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Stiffness Analysis of Wood Chair Frame

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Abstract

This paper presents a stiffness analysis of a statically indeterminate wood-chair side-frame. Numerical calculations are carried out with a 'linear elastic model' for orthotropic materials. The mathematical model is solved by a 'finite element method'. The matrix analysis of structure is carried out by a 'direct stiffness method'. The frame joints are assumed to be ideally rigid and also as semi-rigid. Horizontal displacement of the top point of the back post is calculated for the most frequently used type of loading for the structure. The results of the calculation indicate that chair side frame becomes stiffer as the position of the stretcher is lowered and/or the stretcher cross section is increased. The results revealed that stiffness of joints in a frame had a considerable impact on the structure deflection. A satisfactory agreement was found between the numerical results and the results obtained by direct stiffness method.

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Keywords: wood; chair; joint; stiffness; FEM; direct stiffness method

1. Introduction

In the common structural analysis of a construction, structural behavior for even a simple frame is calculated by considering certain idealizations. Joints are assumed to be ideally rigid or pinned. In most structures, joints are one of the most important components and their significant effect on the structure's behavior could not be ignored in the analysis. Structures analysis using the realistic joint behavior (semi-rigid joint) has become an integral part of the design process of the construction industry. Development of technologies and materials has created a need to introduce this approach in furniture construction design.

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Framed structure represents the most widely used type of furniture constructions. Common furniture frames are structurally complex, manufactured by connecting members with shape-adhesive joints and normally made from wood. Attempts are being made to find applicable methods and solutions that would improve the design process of wooden-frame structures. The analytical models applied so far, are usually limited to solve statically indeterminate problems and provide an approximate preview of a structure's behavior. The significant effect of joint properties on the distribution of internal force in the structure has been neglected by the approach to separate design of members and joints. The literature studied has established that investigations are focused on the numerical methods of furniture analysis. Eckelman introduced the semi-rigid joint concept into furniture analysis by the semi-rigid connection factor. He has shown that the magnitude of the force at any point is a function of the stiffness of essentially all of the members and joints in the frame [1]. Later, authors considered stiffness as design tool and observed different joint properties with different effects in the structure [2]. Numerical methods, such as the 'finite element method', are applicable and effective for the analysis of real wood structures [3, 4]. The limitations of numerical analysis are the complexity of numerical models related to the orthotropic properties of the applied materials and complexity of network geometry. As design and optimization of structure have been largely related to the design of the joint, an attempt has been made to replace whole structure analysis with the consideration of critical structural points (joint) only [5, 6, 7, 8, 9].

2. Research objective and methodology

The aim of this study was to determine stiffness of the wood structure, calculated by different methods and to compare the results in order to determine the effects of method, assumptions and simplifications used in the calculation of the results of a structure's stiffness. The objective was to make transparent what results are to be expected, depending on what approach to structural design was taken.

This study employed a numerical method (FEM) and the matrix analyses (Direct stiffness method) for the analysis of the stiffness of the frames of wooden furniture. The effects of the structural member and joint properties on the behavior of statically indeterminate physical model of wood-furniture construction used in this study were determined. The results obtained on the stiffness were compared in order to describe the influence of the frame stretcher cross-section dimensions and position, and joints properties on the stiffness of wooden constructions.

2.1. Mathematical model

The equation of momentum balance, expressed in the Cartesian tensor notation [10]

$$\int_S \sigma_{ij} n_j dS + \int_V f_i dV = 0 \tag{1}$$

and of the constitutive relation for the elastic material

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} = \frac{1}{2} C_{ijkl}\left(\frac{\partial u_k}{\partial x_l} + \frac{\partial u_l}{\partial x_k}\right) \tag{2}$$

describe the stress and strain of a loaded solid body in static equilibrium. In the equations above, x_j are Cartesian spatial coordinates, V is the volume of solution domain bounded by the surface S, σ_{ij} is the stress tensor, n_j is the outward unit normal to the surface S, f_i is the volume force, C_{ijkl} is the elastic constant tensor components, ε_{kl} is the strain tensor, and u_k represents the point displacement. Twelve non-zero orthotropic elastic constants A_{ij} are related to the Young's modulus E_i, the Poisson's ratio ν_{ij}, and the shear modulus G_{ij}.

In order to complete the mathematical model, the boundary conditions have to be specified. The surface traction f_{Si} and/or the displacement u_S at the domain boundaries are known, i.e.