Engineering Structures 59 (2014) 127–140

Contents lists available at ScienceDirect

Engineering Structures

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

Buckling analysis of simply supported flat glass panels subjected to combined in-plane uniaxial compressive and edgewise shear loads

Chiara Bedon *, Claudio Amadio

University of Trieste, Department of Engineering and Architecture, Piazzale Europa 1, 34127 Trieste, Italy

ARTICLE INFO

Article history:
Received 19 June 2013
Revised 13 October 2013
Accepted 23 October 2013
Available online 26 November 2013

Keywords:
Simply supported flat glass panels
Uniaxial in-plane compression
In-plane shear
Normalized interaction resistant domain
Imperfection shape
Buckling verification approach

ABSTRACT

Glass panels are widely used in modern architectures in the form of stiffeners and load-carrying elements. The frequent use of structural glass and the lack of standardized rules for designers gradually increased the interesting of scientists and researchers in the analysis of structural behaviors associated to various combinations of boundary and loading conditions. Buckling failure certainly represents one of the most crucial condition of collapse. In the paper, particular attention is dedicated to the buckling response of simply supported glass panels subjected to combined in-plane compressive and shearing forces. Based on large series of numerical incremental simulations, the effects of loading ratios, imperfection shapes, slenderness ratios and glass types on their buckling response are investigated. At last, based on analytical interaction formulations of literature, a normalized domain is proposed for their stability check.

1. Introduction

Glass structural elements are widely used in modern architectures, in the form of stiffeners, fins or as a part of roofs, domes, and façades. Glass panels, in particular, are largely used in conjunction with steel or other bearing structures for the realization of large transparent surfaces and lightening spaces. Depending on the loading and boundary conditions of these brittle innovative elements, particular attention should be dedicated to their analysis and dimensioning.

Because of this reason, numerous authors recently focused on the advanced structural analysis of monolithic or laminated glass columns, beams, plates in various boundary and loading scenarios. Recent examples are given in [1–4] respectively for laminated glass beams in lateral–torsional buckling, rectangular/T/X shaped laminated glass columns, hybrid SG-laminated reinforced glass beams in bending, point-supported laminated glass panels under uniform wind pressure.

In any case, buckling represents one of the most crucial conditions of failure. In this work, specific attention is dedicated to the buckling analysis of simply supported glass panels subjected to interacting in-plane compressive and shear loads. As known, this multiple loading condition is quite frequent in structural applications of plates composed of various construction materials. Nevertheless, due to a combination of geometrical and mechanical aspects, it is difficult to be correctly described and predicted.

Interesting analytical calculations and interaction resisting domains for hypersonic aircraft sandwich panels under combined compressive and shear buckling loads are discussed in [5]. Sinur et al. [6] recently focused on the experimental and numerical buckling analysis of steel slender plates subjected to combined bending-shear loads. In their work, investigations were dedicated to thin walled plates commonly used in the construction of bridge girders. Chirica and Beznea [7] studied the effects of multiple delaminations on the buckling response of composite plates affected by combined axial compression and shear. In this specific case investigations were performed, for well-defined combinations of delaminations and loading ratios, on fiber-reinforced panels of ship hulls. As a result, detailed experimental analyses and numerical simulations were performed on various orthotropic panels. Paik [8] focused on the ultimate strength of perforated steel plates subjected to interacting biaxial compressive loads and edge shear loads. Numerical simulations were carried out on various steel plates and closed-form empirical formulae were proposed for a rational prediction of their ultimate buckling strength. The geometrically nonlinear post-buckling behavior of orthotropic laminated panels subjected to combined in-plane shear loads, compression and lateral loading was investigated in [9]. The effects of fiber orientations, number of layers, loading ratios were deeply investigated by means of large series of finite elements analysis based on the Element-based Lagrangian formulation. Also Wang et al. [10] focused on the post-buckling behavior of rectangular

* Corresponding author. Tel.: +39 040 558 3842.
E-mail addresses: bedon@dicar.units.it, c.bedon@libero.it (C. Bedon).

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http://dx.doi.org/10.1016/j.engstruct.2013.10.034

aerospace plates under combined uniaxial and shear stresses. Although their paper focuses on the plastic post-critical response of metal plates, thus characterized by large membrane post-yielding strength effects not typical of brittle glass panels, interesting resisting interaction curves for simply supported Mindlin plates of various geometrical properties were obtained by means of the classical Ritz method.

In the specific field of flat glass panels subjected to in-plane loads, various scientific contributions can be found in literature, but they generally focus on basic and well-defined loading/boundary conditions. Laufs and Mohren [11], for example, focused on the design calculation of constructions composed of steel bearing frames and filling glass panels, investigating the shear-stiffening capabilities of glass plates subjected to diagonal in-plane compression. Luible [12] and Englhardt [13,14] studied the buckling response of monolithic and laminated glass panels simply supported along the four edges and subjected to in-plane axial compressive loads. In both these contributions, based on the Limit State design method, a design approach was proposed for the prevention of their buckling collapse. Englhardt, in particular, suggested a double verification criterion for the stability check of glass panels, based on a maximum stress check as well as on a deformability check of plated glass elements.

