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Analytical solution for interaction forces in beams strengthened with near-surface mounted round bars

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HIGHLIGHTS

- Analytical solution to interaction forces in NSM FRP round bar-strengthened beams.
- Formulation of the tangential interfacial stiffness of adhesive layer.
- Formulation of the normal interfacial stiffness of adhesive layer.
- The proposed analytical solution gives accurate predictions.

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ABSTRACT

The use of near-surface mounted (NSM) FRP composites for strengthening RC beams in flexure has become increasingly popular in the last decade. Compared to the externally bonded (EB) FRP strengthening method, the bond between FRP and concrete is much stronger when the NSM FRP strengthening method is used. However, debonding is still a likely failure mode in RC members strengthened with NSM FRP bars. The debonding in an NSM FRP-strengthened beam may initiate from either of the two ends of an NSM bar (i.e. end debonding) in the form of interfacial debonding or concrete cover separation, both of which are closely related to the existence of large localized interaction forces between the NSM bar and concrete near the bar ends in such beams. This paper presents an analytical solution for the interaction forces in RC beams strengthened with NSM FRP round bars, which are one of the most popular types of FRP bars used for NSM strengthening. The key elements of the proposed analytical solution are two interfacial stiffness parameters (i.e. tangential interfacial stiffness and normal interfacial stiffness). The validity of the proposed analytical solution is also verified using a sophisticated 3D FE model of a RC beam strengthened with a NSM round bar.

1. Introduction

In the past two decades, fiber-reinforced polymer (FRP) composites have become increasingly popular for flexural strengthening of reinforced concrete (RC) beams e.g. [1–4]. The most common way of FRP strengthening of RC beams in flexure is to externally bond (EB) FRP onto the soffit of a beam. This method has been extensively studied, and guidelines have been established for design use. More recently, the near-surface mounted (NSM) FRP strengthening technique has attracted significant attention worldwide as one of the promising new techniques for structural strengthening and as an effective alternative to the externally bonded FRP technique e.g. [1,5]. The NSM FRP technique involves cutting grooves in the concrete cover, filling the grooves with adhesive, and embedding FRP bars into the grooves [1]. FRP bars of various cross-sectional shapes may be used in the NSM strengthening, among which round and rectangular bars have been most commonly used. A typical schematic of NSM FRP for flexural strengthening of RC beams is shown in Fig. 1. Compared to the EB FRP method, the NSM FRP method has a number of advantages including better protection of the FRP reinforcement and a much stronger bond between FRP and concrete [6]. However, the improved bond effectiveness does not preclude the possibility of debonding failure of NSM FRP bars, and indeed debonding is still a likely failure mode in RC members strengthened with NSM FRP bars e.g. [3]. The debonding in an NSM FRP-strengthened beam may initiate from a major intermediate crack (i.e. IC debonding), or from either of the two ends of an NSM bar (i.e. end debonding). For the latter case which is more often observed, the failure may be in the form of interfacial debonding which occurs near the adhesive-to-concrete interface, or in the form of concrete

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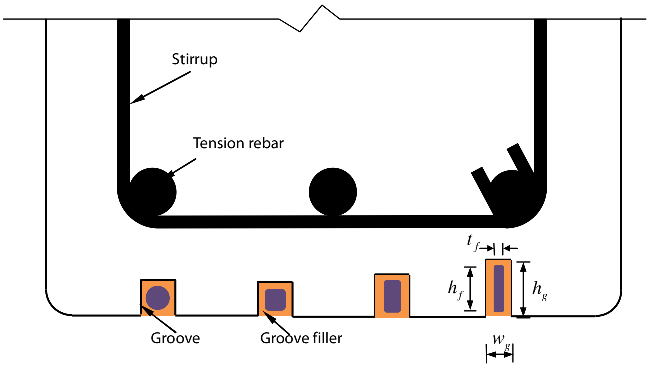


Fig. 1. Schematic of NSM FRP strengthening systems.

separation where the NSM CFRP bars and the concrete cover are torn off along the level of the steel tension reinforcement (as shown in Fig. 2). Both plate end cover separation and interfacial debonding are closely related to the existence of large localized interaction forces between the NSM bar and concrete near the ends of the bar in such strengthened RC beams [7].

