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Laminated connections for structural glass applications under shear loading at different temperatures and strain rates

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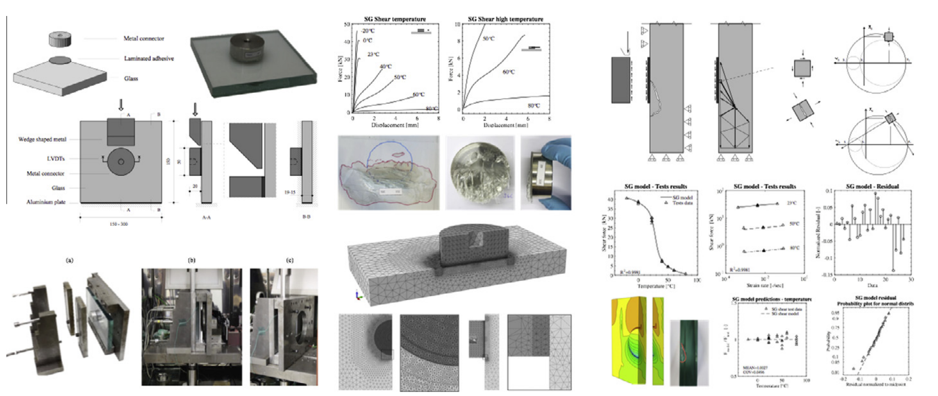
HIGHLIGHTS

- Experimental investigation of novel laminated connections with transparent adhesives under shear loading.
- Quantitative evaluation of temperature and strain rate effects.
- Non-linear finite element analysis for the computation of the three-dimensional stress field distribution.
- Validation with experimental tests.
- Probabilistic development of failure prediction model.

GRAPHICAL ABSTRACT



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ABSTRACT

Connections between structural glass components represent one of the main critical aspects of glass engineering. In the last years, a novel typology of adhesive connections has emerged, known as laminated adhesive connections. Two adhesive materials for laminated connections in glass applications are used in this work: the transparent ionomer SentryGlas® (SG) from Kuraray and the Transparent Structural Silicon Adhesive (TSSA) from Dow Corning. Both SG and TSSA show a complex behaviour dependent on strain rate and temperature. This work presents a study that aims (i) to investigate the mechanical behaviour and strength of this connection typology under shear loading and (ii) to quantify the effects of strain rate and temperature on the strength of the connections. This is done by means of a combined experimental, analytical and numerical study on laminated connections made of circular metal connectors bonded to rectangular glass plates. The experimental investigations presented in this work showed that temperature and strain rate variations have important effects on the mechanical response of the connections. Three-dimensional numerical analyses showed a non-uniform stress field with large gradient over the three dimensions. Through analytical studies, prediction models are finally proposed for the shear resistance of TSSA and SG laminated connections. The models are obtained developing an algorithm for multi-dimensional non-linear models with variable standard deviations. A logarithmic law is proposed for the strain rate effects for both TSSA and SG connections. Linear and inverse hyperbolic-tangent-based laws are instead proposed for the TSSA and SG temperature behaviour respectively.

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1. Introduction

The demand for architectural transparency has steadily increased over the last decades. This trend has inevitably promoted the use of glass in buildings and constructions. Due to the fragile nature of this material, connections between structural glass components represent one of the main critical aspects of glass engineering. This is because glass cannot plastically redistribute the stress peaks occurring where forces are transferred between components. Connections for structural glass components can be either bolted or adhesively bonded. Bolted connections make use of metallic bolts placed through drilled holes to transfer forces into the glass components. Mortar or other softer materials are usually placed between glass and metal parts. Adhesive connections are instead realized by joining glass components to metal parts or to other glass components by means of polymer adhesives. In comparison to bolted connections, adhesive connections are characterized by the following advantages: (i) the transfer of forces is distributed over the full bonded area thus avoiding contact stress intensification (ii) the drilling process and the subsequently reduction of the glass strength at the hole edge is avoided (iii) the architectural flushness is enhanced because the metal parts do not go through the glass (iv) thermal bridges and thermal losses are reduced also because the metal part does not go through the entire glass thickness (v) the residual stress field distribution of the tempering is unaltered at the connection and (vi) gas losses occurring in IGU bolted panels are reduced since the glass is not drilled. Because of these aspects, the use of adhesive connections in structural applications has been considered very promising. Indeed, several research projects have focused on adhesive connections for structural glass applications [1–11].

In the last years, a novel typology of adhesive connections has emerged, known as laminated adhesive connections. The main characteristic of laminated connections is that they make use of the same production process as applied for laminated glass components. In addition, they exhibit high mechanical performance and are fully transparent. In laminated connections, a solid foil of transparent adhesive material is placed between a metal connector and a glass panel. Metal, adhesive and glass are then placed in the vacuum bag and subjected to the standard autoclave process of laminated components. The lamination process is performed by simultaneous application of atmospheric pressure and heat by means of an autoclave. At the end of the lamination process the result is a glass component where the metal part is fully bonded to the glass plate by means of the laminated transparent adhesive.

