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دراسة تأثير وجود فتحة موازية في المفصل الثنائي والمتلاصق بدورة واحدة مع شريحة ربط

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الخلاصة

تم دراسة التأثير المشترك الكامل لشريحة شكلت من لاصق ثنائي وفتحة موازية على توزيع الإجهاد على طول مفصل بدورة واحدة باستخدام طريقة العناصر المحددة تحت تأثير توتر الصافي. قد تم تطوير نموذج العناصر المحدود من المفصل يحتوي على شريحة وفتحة موازية وخط ترابط ثنائي التلاصق. وفي هذه الدراسة تم افتراض بأن كلا من التماسك والتلاصق لهما استقامة هندسية وذات سلوك المواد الخطية. وقد تمت دراسة سلوك خط الترابط للمفاصل ثنائية الالتصاق عن طريق اختبار توزيعات السطوح والحد الأقصى للإجهادات الرئيسية في منتصف مستوي خط الترابط. والجديد في هذه الدراسة هو تحري سلوك خط الترابط لشريحة مكونة من مفصل وحيد المرحلة وتكاملها مع آلية فتحة موازية. نتائج الحساب العددي تبين بشكل ملحوظ بأن الجمع بين استخدام الفتحة الموازية وشريحة الربط في المفصل ثنائي التلاصق المرحلي تقلل من قيمة الذروة للمرحلة بحد كبير. وقد تم تحسين خصائص قوة المفاصل من خلال الدراسات التي تستعمل فيها معايير هندسية مختلفة. وهذا النموذج يفيد في تعزيز قوة مفاصل الألمنيوم ذات مرحلة الواحدة.

An investigation on the effect of parallel slot in bi-adhesive single lap joints with spew fillet

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ABSTRACT

The combined effect of full (spew) fillet formed bi-adhesive and parallel slot in adherend on the stress distribution along the length of adhesive bonded single lap joint (SLJ) was investigated using the finite element (FE) method under pure tension (i.e. twenty parallel slots of dissimilar length and depth and two types of bi-adhesive bonds). The FE model of the joints that had fillet, parallel slot and bi-adhesive bondline was developed. In this study, it is assumed that both adhesive and adherend have geometrical nonlinearity and exhibit linear material behavior. The bondline behavior of bi-adhesively bonded joints has been studied by examining the distributions of the peel and maximum principal stresses at the mid-plane of the bondline. The novelty of this study is to investigate the bondline behavior of fillet formed SLJ with the integration of parallel slot mechanism. The results of the numerical computation show that the combined use of the parallel slot and spew fillet on bi-adhesively bonded lap joint decreased the peak value of the peel and maximum principal stresses markedly. The improvement of the strength properties of the joints has been acquired from the studies in which varying geometric parameters are used. This model may be beneficial to enhance the strength of aluminum SLJ.

Keywords: Bi-adhesive; finite element; parallel slot; single lap joints; spew fillet.

INTRODUCTION

The adhesive bond joints are conventionally used in the aerospace, medical, marine and automotive industries (Cognard *et al.*, 2006; Kumar & Pandey, 2010; Moradi *et al.*, 2013). The traditional mechanical joints such as bolting, riveting etc. may not always fulfill the needs of the advanced engineering practice of today (Cognard *et al.*, 2012; Wahab, 2012; You *et al.*, 2008). It can only be possible to reach the expected performance by achieving good strength–weight and cost-effectiveness ratios. Mechanical joints cannot meet these requirements, thus, adhesives are brought about as the only tool to satisfy them. Although SLJ is the most widespread technique due to its simplicity, the eccentricity of the loading forces causes transverse deflections on the joint, thereby introducing additional normal stresses in the bondline and this decreases the strength characteristic of joint and may result in a failure (Brockmann *et al.*, 2009).

In addition to the geometry of the joints, different boundary conditions also affect the mechanical behavior of adhesively bonded joints. The surging complex joint geometry and its three-dimensional (3D) nature increase the difficulty of obtaining governing equations of overall system on the prediction of the mechanical properties of the adhesively bonded joints (He, 2011).

As the analysis becomes very complex in the mathematical formulation, material non-linearity owing to plastic behavior is difficult to incorporate as well. Also the experiments remain cumbersome and costly. Hence the (FE) analysis has frequently been used for many years in order to deal with all of the aforementioned problems (He, 2011; Nemes & Lachaud, 2009).

