Engineering Structures 117 (2016) 575–590

Contents lists available at ScienceDirect

Engineering Structures

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

The mechanical response of cold bent monolithic glass plates during the bending process

Kyriaki Corinna Datsiou *, Mauro Overend

Glass and Façade Technology Research Group, Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK

ARTICLE INFO

Article history:
Received 11 September 2015
Revised 19 February 2016
Accepted 7 March 2016
Available online 28 March 2016

Keywords:
Cold bending
Monolithic curved glass
Anticlastic surface
Optical quality
Cold bending distortion
Plate instability
Snap-through buckling

ABSTRACT

Cold bending of glass involves the straining of relatively thin glass components, (typically plates), at ambient temperatures, and is a low energy and cost effective manner of creating curvilinear forms required in modern glass applications. Cold bending is also popular because it is thought to eliminate the optical imperfections in curved glass plates that arise during alternative and more conventional thermal bending techniques. Experimental and numerical investigations on the cold bending of monolithic glass plates into anticlastic shapes are undertaken and described in this paper. The aim is to characterise the cold bending behaviour during the bending process and to evaluate the surface/optical quality of the curved plates. Two distinct phenomena of interest are observed: (i) a change in the deformation mode that under particular boundary and loading conditions lead to snap-through buckling and; (ii) a local instability termed "cold bending distortion" that appears on curved plates when certain applied displacement limits are exceeded. This cold bending distortion is found to occur at stresses significantly below the fracture strength of the glass plate, but the distortions can be sufficiently large to breach optical serviceability requirements. An optical quality evaluation procedure for predicting the cold bending response and the resulting optical quality of monolithic glass plates are provided at the end of this paper.

1. Introduction

The demand for flat glass is high and increasing significantly. Since 2009 float glass production has increased by 5% per annum to meet this demand. The building industry has by far the largest share of this market, and accounts for around 80% of all the flat glass produced [1]. This increase is a direct result of the recent architectural requirements for additional lightness, transparency and natural light in new buildings, leading to an increased demand for larger glass panels. In addition, architectural trends increasingly require the use of glass in curvilinear forms to produce smooth free-form facades [2]. The processes available for producing curved glass can be divided in two categories based on whether heat is involved in the process.

Static mould bending and roller bending are the two most common techniques used to create curved glass and involve heating the glass above the transition temperature (550 °C), so that it becomes viscous. In the static mould bending method (also known as sag bending), the desired curvature of the glass is obtained by allowing the heated flat plate to sag under its self-weight, onto a mould. However, different moulds are required for plates of different curvature therefore, this method is neither energy nor cost efficient. Furthermore, the optical quality of the curved glass plate is very sensitive to imperfections in the mould. An alternative technique that also requires the glass to be heated above its transition temperature is roller bending which can be performed either horizontally or by vertical toughening bending. The former is performed in a horizontal bending toughener during the toughening process of glass; wherein adjustable tilting rollers are used to form the desired shape of the heated glass plate. The glass is then submitted to jets of cold air to create the favourable residual stress profile of toughened glass. On the other hand, in vertical toughening bending, the glass is lowered into the furnace in a vertical position and is pressed onto the mould before being toughened. Roller bending methods therefore have adjustable and re-usable "moulds", but the optical quality of the glass plate is affected by the straightness of the rollers, their position relative to one another and more commonly by roller wave distortion.

The optical quality of glass can be assessed qualitatively with the use of a zebra board plate (consisting of black and white stripes). The waviness of the reflected image on the surface of the glass plate is used to assess whether the level of distortion is acceptable. However, this method is subjective as it relies on the experience of the inspector. More recent quantitative methods

---

* Corresponding author.
E-mail address: kd365@cam.ac.uk (K.C. Datsiou).

http://dx.doi.org/10.1016/j.engstruct.2016.03.019
0141-0296/

include: (i) in-contact with the glass gauges (flat bottom or 3-way-contact gauge) that are conveyed along the direction of the distortion while measuring peak to valley height [3,4]; (ii) non-contact distortion measuring systems involving the use of computer vision and high-resolution cameras [5]. Recommendations such as those set in EN 12150-1:2000 [3] are often used to determine whether the optical quality of the curved plate is acceptable. These limit the amplitude of the roller wave distortion in fully toughened glass to 0.5 mm over a length of 300 mm [5]. It is currently, possible to manufacture toughened glass with significantly smaller roller wave distortion amplitudes. In fact, a limit of 0.25 mm is often prescribed for high-end applications. More information on these thermal bending methods can be found in [6–11].

Cold bending is an alternative, and relatively recent, technique of creating curved glass plates. During this process, the curvature is induced elastically at ambient conditions with a relatively small amount of equipment, thereby, making the process energy efficient and also allowing the bending to be executed on site. Cold bent glass can be used to generate either single or doubly curved forms. Single curvature/developable glass surfaces are easier to form, but they are not as popular in architectural design as doubly curved glass provide a much larger architectural freedom and can be used to create smooth, free form, transparent facades. The glass panels of various curvatures that are required in this kind of applications can be cold bent in shape without any requirement for moulds, therefore, minimising their cost and making cold bending an attractive method of creating curved glass surfaces.

