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The effectiveness of resin-based repairs on the inert strength recovery of glass

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HIGHLIGHTS

- We investigate the effectiveness of resins in repairing surface flaws in glass.
- Testing shows that acrylic resin can strengthen glass but are weakened by water.
- Testing shows that strength recovery is dependent on flaw type, resin type, exposure.
- Results suggest that strengthening is caused by more than one mechanism.
- Study shows importance of statistical analysis of test data.

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ABSTRACT

Glass used in buildings is often exposed to sources of surface damage which can have a significant effect on its strength. Existing research suggests that the flaws in glass can successfully be repaired by transparent polymeric resins, but the reasons for the increase in strength are not fully understood and the research to-date is not easily transferable to building applications.

In this study 304 soda lime silica glass specimens covering three flaw scenarios, three repair scenarios and two post-repair exposures are tested in inert conditions. Contact angle measurements and post-failure fractographic analyses are also performed to determine wettability of the resin and resin penetration respectively.

The results show that resin repairs can increase the inert strength of glass, but the results suggest that the strengthening in normal environments results from a combination of at least two mechanisms of which suppression of sub-critical crack growth is one. The acrylic resin used in this study showed the largest strength recovery, but exposure to water had an adverse effect on the inert strength of repaired specimens. Finally, the statistical analysis shows that the mean strength values often reported in literature are not always representative of lower fractile values required in engineering applications.

1. Introduction

Soda-lime-silica glass is widely used in the building industry, especially in façades and other areas where transparency or translucency is required. However, due to its brittle nature, glass is prone to flaws and defects that act as stress concentrators and crack nucleation points thereby significantly reducing its strength. Flaws in glass arise during the float production process, resulting in a random distribution of micro flaws over the glass surface. Further flaws and damage, such as linear scratches and point defects tend to occur during subsequent processing, handling and installation of the glass. Surface damage continues to accumulate during the service life of the glass from wind-borne debris, scratching from human traffic, vandalism etc. These sources of damage therefore cause flaws of various forms and severities, which in turn reduce the strength of the glass component.

In the automotive industry, defects in glass such as chips and pits in windshields are commonly repaired by means of resins. For this, several transparent repair resins are available on the market. In the building industry, however, defects in glass components (e.g. façade panels) often result in the replacement of the full panel to ensure that the panel meets the strength requirements. This is often a costly undertaking both in embodied energy and monetary terms. In this respect, resin repair methods could provide an

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alternative and economically attractive approach, provided that the repair achieves a sufficient strength recovery of the glass.

In literature, several studies focus on the effect of sol–gel and other polymer based resin coatings, on the strength of artificially damaged glass [1–6]. These studies show that the strength of glass may indeed be enhanced by means of these coatings. Different authors attribute the strengthening to either *mechanical*, *physical*, *thermal* or *chemical* phenomena. For example, Briard et al. [3] support a *mechanical* explanation for the observed strengthening, based on an assumed crack-face bridging effect of the applied resin. This involves a very thin layer of resin in the crack in the glass surface which, due to Poisson's ratio effects, provides a resistance to crack opening in the order of the bulk glass. A related *physical* explanation is provided by Fabes et al. [1], who attribute the strengthening due to partial filling and consequent shortening of the crack, so that the surface crack becomes effectively an embedded flaw with a different shape from the original [2]. An alternative strengthening mechanism is attributed to a *thermal* expansion mismatch between the glass and the applied resin which generates crack closure stresses within the flaw, as supported by Hand et al. [2]. A fourth possible strengthening mechanism is *chemical*, wherein the resin is able to shield the crack-tip from humidity, thereby eliminating or reducing the weakening effects of stress corrosion phenomena (aka subcritical crack growth) that is known to occur in the presence of humidity and tensile stress [7,10]. Other strengthening mechanisms have been suggested, such as crack-tip blunting effects, but these are less established. The existing research provides a very useful body of knowledge, for example most studies agree that the level of penetration of the applied coating into the crack is an important parameter, but there are several uncertainties in this field, namely:

