Thin-Walled Structures 106 (2016) 448–458

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Collapse mechanisms and load–deflection curves of unstiffened and stiffened plated structures from bridge design

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ARTICLE INFO

Article history:
Received 10 February 2016
Received in revised form
3 May 2016
Accepted 23 May 2016

Keywords:
Yield-line theory
Collapse mechanism
Stiffened plated elements
Finite element analysis
Load–deflection curve

ABSTRACT

Cross sections of modern bridges are generally build with stiffened plated elements. The verification methods given in Eurocode EN 1993-1-5, to obtain the ultimate buckling resistance of plated structures, result in a time consuming procedure. In addition, the methods are mainly based on the elasticity theory and reduction factors from e.g. experiments are needed. Therefore, an alternative approach to obtain the ultimate resistance of unstiffened and stiffened plates is used. The method is based on a strain-dependent and geometric nonlinear yield-line theory including imperfections. This theory makes it possible to approximate the decreasing part of the load–deflection curve of such stability sensitive structures. The ultimate resistance, as maximum of the load–deflection curve, is approximated by a defined limit value. Therefore, the use of additional reduction factors is not necessary. Collapse mechanisms, which have been determined with the Finite Element Method (FEM) beforehand, are needed in order to apply the yield-line theory.

1. Introduction

Cross sections of modern bridges are generally build with stiffened plated elements. By introducing the design rules of the Eurocode, the verification procedure of such elements was included in EN 1993-1-5 [1]. The two given design methods, the “effective sections method” and the “reduced stresses method”, are mainly based on the elasticity theory. Both methods need as input value the slenderness $\bar{\lambda}$ of the system, which lead in general to the required reduction factor ρ. This reduction factor contains the missing effects resulting from imperfections and nonlinear behaviour of the structure. The reduction factor often came from experiments or from simulations with the FEM and can be used to obtain the ultimate resistance of the plate.

A proposal, to obtain the ultimate resistance of typical unstiffened and stiffened plates, based on the yield-line theory, is made in the following sections. The aim is to provide a simple method for practical use. Therefore, it is necessary to determine the load–deflection curve of such plates, so that the ultimate resistance as maximum of the load–deflection curve can be found without the need of additional reduction factors. This is possible, because the used theory includes effects from plasticity and geometrical nonlinear behaviour and therefore the real behaviour can be described in good approximation, see [2–7].

The load–deflection curve can be approximated by two curves: the increasing part and the decreasing part, as shown in Fig. 1, which are usually described by the out-of-plane deformations w. The increasing part can be described through the elasticity theory, see e.g. [10]. For practical use, this part can also be calculated with the Finite Element Method (FEM). The decreasing part can be described through the plasticity theory, especially with a generalized yield-line theory. The intersection point of both curves give an upper bound for the ultimate limit load, see e.g. [2,11].

In order to obtain the intersection point, the increasing part of the load–deflection curve is needed. An other criterion is used in the following sections. In a good approximation, the maximum of the load–deflection curve is also reached when the membrane-stresses first reach the yield-strength f_y, which happens for plated structures at a longitudinal displacement $u = u_y = a \cdot f_y / E$, see e.g. [10]. By using the described procedure including a strain-dependent yield-line formulation and the described criterion, a good approximation of the load–deflection curve and the ultimate limit load can be obtained without the need of additional reduction factors, see Fig. 2. A similar method was amongst others used in [11] for unstiffened plates with one free edge.

The obtained ultimate load is an upper bound and therefore an approximation to the real ultimate load. In order to get a more

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http://dx.doi.org/10.1016/j.tws.2016.05.020
0263-8231/

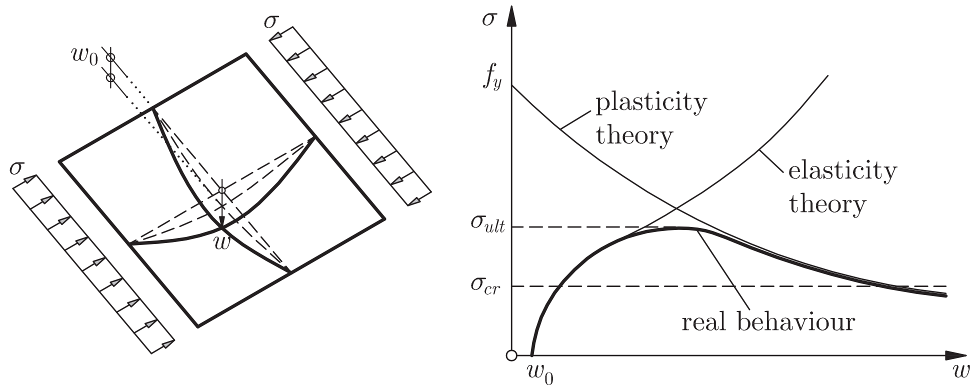

Fig. 1. Load–deflection curve of an unstiffened plate under compression, see e.g. [2,5,8,9].