Cold bending involves the application of out-of-plane loads on the glass surface to create the desired shape of the glass plate, the plate is then restrained in its curved state by means of mechanical fixings or structural adhesives. The glass is therefore subjected to permanent bending stresses throughout its service life. Cold lamination bending [12,13] is another recent technique used to restrain the curved glass plate during the cold bending of laminated glass and involves: (i) bending the un-bonded unit of glass plates and interlayer(s) in the desired shape and; (ii) laminating the un-bonded bent unit in an autoclave. In this case, the interlayer preserves the shape of the glass in place though partially, since initial springback is expected when the restraints are removed after the lamination [12,13].

The relatively low strength of annealed glass makes it inappropriate for cold bending applications, as the radius of curvature that can safely be introduced in an annealed glass plate is generally too large to produce significant curvature in the glass plate. Therefore, toughened glass in the form of heat treated (heat strengthened or fully toughened) or chemically toughened glass is often used in such applications. The maximum curvature that can be achieved in cold bent glass has thus far been limited by the maximum surface stresses, generated during the cold bending process (σ_{cb}), that can be safely be resisted by the toughened glass panel throughout its service life:

$$\sigma_{\text{cb}} \leqslant \frac{\left(f_{\text{AN},d} - \frac{\sigma_{\text{RES}}}{\gamma_{M,\text{RES}}} - \sigma_{\text{app}} \cdot \gamma_{f,\text{app}}\right)}{\gamma_{f,\text{cb}}} \tag{1}$$

where $\left(f_{\text{AN},d} - \frac{\sigma_{\text{RES}}}{\gamma_{M,\text{RES}}}\right)$ is the design strength of toughened glass [14–16], which is the sum total of the design strength of annealed glass, $f_{\text{AN},d}$, and the design compressive residual surface stresses (negative sign) induced by the thermal/chemical toughening $\left(\frac{\sigma_{\text{RES}}}{\gamma_{M,\text{RES}}}\right)$; $\sigma_{\text{app}} \cdot \gamma_{f,\text{app}}$ is the maximum design stress on the surface of the glass induced by loads imposed on the glass during its service life and; $\gamma_{f,\text{cb}}$ is an appropriate safety factor to account for variability during the cold bending process.

Recent research [17] has also shown that there is a significant additional contribution to strength in heat treated glass attributable to crack healing, f_{Heal}, therefore, Eq. (1) becomes:

$$\sigma_{\text{cb}} \leqslant \frac{\left(f_{\text{AN},d} - \frac{\sigma_{\text{RES}}}{\gamma_{M,\text{RES}}} - \sigma_{\text{app}} \cdot \gamma_{f,\text{app}}\right)}{\gamma_{f,\text{cb}}} + f_{\text{Heal}} \tag{2}$$

There is a growing interest in cold bent glass [18–23] and cold bent glass has already been used in real world applications [24–27]. Two of the most notable examples of completed projects is the 125 m long glass shell of the Strasbourg TGV train station consisting of 6 mm heat-strengthened laminated plates and the glass roof of the Victoria and Albert museum in London that covers an area of 370 m^2 and consists of cold bent insulated glass units that are point fixed. Yet, to-date no guideline is available for its manufacture/design process.

Cold bending of glass may be an efficient method for creating curved glass surfaces, but the limited research conducted on cold bent monolithic glass plates to-date indicates that it can result in geometric instabilities [28–30]. Staaks and Eekhout [28,29] reported that the free edges of the glass plate change their shape from straight to curved during the cold bending process. Their bending process involved forcing two corners of the plate out-of-plane while the other two were point fixed (Fig. 1a), thereby creating a hyper surface. In particular, two deformation modes were reported. In the first deformation mode, both diagonals were curved and the edges preserved their initial straightness (Fig. 1b). However, when the out-of-plane displacement at the two corners exceeded 16 times the thickness of the plate, a change in the deformation mode was observed [29]; the plate buckled as one diagonal straightens and the edges become curved (Fig. 1c). This phenomenon is noteworthy because curved edges could result in difficulties when fixing the plate to the frame and/or aligning the edges of adjacent glass plates.

A simplified analytical model was also proposed by Eekhout and Staaks [28,29] to predict this buckling instability. The plate was considered as a system of two diagonal strips spanning between the corners of the plate and intersecting at the centre of the plate, and four rods, one along each of the four edges of the plate. By forcing two corners out of plane, bending increases in the diagonals while the rods connecting the corners are stretched creating an additional axial compression in the diagonals. A change in the deformation mode (instability) occurs when the critical Euler buckling stress is exceeded in one diagonal. However, Eekhout and Staaks were unable to obtain good agreement between their simplified analytical model and their numerical results.

This change of curvature has also been described by Galuppi et al. [30] as snap-through buckling. Snap-through buckling, in the case of a plate, is a sudden change of deformation in the direction of the load in the central regions of the plate. Their analytical

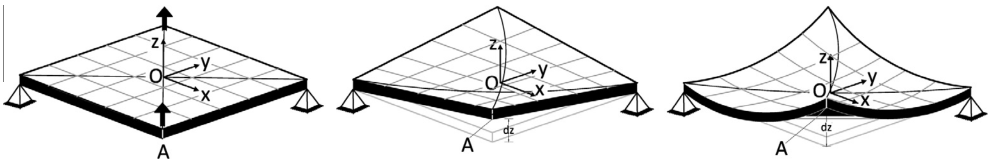

Fig. 1. Deformation modes during the cold bending process (a) undeformed; (b) mode 1 deformation; (c) mode 2 deformation (adapted from [29]).