- There is no consensus on which phenomenon (or combination of phenomena) is/are responsible for the observed glass strengthening.
- The studies to-date perform the tests at ambient lab conditions which makes it difficult to decouple the strengthening effects caused by suppression of subcritical crack growth from the other possible strengthening mechanisms.
- The flaws considered are not representative of the range of flaws typically encountered on glass in buildings.
- Most repair techniques seem to require lab-based resin application procedures, which may preclude their use on real world building sites.
- The strength recovery data is often presented and discussed in terms of mean values which is in itself a useful comparison, but not particularly suitable for engineering applications where low probabilities of failure (or fractile values) govern the selection.

The current study therefore aims to investigate the effects of hand applied resin repair methods, on the strength recovery of artificially damaged and naturally weathered glass panels. This is done by means of strength testing of soda-lime-silica glass specimens that are either repaired by means of resins or left unrepaired. More specifically, three different flaw scenarios, three different repair scenarios and two different post-repair durability exposures are investigated. In contrast to the aforementioned investigations on coating systems that adopt a four-point bending procedure, the current study uses coaxial double ring testing to determine the surface strength of the glass. This provides two advantages: (1) edge failures are eliminated, which facilitates the interpretation of the results; and (2) the fracture strength is independent of flaw orientation [11,12]. Furthermore, the tests in the current study are conducted at inert conditions thereby eliminating humidity and stress corrosion effects on the strength of glass, making it easier to establish the strengthening effects on the inert strength of glass and compare between the different test series. The sample preparations and the testing procedures are explained in detail in Section 2.

In total 304 glass specimens are tested to destruction comprising of 19 series, each consisting of 16 glass specimens. The results are presented and discussed in terms of mean value as well as low fractile values commonly used in engineering applications. In addition to the strength testing, contact angle measurements are performed on the resins to determine wettability of the resin, and post-failure fractographic analyses are performed on the glass fragments to determine resin penetration and flaw size. The underlying theory used to analyse the test results is described in Section 3 and the test results and discussions are presented in Section 4. The conclusions from this study are provided in Section 5.

2. Materials, specimens and methods

Table 1 provides an overview of all 19 test series, each consisting of 16 specimens. One of test series consists of as-received glass. This was left untreated and serves as a control series. The remaining 18 series are divided into 3 flaw scenarios (indented glass; scratched glass; naturally weathered glass), 3 repair scenarios (unrepaired, acrylic resin repair; epoxy resin repair) and 2 post-repair exposure scenarios (1 week in air at indoor ambient conditions; 1 week submersion in water).

2.1. Glass

In this study glass specimens with the following flaw configurations were investigated:

- *As-received glass (AR):* This glass is left untreated prior to strength testing.
- *Indented glass (IN):* A surface flaw is induced by means of a Vickers Hardness Indentation Machine, see Section 2.1.1.
- *Scratched glass (SC):* A linear scratch is induced by means of a custom-made scratching device, see Section 2.1.2.
- *Naturally weathered glass (NW):* The glass contains surface flaws induced by 20 years exposure to natural weathering, see Section 2.1.3.

Table 1
Overview and acronyms of test series, each consisting of 16 specimens.

Surface condition	Repair and post-repair scenario					
	Unrepaired (UR)		Acrylic resin (AC)		Epoxy resin (EP)	
	In air (a)	In water (w)	In air (a)	In water (w)	In air (a)	In water (w)
As received (AR)	AR-UR-a	–	–	–	–	–
Indented (IN)	IN-UR-a	IN-UR-w	IN-AC-a	IN-AC-w	IN-EP-a	IN-EP-w
Scratched (SC)	SC-UR-a	SC-UR-w	SC-AC-a	SC-AC-w	SC-EP-a	SC-EP-w
Naturally weathered (NW)	NW-UR-a	NW-UR-w	NW-AC-a	NW-AC-w	NW-EP-a	NW-EP-w