Composite Structures 167 (2017) 238–250

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Finite Element analysis of post-tensioned SG-laminated glass beams with adhesively bonded steel tendons

Chiara Bedon [a,*], Christian Louter [b]

[a] University of Trieste, Department of Engineering and Architecture, Piazzale Europa 1, 34127 Trieste, Italy
[b] Department of Architectural Engineering and Technology, Faculty of Architecture and the Built Environment, Delft University of Technology (TU Delft), Delft, The Netherlands

ARTICLE INFO

Article history:
Received 27 September 2016
Revised 19 November 2016
Accepted 11 January 2017
Available online 7 February 2017

Keywords:
Finite Element numerical modelling
Experimental testing
Laminated glass
Adhesive joint
Steel tendon
Post-tensioning
Bending performance

ABSTRACT

Taking advantage of past full-scale experimental test results, the bending performance of laminated glass beams with post-tensioned, adhesively bonded steel tendons is explored via refined Finite-Element (FE) models. As far as the primary advantage of the post-tensioned glass beam concept is to provide an initial state of compressive stresses in glass, a marked enhancement of the expected structural performance is expected (i.e. increase of the initial fracture load and redundancy), compared to typically brittle, unreinforced laminated glass beams. Several key aspects can affect the overall performance of such beam typology, first of all the adhesive joint providing the structural interaction between the glass beam and the steel tendon, as well as the geometrical and mechanical properties of each beam component, in relation to the amount of initial post-tensioning force. Based on a first validation of a reference full 3D FE model towards the available past full-scale experimental test results, an extended parametric study is presented in this paper, giving evidence to the effects of several mechanical and geometrical parameters (i.e. steel tendon section, level of the applied post-tensioning force, adhesive joint type and size, etc.) in the bending performance of post-tensioned laminated glass beams at room temperature under quasi-static load.

1. Introduction

In this paper, an extended Finite Element (FE) analysis is proposed to assess the structural in-plane bending performance of post-tensioned laminated glass beams with adhesively bonded steel tendons. In accordance with some reference experimental test results available in literature [1], these post-tensioned glass beams typically consist of a laminated glass web, a bottom stainless steel post-tensioning tendon and an adhesive layer interposed between the tensile (bottom) edge of the laminated glass beam and the steel tendon itself.

Due to the typical tensile brittle nature of glass as well as to its increasing use in buildings and facades in the form of load-bearing structural components – aiming to fully exploit the potential of this rather innovative construction material – the concept of post-tensioned glass beams with steel cables or tendons has been already investigated in the past years. A rather limited number of experimental research projects [2–6] and applications in practice [7] are available, however. The feasibility and potential of laminated glass beams with post-tensioning, adhesively bonded carbon fiber polymer (CFRP) tendons has been also experimentally assessed [5,6]. Some Finite Element extended investigations are also available for the explored post-tensioning design concept [8,9].

Since glass is relatively weak in tension but strong in compression [10], the primary advantage of adding post-tensioning tendons to laminated glass assemblies is to apply a beneficial compressive pre-stress, hence – for the beams object of investigation in the current paper – to enhance the expected overall performance by increasing the initial fracture strength. Secondly, the post-tensioning tendons typically provide safe post-fracture performance and redundancy, since upon fracture of glass the tendons are expected to bridge the cracks and transfer the tensile forces over the cracks themselves. This generates, given a reference post-tensioned glass beam in bending, an efficient internal moment capacity between the tendon and the compressed (top) region of glass, thereby providing the beam significant post-fracture load-carrying performance and ductility.

The post-tensioning of steel or FRP tendons and cables either mechanically anchored or adhesively bonded to glass beams presents a further extension and optimization of the reinforced glass design concept, for which a comprehensive state-of-the-art overview is provided in [11,12].

* Corresponding author.
E-mail address: bedon@dicar.units.it (C. Bedon).

http://dx.doi.org/10.1016/j.compstruct.2017.01.086
0263-8223/

In this paper, based on the past experimental study presented in [1], a further attempt to rationally simulate, explore and optimize the structural response of post-tensioned laminated glass beams with adhesively bonded steel tendons is carried out through advanced, full 3D FE numerical models implemented in the ABAQUS computer software [13].

A short recapitulation of the reference experimental test results is first provided, together with the validation and assessment of the corresponding FE numerical model (M0, in the following sections). The so obtained FE predictions are compared to the test results and critically discussed. As shown, a key role is assigned to a multitude of aspects, including the appropriate description of all the assembling and testing phases (i.e. post-tensioning of the steel tendon followed by bonding with the laminated glass beam and subsequent release of the steel tendon, and successive in-plane bending simulation of the full post-tensioned composite assembly), as well as the accurate mechanical calibration of all the materials and the structural interaction between the specimens components.

Subsequently, the same FE modelling approach is further extended and a parametric FE study – aimed to assess and further optimize the global structural performance of the examined structural typology – is presented. The effects of mechanical as well as geometrical aspects are highlighted, including variations in the steel tendon section, modifications in the adhesive type and thickness, application of different levels of post-tensioning force.

