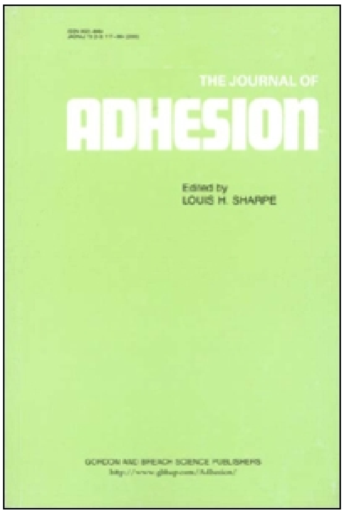

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Three-Dimensional Finite Element Analysis of the Stress Distribution in Bi-Adhesive Bonded Joints

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Three-Dimensional Finite Element Analysis of the Stress Distribution in Bi-Adhesive Bonded Joints

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A 3-D elastic finite element model was developed to investigate the stresses distribution of bi-adhesive bonded joints (i.e., the bond line of joints filled with two adhesives of dissimilar toughness). The effects of the loading mode on the stress distribution of joints, including the single-lap joints under tensile loading (i.e., single-lap joints) and the butt joints under cleavage loading (i.e., cleavage joints), were also studied in detail. Results showed that higher stress, distributed at the contact position of the dissimilar adhesives placed along the bond line of bi-adhesive bonded joints. Also, the maximum stress of the adhesive layer decreased when the length ratios and bonding sequence along the bond line, filled with two dissimilar adhesives, was appropriately designed. At the same time, stress convergence in the adhesive layer of bi-adhesive joints was also obviously reduced in contrast to the mono-adhesive joints. The numerical investigation shows that it is necessary to take into account the change of loading modes when optimizing the bi-adhesive joint design, because of the uneven and complex loading modes of the adhesive bonding structure in the engineering applications.

Keywords: Adhesive joints; Bi-adhesive bonding; Cleavage loading; Finite element methods

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INTRODUCTION

Adhesive bonding is being increasingly used in structural applications. When compared with mechanically fastened joints, adhesive joints have the advantages of fewer sources of stress concentration, a more uniform distribution of loads, and better fatigue properties [1]. The characteristics of adhesive joints also make them attractive in industrial applications, such as aeronautical engineering, automotive engineering, and so on. It was observed from the various experiments and analysis that adhesive joints proved to be more efficient for lightly loaded structures, whereas mechanically fastened joints were more efficient for heavily loaded structures. However, modern adhesives offer a joining technique of interest to engineers in a far wider range of industries. With the development of higher toughness adhesives, we believe that more and more applications of an adhesive bonding technique for the bonding of metal and other heavier loaded structures will be developed. Present researches have shown that adhesive layer should not be distributed with normal stress components. Instead, it should be distributed with shear stress components in order to improve the adhesive joint strength [1]. Therefore, most investigations on the optimization of adhesive joint design have concentrated on mainly joints having a shear stress component that are distributed principally, such as single lap joints, double lap joints, etc.

From another perspective, the cleavage strength is one of the main properties of an adhesively bonded joint. A number of researchers have examined the normal stress distribution in the adhesive layer along the bond line of the cleavage joints. Elastic stress distribution in a typical steel/steel cleavage joint was previously studied by Shahid and Hashim [2,3]. In some of our previous studies [4], 3-D stress distributions in the adhesive layer of cleavage joints were also described. In addition, Adams *et al*. [1] suggested that it was necessary to avoid using adhesively bonded joints under a cleavage load and to change the form of the joint so as to shift the cleavage load to a tensile shear loading in practical engineering structures. In engineering applications, the loading modes of an adhesively bonded structure are uneven and complex. So, it is necessary and important to investigate further the stress distribution in adhesive joints with different joint types, joint geometries, loading modes, and so on.

Many investigations on the optimization of joint style, such as additive adhesive fillets [5], wavy joints [6,7], bi-adhesive bonded joints [8,9], etc., have been implemented to improve stress distribution and, thus, joint strength. With the development of the controlled adhesive modulus technique, adhesive joint strength has been improved. A technique that utilizes a bond line with a variable modulus adhesive, to relieve the high-stress concentrations at the end regions of the overlap, will obviously improve adhesive joint strength. Notably, the work that has been carried out has used single lap metallic adhesive bonded joints under tensile loading. Sancaktar and Kumar [10] selectively toughened the adhesive at the ends of the overlap, and Pires *et al*. [8] presented a study of the application of two adhesives with different stiffnesses along the overlap length in single lap joints. The results showed a measurable increase in strength of the bi-adhesive bonded joints compared with those in which single adhesives were used over the full length of the bond line. In addition, Fitton *et al*. [9] developed a linear finite element model to optimize the bond line properties and to help understand how variable modulus bond lines distribute stress and strain. Both authors found that the use of graded modulus bond lines increased the strength of the joint. However, in both of these studies, the influence of loading modes and joints types on the optimization of the bond line properties was not examined.

In this paper, a novel (3-D) finite element model was introduced to understand how variable modulus bond lines distribute the stress and strain of bi-adhesive joints under variable loading modes, including cleavage joints and single lap joints. Joints were made with a variable modulus bond line consisting of two dissimilar adhesives. Cleavage joints and single lap joints were simultaneously studied in order to investigate the influence of a variable loading mode on the stress distribution of bi-adhesive joints. Relatively long overlaps were used primarily to enable the physical placement of different adhesives along the overlap length. However, such overlaps are also realistic in some industrial applications. These adhesives are referred to as high and low modulus throughout this paper, although these terms are only relative. The high modulus adhesive used was typical of a structural adhesive that was previously used for joining metal structure.

2. FINITE ELEMENT MODEL

The structural steel AIS 1045 was used as an adherend and was bonded with two kinds of modified epoxy resin adhesives, namely high elastic modulus Adhesive I and low elastic modulus Adhesive II, whose mechanical parameters are listed in Table 1. Both the adhesives and adherends were assumed to behave as elastic-plastic, isotropic materials. It was assumed that the structure of the bonded cleavage joints was in good condition and no defects existed at the interface and within the inner adhesive layer.

