Thin-Walled Structures 79 (2014) 129–137

Contents lists available at ScienceDirect

Thin-Walled Structures

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

A preliminary design formula for the strength of stiffened curved panels by design of experiment method

K.L. Tran [a], C. Douthe [b,*], K. Sab [c], J. Dallot [a], L. Davaine [d]

[a] SNCF, Direction de l'Ingénierie, 6, av. F. Mitterrand, F-93574 La Plaine St Denis, France
[b] Université Paris-Est, IFSTTAR, F-77447 Marne-la-Vallée, France
[c] Université Paris-Est, Laboratoire Navier (UMR 8205), ENPC, IFSTTAR, CNRS, F-77455 Marne-la-vallée Cedex 2, France
[d] Ingérop, Expertises et Structure, 168/172, bd de Verdun, F-92408 Courbevoie, France

ARTICLE INFO

Article history:
Received 18 October 2013
Received in revised form
6 January 2014
Accepted 17 February 2014
Available online 6 March 2014

Keywords:
xxxDesign of computer experiments
Response surface
Cylindrical curved panels
Stiffeners
Stability
GMNIA

ABSTRACT

In bridge construction, the use of stiffened plates for box-girder or steel beams is common day to day practice. The advantages of the stiffening from the economical and mechanical points of view are unanimously recognized. For curved steel panels, however, applications are more recent and the literature on their mechanical behaviour including the influence of stiffeners is therefore limited. Their design with actual finite element software is possible but significantly time-consuming and this reduces the number of parameters which can be investigated to optimise each panel. The present paper is thus dedicated to the development of a preliminary design formula for the determination of the ultimate strength of stiffened cylindrical steel panels. This approximate formula is developed with the help of a design of experiment method which has been adapted from the current statistical knowledge. This method is first presented, and its feasibility as well as its efficiency are illustrated through an application to the reference case of unstiffened curved panels. Then, the case of stiffened curved panels is investigated and a preliminary design formula is developed. The ease of use of this formula for preliminary design is finally illustrated in a cost optimisation problem.

1. Introduction

The interest of stiffening steel plates or panels to increase their strength under compression has been known for almost a century [1]. In the field of structural engineering, the use of such panels is a common practice, for example in bottom flanges of box-girder bridges. Recent developments of the curving process allowed for the use of curved panels in civil engineering structures where they offer attractive aesthetic and aerodynamic possibilities. The verification of these panels is yet difficult due to a lack of specifications, especially in European Standards: EN 1993-1-5 [2] gives specifications for flat or slightly curved panels with the condition $R \geq R_{lim} = b^2/t_p$ (where R is the curvature radius of the panel, b its width and t_p its thickness) and EN 1993-1-6 [3] deals only with revolution cylindrical shells. Nevertheless the curved panels in bridges have characteristics exactly between these two conditions, as illustrated in the case of the Confluences bridge in Angers, France 2011 (Fig. 1), whose radius $R = 80$ m is much smaller than the limit of EN 1993-1-5: $R_{lim} = 1440$ m (with $b = 4.8$ m and $t = 16$ mm) and for which EN 1993-1-6 is not applicable neither because these curved flanges are not full revolution cylinders.

From an academic point of view, the articles related to the buckling theory of curved panels are not so numerous due to the complexity of the studied problem and also due to its late application in the bridge construction. First investigations were conducted in the forties by Batdorf and Schildcrout [4] and Schildcrout and Stein [5] who showed that the stiffeners and the curvature increase the critical buckling strength. A state of the art on curved stiffened panels was then proposed by Becker [6] in 1958 in his handbook on structural stability. Based on experimental results (provided by [7,1,8]), he confirmed that, when a stiffened flat panel is bent to a circular curve, its buckling stress is slightly increased (around 6% for the tested specimen which is relatively few compared to the effect of stiffening alone or curvature alone). More recent parametric studies based on numerical examples and the finite element modelling (e.g. [9,10] or [11]) investigated and quantified the influence of the main parameters on the ultimate strength of curved stiffened plates. They however did not lead to a practical criterion for the evaluation of the resistance of such panels which is therefore still an open question.