As a first stage of an ongoing research study, based on the available full-scale experimental results, post-tensioned beams subjected to quasi-static monotonic bending loads and room temperatures are taken into account only.

2. Brief summary of past experimental tests

The current research investigation takes advantage of an exploratory experimental study recently carried out at École Polytechnique Fédérale de Lausanne (EPFL) on post-tensioned laminated glass beams with adhesively bonded steel tendons [1]. Within that study, which comprised of eight specimens in total, a series of three full-scale glass beams with adhesively bonded post-tensioning steel tendons were tested in four-point bending.

The typical post-tensioned beam investigated in this paper, having a total span $L = 1500$ mm, consists of a laminated glass (LG) beam composed of three polished edges layers of annealed float glass (6 and 10 mm the nominal thickness of external and middle layers respectively), with a nominal height of 125 mm. Bonding of the glass layers is achieved via SentryGlas® (SG) sheets with nominal thickness 1.52 mm. For the stainless steel tendon (grade 1.4301), a solid cross-section with 25 mm width and 3 mm the thickness is used. An adhesive layer, 0.1 mm in nominal thickness, composed of a two-component epoxy adhesive (3M Scotch-Weld DP490 [14]), is finally interposed between the LG beam and the bottom steel tendon, to provide an appropriate structural interaction between them. At a preliminary stage of the experimental program, the post-tensioned specimens were subjected to an initial post-tensioning force $P_0 = 30$ kN.

Fig. 1 presents the typical cross-section for such specimens, while an overview of the test setup, loading scheme and measured load-deflection curves is summarized in Fig. 2. Additional details related to the assembly and testing of the full-scale experimental specimens can be found in [1].

While the past literature contribution [1] presented a full-scale experimental validation of such design concept, including the comparison with fully unreinforced glass beam specimens (Fig. 1(a)) or post-tensioned beams with mechanically anchored tendons, this research paper focuses on the beam specimens with adhesively bonded, post-tensioning steel tendons, as given in Fig. 1(b), including a critical comparison of experimental and Finite-Element numerical results, as well as an extended parametric investigation.

Based on [1], in particular, given a cross-section like Fig. 1(b) and the test setup of Fig. 2(a), the effect of an assigned initial post-tensioning force P_0 for the steel tendon is expected to manifest in the form of an upward deflection of the fully composite beam, with a corresponding bi-triangular distribution of initial stresses having maximum compressive (absolute) values at the bottom edge of the specimen. Assuming the in-plane bending loads are applied in accordance with the test setup of Fig. 2, in the hypothesis of a fully structural interaction between the LG beam and the steel tendon, the first tensile cracking of glass can be hence prevented as far as the total effect of post-tensioning and bending loads does not exceed the reference tensile resistance of glass σ_{tk}. Furthermore, the actual bending resistance is expected to depend on several mechanical and geometrical aspects, such as the type of glass (i.e. in the case any pre-stressing treatment is used rather than annealed float glass only), as well as the cross-section geometry, beam size and reinforcement percentage, as also studied in [15] for reinforced glass beams. For the current study, however, the main interest in this respect is to investigate the effects of the level of post-tensioning force in the steel tendon on the initial cracking resistance of the post-tensioned glass beams. The post-cracked stage takes in fact further advantage from the steel tendon alone.

The past experimental study presented in [1] typically emphasized the high potential of the explored design concept, with beneficial effects of the post-tensioning tendon – compared to the unreinforced LG section alone – but also in a significant post-fracture resistance and typically ductile collapse mechanism (see Fig. 2(b)).

3. Finite-Element numerical investigation

Based on the available experimental test results [1], an extended investigation of the same design concept was carried out in this paper by means of geometrically and mechanically refined, full 3D solid FE models implemented in the ABAQUS computer software [13], see Fig. 3.

3.1. FE model assembly of the reference model (M0) and solving approach

The FE exploratory investigation was performed by giving careful attention to several aspects, including the mechanical calibration of the constitutive laws for the materials (steel, glass, SG, adhesive), the FE description of the post-tensioning phase and related effects on the full composite assembly, as well as the implementation of an appropriate mechanical interaction between the steel tendon and the laminated glass beam (see also Section 3.3 for further details).

For this purpose, the typical FE model consisted of 3D solid elements for (i) the laminated glass beam, (ii) the stainless steel tendon and (iii) the adhesive layer.

In terms of geometrical features, the nominal dimensions were considered for all the specimens components, see Section 2. 8-Node, brick elements (C3D8R type) available in the ABAQUS library were then used. In doing so, two major meshing approaches were taken into account for each beam component, i.e. a free meshing technique for the laminated glass beam and a regular mesh pattern for the steel tendon and the adhesive layer. In the first case, the average size of the brick elements was set in the range comprised between 1.5 mm and 30 mm (with dense mesh pattern at the tensile edge of the beam, see Fig. 3), in order to