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DESIGN OF ADHESIVE BONDED JOINT USING ALUMINUM SANDWICH SHEET

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ABSTRACT–Recently, weight reduction of vehicles has been of great interest, and consequently the use of composite materials in the automotive industry is increasing every year. Composite sandwich panels which consist of two skins and core materials are replacing steels in automotive floor and door. The substitution of one material for another is accompanied by change of joining method, so that adhesive bonding has been popularly used for joining method of composite materials. In the case of adhesive bonding of composite materials, there could be loss in the joint strength by delamination of two faceplates or cracking on faceplate. Thus, it is necessary to prevent loss in the joint strength by designing the joint geometry. In the present paper, adhesive bonding of aluminum sandwich sheet was tried. For understanding joint behavior, studies on stresses in the single lap joint were reviewed and failure modes of composite material were analyzed. Strength tests on the single lap joint consisting of aluminum sandwich sheet and steel were performed and variation of the joint strength with the joint configuration was shown. Based on these results, design guide of adhesive bonding in aluminum sandwich sheet was suggested.

KEY WORDS : Adhesive bonding, Single lap joint, Aluminum sandwich sheet

1. INTRODUCTION

Recently, weight reduction of vehicles has been of great interest, and consequently the use of composite materials in the automotive industry is increasing every year. Composite sandwich panels which consist of two skins and core materials are replacing steels in automotive floor and door. The substitution of one material for another is accompanied by change of joining method. Conventional joining method, namely, resistance spot welding cannot be applied to composite material, so that adhesive bonding and mechanical fastening have been used for joining method of composite material. Adhesively bonded joints have an advantage over traditional mechanically fastened joints in that they avoid drilled holes, consequently stress concentration, and loss in the joint strength. There are also benefits to be achieved from using adhesives instead of welding in numerous occasions.

In adhesive bonding, the joint strength is significantly varied with the joint geometry despite same bonding area. Figure 1 illustrates the variation of the joint strength with the joint geometry (Hart-Smith, 1974). It is known that the single lap joint is the weakest joint. Despite this weakness, the single lap joint is one of the most commonly used joints and is the configuration most often used for testing adhesives. Further, in some applications related to automotive body, the single lap joint is the only applicable type of joint. Thus, a lot of joint designs for increasing strength in the single lap joint have been tried. In the case of bonding composite materials, the single lap joint has not been used as a basic design for load-bearing joints. The eccentricity of loading path in the single lap joint causes premature joint failure by delamination within the sandwich facesheet (Hart-Smith, 1978).

Recently, novel type of thin sandwich sheet has been developed related to the weight reduction of vehicle. It is important to evaluate failure mode such as the delamination (Markaki and Clyne, 2003). But, in the case of novel type of thin sandwich sheet such as aluminum sandwich sheet, there are few researches about failure mode when adhesive bonding is applied.

In the present paper, adhesive bonding of aluminum sandwich sheet was tried. For understanding joint behavior, studies on stresses in the single lap joint were reviewed and failure mode of composite material was analyzed. Strength tests on the single lap joint consisting of aluminum sandwich sheet and steel were performed and variation of joint strength with joint configuration was shown. Based on these results, design guide of adhesive bonding in aluminum sandwich sheet was suggested.

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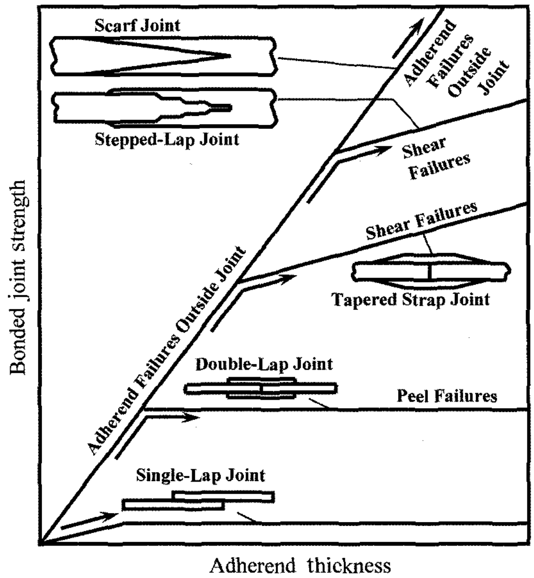


Figure 1. Variation of the joint strength with the joint geometry.

