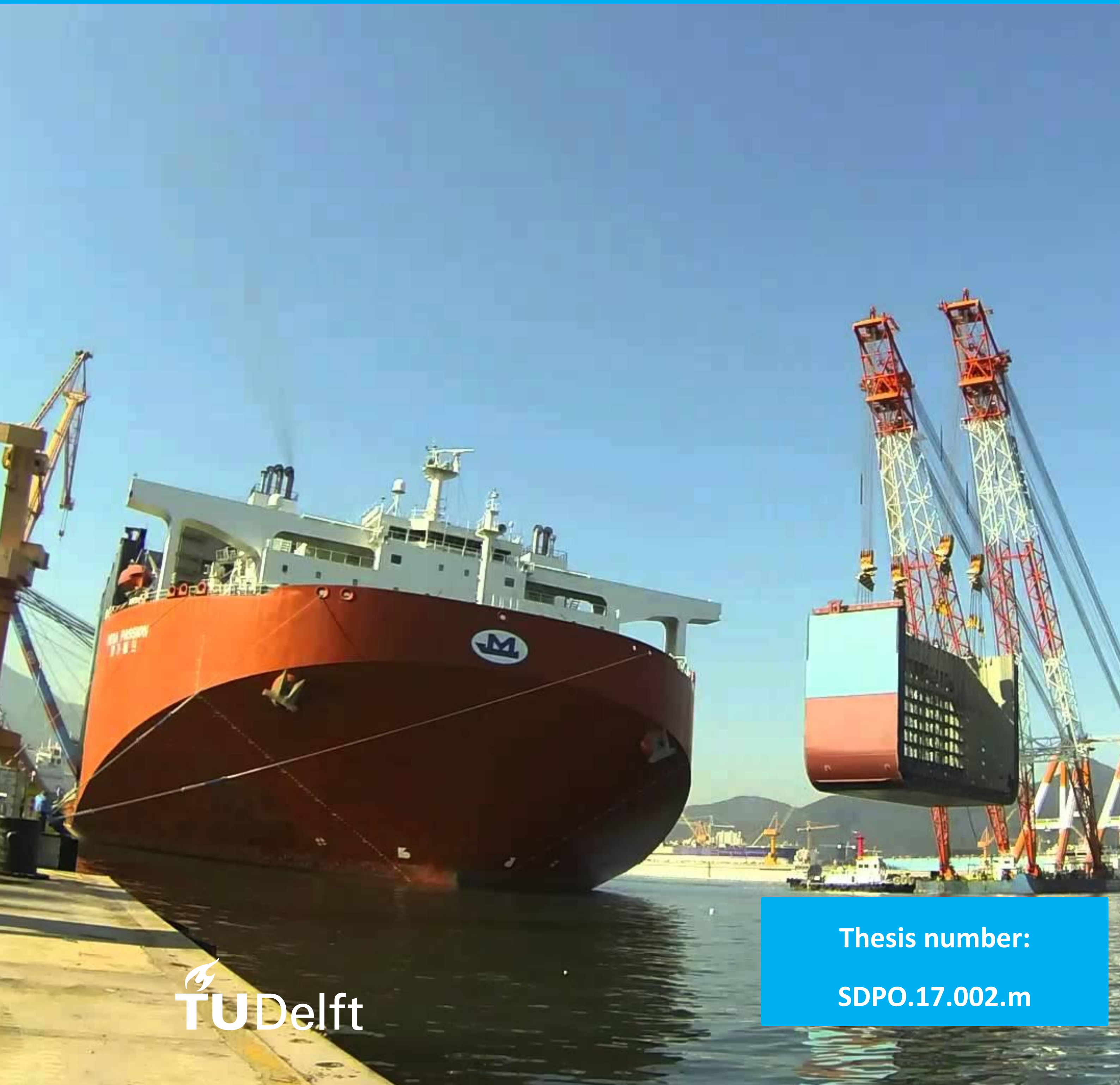
Jindao Sun

Investigation of the application of adhesively bonded lifting lugs in ship building



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Investigation of the Application of adhesively bonded lifting lugs in ship building

By

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Abstract

Defects are produced when lifting lugs being welded on ship sections during the building process. The large amount of heat produced in the welding work causes “heat affected zone” in the base metal on sections and destroys painted coatings on the plates; and residual stress decreases the mechanical performance of the steel plates. To eliminate the defects, it is hypothesized that “structural adhesive bonding” can replace welding for installing lifting lugs to some extent. An investigation of the application of adhesively bonded lifting lugs in ship building is processed to give methods for the application and check the feasibility of replacing welded lifting lugs with adhesively bonded lifting lugs.

