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Higher-order stiffness matrices in nonlinear finite element analysis of plane truss structures

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ABSTRACT

There are enormous number of steel truss bridges in the U.S. and around the world. Elementary theory of structural analysis or linear elastic small displacement finite element method is typically used for analysis and design of these bridges. However, steel bridges may face large deflections and inelastic displacements due to unexpected live loads and/or unfavorable environmental conditions. Therefore, there is a need for the second- or higher-order elastic and/or inelastic analysis of these bridges. This article presents a methodology for the elastic large displacement analysis of plane trusses that are novel in bridge engineering practice.

Higher-order stiffness matrices are derived and implemented in conjunction with the finite element procedure and updated Lagrangian description for the nonlinear analysis of plane truss structures. A numerical method, a modified Riks–Wempner approach, is used for the solution of geometric nonlinear plane truss problems. Numerical examples and results are presented to check the accuracy of the software developed by comparing the results of numerical examples with theoretical results and examples published by other authors. In this research, the concept of Object-Oriented technology and C++ programming language are used for coding and software developed.

1. Introduction

To reflect the real behavior of structures under ultimate or abnormal loading conditions, nonlinear analysis should be adopted instead of linear analysis, since most structures exhibit some nonlinear behavior before reaching their limits of resistance. In the analysis of structural systems, two different types of structural nonlinearities have been identified. They are material nonlinearity and geometric nonlinearity. In this work, geometric nonlinearity for plane trusses is considered and the load–deflection paths of several trusses are traced and compared to existing literature and benchmark problems.

Nonlinear analysis of truss structures has been widely investigated by many researchers during the past four decades. In the late 1960s, Mallett and Schmit [1] solved nonlinear structural problems involved with geometric nonlinearities and elastic buckling of members by using the energy search. Then, in the early 1970s, Wolf [2] analyzed the post-buckling strength of large space-trusses, and in the early 1980s, Paradiso and Tempesta [3] investigated member buckling effects in non-linear analysis of space trusses. Later on, Ramm [4] proposed strategies for tracing the nonlinear response near limit points.

The Newton–Raphson method is one of the oldest iterative methods that still widely used to solve nonlinear problems. Most iterative methods in the solution of nonlinear problems can be treated as the variation of this method. Since the failure of the Newton–Raphson method in solving problems involving limit-points has been reported in several studies, see, e.g., Szilard [5], Crisfield [6], and Yang and Kuo [7], the arc-length method which was initially proposed by Wempner [8] and Riks [9] became the most powerful and effective method to solve nonlinear problems. The first modified Rik–Wempner method currently in use is the result of improvements by Crisfield [10]. Subsequently, a modified Riks technique was applied to the finite element method by Tsai and Palazotto [11] in order to trace the nonlinear response from the pre-limit point into the post-limit range for a composite cylindrical shell-like structure. Xu and Mirmiran [12] applied this method to investigate the looping behavior of arches using the co-rotational finite element.

The nonlinear analysis of the truss structures considered by both geometric and material nonlinearities has been extensively investigated in various ways. Papadrakakis [13] used the dynamic relaxation method to investigate the post-critical ultimate load conditions of space trusses. Hill et al. [14] developed a

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