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A novel functional coating and a reliable design approach to fully exploit the strength of annealed glass

By

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Abstract

Glass is increasingly being used in structural applications nowadays. Large glass façades, all-glass staircases, roofs, walkways, and spectacular long suspended bridges are all hallmarks of the modern architecture. However, the intrinsic strength of annealed glass is not fully exploited due to the stress corrosion and the lack of a universal and reliable design method. Therefore, the design of glass components is redundant and conservative, resulting mainly in costs and emissions increase. Moreover, from an architectural point of view, oversized load-bearing glass members are undesirable.

Stress corrosion is a chemical phenomenon which affects annealed glass. This phenomenon, also known as static fatigue, causes a reduction of the tensile strength due to the combined presence of applied tensile stress and humidity. As a result, the actual strength of annealed glass components is limited. According to previous findings published in the literature, stress corrosion can be prevented by avoiding the interaction between water molecules and the silica network.

Besides the stress corrosion, the glass strength is prevented from being fully exploited due to the lack of a generally valid design approach. The large dispersion in size and position of flaws determines a wide variability of the failure stress, hence a distinct and universally acceptable glass strength cannot be identified. As a consequence, deterministic approaches, that nowadays are widely adopted for the design of glass components, lose in reliability and enforce to adopt large safety factors, limiting the actual load-carrying capacity of glass members. Several researchers have raised serious concerns regarding the applicability and accuracy of the deterministic design approach. The main reason of concern is that the glass strength is not a true material property since it varies, not only with the statistical flaws distribution, but also with the test setup and the element size.

In the first part of the research project, a UV cured coating combining hydrophobicity and barrier to water vapour with good adhesion to glass, has been investigated and developed for preventing stress corrosion in annealed glass. The coating is obtained by combining a cycloaliphatic diacrylate resin with a very low amount of a perfluoropolyether methacrylate co-monomer, which migrated to the free surface, creating a compositionally graded coating. The adhesion to glass is improved, using as a primer an acrylated silane able to co-react with the resins. The coating effectiveness is assessed experimentally by comparing the load-carrying capacities of coated and un-coated glass plates. New and naturally aged glasses are analysed. The results evidence an increase of the design bending strength between 60 and 90% with respect to the strength of un-coated glass. The durability of the polymeric coating is also examined. Three scenarios are analysed in terms of ageing: (i) cyclic loading, carried out by subjecting coated samples to repetitive loading; (ii) natural weathering, performed by exposing coated samples to atmospheric agents; (iii) artificial weathering, conducted by exposing coated specimens to fluorescent UV lamps, heat and humidity. The coating's durability is determined indirectly, based on its residual effectiveness in preventing stress corrosion, by comparing the bending strength of aged coated glass specimens to that of un-coated and freshly coated specimens using the coaxial double ring test. The obtained results demonstrate that the proposed formulation is nearly insensitive to cyclic loading, has excellent performance in case of natural weathering, while is slightly more sensitive to artificial weathering.

In the second part of the research project a novel computational methodology aiming for a safe and optimized design of glass components has been developed. The methodology, that adopts a stress intensity factors-based fracture criterion, can be applied to predict the edge strength of glass components with arbitrary geometry and edge flaws scenario. The novel developed methodology consists of: (i) modelling the structural element through the finite element method, (ii) randomly applying to the FE model a population of flaws extracted from a pre-defined statistical distribution function, (iii) computing the related stress intensity factors, (iv) evaluating the load carrying capacity by equating the maximum stress intensity factor to the fracture toughness. Because of the stochastic nature of the problem, where the size of the edge flaws is the random variable, the Monte Carlo method is used to obtain the cumulative distribution function of the failure load. Finally, the critical load referred to a chosen probability of failure is derived. The eXtended Finite Element method is used because of its intrinsic capability to deal with multiple cracks of any position

and length without adapting the mesh topology, and because it allows for a direct evaluation of the stress intensity factors at the tip of the cracks without any post-processing. The current version of the numerical methodology is limited to plane stress/strain models, although its extension to 3D problems is quite straightforward. Several case studies are shown to demonstrate the accuracy and reliability of the method in assessing the structural integrity of glass components. It is also shown that by adopting the developed method rather than a stress-based approach, the load-carrying capacity prediction increases by 21 to 82%, depending on the stress gradient along the glass component. In conclusion, the methodology provided has huge potentiality for being generalized for all brittle materials and thus applied to ceramics as well as polysilicon structures for micro-electro-mechanical systems (MEMS).