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Full scale analysis of FRP strengthened plates with irregular layouts

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ABSTRACT

The analysis of plates, slabs, or walls, strengthened with fiber reinforced polymer (FRP) composite materials, presents multi-faceted analytical, modeling, and computational challenges. Current analysis tools, including 3D and 2D analyses, still face the challenge of handling full scale, realistic, and geometrically irregular FRP strengthened plate-like structures. Consequently, the understanding of the intricate behavior of this increasingly prevalent structural form is far from being complete. Specifically, the ability to locate and quantify stress concentrations along geometrically irregular FRP edges and contours of existing delaminated regions is not fully developed. This paper presents a specially tailored, multi-layered, high-order plate model, and a corresponding triangular finite element, which aims at meeting the modeling and computational challenges. The formulation mitigates shear locking through augmentation of the shear-bending decomposition and its generalization to the case of high-order, multi-layered configuration. It thus enables analyzing FRP strengthened plate-like structures of general geometry, layout, strengthening scheme, and existing, irregular delaminations. The latter feature is realized by introducing an interface modeling which handles different bond/delamination interfacial conditions in a unified approach. The present work helps shedding new light on the complex and irregular stress concentrations that govern the principle failure mechanisms of this multi-layered structural form.

1. Introduction

The use of Fiber Reinforced Polymer (FRP) composite materials to enhance the performance of existing structures has become increasingly widespread in recent years. Modern building codes require structural elements to have increased strength capacities. These requirements are not met in many existing structures because at the time of building, either the code's requirements were less severe or no codes existed. Structural members that require strengthening include beams, columns, and arches, as well as slabs, shear walls, and masonry walls. External bonding of FRP strips or patches to such structural elements to increase their strength has been a preferred choice by many engineers (see Hollaway [1]).

When FRP is used to strengthen plate elements such as slabs and masonry walls, the FRP layer is often applied over a small portion of the plate's surface. Also, this strengthened region is often geometrically irregular, meaning its contours do not coincide with a rectangular axis system. Diagonal FRP strips used to strengthen shear and masonry walls, irregular strengthening schemes around openings in slabs, and strengthening of non-rectangular plates are but a few examples Enochsson et al. [2].

A characteristic feature of FRP strengthened members is that their proper function critically depends on the bond between the structural element and the FRP layer. Experience has shown that failure of FRP strengthened beams is in many cases attributed to a debonding failure. A principal debonding failure mode is the edge-debonding mechanism. This mechanism initiates due to the peeling and shear stresses found in the concrete–adhesive interface at the edges of the FRP sheet. These in turn, cause an unstable propagation of debonding towards the center of the element, usually along the same interface. In FRP strengthened plates, a similar mechanism is possible whereby stress concentration at the edges of the FRP sheets (which take more complex patterns compared with beams) cause the onset of a debonding failure (see Limam and Foret [3]). Another possible interfacial failure mechanism in 2D elements is the delaminated-region debonding which initiates along the contours of existing delaminated regions. Delaminated regions in FRP strengthened structures may be caused by poor workmanship, unleveled bonded surfaces, substrate cracks, etc. As such, they are by nature geometrically irregular (Katunin et al. [4], Xu et al. [5]). Note that the term delaminated region (or delamination) is used here to denote an existing or initial *state* in which there exists a well-defined zone where there is an interfacial separation. The term debonding is used here when referring to the *process* of interfacial separation, where a delaminated region grows into previously

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perfectly bonded regions due to the structural response. In both edge-debonding and delaminated-region debonding, geometric irregularity is at play, stemming either from a non-orthogonal strengthened region, from the curved contours of delaminated regions, or in the general case – from a combination of both. This paper studies the behavior of full-scale FRP strengthened plates with irregular geometric layouts and aims to quantify the impact of such layouts on the stress concentrations that can potentially trigger the initiation of the aforementioned debonding mechanisms.

When considering a modeling approach to FRP strengthened plates, particularly one that aims to capture the salient features associated with the stress concentrations and the irregularity of border contours (contours of FRP patches or contours that delineate delaminated regions), a model must include in the formulation three necessary features:

1. Geometric flexibility that enables modeling geometric irregularities.
2. Interface modeling that enables accounting for bonded as well as delaminated regions in a unified manner.
3. A sufficiently rich displacement field in the adhesive layer to capture the peeling and shear stresses and their high gradients along border contours, which either separate strengthened and un-strengthened regions or delineate irregular delaminated regions. Specifically, the displacement fields must allow for at least a linear distribution of the transverse normal stresses across the thickness of the adhesive layer and they must account for the stress concentrations that are governed by the 3D coupling of all stress components.

