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Numerical analysis of glass-FRP post-tensioned beams – Review and assessment

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ABSTRACT

Architectural trends to include transparency in structural systems lead to the implementation, in the last decades, of structural glass load-bearing components able to substitute traditional construction materials like timber, steel, concrete.

In this paper, the structural bending performance of post-tensioned, glass-FRP hybrid beams is evaluated by means of advanced Finite-Element (FE) numerical analyses. To this aim, a concise recapitulation of existing research on several typologies of glass-FRP hybrid beams is first provided. Based on earlier experimental and preliminary FE research outcomes, further detailed discussion is then proposed for the specific concept of glass-FRP post-tensioned glass beams. FE parametric simulations for quasi-static bending loading configuration and room temperature are compared for such systems, typically including a laminated glass (LG) cross-section and an adhesively connected, post-tensioning FRP tendon. As shown, several aspects should be properly taken into account when investigating the overall performance of these systems, as far as both their elastic and post-cracked performance are highly sensitive to various mechanical and geometrical input parameters. A sensitivity FE study is hence presented, aiming to better explore their typical performance.

1. Introduction

Architectural trends to include transparency in structural systems lead to the implementation, in the last decades, of structural glass load-bearing components able to substitute traditional construction materials like timber, steel, concrete. In most cases, aiming to further enhance the structural performance of a typically tensile brittle material, research studies and design projects have been in fact focused on composite glass systems. Especially for beam structures, composite glass beam systems are explored in which glass is combined with metal, timber or Fibre Reinforced Polymer (FRP) composites [1,2].

For glass-FRP composite beam solutions in specific, it is noted that these are typically obtained by adhesively bonding a monolithic or laminated glass (LG) section (namely representing the web of the so assembled systems) with one or more FRP sections, consisting in various FRP solutions as well as specific geometrical/mechanical properties [3–9].

In this paper, based on [10,11], a specific typology of the recalled glass-FRP solutions is selected, being composed of an LG cross-section with an adhesively bonded bottom tendon consisting of a Carbon Fibre Reinforced Polymer (CFRP) solid section.

As shown, compared to other existing glass-FRP hybrid solutions, the CFRP reinforcement has a double beneficial effect, since it provides additional tensile reinforcement to glass but especially a relevant post-tensioning contribution to the resisting cross-section. As far as the bending performance of such beams has to be optimized, however, several geometrical and mechanical aspects should be properly taken into account and calibrated. To this aim, based on past experimental and preliminary FE studies for the selected hybrid solution [10,11], an FE parametric investigation is carried out in ABAQUS [12] with full 3D solid models, aiming to provide an insight on the potential and criticalities of these rather innovative structural systems.

2. State-of-the-art on glass-FRP beam research

2.1. Experimental research

So far, several researchers experimentally investigated the structural performance of glass-FRP beams characterized by various geometrical features. The common aspect of all the experimental studies available in literature is basically given by hybrid beams

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in which the web consists of a glass pane that is solicited about its major axis, while FRP reinforcements can take several forms.

Despite the variability of possible solutions of glass-FRP beams bending about their major axis, the existing research projects are here distinguished in two major groups, namely (a) reinforced or (b) post-tensioned glass-FRP beams.

Within the group (a) of glass-FRP beams, the bending stiffness and resistance of a traditional monolithic or LG section is generally enhanced via adhesively bonded FRP profiles or embedded rods.

CFRP reinforced glass beams have been first investigated and applied by Palumbo et al. [3]. The beams consisted of a laminated annealed float glass web and an CFRP section which was adhesively bonded at the tensile edge. The concept has been experimentally investigated on scaled beam models and has then been applied in a roof covering for the 'Loggia de Vicari' in Italy. Glass Fibre Reinforced Polymer (GFRP) pultruded profiles have been used in the research project of Correia et al. [4] and Valarinho et al. [5] to act as flanges for I-shaped composite beams. In this respect, the GFRP flanges both act as lateral stiffeners and post-cracking reinforcement In their experimental investigation, the typical I-beam consisted of an annealed glass web and solid/angular GFRP pultruded profiles adhesively connected to glass. The main difference in such specimens was represented by the shape and size of GFRP profiles, by the total span of the beams and by the adhesive connection (type and thickness of adhesive).

A different FRP reinforced glass beam design concept has been explored by Louter et al. [6], that focused on the structural performance of glass beams with CFRP or GFRP cords (both round or flat rods) physically embedded within the interlayer of a traditional laminated glass panel. Speranzini and Agnetti [7] investigated the structural performance of composite sections in which C-shaped pultruded GFRP profiles were used at the bottom of the beam. Speranzini and Neri [8] explored then a further concept of glass-FRP composite beams. Their typical beam configuration consisted in alternating float glass sheets with vertical layers of GFRP, connected to the adjacent glass panels via a two-component epoxy resin.

