Chapter 1

Introductory Chapter: Structural Adhesive Bonded Joints

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Additional information is available at the end of the chapter

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1. Introduction

Adhesives produced from the traditional tools have been used for thousands of years. The advantages of using adhesively bonding techniques instead of classical mechanical fasteners can be listed as joining similar/dissimilar materials, significantly reducing the stress concentrations, providing more-uniform stress distributions along the overlap length, savings in weight and cost, eliminating any cuts/holes in the joint, etc. Adhesive bonding is often an appropriate choice for joining similar/dissimilar substrates (various substrate combinations, e.g., metal-to-metal, metal-to-composite, metal-to-rubber, metal-to-glass, metal-to-wood, etc.). Subject of adhesive bonding is also multidisciplinary in nature since it deals with adhesives drawn from the disciplines of chemical, mechanical, medical and medicine, biological, and other sciences. Adhesives have therefore become a key research area because of their potential applications. Today, adhesives are used extensively in aerospace, industrial, and medical applications. Three basic types of adhesively bonded joints used commonly are shown in **Figure 1**.

Choosing an appropriate joining technique is important to have strong joints. Single lap-joint (SLJ) is a simple joint type that allows for joining two adherends easily (**Figure 1a**). The slope of the scarf is the main factor determining the stresses developed on the inclined section of scarf joints (**Figure 1b**). Butt joint is another simple joining technique, and can have some disadvantages due to the small overlap area (**Figure 1c**). Each lap-joint type has therefore comparative advantages and disadvantages over the others. It is therefore important to choose the appropriate lap-joint type considering the application purposes. In addition to joint types, mechanical properties of adhesive/adherend materials, overlap length, thicknesses of adhesive/adherend, etc., affect stresses developed in the joint and hence the joint strength.

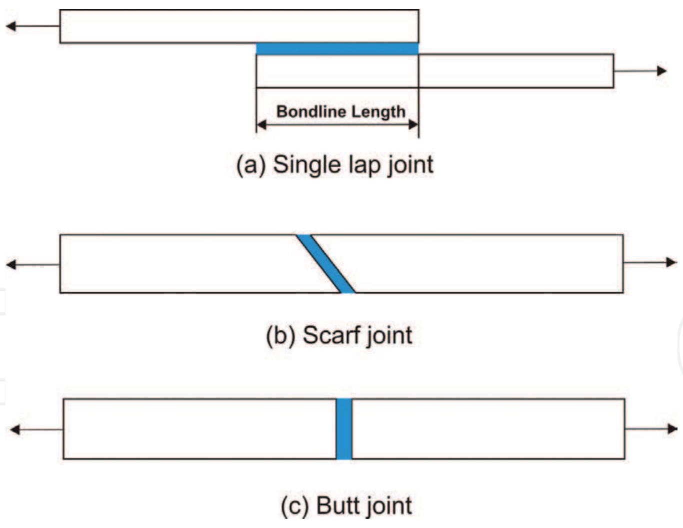

Figure 1. Three basic types of adhesively bonded joints.

This study aims to review some advancements in applications of the structural adhesively bonded joints. SLJ, the simplest form of adhesive joints, was introduced first and its characteristic behaviors of stress distributions along the bondline were given and discussed. In the adhesively bonded joint applications, reducing the stress concentrations and maximizing the failure load are the important issues to be solved. Many different techniques have been proposed to reduce stress concentrations. Grading the adhesive band has recently come to the fore among the reported remedies to overcome the problems faced by lap-joint applications. Two important applications of grading the adhesive band are using the bi-adhesive and modulus-graded bondlines in lap joints. The bi-adhesive bondline consists of three individual regions by a combination of stiff and flexible adhesives along the bondline, in which the flexible adhesives locate at the bondline ends and the stiff adhesive locates in the middle of the overlap. Second remedy is to use the modulus-graded bondline, in which bondline is graded functionally along the overlap length. This study aims to discuss the role of the adhesive layer on shear stress distributions and review some advancements in applications of the bi-adhesive and modulus-graded joints. Each joining technique was discussed briefly and compared with the joints bonded with a mono-adhesive alone.