TABLE 1 Mechanical Properties of the Material Used

Material	Elasticity modulus E (GPa)	Poission's ratio ν
AIS 1045 Steel	200.0	0.27
High elastic modulus Adhesive I	2.9	0.34
Low elastic modulus Adhesive II	0.5	0.34

Computations were made using Microsoft code ANSYS 8.0. The element used was defined by eight nodes having three degrees of freedom at each node with translations in the nodal x, y, and z directions (named SOLID45 in the ANSYS library). This element was used throughout this study for the adherend as well as the adhesives. In this study, meshes of the adhesive layer and local adherend near the overlap region have been refined to satisfy the simulation accuracy requirement in this paper, and the meshes refined were accurate enough compared with those meshes used in the related literature [4,11,12].

According to the 3-D stress analysis results of joints obtained in the present literature [4,11,12], there exists a peak stress of the adhesive layer at the interface of the bond line in the middle of joint width. In this study, the stress state in the adhesive layer is investigated in detail.

Here, we define the convergence of stress distribution along the bond line by the parameter K_t as follows:

$$K_t = \frac{S_1}{P/A} ,$$

where K_t is a stress convergence coefficient of the bond line, S_1 is a peak value of the maximum principal stress in the bond line, P is the external load, and A is the overlap region area of the joints.

Here, we introduce the Maximum Principle Stress parameter to indicate the yield potential of the adhesives, instead of the von Mises Equivalent Stress [13]. According to Reference [13], von Mises equivalent Stress is the main parameter indicating the yield potential of metals, and the Maximum Principle Stress is appropriate to indicate the yield potential of the toughened adhesive.

2.1. Cleavage Joints

The cleavage joints considered in this study are shown in Fig. 1a. The adhesive thickness is 0.20 mm, the adherend length is 32 mm, the adherend width is 25 mm, and the adherend total thickness is 16 mm.

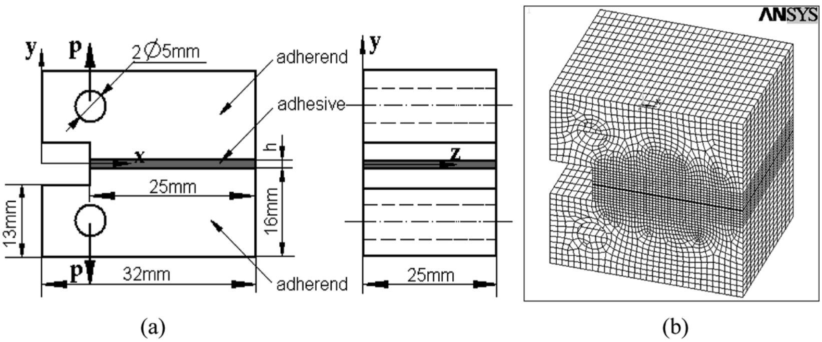

FIGURE 1 (a) Shape and size of specimen (b) finite element model.

A 3-D finite element analysis was performed considering an applied static force of 10 KN. The finite element meshes used in this investigation are shown in Fig. 1b; finer meshes were used near the adhesive layer. Because discontinuities in joint material properties could cause regions of high stress gradients with rapidly varying stresses, finer meshes were necessary near the adhesive layer.

In the present paper, variable modulus adhesives placed along the bond line are shown in Fig. 2, in which there are two cases: (a) and (b), where L denotes the length of the left end of bond line filled with a lower elastic modulus adhesive, and H denotes the length in the

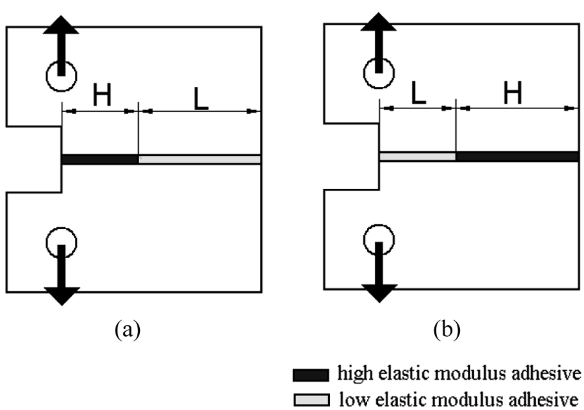

FIGURE 2 Adhesive bonded models under cleavage loading with bi-adhesives.

middle of the overlap region filled with a higher elastic modulus adhesive.

2.2. Single-Lap Shear Joints

The single-lap adhesive bonded joints considered in this study are shown in Fig. 3(a). The adhesive thickness is 0.20 mm, the adherend length is 100 mm, the adherend width is 25 mm, and the adherend thickness is 2 mm. The material parameters of the adherend and adhesives used in the single-lap joints are the same as those parameters with cleavage joints, as shown in Table 1.

A 3-D finite element analysis was performed considering an applied static force of 5 kN. The finite element mesh used in this investigation is seen in Figs. 3(b) and (c), and finer meshes are also used inside the adhesive layer.

In the section of the single-lap bi-adhesive bonded joints, a bond line filled with variable modulus adhesives is set as shown in Fig. 4. L denotes the 1/2 length of the bond line filled with a low elastic

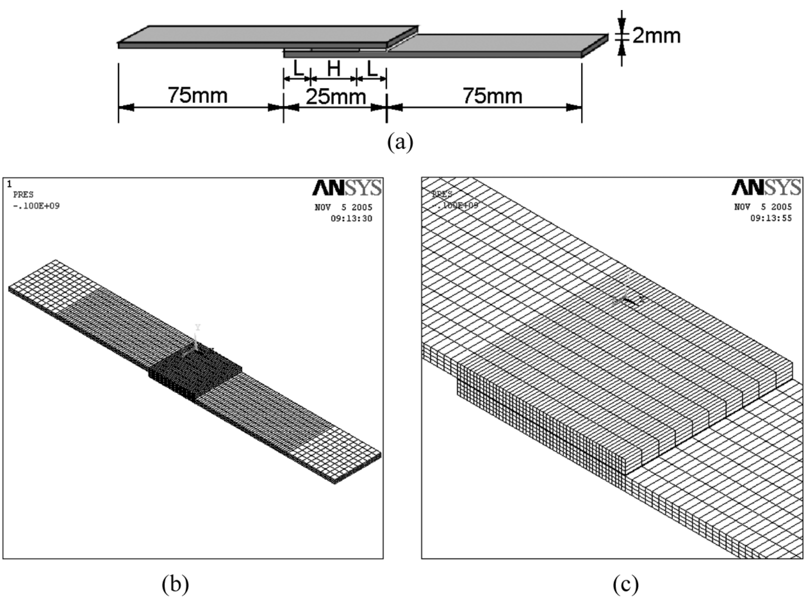

FIGURE 3 (a) Shape and size of specimen of single-lap joints under tensile loading, (b) corresponding finite element model, and (c) local mesh at the lap region.