Existing modeling approaches to FRP strengthened plates adopt almost exclusively the Finite-Element (FE) method. The 3D nature of the problem, the localized effects, and the geometric irregularity make analytical solutions unfeasible. 3D continuum based FE formulations seem to be the most straightforward approach to dealing with the intricacies of the physical problem at hand. However, such an approach turns out to have a very high computational cost due to the orders-of-magnitude differences of length scales in this problem. While the order of magnitude of the thickness of the adhesive and the FRP is 10^0 mm, the plate's thickness and in-plane dimensions are 10^2 mm and $10^3 - 10^4$ mm, respectively. The characteristic length scale that governs the stress concentration at the border contours corresponds to the smallest length scale of 10^0 mm. Considering these two features in the context of an FE mesh, on the one hand, very small elements are required in the adhesive layer to capture the high stress and deformation gradients, and on the other hand, the mesh has to extend throughout the plate's volume. This results in too many elements and DOF's for practical application. Due to the excessive computational effort involved in such 3D FE model, several works either ignore the adhesive layer as such or represent its structural behavior by simplified means, (e.g Kim et al. [6], Enochsson et al. [2], Elsayed et al. [7] and Lesmana and Hu [8]). Such approaches cannot account for the high stresses and deformation gradients responsible for the initiation of debonding mechanisms (Kim et al. [6]). A 3D FE model that accounts for the adhesive layer using a corresponding refined mesh has not been found, probably because the excessive computational effort associated with such an analysis renders it unfeasible.

Milani [9] used a different type of 3D approach to FRP strengthened plate-like elements and analyzed the limit state of FRP strengthened masonry walls. 4-noded, rigid tetrahedrons were used to model bricks and stones, 3-noded rigid elements were used to model the FRP layer, and interface elements of zero thickness were used to model the mortar and the adhesive layers. The model focused on the limit state analysis, taking into account in an approximate way delaminations. It did not look into the localized effects focused in the adhesive layer or into the combined global–local phenomena that evolve near the delaminated region.

2D structural finite elements, in which displacement fields through the thickness of the layers are assumed and meshing through the thickness is avoided, are more computationally feasible than detailed 3D solid elements. Elmalich and Rabinovitch [10–12] presented a series of such FE formulations for FRP strengthened walls. All of them feature a bilinear rectangular element with a high-order displacement field in the adhesive layer, which allows capturing the stress conditions at the boundaries of the delaminated region. However, the types of elements formulated limited the analysis to layouts and delaminated regions that are outlined by straight lines. In the later works [11,12], non-linear strain terms which allow capturing wrinkling in the FRP layer and different possible bonding and contact conditions at the interfaces were incorporated. The shortcomings of these formulations are that realistic, irregular, border contours (e.g. curved delaminations, diagonal FRP strips) cannot be accounted for and that analyses of real size problems still involve an excessive computational load. This drawback is partially attributed to the inability to locally refine the mesh. Teng et al. [13] proposed two 2D finite element formulations that attempt to capture in-plane slip between the concrete and FRP layers. The first formulation included a zero thickness layer instead of the adhesive layer. In the other, the adhesive layer was modeled as a Reissner–Mindlin plate. Both approaches neglect the deformability of the adhesive layer in the thickness direction and the need to capture the stress and deformation gradients. In addition, both works use rectangular elements, which cannot effectively model geometrically irregular problems. Marjanović et al. [14] presented a rectangular 9-node FE model for delamination analysis in multi-layered plates. However, a linear in-plane displacement and a constant transverse displacement across the thickness of the layers were assumed. Such a displacement field does not allow capturing the high gradients in the adhesive layer, particularly the variation of the transverse normal stress.

The literature review shows that a computational tool capable of a full-scale analysis of FRP strengthened plates with realistic, irregular layouts and delaminations is not available yet. The models found in the literature do not possess the aforementioned three necessary features for the task at hand, which points to a knowledge gap in the understanding of the behavior of FRP strengthened plates and walls.

The objective of this paper is therefore to gain insight into the structural response of full-scale FRP strengthened plate structures with realistic, geometrically irregular layouts and delaminated regions. This includes the global structural response as well as the non-uniform and steep interfacial stress distributions along border contours. Emphasis is placed on irregular strengthening schemes used in engineering practice, on irregular delaminated regions, and on the analytical and numerical tools needed for their handling. To achieve these goals, an analytic model and a specially tailored triangular finite element model, are developed. These include the aforementioned necessary features for the task at hand. Specifically, the multi-layered, triangular finite element includes:

a) Special interface modeling to account for various possible bond/delamination conditions at the physical interfaces of the strengthened plate;
b) A high-order displacement field in the adhesive layer to account for stress concentrations along border contours;
c) Geometrically non-linear strain terms.

In addition, computational efficiency is gained through the ability to refine a triangular mesh very locally. Integrating all these features, the present formulation aims at overcoming the limitations of the other elements, and handling irregular configurations of full scale FRP strengthened structures.