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Experimental and finite element analysis of the long-term behaviour of GFRP-concrete hybrid beams fabricated using adhesive bonding

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ABSTRACT

This paper presents experimental and numerical investigations about the short- and long-term behaviour of a hybrid beam consisting of a GFRP pultruded profile bonded by an epoxy adhesive joint to a reinforced concrete slab. The experimental program included flexural creep tests on GFRP I-profiles and on hybrid beams subjected to constant loads. The deflections and the longitudinal strains were measured in natural environmental conditions and recorded for time durations up to 3500 h. Also, three-dimensional models, based on the incremental form of the linear viscoelastic theory, were proposed to study the evolution of strains and stresses over time for the structures. The results of the sustained-load test show that creep deflections on the order of 27–37% of the initial static deflections were observed for the hybrid beams after about 5 months of loading. It is also found that, for the hybrid beam, the rapid degradation of bond strength, resulted from the combined effect of environmental conditions and applied loading, leads to debonding and subsequently a brutal failure. Furthermore, the finite-element analysis is found to be able to simulate the long-term behaviour of the hybrid beam and help understand the complex changes in the stress state that occur over time.

1. Introduction

In recent years, pultruded glass fibre-reinforced polymer (GFRP) profiles are increasingly used in civil engineering applications as construction materials in both building systems and bridges, due to their favourable properties such as light weight, corrosion resistance, ease of installation and low electromagnetic transparency [1,2]. While pure GFRP structures can be useful, greater benefits appeared with their use in hybrid systems. In particular, hybrid structural systems combining GFRP pultruded profiles and traditional materials such as concrete slabs have been proposed by different authors [3–9] to overcome some mechanical disadvantages of the GFRP pultruded profiles, namely the high deformability, the low elasticity and shear moduli, the brittle failure and the susceptibility to instability phenomena (local and global buckling, web crippling) [4,5,9–11]. Hybrid pultruded GFRP concrete beams, in which a concrete slab is connected to a pultruded GFRP profile by an epoxy bonded joint, represent an economical structural solution for building and footbridge applications. This new hybrid system has been the focus of numerous studies [4–10,12–14]. All the previously mentioned studies showed the high potential of this mixture in terms of structural performance and installation costs.

Tests performed so far on hybrid beams with bonded joints have demonstrated that an adhesive layer can provide a high connection strength and can help to overcome the disadvantages resulting from the traditional assembly techniques such as bolting. In addition, the use of bonded joints has impeded the occurrence of slip which provides a complete shear interaction between the concrete slab and the top flange of GFRP profile [4–7,9,12]. Notwithstanding, the previously mentioned studies have focused mostly on the static mechanical performance and short-term behaviour of such hybrid beams and have proposed accurate models and good methods to determine the strength of hybrid members and to predict their short-term deformation behaviour, as well as other serviceability criteria. Static testing, however, cannot assess the long-term performance and behaviour of the hybrid beams. The potential long-term viscoelastic response of the hybrid beam under loading must be anticipated and accommodated in design, because creep can lead to a gradual decrease of the structural effective stiffness and result in unacceptably large deformations. Nevertheless, the time-dependent behaviour (creep response) of these beams when subjected to permanent load under natural environmental conditions was not thoroughly investigated and remains one of the greatest challenges. It seems therefore essential to improve the knowledge on the long-term behaviour of these bonded structures to ensure the safety and predict their long-term performance under real environmental and loading conditions.

In this context, the aim of the present study, is to contribute to the

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current efforts to increase the knowledge and understanding of the long-term behaviour of hybrid beams. To meet this objective, this study presents experimental and numerical investigations about the creep behaviour of a hybrid beam consisting of an I-shaped GFRP pultruded profile bonded to a reinforced concrete slab. Following a brief review of creep in GFRP-concrete hybrid structures and GFRP pultruded materials, the experimental study conducted by the authors and the numerical formulation of the Finite Element (FE) Methods are presented. Three full-scale tests of simply supported hybrid beams and one full-scale test of a simply supported GFRP pultruded profile subjected to sustained loads for over 140 days are presented herein, of which the variation of the deflection and strains with time is analysed. Additionally, to examine the effects of the environmental agents in the bending strength of the hybrid beams, static bending tests performed on a hybrid beam subjected only to the outdoor environment during the creep tests and on an unaged (control) beam are presented. Based on the incremental form of the linear viscoelasticity theory, three-dimensional FE models are developed to simulate the creep response of the GFRP pultruded profiles and hybrid beams. An ageing generalized Maxwell chain model is used to derive the viscoelastic constitutive law of the concrete, whereas for the orthotropic GFRP-profile, a non-ageing generalized Maxwell chain model is adopted to identify both the longitudinal and shear constitutive laws. The proposed models are subsequently validated against the creep test results reported in this paper. Finally, numerical analyses are then conducted by using the calibrated FE models and the evolution of the displacement, strains and stresses over the time are presented.

