Thin-Walled Structures 102 (2016) 258–272

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

A compression model for ultimate postbuckling shear strength

Jonathan D. Glassman [a], Maria E. Moreyra Garlock [b,*]

[a] Exponent Failure Analysis Associates, United States
[b] Department of Civil and Environmental Engineering, Princeton University, United States

ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form
7 November 2015
Accepted 15 January 2016
Available online 10 February 2016

Keywords:
Tension field
Shear buckling
Postbuckling
Plate girder
Plate buckling

ABSTRACT

Tension field theory has traditionally been used to determine the ultimate postbuckling shear strength of steel plates. More than a dozen theories have been proposed in the last nine decades to describe and predict this phenomenon, and all are based on the tensile response of the web plate, referred to as tension field action. Alternatively, in this paper a compression approach for determining the ultimate postbuckling shear strength is studied. First, an experimentally-validated finite element model is used to examine the mechanics of plate shear buckling. The response is shown to be similar to axially compressed plates, but in this case the axial compression is acting on a diagonal. Then a physical model and formulation based on the compressive strength of the plate is developed for predicting the ultimate postbuckling shear strength of a plate. For common design parameters of most bridge and building structures, this compression approach produces strengths that are closer to experimental and finite element results than the best and commonly accepted formulation based on tension field action. Overall, the results of this study show that a compression approach to predicting the postbuckling shear capacity of plates is an honest representation of shear buckling mechanics and has good correlation to extensive experimental results, where in many cases improved correlation is seen compared to formulations based on tension field action.

1. Introduction

Plate shear buckling is an intriguing phenomenon because, unlike compressive structural elements (a column, for example) that lose their load-carrying capacity once elastic buckling has occurred, plates that elastically buckle due to shear still possess a significant amount of postbuckling shear strength. This postbuckling behavior has attracted the attention of researchers and engineers since the 1880s. Attempts to quantify this behavior led to the historical development of tension field theory, which argues that the source of this postbuckling shear strength is the development of tensile stresses in a defined diagonal field that is mobilized post-elastic shear buckling. Beginning with Wagner in 1931 [5], more than a dozen proposals have been developed to explain and predict the postbuckling shear strength based on tension field action. Previous authors have provided extensive discussions on the various proposed plate shear buckling models throughout the literature [1,2,3], and all are based on tension field action. As Yoo and Lee [3] point out, this fact "is testimony to the complexity of tension field action. This may be the largest number of failure theories devoted to a single topic in structural mechanics". While a tension field does form, compression is always the catalyst to buckling, and further, many of the assumptions inherent to tension field theory have since been proven to be inaccurate as will be discussed later. These observations motivated the authors to examine postbuckling shear behavior based on a compression approach.

Tension field theory is based on the key assumptions that (1) compressive stresses cease to increase in the postbuckling range [3,4], and (2) the stiffeners, flanges, or both anchor the tension field. The first assumption was proposed by H. Wagner in 1931 and stated that once elastic shear buckling occurred in the web, compressive stresses do not increase and any additional (or postbuckling) shear strength is mobilized due to the formation of diagonal tensile stresses [1,5,6,7]. This assumption is simultaneously the most important and most controversial because accepting it transforms a buckling problem, which is inherently a compression problem, into one based on tension. It is a fascinating historical irony to formulate a buckling problem in terms of tension, but one rooted in compelling experimental observations. However, the assumption that compressive stresses do not increase in the postbuckling range was shown not to be accurate based on findings from numerous authors using finite element (FE) analysis [2,3,8,9,10,11]. In fact, near the edges, compressive stresses increase considerably [3].

* Corresponding author.
E-mail addresses: jglassman@exponent.com (J.D. Glassman), mgarlock@princeton.edu (M.E. Moreyra Garlock).