Not only the analytical methods, but also the experimental methods constitute restrictions. In analytical method, as an assumption, some of the hypotheses require the models to be simplified for being formulated. Constancy of the distribution of the peel and normal stress throughout the thickness of the adhesive and the restriction of transverse deformations in the adherends may be given as examples for the aforementioned assumption. As a result, analytical solutions can be applied only when there are simple geometries at hand (in case of absence of slots, fillets, etc); if there are parts such as slots and fillets increasing the complexity of the structure, analytical solutions seem to be inapplicable. On the other hand, in the case of experimental method, for experimental evaluation of the bondline behavior, specific equipments and skilled technicians are required; which consequently increases the costs of tests (Diaz *et al.*, 2010).

The parameters that influence the stress distributions in the adhesively bonding region can be classified into two categories. The first is known as material parameters, which includes the adherend and the adhesive material properties. The second is geometric parameters, which include the thickness of the adhesive layer, the thickness of the adherend, the length of overlap and the slot dimensions (Her, 1999).

Many researchers have been concerned with both adhesive and adherend in order to enhance the joint efficiency (Gleich *et al.*, 2001; Lang & Mallick, 1998; Tsai & Morton, 1995). In several researches, the effect of spew fillet and spew geometries on adhesive stress distribution in SLJs was studied (Lang & Mallick, 1998; You *et al.*, 2003). Two-dimensional, FE analyses were performed by Tsai and Morton (1995) to simulate the mechanical response of the SLJ and the effect of a spew fillet. Fessel *et al.* (2007) supported their numerical results with conducting the experiment, studied how the improvement of the joint geometry is effective for enhancing the joint strength. They showed that the use of reverse-bent results in better strength properties compared to conventional lap joint. Pires *et al.* (2006) reported that the use of a hybrid adhesives improves the joint strength, compared to the cases preferred single adhesives in the bondline. Fitton and Broughton (2005) investigated the effect of changing adhesive modulus in hybrid adhesive SLJ using both experimental and numerical techniques. They concluded that higher shear strength adhesive should be used in the center of the bondline to obtain good strength properties. Temiz (2006) examined the stress distribution of the double lap joint, constituted using one stiff adhesive applied in the middle of bondline and one flexible adhesive applied towards the edges, subjected to external bending moments. The lap joints subjected to bending moment were investigated by Grant *et al.* (2009) in the point of different geometric parameters such as the adhesive thickness, overlap length and fillet shape. Diaz *et al.* (2010) carried out a parametric investigation of 3D FE models of carbon fiber-reinforced polymer SLJs using an epoxy-resin adhesive layer. Cognard *et al.* (2012) performed an optimal joined design analysis by comparing the mechanical response of SLJs and cylindrical joints under the tensile and compression loads. They show that the changes in geometry may lead to improvement in the failure resistance of the joints. The shear and peeling stresses of a bi-adhesively bonded double lap joint were investigated by Özer and Öz (2012). They showed that the considerable decrease in the stress components of the hybrid adhesive joints can be seen from the numerical simulation, compared with the joints bonded with single adhesives. They also emphasized the influence of bond-length ratios on the residual stress. Samaei *et al.* (2014) investigated adhesively bonded joints, and the influence of geometric parameters and mechanical properties of the adhesive in single lap aluminum structures under tensile load.

In this study, various FE models of a bi-adhesively bonded spew fillet SLJ were examined in order to understand the combined effect of varying slot geometry and bondline configuration on the stress responses that are located at the adhesive midline.

FINITE ELEMENT MODEL

In this study, Aluminium was determined as an adherend and Terokal 5045 and Hysol EA 9313 were used as the flexible and stiff adhesive respectively. The material properties of the aforesaid adherend and adhesive are given in Table 1. The determination of adherend and adhesive materials were specified according to the practical use in the engineering applications and literature (Özer & Öz, 2014). Also the location adjustment of flexible and stiffer adhesives are defined through the study of Kumar and Pandey (2010) since the higher joint strength can be achieved by the use of adhesive with low modulus at the ends of overlap in a bondline of the joint that can result in a major decrease on the stress concentration.