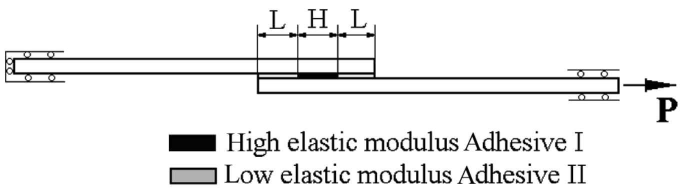

FIGURE 4 Schematic of single-lap joints with symmetrical distribution of low-high-low modulus adhesives.

modulus adhesive, and H denotes the length of the bond line filled with high elastic modulus adhesive.

3. RESULTS AND DISCUSSION

3.1. Effect of Different L/H Ratios on the Stress Distributions of Cleavage Joints

In this section, two cases, A and B, are investigated for bi-adhesive cleavage joints, as shown in Fig. 2, with an exterior loading of 10 kN.

3.1.1. Case A

The bond line is filled with a high elastic modulus adhesive on the left side and a low elastic modulus adhesive on the right side.

The stresses distribution of the cleavage joints is analyzed using the 3-D finite element method (FEM). Results show that there exist complicated 3-D stress states in the cleavage joints, mainly including 3-D normal stress components and 3-D shear stress components; the values of the shear stress components are far less than the normal stress components. Consequently, observations are made in particular of the maximum principal stress and normal stress components at the interfaces of the adhesive layer. These observations provide useful insight into the 3-D nature of the problem. Figures 5(a)–(f) show the normal stress components and shear stress components distribution contour at the surface of the bond line of the bi-adhesive bonded joints under cleavage loading, where P = 10 kN, H/L = 12.5 mm/12.5 mm. Figures 6(a)–(d) present the stress distribution along the bond line at the upper interface of the adhesive layer, in which the ratio of the bond line's lengths of high modulus adhesive (left segment) to the lengths of low modulus adhesive (middle segment), H/L, are taken as 2.5 mm/ 22.5 mm, 7.5 mm/17.5 mm, 12.5 mm/12.5 mm, 17.5 mm/7.5 mm, and 22.5 mm/2.5 mm, respectively. With the increase of H/L ratios, a

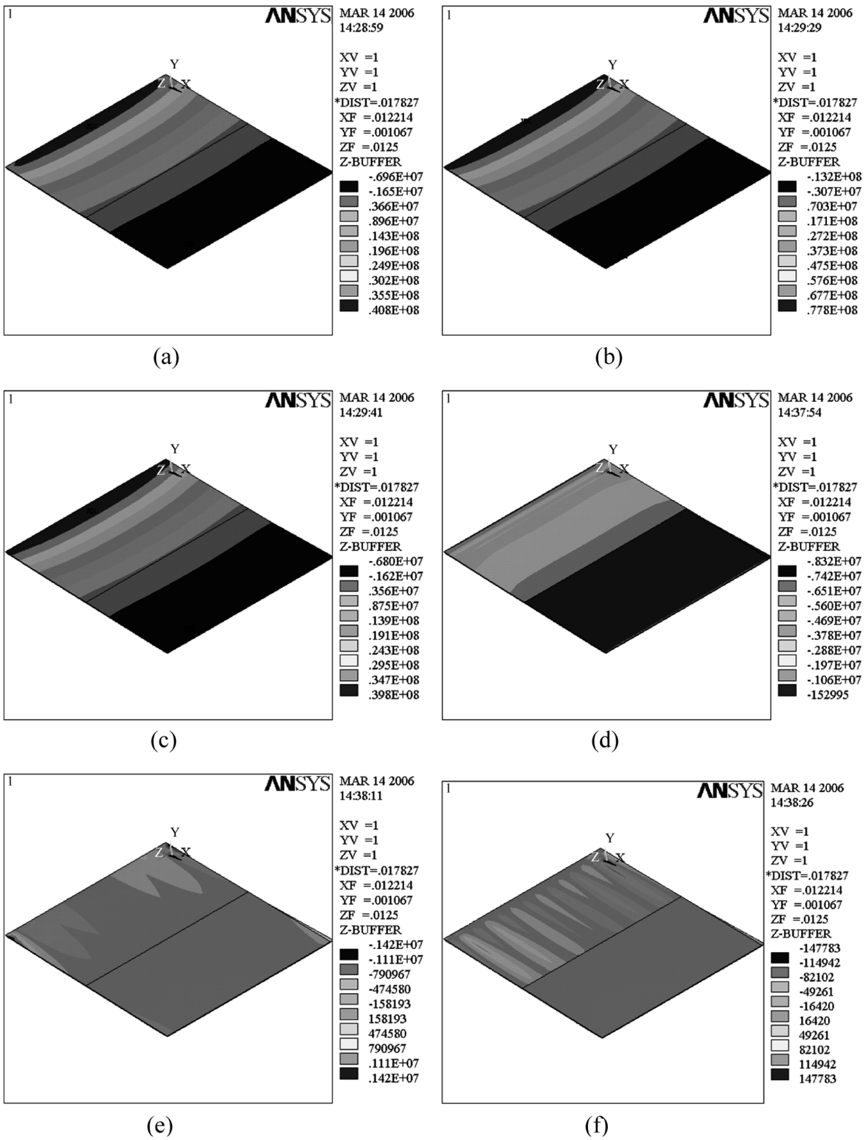

FIGURE 5 (a) X-direction normal stress SX, (b) Y-direction normal stress SY, (c) Z-direction normal stress SZ, (d) x-y Plane shear stress SXY, (e) y-z Plane shear stress SYZ, (f) x-z Plane shear stress SXZ at the interface of bi-adhesive bond line (P = 10 kN, H/L = 12.5 mm/12.5 mm).

