Thin-Walled Structures 81 (2014) 225–235

Contents lists available at ScienceDirect

Thin-Walled Structures

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

The in-plane shear failure of transversely stiffened thin plates

J. Loughlan *, N. Hussain

Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire, UK

ARTICLE INFO

Available online 27 March 2014

Keywords:
Stiffened plates
In-plane shear
Post-buckling
Mode jumping
Elasto-plastic unloading

ABSTRACT

This paper examines the response of stiffened plates with plain flat outstands when subjected to in-plane shear loading in the form of applied in-plane shear displacement. The buckling and post-buckling failure capabilities of thin plates subjected to in-plane shear, can, of course, be improved through the introduction of stiffening elements whose flexural and torsional rigidities can contribute significantly towards a more stabilised structural system. This paper details appropriate suitable finite element modelling strategies and procedures to enable the determination of the post-buckled failure response of the stiffened shear panels and to highlight the significant influence of the stiffeners. The modelling procedures are able to describe the complete loading history of the stiffened panel structures from the onset of initial buckling through the elastic post-buckling phase of behaviour involving the considerable interaction between plate and stiffener and then through initial material yielding and yield propagation to ultimate conditions and elasto-plastic unloading.

1. Introduction

Stiffened plating is used widely in many fields of engineering with applications to be found in mechanical, civil, aeronautical, and marine engineering to name some. Stiffened panels are efficient structural elements which readily contribute to the light-weighting of large structural systems and which can be tailor designed with the appropriate strength and stiffness requirements for any particular application. In practice, stiffened panels are more than likely to be subjected to complex, combined in-plane and lateral loading systems such as that which would be experienced in the wing structure of a large civilian airliner or in the hull structure of a large ship. Our knowledge and understanding of the structural performance and failure mechanics of stiffened plating under complex loading is at a fairly sophisticated level at present due to the wide body of research that has been carried out over the years. Today's research continues to advance our knowledge and to contribute significantly to the efficient design of stiffened plate structural systems. The considerable advances made in finite element software and computing technology have been influential in aiding progress. These have evolved to such a sophisticated level that today we are verging on the possibility of virtual testing to aid us in our quest for safe, reliable and efficient structural designs.

Many researchers have investigated the effect of utilising transverse and longitudinal stiffeners on buckling and post-buckling response and on the failure mechanics of thin-walled stiffened plate structural systems. Although the concept of post-buckling strength was introduced by Wilson [1] in 1886, little or no further research was carried out in the years that followed and the critical buckling stress was used as a design parameter until the 1960s due to the lack of means to evaluate post-buckling behaviour. The post-buckling reserve is, of course, an additional load carried by the structural system after the initiation of critical buckling to the point where the ultimate strength is achieved and it depends on several factors such as the structural geometry, boundary conditions, material properties and the loading conditions applied.

Bryan [2] introduced the first equation for determining the elastic buckling of flat plates in compression. With regard to in-plane shear loading, Timoshenko [3] assumed that the buckle pattern was symmetric and suggested an appropriate equation for the buckling of rectangular plates under the action of in-plane shear stresses. Stein and Neff [4] determined the buckling stresses more accurately by taking into account both the symmetric and anti-symmetric buckling patterns of simply supported flat plates in shear. Budiansky and Connor [5] evaluated the theoretical shear buckling stress of clamped rectangular plates for both the symmetric and anti-symmetric buckling modes. Stein and Fralich [6] presented a theoretical solution to determine the critical in-plane shear buckling stress of an infinitely long simply supported flat plate with equally spaced transverse stiffeners. Their work assumed that the stiffeners possessed no torsional stiffness but were fully effective with regard to in-plane bending. Basler and Thürlimann [7] carried out an analysis and experimental studies regarding the post-buckling strength of plate girders and proposed that the transverse stiffeners could be cut short along the tension

* Corresponding author. Tel.: +44 1509 227213.
E-mail address: j.loughlan@lboro.ac.uk (J. Loughlan).

