Engineering Structures 133 (2017) 14–23

Contents lists available at ScienceDirect

Engineering Structures

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

Investigation on flexural buckling of laminated glass columns under axial compression

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ARTICLE INFO

Article history:
Received 3 August 2016
Revised 1 December 2016
Accepted 6 December 2016

Keywords:
Laminated glass
Multi-layered
Buckling
Axial compression
Initial geometrical imperfection
Design buckling curve

ABSTRACT

Due to its relatively good safety performance and aesthetic benefits, laminated glass (LG) is increasingly being used as load-carrying members in modern buildings. This paper presents a study into one application scenario of structural LG subjected to axial compression. The aim of the study is to reveal the flexural buckling behavior of the LG columns made up of multi-layered annealed glass plies. The LG specimens respectively consisted of two, three and four plies of annealed glass, bonded together by two prominent types of adhesives. To reach the research aim, both full-scale tests and nonlinear numerical simulations were carried out. Based on the test and numerical results, the influences of interlayer type, laminate number, load duration and ambient temperature on the buckling resistance of the LG columns were studied in detail. In addition, the applicability of the so-called Southwell plot method for LG columns was examined and discussed. Subsequently a characteristic initial geometrical imperfection for LG columns made of annealed glass was suggested. Finally design buckling curves were proposed for LG columns carrying axial loads with the various durations in various ambient temperatures. The results obtained are expected to provide supplementary information that is currently lacking in existing literature.

1. Introduction

Laminated glass (LG) consists of two or more glass plies bonded together by elastomeric interlayer materials, and is widely applied in modern buildings thanks to its good safety and security performance. In recent years, the role of architectural LG has been gradually extended from secondary elements (e.g. windows and barriers) to more important load-carrying members in aesthetically demanding buildings [1–3].

As has been known, the compressive strength of glass is almost higher than that of all other building materials including steel and concrete [4]. This benefit allows the LG suitable to be employed as columns carrying compressive loads. LG columns used in practice are usually manufactured from narrow glass plies, so their slenderness about weak bending axis is normally high. This characteristic makes LG columns prone to flexural buckling. Over the past few years, some literature has been available on the buckling performance of LG columns in terms of critical buckling loads [5–7], sizes and shapes of initial geometrical imperfections [8], and buckling resistances [9–15]. However these available investigations were mostly focused on the LG columns made up of two glass plies.

In engineering practice, LG with thick or deep section is often required in circumstances where relatively heavy loads are imposed on. Since an individual glass ply is usually manufactured in standard thicknesses of between 2 and 19 mm [4], LG carrying heavy loads normally consists of multi-layered glass plies, e.g. three glass plies or more. Moreover, due to the brittle nature of glass, in addition to adequate resistance under the ultimate limit design scenario, load-carrying LG must also have sufficient redundancy so that if some glass panes are broken by accidental actions (such as impacting and scratching), the remaining glass panes can still have adequate strength to carry applied loads [16]. From this point of view LG made up of multi-layered glass plies is also preferable because of good redundancy it possesses in surviving the accidental design scenarios. Machado-e-Costa et al. and Huang et al. [17,18] have studied the structural behaviors of multi-layered LG beams subjected to in-plane bending.

This paper reports a series of experimental and numerical studies for the flexural buckling behavior of multi-layered LG columns subjected to axial compression. The investigated LG samples are respectively made up of two, three and four plies of annealed glass. The adopted interlayer materials are SentryGlas® Plus (SGP) and

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http://dx.doi.org/10.1016/j.engstruct.2016.12.006
0141-0296/

polyvinyl butyral (PVB), which are commonly used in practice [19]. The LG column specimens are pinned at two ends and have slenderness ratios ranging from 0.65 to 3.7. The buckling resistance of the LG specimens is studied in detail, whilst considering the influence of interlayer type, laminate number, load duration and ambient temperature. Also investigated are the initial geometrical imperfections of the LG columns. Based on the experimental and numerical results, design buckling curves are calibrated and proposed for the LG columns sustaining axial compressive loads with various durations in various ambient temperatures.

2. Test program

The experimental program comprised a total of 21 full-scale tests conducted in the State Key Laboratory of Building Safety and Environment at China Academy of Building Research.

