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A novel triaxial failure model for adhesive connections in structural glass applications

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ABSTRACT

Structural adhesive connections for glass applications have been widely investigated in the past years, because of their enhanced mechanical performance when compared to bolted connections. However, due to the lack of established design methods and failure criteria, laboratory tests must always be performed, when adhesive connections are used in real-world structural applications. Because of the above, this work presents the analytical development of a Generalized Triaxial Model (here called GTM) that describes a novel failure criterion for adhesive materials in structural glass applications. This is done developing a generalized triaxial model defined over the three-dimensional stress space, which accounts for the non-linear effects of strain rate and temperature variation. The main output of this work is a five-dimensional formulation that allows to account for a generic stress state by a governing equation expressed as a function of the three-dimensional stress tensor. Both deviatoric and hydrostatic energetic components are taken into consideration by means of a non-linear function of the two contributions. The governing equation is represented in the stress space by a revolution surface that is axial-symmetric with respect to the hydrostatic axis, thus independent of the third stress invariant. The proposed model is suitable for isotropic materials and it is here applied to SentryGlas and TSSA, two adhesive materials used in structural glass applications, for which extensive test campaigns have been performed but for which no failure criteria are available yet in literature. Firstly, the proposed model is analytically compared to other existing general failure criteria. It is shown that some of the existing models that can be found in literature can be seen as a particular case of the proposed model. Then, the model is compared with the experimental results under different loading conditions, strain rates and temperatures. The results are found to be in line with the model predictions for both materials. Additional tensile-torsion tests are also performed to validate the proposed model at varying values of the hydrostatic angle.

1. Introduction

Connections between structural components often represent a critical aspect of structural engineering. This is of particular importance in structural applications with glass, as high stress intensification cannot be plastically redistributed due to its brittle mechanical response.

Because of the above mentioned reason, adhesive connections have been widely investigated in the past years, especially in the field of structural glass. Several experimental and numerical studies on adhesive connections for structural glass applications can be found in literature [1–7]. More specifically, adhesive connections have been investigated in applications with different geometries, loading conditions (such as tensile and shear loading), strain rate and temperatures. In addition, structural adhesive connections have been also used in full-scale structural glass projects [8–13].

When adhesive connections are used in real-world projects (Fig. 1), laboratory tests are usually performed due to the lack of established design methods and failure criteria. Tests are performed either on small or full-scale samples, with geometry and loading conditions as close as possible to the application. However, as no failure criteria or established design methods are available in literature these tests are repeated for every new project. This is because the results from previous tests cannot be, from a theoretical point of view, directly extended to different geometries and loading conditions, i.e. different configurations of the stress tensor occurring in the material. Therefore there is the need to develop a generalized failure criterion that can be applied to any

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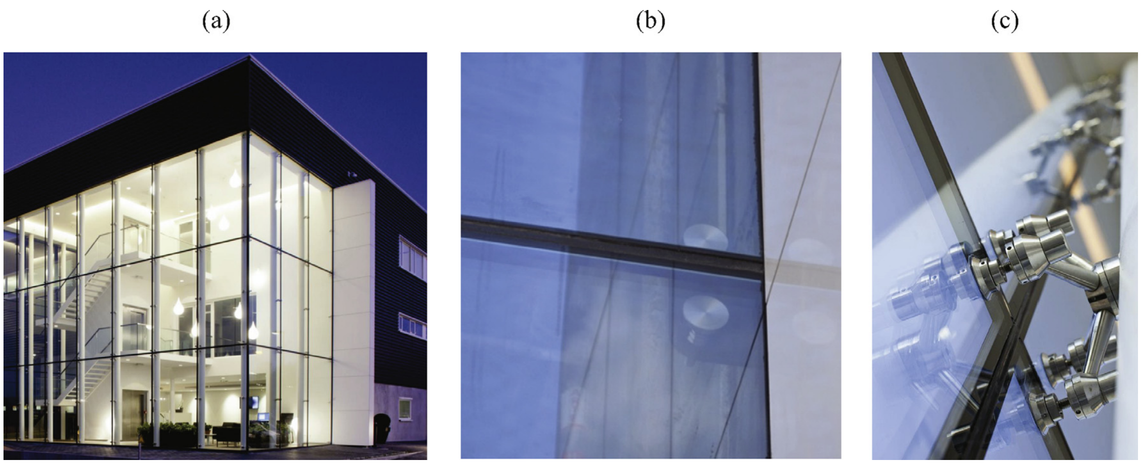

Fig. 1. Dow Corning European Distribution Center in Feluy (Belgium) (a) Global view of the project (b) external close view of the TSSA laminated connections (b) internal close view of the TSSA laminated connections (Photos courtesy of Dow Corning).

generic configuration of the stress tensor, rather than specific load conditions such as pure tensile and shear loading.

