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Pablo Zavattieri · Majid Minary · Martha Grady
Kathryn Dannemann · Wendy Crone *Editors*

Mechanics of Biological Systems, Materials and other topics in Experimental and Applied Mechanics, Volume 4

Proceedings of the 2017 Annual Conference on Experimental and Applied Mechanics

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Preface

Mechanics of Biological Systems, Materials and Other Topics in Experimental and Applied Mechanics represents one of nine volumes of technical papers presented at the 2017 SEM Annual Conference and Exposition on Experimental and Applied Mechanics organized by the Society for Experimental Mechanics and held in Indianapolis, IN, June 12–15, 2017. The complete proceedings also includes volumes on *Dynamic Behavior of Materials; Challenges in Mechanics of Time-Dependent Materials; Advancement of Optical Methods in Experimental Mechanics; Micro- and Nanomechanics; Mechanics of Biological Systems and Materials; Mechanics of Composite, Hybrid and Multifunctional Materials; Fracture, Fatigue, Failure and Damage Evolution; Residual Stress, Thermomechanics and Infrared Imaging, Hybrid Techniques and Inverse Problems; and Mechanics of Additive and Advanced Manufacturing.*

Each collection presents early findings from experimental and computational investigations on an important area within experimental mechanics, the mechanics of biological systems and materials, and other topics in experimental and applied mechanics such as education and research in progress, to name a few.

The biological systems and materials segment of this volume summarizes the exchange of ideas and information among scientists and engineers involved in the research and analysis of how mechanical loads interact with the structure, properties, and function of living organisms and their tissues. The scope includes experimental, imaging, numerical, and mathematical techniques and tools spanning various lengths and time scales. Establishing this symposium at the Annual Meeting of the Society for Experimental Mechanics provides a venue where state-of-the-art experimental methods can be leveraged in the study of biological and bio-inspired materials, traumatic brain injury, cell mechanics, and biomechanics in general. A major goal of the symposium was for participants to collaborate in the asking of fundamental questions and the development of new techniques to address bio-inspired problems in society, human health, and the natural world. The organizers would like to thank all the speakers and staff at SEM for enabling a successful program.

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Chapter 1
Design of Bolted Connection in Composite Beams for Moment Resistance

H. K. Cho, J. M. Considine, D. R. Rammer, and R. E. Rowlands

Abstract Bolted/pinned joints in orthotropic composite materials have received considerable attention over the years. Bolt fastening is one of the most commonly used methods to connect wood to wood and/or wood to steel, etc. Stresses at such connections can be the “Achilles’ heel”, causing structural failures. Notwithstanding the challenges in stress analyzing bolted joints, their advantages and widespread use motivate developing ability to optimize their design.

Acknowledging the above, a finite element code is combined here with a screening optimization algorithm to optimize a bolt-hole pattern used to connect orthotropic wood members. A loaded wood beam having four connecting bolt holes at one end is optimized. The ultimate goal is to find optimal hole pattern and/or individual hole position under given load and displacement boundary conditions.

Keywords Optimization • Orthotropic material • Wood • Hole • Bolted joints • FEA

1.1 Introduction

Motivated by features such as ease of assembly, bolted joints are commonly used in steel and wood structures. Although considerable related literature exists on the mechanics of loaded holes [1–4], little appears to be available on optimizing bolted connections in wood. Wood is a natural and recyclable orthotropic material which is receiving extensive current attention for multi-story structures. Beam connections are critical for all multi-story wood structures, but especially in earthquake prone zones.

Optimization of bolt-hole pattern is carried out for a loaded wooden (Douglas Fir) beam so as to minimize the bearing stresses at the holes and beam deflection. Four bolt holes are involved. While theoretical formulae are available for analyzing stresses and strains around loaded holes, such studies tend to be limited to a single hole in an infinite member. In order to reduce the number of experiments examining bolt hole configuration, a FEM analysis was the primary component of the initial investigation.

