1) (Madsen 2000).

Table 1.1: Different recommended bolt hole oversize in different parts of the world.

Country	*Oversize*
USA	Minimum of 1/32 in. (0.8 mm) to a maximum of 1/16 in. (1.6 mm)
Australia	10 percent of bolt diameter
Canada	Larger than 1mm but no more than 2 mm
Europe	Less than 1mm
New Zealand	Less than 1.5 mm

In the U.S., bolt holes are recommended to be 1/16 in. (1.6 mm) larger than the bolt diameter. Despite this practice, the existence of oversized holes has been largely ignored by researchers. Joints containing bolts were often studied using tight fit, where the bolt hole tolerance was just large enough to insert the fastener. But, hole oversize may significantly influence joint behavior, especially in a joint containing an array of bolts as the exact location of each bolt within the hole becomes a random variable.

Studies advanced by Moss and Carr (1988), Stewart et al. (1988), Dolan and Foschi (1989), Dolan and Madsen (1992), and Dolan et al. (1994a and b) have established the importance of cyclic and dynamic testing and analysis. Joints exhibit different and much more complex deformation mechanisms under cyclic or dynamic loading than when exposed to unidirectional forces. One characteristic that provides much difficulty for prediction models is the response dependency on loading history of joints in wood, also referred to as the "memory effect" elsewhere. Load history dependency describes the case where hole oversize or parts of the hole may grow because the elastic limit in the wood was exceeded in a previous cycle and the surrounding wood fibers were crushed locally. Another problem is that, when loaded cyclically, a multiple-bolt joint whose holes are drilled oversize turns into a slack system. The response of slack systems in timber is notoriously difficult to predict and no prediction models of any sort could be identified that accomplished such a task. That helps explain why disturbingly little, if any, research has been done to quantify the performance of reversed cyclically loaded, multiple-bolt timber joints.

1.3 Modeling Timber Joints

Experimental testing allows close monitoring of joint behavior under controlled loading conditions. Experiments are frequently necessary to provide the information needed for full comprehension of the matter studied. Yet, it is often not practical to design experiments that cover all of the possible variables that have any significant influence on the outcome. For example, in the case of multiple-bolt joints, significant variables include, but are not limited to, different displacing or loading functions, varying geometries, different member materials, manufacturing tolerances, moisture content variations, material defects, material density variations, different fastener material and quality, and weathering and aging effects. It is therefore necessary to model subassemblies and move towards modeling of complete structures and validate these models with limited tests (e.g. Falk and Moody 1989). This has historically been done with static monotonic loads and more recently with dynamic loads (Dolan 1989).

Experimental analysis should complement theoretical analysis. Any type of theoretical modeling not only aids in understanding, but also allows for experimental studies to be more specialized. According to Haller (1998), theoretical analysis may be categorized as experimentally based, mechanically based, numerically based, or analytically based (Figure 1.3). Experimentally based modeling focuses mainly on interpolation and curve fitting from test data. Testing involves moderate effort, but the analysis is fairly inflexible to changes in joint design and innovations because extrapolations are generally not valid. Purely empirical models contribute little to the overall comprehension of complicated interactions of parameters and are frequently cumbersome to use. Yet the matter studied is hardly abstracted. Mechanics based models often discretize the structure by means of linear or non-linear springs connected to finite, massless beams with lumped masses. These models are relatively easy to use, imply little effort to develop and contribute a fair amount of comprehension to the subject area. However, the flexibility to change joint design or to investigate innovative connections is limited. Numerical analysis today typically involves the finite element technique. Although, according to Haller, this approach is the most flexible and can be regarded as a substitute for tedious and costly experimental studies, it is just that, a substitute for testing. It hardly assists in understanding connection behavior and is of very limited use for designers. Moreover, a major deficiency of the finite element approach to modeling wood assemblies is its reliance on the full range of basic material properties. Attributed to the directional properties of wood and its natural variability among species and per unit volume, not all basic properties and their interaction reported in the literature are backed by sound statistical analysis, for some properties are almost impossible to determine. Analytical models contribute the most to understanding the factors influencing joint behavior. Though, similar to finite element analysis, a large amount of effort is needed but is offset by facilitated utilization.

Not all models fit into a single category, however. Sometimes experimentally rooted formulations are incorporated in analytical or numerical models to simplify the problem at hand. For example, MULTBOLT, the model devised in this work, is a hybrid because it employs mechanically, analytically and empirically based formulations. The complex hysteresis mechanism was found to be best modeled using a partly empirical model, whereas global structural interactions were mechanically approximated.

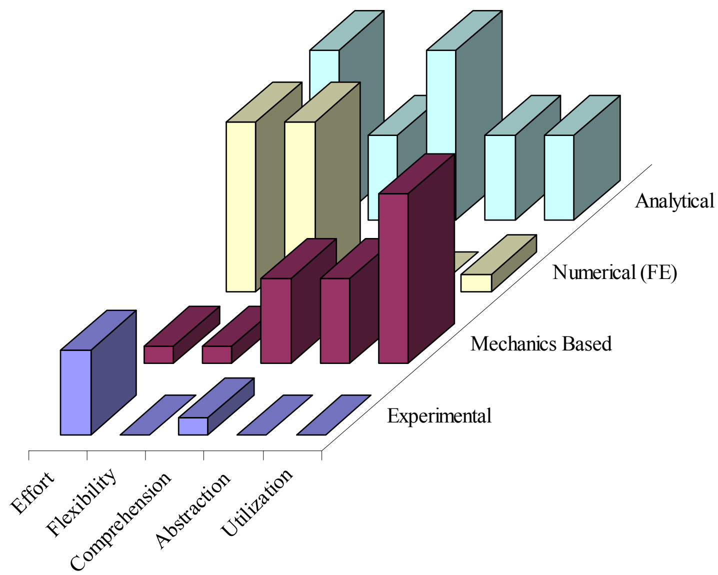

Figure 1.3: Evaluation of modeling approaches (adopted from Haller, 1998)