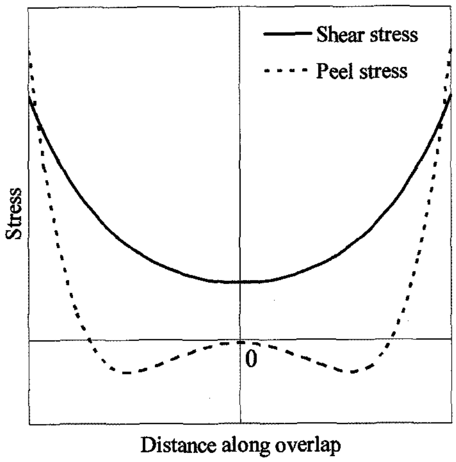


Figure 2. Shear and peel stress distribution in the single lap joint.

2. REVIEW ON STRESS ANALYSIS IN THE SINGLE LAP JOINT

Many researches have been done about the analysis of lap joint over the last fifty years. Numerical works have been studied by a number of authors, such as Volkersen (1938), Goland and Reissner (1944), Hart-Smith (1973) and Oplinger (1991), which have used the beam or plate theory to model lap joint behavior. Other researchers such as Renton and Vinson (1977), Allman (1977), and Chen and Cheng (1984), studied two-dimensional elastic solutions to ensure the satisfaction of the stress-free boundary conditions. Wooley and Carver (1971), Adams and Peppiatt (1974), Crocombe and Adams (1981), and Harris and Adams (1984), provided detailed geometric and material parameter studies with geometric linearity or nonlinearity of the specimens with or without a spew fillet. Despite the volume of work, there are still some controversial and unresolved issues as to predicting the adhesive stress distribution and magnitude.

When a tensile load exerted on the single lap joint, stresses in the adhesive layer are not uniform. Shear stress and peel stress in the adhesive layer reach a maximum at each end of the overlap. Shear stress arises from the differential straining of the adherend and peel stress arises from the eccentricity of the loading path. The eccentricity of the loading path generates significant bending and therefore makes behavior of joint geometrically nonlinear. Peel stress is a major factor in the fracture of the single lap joint. It frequently leads to joint fracture by enabling cracks to initiate and propagate from the ends of the overlap. Indeed, shear fracture in the adhesive layer is never observed. Thus, the reduction of peel stress can lead to higher joint strength and this is a design principle of the single lap joint. As mentioned above, there are numerous studies about stresses in adhesive layer. But, the practice of precise representation may seem unnecessary for engineering design because the characteristics of the answers remain the same. Among the important conclusions to be drawn from both experimental and numerical studies are those listed below:

(1) The stresses in the adhesive layer are not uniform, and the stress concentrations arise from the differential straining of the bonded substrates and from the eccentricity of the loading path. Figure 2 shows well-known shear and peel stress distribution, although there still remain controversial issues.
(2) In most cases, fracture in adhesive layer occurs by peel stress, not shear stress.
(3) In general, peel and shear stress concentration is higher for stiff adhesive than for soft adhesive.
(4) Thicker adhesive layer reduce the peel stress. This is why local thickening of the adhesive layer at the ends of the overlap is such a powerful technique in improving the joint strength.
(5) The presence of spews can reduce peak stresses and therefore increase the joint strength.
(6) The replacement of the adherend by stiffer, stronger materials is known to increase the joint strength.
(7) Increasing the thickness of the adherend increases the joint strength.
(8) Increasing the width of the joint has the effect of giving proportional increase in strength while increasing the overlap beyond a certain limit has very little effect at all.
(9) Using a sufficiently long overlap can reduce the

eccentricity of the loading path and therefore increase the joint strength.

(10) Thickness of adhesive layer should be as thin as possible, provided that adhesive is well applied on the area to be bonded.