For RC beams strengthened in flexure with EB FRP/steel plates (referred to as “plated RC beams” for brevity), a large number of closed-form analytical solutions have been developed for the interfacial shear and normal stresses. These include analytical solutions based on the direct deformation compatibility consideration e.g. [8–16], solutions based on a staged analysis approach e.g. [17–20] and solutions based on the complementary energy approach e.g. [21–23]. Among these analytical solutions, Smith and Teng’s solution [10] appears to be one of the most cited solution because of its accuracy and relatively simple form. This solution by Smith and Teng [10] has been used by many researchers as a standard reference solution to verify results from their own solutions, and has also been extended to consider additional issues such as thermal loading e.g. [11], the shear deformation effect e.g. [12–15] and beam curvature [18]. Recently, Zhang and Teng [7] proposed a closed-form solution for the interfacial interaction forces in RC beams strengthened with NSM rectangular FRP bars based on Smith and Teng’s solution [10]. Zhang and Teng’s solution [7] includes the establishment of approximate equations for the interfacial stiffness parameters, and has been demonstrated by a 3D linear elastic finite element (FE) model.

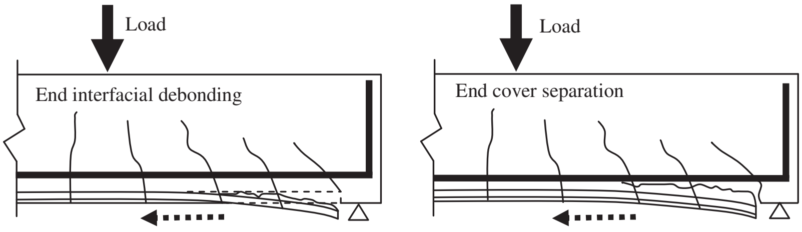
This paper aims to develop closed-form analytical solutions for the interaction forces in RC beams strengthened with NSM round FRP bars. The present study generally follows the approach taken by Zhang and Teng [7] for NSM rectangular bars, with the establishment of interfacial stiffness parameters being a key issue.

2. Analysis approach

Smith and Teng [10] developed analytical solutions for interfacial stresses in FRP/steel plated RC beams, which is essentially a plain stress problem with the width of the adhesive layer being equal to that of the FRP/steel plate and the thickness of the adhesive layer being a constant. Smith and Teng [10] assumed the interfacial stresses to be constant across the width and thickness of the adhesive layer, and obtained closed-form solutions for both interfacial shear stresses and interfacial normal stresses based on deformation compatibility.

Different from plated RC beams, the adhesive layer is not a plane layer in an RC beam strengthened with an NSM FRP bar. Such an NSM FRP-strengthened beam is therefore a truly 3-D problem. In order to derive a closed-form solution for such beams by extending Smith and Teng’s solution [10], Zhang and Teng [7] proposed to simplify this problem into a plane stress problem (Fig. 3). To do this, Zhang and Teng [7] introduced a pair of interfacial interaction forces per unit length of the NSM bar-to-concrete interface (i.e. F_t and F_n, see Fig. 3). Here, F_t and F_n are the interaction forces in the tangential direction and the normal (vertical) direction respectively; subscripts t and n denote the tangential and the normal directions respectively. Correspondingly, Zhang and Teng [7] also introduced two interfacial stiffness parameters, namely, the tangential interfacial stiffness k_t and the normal interfacial stiffness k_n (Fig. 3b), which are defined to be the interfacial interaction forces between the NSM bar and concrete per unit length corresponding to a unit relative displacement between the NSM bar and concrete in the designated direction (see Fig. 4). In order to obtain k_t and k_n, the following procedure was adopted by Zhang and Teng [7]: (1) obtaining the stress distribution within the adhesive layer using finite element (FE) analysis; and (2) calculating k_t and k_n by integrating stresses along the mid-thickness path of the adhesive layer, based on results from the FE analysis. With the interfacial stiffnesses k_t and k_n obtained above for NSM bar-to-concrete interface, Smith and Teng’s solution [10] can be extended for NSM FRP-strengthened concrete beams.

Zhang and Teng’s approach [7] was shown to perform well for beams strengthened with rectangular NSM FRP bars. However, when a round bar is used for NSM strengthening, the thickness of adhesive layer is typically non-uniform over the perimeter of the bar (Fig. 1). It is thus inconvenient to use the mid-thickness path of adhesive layer for integration of stresses as did by Zhang and Teng [7] to obtain the interfacial stiffness. Therefore, instead of integrating stresses, the interfacial stiffness parameters were obtained directly based on their definitions (see above) in the present study, making use of FE models. According to the definitions of interfacial stiffness parameters, the interaction force between the NSM bar and concrete per unit length needs to be found out for a unit relative displacement between the two in the designated direction. Therefore, the FE models consisted of an NSM round bar, the surrounding adhesive layer and the groove surface which was set to be a fixed boundary of the adhesive layer. With such FE models, the interfacial stiffness was just equal to the total reaction force of the boundary (i.e. the groove surface) when a unit displacement (i.e. 1 mm) was applied to the NSM bar in the designated direction. Details of the FE models are further discussed later.



(a) End interfacial debonding (b) End cover separation

Fig. 2. Schematic of end debonding failures.