http://dx.doi.org/10.1016/j.tws.2016.01.016
0263-8231/

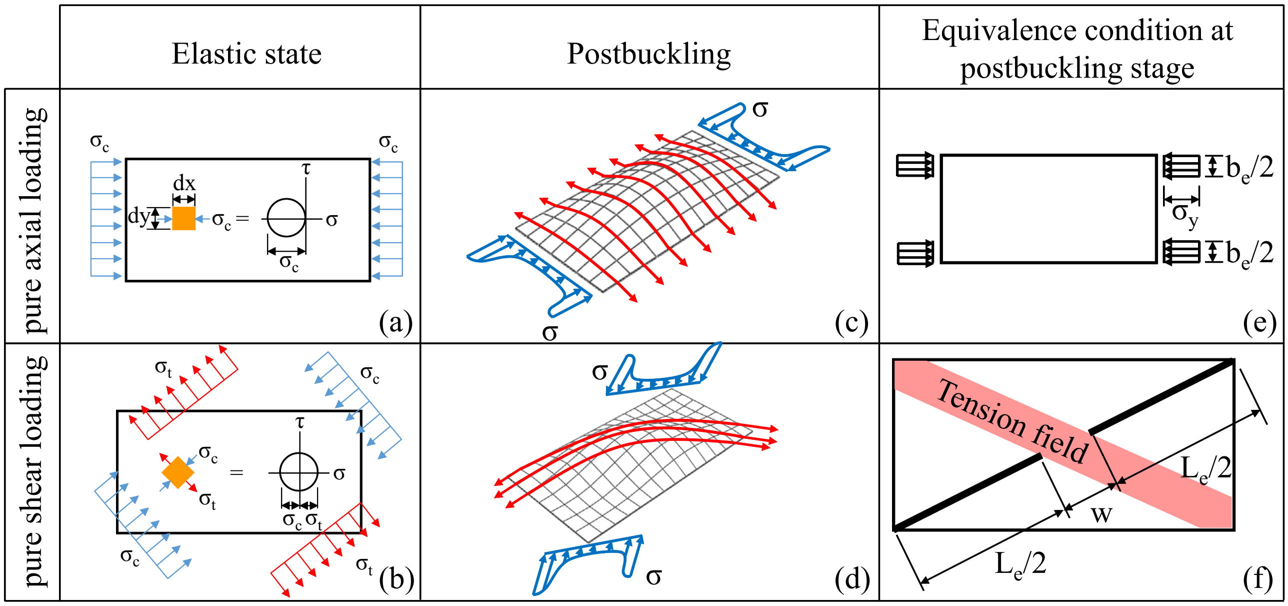

Fig. 1. Plate behavior (simply supported) under pure axial load compared to pure shear load.

The second assumption has its basis in the earliest recorded explanation for the postbuckling shear strength of stiffened plate girder webs offered by J. M. Wilson in 1886 [1,12]. His explanation arguably established the foundation of tension field theory by suggesting that the transverse stiffeners act like the posts of a Pratt truss, with the web handling the duty of carrying the diagonal tensile stresses. However, previous researchers have found that the large axial loads expected to develop in the transverse stiffeners due to anchoring the diagonal tension field were smaller than expected for a truss action to develop as assumed [3,8,9,13]. Similarly, Yoo and Lee [3] found that the vertical stresses reduce to zero near the flange, thus indicating that the flange does not act as an anchor to the tension field.

This paper draws parallels to axially compressed simply supported plates as shown in Fig. 1. Comparing Fig. 1(a) and (b) we note that, in an elastic state, a plate in pure shear is similar to an axially compressed plate except that it is loaded on a diagonal with equal tensile stresses acting perpendicularly. In Fig. 1(c) and (d) we note that in the postbuckling range, both the axially compressed plate and the pure shear loaded plate develop a field of tension perpendicular to the field of compression. It is this tension field, in both cases, that allows postbuckling strength to develop. In both cases, the compressive stresses increase at the edges leading to similar patterns of stress distributions. Physically this distribution can be explained by considering that the out-of-plane deformations are largest at the center of the plate. The larger the out-of-plane deformations the smaller the axial rigidity, therefore near the center, the stresses will not increase much (or at all) after elastic buckling. Near the edges, the out-of-plane deformations are much smaller and therefore the stresses continue to increase after elastic buckling.

This paper presents a novel approach to predicting the postbuckling shear capacity of plates based on the compressive behavior dominating the mechanical response. The proposed approach does not ignore the tension field, which is actually shown to provide additional stability such that postbuckling shear capacity may be mobilized. Closed-form equations are presented to predict the postbuckling (ultimate) shear buckling capacity of steel plates. Note that it is not the authors′ intention to propose that these equations be directly incorporated into design codes. To meet such a goal, the equations may need to be simplified and perhaps also developed for a broader range of parameters. The fundamental goal of the work presented in this paper is to show the strong promise of a compression-based model for predicting the ultimate buckling load of a plate loaded in shear.

Since, as just illustrated, the behavior of a plate under pure shear is similar to that under pure axial load, the proposed approach is based on considering the plate acting as a column on a diagonal. The parallel of this approach to axially loaded plates is illustrated by comparing Fig. 1(e) and (f). In an axially loaded plate, the "equivalence condition" for evaluating the postbuckling strength of the plate is done by transforming the postbuckling stress distribution shown in Fig. 1(c) into a stress distribution acting over an equivalent width, b_e [14]. For plates loaded in pure shear, we propose instead to make the equivalence condition based on the length of the diagonal column. The equivalent column length, L_e, is equal to the diagonal length of the plate minus the width of the tension field. The challenge is then to predict (1) the width of the tension field, (2) the axial load on this equivalent column, and (3) convert that axial load to a shear load. This paper illustrates this procedure to arrive at a formulation to predict the postbuckling shear capacity of plates. This compression approach is compared to the best and most well-known formulation for postbuckling shear strength of plates developed by Basler in 1961 [4], which is based on tension field theory. The next section therefore describes Basler's approach in detail.

2. Basler's tension field approach

White and Barker [2] compare the shear resistance of the twelve "most promising" tension field based models to the experimental results of 115–129 tests of steel I-girders. They found the model by Basler [4], which is implemented in AASHTO [15] and AISC [14], to have the "best combination of accuracy and simplicity". This section therefore focuses on this Basler model, which will be used as a comparison to a compression model that will be developed in this paper. In addition, Porter et al. [16], and Höglund [17,18] will be briefly discussed in this section since these currently serve as the basis for the European design codes [1,15,16,17].

In 1961, Konrad Basler suggested a model to calculate the ultimate postbuckling shear strength of steel plate girders derived