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Experimental investigations of statically indeterminate reinforced glass beams

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HIGHLIGHTS

- A custom-made statically indeterminate five-point bending setup was successfully built.
- The effectiveness of applying statically indeterminacy for reinforced glass beams was proven.
- Structural element safety as well as system safety were achieved.
- Temperature and reinforcement have a significant effect on the load-carrying behaviour.
- A good design of the glass-to-reinforcement bond is critical to achieve satisfying load-carrying behaviour.

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ABSTRACT

A lot of 'hybrid' structural glass beam concepts were developed in the past years to overcome the brittle failure behaviour of glass. These beams possess a safe failure behaviour through post-fracture strength and ductility. Promising is the concept of reinforced laminated glass beams in which stainless steel reinforcement sections are included in the glass laminate and provide a post-fracture load-carrying mechanism. This type of beams was extensively tested in three- and four-point bending for a variety of environmental conditions (e.g. temperature and humidity), geometrical scale, reinforcement percentage and element robustness. The concept proved to be satisfying. In addition to element safety, today's buildings also require significant system safety. This paper presents an experimental test programme in which the load-carrying behaviour of statically indeterminate reinforced laminated glass beams is investigated. The beam specimens were tested in five-point bending (three supports and two load points) at 23 °C and 60 °C, at a humidity level of 55%. In addition, two different reinforcement percentages were investigated. The beams illustrated satisfying failure behaviour in all cases, proving the effectiveness of applying reinforced laminated glass beams in statically indeterminate systems. The effect of temperature is primarily observed in the fractured and plastic phases. There, the specimens at 60 °C illustrated lower bending stiffness and slip of reinforcement, which resulted in a lower post-fracture strength. The temperature effect was larger for the beams with high reinforcement percentage. The load-carrying behaviour and load redistribution were highly dependent on the reinforcement percentage. A higher reinforcement percentage resulted in higher bending stiffness in all phases of the model. In addition, a higher initial failure load, yield point and post-fracture strength was achieved. Finally, also a different collapse mechanism was observed for both tested reinforcement percentages.

1. Introduction

Aiming for increased transparency, researchers and engineers have been investigating ways to apply structural glass elements in buildings. Today, structural elements are required to possess a safe failure behaviour (element safety). As glass is a brittle material, safe failure behaviour is translated into sufficient post-fracture strength and ductility. Especially in the field of structural glass beams, previously basic research has been performed to develop beams that meet those requirements. In a final stage, this has led to the 'hybrid glass beam' in which glass is combined with another material that provides post-fracture strength and ductility to the beam. A broad overview of investigated concepts can be found in [1,2]. A promising concept for practical applications is the stainless steel reinforced laminated glass beam which is developed considering the concept of reinforced concrete. Stainless steel

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sections are added at the tensile sides of the glass laminate and serve as crack bridges for the fractured glass zone. As a result, the reinforcement and intact compressive glass zone form an internal resisting moment that provides the beam with its post-fracture load-carrying capacity. As stainless steel is a ductile material, the reinforced glass beam's post-fracture behaviour usually also is ductile (if the interlayer possesses a sufficiently high shear modulus and strength) the reinforced glass beam also fails in a ductile way.

1.1. Verifying effectiveness in a statically determinate system

The concept was intensively investigated, through experimental four-point bending tests, to assess the effects of temperature (cycles), humidity, reinforcement percentage, glass type and beam size [3,4]. As the beam specimens in the current paper are based on those in [3,4] (using SentryGlas® as interlayer material), the main results of the latter tests are briefly discussed here. To investigate the effect of temperature, four-point bending tests were performed at −20 °C, 23 °C and 60 °C. It was concluded that low as well as high temperatures had a negative effect on the post-fracture response of the beams, as more excessive local debonding of reinforcement occurred. However, the overall load-carrying behaviour had significant post-fracture bearing capacity. Thermal cycling had an insignificant effect on the structural behaviour but could become more important for larger beam configurations due to larger differences in thermal expansion between glass and reinforcement. Applying the beams in a humid environment remains questionable, as two out of three tested beams illustrated the same performance as a non-exposed beam. However, the other one suffered extensive delamination in the post-fracture stage. It was concluded that additional research is required. The beams also performed well during the long-duration loading tests. Despite some creep deformation due to creep in the interlayer and glass fracture, a fractured beam was able to carry 80% of the predicted ultimate failure load for more than 22 months. Testing beams composed of stronger glass types (heat-strengthened and fully tempered glass) yielded higher initial failure loads. However, a reduction of post-fracture strength and deformation capacity due to the finer fracture pattern has to be taken into account. Larger glass shards (typical for ANG) are easier for the interlayer to hold together and make stress transfer more feasible. Reinforcement percentage significantly influences the beam's structural response, as it increases the initial failure load, post-fracture strength and bending stiffness. Finally, it was concluded that beam size has only a limited effect on the load-carrying behaviour, as a slightly lower post-fracture strength was encountered than expected. However, additional research is required to explain this phenomenon. In addition, the inherent element robustness of these reinforced glass beams was confirmed by testing beams in which one and/or two glass panes were artificially damaged prior to testing [5]. The reinforcement forms a secondary load-transfer path wich easily bridges the damaged glass zones.