2. Structural adhesive joints

2.1. Mono-adhesive bondline

Single lap joints have been studied by many authors [1–8]. As seen in **Figure 2**, load eccentricity results in developing the bending moments in an SLJ subjected to an axial loading. **Figure 2** shows the characteristic behavior of the peel and shear stress distributions along the bondline length.

It is seen from **Figure 2** that both shear and peel stresses become peak at overlap ends. However, higher peel stresses develop at the overlap ends due to bending moment effect. Single lap joints

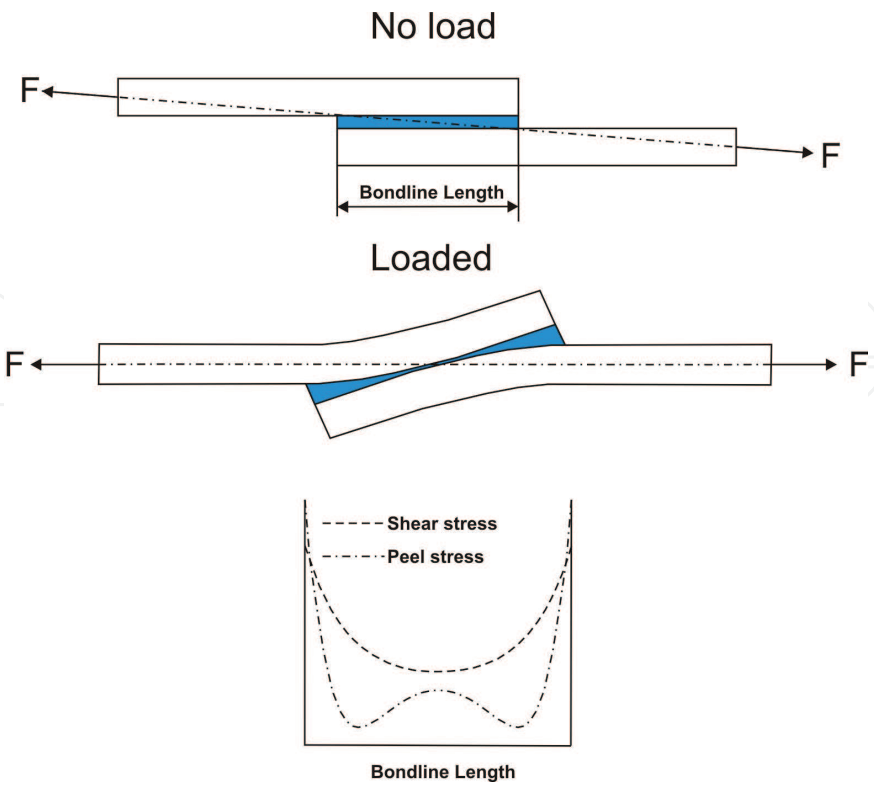

Figure 2. Deformed shape of an SLJ and stress distributions along its bondline length.

bonded with a mono-adhesive alone are widely used joints, however, weak in local stress concentrations at the overlap ends. High stress regions at the overlap ends reduce their failure loads and hence joint strengths. When adhesively bonded joint is subjected to tensile load, load is transferred mainly by shear stress developed in the adhesive layer. The first analytical model for assessing the adhesive shear stresses of bonded joints was developed by Volkersen [9]. His model is also called shear-lag model, which neglects the bending moment. The adhesive shear stress distribution is defined in the Volkersen model as follows:

$$\tau = \frac{F\omega}{2b}\frac{\cosh(\omega x)}{\sinh(\omega l/2)} + \left(\frac{t_t - t_b}{t_t + t_b}\right)\left(\frac{\omega l}{2}\right)\frac{\sinh(\omega x)}{\cosh(\omega l/2)} \tag{1}$$

where

$$\omega = \sqrt{\frac{G_a}{Et_t t_a}\left(1 + \frac{t_t}{t_b}\right)} \tag{2}$$

In which, ω is the characteristic shear-lag distance. t_t and t_b are the top and bottom adherend thicknesses, respectively. *b* and *l* are the bond width and bond length, respectively. E, G_a, and F are the adherend modulus, adhesive shear modulus, and applied force, respectively. The x-axis passes through the mid-plane of the adhesive layer. As seen from **Figure 2**, high peel and shear stress concentrations develop at the overlap ends. There have been many attempts to reduce the stress concentrations of SLJ and improve its failure loads [10–12].