3. FAILURE MECHANISM OF COMPOSITE MATERIALS

3.1. Failure Modes in Composite Single Lap Joint

Failure modes in adhesively-bonded composite joints are significantly different from those in joints with metal adherends. In addition to adhesive or cohesive failure in the adhesive layer, and net tensile failures of the adherend which are typically in joints with metal adherends, two other modes of failure are possible, particularly in the single lap joint; lateral cracking and interlaminar failure. Figure 3 shows four possible modes of failure in the single lap joint with composite material. In adhesive terminology, adhesive failure means the destruction of the bond between adherend and adhesive and cohesive failure means a fracture wholly within the adhesive material. Lateral cracking can occur when there is severe lateral contraction. This type of failure is most frequent in unidirectional material with non-identical adherends. The most problematic matter is the interlaminar failure which results from flaw growth between layers. The eccentricity of loading path in the single lap joint causes premature joint failure by delamination, and consequently the joint capacity is greatly reduced.

In the case of the single lap joint, bending failure of adherends may occur because of high moments at the ends of the overlap. For metal adherends, bending failures take the form of plastic bending and hinge formation, while for composite adherends the bending failures are brittle in nature. In this study, failure modes of adhesively-bonded single lap joint consisting of aluminum sandwich sheet and steel was examined and compared with those of conventional composite.

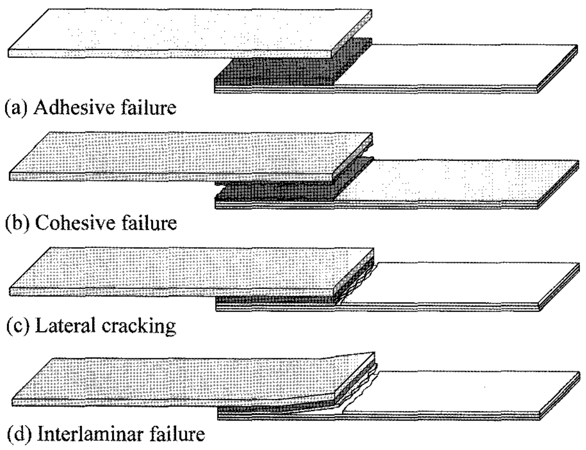


Figure 3. Four possible failure modes of composite material.

3.2. Single Lap Test

Aluminum sandwich sheet and medium carbon steel were bonded using a methacylate-based adhesive named PLEXUS MA820. Aluminum sandwich sheet named Hylite consists of two aluminum sheets and a layer of polypropylene in between. Adhesive which can be cured at room temperature was selected because hot-setting adhesive have the possibility of melting polypropylene. The reason for bonding aluminum sandwich sheet and steel is that it usually occurs in automotive body. The geometry and dimensions of the single lap joint are shown in Figure 4. The overlap length was taken as 20 mm for the first try and increased by 10 mm. The mechanical properties of these two adherends are given in Table 1. Since adhesive accumulations around the adhesive free ends, called spew fillet have a considerable effect on the peak stresses arising at the adhesive free ends, it was eliminated for evaluating pure joint strength.

3.3. Failure Mechanism

The deformed shape of the single lap joint after failure is shown in Figure 5. Plastic hinge occurred at the overlap end corner of aluminum sandwich sheet. Figure 6 shows variation of joint strength with the overlap length. At the overlap length of 20 mm and 30 mm, the cohesive failure occurred. Beyond 30 mm, aluminum sandwich panel yielded before the adhesive is failed. From these results, minimum overlap length can be set to 40 mm. 40 mm overlap is used throughout all tests after this. Failure of aluminum sandwich panel, as shown in Figure 7, was initiated from the skin surface. It was observed that lateral cracking on the skin surface and severe width contraction. As would be expected from failure mode of

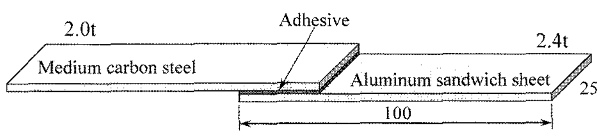


Figure 4. The geometry and dimensions of the single lap joint.

Table 1. Mechanical properties of adherends.