In terms of (b) post-tensioned glass-FRP beams, few experimental studies only have been carried out. Louter et al. [10], in particular, explored the efficiency of a further design concept, in which a traditional LG beam composed of three annealed glass layers and SentryGlas® (SG) foils was reinforced with a pre-stressed CFRP tendon adhesively connected at the bottom edge of the resisting cross-section, see Fig. 1.

Together with the additional bending stiffness and strength implicitly provided to the LG section by the CFRP tendon, further enhancement of the expected bending performance of the so assembled system was given by the introduction of an initial pre-stressing force P_0 = 13.6 kN in the tendon itself. As such, as also shown in [10], the glass-CFRP beam proved to offer high post-cracked residual resistance and ductility, compared to the reference LG section.

2.2. Finite-Element numerical research on hybrid glass beams

Finite-Element modelling generally represents an efficient tool to assess the overall performance of several structural systems. In doing so, depending on the specific system object of investigation, key aspects are typically represented by the correct mechanical calibration of materials, as well as by the implementation of a realistic reciprocal interaction between the system components, etc. This is especially true in the case FE simulations are aimed to take into account damage propagation and possible failure mechanisms.

In terms of FE simulation of hybrid glass beams, with careful consideration of the post-fracture response of these systems, several research efforts can be found in literature. Most of them include the structural analysis of steel-glass reinforced composite beams, namely obtained by adhesively bonding a stainless steel tendon or reinforcement section and a traditional beam, composed both of monolithic or multilayer LG. Louter and Nielsen [13] first and Bedon and Louter [14] later, for example, explored the bending performance of LG beams with a steel tendon bonded at their tensile edge. The difference between [13] and [14], given the same beam specimens, was basically represented by the FE modelling assumptions for the description of tensile cracking of glass and thus by the corresponding solving approach with the ABAQUS computer software, namely involving – in the first case – a self-made material user subroutine and – in the second case – the "*brittle cracking*" damage model available in ABAQUS for ceramics. The research topic and FE modelling approach presented in [14] was then also explored in [15], giving evidence of structural effects and possible benefits on the overall performance of the same composite beams, due to initial pre-stressing forces applied in the steel tendon.

In accordance with [13] and related FE assumptions, a mostly similar steel-glass design concept was analysed in [16], while Martens et al. [17] further extended the modelling approach proposed in [14], aiming to assess the structural performance of statically indeterminate steel-glass reinforced beams.

Following [11,14,17], in [18] the post-cracked flexural performance of timber-glass hybrid beams was numerically explored and compared to corresponding full-scale experimental results.

LG beams with un-bonded, mechanically anchored post-tensioning steel tendons have been finally investigated in [19], via efficient FE models able to take into account the mechanical behaviour of each beam component, as well as the possible tendon-to-glass interaction during bending. Differing from [14], the "*concrete damaged plasticity*" model originally implemented in ABAQUS for reinforced concrete structures was used, with appropriate mechanical calibration. Careful attention was paid for the pre-stressing stage as well as for the implementation of appropriate mechanical connectors able to describe any possible physical contact and interaction between the steel tendons and the LG beam in bending.

While several FE studies are available for steel-glass reinforced and post-tensioned beams, few FE efforts have been dedicated, on the other hand, to the analysis of the post-cracked performance of glass-FRP hybrid solutions. In Neto et al. [20], for example, the structural behaviour of glass-GFRP beams tested in [4] was numerically investigated. As an alternative to the smeared damage model proposed in [11,14], the FE investigation was carried out based on a Discrete Strong Discontinuity Approach (DSDA) able to account for the tensile brittle nature of glass. In [11], as a further extension of [14], a preliminary assessment of the experimental test results recalled in Fig. 1 for post-tensioned glass-CFRP beams was carried out. Compared to [14], additional attention was spent in the FE implementation of such models, in order to properly describe the post-tensioning phase as well as the related effects on each beam component. The FE results obtained from a reference numerical model (labelled as "M0", in the following sections) generally highlighted the potential of the basic modelling assumptions, as well as the rather close correlation with the corresponding test results (see for example Fig. 2).

As also experimentally observed for the same beam typology, in particular, the overall FE performance of glass-CFRP post-tensioned beams presented in [10,11] was found to be associated to four specific phases, i.e. labeled as A, B, C and D in Fig. 2(a). As far as the beam specimens proved to offer interesting bending potential up to a maximum deflection of ≈25 mm (≈/60 the total span), the first stage of their bending response, up to point A, was basically governed by the linear elastic stiffness of the fully