2.1. Specimens

An overview of the test specimens is presented in Table 1. The test specimens were labeled in an order indicating the loading condition (compression), number and type of interlayer, and section thickness of the specimen. It is worth noting that the section thickness in this paper refers to the total nominal glass thickness (excluding the thickness of interlayer). The LG specimens consisted of annealed float glass plies laminated together by SGP or PVB interlayer. All of the LG specimens had a constant effective length of 2700 mm and a constant section depth of 300 mm. The SGP LG specimens were of three different section thicknesses, i.e. 24 mm, 32 mm and 40 mm. The PVB LG specimens were of two different section thicknesses, i.e. 24 mm and 40 mm. The nominal thickness of individual glass ply making up each LG specimen is illustrated in Table 1. The individual nominal thicknesses of the SGP and PVB interlayer were 1.78 mm and 1.52 mm, respectively. The edges of the LG specimens were all fine polished to minimize flaws.

2.2. Test set-up

The LG specimens were tested under axial compression. A schematic diagram of the test setup is shown in Fig. 1. At each end the LG specimen was contained in a steel channel having convex half round. The steel channel was fit into a steel plate having concave half round. Thus the boundary condition of pinned-end joint was constructed for the LG specimen. Loads were introduced by a 30 T hydraulic jack. At the loading point, a ball hinge was used between the loading jack and the steel plate to ensure that the load was applied at the center of the LG specimen. Nylon strips with a thickness of 2 mm were used as cushions between the steel and the glass to prevent high stress concentration in the glass.

2.3. Test instrumentation and procedure

Data acquired from the tests consisted of applied loads, displacement and elastic strains of the LG specimens. These data were measured by a load cell, four LVDTs and a number of strain gauges. Two two-dimensional (capable of simultaneously measuring horizontal and vertical displacement of a given point) LVDTs were placed at the mid-span of the LG specimens. The other two one-dimensional LVDTs were placed on the steel channel at the loading end. The accuracies of the load cell and the LVDTs were 0.1 kN and 0.01 mm. Three one-way strain gauges were attached along the longitudinal direction on each face of the LG specimen at the mid-span. The strain gauges were foil type with sensitivity of 2.18 ± 1%. The testing data were obtained at a rate of one measurement per second. The testing was continued beyond the peak load until the LG specimens fractured. The loading jack moved approximately at a rate of 0.15 mm/min before glass breakage occurred.

3. Test results

Table 2 presents the results in terms of the average measured section thickness (t), section depth (h), failure stress (σ_{failure}), buckling resistance (P_{Rd}), load duration and ambient temperature during testing for each specimen. The measurements of the section thickness and depth were made at the mid-height, quarter-heights, and ends of the specimen. The values of σ_{failure} were determined by multiplying the measured tensile strains at fracture with the Young's modulus (70,000 N/mm^2) of the glass. The buckling resistance referred to the load level at which glass fracture occurred.

The tests were carried out in room temperatures ranging from 18.0 °C to 22.9 °C. For the SGP LG specimens the mean testing duration was 16 min 50 s, and for the PVB LG specimens the mean testing duration was 11 min 55 s.

The curves of applied loads against corresponding mid-height lateral displacement of the LG specimens were plotted and presented in Fig. 2. They were grouped into five graphs according to the nominal section thickness and type of interlayer. As can be seen from Fig. 2(a)–(e), the load-lateral displacement curves of the LG specimens are all characterized by a load-ascending stage and a load-platform stage. In the first stage the applied loads incrementally increase with the displacement, while in the second stage a large increase in displacement only results in a small change in load level. This characteristic indicates that all of the LG specimens lost load-carrying capacities due to buckling. It may be also observed from Fig. 2 that the load-displacement responses of two nominally identical specimens are somewhat different in some cases, such as C-1SG-24-1 and C-1SG-24-2. Since all the specimens were manufactured, delivered, installed and tested in the same fashion, such a variation may indicate that the load-displacement

Table 1
Overview of test specimens.

Specimens	Interlayer material	Interlayer thickness (mm)	Glass thickness (mm)	Number of specimens
C-1SG-24	SGP	1.78	12 + 12	2
C-2SG-24	SGP	1.78 × 2	8 + 8 + 8	2
C-3SG-24	SGP	1.78 × 3	6 + 6 + 6 + 6	2
C-1SG-32	SGP	1.78	16 + 16	1
C-2SG-32	SGP	1.78 × 2	10 + 12 + 10	2
C-3SG-32	SGP	1.78 × 3	8 + 8 + 8 + 8	2
C-2SG-40	SGP	1.78 × 2	12 + 16 + 12	2
C-3SG-40	SGP	1.78 × 3	10 + 10 + 10 + 10	2
C-1PVB-24	PVB	1.52	12 + 12	2
C-3PVB-24	PVB	1.52 × 3	6 + 6 + 6 + 6	1
C-2PVB-40	PVB	1.52 × 2	12 + 16 + 12	1
C-3PVB-40	PVB	1.52 × 3	10 + 10 + 10 + 10	2