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# Practical expressions for the design of laminated glass

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ABSTRACT

Due to deformability of the polymeric interlayer, stiffness and strength of laminated glass are usually less than those corresponding to a monolith with same total thickness. A practical design tool consists in the definition of the *deflection*- and *stress-effective thickness*, i.e., the thickness of an equivalent *monolithic* glass that would correspond to, respectively, the same deflection and peak stress of the *laminated* glass, under the same constraint and load conditions. Very recently, a new model has been proposed for the evaluation of the effective thickness. Here, a comparison is made with the classical approach by Wölfel–Bennison [1,2] and the new method is applied to the most common cases of the design practice, providing synthetic tables for ease of reference and immediate applicability.



## 1. Introduction

An effective technique to enhance the post-glass-breakage performance of architectural glazing consists in bonding glass plies together with polymeric interlayers via *lamination* in autoclave at high temperature and pressure. In such a way a laminated glass acquires safety properties because, after breakage, shards remain attached to the polymer and the system maintains a small but significant load bearing capacity, avoiding injuries due to catastrophic collapse.

Stiffness and strength of laminated glass may be considerably less than those of a monolithic glass with the same total thickness, because the interlayer is unable to provide a perfect shear coupling. As a matter of fact, the response is affected by the shear stiffness of the polymer (in particular by its shear modulus $G$), that regulates the relative sliding of the constituent glass plies. The laminated glass beam can be regarded as a very particular sandwich structure, a problem widely treated since the 1960s [3,4], because the bending stiffness is concentrated in the glass plies, whereas the interlayer only provides shear stiffness [5,6].

Two borderline cases can be recognized: (i) the *monolithic* limit for $G \to \infty$, where the two glass plies are perfectly bonded together (Fig. 1a) and the flexural inertia is that corresponding to the total thickness of the laminated glass; (ii) the *layered* limit for $G \to 0$, with free-sliding plies (Fig. 1b), for which the flexural inertia is the sum of the inertia of the isolated plies. In general, the real condition is intermediate between these two borderline cases (Fig. 1c).

Polymers are highly viscoelastic and, consequently, their response depends upon load duration and temperature. In the design practice a full viscoelastic analysis is seldom performed, but rheological effects are taken into account by considering, for the shear modulus $G$, the secant stiffness at the end of the load history at actual room temperature. The problem is thus simplified and reduced to a case in which all the materials, including the interlayer, are considered linear elastic. Moreover, at least as a first order approximation for a preliminary design, geometric non-linearities can be neglected when in-plane loads are absent.

In numerical computations, the response of laminated glass could be conveniently modeled by a *layered* shell element that takes into account the competing stiffness between glass and interlayer, but most of the commercial numerical codes do not have such elements in their library. On the other hand, a full three-dimensional analysis is complicated and time consuming. This is why, in the design practice and especially in the preliminary design, it is very useful to consider approximate methods for the calculation of laminated glass.

Currently, the most used approach is probably that proposed by Bennison [2] based upon the theory for composed sandwich beams proposed by Wölfel [1]. To illustrate, consider a laminated beam of length $l$ and width $b$ composed of two glass plies of thickness $h_1$ and $h_2$ and Young's modulus $E$, connected by a polymeric interlayer of thickness $t$ and shear modulus $G$ (Fig. 2).

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