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

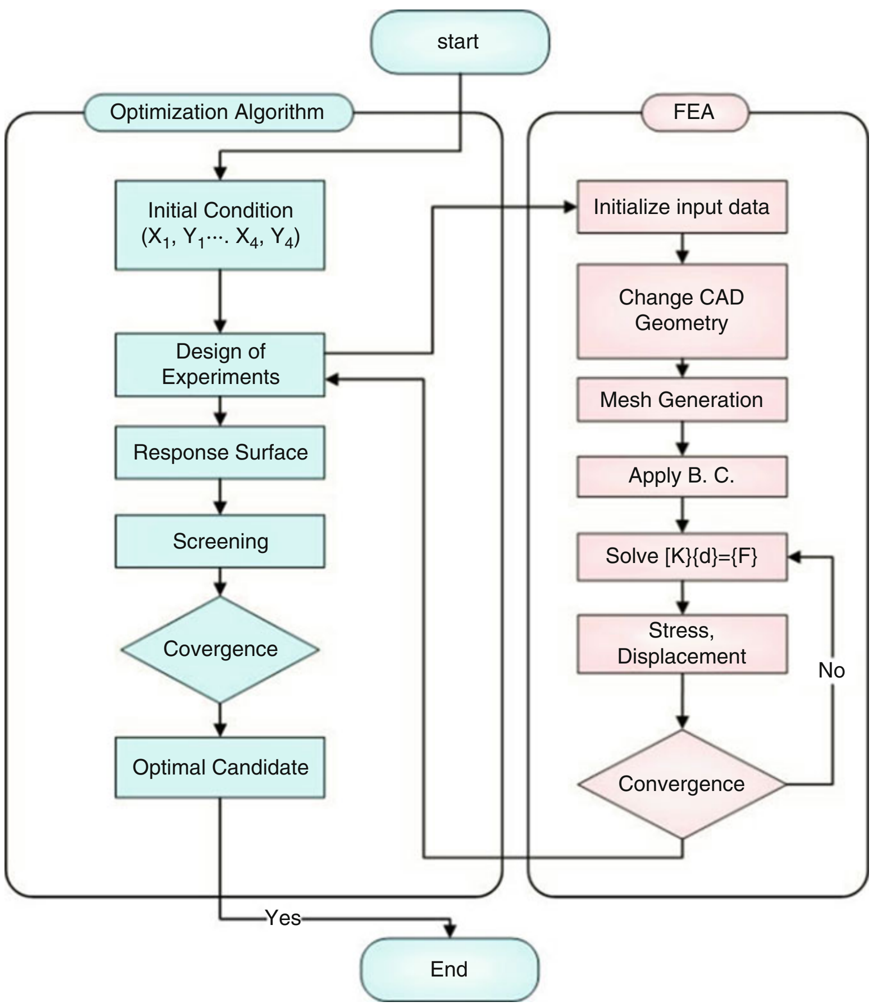

Fig. 1.1 Schematic diagram of the optimization architecture process

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

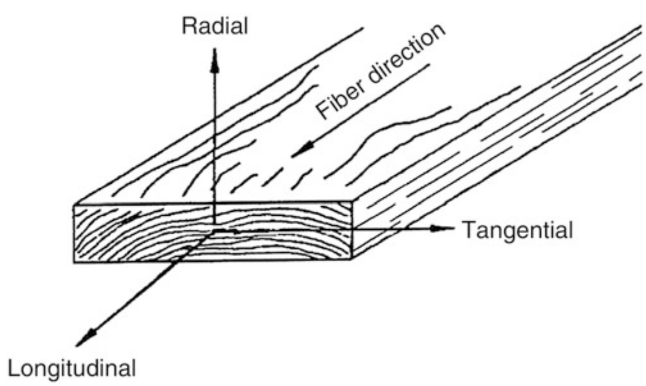

Fig. 1.2 Orthotropic material directions in wood

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

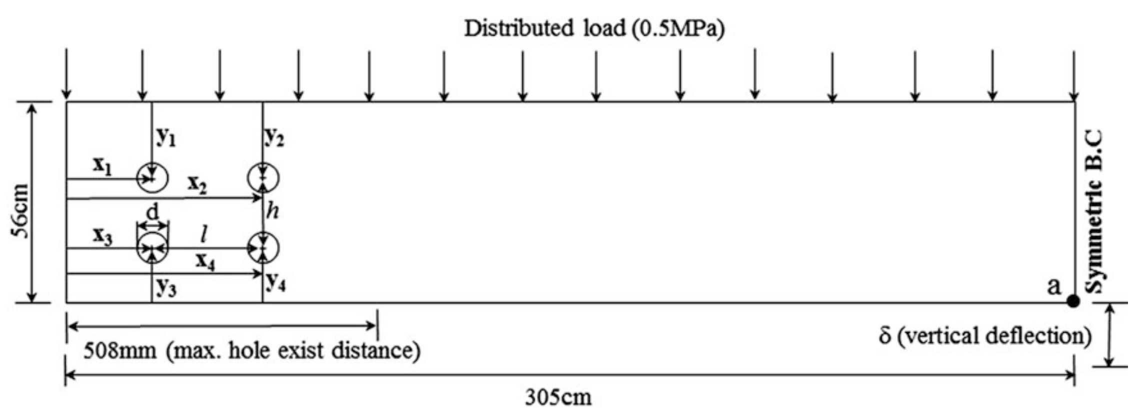

Fig. 1.3 Geometry configuration and dimension of the optimization analysis problem

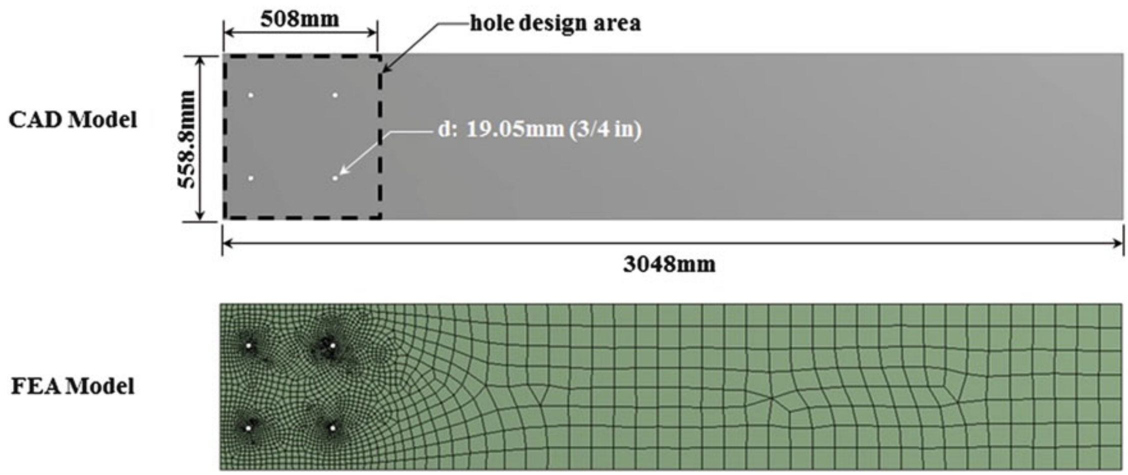

Fig. 1.4 CAD geometry and example FEA model employed. FE mesh changes with each analysis

Constraints.

$$\begin{aligned} &1)\ 4d \le x_1, x_3 \le 7d \\ &2)\ y_1, y_2, y_3, y_4 \ge 2d \\ &3)\ 1.5d \le \mathrm{h} \le 16d \\ &4)\ \mathrm{l} \ge 4d \end{aligned} \tag{1.3}$$

where d = 19.1 mm is the bolt diameter.

The constraints applied to the optimization analysis are shown in Eq. 1.3 and represent position conditions which should be satisfied by each hole after the optimization process. The positions of holes 1 and 3 in the x direction should be greater than 4*d* and less than 7*d*. The geometric constraints also define the distance between the holes and the minimum distance from the outer edges of the rectangular beam. The optimization proceeds by finding the response surface and then randomly distributing a number of candidates on the response surface to obtain an optimal solution. Many analyses are therefore needed to accurately construct such response surfaces in the optimization calculations. Upon each analysis step, both the positions of the holes and the shape of the FEM mesh changes.

The FE model shown in Fig. 1.4 represents a mesh using the ANSYS automatic of mesh generation. One of the most important results of the FEA model is determination of the stress concentrations at each hole. This phenomenon is very significant in orthotropic materials, such as wood, which have different moduli in the longitudinal and transverse directions. The sizes of the elements immediately adjacent to each hole are small (less than16 mm^2) in order to enhance the accuracy of stress calculation. The area of the element is about 1.4% of the hole area. The entire model was divided into finite elements by the auto mesh process. The aspect ratio is set to be smaller than 2, and Jacobian is set to be 0.3 or more. Since the shape of the model is not complicated, the mesh generation process converges well.

The right section of the plate is meshed with the relatively large elements because there are no steep stress gradients. Compatible with prevalent practice, the present boundary conditions correspond to those for rigid bolts, and zero bolt-wood friction and bolt clearance. The contact response between the hole and the bolt is automatically determined and calculated based on these conditions.

1.4 Results

The deflection at the right end of the beam, and the von Mises stress at each hole, were simultaneously determined as the objective function and optimization is performed to minimize the end deflection.

