Engineering Structures 61 (2014) 140–152

Contents lists available at ScienceDirect

Engineering Structures

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

Rheology of cold-lamination-bending for curved glazing

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ARTICLE INFO

Article history:
Received 16 September 2013
Revised 1 January 2014
Accepted 4 January 2014
Available online 7 February 2014

Keywords:
Cold lamination bending
Curved glazing
Structural glass
Layered composite
Viscoelasticity
Laminated glass

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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http://dx.doi.org/10.1016/j.engstruct.2014.01.003
0141-0296/

polymer, whose effects must be precisely predicted to obtain the prescribed curved surface. The traditional approach is to use computer-aided structural analysis and superposition of effects, but there are various level of accuracy in this procedure. In particular, the evaluation of the shear coupling provided by the polymeric interlayer is complicated by its viscoelastic response, which is highly time-dependent and temperature-dependent. In the design practice it is usual to rely upon approximate solutions, the most common of which considers the polymer as a linear elastic material, characterized by a proper secant shear modulus, calibrated according to temperature and characteristic duration of the design actions. Such an approximation, usually referred to as the *quasi-elastic* method, is equivalent to neglecting the memory effect of the viscoelastic material. This provides estimates on the side of safety in the case of monotone loading histories [11], but there may be loading-unloading paths for which the approximate approach gives results that are not conservative [14]. Geometric non-linearities are usually important because of the slenderness of the laminated panel [1,9], but can be neglected, at least as a first order approximation, when the loads are mainly orthogonal to the panel surface and no in-plane forces are present. This is not the case when buckling phenomena are possible, in which the viscoelasticity of the interlayer plays a definitive role [15].

A major issue in the cold-lamination-bending process that still needs clarification is how to precisely model the phase when bending takes place and the successive transient relaxation. This is a prerequisite to determine how the curvature will change over time and how the viscoelastic properties of the interlayer may affect the duration and relaxation of the imposed distortion. Since the process is composed of different phases, in view of computer-aided structural calculations it is important to establish when, and within which limits, superposition of effects is applicable. Moreover, it must be verified whether the application of simplified models, like the quasi-elastic approximation, can be used without appreciable errors.

In order to answer to the aforementioned questions, we consider the paradigmatic case of a laminated panel with single-curvature, obtained through the cold-lamination-bending process. The shear dislocations induced during the distortion phase are properly taken into account in a sandwich beam model with viscoelastic core, whose governing equations are determined using an approach *à là* Newmark [12]. The relationship between this approach and a proper use of the superposition of effects is described. Moreover, the accuracy of the quasi-elastic approximation and the possibility of using the superposition of effects within this simplifying assumption is critically discussed. The influence of the viscoelastic properties of the interlayer on the long term performance during service life is highlighted by making reference to different in type commercial interlayers.

2. The distributed dislocation approach to cold lamination bending. Superposition of effects

The rheological response of laminated glass when initially cold bent and afterwards processed in autoclave is now examined in detail. Considering that, when deformed, there is a relative shear slip between the glass plies not yet coupled by the polymeric interlayer (free sliding plies), a model is developed for evaluating the time-dependent response of the laminated package after that the bond is executed in autoclave. Such a method is based upon consideration of the initial relative distortion between the plies and, because of this, it is referred to as the *distributed dislocation* approach.

2.1. The cold lamination bending process

The process that leads to a permanent cold-bent distortion of laminated glass is organized in the following three phases, schematically represented in Fig. 1.

- Phase *I*, *distortion*. The yet-not-coupled glass plies and interlayer are cold-bent into the desired shape by external actions, schematically represented in Fig. 1 by the pressure on a negative mould. This produces the relative slip between glass and interlayer, which is equivalent to a distributed shear dislocation between the glass plies. Then, the so-deformed unit is laminated in autoclave, so that the interlayer bonds the glass plies while in the distorted configuration.
- Phase *II*, *transient*. When lamination process is finished, the actions that had forced the cold-bending are removed. Glass plies would tend to return straight but they are now bonded by the interlayer. Due to the viscoelastic deformation of the interlayer itself, there is an initial spring-back followed by a long-term relaxation.
- Phase *III*, *final forcing*. After a certain time, which depends upon the handling process, the laminated glass panel is fixed in the desired final shape. As represented in the picture, this may be done, for example, by forcing the panel and by gluing its borders to a curved, sufficiently stiff, contouring frame. Again, the viscoelastic behavior of the interlayer causes a redistribution of stress in the glass plies, provoking in general the relaxation of the constraint reaction forces.

It should be mentioned that, in manufacturing reality, the initial spring-back and relaxation is partially blocked or delayed, as the laminate has to be released from the mould, which takes a certain time (30–150 s, depending on the fixing to the mould). Indeed, it is very difficult to analyze this transient stage because the timing of the constraint conditions may considerably vary according to the manufacturing. However, this does not effect the long-term response, although it may have a short-term influence on stress and deformation that should be analyzed case by case, for the specific conditions. Therefore, in the present article, we will suppose that the release at the beginning of Phase *II* is instantaneous. We may infer, albeit tentatively, that if the release is gradual, a smoother transition rather than a sharp spring-back will be observed, but its characterization goes beyond the scope of this article.

Moreover, it should also be observed that Phases *I* and *II* are always obligatory for cold lamination bending, but Phase *III* is a possible option. In fact, it is also not uncommon to "overbend" the glass in phase *I* to obtain the desired deformation for using the panel in a building after the handling time, during which part of the relaxation occurs. However, it is very difficult to *precisely*

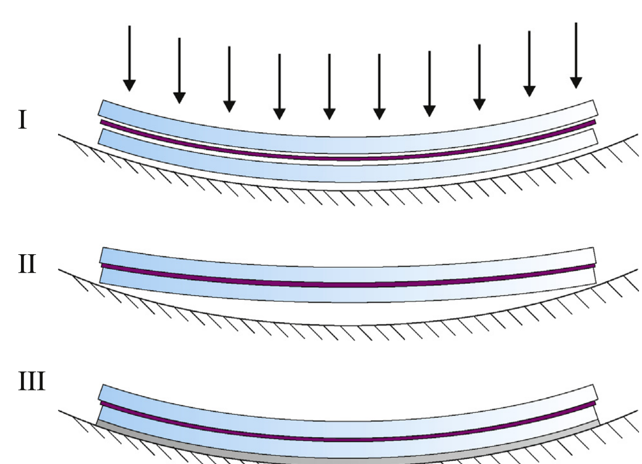

Fig. 1. Phase *I*: cold bent distortion introduced through forcing and successive lamination; phase *II*: transient of the distorted package after forcing actions have been removed; phase *III*: final forcing in the desired position.