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Effect of curvature and aspect ratio on shear resistance of unstiffened plates

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ABSTRACT

In order to investigate the effects of aspect ratio, curvature, and slenderness on the shear behavior of flat and curved plates, a parametric study is conducted. The simulations were performed by ABAQUS software. Theoretical relations were used to verify the validity of the out-coming numerical results. Comparing the results obtained from the FEM analysis with those from AASHTO, it is observed that the AASHTO shear strength of plates with aspect ratios less than 1.71 is non-conservatively more than the FEM results. For instance, in a flat plate with an aspect ratio of one, the difference between these two values is close to 8%. On the contrary, as the aspect ratio increases, the values of shear strength obtained from AASHTO are less than those derived from FEM. The difference of these two values reaches up to 11% in the case of plates with larger values of curvature. This study reveals that the curvature is a parameter which severely affects the shear behavior of plates. It is suggested that for a proper estimation of the elastic shear behavior of curved plates, this parameter must be taken into account. It is also observed that decreasing the slenderness results in lower effect of the curvature on the shear strength. Unlike the elastic range, in the plastic range of slenderness parameter, the shear strength of flat and curved plates could be considered equal.

1. Introduction

1.1. Background

Steel plates are widely used in engineering structures. Plate girders, gas and liquid containment structures, shelters, offshore structures, vessel fuselages, slabs, and steel plate shear walls are examples of engineering usage of such elements. On the other hand, there are some situations that curved plates are preferred to flat plates. For example need to smooth traffic transferring and restrictions on a straight path, along with the economic, environmental, and aesthetic considerations have resulted in wide use of curved plates for bridges [1]. Therefore, understanding the shear behavior of flat and curved steel plates has been the focus of many studies for several decades and much progress has been made in this field.

1.2. Literature review

In spite of extensive literature devoted to this field, the complexity of shear behavior, arising from the interaction of geometrical buckling and material yielding, has not been solved yet. An unstiffened slender plate buckles elastically at early stages of loading and it experiences geometrical and material nonlinearities during its postbuckling behavior [2]. On the other hand, a thick plate yields before buckling. Therefore, no postbuckling capacity is expected for a thick plate. For intermediate thicknesses, there are nearly simultaneous material yielding and geometrical instability [3]. Various parameters affect the buckling behavior of the plates. Some of these parameters are: material properties, loading and boundary conditions, aspect ratio, curvature, initial imperfections, and slenderness of plates. Accordingly, during the past century, a lot of research dealt with evaluating these parameters. With regard to this, studies on the shear buckling behavior of plates may be categorized in the following three areas: flat plates, curved plates, and imperfection sensitivity studies.

1.2.1. Studies on shear behavior of flat plates

Elastic buckling load of unstiffened flat plates was first studied by Bryan [4]. During the past century, buckling and postbuckling behavior of slender shear plates has been extensively studied and well documented. Timoshenko [5] utilized the energy method to study buckling of rectangular plates under the action of in-plane shear stresses. He only considered the symmetrical buckling mode. This limitation led to an error in the prediction of critical stresses where antisymmetric buckling was the governing mode. It must be noted that if the number of out-of-plane peaks is even, buckling is called antisymmetric and if the number is odd, it is called symmetric. Stein and Neff [6] considered both symmetric and antisymmetric buckling modes. Bediansky and Connor [7] applied the Lagrangian multiplier method and to compute both the upper and lower limits of the theoretical shear

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buckling stress for clamped rectangular plates. Allen and Bulson [8] published these works in a comprehensive review on the background to buckling.

Alinia et al. [2] used elasto-plastic large deformation finite element analysis to describe the postbuckling behavior of slender shear panels. They concluded that the buckling behavior of shear plates can be summarized as follows: 1) material yielding starts on one face before the other one; but at the ultimate load, both faces have full yield bands, 2) a large portion of the postbuckling behavior of slender shear panels is governed by geometrical nonlinearity; while material nonlinearity activates only in the final stages, 3) support conditions have no significant effect on the through the thickness bending stresses and yield pattern of panels, and 4) the membrane action in a plate decreases with the increase in the thickness of the plate, while bending action increases [9–11]. The plastic buckling behavior of thick plates has been studied by several investigators (e.g. Gerard [12], Stowell [13] and Bijlaard [14]). Bleich [15] proposed a simplified theory to present the elasto-plastic buckling behavior of plates which seemed to be in close agreement with experimental results. Aspects of post-bifurcation behavior and imperfection-sensitivity on the plastic buckling of structures were investigated by Hutchinson [16].

1.2.2. Studies on shear behavior of curved plates

As mentioned above, the buckling and postbuckling behavior of slender flat plates has been extensively studied. However, owing to the nonexistence of simple trigonometric shape functions for shear buckling modes of curved plates, it is more difficult to calculate their theoretical buckling loads [17]. One of the earliest studies on the buckling behavior of a long, slightly curved plate under uniform shear stress was made by Leggett in 1937 [18]. Reconsidering large curvature panels, Kromm published the results of his studies in 1939 [19]. In the two aforementioned studies, the longitudinal edges were assumed to be simply supported. Allowing tangential displacements normal to simple edges, the calculated buckling stresses in [19] became less than those found by Leggett. The difference between these two results increases with increasing the curvature parameter.