In Bedon and Amadio [15], an equivalent thickness formulation has been recently proposed for the buckling analysis of geometrically imperfect laminated glass panels in various boundary conditions, subjected to in-plane axial compressive loads. Based on buckling verification criteria available in literature for structural elements composed of traditional construction materials [16], an Eurocode-based buckling curve, appropriately calibrated to numerical and experimental predictions [12–14], has then been proposed in [17] for the stability check of axially compressed glass panels affected by initial geometrical imperfections. Wellershoff [18] investigated the structural behavior of glass panels subjected to in-plane shear loads, focusing on the shear buckling failure of circumferentially glued glass plates. Mocibob [20] studied the specific load-carrying behavior of glass panels under shear loads and continuously or pointy supported along two edges. Based on extended experimental and numerical predictions, he highlighted the effects of shape/amplitude of initial geometrical imperfections on the load out-of-plane response of monolithic and laminated glass panels under pure shearing forces. In [21], an equivalent thickness approach has been proposed for the buckling analysis of simply supported laminated glass panels subjected to in-plane shear loads.

Although scientific researches for glass panels are numerous, the typical buckling response of glass panels under in-plane loads represents a topic not totally well known. In addition, the large request of glass components in structural applications requires more and more investigations and knowledge.

Because of this reason, in this paper results of a detailed numerical investigation performed with the ABAQUS/Standard computer package [22] on glass panels simply supported along the four edges, affected by initial geometrical imperfections and subjected to interacting in-plane compressive/shear loads are discussed. The effects of various geometrical defects, aspect ratios, loading ratios and normalized slendernesses on their structural behavior are highlighted. Based on a very recent contribution [23], particular attention is dedicated to the shape of the assumed imperfection. As shown, the combination of multiple mechanical and geometrical aspects can manifest in quite different buckling responses. Nevertheless, based on collected results, a normalized interaction resistant domain, well agreeing also with approximate analytical formulations of literature [29–33], can be obtained for a rational buckling verification of generic simply supported glass panels under combined in-plane compressive and shear stresses.

2. Buckling analysis of flat glass panels under in-plane loads

Flat glass elements are widely used in practice for the construction of architectural solutions based on the high esthetic potentiality of this relatively innovative structural material. Frequent applications can be found, for example, in domes, roofs, façades or composite glass–steel frameworks, where glass interacts with steel bearing systems and enables the development of transparent fascinating surfaces. Depending on the specific application, however, the use of glass elements such as plates, membranes, bracing members is directly connected to the occurring of “basic” or “combined” in-plane loads in them. Typical examples include simply supported glass panels subjected to simple loading conditions such as uniaxial in-plane compression, in-plane shear, as well as multiple interacting loads, such as in-plane shear and orthogonal distributed pressures, uniaxial in-plane compression and in-plane shear, biaxial in-plane compression.

In this work, results of numerical investigations proposed in a previous contributions for the buckling analysis of glass panels subjected to pure in-plane uniaxial compression or pure in-plane shear are firstly recalled [15,17]. Subsequently, the buckling response of simply supported glass panels subjected to combined in-plane compressive/shear loads is deeply investigated and a possible non-dimensional resisting domain is proposed, as discussed in detail in the following sections.

2.1. Simply supported glass panels under in-plane uniaxial compression

Let us consider the $a \times b$, t-thick monolithic glass panel depicted in Fig. 1. The panel is supposed to be simply supported along the four edges and subjected to a uniformly distributed, in-plane uniaxial compressive load N_y (force per unit of length).

As recently recalled in [15], its buckling analysis can be performed by means of classical analytical models based on the linear elastic bending theory of flat homogeneous isotropic plates [24].

If the modal shape of the panel is supposed described by m and n half-sine waves along y and x-directions, respectively, and its aspect ratio α is defined as $\alpha = a/b$, the critical buckling load $N_{y,cr}^{(E)}$ can be expressed as:

$$N_{y,cr}^{(E)} = \left(\frac{m}{\alpha} + \frac{\alpha}{m}\right)^2 \frac{\pi^2 D}{b^2} = k_\sigma \frac{\pi^2 D}{b^2}, \qquad (1)$$

with:

$$k_\sigma = \begin{cases} \left(\frac{1}{\alpha} + \alpha\right)^2 & \text{if} \quad \alpha < 1 \\ \cong 4.00 & \text{if} \quad \alpha \geqslant 1 \end{cases}, \qquad (2)$$

a buckling coefficient able to minimize $N_{y,cr}^{(E)}$ (Eq. (1)); $D = Et^3/12(1 - \nu^2)$ the bending stiffness of the panel (unit of length); E, ν the Young’s modulus and the Poisson’s ratio of glass.

As known, the critical buckling load represents an interesting information for the estimation of the buckling strength of the panel. Nevertheless, due to the over-strengthening effects due to the typical post-buckling membrane effects, it does not express at best its real ultimate strength.

As a result, in order to check the stability of an in-plane compressed glass panel, multiple conditions should be verified simultaneously to prevent a possible buckling failure. First, a rational buckling verification should take into account the possible effects of load or boundary eccentricities, as well as the presence of possible production imperfections and residual stresses. As suggested by Englhardt [13,14], based on large experimental and numerical investigations performed on in-plane compressed simply supported glass panels, this effects can be rationally taken into