	Elastic modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)
Steel	209	250	410
Aluminum sandwich sheet	14.9	32	78

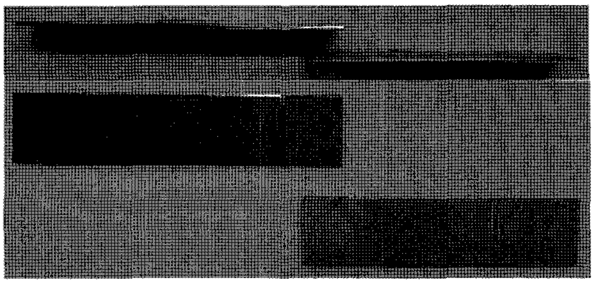


Figure 5. The deformed shape of the single lap joint at overlap length of 20 mm.

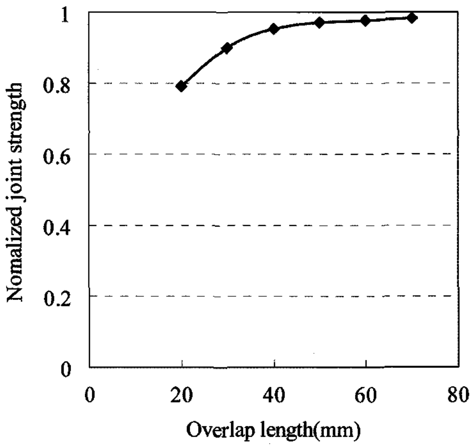


Figure 6. Variation of joint strength with the overlap length.

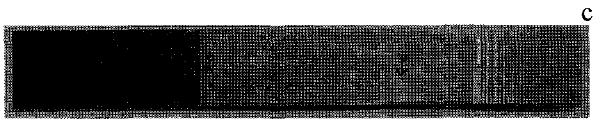


Figure 7. The deformed shape of the single lap joint at overlap length of 60 mm.

omposite material, this cracking is a kind of bending failure which is caused by eccentricity of loading path in the single lap joint. From engineering design view, a crack caused by peel stress and width contraction caused by Poisson's ratio could be major input to the design of single lap joint. In next try, spew fillet and local thickening of the adhesive is introduced to reduce peel stress concentration near the overlap end. Also, change of bonding area shape is tried to relax lateral stress caused by width contraction.

4. EFFECT OF JOINT GEOMETRY ON JOINT STRENGTH

4.1. Effect of Steel Geometry on Joint Strength

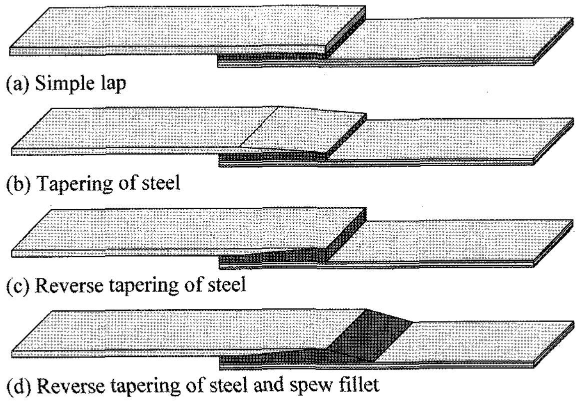


Figure 8. Modified geometries of the single lap joint.

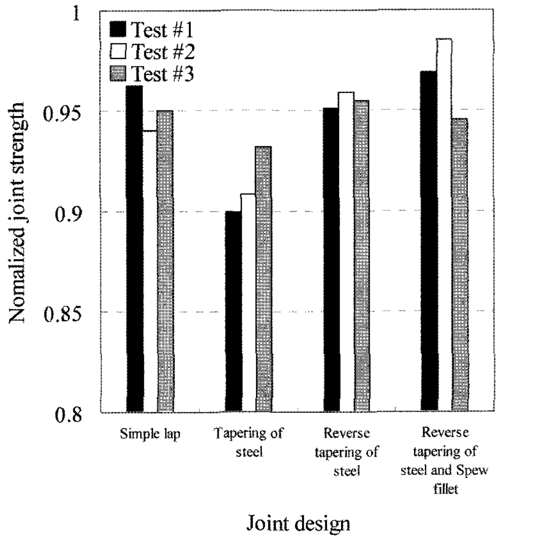


Figure 9. Variation of the joint strength with the joint design.

