Engineering Structures 159 (2018) 99–109

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Design optimization of stiffened panels using finite element integrated force method

A. Singh[a,b], F. Yang[c], R. Sedaghati[b,*]

[a] Bell Helicopter, Montreal, Quebec, Canada
[b] Department of Mechanical, Industrial and Aerospace Engineering, Concordia University, Montreal, Quebec, Canada
[c] Research Center for Intelligent Materials and Structures, Huaqiao University, Xiamen, Fujian, China

ARTICLE INFO

Keywords:
Stiffened panel
Force method
Finite element analysis
Stability analysis

ABSTRACT

The objective of the present paper is to develop an efficient and accurate design optimization procedure to minimize the mass of the stiffened panels subjected to uniform compression loading, while guarding against the buckling failure. A Finite Element (FE) model based on the Integrated Force Method (IFM) is developed to perform the buckling analysis of stiffened panels. It has been shown that the finite element analysis based on the force methodology is able to predict the critical buckling load accurately and efficiently. The Sequential Quadratic Programming (SQP) is then applied to the established IFM model to minimize the mass of stiffened panels while guarding against buckling failure. An efficient analytical formulation to perform the sensitivity analysis is formulated using the developed finite element force method, and then utilized in the SQP formulation as the gradient information. Illustrated examples have been presented to verify the validities of the proposed methodologies. It has been shown that comparing to the numerical sensitivity analysis, the design optimization using the developed analytical sensitivity formulation is very efficient and accurate.

1. Introduction

Stiffened panels are widely used in civil engineering, aerospace and marine structures due to their economic and structural benefits. These types of structures are mostly subjected to the compression loading, and thus their bulking stability is of great interest [1–6]. Among all the numerical methods, the Finite Element Method (FEM) which is based on the Displacement Method (DM) is found to be frequently used by researchers [4–6]. However, to correctly evaluate the critical buckling load of the stiffened panel, a very accurate finite element model or higher order elements are required, which subsequently increases the computational time. This is especially more challenging for design optimization problems in which the FEM is combined with gradient based optimization algorithms. During each optimization iteration, the FEM is generally called several times, and the objective and constraint gradient information are required for successful termination of optimization algorithm.

To overcome the limitations associated with the conventional FEM, a new automated formulation of the force method known as the Integrated Force Method (IFM) has been developed by Patnaik and his collaborators [7–10]. The IFM has been validated on various structural analysis problems and shown excellent accuracy. It has been shown that the IFM can provide excellent accuracy with high computational efficiency comparing with the FEM [11]. The application of the IFM to structural optimization was first proposed by Patnaik [12]. The closed form of the sensitivity analysis of truss/frame structures were developed to optimally design truss and beam type structures subjected to stress and displacement constraints [13,14]. Sedaghati et al. [15] applied the IFM to truss and frame structures with single and multiple frequency constraints, and shown that the optimum for structural problems with multiple frequency constraints may be affected by using different analysis procedures (force or displacement method). Recently, Wei and Patnaik [16] investigated the probabilistic sensitivity analysis of IFM. They [16] developed stochastic sensitivity analysis formulation of IFM using the perturbation method and applied it to the truss structures.

The purpose of the present paper is to develop the design optimization methodology based on the IFM to minimize the mass of stiffened panels under system buckling constraint. Firstly, the elastic buckling analysis model for stiffened panels using the IFM is established. Then the sensitivity formulation using the established IFM model is derived to provide the gradient information for the design optimization problem. Finally, the mathematical nonlinear programming technique based on Sequential Quadratic Programming (SQP) optimization

* Corresponding author.
E-mail address: Ramin.Sedaghati@concordia.ca (R. Sedaghati).

https://doi.org/10.1016/j.engstruct.2017.12.040
Received 14 October 2016; Received in revised form 31 July 2017; Accepted 21 December 2017
0141-0296/ © 2017 Elsevier Ltd. All rights reserved.

algorithm is combined with the developed IFM and sensitivity formulations to optimally design different types of stiffened panels under system buckling constraint. Illustrative examples are presented to demonstrate the validity of the proposed methodology.

2. Integrated force method (IFM)

The IFM is an automated form of the force method, in which the internal forces are obtained by simultaneously considering the equilibrium and compatibility equations. The equilibrium equations based on the force balance (equilibrium) and can be written as:

$$\{P\} = [B]\{F\} \tag{1}$$

where $\{F\}$ and $\{P\}$ are the unknown independent internal forces and nodal load vectors, respectively; $[B]$ is the equilibrium matrix ($m \times n$), and m and n are the size of the nodal load factor and internal force vectors, respectively. The structure will then have r (n-m) compatibility equations which can be expressed as:

$$\{\delta R\} = [C][G]\{F\} \tag{2}$$

where $[C]$ is the compatibility matrix ($r \times n$); $[G]$ is the flexibility matrix ($n \times n$); and $\{\delta R\}$ is the effective initial deformation vector (r component) [17–19]. Finally, the equilibrium and compatibility equations (Eqs. (1) and (2)) can be combined together to obtain the governing equations of the IFM as:

$$\{F\} = [S]^{-1}\{P^*\} = \begin{bmatrix} [B] \\ [C][G] \end{bmatrix}^{-1} \begin{Bmatrix} \{P\} \\ \{0\}_r \end{Bmatrix} \tag{3}$$

Therefore, the internal force vector $\{F\}$ can be directly solved based on the Eq. (3). The governing equations for the frequency and bucking analysis using IFM can also be expressed as [19–22]:

$$[[S]-\lambda[S]_b]\{F\} = \{0\} \tag{4}$$

where

$$[S_b] = [K_g][J][G] \tag{5}$$

in which $[K_g]$ is the geometric stiffness matrix, and $[J]$ is the deformation matrix ($m \times n$) representing the top m rows of the transpose of the matrix $[S]^{-1}$.