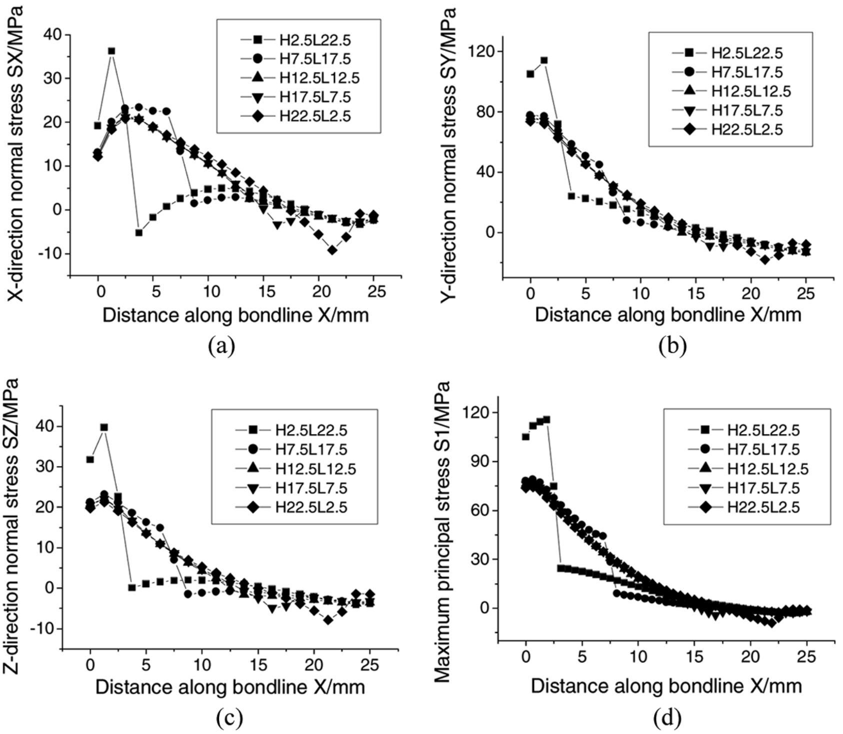

FIGURE 6 (a) X-direction normal stress SX, (b) Y-direction normal stress SY, (c) Z-direction normal stress SZ, (d) Maximum principal stress S1 at the interface of bondline in the middle of width of variable modulus adhesive (H/L is 2.5 mm/22.5 mm, 7.5 mm/17.5 mm, 12.5 mm/12.5 mm, 22.5 mm/2.5 mm, mm, respectively).

notable transfer of the stress distribution of the adhesive layer also occurs. Results show that compared with the stress distribution of the bond line of the cleavage joints bonded by a mono-adhesive, in which the higher stress is at the edge of the bond line near the loaded edge of the joints, the higher stress of the bond line of joints bonded by bi-adhesives is inclined to move towards the combining site of the two kinds of adhesives in the bond line. The peak values of normal stress components, SX, SY, SZ, and the shear stress component SXY in Plane X-Y all obviously decrease accordingly. However, the other shear stress components, SYZ and SZX, are almost equal to zero, as shown in the Figs. 6(a)–(d).

3.1.2. Case B

The bond line is filled with a low elastic modulus adhesive on the left side and a high elastic modulus adhesive on the right side.

Figures 7(a)–(d) present the stress distribution along the bond line at the upper interface of the adhesive layer, where the L/H ratios of the bond line that is filled with a low modulus adhesive (on the left segment) compared with the bond line that is filled with a high modulus adhesive (in the middle segment) are set as 2.5 mm/22.5 mm, 7.5 mm/17.5 mm, 12.5 mm/12.5 mm, 17.5 mm/7.5 mm, and 22.5 mm/2.5 mm, respectively. With the increase of L/H ratios, the stress distribution of each stress component along the bond line in Case B is coincident with the distribution in Case A. There exist, however, some differences between the two cases. The stress convergence of the bond line occurring in Case A is obviously higher than that convergence in Case B.

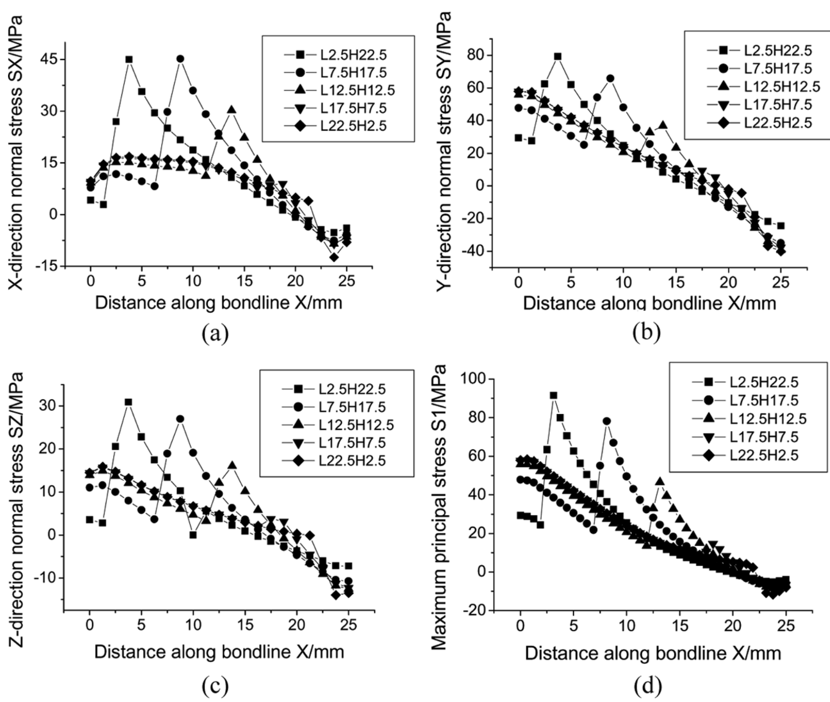

FIGURE 7 (a) X-direction normal stress SX, (b) Y-direction normal stress SY, (c) Z-direction normal stress SZ, (d) Maximum principal stress S1 distribution at the interface of bond line in the middle of width of variable modulus adhesive (L/H is 2.5 mm/22.5 mm, 7.5 mm/17.5 mm, 12.5 mm/12.5 mm, 22.5 mm/2.5 mm, respectively).