http://dx.doi.org/10.1016/j.tws.2014.02.027
0263-8231/

flange as the welding of the stiffener to the flange causes a reduction in the fatigue strength which could lead to brittle fracture. The suggested clearance between the stiffener and flange should not be more than four times of the web thickness. However, the clearance on the compressive flange was not recommended. Basler [8] suggested that due to excessive shear stress after critical buckling a diagonal tension field is developed and the vertical component of the diagonal tensile stress acts as a direct compressive force, which is resisted by the transverse stiffener. Therefore, it was assumed that the transverse stiffener behaves as a column and there should be adequate cross sectional area in order to avoid the local buckling of the stiffener and to obtain the full post-buckling strength. Cook and Rockey [9] extended the work of Stein and Fralich [6] and obtained a theoretical model to evaluate the critical buckling stress of infinitely long plates under shear loading but with clamped longitudinal edges instead of the simple support condition. It was reported that due to clamped boundary conditions the required rigidity of the stiffener to stiffen the plate was considerably reduced. Results obtained from their analysis were compared with available test data and found to be reasonably close. Cook and Rockey [10] studied the shear buckling of infinitely long plates for both the simple support and clamped boundary conditions utilising closed section transverse stiffeners instead of open section stiffeners. They proposed the use of closed section stiffeners since these were found to significantly enhance the shear buckling resistance of the plates resulting from their superior stiffness qualities. Rockey and Cook [11] continued their earlier work and were able to obtain a useful design relationship between the critical shear buckling stress and the ratio of the torsional rigidity to flexural rigidity of the stiffener for the case of clamped infinitely long plates with transverse stiffeners. Plank and Williams [12] have studied the behaviour of stiffened panels with different stiffener geometries. The panels were subjected to combined shear and compressive loading and useful interaction curves were obtained which reflected the influence of the different stiffener geometries. Loughlan [13] presented a finite strip formulation to determine the critical buckling stress and natural frequencies of vibration for metallic shear loaded stiffened panels. This work illustrated the significant influence of in-plane shear loading on the natural frequencies of vibration of the panels and was able to demonstrate the well-known fact that when the applied shear is critical, the natural frequency of the panel becomes zero. Loughlan [14] studied the behaviour of carbon fibre composite stiffened panels subjected to combined in-plane compression and shear loading using the finite strip method. Interaction curves were obtained from this work and the influence of the bending and torsional stiffnesses of the stiffeners on the critical buckling levels was outlined in detail. Ueda et al. [15] investigated the behaviour of stiffened flat rectangular plates with the stiffeners employed in the longitudinal direction. The stiffened plates were subjected to combined biaxial compression and shear loading and appropriate interaction expressions were developed to describe the buckling and ultimate capacity of the plates under the combined loading.

Lee et al. [16] have investigated the behaviour of transverse stiffeners attached to shear web panels through a three-dimensional nonlinear finite element analysis. It was found from this work that the intermediate transverse stiffeners attached on shear web panels are not necessarily subjected to axial compression in the postbuckling range of behaviour, and as a result, it was suggested by these researchers that the requirement for minimum stiffener areas in current design specifications could be relaxed or eliminated. Lee et al. [17] conducted an experiment in order to investigate the behaviour of the intermediate transverse stiffeners during postbuckling. The test results confirmed their earlier findings [16] and a new design rule for the sizing of the transverse stiffeners was formulated through extensive nonlinear finite element analysis data verified by test results.

Having confirmed that the Basler [8] equation gives a close estimate of the force in a rigid stiffener, Xie and Chapman [18] used this as a basis to develop a design formula for predicting the axial forces in actual stiffeners with a finite axial rigidity. This was achieved by incorporating coefficients which were determined by means of non-linear finite element results produced using the general-purpose FE program abaqus. The non-deflecting stiffener model with finite axial rigidity is shown in this work to provide a sufficiently accurate estimation of the axial force in a real stiffener.

A computational model for the analysis of the global buckling and post-buckling of stiffened panels has been derived by Byklum et al. [19]. The model is formulated using large deflection plate theory and energy principles. The procedure is semi-analytical in nature and any combination of biaxial in-plane compression or tension, shear, and lateral pressure may be analysed. The load–deflection curves produced by the proposed model are compared with results from nonlinear finite element and good correspondence is illustrated.

Alinia [20] used the finite element method to study the buckling performance of stiffened plates subjected to in-plane shear loading with a particular emphasis on the optimal aspects of the stiffener design. This work concluded that to achieve optimum panel designs, the optimal flexural stiffness ratio of the stiffener to the plate corresponds to the point where the buckling mode changes from overall buckling to local buckling. It was also suggested that the number of panels produced due to the utilisation of intermediate stiffeners should not be less than the overall aspect ratio of the plate.

Murphy et al. [21] have demonstrated that using a commercial implicit code, the finite element method can be used successfully to model the post-buckling behaviour of flat aircraft riveted panels subjected to shear loading. This work develops appropriate modelling procedures for the flat riveted panels investigating element selection, mesh density idealisation and material modelling selection, with the obtained results being validated against mechanical tests. The work has also generated a series of guidelines for the non-linear computational analysis of flat riveted panels subjected to uniform shear loading.

Featherston et al. [22] carried out an experiment to examine the buckling and postbuckling behaviour of a stiffened panel loaded in-plane to produce a combination of shear, compressive and in-plane bending stresses. Of particular interest was the transfer of load from the plates, constituting this panel, into the stiffeners at higher loads. The stiffened panel structure was seen to behave in a stable manner in the postbuckling period and was shown to be capable of supporting loads in excess of four times the initial buckling load. A relatively simple nonlinear finite element analysis was shown to accurately predict this behaviour at up to twice the initial buckling load.

Alinia and Shirazi [23] proposed design formulations by presenting a parametric study to evaluate the optimal dimensions of single sided flat stiffeners utilised in steel plate shear walls. By carrying out finite element analysis it was observed that there exists a certain relation between optimal thickness, height of the stiffener and plate dimensions. It was also illustrated with the help of nonlinear analysis that the post buckled reserved remained almost the same for various optimal dimensions of stiffeners.

In this paper the work presented is, essentially, that of numerical simulation with the view to developing accurate and reliable modelling strategies and solution procedures, which will provide an in-depth understanding of the complex failure mechanics of stiffened shear webs. Results are presented in the paper for the case of stiffeners with less than the critical rigidity required to hold the stiffener line as a nodal line in the buckling mode and