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Buckling phenomena in double curved cold-bent glass

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ABSTRACT

Double curved anticlastic glazed surfaces are widely used for free-form façades and roofs of modern buildings. An effective technique consists in cold bending rectangular glass plies by twisting them with forces applied at the corners. The linear Kirchhoff–Love theory predicts that the deformed shape is a hyperbolic paraboloid, which preserves the straightness of the edges. However, experiments have provided evidence that a particular form of instability occurs above a certain limit of the distortion: one of the principal curvatures becomes dominant with respect to the other, the plate bulges into an asymmetric configuration and the edges are not any more straight. Here, a simple model is presented that, using a modified version of Mansfield's inextensional theory for thin plates, is able to interpret this phenomenon. Results are in good agreement with numerical experiments using large deflection theory. Moreover, the possibility of increasing the limit of the stable configuration by stiffening the edges is investigated.

1. Introduction

Curved glass is a powerful tool of aesthetic design for its transparency and capacity of diffusing the light and delimit a place without the barriers of a flat wall. Because of this, its use characterizes the most recent architectural trend towards twisted and free-form shaped surfaces. The number of constructions with transparent curved envelops is constantly increasing, including tall buildings, airports, exhibition areas, museums, concert halls and shopping arcades. In most applications, for safety reasons, glass has to be laminated with polymeric interlayers with a process at high pressure at temperature in an autoclave that produces a chemical bond between glass and polymer. Curving of laminated glass represents an additional difficulty, but its use is often imposed by building codes because, in case of rupture, the interlayer retains the glass shards avoiding major damage to property and human life. The difficulty increases even more so in the case of multiple-glazed envelopes, composed of several plies separated by spacers and glued at the borders, which are necessary to limit thermal loss and increase the energetic efficiency of the building. There is an increasing need for the massive production of curved panels for high-performance glazing, which represents the current challenge for both the industry and the designer.

Curved glass is traditionally produced through hot-forming processes. In *sag bending*, flat plates are placed on a negative curved mould and then heated up to a temperature at which glass softens and becomes plastic; the action of gravity produces the uniform contact with the support and, when glass is cooled down, it retains the shape of the mould. Another technique is *press bending*, where glass is formed by using a stainless steel mold face and head that presses the panel into the shape of the mold. In any case, the size of curved glass is limited by the size of the ovens, while every shape requires a dedicated mould, making this process attractive only for large quantities of *identical* panels. Moreover, glass cannot be hot-formed after lamination, because the polymeric interlayer cannot withstand the operating temperatures. Therefore, glass plies have to be hot-curved first and successively bonded together through the interlayer, but this process is not simple, requires very strict tolerances, and the greater encumbrance of the curved laminates with respect to the flat ones requires more space in the autoclave and, consequently, limits the production rate. In the case of multiple-glazed units, the bonding between the curved panels through the spaces requires even stricter tolerances and necessitates a special apparatus.

Cold bending of glass is a relative recent fabrication process. Flat glass panes are brought to the desired geometry by means of external contact forces, which hold the curved glass unit in the desired form. Consequently, glass can be curved directly at the construction site, holding it in place by clamping strips. This technique is increasingly developing because it has at least two major advantages. First, it does not need any negative template and, secondly, the degree of curvature can be easily modified through a slight variation of the constraining action. This allows for the construction, at relatively low cost, of curved free-form surfaces where all the glass panels may have slightly different geometries [1–3]. Moreover, the tolerances required to fit with the

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