In a former study, the authors [12] had investigated the case of xxxunstiffened cylindrical curved panels under axial compression and established a set of formulas for the evaluation of the ultimate

* Corresponding author. Tel.: +33 1 81 66 81 36.
E-mail address: cyril.douthe@ifsttar.fr (C. Douthe).

http://dx.doi.org/10.1016/j.tws.2014.02.012
0263-8231

Nomenclature

α_Z	parameter characterising the imperfections sensitivity
β	parameter characterising the asymptotic behaviour of the panel
β_0	constant term and average value of the approximated response
β_i	coefficient characterising the effect of the variable X_i
β_{ij}	coefficient characterising the interaction of the variables X_i and X_j
χ	reduction factor for the panel buckling according to EC3
$\overline{\lambda}$	relative slenderness of the panel according to EC3
$\overline{\lambda}_0$	slenderness separating plastic buckling from elasto-plastic buckling
ρ	steel density
σ_{ult}	ultimate strength of the panel
a	length of the panel
b	width of the panel
d	distance between stiffeners
f_y	yield stress of the panel
h_s	height of stiffeners
K_f	fabrication costs
k_f	fabrication cost per volume unit
K_m	material costs (steel cost)
k_m	material cost per volume unit
$k_{a/b}$	parameter characterising the influence of the aspect ratio
m	number of unknown coefficients in the approximated model
n	number of simulations or numerical experiments
N_{app}	normal force applied to the panel
N_{ult}	capacity of the panel
p	number of input variables
R	curvature radius of the panel
T_i	manufacturing time of the ith operation
t_p	thickness of the panel
t_s	thickness of stiffeners
V	total volume of the curved panel
X_i	generic name of the ith input variable
X_i^j	jth value of the ith input variable
Y, $\hat{Y}$	response and approximated response
Y^j	jth value of the response
Z	curvature parameter defined by $Z = b^2/Rt_p$

strength (which were confirmed by [13]). These semi-analytic formulas had been fitted on a total of 524 combinations of the main parameters. Each calculus involved Geometrical and Material Non-linearity with Imperfection Analysis (GMNIA) and required between 5 and 10 min depending on the refinement of the mesh. Considering the fact that in the case of stiffened panels the number of parameters is considerably larger, re-employing the same methodology seemed unrealistic. It appeared hence that there is a need for a robust strategy for the choice of the set of tested models and for the measure of the approximated model accuracy. Such a strategy exists for the design of physical experiments as well as for that of computer experiments, they are known as “design of experiments methods”.

In the following, the authors present first the characteristics of computer experiment strategies. Afterwards the feasibility and ease of use of the methodology as well as its efficiency are illustrated through an application to the reference case of unstiffened curved panels. Then, the case of stiffened curved panels is investigated and a preliminary design formula is developed. The interest of this formula for early stages of design is finally illustrated by a short example of cost optimisation.

2. Design of computer experiments

2.1. Background of the design of experiments method

Design of experiment (DOE) methods exist since the beginning of scientific experiment. The first formal theory for the design of experiments in a “modern sense” was published by Fisher [14] in the 1920s and 1930s, while working on improving agricultural yield. Since the 1940s, various researchers have promoted and developed the use of experiments strategies in many other areas [15]. In the late 1970s, the theory of Taguchi [16] on quality improvement made the design of experiment to be widely used in the industrial environment. In the past 20 years, advances in computational power have led to the study of physical process through computer simulated experiments, which tends to replace physical experiments in cases where the number of variables is too large to consider performing a physical experiment or where it is simply economically prohibitive to run an experiment on the scale required to gather sufficient information.

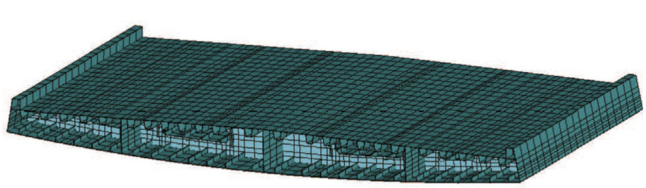

Fig. 1. Stiffened curved panel of the Confluences Bridge in Angers (France, 2011).

Computer experiments differ from traditional physical experiment in their deterministic character meaning that the computer produces identical answers for the same set of experimental parameters. The error in computer experiments is no longer due to random effects which are derived from the variability in experimental units, the order of experiments or the locations of the tests. However, it was shown that in many cases, the systematic error between a deterministic model and its approximation has a normal distribution, so that standard statistical techniques can still be applied [17]. Several authors [17–19] also insisted on the fact that the selection of parameter's values for computer runs is still an experimental design problem of primary importance, especially considering the quantification of uncertainty of the model on a statistical point of view. Indeed, as not every combination of parameters can be tested, uncertainty and hazard enter the deterministic process through the choice of tested combinations. The design of a computer experiment is hence at the border of a physical and a statistical problem which specificities are emphasized in the following section.

2.2. General progress of the design of computer experiment method

Schematically, a numerical model can be considered as a process: the user specifies the combinations of (input) variables to the computer simulator from which the responses (output) are generated. Fig. 2 illustrates this process in the simple case where there are only two input values (X_1 and X_2) and one response Y. Each variable can take a value from “low” to “high”. The set of all domains of variation