Based on the above motivation, this work proposes a Generalized Triaxial Model (here called GTM) that describes a failure criterion for adhesive materials in structural glass applications. In particular, this work focuses on the development of a non-linear failure criterion suitable for isotropic materials. The criterion is here applied to two adhesive materials for which no failure criteria are available in literature: TSSA (Transparent Structural Silicon Adhesive from Dow Corning) and SG ionomer (SentryGlas® from Kuraray). In particular, while in [14,15] the analysis focused on specific loading conditions, i.e. on selected stress state of the adhesive, this work aims to extend the studies to a multi-dimensional model that accounts for any generic stress state. This is done developing a triaxial model defined over the three-dimensional stress space and that accounts for the non-linear effects of strain rate and temperature variation.

The goal of this work is to present the analytical formulation of the proposed model, rather than focusing on numerical values of coefficients. The latter can always be updated and accuracy enhanced with new tests or updated for new materials. The main objective of the work is instead to present the main governing equations of the proposed failure criterion, to provide an overview of its analytical properties, to perform an analytical comparison with existing failure criteria, to describe its fundamental hypothesis and its analytical limitations. Although the failure criterion here developed is applied to two adhesive materials used in structural glass applications, the analytical equations of the model are of general validity and as such they are generally suitable for isotropic structural materials.

Firstly, the theoretical bases and main equations that are necessary for a concise analytical description of the failure criterion are given in Section 2. Stress state equations in the Haigh-Westergaard space are derived in orthogonal and cylindrical coordinates. This section provides an essential analytical framework to present the analytical formulation of the proposed model in a concise yet complete manner. Secondly, the main characteristics of the existing failure criteria are discussed in Section 3. The governing equations are rearranged in a consistent form. The analytical equations presented and rearranged in this section enable a direct and brief analytical comparison of existing failure criteria with the proposed model. Thirdly, a generalized triaxial model is developed as a function of the three-dimensional stress space, strain rate and temperature, in Section 4. The proposed model is then compared to existing models and to experimental results at selected values of the hydrostatic angle in Section 5. Finally, additional tests are performed, at varying configurations of the stress tensor, to validate the proposed model at varying hydrostatic angles. Tensile-torsion tests are performed at different force-torque ratios and results are compared to the proposed model.

2. Theoretical framework

In this section, the analytical bases necessary for the definition and the mechanical interpretation of failure criteria are given. The mathematical derivation and equation derived in this section are essential to be able to develop the failure criteria by means of concise yet analytically complete equations. In particular, three different stress-space coordinate systems are derived. These will allow in the following sections (i) to provide concise yet complete analytical descriptions of existing failure criteria and (ii) to develop a generalized failure criterion for TSSA and SG laminated connections under generic three-dimensional stress state. Many basic aspects and analytical formulation of solid mechanics are given as known in this section for the sake of brevity. Only some key theoretical concepts and equation are introduced here as essential for the understanding of the following sections. For more in depth reading on these concepts the reader could refer to [16,17].

2.1. Stress state in solid body, stress tensors and invariants

Consider a continuous solid body B, in equilibrium, subjected to boundary conditions Ω, body forces f_b, and surface forces f (Fig. 2). When dividing the body in two parts, B_1 and B_2, by a cutting plane π, containing point P and with normal n, surfaces S_1 and S_2 are created. In an x-y-z reference system, the plane π is fully determined by the point P and the normal n, with the latter not being necessarily parallel to one of the axes. Now, to guarantee the equilibrium of each body part, force fields are acting onto the surfaces S_1 and S_2. Before the cutting, these forces were applied by B_1 to B_2 and vice versa. Considering an infinitesimal area dA part of the surface S, centred around the point P, the total stress[1] vector t_n is defined by Eq. (1) [18]. In (1), dR is the vector sum of the forces acting on the surface dA. The same procedure can be repeated for any generic plane π_i containing the point P. Having full mathematical information of the stress state at point P means to know magnitude and direction of the vector t_n for any plane π_i containing the point P [19].

$$\boldsymbol{t_n} = \lim_{dA\to 0}\frac{dR}{dA} \tag{1}$$

The total stress vector is the vector sum of two components, σ_n and τ_π. The component σ_n is called normal stress, and represents the t_n-

[1] It is considered a solid body that also satisfy the condition of having the momentum of R with respect to P equal to zero, i.e. B is a non-polar solid.