An optimization algorithm is combined with FEA module to optimize the design. Commercial FEA software, ANSYS Xplorer, is used for the optimization. The main solver consists of a general static analysis FEA code and optimization algorithm. The process iterates until convergence of the optimization algorithm is reached. Since numerous iterations are needed to obtain an accurate solution, the iteration process time-consuming. During the process, the geometric model configuration changes at every step. Corresponding to the model shape modifications, new mesh-generation, application of boundary condition and static stress analysis are conducted.

Since the maximum contact stress at hole boundaries are a criterion for the optimization analysis, accurate values of these bearing stresses are necessary, though this effort examines the 2-dimensional case only. Several numerical and/or experimental studies appear in the literature which attempt to account for the actual bolt-hole contact stresses. In the present

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study, bolt contact conditions with a special function is adopted which well represents the contact bolt-hole phenomena. The iteration software process including both FEA and optimization algorithm enables one to find several optimal hole positions in the elastic wood plate.

1.2 Optimization Architecture

Optimization is achieved with ANSYS Xplorer. The method performs the theoretical background and processes the optimization according to a slightly different technique than most conventional optimization numerical methods. The conventional methods search the highest and lowest points by calculating the slope of the design domain, or random search method like genetic algorithm which generates a number of candidates and repeat iteration to reach the ultimate point. The method is called 'natural selection and degeneration.

The present optimization process is shown in Fig. 1.1. The individual optimization and FEA module mutually exchange results to obtain a solution. The optimization module defines the design variables and then determines the sampling points by the well-known DOE (design of experiment) method [5]. It provides a screening set to determine the overall trends of the meta-model to better guide the choice of options in optimal space filling design.

The finite element analysis results at individual sampling points are calculated to obtain an exact solution at a specific point. The ultimate goal of design sampling point (design point) determination by such an experimental design method is to find the "response surface" in the design area to be used for the final optimization. Constructing the response surface as