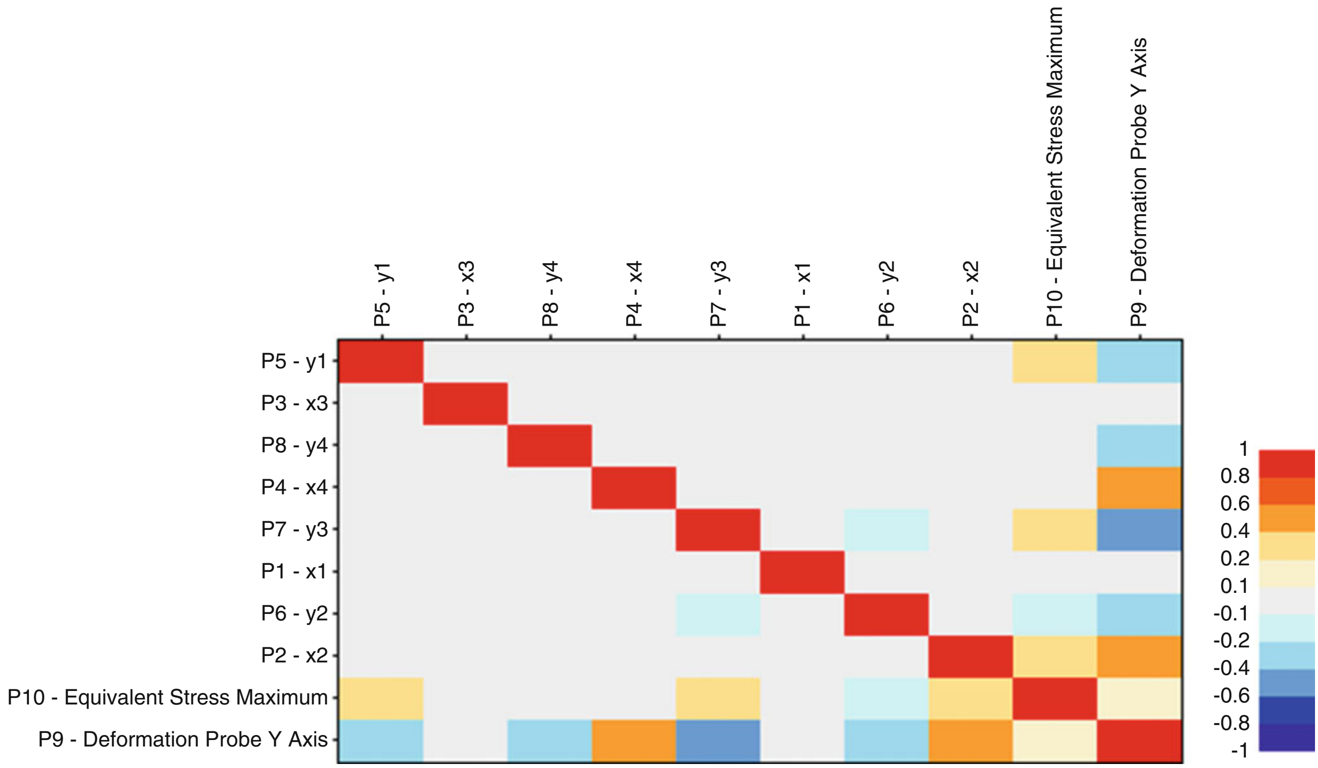

Fig. 1.5 Correlation matrix of the design variables and objective function

Table 1.3 Optimization results

	Hole location											
	Hole 1		Hole 2		Hole 3		Hole 4		Results			
Name.	x_1(mm)	y_1 (mm)	x_2 (mm)	y_2 (mm)	x_3 (mm)	y_3 (mm)	x_4 (mm)	y_4 (mm)	Max. von Mises stress (MPa)	Enhance -ment (%)	Vertical deflection (mm)	Enhance -ment (%)
Initial	95.3	139.5	381.0	139.5	95.3	139.5	381.0	139.5	**147.5**	**0**	**13.0**	**0**
Candidate 1	119.5	74.8	348.8	158.5	91.6	81.7	324.6	40.1	**125.7**	**14.8**	**11.9**	**9.1**
Candidate 2	132.0	87.7	472.7	233.5	125.1	119.2	480.1	70.8	**126.6**	**14.1**	**10.9**	**16.6**
Candidate 3	111.3	114.1	420.8	245.5	78.6	69.8	262.4	72.9	**116.4**	**21.1**	**12.9**	**1.0**

As a preliminary step towards optimization, the strength of dependency between design variables and objective functions is calculated and presented in the form of a matrix in Fig. 1.5. The closer to −1 and 1 in Fig. 1.5, the higher the interdependence. It can be seen that the deflection is more dependent on the positional parameters of the hole than the stress, and the position of hole 4 and hole 2 has a great influence on point **a** deflection in Fig.1.3. Interpretation of these charts can improve understanding of overall design and infer design criteria.