The single lap tests on four joint designs were tried to increase the joint strength, which is similar to the test tried by Adams and Wake (1984). Figure 8 shows four designs of the single lap joint, i.e., simple lap, tapering of steel, reverse tapering of steel, reverse tapering of steel and spew fillet. Figure 9 shows the normalized joint strength as a change of joint design. Tapering of steel provides a more uniform shear stress distribution in the overlap. However, this joint showed the poorest strength among four designs. This represents that failure of the single lap joint is caused by peel stress, not shear stress. Reverse tapering of steel is known to reduce peel stress concentration by local thickening of adhesive as well as shear stress concentration. This joint showed a slight increase in the joint strength, which seems to be caused by reduction of peel stress at the end of overlap. The joint

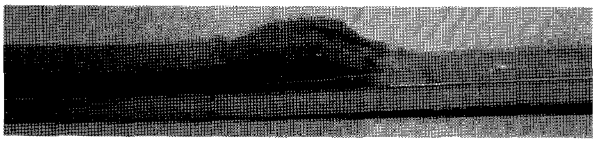
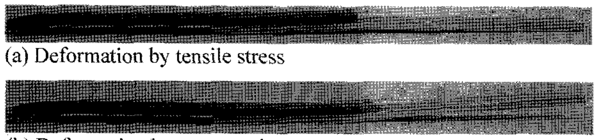


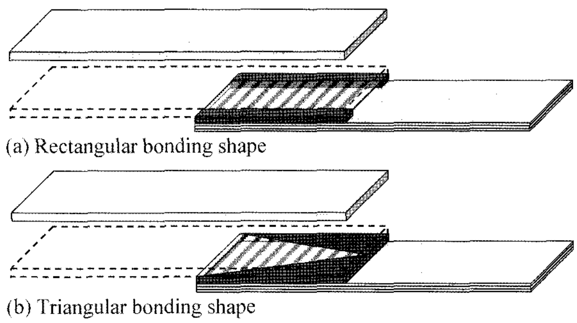
Figure 10. Spew fillet geometry.



(a) Deformation by tensile stress

(b) Deformation by compressive stress

Figure 11. Deformed shape of the single lap joint.



(a) Rectangular bonding shape

(b) Triangular bonding shape

Figure 12. Modified shape of the bonding area.

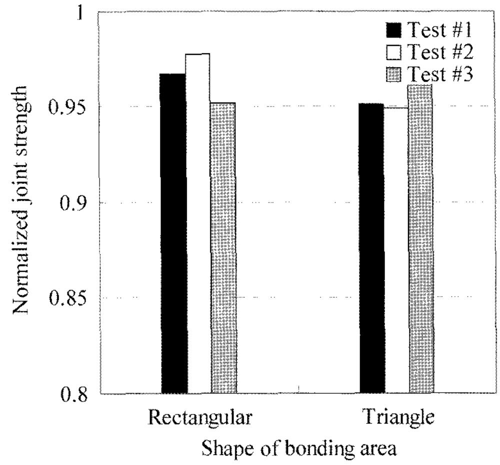


Figure 13. Variation of the joint strength with the shape of bonding area.

with reverse tapering of steel and spew fillet showed good joint strength, but dramatic increase of joint strength which was shown in results of Adams and Wake, was not seen. Spew fillet have two positive effects on the joint strength. One is reduction of shear and peel stress concentration. The other is that spew fillet can play a role as moment-resistance, as rivet in riv-bonding. In riv-bonding which means combination of adhesive with rivet, adhesive itself becomes the principal bonding agent while rivet serves as a tool in the fixing process and relieves the damage caused by peel stress. In this experiment, the boundary of the adherend and adhesive is weak, so that the spew is not cracked but is pulled away from the loaded adherend surface, which is shown in Figure 10. This is because there was not dramatic increase in the joint strength.

