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Optimal cold bending of laminated glass

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ABSTRACT

Cold-bending of laminated glass panels, by forcing their contact with a constraining frame, is a promising technique for free-form glazed surfaces. Their static state varies in time due to the viscosity of the polymeric interlayer, which causes the decay of the shear-coupling of the constituent glass plies. The direct problem consists in calculating the spatial and temporal evolution of stress after cold-bending. Considering an equivalent secant elastic shear-modulus for the interlayer to account for its viscoelasticity, various conditions for cylindrical deformations are analyzed in detail. A "conjugate-beam analogy" is proposed for the inverse problem, i.e., to determine the deformed shape that, at a prescribed time, provides the desired state of stress. Remarkably, the simplest constant-curvature deformation, often used for cold bending, produces high shear stress concentrations in the interlayer with consequent risks of delamination. For the same sag, better linear or cubic distribution of shear stress are attained with slightly different deformations, compatibly with glass strength. Among the considered cases, the optimal configuration is sinusoidal, because it provides the smoothest distribution of shear stress with inappreciable geometric differences with respect to the circular shape.

1. Introduction

Curved glass is a powerful tool of aesthetic design, and its use is steadily increasing in modern architecture. There are two main categories of production processes: hot bending and cold bending. Hot bent glass is obtained by heating sheets of glass until they reach the softening point (glass transition temperature) and curving them into the desired shape against a negative form. Cold bending is a recent fabrication process that is widely developing because it allows for the construction, at relatively low cost, of curved free-form glazed surfaces with no need of negative moulds. In general, the cold bent surface is a single-curvature developable surface. Cold bending into a double curved shape is also possible (Beer, 2013; Galuppi et al., 2014), but since this produces high membrane stress, single-curvature bending remains the most used technique, also because recent advances in theoretical algorithms allow for the discretization of any surface using single curvature panels only. Therefore, large double-curvature glazing of any form can be approximated by cylindrically bent panels (Pottmann et al., 2008; Eigensatz et al., 2010).

In cold bending, flat glass panels are brought to the desired geometry by external contact forces, constraining the curved glass unit in the desired shape. The most common technique[1] consists in curving glass at the construction site, holding it in place with clamps or adhesives against an underlying frame. Laminated glass is particularly adapt for cold bending. This is a sandwich structure composed by two or more glass plies bonded together by thin polymeric interlayers with a process at high temperature and pressure in autoclave. The limited shear coupling of the glass plies through the interlayer (Behr et al., 1993; Hooper, 1973) reduces the overall stiffness of the panel, increasing the maximum attainable curvature through cold bending compatibly with the material strength. As pointed out by Norville et al. (1998), in general the bending stiffness of laminated glass is intermediate between the *layered limit* (free-sliding glass plies) and the *monolithic limit* (shear-rigid interlayer). Since stress and strain in the monolithic limit are much lower than in the layered limit, appropriate consideration of the shear coupling offered by the interlayer is important to achieve an economical design. The problem has been considered by many authors, one of the most recent contribution being the careful finite element analysis by Ivanov (2006) that includes a list of the most relevant literature.

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[1] Another technique consists in laminating a package while being constrained in the desired shape, so that after lamination it is the bond of the interlayer that keeps the assembly in the curved state. This procedure, usually denoted *cold lamination bending* (Kassnel-Henneberg, 2011; de Vericourt; Fildhulth and Knippers, 2011), is not considered here.

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