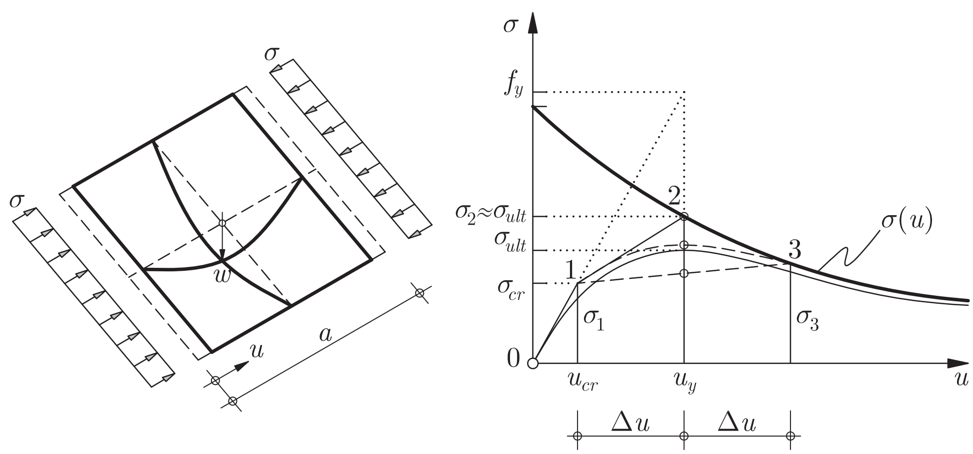

Fig. 2. Approximation of the load–deflection curve and the ultimate load, see [7].

realistic result and a better approximation of the ultimate load the following three geometric proposals were used (see Fig. 2):

$$\sigma_{approx,1} = \sigma_2$$
$$\sigma_{approx,2} = \frac{1}{2} \cdot \left(\frac{\sigma_1 + \sigma_3}{2} + \sigma_2 \right)$$
$$\sigma_{approx,3} = \frac{\sigma_1 + \sigma_3}{2} \quad (1)$$

The proposals 2 and 3 make only sense for structures with a supercritical structural behaviour, i.e. $\sigma_{cr} < \sigma_{ult}$ and therefore $\sigma_1 = \sigma_{cr}$ is used. Unstiffened plates with a ratio $\alpha = a/b > 1$ typically have this structural behaviour. Stiffened plates, similar to a column, can also behave column-like, i.e. $\sigma_{cr} > \sigma_{ult}$. In this case, the connecting line between point 1 and 2 in Fig. 2 becomes horizontal and $\sigma_{approx} = \sigma_2$ is used as approximation of the ultimate load. This also means that $\sigma_1 = \sigma_{ult} < \sigma_{cr}$.

2. Determination of collapse mechanisms and yield-line analysis

The procedure described in Section 1 is based on a kinematic collapse mechanism, which is not yet known but which can be obtained with the FEM. Subsequently, the obtained mechanisms will be described analytically with the help of the generalized yield-line method, to obtain the load–deflection curve. The next subsections contain a short description of how this methods work. The procedure will be applied especially to unstiffened and stiffened plates with the following methodology:

1. Determination of collapse mechanisms by using the FEM (Software Ansys [12]),
2. Preparation and description of the obtained mechanisms by using the generalized yield-line method,
3. Comparison of the approximated load–deflection curve and the ultimate load with the results obtained with the FEM and the ultimate load coming from EN 1993-1-5.

The collapse mechanism for unstiffened plates under pure compression is well known, see Fig. 3. Therefore, the scope of application was extended to a stress gradient of $1 \geq \psi \geq 0$. For stiffened plates the focus lies on plates build with trapezoidal stiffeners, see Table 1, which is typical for plated structures of modern bridges.

2.1. Collapse mechanisms by FEM

Possible collapse mechanisms can be determined through experimentation but also numerically by using the FEM. This last one is used to examine a wide range of unstiffened and stiffened plates. Therefore, it is necessary to perform a geometric and material nonlinear analysis including imperfections. A bilinear stress-strain curve (ideal elastic, perfect plastic) is used for the material behaviour. The main problem when calculating plates under compression is, how to model the shape of the imperfections. Especially in the case of stiffened plates, the combination of the imperfections of the global panel and the local subpanels requires special attention.

Information about how to deal with the shape and amplitude of the imperfections can be found in Annex C of EN 1993-1-5. Here, an equivalent geometric imperfection shape is used, in form of a combination of different eigenmodes from a linear buckling