2.2. Modulus-graded bondline

One of the important remedies to overcome some deficiencies (i.e., stress concentration, decreasing in joint strength, etc.) arising in lap joints is grading the adhesive properties along the bondline. The earliest study on grading the modulus of an adhesive along the overlap length was performed by Raphael [14]. He splitted the adhesive bondline into finite number of discrete parts (**Figure 3**).

His model is based on the shear-lag concept of Volkersen, and therefore neglects the peel stress effect [13]. The work was undertaken as part of a program to design and test bonded rocket motor cases. The aim was to obtain the highest possible joint strength for a simple overlap. However, Raphael did not report any experimental work nor, indeed, quantify the possible benefits of a variable modulus bondline [14].

Figure 4 shows an SLJ bonded with the modulus-graded bondline. Recently, Carbas et al. [15] developed a simple analytical model to study the performance of the functionally graded joints.

In addition to numerical study, Carbas and others [16] also performed experimental study and used induction heating system to have a graded cure and joints with the adhesive gradually modified along the overlap. The induction system was set to allow the induction heating at the overlap ends and the induction cooling in the middle. They also performed analytical analyses to predict the failure load of the joints with graded cure and isothermal cure.

Modulus-graded joints have been studied in a limited number of papers in the literature and still open for numerical/analytical/experimental studies. The reader may refer to the following articles for current applications [17–23].

2.3. Bi-adhesive bondline

Bi-adhesive joint is an alternative stress-management technique for adhesively bonded lap joints. Its bondline includes a combination of stiff and flexible adhesives (**Figure 5**). This joint type including two types of adhesives in the overlap region is called as bi-adhesive, hybrid-adhesive, and mixed-adhesive joints in the literature.

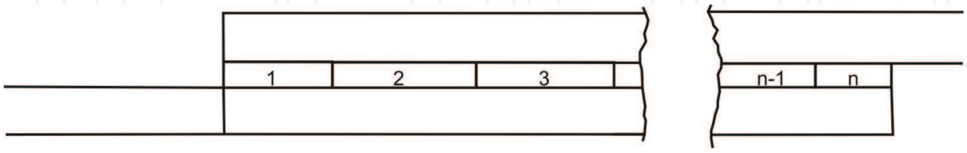

Figure 3. Raphael’s modulus-graded bondline.

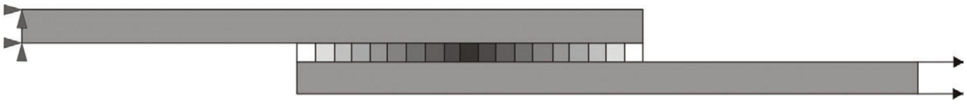

Figure 4. An SLJ bonded with the modulus-graded bondline.

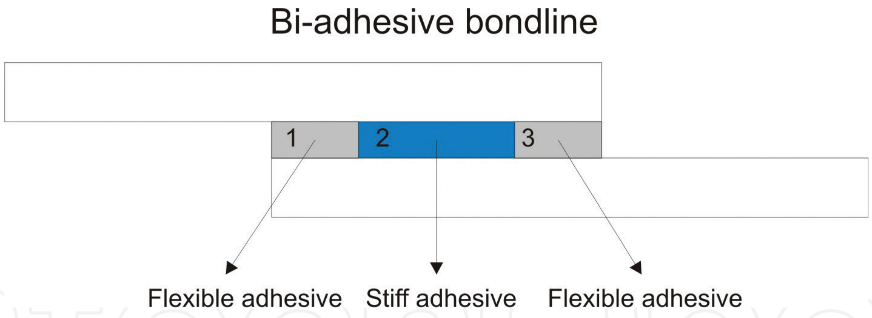

Figure 5. Bi-adhesive single lap-joint.

