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An analytical model and stress analysis of one-side bonded composite patch to metal reinforcement

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ABSTRACT

In this work, a novel, analytical and realistic model has been developed to investigate the stresses of bonded composite patch reinforcement to metallic plates that accounts for the effects of large deflections both outside and inside the overlap. The model is designed to deal with the one-side bonded reinforcement and it is able to compute axial tension force, bending deflections, and interfacial stresses of the bondline and interlaminar stresses throughout the patch. A comparison study with numerical simulation indicates that shear and peeling stresses from present methods generally match very well with finite element results, except for the peak values near the free edge. The present solution predicts larger peak values, which may be caused by the assumption of identical displacement in both the substrate and the patch and the effects of large deflections. Present work may provide a rapid and accurate solution to the stress analysis and design of bonded composite patch reinforcement to metallic structures after uniform corrosion.

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1. Introduction

A bonded composite repair consists of a fiber reinforced composite patch that is bonded to a damaged or weakened structure to reduce stresses and prevent or reduce continuing damage or crack growth. From a geometrical consideration, bonded repairs fall into two categories: two-side (symmetric, balanced) and one-sided (asymmetric, unbalanced). In the former case two identical reinforcements are bonded on the two surfaces of a damaged plate. This symmetric arrangement ensures that there is no out-of-plane bending over the repaired region, provided the damaged plate is subjected to extensional loads only. In actual repairs, however, one-sided repair is often adopted, in which composite patch is applied and attached to only one side of the panel [1–3]. This is because that most often only one face of the structure to be repaired is accessible and sometimes only one side of a structure is allowed to be patched. The out-of-plane bending caused by the shift of the neutral plane away from that of the plate being repaired increases the stress intensity in the parent plate and causes additional adhesive peel stresses and bending stress. Thus, if these factors are not properly accounted for in the analysis, it could lead to premature failure. Bending effect may considerably lower the repair efficiency, as recognized by a number of authors in the literature [5–8]. This paper shall focus on analysis of stresses, deformations and bending effects of one-sided reinforced plate.

As an efficient and cost-effective means of repairing damaged structures, bonded composite patch repair technology has been continuously receiving attention for enhancing fatigue resistance and restoring the stiffness and strength of the structures [1–5]. Compared to conventional repair technology, some of the main advantages of adhesively bonded patch repairs are: the ability to join dissimilar materials and damage-sensitive materials, smooth stress distribution, weight reduction, easy fabrication of complicated shapes, excellent thermal and insulation properties, compatible vibration response and enhanced damping control, smoother aerodynamic surfaces and an improvement in corrosion and fatigue resistance. To successfully apply this technique to practical problems, a deep understanding of the failure behavior of adhesively bonded repairs is needed in order to fully achieve the benefits of adhesive bonding or bonded joints [9–15]. Accurate stress analysis is essential for understanding the failure of bonded composite patch reinforcements. One important aspect in designing a bonded patch is stress analysis and strength prediction. As a bonded patch is similar to an adhesive-bonded joint, the concepts and methodologies developed for analyzing stresses in bonded joints can be readily applied to conducting stress calculation for a bonded patch. There is a large amount of literature on stress analysis of the bonded joints in the literature.

The well-known analysis of the single lap joint by Goland and Reissner (GR) [16] provided important contributions to the stress analysis of adhesive joints by clarifying not only the importance of adhesive peel stresses in joint failure, but also the role of bending deflections of the joint in controlling the level of the stresses in the

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adhesive layer. Subsequent efforts have devoted to the need for corrections to the Goland and Reissner solution.

Hart-Smith (HS) [17,18] suggested that such an approach was inconsistent with the force and moment distributions of the individual adherend at either end of the overlap. To deal with this situation, Hart-Smith provided a modified analysis that leads to predictions for the lateral deflections of the system, which departed radically from those of the GR solution. In his modified solution, Hart-Smith treated the individual adherend as a decoupled beam in order to apply end conditions to the adherend independently as a means of correcting what were perceived to be the deficiencies of the GR solution. In the course of this analysis, the effect of bending deflections on the moment distribution in the overlap region was omitted. The departure of the Hart-Smith predictions from that of GR solution was strongly influenced by this aspect of the analysis and need to be reconsidered.

Oplinger [19] presented a more detailed analysis. Departing from the analysis of Goland and Reissner, he took into account the effects of large deflections both outside and inside the overlap, also considering the individual deformation of the upper and lower adherends in the overlap. Oplinger found similar results to those of GR solution for large adherend to adhesive layer thickness ratios, and substantial differences for relatively thin adherends. In Oplinger's model, substrate and the patch must have the identical thickness, which restricts his solutions to be applied in practical analysis.

