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Finite element prediction of interfacial stresses in structural members bonded with a thin plate

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ABSTRACT

The strength or stiffness of a reinforced concrete (RC), metallic or timber member can be increased by bonding a thin FRP or steel plate to its external surface. In such plated members, debonding of the thin plate from the original member is often the controlling failure mode, and such debonding depends strongly on the interfacial stresses in the adhesive layer between the member and the plate. This paper is concerned with the prediction of these interfacial stresses using the finite element method. The paper is primarily focused on simply-supported straight plated beams subjected to a uniformly-distributed load as a widely studied benchmark case. Five different finite element modeling approaches based on different assumptions for the deformations of the three components of such a plated beam (beam, adhesive layer and plate) are described. The predictions of the five models are then compared with each other and with analytical solutions of different levels of sophistication. These comparisons illustrate clearly how each assumption affects the predicted interfacial stresses and identify the beam–spring–beam (B–S–B) model as a relatively simple yet sufficiently accurate model for practical use in predicting interfacial stresses and debonding failure in more complex structural members bonded with a thin plate. To illustrate the versatility and power of the B–S–B type model, interfacial stresses in two more complicated structures (a plated flat panel and a plated curved panel) obtained from the same type of model are presented and discussed. These results provide useful insight into the risk of debonding in such plated panels.

1. Introduction

The strength or stiffness of a reinforced concrete (RC), metallic or timber member can be increased by bonding a thin FRP or steel plate to its external surface. In such plated members, debonding of the thin plate from the original member is often the controlling failure mode (e.g. [1,2]), and such debonding depends strongly on the interfacial stresses in the adhesive layer between the member and the plate. This paper is concerned with the prediction of such interfacial stresses using the finite element (FE) method.

Almost all existing studies on interfacial stresses in plated structural members have dealt with only simply-supported straight beams (or one-way slabs/panels) of constant section bonded with a thin tension-face plate and subjected to simple loadings. The only exceptions appear to be the study by Stratford and Cadei [3] which covered beams of varying section and the study by De Lorenzis et al. [4] which developed an approximate analytical solution for plated curved beams. Most existing studies on debonding failures of plated members have also been concerned with such plated beams [5]. Given this background, the present paper is also primarily focused on simply-supported straight plated beams subjected to a uniformly-distributed load as a widely studied benchmark case.

Most of the existing studies on interfacial stresses in plated beams are analytical, but rigorous numerical studies also exist (e.g. [5]). Among the analytical solutions, many are based on the assumption that the interfacial shear and normal stresses are constant across the thickness of the adhesive layer, although this assumption is not always stated clearly in the analysis. For a review of solutions of this type and a comparison of their differences, the reader is referred to the paper by Smith and Teng [6]. Analytical solutions of this type developed after the work of Smith and Teng [6] include Deng et al. [7], Stratford and Cadei [3], Tounsi [8], Yang and Wu [9] and De Lorenzis et al. [4], Tounsi and Benyoucef [10], and Tounsi et al. [11]. The recent solutions of Tounsi [8], Yang and Wu [9] and Tounsi et al. [11] examined the effect of shear deformation in the beam on interfacial stresses, but Tounsi's solution [8] is in serious error [9]. In addition, Al-Emrani and Kliger [12] and Benachour et al. [13] presented solutions of this type for interfacial stresses in beams bonded with a prestressed FRP plate. The advantage of these simple approximate solutions is that they lead to relatively simple closed-form expressions for the interfacial stresses. However, this simplicity means that the predicted interfacial shear stress reaches its maximum value at the

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List of abbreviations

FE	Finite element
UDL	Uniformly distributed load
RC	Reinforced concrete
PA	Plate–adhesive interface
MA	Middle adhesive section
AB	Adhesive–beam interface
B–2D–B	Finite element model in which the beam and the bonded plate are both modeled using beam elements (B) while the adhesive layer is modeled using plane stress elements (2D)
2D–2D–2D	Finite element model in which the beam, the adhesive layer and the bonded plate are all modeled using plane stress elements (2D)
B–S–T	Finite element model in which the beam is modeled using beam elements (B), the adhesive layer using spring elements (S) and the bonded plate using truss elements (T)
2D–2D–B	Finite element model in which the beam and the adhesive layer are both modeled using plane stress elements (2D) while the bonded plate is modeled using beam elements (B)
B–S–B	Finite element model in which the beam and the bonded plate are both modeled using beam elements (B) while the adhesive layer is modeled using spring elements (S)
S–S–S	Finite element model in which the panel and the bonded plate are both modeled using shell elements (S) while the adhesive layer is modeled using spring elements (S)

end of the adhesive layer, which violates the condition of a stress-free end of the adhesive layer. The interfacial stresses from these solutions are similar to those at the mid-adhesive section (MA section) from a rigorous FE analysis using plane stress elements [5], but the more complex variations of the interfacial stresses within the adhesive layer cannot be captured by them.

