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Structural behavior and inter-layer displacements in CFRP plated steel beams – Optical measurements, analysis, and comparative verification

Christoph Czaderski [a,*], Oded Rabinovitch [b,1]

[a] Empa, Swiss Federal Laboratories for Materials Testing and Research, Überlandstrasse 129, 8600 Dübendorf, Switzerland
[b] Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

The linear elastic structural behavior of steel beams strengthened with externally bonded composite materials is experimentally and analytically investigated. The paper focuses on the full-field inter-layer relative displacements between the beam and the FRP layer. Such displacements result from the interaction between the adhesively bonded components and it is the integrated outcome of the interfacial conditions and the deformability of the adhesive. As such, it is commonly adopted as the state variable in simplified bond shear stress–slip representations. This aspect, as well as other aspects of the global and localized structural response, is analytically and experimentally quantified. The experiment includes a simply supported steel beam strengthened with a CFRP plate. A 3D image correlation technique with sequential measurements is used for the assessment of the full-field inter-layer displacements along the beam. The analysis adopts a high order modeling approach that accounts for the 2D stress and displacement fields through the depth of the adhesive and a 1D shear stress–slip approach using only a linear increasing branch. The comparison between the results provides validation of the analytical and experimental capabilities with emphasis on the inter-layer effects. One of the interesting findings which is discussed and explained in this paper is the fact that the slip values calculated with the shear stress–slip approach are notably different from the ones that can be measured experimentally and determined by the high order model.

1. Introduction

The use of externally bonded reinforcement made of fiber reinforced polymer (FRP) for structural strengthening is a state of the art technique worldwide. The ability to provide an existing structure with an additional layer of high strength, high modulus and light weight reinforcement opens the way to many structural strengthening and upgrading applications. The ease of installation on site, the ability to adjust the geometry of the bonded layer to the surface of the element, and the improved environmental resistance of the composite material contribute to the attractiveness of this strengthening method.

An enormous experimental and analytical effort has been allocated in the past two decades to the investigation of structural elements strengthened with composite materials. In particular, beams strengthened for flexure with externally bonded FRP plates, strips, or sheets were the subject of many experimental and analytical studies. These studies revealed that the FRP strengthened beam is governed by a unique family of physical phenomena. Localized effects near irregular points, debonding failure modes (e.g. [1–6]), relative longitudinal displacements between the adhesively joined components [7], and inter-layer slip are examples of these unique phenomena. In this paper, "slip" is defined as the elastic displacement between two adherents due to deformation of the adhesive or gradual degradation of its interfaces. The relative longitudinal displacement is defined as the difference between the absolute longitudinal displacements of any two selected points located at the same X coordinate, and it includes the slip and other contributions.

The FRP strengthened beam sets significant analytical and experimental challenges. Both challenges stem from the combination of dissimilar components into a unified structural element. In particular, the layered structure and the differences in geometrical scales and elastic properties play a critical role. One of the most important and challenging aspect of the structural behavior of the FRP strengthened beam is the interaction between the existing beam and the bonded FRP layer. This interaction is achieved through a layer of deformable adhesive material. Therefore, the interaction between the components is associated with the evolution of deformations in the adhesive layer. The deformations in the adhesive and the degradation of the interfaces accumulate to relative longitudinal and vertical displacements between the beam

* Corresponding author. Tel.: +41 44 823 55 11; fax: +41 44 823 44 55.
E-mail address: christoph.czaderski@empa.ch (C. Czaderski).
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and the FRP layer. The experimental assessment and the analytical prediction of the relative displacements are critical for understanding, quantifying, and controlling the interaction between the bonded components.

In many cases, the interaction between the bonded components, the bond behavior, and the evolution of debonding mechanism are addressed through a shear stress–slip approach (e.g. [8]). This approach uses a bond shear stress to longitudinal slip relation that attributes the elastic and, in turn, inelastic, slip to a corresponding bond shear stress at an artificial interface between the FRP and the beam. In reality, such interface does not exist but the two materials are joined together through an adhesive layer of finite (and, in most cases, not negligible) thickness. The shear stress–slip approach accounts for some aspects of the elastic or inelastic deformability of the adhesive layer and its interfaces and allows for a relatively simple inelastic analysis that simulates the interfacial damage accumulation (debonding). However, other critical effects and, mainly, the 2D stress and deformation fields in the adhesive itself, the vertical component of the relative displacement (separation), the variation of the stresses through the thickness of the layer, the effect of the shear stress free boundary condition on the stress concentrations near the plate ends, and the coupling between the shear stresses, the normal stresses, and their gradients are not taken into account. This observation highlights the importance of the experimental and analytical quantification of the bond mechanism, the interaction between the components, the deformations of the adhesive layer, and the relative displacements between the beam and the FRP. These aspects, which play a critical role in the modeling of the strengthened beam and in the evolution of the inter-laminar damage (debonding), are addressed here.