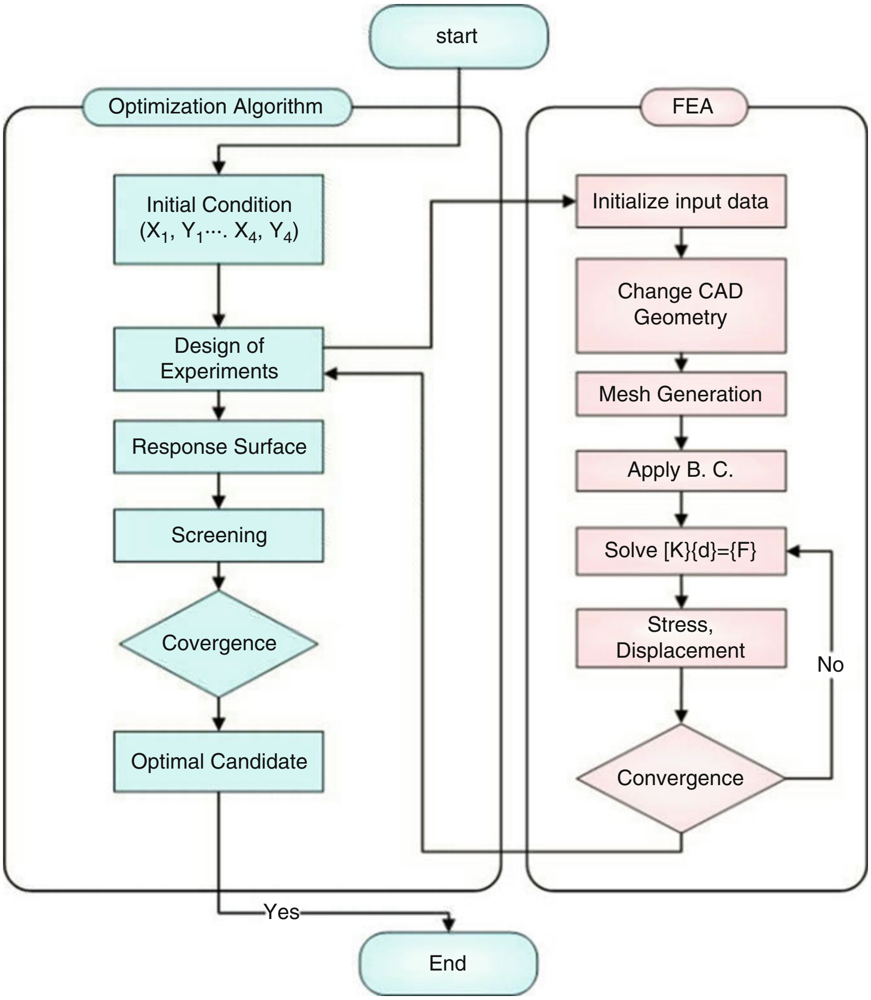

Fig. 1.1 Schematic diagram of the optimization architecture process

close to the actual solution as possible is important in determining the accuracy of the analysis. The accuracy of a response surface depends on several factors: complexity of the variations of the solution, number of points in the original design of experiments and the choice of the response surface type [5].

Various theories have been utilized to calculate the response surface. A Kriging scheme is used here to better represent complex nonlinear design surfaces. After the response surfaces have been computed, the design can be thoroughly investigated using a variety of numerical tools and valid design points identified by optimization techniques. We used the screening methods as an optimization method to obtain the final optimal solution. The screening scheme, which can be used for response surface optimization, allows one to generate a new sample set and sort its samples based on objectives and constraints. It is a non-iterative approach that is available for all types of input parameters.

The method effectively distributes a large number of candidates in the entire design domain and then provides the best several results through an accurate assessment. This optimization process is called “goal driven optimization”. Advantages of this method are that the optimal solution is very effective in preventing entrapped local minimum and/or maximum, and it easily and rapidly finds a global optimal point. The computation time is also much less than that of the genetic algorithm approach which finds the optimal solution by the conventional random method. A disadvantage of the method is that the numerical calculation processes are relatively complex and the accuracy of the optimal solution may be somewhat reduced if the response surface is not correctly constructed.

1.3 Application

1.3.1 Material Properties of Wood Beam

An optimization analysis has been carried out here on a wood (Douglas-Fir) beam containing bolt holes. Wood is n orthotropic composite material and its mechanical properties are well known, Fig. 1.2 [6]. Relative to bolted joints, the present objective is to enhance the mechanical performance through the optimization of the bolt hole. The member used in this analysis is a relatively thin wooden beam, and due to a negligibly small variation of the material properties through the thickness, the wood beam can be implemented as a 2D (plane stress) model.

Table 1.1 shows the properties of Douglas-Fir wood [6, 7] need for the FEM analysis. The stiffness and physical properties of wood have some different characteristics from the physical properties of metal.

The effect of temperature on material properties is relatively small in wood, but the effect of moisture content is relatively large. For materials with very high longitudinal and transverse stiffness, such as wood, much attention is needed in stress analysis, e.g., stress distributions can be highly influenced by the material directionality. This can be particularly important

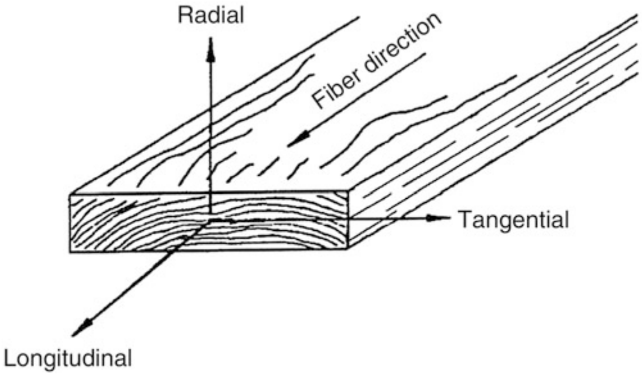

Fig. 1.2 Orthotropic material directions in wood

Table 1.1 Material properties of Douglas-Fir

Properties	
E_L (GPa)	13.53
E_T (GPa)	0.77
G_{LT} (GPa)	1.06
ν_{LT}	0.45

at the stress concentrations near bolt holes. In addition, unlike ordinary metal materials, wood exhibits higher longitudinal tensile than compressive strengths. Table 1.2 shows strengths of Douglas-Fir.