To overcome the limitations of the simple approximate solutions, more accurate higher-order analyses have also been presented (e.g. [14–18]) in which some of the assumptions used in the approximate solutions are removed. Typically, the higher order solutions predict a zero shear stress at the ends of the adhesive layer, and cater for the variations of stresses across the adhesive layer thickness. The precise limitations of these higher-order solutions are somewhat unclear and need further clarification.

Between the simple approximate analytical solutions and a 2D elasticity solution as approximated by a full 2D FE model for a plated beam where the beam, the adhesive layer and the plate are all represented by plane stress elements (e.g. [5]), many possible solutions exist, depending on the assumptions adopted. A 2D solution is the most accurate solution possible if the widths of the original beam, the adhesive layer and the bonded plate are the same. The higher-order solutions mentioned above are examples of intermediate solutions between these two extremes. While these intermediate solutions may be pursued analytically, a more direct and flexible approach is to use the FE method which can cater for any geometric (e.g. curved beams; two-way slabs), sectional (e.g. tapered beams), loading (e.g. a linearly varying distributed load) and boundary (e.g. continuous beams) conditions. In this paper, five different FE modeling approaches based on different assumptions of the deformations of the three components (beam, adhesive layer and plate) of a plated beam are described. The predictions of the five models are then compared with each other and with analytical solutions of different levels of sophistication. The aims of these comparisons are to illustrate clearly how each assumption affects the predicted interfacial stresses, to assess the limitations and accuracy of the existing analytical solutions, and to examine the advantages and disadvantages of the different FE modeling approaches. The conclusions drawn from these comparisons can be used to guide future investigations into interfacial stresses in all kinds of plated structural members. These comparisons illustrate clearly how each assumption affects the predicted interfacial stresses and identify the beam–spring–beam (B–S–B) model as a relatively simple yet sufficiently accurate model for practical use in predicting interfacial stresses and debonding failure in more complex structural members bonded with a thin plate. To illustrate the versatility and power of the B–S–B type model, interfacial stresses in two more complicated structures (a plated flat panel and a plated curved panel) obtained from the same type of model are presented and discussed.

Table 1
Material properties of a plated concrete beam.

Component	Elastic modulus (MPa)	Poisson's ratio
Concrete beam	30,000	0.18
Adhesive	3,000	0.35
Soffit plate	200,000	0.3

It should be noted that the three components of a beam are all assumed to be linear elastic in the present study. This linear elastic materials assumption should not be seen as a significant deficiency of the study as in plated metallic and timber beams, all materials are expected to remain linear elastic before the initiation of interfacial failure near a plate end. In plated RC beams, cracking of concrete is more likely to affect plate end interfacial stresses, but as the plate ends are normally located in a low moment zone (e.g. near the support of a simply-supported beam), such a linear elastic analysis is still of great value in understanding and predicting plate end debonding failure [19].

It should also be noted that the term "interface" is used in two different ways in this paper. It is used to refer to the adhesive layer which forms the interface between the beam (or the original structural member in the general case) and the thin bonded plate when the physical thickness of the adhesive layer is not a significant issue apart from its effect on the stiffness of the adhesive layer. It is also used to refer to one of the two physical interfaces, the plate-adhesive (PA) interface and the adhesive-beam (AB) interface.

2. FE modeling approaches

A simply supported RC beam (Fig. 1) bonded with a steel soffit plate under a uniformly distributed load (UDL) was chosen as the benchmark beam to be studied. All three components of the plated beam were assumed to be linear elastic and isotropic. The span of the RC beam is 3000 mm, the length of the plate is 2400 mm, and the UDL is 30 kN/m. The geometric and material properties of all three components are given in Fig. 1 and Table 1 respectively. The material properties are those used by Shen et al. [15].

Five FE models with different degrees of simplification (Fig. 2) were built to analyze this problem (Fig. 1). The following types of element were used and are denoted using suitable characters in the parentheses: plane stress elements (2D), beam elements (B), shear-tension (or shear only) spring elements (S), and truss elements (T). Depending on the types of elements used, a model can be referred to using a set of characters representing the three types of elements used to model the beam, the adhesive layer and the bonded plate respectively (Fig. 2). For example, in a B–2D–B model, the beam is modeled using beam elements, the adhesive layer