Journal of Constructional Steel Research 66 (2010) 1218–1231

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

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

Optimal stiffener design of moderately thick plates under uniaxial and biaxial compression

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ARTICLE INFO

Article history:
Received 5 November 2009
Accepted 3 April 2010

Keywords:
Moderately thick plate
Stiffened panel
Biaxial compression
Optimization method
Ultimate strength

ABSTRACT

In this paper, the optimal stiffener design of moderately thick plates under uniaxial and biaxial compression is investigated on the premise that the plate thickness and the required ultimate strength are given. As the theoretical basis of stiffener design, the ultimate strength formulations of weak stiffened thick panels under in-plane biaxial compression are first developed on the basis of large deflection orthotropic plate theory, in which the post-weld initial deflection is taken into account. The von Mises yield criterion is employed to determine the limit state of the panel, and the Nelder–Mead simplex algorithm is used to obtain the efficient solution of nonlinear differential equations. The optimization method presented is based on the stiffener design principles of the overall instability stress and of the working stress. In the optimization formulation, the numbers and geometric sizes of the stiffeners are defined as design variables; the weight ratio of stiffeners to plate is taken as a single objective function; requirements against overall buckling of the panel, local buckling of the plates between the stiffeners and local buckling of the stiffeners themselves are set as constraint functions. Results of both design examples and parameter studies show that, for moderately thick plates, the stiffener weight given by the proposed optimization method is much lower than the weight determined by the current stiffener design method on the premise of the same requirement of structural safety. Using the present optimization method to obtain the lightest and the most effective stiffener layout for moderately thick plates is proposed.

1. Introduction

Stiffened panels have wide applications in civil engineering, aerospace and marine structures, since the stiffeners are efficient in enhancing the bearing capacity of the compressed plate and are convenient to be welded to the base plate. Interest in mechanical behaviors including overall buckling, local buckling and ultimate strength of the stiffened panel has been widespread in recent years. The stiffener design is of great importance for the stiffened panel due to its significant impact on these behaviors.

Generally, there are three principles, namely the principle of yield stress, the principle of overall instability stress and the principle of working stress, to be employed for the stiffener design of a stiffened panel. According to these three principles, the ultimate strength of the panel should be no less than the panel's yield stress, the member's overall instability stress and the panel's working stress, respectively. When the principle of yield stress, as mostly recommended in the current design codes [1–3], is adopted, the stiffeners are expected to be strong enough to provide rigid supports for the plate, and the required cross-section area and moment of inertia of stiffeners increase dramatically as the plate thickness is increased. This may lead to impractically high requirements of stiffeners for moderately thick or thick plates. But the reality is that a moderately thick plate stiffened by weak stiffeners can usually satisfy the requirement of structural safety because the ultimate strength of the unstiffened moderately thick plate is rather high. It is said that the current stiffener design method based on the principle of yield stress is unsuitable for moderately thick plates and it is convenient to adopt a more flexible stiffener design method based on the principle of overall instability stress or on the principle of working stress to obtain the lightest and the most effective layout of stiffeners for moderately thick plates. With more and more moderately thick plates whose slenderness ratios are relatively small being used in practical structures, it is necessary and meaningful to make a further study on the optimal stiffener design of moderately thick plates.

A large number of studies on the optimization of stiffened panels have been previously undertaken in the past 40 years with the objectives of minimizing the weight of plate/stiffener assemblies

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doi:10.1016/j.jcsr.2010.04.003