1.2. Benefits of the statically indeterminate system

In addition to their individual element safety, the structural members making up (a part of) the entire structure should collectively provide a sufficient level of safety (i.e. system safety). This requirement is for example realised by introducing redundancy into the structure so that there are several ways to transfer the loads to the foundation (i.e. enabling alternative load paths). A way to incorporate this kind of safety for the case of structural beams is the application of statically indeterminate support conditions. Stress redistribution between supports and spans can enable such a system to withstand extensive damage and even accidental support failure due to e.g. a terrorist attack, car accident, etc. Moreover, statical indeterminacy enables the engineer to come up with a more economic design than would be possible with statically determinate systems. Despite the general acknowledgement of its benefits in steel and concrete construction, the statically indeterminate beam system is hardly applied in glass construction. The main reason for this is the lack of sufficient research to prove its effectiveness. To the authors' best knowledge, only a single hybrid glass beam concept was tested for statically indeterminate support conditions. In the latter research, glass-GFRP composite beams were subjected to five-point bending with two spans of 1.40 m, at room temperature [6]. In addition to an assessment of the overall load-carrying behaviour and its features, the effect of adhesive stiffness (to realise the glass-GFRP bond) on the latter was investigated. The investigation concluded that it is feasible to apply the glass-GFRP composite beams in statically indeterminate systems, as safe pseudo-ductile failure behaviour was encountered. Furthermore, the post-fracture performance is dependent on adhesive stiffness. The beams composed with the least stiff adhesive yielded the highest relative post-fracture strength (relative to the load at first glass fracture). Moreover, all beams illustrated stress redistribution capacity in the fractured phase, in particular the ones composed with the least stiff adhesive. However, it is stated that stress redistribution was only triggered due to glass fracture and therefore the former was only momentarily observed. As GFRP is not a ductile material, no classic stress redistribution (i.e. through the formation of plastic hinges as for steel and reinforced concrete beams) was possible. For the case of steel reinforced glass beams, stress redistribution is expected to be possible through glass fracture and plastic hinge formation.

Preliminary numerical simulations were performed by the authors to assess the load-carrying behaviour of statically indeterminate reinforced glass beams, assuming rigid supports [7]. The effect of reinforcement percentage and load redistribution capacity were investigated. It was concluded that the beam specimens illustrated safe failure behaviour with significant post-fracture strength and ductility. A lower reinforcement percentage led to lower bending stiffness, initial failure load and ultimate collapse load. Furthermore, the simulations illustrated load redistribution in two phases: (1) minor redistribution in the fractured phase and (2) major redistribution in the plastic phase. From this research, it was concluded that reinforced laminated glass beams could be applied in statically indeterminate systems, illustrating safe failure behaviour and load redistribution capacity.

This paper presents an experimental test programme in which the effectiveness of applying reinforced laminated glass beams in statically indeterminate systems is investigated. Two criteria are important, namely structural element safety and system safety. To satisfy both, the beam has to exhibit a post-fracture phase characterised by significant load-carrying capacity and ductility on one hand (element safety) and should form all plastic hinges, thus illustrating stress redistribution, prior to ultimate collapse (system safety). In addition, an assessment of the effects of temperature and reinforcement percentage on the load-carrying behaviour is performed. Finally, the effect of reinforcement slip is explained and related to experimental observations.

2. Experimental test specimens and setup

In this section, the different beam specimens and their composing materials are explained followed by a detailed presentation of the experimental setup.

2.1. Geometry and materials

The only difference between both laminated beam sections, depicted in Fig. 1, is the reinforcement section, which is either a solid (a) or a hollow square profile (b). A typical specimen is composed of a 6 mm × 125 mm–10 mm × 105 mm–6 mm × 125 mm triple-layered laminate of annealed float glass (ANG) panes, in