In Case B, the L/H ratios in the case of the lowest stress convergence occurring in the adhesive layer were simulated by using the design optimization simulator of finite element analysis software, ANSYS 8.0. The results show that the stress convergence of the bond line reaches the lowest level in the case of the geometric of the cleavage joints shown in this study when the L/H ratio equals 10 mm/15 mm.

To understand the difference between the stress distribution of cleavage joints bonded by bi-adhesives and those joints bonded by a mono-adhesive, stress distributions in the adhesive layer of joints have been investigated in the present paper. In three cases where joints were bonded by a simple high elastic modulus adhesive Layer I, a low elastic modulus adhesive Layer II, and a bi-adhesive layer with the correct bonding sequence and the optimum ratio of bond line length of low modulus adhesive (at the left side) to high modulus adhesive (in the middle segment), the L/H ratio equaled to 10 mm/15 mm. Results show that the higher stresses region of the bond line of joints bonded by bi-adhesives is inclined to move towards the combining site of the two kinds of adhesive, as shown in Figs. 8 (a)–(d). However, the higher stress region of the bond line of cleavage joints bonded by a single adhesive exists at the edge of the bond line near the loading position of the joints.

3.2. Effect of Different L/H Ratios on the Stress Distributions of Single-Lap Shear Joints

The stress distribution of single-Lap shear joints with bi-adhesive bonding was also investigated in detail. In Case A, the high modulus adhesive was in placed both ends of the overlap region and the low modulus adhesive was placed in the middle of the bond line, namely, L-H-L (see Fig. 4) and L-H-R (in Fig. 9). In Case B, the low modulus adhesive was placed in both ends of the overlap region, and the high modulus adhesive was placed in the middle of the bond line, namely, H-L-H (see Fig. 10) and H-L-R (see Fig. 11).

3.2.1. Symmetrical Distribution of Dissimilar Modulus Adhesives Along the Bond Line

1) Type: L-H-L (Low Modulus Adhesive II-High Modulus Adhesive I-Low Modulus Adhesive II Placed Along the Bond Line). The schematic view of single lap joints with this symmetrical bonding sequence is shown in Fig. 4, where the type is L-H-L; *i.e.*, a low modulus Adhesive II is placed at both ends of the overlap region, and a high modulus Adhesive I is placed in the middle of the overlap region.

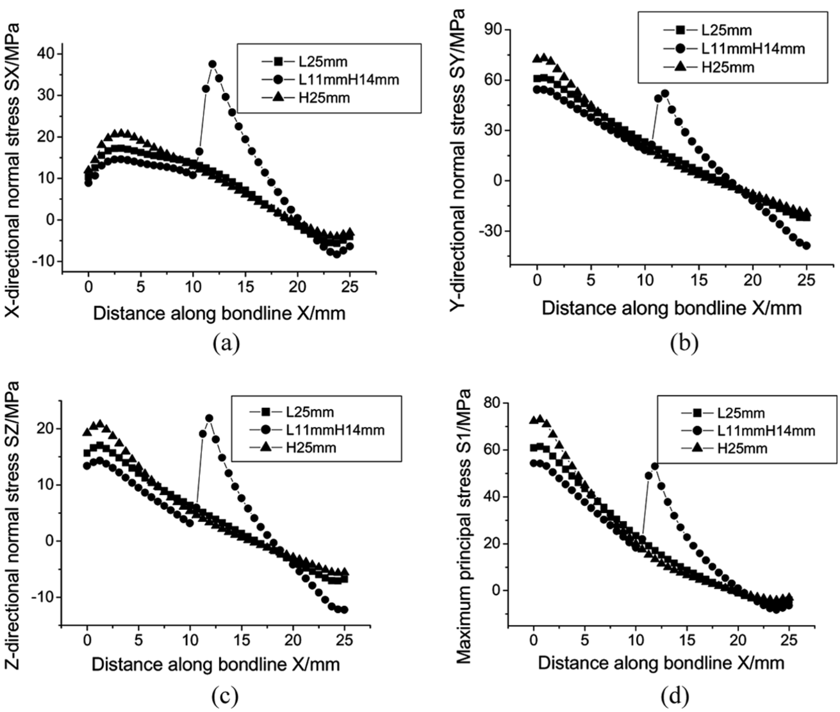

FIGURE 8 (a) X-direction normal stress SX, (b) Y-direction normal stress SY, (c) Z-direction normal stress SZ, (d) Maximum principal stress S1 at the interface of bond line in the middle of width of mono-adhesive (L = 22.5 mm, H = 22.5 mm), and bi-adhesive (L/H = 11 mm/14 mm).

Figures 12 (a)–(g) show the contours of the stress component distribution at the interface of the adhesive layer while overlapping the length of the low strength adhesive, L, is 6.25 mm, and that distribution of the high strength adhesive, H, is 12.5 mm. It is seen that higher stress distribute at the contact position of the two adhesives

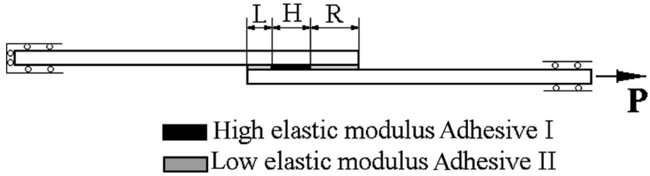

FIGURE 9 Schematic of single-lap joints with unsymmetrical distribution of low-high-low modulus adhesives bonding sequence.