Compared to the large amounts of literature in bonded joints, the stress analysis of bonded reinforcement has been seldom addressed in the literature. Moreover, the above analytical methods mainly focus on obtaining the adhesive stresses, while generally ignoring stresses in the adherend, particularly the interlaminar stresses, which are known to be the key contributor to failure of laminated composite patches.

Correct calculation of stress distributions in bonded reinforcement is of key importance for proposing proper design rules or codes suitable for structural bonded repairs. A closed-form solution for the stress analysis of an unbalanced repair has been developed in the present work with an extended approach following from the Oplinger solution for a single-lap joint. This new model can handle different thickness and materials of the adherend overcoming the deficiencies of identical thickness in Oplinger's model. A conventional 1D-beam model is employed for calculating the load transfer between the substrate and the patch via the adhesive. The issue of the influence of bending deflection in the single-sided reinforcement is investigated through the use of a more realistic model in which adhesive 1ayer deflection is allowed to decouple the two halves of the repair in the bending deflection analysis, while retaining the influence of lateral deflections on the moment distribution in the overlap region as well as in the remainder of the reinforcement. The resulting formulation provides an alternative method of correcting for the deficiencies which Hart-Smith perceived in the GR bending analysis, while maintaining a realistic treatment of the moment distribution in the center parts of the bonded joint. Interfacial shear stress in the adhesive layer is related to the longitudinal displacement difference between the top of the substrate and the bottom of the patch. Interfacial normal stress is related to vertical deformation compatibility between substrate and the bonded patch. After the distributions of the normal internal force in the patch and flexural deflection along the substrate as well as peel and shear stress distributions in the adhesive are calculated, we further study the general two dimensional stress state in the patch. By solving the two dimensional equilibrium equations and using appropriate boundary conditions, we can determine the transverse stress in the patch. The present integrated solution provides a useful but simple tool for understanding the bond behavior and for exploitation in developing a design rule.

2. Definition of the problem and assumptions

The geometric configuration of steel plate bonded by one-sided composite patch is shown in Fig. 1. The length of patched region is $2l$. The unpatched length is l_0, respectively. The applied tension load is T_0.

In this work, both the substrate and patch, as well as adhesive layer, are modeled as linear elastic material. Deformations of substrate and patch are caused or driven by bending moments, axial and shear forces. The adhesive layer is assumed to be subjected to constant stress distribution across its thickness.

Under normal stress in the transverse direction, the adhesive layer will deform, so that the vertical displacement at the bottom of patch differs from that at the top of substrate. These thickness-wise deformations of the adhesive are assumed to have a negligible effect on the interfacial shear stress distribution to transfer the load. That is, in finding the interfacial shear stress, the flexural displacement in the substrate and the patch is assumed to be equal, so that it decouples the governing partial differential equations. The same assumption has been used in literatures [20,21]. This assumption is not used in the determination of interfacial normal stress.

3. Deflection in unpatched segment

The loads, force resultants and displacements of unpatched segment are shown in Fig. 2.

The equilibrium equations are given by

$$T_s = T_0 \tag{1}$$

$$M_s = T_0 w \tag{2}$$

The stress–strain relationships of steel plate are expressed as

$$M_s = D_s w_{,xx}; \quad D_s = \frac{1}{12} E_s t_s^{\,3} \tag{3}$$

Substituting into Eq. (2) gives

$$D_s w_{,xx} - T_0 w = 0 \tag{4}$$

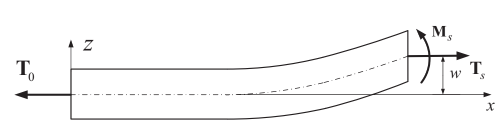

Fig. 2. Loads and displacement of unpatched segment.

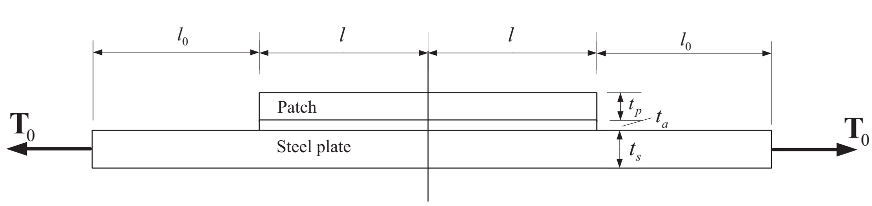

Fig. 1. Steel plate one-sided bonded by composite patch.

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