The experimental challenges set by the FRP strengthened beam are mainly affected by the different length scales of the physical phenomena. The global scale response due to overall bending is relatively easy to be measured. On the other hand, it is extremely difficult to collect reliable experimental data regarding the behavior of the bonded FRP layer itself and its interaction with the beam through the adhesive layer. By using electronic displacement transducers, the measurement of the relative displacement between the FRP layer and the beam is only possible at some selected points. By using mechanical strain gauges, this quantity can only be measured as a mean value over the length of the mechanical strain gauge, see for example [9]. Other potential measurement techniques include electronic speckle pattern interferometry (ESPI), e.g. [10], moiré interferometry, e.g. [11] or photogrammetry, e.g. [12].

Image correlation is an emerging technology that can be applied to assess the response of FRP strengthened structures. For example, a 2D image correlation measurement system was used in [13] for the assessment of the strains in pull-off tests conducted on FRP composites glued to concrete blocks. The relative displacement between the FRP and concrete was called "relative slip" and was calculated by integrating the FRP axial strain whereas the bond shear stress was determined based on the derivative of the FRP strain and the elastic properties. An image correlation system was adopted in [14] to measure the deformations of the FRP strip in sections between two cracks. A digital image correlation technique was used in [15] to monitor a strip that was glued on a two span beam. In [16], measurements of longitudinal strain in the FRP strip with a 3D image correlation technique were used to evaluate the interfacial shear stresses in FRP strengthened RC beams. Full-field measurements of a RC beam that was strengthened with a CFRP strip by using a 3D image correlation measurement system were presented in [7]. The continuous slip between a CFRP strip and the concrete surface were measured along almost the entire beam length. The measurements showed that not only high local slip occurred in the region of the cracks but also global slip was observed at the strip ends. In this investigation, slip was taken as the relative longitudinal displacements between the externally bonded FRP strip and the outer face of the concrete beam.

The analytical challenges include the modeling and the analysis of the element while taking the global and the local phenomena into account. Analytical methodologies that use a composite section approach with a linear strain distribution (e.g. [17–19]); methodologies that adopts an artificial interface approach and account for the shear stress–slip effect and the longitudinal action of the FRP strip only (e.g. [5,20–23]); and methodologies that extend the shear stress–slip approach to peeling-separation effects (e.g. [24–29]) are found in the literature. A high order model that is based on a layerwise modeling of the entire element and a 2D elasticity representation of the adhesive layer was presented in [30]. This model accounts for a deformable adhesive layer of finite thickness and allows the consideration of the stress field in the adhesive layer, the shear free boundary condition, the local equilibrium conditions, and their impact on stress concentrations near irregular points. Experimental verification of some of the global aspects of the model was presented in [31], however, with the absence of adequate experimental techniques, a refined experimental validation of the capabilities of the model is still called for.

In this paper, the structural response of the FRP strengthened beam and, particularly, the interaction between the bonded FRP layer and the existing beam through the adhesive layer, are experimentally and analytically addressed. A new class of experimental results obtained using a 3D image correlation method are presented. Analytical results obtained through a high order model [30] and a simplified shear–slip model are then compared with the experimental findings. The objectives of the paper are to analytically and experimentally explore the linear elastic response of the strengthened beam and, mainly, the inter-layer displacements between the bonded components, and to provide further validation and verification of the theoretical models. The experimental techniques and the image correlation data acquisition methodology are presented first. They are followed by a description of the high order model (HOM) [30] and a simplified shear stress–slip model (SSM). In both analytical models, the treatment is limited to the linear elastic regime. The experimental and analytical methodologies are used to study the response of a steel beam strengthened with a CFRP layer. Emphasis is placed on the relative longitudinal displacements between the beam and the FRP layer. A discussion of the results, comparison between the analytical and experimental results, and complementary results provided by the analytical models are then presented. A summary and conclusions close the paper.

2. Experiments

The objectives of the paper mainly focus on the fundamentals of the stress transfer mechanism and the evolution of relative longitudinal displacements and "inter-layer slip" between the bonded components. To achieve this, the experimental study examines a FRP strengthened steel beam tested in the linear elastic loading range. The choice of a steel beam (over a reinforced concrete one) allows for a clear identification of the relative displacement between the components and their interaction through the adhesive layer due to its linear response, the absence of cracking, and the controlled surface.

2.1. Setup

A H shaped HEA 120 steel beam is tested in a four point bending scheme with a clear span of 3.0 m. The experimental setup is