Based on the above introduction, one can easily realize that the key issues for the IFM is to obtain the equilibrium matrix, $[B]$, the flexibility matrix, $[G]$ and the compatibility matrix, $[C]$, which will be summarized in the following sub-sections. The definition of the geometric stiffness matrix $[K_g]$ is directly related to the selected element, and it will be presented in the next section.

2.1. The equilibrium matrix ([B])

Similar to the displacement method the displacements $\{U\}$ are interpolated in terms of nodal displacements $\{U_e\}$ as:

$$\{U\} = [N]\{U_e\} \tag{6}$$

where $[N]$ is the displacement interpolation matrix (shape function). Stresses $\{\sigma\}$ are also interpolated in terms of independent internal forces $\{F\}$, which are unknown in the formulation as:

$$\{\sigma\} = [Y]\{F\} \tag{7}$$

where $[Y]$ is the stress interpolation matrix. Based on Eq. (6), the strain can be expressed as:

$$\{\varepsilon\} = [L]([N])\{U_e\} = [Z]\{U_e\} \tag{8}$$

where $[Z] = [L][N]$ and $[L]$ is the matrix of differential operator based on the definition of the coordinate.

Applying the principle of virtual work, one can obtain the general expression of the equilibrium matrix $[B]$ through the domain (v) as:

$$[B] = \int_v [Z]^T[Y]dv \tag{9}$$

On the basis of the internal complimentary virtual work related to the internal virtual force vector $\{\delta F\}$, one can obtain the Displacement Deformation Relationship (DDR) between the elastic deformation vector, $\{\beta_e\}$, and the nodal displacement vector, $\{U_e\}$, as:

$$\{\beta_e\} = [B]^T\{U_e\} \tag{10}$$

2.2. The flexibility matrix ([G])

Based on Eq. (7), and the stress-strain relationship:

$$\{\varepsilon\} = [D]\{\sigma\} \tag{11}$$

where $[D]$ is the compliance matrix, one can apply the principle of the complementary strain energy and the castigliano's theory to obtain the expression of the flexibility matrix as:

$$[G] = \frac{1}{2}\int_v [Y]^T[D][Y]dv \tag{12}$$

and the expression of the elastic deformation vector, $\{\beta_e\}$, can then be described as:

$$\{\beta_e\} = [G]\{F\} \tag{13}$$

2.3. The compatibility matrix ([C])

The compatibility is the condition of strain and deformation balance, and required the compatibility equation as:

$$[C]\{\beta\} = 0 \tag{14}$$

It should be noted that the deformation vector $\{\beta\}$ consists of the initial deformation vector, $\{\beta_0\}$, and the elastic deformation $\{\beta_e\}$, as $\{\beta\} = \{\beta_0\} + \{\beta_e\}$, and then

$$[C]\{\beta_e\} = \{\delta R\} \tag{15}$$

3. Finite element model of the stiffened panel using IFM

The stiffened panel, as shown in Fig. 1, consists of a flat plate and a stiffener. The mid plane of the plate is considered as reference plane for both the plate and the stiffener. The stiffener and the plate are assumed to be buckle simultaneously and the model is based on the behavior of the plate-stiffener system. The stiffener is assumed to be of solid cross section (ignoring the warping effects). The bending strain, developed due to the action of in plane loading, is considered for the buckling analysis. The central axis of the stiffener is eccentric from the reference axis by the distance e, which is called eccentricity of the stiffener. The eccentricity of the stiffener is taken into account in the finite element model by considering the additional in-plane deformation produced by eccentricity of the stiffener. The finite element model for the elastic

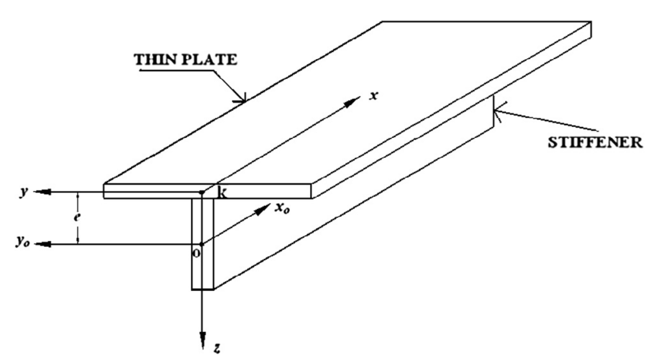

Fig. 1. Stiffened panel.

Download English Version:

https://daneshyari.com/en/article/6738483

Download Persian Version:

https://daneshyari.com/article/6738483

Daneshyari.com