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Rheology of cold-lamination-bending for curved glazing

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ABSTRACT

A promising technique to obtain free-form curved glazing consists in cold-bending glass panels by forcing them in the desired position. When the glass is laminated, the static state of the forced panel varies in time because of the viscoelasticity of the polymeric interlayer, which causes the decay of the shear-coupling of the constituent glass plies. Here, a model is presented to calculate the evolution of stress and deformation in single-curvature cold-bent laminated glass when, in particular, the glass plies are first cold-bent and, in this condition, are successively laminated in autoclave. With this technique, referred to as *cold-lamination-bending*, the successive bonding of the plies through the interlayer partially maintains the curvature after that forcing actions are removed. An approximate method based upon a quasi-elastic approach is presented and compared in paradigmatic examples with the full viscoelastic approach.

1. Introduction

Bent glass has been used for building purposes since the early nineteenth century, yet this is still a dynamic product that has far from exhausted its potential. Being a powerful tool of aesthetic design, its use is steadily increasing along with other uses of glass in modern architecture. Bent glass has been used primarily in public buildings, office complexes and in the façades of corporate facilities. Typical building projects include airports, exhibition areas, museums, concert halls and shopping arcades, both for interior and exterior applications. Possible uses include façades and display windows, skylights and cupolas, skywalks, entrances, revolving doors, canopies, winter gardens and conservatories, railings for staircases and elevated walkways, elevators, partitions.

There are two main categories of production: hot-bending and cold-bending. Hot-bent glass is obtained by heating sheets of glass until it reaches the softening point (glass transition temperature) and curving them into the desired shape using moulds. Both single- and double-curvature surfaces can be obtained, but a strong limitation is represented by the need of a negative form. In recent years, numerically-controlled machines have been developed that allow to obtain hot-bent surfaces with simple curvature whose radius is arbitrarily variable in a continuous manner, but this technology is quite expensive. Cold-bending is a recent fabrication process that is increasingly developing because it allows for the construction, at relatively low cost, of curved free-form surfaces without any need of negative moulds. In general, the cold-bent surface is a single-curvature developable surface; cold-bending into a double curved shape is possible, but results in high membrane stress levels and low curvature of the laminate, so that the economic advantage of cold-bending in manufacturing is lost. However, recent advances in theoretical algorithms allow for the discretization of any surface using only single curvature panels, thus permitting the construction of smooth double curvature glazing of any form [23,7]. This solution is very effective in cost reduction although it certainly has its limits. In fact, it is particularly adapt for surfaces with low curvature because the discretization of double curvature by single curved elements may lead to modifications of the initial shape in order to be able to panelise.

In cold-bending, 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. Two basic techniques are used here. The most common one consists in curving glass at the construction site, holding it in place by clamping strips. But the most advanced technique, applicable to laminated glass only, consists in bending the glass in factory before laminating so that it is the interlayer that keeps it in the desired shape. The latter procedure, usually denoted *cold-lamination-bending*, consists of two different phases. Firstly, a package composed of glass plies intercalated with sheets of polymer is deformed together by means of a bending device (mould), which keeps deformation constant during the successive autoclave lamination at high pressure and temperature [17,6,8]. Once out from autoclave, the bending device is removed, but the now coupled laminated package maintains the deformed shape through the interlayer.

However, the curved laminate suffers an initial springing back followed by a long-term relaxation due to the viscoelasticity of the

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