1.3.2 *Optimization Features*

The wood beam analyzed is 305 cm × 56 cm with four bolt holes on the left end for connection. Beam thickness is 25.4 mm and the diameter of the bolt holes is 19.1 mm (3/4 in.). The boundary conditions are shown in Fig. 1.3. As shown in Fig. 1.3, a symmetric boundary condition is applied at the right end, and a 0.5 MPa uniformly distributed load is applied along the top face of the beam.

The problem definition of optimization of the bolt hole position is as follows. First, the design area for the holes shown in Fig. 1.4 is a rectangular area of 51 cm × 56 cm at the left end of the beam. The goal is to determine the optimum location within this area of the four individual holes upon loading the beam. The objective function for optimization is defined as a multi-objective function which combines the vertical deflection at the left end of the rectangular wood beam in Fig. 1.3, **a**, and maximum von Mises stress around the holes. The optimization process minimizes the objective function. A symmetric boundary condition is imposed at the right end of the beam.

Eight coordinates (x_1, y_1, x_2, y_2, x_3, y_3, x_4, y_4), two for each hole, were defined as the design parameters. As shown in Fig. 1.3, the *x*-coordinate represents the straight line distance measured from the left end to the hole center, and the y-coordinate is defined as the absolute value of the straight line distance from the upper and lower sides of the beam to the hole center.

Objective function

$$F\left(x_1, y_1, \cdots, x_4, y_4\right) = \delta_v(a) + \sigma_{\max.von\ Mises}\ (around\ hole) \tag{1.1}$$

Design variables.

$$x_1, y_1, x_2, y_2, x_3, y_3, x_4, y_4 \tag{1.2}$$

Table 1.2 Directional strengths of Douglas-Fir

Strength parameter	
Longitudinal tensile (GPa)	90.0
Longitudinal compression (GPa)	47.6
Tangential tensile (GPa)	2.7
Tangential compression (GPa)	5.3
Shear (longitudinal – Tangential) (GPa)	9.7

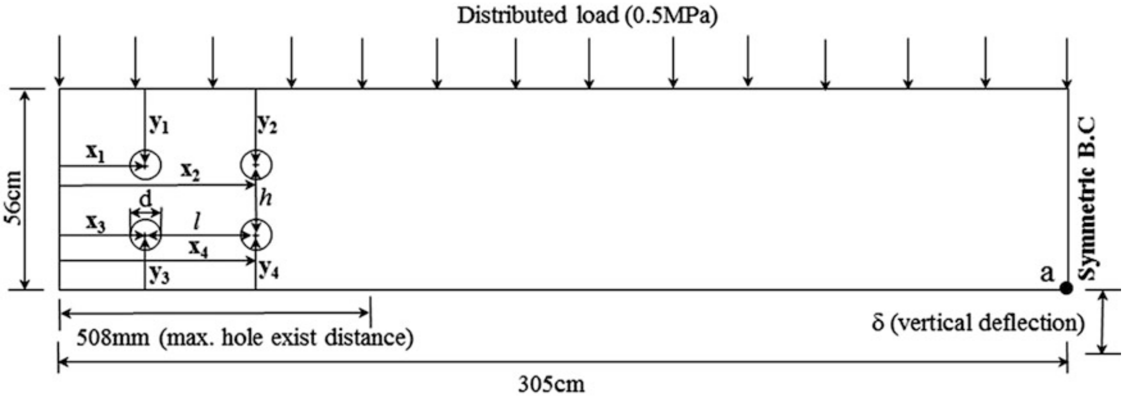

Fig. 1.3 Geometry configuration and dimension of the optimization analysis problem