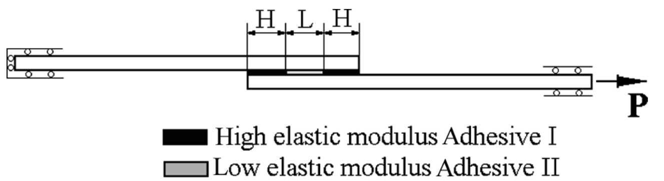

FIGURE 10 Schematic of single-lap joints with symmetrical distribution with high-low-high modulus adhesives bonding sequence.

in the bi-adhesive layer, and the lower stress region exists at the end of overlap in the adhesive layer. However, according to the stress distribution of the single lap shear joints bonded with mono-adhesive in the related literature [2,6], the higher stress region in the adhesive layer exists at the ends of the overlap region, and the lower stress exists in the middle of the bond line. So, we can see that changing the adhesive modulus distribution along the bond line may cause the stress convergence in the adhesive layer to decrease markedly. The effect of the length ratios of the bond line with a high modulus adhesive to the low modulus adhesive on the stress distribution in the bi-adhesive layer also has been investigated. With the increase of the L/H ratio, the maximum values of stress components and the maximum principle stress, S1, of the adhesive layer are inclined to initially increase and then decrease, as shown in Fig. 13. When the L/H ratio is set at 6.25 mm/12.5 mm, the peak value of stress distribution in the adhesive layer is the smallest among the five cases of Fig. 13.

2) Type: H-L-H (High Modulus Adhesive I-Low Modulus Adhesive II-High Modulus Adhesive I Placed Along the Bond Line). The schematic view of single lap joints with this symmetrical bonding sequence is shown in Fig. 10, which indicates that when the type is H-L-H; *i.e.*, a high modulus Adhesive I is placed at both ends of the overlap region along the bond line, and a low modulus Adhesive II is placed in the

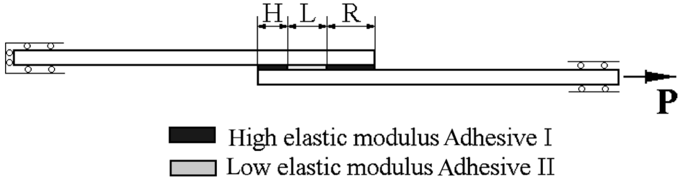

FIGURE 11 Schematic of single-lap joints with unsymmetrical distribution of high-low-high modulus adhesives bonding sequence.

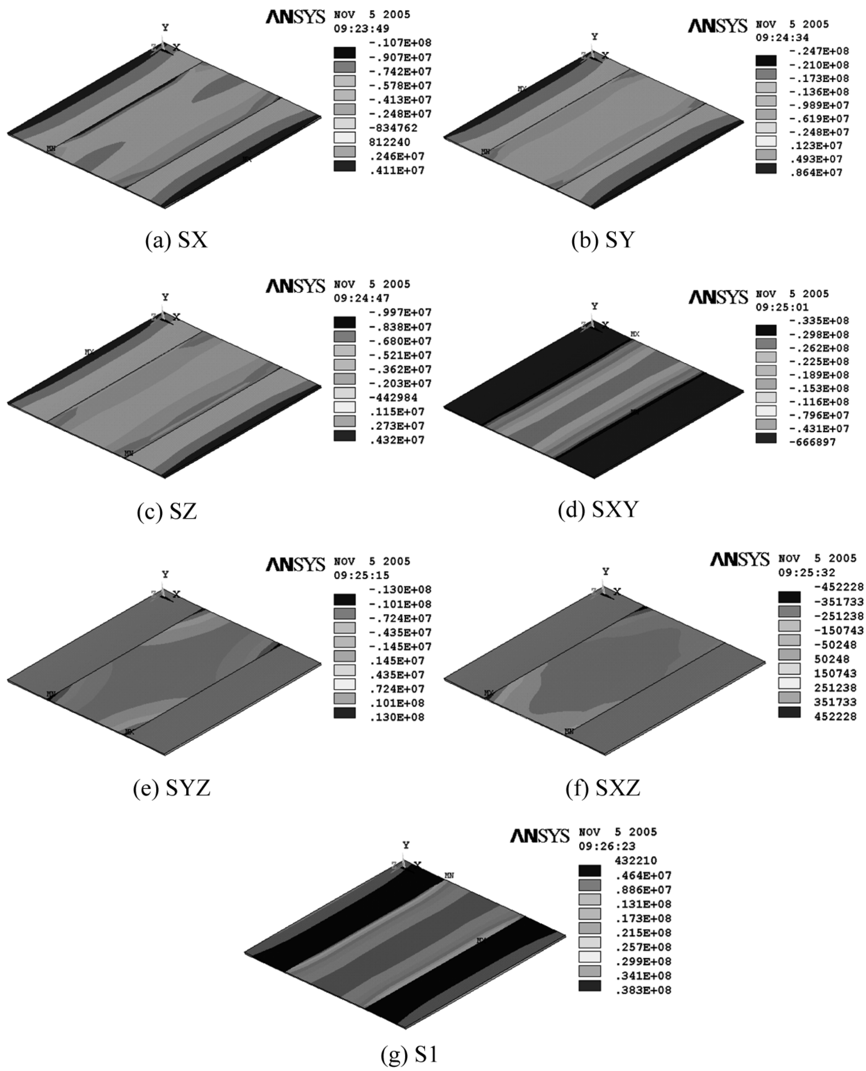

FIGURE 12 (a) X-direction normal stress SX, (b) Y-direction normal stress SY, (c) Z-direction normal stress SZ, (d) x-y Plane shear stress SXY, (e) y-z Plane shear stress SYZ, (f) x-z Plane shear stress SXZ, and (g) maximum principal stress S1 distribution at the interface of bond line in the middle of width with low-high-low modulus adhesives bonding sequence (P = 5 kN, L/H = 6.25 mm/12.5 mm).