Table 1. Material properties of adhered and adhesive

	Young's modulus (MPa)	Shear strength (MPa)	Poisson's ratio
Aluminium	71700	152	0.33
Stiff Adhesive	2274	27.6	0.36
Flexible Adhesive	437.4	20	0.38

The dimensions and boundary conditions of modelled bi-adhesively bonded SLJ are shown in Figure 1. In this figure, M (M is one of the edge of spew fillet, which is an equilateral triangle) is 2.5 mm, and t (0.2 mm) and k (2 mm) are the thickness of the adherends and the adhesive, respectively. In the analyses of the adhesive mid-bondline, S+2B total overlap length formulation was considered and taken as 12.5mm. Also the width of joint was set as 25 mm. The values of other dimensions are presented in Table 2.

Table 2. Geometric dimensions of models

	S (mm)	B (mm)
Case 1 (25-75-25 Model)	7.5	2.5
Case 2 (35-55-35 Model)	5.5	3.5

In the models, the first and last number are used to denote the length of flexible adhesives and second number denotes the length of stiff adhesive in decimilimeters.

The SLJ was meshed with tetrahedral elements. The entire mesh of the SLJ consisted of 302,262 isoparametric elements with 1,422,586 nodes. Element numbers are determined according to the prior works (Adin, 2012; Özer & Öz, 2012; Yan *et al.*, 2007) and it was seen that the increment on the element numbers over the defined value did not have a noticeable effect on the results, whereas it increased processing time dramatically. Due to the joint geometry, tetrahedral elements were used in the fillet location and quadrilateral elements were used in the rest of mesh (see Figure 2). The elastostatic FE analyses were also performed using ANSYS 15.0 (Swanson Inc., Houston, PA) FE commercial software considering geometric non-linearity. Number of elements on the critical points (i.e ends of overlap region) in adhesive layer were increased due to the stress concentration.

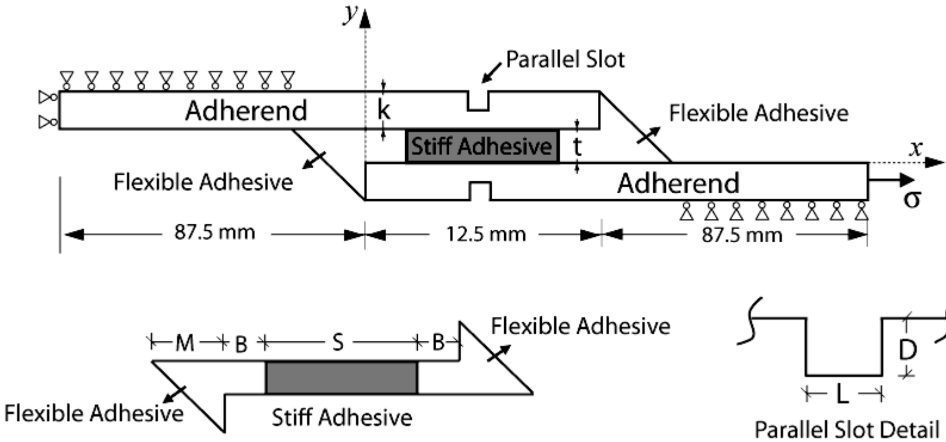

Fig. 1. Geometry model of full filled bi-adhesive SLJ and the load condition

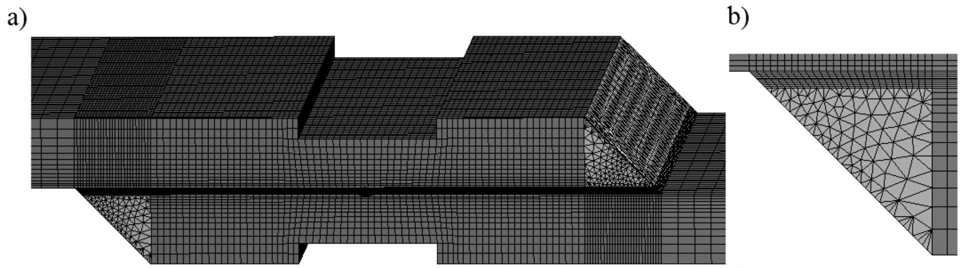

Fig. 2. (a) 3D Mesh model (b) Detailed view of the FE models

The applied load, placed at the end of the lower adherend, is 60 MPa. All degrees of freedom were mounted at the loaded end of lower adherend except for the longitudinal displacements. At the upper adherend end, all degrees of freedom were to be restrained. The details are shown in Figure 1.

In this paper, the influences of the depth (D) and length (L) of parallel slot on stress distributions (normal and maximum principal stress) of mid-bondline of two different bi-adhesively bonded joints result from a combination of flexible and stiffer adhesives with aluminum adherend were investigated. The geometric dimensions of the joints are given in Table 2.