Three 'best' bolt-hole configurations were suggested through optimization analysis and are shown in Table 1.2. Results of deflection and stress for each of the three solutions (Candidates 1, 2 and 3) are compared with those of the initial design. In the initial design, the von Mises stress was 147.5 MPa, but for optimized candidates 1, 2 and 3, the stresses are 125.7 MPa, 126.6 MPa, and 116.4 MPa, respectively, which decreased by 14.8%, 14.1%, and 21.1%, respectively. In the case of the end-beam displacement, the initial displacement was 13 mm, but that was decreased by 9.1%, 16.6% and 1.0%, respectively, under optimization. Among the candidates of this optimum design solution, the best result situation can be selected according to the design purpose such as consideration of displacement and/or stress.

Figure 1.6 shows the hole locations for the three optimization candidates. The positions of the initial holes are represented by circles, and the optimized hole patterns are represented by filled black circles. The position of each relocated hole satisfies all of the constraints given in Eq. 1.3, and the exact coordinates are shown in Table 1.3.

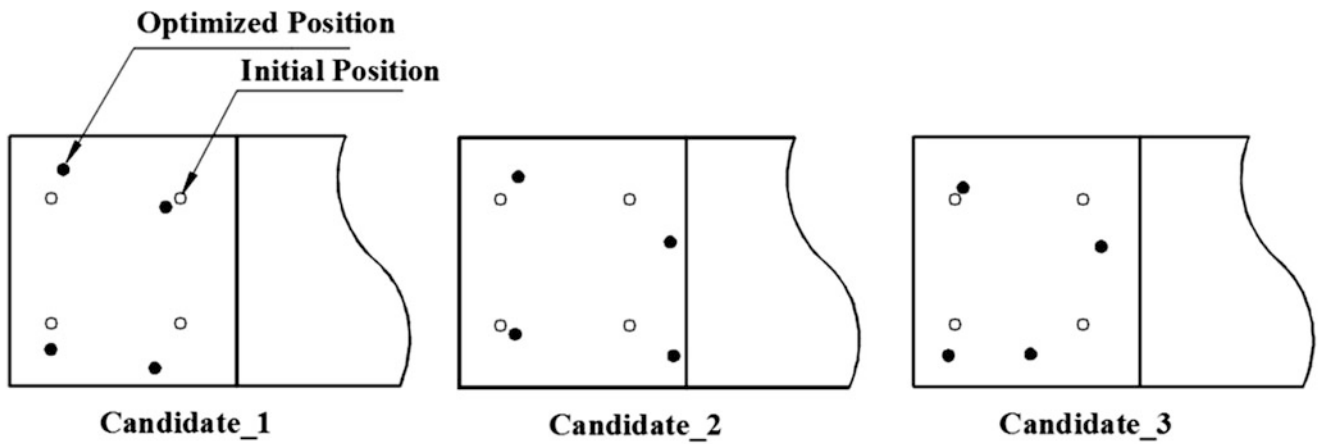

Fig. 1.6 Optimization results (three optimal hole-pattern candidates)

1.5 Summary, Discussion and Conclusions

The procedure, methodology and the analyses on the optimization of the hole pattern for a bolted wood joint are presented. Optimization was performed on a wood beam subjected to a distributed load and containing four bolt holes near one end. Optimal hole positions were determined numerically to minimize the maximum bearing stress at the holes and the vertical deflection at the end of the hole and thereby providing increased moment resistance at the connection.

The deflection and stresses of the optimized hole pattern were 14 ∼ 20% more effective than the design of the original conventionally-located square pattern for the holes. When solving the optimization problem of determining the positions of multiple holes as here, the probability of finding a local maximum point and a minimum point by a combination of a plurality of hole patterns is very high.

There are many difficulties in solving the complex problem of determining the best positions of many holes such as using the conventional gradient optimization method. The optimization problem by the gradient method is very likely to find the local maximum and minimum points because the hole pattern optimization problem has a relatively flat design surface, providing many minima. Therefore, as a method for locating the global optimal point in a complex design domain, it is effective to distribute a large number of candidate groups in the entire design domain to obtain the best result.

The analytical procedures adopted here are highly applicable and could be used with small additional effort for supplementary holes in the bolt pattern.

Although many papers have addressed problems of stress analysis, design, and optimization of holes, the authors are unaware of any previous publication which optimizes the bolt-hole pattern involving multiple holes in an orthotropic material. Future considerations include combining an optimization such as here with a strength criterion and experimental information, including optical stress analyses.

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