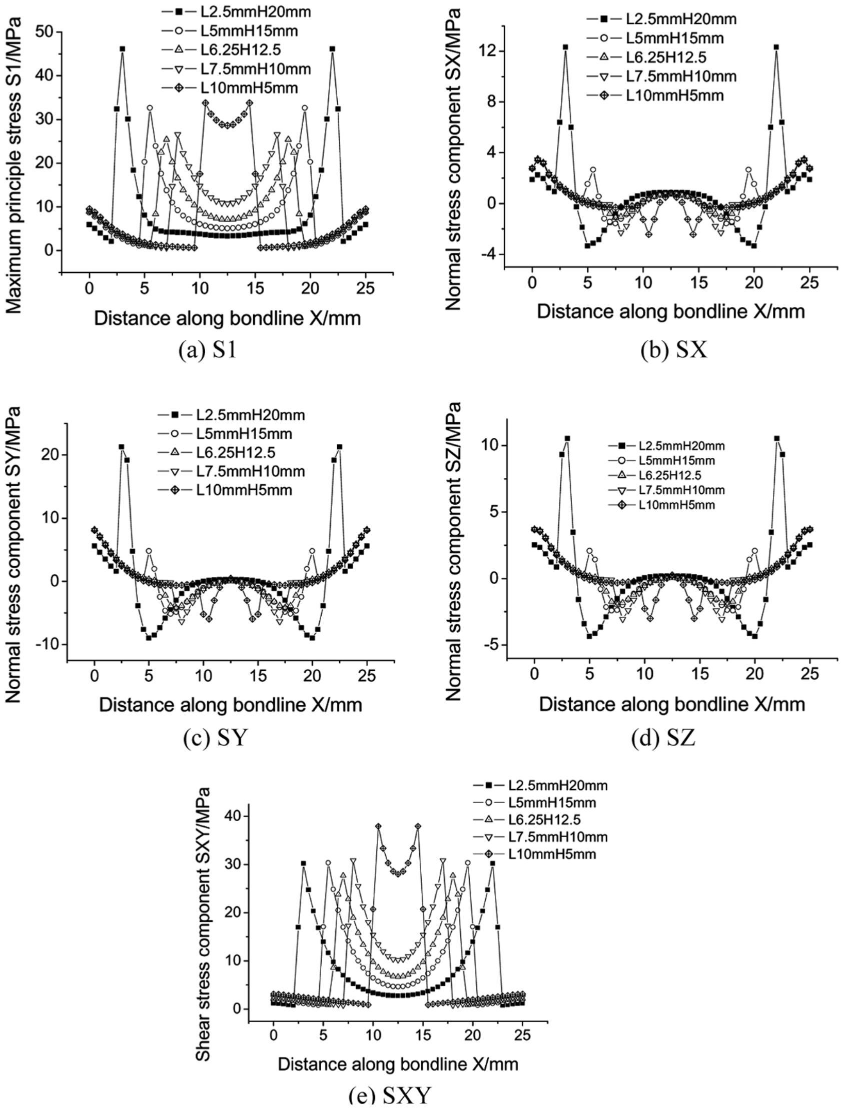

FIGURE 13 (a) Maximum principal stress S1, (b) X-direction normal stress SX, (c) Y-direction normal stress SY, (d) Z-direction normal stress SZ, and (e) x-y Plane shear stress SXY distribution in the middle of bond line at the center of width (z = 12.5 mm) with low-high-low modulus adhesives bonding sequence (P = 5 kN, L/H is taken as 2.5 mm/20 mm, 5 mm/15 mm, 6.25 mm/12.5 mm, 7.5 mm/10 mm, 10 mm/5 mm, respectively).

middle of the bond line, higher stress exists at the ends of the overlap region in the adhesive layer. Moreover, there mainly exist shear stress components in the adhesive layer. With the increment of the L/H ratio, the maximum stress of the adhesive layer is inclined to decrease, as shown in Figs. 14–15 shows K_t of the bond line with different adhesive sequences and the length ratios when symmetrical distribution of the bi-adhesive layer occurs (No.1, No. 2, No.3, No.4, and No.5 denote 2.5 mm/20 mm/2.5 mm, 5 mm/15 mm/5 mm, 6.2 5mm/ 12.5 mm/ 6.25 mm, 7.5 mm/10 mm/7.5 mm, and 10 mm/5 mm/10 mm, respectively), we find that the bi-adhesive bonding sequence of L-H-L is prior to that of H-L-H for single lap joints designed to require less stress convergence of joints.

3.2.2. Unsymmetrical Distribution of Dissimilar Modulus Adhesives Along the Bond Line

To investigate the unsymmetrical distribution of variable modulus adhesives along the bond line on the stress distribution of adhesive joints, the following two cases have been studied, in which the length of the bond line with one modulus adhesive in the overlap region was kept constant.

1) Type: L-H-R (Low Modulus Adhesive II-High Modulus Adhesive I-Low Modulus Adhesive I Placed Along the Bond Line). In this case, a low modulus adhesive was placed at both of ends the adhesive layer along the bond line, and the high modulus adhesive was placed

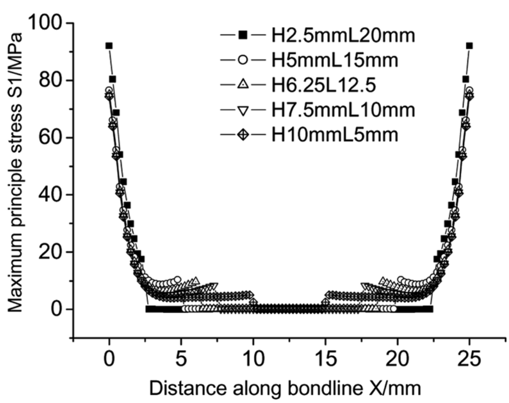

FIGURE 14 Maximum principal stress S1 distribution in the middle of bond line at the center of width (z = 12.5 mm) with high-low-high modulus adhesives bonding sequence (P = 5 kN, H/L is taken as 2.5 mm/20 mm, 5 mm/15 mm, 6.25 mm/12.5 mm, 7.5 mm/10 mm, 10 mm/5 mm, respectively).

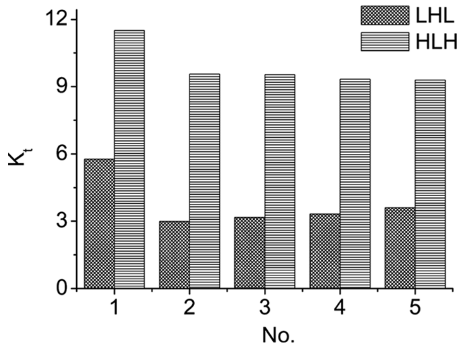

FIGURE 15 Kt of bond line at different bonding sequence and length ratio with symmetrical distribution of bi-adhesive layer (No.1, No. 2, No.3, No.4, and No.5 denote 2.5 mm/20 mm/2.5 mm, 5 mm/15 mm/5 mm, 6.25 mm/12.5 mm/6.25 mm, 7.5 mm/10 mm/7.5 mm, and 10 mm/5 mm/10 mm, respectively).

in the middle of overlap region, as shown in Fig. 9. When the whole overlap length and the length of adhesive I layer in the middle of the bond line was kept constant, the maximum stress of the adhesive layer is inclined to decrease with the increment of the length of the adhesive II layer at the left side of the bond line, as shown in Fig. 16.