The centers of the slot and stiff adhesive illustrated in Figure 1 were placed concentrically in order to obtain the reduction on the stress concentration on the center of stiff adhesive.

In the aforesaid analyses, four different slot lengths (L=1, 2, 3 and 4 mm) were used for each model and the influence of five different slot depths (D=0.4, 0.5, 0.6, 0.7 and 0.8 mm) on the mechanical properties of joints were investigated for each slot length. Consequently the designated forty different slot models were examined.

As shown in Figure 1, the location of the origin of the x coordinate is at the top of the lower adherend and the location of the origin of the y coordinate is at the left edge of the fillet.

NUMERICAL RESULTS AND DISCUSSION

The peel and shear stresses are very important parameters for the optimal design of the lap joints. These parameters (mostly the peel) are highly influential on the failure of the lap joints. In order to obtain good strength properties, the lap joints should be designated to induce the low peel and shear stresses. However, in this study, the shear stresses remained the same for the each designed model since the differences between the models were the geometric parameters, such as the stiff adhesive length, slot length and slot depth.

The analysis showed that the stress values change along the transverse coordinate (z). In this study, the results obtained from the mid-plane of the adhesive were taken into consideration hence the maximum values of the peel stress occur at z=12.5 mm (the width of bond is 25 mm).

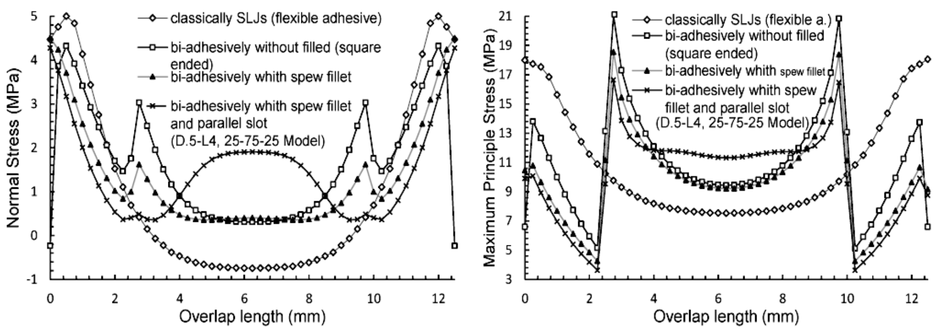

Fig. 3. Effect of the pure spew fillet, pure parallel slot and the combination of both on the bi-adhesively bonded lap joint

As seen in Figures 3(a) and 3(b), the maximum principal stress in the stiff adhesive part of the bi-adhesive bondline is higher than that in the flexible adhesive part of the bi-adhesively bonded joint.

In Figure 3., the comparison of the normal stress (y-orientation) distributions of the mid-bondline of spew fillet bonded bi-adhesive joint and square ended (without fillet) bi-adhesively joint shows that 10.6% stress reduction can be obtained at the confluence line of stiff and flexible adhesive of the joint with the inclusion of a spew fillet. Also the maximum values of normal and maximum principal stress in the bondline of the bi-adhesive joint with spew fillet model were 10.9% and 11.6% lower than bi-adhesively without filled (square ended) model. In other words, the spew fillet resulted in 10.6% and 11.6% reduction on the normal and maximum principal stress respectively. Similarly, the parallel slots caused 10.7% and 10.4% decrease on stress values in the joints having spew fillet. Also normal and maximum principal stress of conventional bi-adhesively bonded SLJ could be decreased notably using both parallel slots and spew fillet by 23.2% and 20.8% respectively.

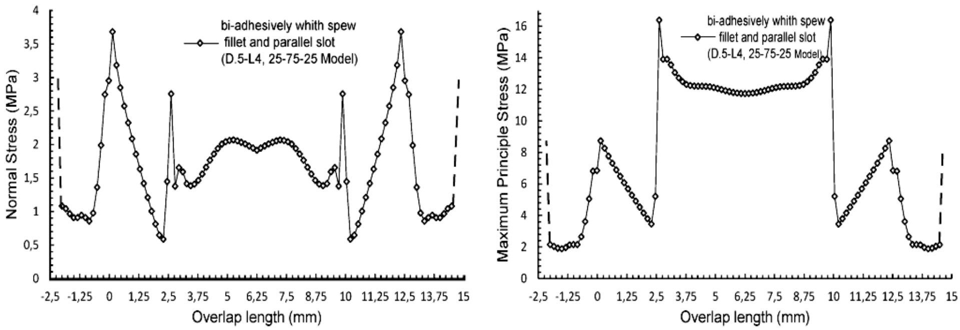

Fig. 4. Stress distribution of the interface between the adhesive and the substrate.