The stiff adhesive should be located in the middle and flexible adhesive at the ends of the bondline. The earliest study on the bi-adhesive joints was performed by Raphael [13]. Özer and Öz [24, 25] performed numerical studies to investigate the state of stress in the bi-adhesive bondline. In their other study [26], they also performed an experimental study to assess the effect of a bi-adhesive bondline on the failure load of both mono- and bi-adhesive SLJs. Their results were discussed briefly in **Figure 6**. **Figure 6** shows the characteristic behaviors of shear stress distributions along the mid-plane of the mono- and bi-adhesive layers. For comparison purposes, the shear stress distributions for the mono-flexible and mono-stiff adhesives were also given for mono-adhesive SLJs. As can be seen from **Figure 6**, shear stress distribution for the mono-flexible adhesive is more uniform than that of the mono-stiff adhesive and there is a lower stress concentration at the overlap edges. As a result, it is seen that the shear stress concentrations occurred at the overlap edges for mono-adhesive joints.

However, in the bi-adhesive bondline, as can be seen in **Figure 6**, the position of the maximum shear stress moves to a new position between adhesives (i.e., to the ends of the stiff adhesive in the middle). As reported above, the maximum shear stresses becomes peak at the overlap edges for mono-adhesive joints, however, it becomes peak at the contact interfaces for bi-adhesive joints.

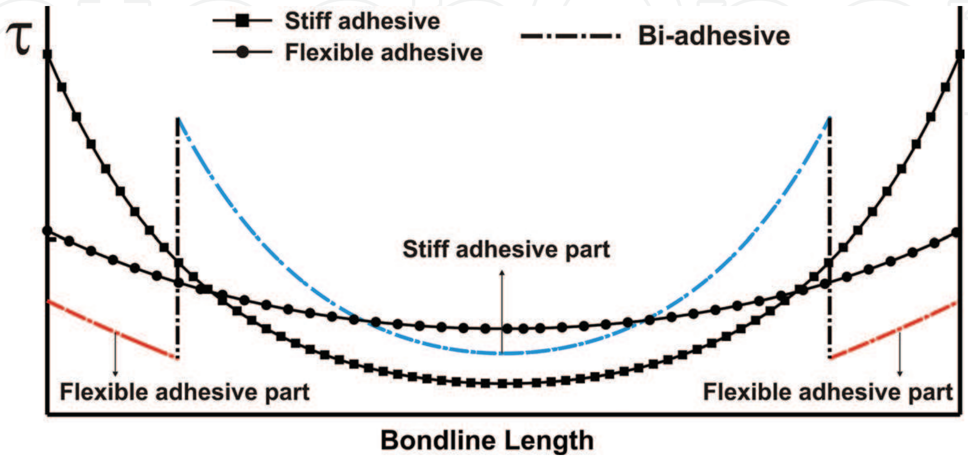

Figure 6. Characteristic behavior of shear stress distributions along mono- and bi-adhesive bondlines.

Therefore, it is seen that peak shear stress decreases at the overlap edges and increases at the contact interfaces (i.e., at the ends of the stiff adhesive) in the bi-adhesive bondline. It can be concluded that stiff adhesive in the middle contributes its high shear-strength-capacity to the bi-adhesive joint. Therefore, high stress concentrations at the bondline ends can be reduced by using bi-adhesive bondline. However, it is important to select the appropriate adhesive type for the bi-adhesive bondline. In addition, amounts of the stiff/flexible adhesives used in the bi-adhesive bondline also affect the shear stress values.

There are a limited number of publications in the open literature about the bi-adhesive joints. The reader may refer to the following articles for current applications of the joints bonded with bi-adhesive bondline [27–33].

3. Conclusion

It is known that high stress concentrations develop at the overlap ends of the adhesively bonded joints. Grading the adhesive band has recently come to the fore among the reported remedies to overcome the problems faced by lap-joint applications. In this study, the role of the adhesive layer on stress distributions was reviewed. Joining techniques using the bi-adhesive and modulus-graded bondlines were discussed briefly and compared with the joints bonded with a mono-adhesive alone. It is seen that high stress concentrations at the ends can be reduced by using these techniques. It is therefore concluded that stress concentration and joint strength can be optimized by using modulus-graded and bi-adhesive bondlines in the lap joints.

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