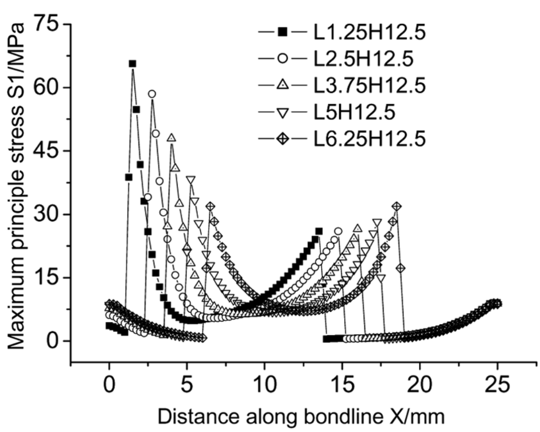

FIGURE 16 Maximum principal stress S1 distribution along the bond line in the middle of adhesive layer at the center of width (z = 12.5 mm) with unsymmetrical low-high-low modulus adhesives bonding sequence (P = 5 kN, H/L is taken as 1.25 mm/12.5 mm, 2.5 mm/12.5 mm, 3.75 mm/12.5 mm, 5 mm/12.5 mm, 6.25 mm/12.5 mm, respectively).

Moreover, among the five cases in Fig. 16, the maximum stress of the adhesive layer in each case lie in the contact region of the two different modulus adhesives.

2) Type: H-L-R (High Modulus Adhesive I-Low Modulus Adhesive II-High Modulus Adhesive I Placed Along the Bond Line). In this case, a high modulus Adhesive I was placed at both ends of the bond line, and the low modulus Adhesive II was placed in the middle of the overlap region, as shown in Fig. 11. When the whole overlap length and the length of the Adhesive II layer were kept constant, the maximum stress in the adhesive layer was inclined to decrease with the increment of length of the Adhesive I layer at the left side of the bond line. Among the five cases in Fig. 17, the maximum stress in the adhesive layer lies at the end of the overlap region along the bond line. Moreover, Fig. 18 shows that as K_t of the adhesive layer at the variable bonding sequence and the length ratio as the unsymmetrical distributing of bi-adhesive layer occurs (No.1, No. 2, No.3, No.4, and No.5 denote 2.5 mm/20 mm/2.5 mm, 5 mm/15 mm/5 mm, 6.25 mm/12.5 mm/6.25 mm, 7.5 mm/10 mm/7.5 mm, and 10 mm/5 mm/10 mm, respectively), we find that bi-adhesive bonding sequence of L-H-R is prior to that of H-L-R for single lap joints designs that require less stress convergence of joints.

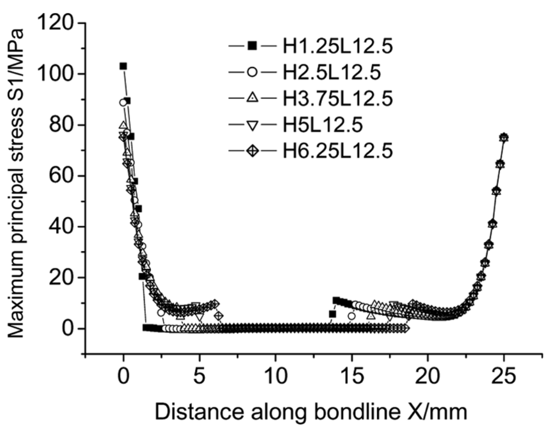

FIGURE 17 Maximum principal stress S1 distribution along the bond line in the middle of adhesive layer at the center of width (z = 12.5 mm) with unsymmetrical distribution of high-low-high modulus adhesives bonding sequence (P = 5 kN, L/H is taken as 1.25 mm/12.5 mm, 2.5 mm/12.5 mm, 3.75 mm/12.5 mm, 5 mm/12.5 mm, 6.25 mm/12.5 mm, respectively).

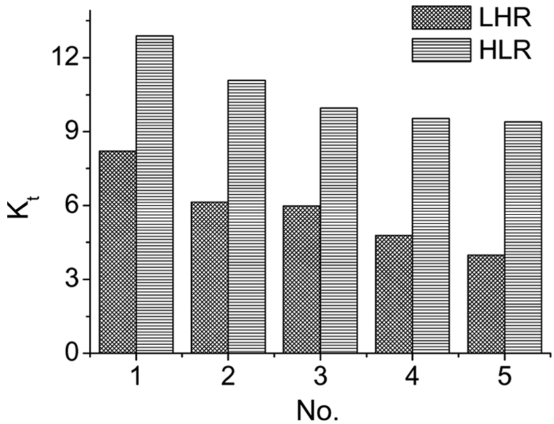

FIGURE 18 K_t of bond line at different bonding sequence and length ratio with unsymmetrical distribution of bi-adhesive layer (No.1, No. 2, No.3, No.4, and No.5 denote 2.5 mm/20 mm/2.5 mm, 5 mm/15 mm/5 mm, 6.25 mm/12.5 mm/6.25 mm, 7.5 mm/10 mm/7.5 mm, and 10 mm/5 mm/10 mm, respectively).

4. CONCLUSION

This paper describes a 3-D elastic finite element model to help understand how bond lines with variable modules adhesives distribute stress in bi-adhesive joints in contrast to mono-adhesive joints. Results show that compared with higher stress regions in the bond line of cleavage joints existing at the edge of the bond line near the loaded edge of the joints, the higher stress region in the bond line of bi-adhesives joints is inclined to move towards the combining site of the two kinds of adhesives. Moreover there possibly exists much less stress convergence at the interface and inner area of the bond line where the bi-adhesive bonding sequence and the length ratio of low modulus adhesive to high modulus adhusive in the bound line were appropriately selected. In addition, the stress convergence coefficient of the adhesive layer has been defined to study the effect of the bi-adhesive bonding sequence and length ratio of a high modulus adhesive to low modulus adhesive on the stress convergence of joints.

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