In Figure 4, the abscissas are -2.5 and 15 mm for the end of left and right fillet respectively. They are 2.5 and 10 mm for the left and right confluence interface between the stiff and flexible adhesives and 0 and 12.5 mm for the ends of lower and upper adherend.

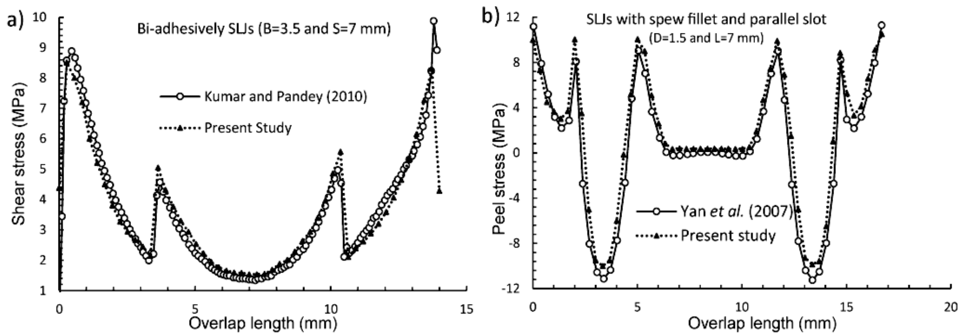

Fig. 5. The validation results of bi-adhesive and mono adhesive SLJ with spew fillet and parallel slot

The FE validation was done by using two different models obtained from literature with similar boundary conditions and materials. The first model was a bi-adhesively bonded SLJ, which was studied by Kumar & Pandey (2010) and second model was mono-adhesively bonded SLJ with spew fillet and parallel slot which was used by Yan et al. (2007). The results were plotted against those obtained from literature (See Figure 5). From the figure, it is obvious that the present FE results and the results obtained from literature are in close agreement with each other.

In Figures 6 and 7 the effects of parallel slot (depth=0.4-0.8 mm and length=1-4mm) on the stress distribution of joint with bi-adhesive bond consists of stiff adhesive (length=5.5 and 7.5mm) and flexible adhesive (length=2.5 and 3.5mm) in the mid-bondline (y=0.1 mm) are presented.

Having been performed into a parallel slot, the adherend may be the reason for the reduction of the stiffness of the part of the adherend placed on the bondline. The decrease on the peak value of stresses took place at both ends and transfer of a good deal of stress along the middle part that corresponds to a parallel slot in the mid-bondline are also due to this process.

These processes were investigated as two different cases using varying geometrical parameters.

Case 1

In this case, the stiff adhesive bond line (S) was determined as 7.5 mm and flexible adhesive bond line (B) was 2.5 mm.

The parallel slot length L was kept constant at 1 mm, the parallel slot depth D was set as 0.4, 0.5, 0.6, 0.7 and 0.8 mm, respectively. The effect of the parallel slot depth on the normal and maximum principal stress distribution in the mid-bondline (y=0.1 mm) are illustrated in Figures 6(a) and 6(e) respectively. Similarly when L was kept constant at 2 mm, the parallel slot depth D was set as 0.4, 0.5, 0.6, 0.7 and 0.8 mm, respectively. The stress distributions are presented in Figures 6(b) and 6(f).

When the parallel slot depth was kept constant at 0.8 mm, the peak value of the stress decreased to the level of 8.1% on the condition that the slot length was increased from 1 mm to 2 mm. While slot depth was 0.4 mm, the peak value decreased only by 0.9%. The aforementioned changes in the stress value can be seen in Figures 6(a) and 6(b).

When the length of slot was increased from 2 mm to 3 mm and the depth was 0.8 mm, the maximum stress value decreased by 4.8%. When the slot depth was set as 0.4 mm, the decrement on the peak stress value was about 1.3% (See Figures 6b and 6c).

When the parallel slot depth was kept constant at 0.8 mm, the peak value of the stress decreased to the level of 4.7% on the condition that the slot length was increased from 3 mm to 4 mm. While slot depth was 0.4 mm, the decrease on the peak value was only 1.8% (See Figures 6c and 6d).