Nomenclature

L_x	Panel length in the x direction
L_y	Panel width in the y direction
t	Panel thickness
α	Overall aspect ratio of stiffened panel, $\alpha = L_x/L_y$
β	Overall slenderness ratio of stiffened panel, $\beta = L_y/t$ or $\beta = L_x/t$
n_x, n_y	Numbers of x-stiffeners and y-stiffeners
a	Equal spacing between y-stiffeners, $b = L_y/(n_x+1)$
b	Equal spacing between x-stiffeners, $a = L_x/(n_y+1)$
h_{wx}, h_{wy}	Web heights of x-stiffeners and y-stiffeners
t_{wx}, t_{wy}	Web thicknesses of x-stiffeners and y-stiffeners
b_{fx}, b_{fy}	Flange widths of x-stiffeners and y-stiffeners
t_{fx}, t_{fy}	Flange thicknesses of x-stiffeners and y-stiffeners
A_{sx}, A_{sy}	Cross-section area of plate–stiffener joints in the x and y directions
I_x, I_y	Cross-section moments of inertia of plate–stiffener joints in the x and y directions, about the centroidal axis of the plate
z_{ox}, z_{oy}	Distances of stiffener's centroid from centroidal axis of the plate, in the x and y directions
$F_{y,p}$	Yield stress of plate
$F_{y,s}$	Yield stress of stiffeners
E	Young's modulus of steel, 2.1×10^5 MPa
ν	Poisson ratio of steel, 0.3
E_x, E_y	Young's moduli of orthotropic plate in the x and y directions
ν_{xy}, ν_{yx}	Poisson ratios of orthotropic plate in the x and y directions
G_{xy}	Elastic shear modulus of orthotropic plate
D_x, D_y	Flexural stiffnesses of orthotropic plate in the x and y directions
H	Torsional stiffness of orthotropic plate
$F_{y,eq}$	Equivalent yield stress of orthotropic plate
F	Airy stress function
σ_x, σ_y, τ	Axial stresses in the x and y directions and shear stress on the edges of orthotropic plate
w_o	Initial deflection function
A_{om}	Post-weld initial deflection amplitude
K_{wo}	Initial deflection factor
w	Loaded deflection function
A_m	Loaded deflection amplitude
m, n	Half wave numbers of the buckling mode in the x and y directions
$\sigma_{x,\max}$, $\sigma_{x,\min}$	Maximum stress and minimum stress inside orthotropic plate in the x direction
$\sigma_{y,\max}$, $\sigma_{y,\min}$	Maximum stress and minimum stress inside orthotropic plate in the y direction
σ_{xu}, σ_{yu}	Ultimate strengths of orthotropic plate (i.e. weak stiffened thick panel) in the x and y directions
R_{xu}, R_{yu}	Ultimate strength factors of stiffened panel in the x and y directions
ϕ	Overall stability factor of compression member
σ_{x0}, σ_{y0}	Working stresses of stiffened panel in the x and y directions
$\sigma_{ND,x}$, $\sigma_{ND,y}$	Required ultimate strengths of stiffened panel in the x and y directions
$n_{x,\min}$, $n_{y,\min}$	Required minimum numbers of x-stiffeners and y-stiffeners
G	Weight ratio of stiffeners to plate
K_s	Stiffener weight ratio of optimal solution to code solution
P_s	Stiffener weight reduction percentage of global optimal solution when compared to code solution

under stability constraints. Schmidt et al. [4] presented two nonlinear programming strategies to optimize orthogonally stiffened plates by using orthotropic plate theory with smeared stiffeners in the formulation of the global buckling constraint. Patnaik et al. [5] optimized the Schmidt plate by assuming that the stiffeners in the same direction are of identical geometric properties. Burns et al. [6] proposed an optimization method for stiffened plates under uniform compression and combined shear and uniform compression. Bushnell [7] developed an optimization programs called PANDA for the minimum-weight design of stiffened panels subjected to combined in-plane loads. Peng and Sridharan [8] presented a strategy for minimum weight design of axially compressed stiffened panels based on Powell's algorithm. Brosowski and Ghavami [9] used the Perry–Robertson formula modified by Murray to deal with the multi-criteria optimization problem of longitudinally stiffened plates. Bedair [10] focused on the efficient design of stiffened plates by investigating the influence of plate/stiffener geometric parameters on the buckling behavior. Liptona [11] provided a mathematical formulation of optimal design for stiffener-reinforced plates subject to random transverse loads. Alinia [12] studied the optimization of stiffeners in plates subject to shear loadings based on eigenvalue analysis using the ANSYS finite element method. Leheta and Mansour [13] developed a reliability-based methodology for structural optimization of stiffened panels which are typical of those found in the deck or bottom of longitudinally stiffened ships. Other optimization strategies such as the genetic algorithm and response surface method were also employed in the optimal design of stiffened plates and composite stiffened panels by Nagendra et al. [14], Iuspa and Ruocco [15], Badran et al. [16] and Rikardsa et al. [17,18]. Many of the previous studies were based on eigenvalue buckling analyses and little research has been concerned with limit-point buckling analyses. For a moderately thick plate, limit-point buckling analysis is more meaningful because the elastic buckling stress is much higher than the elasto-plastic ultimate strength in most cases. Also, most ultimate strength calculation methods were limited to the strut approach rather than the equivalent orthotropic plate approach which has been proved to be more suitable for panels composed of thick plates and weak stiffeners. Moreover, most researchers took the plate thickness as one of the design variables and few addressed the distinction between a thick plate and a thin plate. The optimization method for the stiffener design of moderately thick plates has not been investigated in published articles.

This paper focuses on the optimal stiffener design for a moderately thick panel whose plate thickness and required ultimate strength are given, with considering the load cases of in-plane uniaxial and biaxial compression. The ultimate strength formulations for weak stiffened thick panels under in-plane biaxial compression on the basis of the large deflection orthotropic plate theory are first developed. The post-weld initial deflection is taken into account and the von Mises yield criterion is employed to determine the limit state of the panel. The analytic calculation is executed by utilizing the MATLAB mathematical software in which the Nelder–Mead simplex algorithm is used to obtain the efficient solution of nonlinear differential equations. Subsequently, the optimization method based on the stiffener design principles of overall instability stress and of working stress is presented, by utilizing the previously developed ultimate strength formulations as a theoretical basis. Two optimization theories, named constrained mixed integer nonlinear programming (CMINLP) and constrained nonlinear programming (CNLP), are adopted according to different purposes. In the optimization formulation, the numbers and geometric sizes of the stiffeners are defined as design variables; the weight ratio of the stiffeners to the plate is taken as a single objective function; requirements against overall buckling of the panel, local buckling of the plates between the stiffeners and local buckling of the stiffeners