1.4 Objectives

In view of improving the understanding of single- and multiple-bolt joints in timber, a theoretical model that furnishes scientists and designers alike with accurate information of load-displacement relation, not tied to a single input function, would be beneficial. Thus, the primary objective of this work is to formulate a general model that is capable of predicting the load-displacement relationship, load distribution, capacity, and energy absorption characteristics of multiple-bolt timber joints of various configurations and subjected to reversed cyclic displacing functions. Using the model along with complementary testing, it should be possible to make inferences about the group action effect (i.e. the interaction of individual fasteners) as a result of varying numbers of bolts in a row. Furthermore, it is aimed to compare and evaluate the response of joints stressed monotonically with joints subjected to reversed cyclic displacement.

1.5 Scope and Limitations

Only wood joints in single shear, loaded parallel to the grain, are considered (Figure 1.4). That is, joints are studied that consist of two members connected with one or more bolts, where the abutting surfaces of the two members form the shear plane. The inherent asymmetry of single shear joints introduces moments and forces acting perpendicular to the shear plane. Nevertheless, any forces or moments caused by asymmetry are neglected throughout this work. Joints are tested in such a fashion that out-of-plane forces are taken up by the test fixture. Essentially, joints are treated as a half of a symmetric double-shear (three-member) joint.

This work focuses on the short-duration behavior of multiple-bolt joints. Effects attributed to 'time effects' such as moisture content variations, as well as creep, weathering, or aging, are not considered.

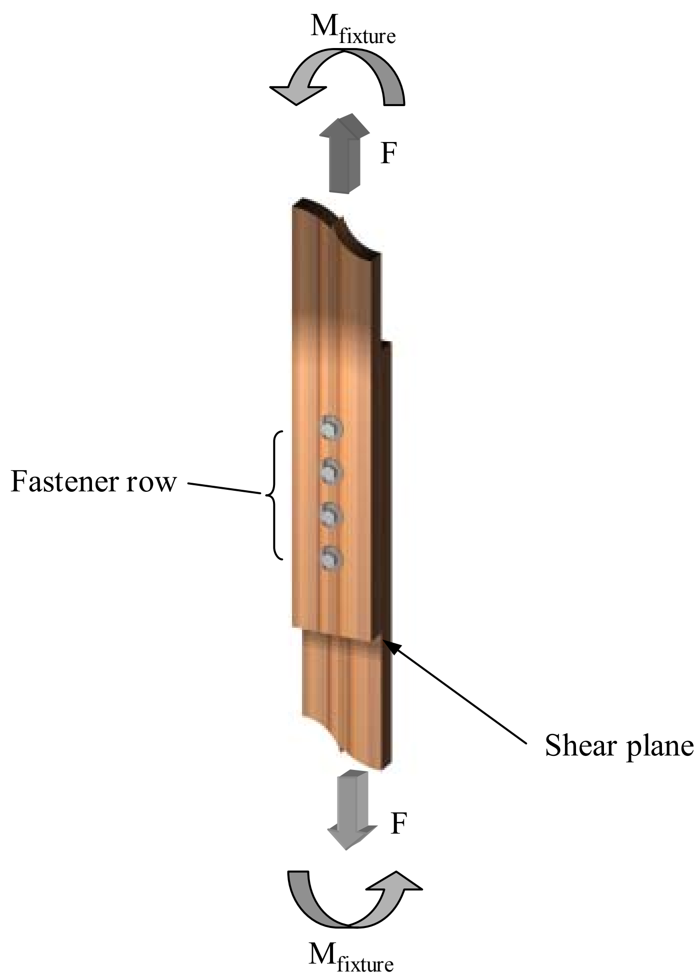

Figure 1.4: Example of a multiple-bolt joint in single shear. A row of bolts is defined as shown in the figure. Moments caused by asymmetry are taken up by the test fixture.

The main focus of this study was the development of MULTBOLT, a generic model that predicts the load-displacement behavior of multiple-bolt joints under reversed cyclic and other displacement functions within the elastic *and* inelastic response range up to maximum load. Some testing was employed to validate the model. MULTBOLT is an array of five models that have been interfaced and are solved numerically. A new mathematical hysteresis model describes the force of the individual bolt at each time step increment; a mechanically based structural stiffness model accounts for the interaction of one bolt with another bolt within the joint; an analytically based failure model computes the stresses at each time step and initiates failure if crack length equals fastener spacing; a stochastic model varies main input parameters; and a system identification routine estimates hysteresis parameters. MULTBOLT was written in FORTRAN. At the present stage, MULTBOLT has the following limitations:

- Throughout this work, displacement is the independent variable. In other words, predictions are made based on a displacing function imposed on the joint. With minor modifications, MULTBOLT is also capable of making predictions based on a loading function.
- MULTBOLT currently employs load-displacement data from reversed cyclic tests of single bolt joints. This is only a temporary limitation, however, until more experimental or analytical data are available and stochastic hysteresis parameter modeling becomes feasible. Thus, due to a relatively small number of tests conducted, MULTBOLT is limited, for now, to one fastener size, one species and two member thicknesses.
- MULTBOLT is *not* limited to a certain displacement function. However, the model has not been validated for functions introducing inertia effects.
- MULTBOLT does not account for more than one row of fasteners, because row interaction was not studied. The integration of row effects is a possible addition in the future.