Two adhesive materials for laminated connections in glass applications are used in this work: the transparent ionomer SentryGlas® (SG) from Kuraray and the Transparent Structural Silicon Adhesive (TSSA) from Dow Corning. Laminated connections have been used in several projects worldwide. Applications of SG laminated connections can be found [13–18] and TSSA applications in [19]. More detailed information on these materials and existing literature on laminated connections are given in the following sections. Table 1 collects a summary of the basic material properties provided by standards and material producers for SG, TSSA and other material properties used in this work. Further material properties used in this work are taken for the experimental investigation performed in [12].

Table 1
Materials properties provided by standards and material producers.

Property	Density	α_T	E	ν	σ_{max}	ε_{max}
Unit	g/cm^3	10^{-5}/°C	MPa	–	MPa	%
SG[a]	0.95	15–10	692–0.5	0.5–0.4	34.5	400
TSSA[b]	n/a	n/a	9.0–4.5	n/a	8.5	250
Glass[c]	2.50	9	70000	0.23	45[e]	0.06
Stainless steel 1.4404[d]	7.85	16	200000	0.3	530[f]	40

a) [20,21] (It should be noticed that these values are time and temperature dependent.) b) [22] c) [23–25] d) [26,27] e) characteristic equi-biaxial bending stress at 2 MPa/s f) ultimate stress.

1.1. Ionomer SentryGlas® (SG)

SentryGlas® (SG) is a thermoplastic transparent ionomer polymer used in laminated glass applications as interlayer. The glass transition temperature of SG is at 50–55 °C [28,29].[1] Compared to other interlayers such as PVB and EVA, SG is characterized by higher stiffness, enhanced durability and higher mechanical resistance. From a chemical point of view, ionomers are polymeric materials in which the main repetitive sequence of monomers is characterized by additional ionic groups. Ionomers belong to the category of polyelectrolyte. More specifically, ionomers are often defined as polyelectrolytes with ionic groups not exceeding 20 mol% [30]. Other authors, instead, more generally define ionomers as polymeric materials with mechanical performance influenced by the ionic group interactions and the subsequent formation of ionic aggregates [31]. It is indeed the attraction between ionic groups and the subsequent cross-links between polymeric chains that enhances the physical properties and the mechanical response of the polymer [32]. The SG is currently produced in foil thickness of 0.76, 0.89 and 1.52 mm. SG foils are rather rigid at room temperature and usually require the use of sharp tools to cut the foil to the desired size and geometry. In the production of laminated glass connections, glass, SG foil and metal parts are placed in a vacuum bag and subjected to an autoclave process.[2] The lamination process consists in a single cycle of simultaneous application of heat and pressure. Typically, a temperature of 135 °C and a pressure of 12 bar are applied for a minimum plateau time of 60 min.[3] Subsequently, to achieve a good lamination quality, the cooling phase should be performed with a minimum rate of 2–3 °C/min. At the end of the autoclave process, the SG material is fully transparent.[4]

Several authors have investigated the mechanical response of SG-laminated components [33–44] and the SG-bulk material [12,45–51]. Conversely, studies on the resistance of SG laminated connections are rather limited. Exploratory tests on SG laminated connections bonded to the glass surfaces are performed by Peters in [52]. In [52], a rectangular metal connector is bonded to the surface of a laminated glass panel. Tests are then performed clamping the glass panel and applying tensile force to the metal connection. Tests are performed at room temperature. In the work performed by Belis et al. [53–55] a broad screening of adhesive connections is performed via a large experimental campaign to select promising adhesives for glass applications. Tests are performed on aluminium-glass single lap joints at reference condition and after exposition to artificial aging protocols (4 and 12 weeks exposition to 90% R.H and 50 °C). Tests were performed at room temperature. Based on the experimental observation, SG connections have been indicated, among others, as a promising candidate for adhesive

[1] This is higher than other common interlayer polymers used in laminated components, such as standard PVB with a typical glass transition temperature around 15–20 °C.

[2] As an alternative to the autoclave-vacuum process, silicon bag are also used. In these cases, the components are placed inside a vacuumized silicon bag that is then placed inside a oven. This process is often commercially indicated as Tema.

[3] Material producer suggests that optimum values of temperature and pressure depend on the several factors and vary among different glass manufactures (e.g. autoclave size, panel size, factory, etc...). Therefore, the values mentioned in this manuscript must be considered to be only indicatives. For more details the reader should refer to the material producer or certified glass manufactures.

[4] However, it should be noticed that before lamination the SG foils appear not fully transparent because of the micro-channels intentionally realized on the SG surfaces. These micro-channels reduce the risk of air-bubble inclusion since the air can flow out of the component during the lamination.