Consequently, the computational results showed that optimum peel stress can be obtained in the case of bi-adhesive SLJs with spew fillet bonded with the geometrical parameters in which slot depth (D) is 0.8 mm and the length is (L) 4 mm (see Table

3.a). Similarly, optimum maximum principal stress can be obtained in the case of the geometrical parameters in which slot depth (D) is 0.8 and the length (L) is 4 mm (see Table 3.b).

Table 3. Result of maximum values of maximum principal stress and normal stress for Case 1.

	L1	L2	L3	L4
D.4	4.3964	4.3579	4.3022	4.2265
D.5	4.3713	4.3197	4.2451	4.1442
D.6	4.3427	4.2771	4.1823	4.0540
D.7	4.3101	4.2300	4.1131	3.9556
D.8	4.6180	4.2438	4.0388	3.8504

a) Maximum Peel Stress values

	L1	L2	L3	L4
D.4	18.51	18.217	17.988	17.89
D.5	18.209	17.849	17.569	17.457
D.6	17.885	17.459	17.121	16.988
D.7	17.534	17.038	16.632	16.465
D.8	17.159	16.585	16.094	15.873

b) Maximum principal stress values

Case 2

All the geometrical dimensions were same as Case 1 except stiff and flexible adhesive dimensions. Here, flexible and stiff adhesive bond lengths (B and S) were 3.5 mm and 5.5 mm respectively.

When the parallel slot depth was kept constant at 0.8 mm, the peak value of the stress decreased to the level of 3.2% on the condition that the slot length was increased from 1 mm to 2 mm. While slot depth was 0.4 mm, the peak value decreases only by 1%. The mentioned changes in the stress value can be seen in Figures 7(a) and 7(b).

When the length of slot was increased from 2 mm to 3 mm and the depth was 0.8 mm, the maximum stress value decreased by 3.4%. When the slot depth was set as 0.4 mm, the decrement on the peak stress value was about 1.3% (See Figures 7b and 7c).

Table 4. Result of maximum values of principal stress and normal stress for Case 2

	L1	L2	L3	L4
D.4	4.719	4.670	4.608	4.529
D.5	4.685	4.622	4.540	4.437
D.6	4.648	4.570	4.467	4.772
D.7	4.608	4.513	4.387	4.228
D.8	4.599	4.452	4.302	4.113

a) Maximum Peel Stress values

	L1	L2	L3	L4
D.4	17.092	16.996	17.198	17.704
D.5	16.751	16.677	16.991	17.689
D.6	16.394	16.340	16.770	17.676
D.7	16.801	16.267	16.536	17.675
D.8	17.918	17.050	16.273	17.664

b) Maximum principal stress values

When the parallel slot depth was kept constant at 0.8 mm, and the slot length was increased from 3 mm to 4 mm, the peak value of the stress decreased to the level of 4.4%. While slot depth was 0.4 mm, the decrease on the peak value was only 1.7% (See Figures 7c and 7d.).

For the peel stress values of each joint models (Case 1 and Case 2), single peak point occurred on the flexible adhesive, when the slot length was 1, 2 or 3 mm. if the slot length was 4 mm, double peak points were seen (see Figures 6 and 7).

DISCUSSION AND CONCLUSIONS

This paper has analyzed the influence of various geometrical parameters in the bi-adhesively bonded joint with spew fillet.

The axially loaded bi-adhesively bonded SLJ with spew fillet and parallel slot was analyzed considering geometric nonlinearities to understand the mechanical behavior of joint at a graded bondline using 3D FE method. Also alteration of stress distributions in the mid-bondline was investigated. The followings are the results of analysis:

- When the depth of parallel slot increased, the maximum value of peel stress in the mid-plane of bondline near the end of each adherend remained constant and the stress level along the stiff adhesive decreased, whereas the stress values along the flexible adhesive increased. The decrease in the maximum value of S_x, the longitudinal stress, which is in the mid-bondline near the free end of the adherend and the increase in the stress level in the middle part, corresponding to the parallel slot, are also the results of the same situation.