Real plates are not perfect, but have some initial imperfections like deviations from nominal geometric parameters, load eccentricities or variations in material properties and other irregularities [20]. Nowadays, the deterministic design of shells and shell-like structures is essentially based on one of the following two approaches: 1) classical critical load (bifurcation) analysis combined with empirical known factors [21], which represents lower bounds to the available experimental data, and 2) numerical simulation by finite element analysis [22]. Several numerical investigations were conducted to find the maximum supported load up to the onset of buckling and to relate the buckling strength to the magnitude and form of initial imperfections [20,23,24]. Two early theoretical studies on the effect of initial imperfections on the buckling load of curved plates was made by Koiter in 1945 [25] and by Donnell and Wan in 1950 [26]. In addition, a large number of other numerical investigations were conducted to find the minimum supported load in the postbuckling range [22,27,28].

Investigation on the behavior of cylindrical shell tubes is another field of research on the curved plate shear buckling. In a tube with uniform wall thickness, torsion induces uniform shear stresses. Studies in this field are categorized in two experimental and theoretical researches. The early experimental researches were done to determine experimental elastic buckling loads of thin-walled cylindrical shells and to check the theoretical results (Donnell 1933 [29]). Later, experiments with a special focus on the whole load-deflection path were conducted by Lundquist 1932 [30]; Nash 1957 [31]; Yamaki 1976 [32]. The first approximate theoretical solution was obtained by Donnell 1933 [29]. More accurate ones can be found in some other researches such as Timoshenko 1936 [33], Batdorf 1947 [34], and Flügge 1973 [35]. A detailed overview is given by Yamaki 1984 [36].

1.2.3. Imperfection sensitivity studies

Initial imperfections, such as deviation from nominal geometric dimensions, load eccentricity and variations in material properties are inevitable in steel structures. Interest in the influence of imperfections on structures was stimulated in the 1960s realizing that they had a significant impact on the computation of buckling loads [37]. In 1945, Koiter [27] developed a general theory for the initial postbuckling behavior of elastic systems. The theory presents an approximate sensitivity law which estimates the reduced buckling load due to small shape imperfections. In 1970, Koiter's law was implemented to find the maximum supported load up to the onset of buckling and to relate the buckling strength to the magnitude and shape of initial imperfections [23]. A nearly theoretical study on the effect of initial imperfections on the buckling load was then proposed in 1976 [27].

Two commonly used techniques to model imperfection distributions are: 1) adopting a sinusoidal wave, and 2) using one of the eigenmodes obtained from elastic buckling analysis [38]. Usually, the first eigenmode with the amplitude based on the considerations of fabrication procedures provides with a good simulation for imperfections [22]. Featherston [20] studied the effects of different imperfection shapes and amplitudes on the buckling and postbuckling behavior of flat panels under combined compression and shear. It was shown that initial imperfection has a significant effect on the buckling load of curved plates under compression. Maiorana et al. [39] studied stability of imperfect web plates subjected to patch loads and concluded that their first eigenmode can be assumed as the initial configuration in the postbuckling behavior studies. It was shown that, if the curvature is low, buckling behavior of curved panels under shear is fairly similar to flat plates; thus, for low curvature panels also, it is sufficient to use initial imperfections based on only the first eigenmode shape [40]. In 1972, Hutchinson [41] investigated the postbuckling behavior of structures undergoing plastic deformations and he pointed out the importance of imperfections in plastic buckling. Using sinusoidal initial imperfections, Ikeda et al. [42], in 2007, studied the behavior of imperfect flat plate under compression. Various tolerances for the amplitude of imperfections are suggested in the existing specification codes based on different experiences. EN 1993-1-5 [43] recommends to use imperfections based on the critical plate buckling mode and the maximum amplitude of 0.005 times the smaller dimension of the panel. The maximum imperfection amplitude can also be taken as a fraction of the plate thickness. Carlsen and Czujko [44] and Antoniou [45] suggested relationships for estimating the maximum probable imperfection amplitude of plates in terms of both their widths and thicknesses.

1.3. Aims and scopes

Increasingly use of curved plates has increased the need to more in-depth research on the shear behavior of these plates. According to the literature, it can be seen that most of researches on the shear behavior of plates are one-parametric study. So, conducting a comprehensive study which considers the effect of all effective parameters on the elastic and plastic shear buckling behavior is necessary. Consequently, in this study, considering the aspect ratio, common values of curvature and slenderness, FEM models for parametric study have been constructed. Using these models, the effect of the above mentioned parameters on the elastic shear buckling strength and shear strength of plates have been studied.

2. Method of study

2.1. Details and geometric properties of models

In order to investigate the research objectives, 156 rectangular plates were considered. The models include 13 different thicknesses of 6 to 30 mm, three curvature radiuses of 30, 60, and ∞ m, and four aspect