Another noteworthy feature was found in this experiment. Although the same type of failure which is a crack on the skin surface was observed, the rotation direction of the sandwich sheet is not same. While sandwich sheet in simple lap joint is deformed by tensile stress near the overlap end, sandwich sheet in joint with reverse tapering is deformed by compressive stress. Figure 11 shows the difference of deformed shape. Since stresses near the overlap end is very complex and difficult to predict, variation of stresses with the joint geometry cannot be described accurately. However, design for increasing joint strength can be clear. Failure of sandwich sheet is caused by the bending due to tensile or compressive stress near the overlap end, so that design for minimizing bending deflection can be guideline for this type of joint. Indeed, bending deflection in the joint with reverse tapering and spew fillet, which showed the largest joint strength, was small compared to other joints.

4.2. Effect of Shape of Bonding Area on the Joint Strength

In this experiment, most cracks in sandwich sheet occurred at the end of overlap near loading and joint width was significantly contracted at this region. Taking this deformation into consideration, it can be thought that stresses by anticlastic bending affect failure mode. If sandwich sheet in overlap region is allowed to contract or expand, additional stresses by the anticlastic bending may be reduced or eliminated. Based on this supposition, shape of bonding area is changed as shown in Figure 12. The shape of bonding area is designed not to restrain lateral movement while keeping the same bonding area. Figure 13 shows variation of the joint strength with the shape of bonding area. The joint with change of bonding shape have a slight increase in the joint strength. From these results, it can be concluded that restraining lateral movement have the possibility to decrease the joint strength because of additional stresses occurred by the restraint, but influence on the joint strength is not large.

4.3. Discussion

In this experiment, the boundary of the adherend and adhesive is weak, so that the spew cannot play a role as moment-resistance, and consequently, the increase of the joint strength is slight. This represents that adhesive selection may be wrong. As mentioned above, there is a limit of temperature in applying aluminum sandwich sheet, 145°C, so that an epoxy-based adhesive cannot be used in this study. If it is possible to apply an epoxy-based adhesive without heat-curing, crack in the spew fillet or adherend failure away from the overlap region will be expected, which means the joint strength is the same with the tensile strength of parent material. Before this study, we tried the same type of test using methacylate and anaerobic adhesive named Loctite 648. But, results were not good because of anaerobic property of adhesive. It is difficult to make spew fillet geometry in anaerobic adhesive. In conclusion, making spew fillet with the adhesive which have strong adhesion is the best solution to increase the joint strength because it restrains bending deflection. If adhesive cannot make spew fillet or have the weakness in adhesion, moment-resistance such as rivet should be used for minimizing bending deflection.

In bonding of composite material, the most problematic failure mode is delamination of composite material. In this experiment, we have not observed delamination for any type of adhesive joint.

5. CONCLUSIONS

Adhesive bonding of aluminum sandwich panel was tried. For understanding joint behavior, studies on stresses in the single lap joint were reviewed and failure modes of composite material were analyzed. By tension test of adhesively-bonded single lap joint using aluminum sandwich sheet, minimum overlap length can be set to 40 mm. Variation of the joint strength with the joint geometry and the shape of bonding area was shown. Based on these results, the following conclusions can be drawn.

(1) The failure in the single lap joint is governed by not shear stress but peel stress.
(2) Failure mode of aluminum sandwich sheet in the single lap joint is a cracking on the skin surface. Failure by delamination was not observed for any type of adhesive joint.
(3) In applying spew geometry, the spew is not cracked but is pulled away from the loaded adherend surface by the peel stresses in the spew. In this study, spew fillet cannot play a role as moment-resistance, and consequently, the increase of the joint strength is slight.
(4) Although the same type of failure which is a crack on the skin surface was observed, the rotation direction of the sandwich sheet is not same. While sandwich sheet in simple lap joint is deformed by tensile stress near the overlap end, sandwich sheet in the joint with reverse tapering is deformed by compressive stress.
(5) From the view of the joint strength, design criteria can be clear: minimizing bending deflection increases the joint strength.
(6) To avoid the failure by peel stress, it is necessary to make spew fillet with the adhesive which have strong adhesion. If adhesive cannot support this, moment-resistance such as rivet should be used for minimizing bending deflection.
(7) Restraining lateral movement have the possibility to decrease the joint strength because of additional stresses occurred by the restraint, but influence on the joint strength is not large.

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