- The increment on the parallel slot length of the adherend leads to the lower peel stress in the adhesively bonded region. As increasing the slot length in the models having longer stiff adhesive length (Case 1) leads to decrease in the normal stress, the joints having the shorter bond length (Case 2) has an opposite situation. Also it is a cause for the appreciable differences on the results of maximum peel stress for Case 2.
- In contrast to decrease in stress provided by increasing the depth of slot in some of the bond models with longer stiff adhesive length (for ex. D=3mm-4mm), a steady increase can be seen in bond models with shorter stiff adhesive length.
- The proper combination of bond-length and parallel slot geometry ratios results in an optimal stress distribution in the graded bondline.
- The peak value of peel stress always occurs at the end of overlap length, except for D.8 L1 and D.08 L2 configuration of Case 1 and D.8 L1 of Case 2. Also the maximum principal stress value is usually seen at the merging interface of stiff and flexible adhesives.
- For all conditions, maximum peel stress values in Case 1 are approximately 7% lower than Case 2.

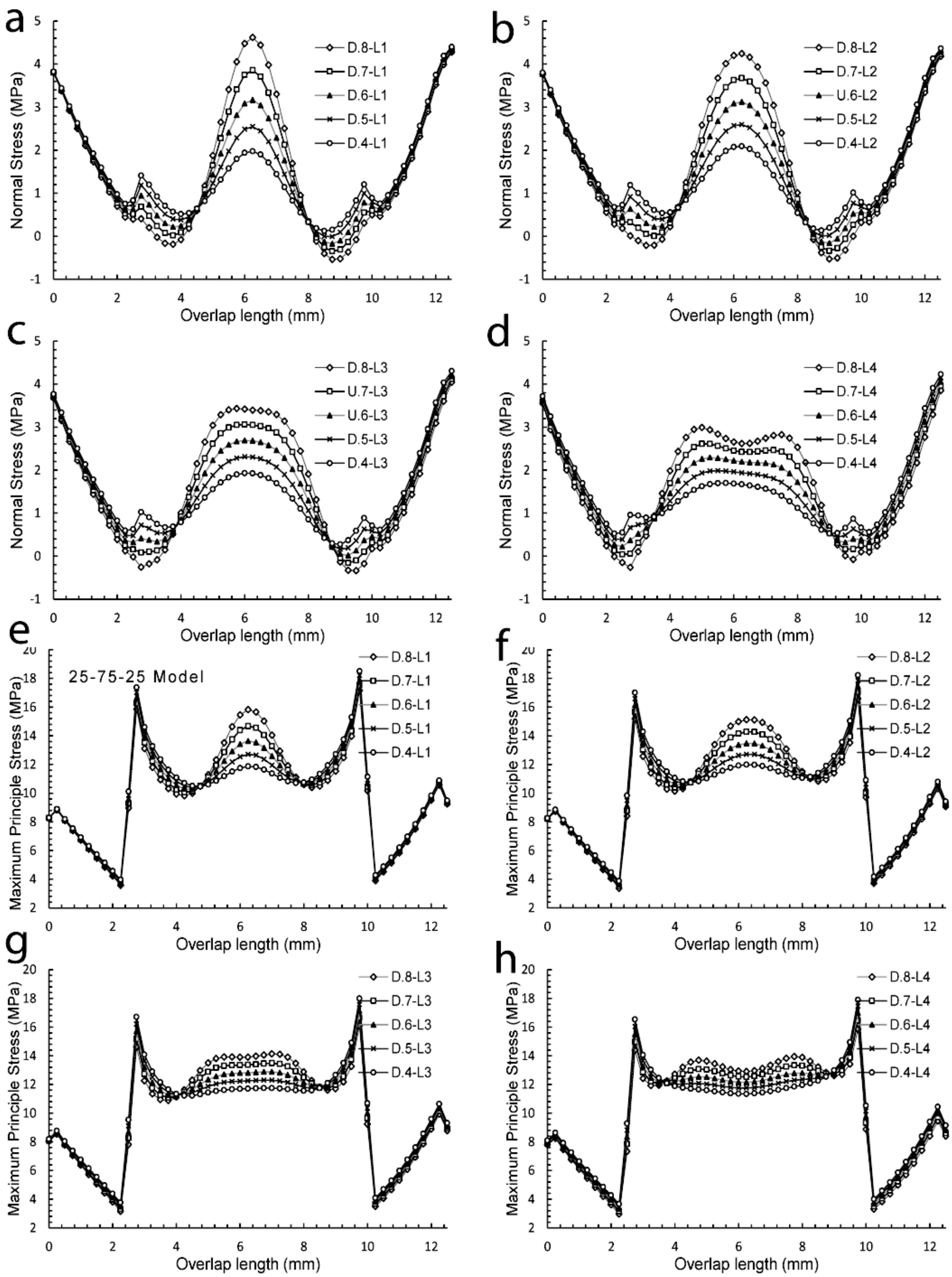

Fig. 6. Effect of the slot depth and length on the 25-75-25 Model (Case 1)

