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Cold-lamination-bending of glass: Sinusoidal is better than circular

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ABSTRACT

Cold-lamination-bending (CLB) of glass consists, first, in constraining the unbonded glass-interlayer package in the desired curved shape and, second, in performing the lamination process in autoclave. Releasing the laminate, the curvature is only partially maintained through the interlayer bond, due to an initial spring-back followed by the relaxation of the polymeric interlayer. Here, the whole process of single-curvature CLB, including the phase of release and the consequent contact problem with the constraining mould, is analyzed using sandwich beam theory. Comparisons are made between "stiff" interlayers (like Ionoplastic Polymers) and "soft" interlayers (like PVB). The time-dependent redistribution of stresses due to the interlayer viscosity is found for any assigned initial shape of the mould. Remarkably, the constant-curvature shape, indeed the most used, provokes shear stress concentrations in the interlayer with consequent risks of delamination. The sinusoidal shape, which for typical values of the deformation inappreciably differs from the circular one, provides a much smoother distribution of the shear stresses. A properly-designed gradual release of the laminated glass from the mould can substantially contribute to mitigate the peak stresses.

1. Introduction

The use of curved laminated glass, either hot-bent or cold-bent, is constantly growing and represents the leading feature of a modern architectural trend. Hot-bent laminated glass is produced, first, by heating glass sheets up to the softening point and curving them against a negative form; secondly, by performing the lamination process in autoclave. A crucial issue in this process consists in obtaining glass plies that fit together perfectly, with curvatures only slightly different one another. Recent works have treated analytically the flexural response of hot-bent laminated glass, evidencing the strong effect of the curvature in enhancing the shear coupling of the plies through the interlayer [3,26,23]. Cold-bending consists in forcing in the desired position initially-flat glass, laminated with the standard process in autoclave, so that the curvature is produced through elastic straining. The second process has widely developed because it allows to construct low-cost free-form glazed surfaces, being the expensive negative forms not necessary [6]. However, it requires a strong structural frame to withstand the constraining forces necessary to elastically bend the element, forces without which the glass would return to be straight.

A more recent technique is *Cold-Lamination-Bending* (CLB), in which the *unbonded* glass-interlayer package is deformed in the desired shape with provisional constraints and, in this configuration, the lamination process in autoclave is performed. When the constraints are removed, the curved laminate suffers an initial springing back followed by a relaxation due to the decay of the shear-coupling of the glass plies, associated with the viscosity of the polymeric interlayer. However, much of the curvature is preserved, so that the result is similar to a hot-bent glass, because no constraining forces are needed, but the production cost is much lower, because the process at high temperature is skipped. The cold-lamination-bending process can be employed to produce not only single-curvature, but also double-curvature panels with either synclastic or anticlastic curvatures [14]. However, the attainable curvatures are usually quite small, because of the limitations due to the tensile strength of glass and to possible buckling instabilities [17].

It is important to rely upon simple models to describe the CLB process at least for two reasons. On the one hand, a qualitative, though approximate, solution in closed form can contribute to the understanding of the importance of the various parameters to achieve an *optimal design*. On the other hand, as confirmed later on, stress concentrations/singularities may arise in some cases: this information is somehow lost in standard FEM analyses, because the use of regular shape-functions smears the critical states on the size of the finite element (mesh dependence).

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