2. Literature review

Regardless of the polymer nature of the eventual GFRP profile and of the viscoelastic behaviour of concrete [15], a hybrid beam currently needs to be tested at full-scale under permanent load to validate its structural performance during its service life. This is due to the fact that, till the present time, reasonable doubt exists if, in real civil engineering applications such as footbridges, the structural behaviour and performance can remain sufficient to ensure the safety of hybrid structures. The available scientific literature does not offer much in the way of information concerning the time-dependent behaviour of GFRP-concrete bonded hybrid beams. There are only three studies reported in the literature about the creep response of GFRP–concrete hybrid structures. The hybrid beams in these three studies were made of GFRP pultruded I-section profiles connected to a thin steel fibre reinforced self-compacting concrete (SFRSCC) slab by M10 steel anchors and a thick epoxy adhesive layer [2,16,17]. In the study carried out by Mendes et al. [16], two simply supported beams were tested under uniform bending load during more than 50 days. The authors proposed an analytical model to estimate the long-term deflection using the creep model proposed by Bank [11] for the GFRP profiles and the “CEB-FIP 1990” creep model for the SFRSCC slab. A good agreement between experimental and analytical results was obtained. However, the proposed analytical model did not take into consideration the shear deformability of the GFRP profiles (instantaneous and long-term), which is generally not negligible for GFRP profiles [18,19]. Gonilha et al. [2] presented experimental and numerical investigations on the creep behaviour of a 6-m footbridge prototype under uniform bending load with varying load levels and environmental conditions. The analytical model proposed by the authors to predict the total deflection of hybrid footbridge at midspan was based on the Timoshenko beam theory which takes into consideration the effects of the shearing deformation on the flexural deflection of the footbridge during creep test [20]. The time-dependent flexural and shear moduli of the GFRP pultruded profile were identified using the empirical laws proposed by Bank [11] and/or by EuroComp [21], whereas for the SFRSCC deck the viscoelasticity modulus was calculated by the creep model proposed by Eurocode 2 [22] for normal concrete. The results of this study showed that the mixed model in which the tension creep model proposed by EuroComp and the flexure creep model proposed by Bank were used to identify, respectively, the elasticity and shear moduli of the GFRP profile is able to predict the experimentally-measured deflections with a good accuracy in the different environmental conditions and under the different loading levels. On the other hand, the power laws of Findley were used to predict and fit the experimental data. The comparison between the long-time deflection predicted values of the Findley’s power laws and those of the mixed proposed model showed that the Findley’s power law regressions of short-term experimental tests diverge considerably from the analytical predictions. It was also reported in their study that this type of regression is not adequate for predicting long-term creep deflections in GFRP–concrete hybrid structures due to the fact that the creep behaviour of concrete does not follow Findley’s power law. It is also important to note that the slip at the GFRP-SFRSCC interface and the creep response of the adhesive joint was not taken into account in their study. Recently, Gonilha et al. [17] investigated the creep behaviour of a 11-m footbridge prototype under uniform bending load. The power laws of Findley and the creep model proposed by Eurocode 2 [22] were used respectively to predict the viscoelastic moduli of the GFRP pultruded profile and the concrete slab. Therefore, the time-dependent deflection at midspan was calculated using Timoshenko beam theory. The obtained results showed a good adjustment between the analytical model to the experimental results.

On the contrary, prediction of the deformation and long-term response of FRP materials has emerged as an independent scientific endeavour and attracted the interest of many researchers. There have been numerous published studies on the time-dependent behaviour of pultruded GFRP profiles for civil engineering applications [18,23–30]. One of the first published investigations on this subject was performed by Holmes and Rahman [23]. They tested 3 GFRP box section beams under 4-points bending load for up to 20 months. The experimental results were compared with three empirical equations formulated using the first 2000 h of the experimental data (including Findley’s model). The experimental tensile and shear strains showed relative consistency with the predicted values, while the compression strains did not compare well with any of the models. They could not recommend any model to the exclusion of all others. Bank and Mosallam [18,24] investigated the time dependent behaviour of a portal frame structure constructed from three glass-reinforced vinylester pultruded profiles. The power laws of Findley were used to predict the viscoelastic moduli of GFRP pultruded beam (longitudinal flexural and shear moduli) and the time-dependent deflection at midspan was calculated using Timoshenko beam theory. The predictive models were in good agreement with the measured creep deformations and deflections. Mottram [28] studied experimentally the time-dependent behaviour of panel assemblies constructed from pultruded glass/polyester I-sections sandwiched between pultruded FRP plates. Predictive models for the time-dependent moduli (viscoelastic flexural and shear moduli) and deflections, like that proposed by [24], were developed using the data collected from the experiment. Sá et al. [25,26], recently, investigated the creep behaviour of GFRP pultruded elements at two different scales; small-scale specimens (coupons samples) and full-scale profiles. The experimental results showed that the creep behaviour of the coupon specimens, especially the flange’s specimens, was similar to the behaviour of the full-scale profile. In their analytical study, the authors proposed two approaches to predict the long-term creep behaviour of the tested specimens: (i) a phenomenological approach by using two linear viscoelastic models (Burger–Kelvin model and Prony-Dirichlet series) and (ii) an empirical approach by using the Findley’s power laws. The authors found that the Findley model is the best approach to simulate the creep behaviour of pultruded GFRP materials, in a very long-term analysis. Bottoni et al. [29] developed a FE model for more detailed research on the creep behaviour of pultruded beams under different loading conditions; and Bottoni et al. [30] experimentally investigated the creep behaviour of pultruded GFRP specimens (E-glass/Polyester)