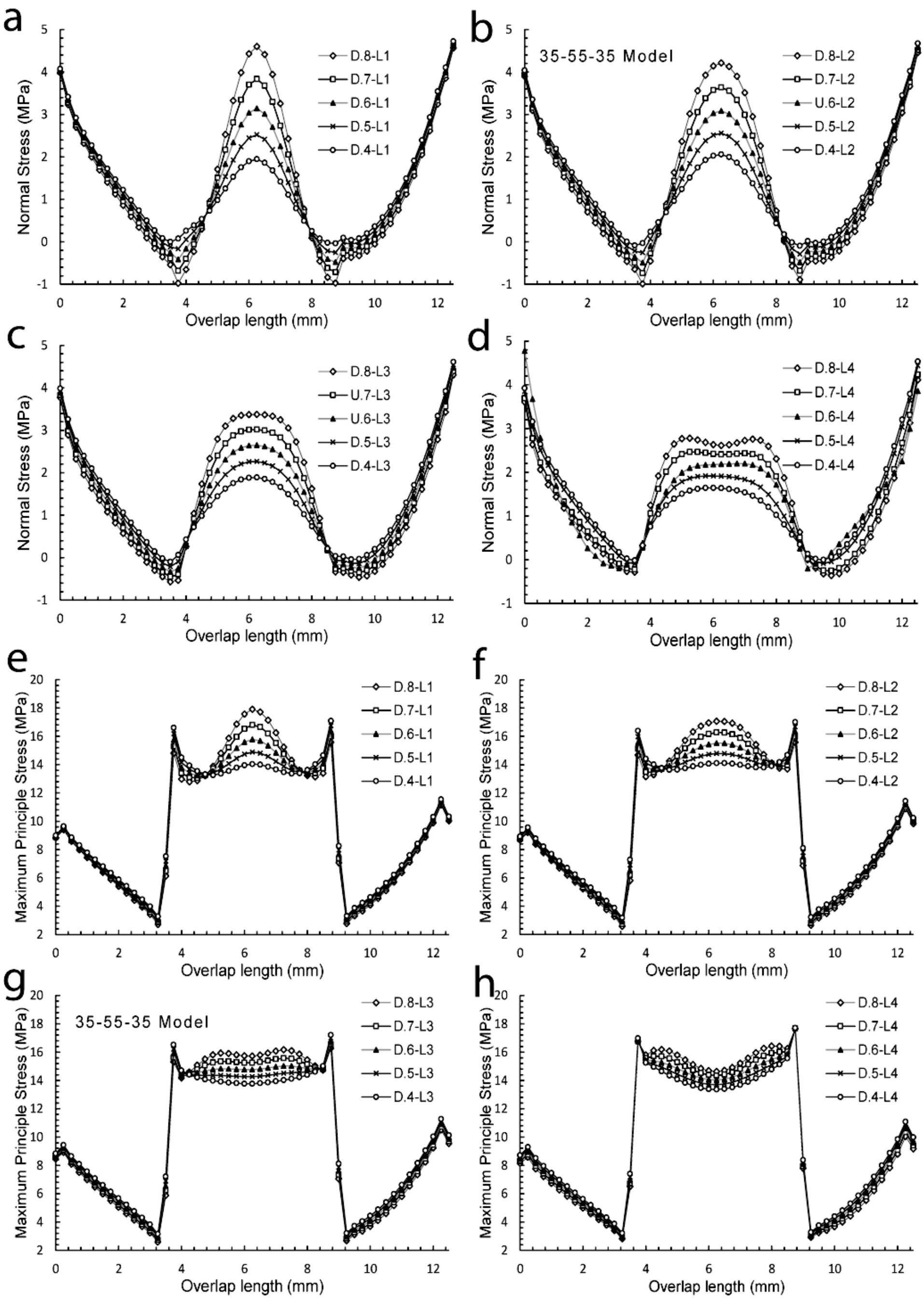

Fig. 7. Effect of the slot depth and length on the 35-55-35 Model (Case 2).

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