In the research, a serious of rules for adhesively bonded lifting lugs is adapted from rules for welded lifting lugs; “structural adhesives”, “adhesive bonding joints”, “the shape and geometry of lifting lugs” and “positions for installation” are investigated. Then adhesively bonded lifting lugs are designed based on the adapted rules; and then improved after the evaluation by FEM simulation.

The results show that adhesively bonded lifting lugs can replace welding lifting lugs with high probability when the capacity is less than 20ton; when the capacity is between 20ton and 30ton, limitations such as “not enough bonding area” and “no positions for installation” constrain the replacement. When the capacity of a lifting lug is above 30ton, adhesively bonded lifting lugs cannot replace welded lifting lugs.

I. Background

1. Introduction

Currently, "sectional method of hull construction" is used in the ship building process. Wikipedia [1] describes it as: "*Modern shipbuilding makes considerable use of prefabricated sections. Entire multi-deck segments of the hull or superstructure will be built elsewhere in the yard, transported to the building dock or slipway, and then lifted into place*". When lifting sections in the building process, lifting lugs are used to connect the cable from cranes; and most lifting lugs are welded on ship sections. Figure 1.0.1 shows a section lifted by a crane in the building process and Figure 1.0.2 shows a welded lifting lug.

Figure 1.0.1 A lifted section in building process (World maritime news [2])

Figure 1.0.2 A welded lifting lug (AUTODESK.COMMUNITY [3])

Welding lifting lugs on ship sections causes extra big problems to the sections. Adhesive bonding can eliminate the defects according to its advantages; so using adhesively bonded lifting lugs might be a good solution. Adhesive bonding and welding are different in application and requirements; so the application of adhesively bonded lifting lugs will be investigated and research is going to be processed to judge the feasibility and give some basic advice for the potential application. In this part, an overview of the research is given.

1.1 Background

1.1.1 Defects of welded lifting lugs

In the beginning, defects caused by welded lifting lugs are given to show how welded lifting lugs affect the performance of the base metal on ship sections. Damages are produced mainly in the installing process caused by the welding work; while in the removing process (for lifting lugs must be removed after lifting work), gas cutting or gouging leads to damages. To find out the exactly damages and their harm to the sections, an interview was made with *Adriaan Visser*, who works as the Production Manager in IHC IQIP. Three main kinds of damages are concluded in the interview, they are Heat Affected Zone (HAZ), residual stress and coating damages; the following parts will talk about these aspects.

Firstly, the most obvious damage provided by welded lifting lugs is the HAZ; HAZ is caused by large amount of heat produced in the welding, gouging or gas cutting process; the HAZ appears around the welding seam or area experiencing gas cutting or gouging work. Figure 1.1.1 shows the distribution of a HAZ around a welding seam.

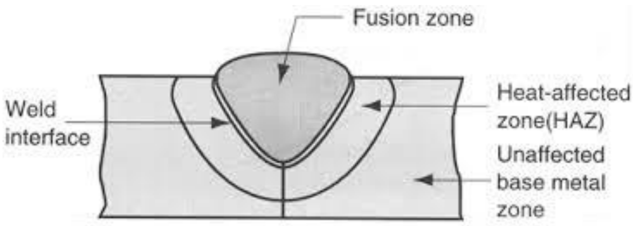


Figure 1.1.1 Heat Affected Zone around welding seam (SlideShare [4])

The HAZ is defined as *"the portion of the base metal that was not melted during brazing and cutting/welding, but whose microstructure and mechanical properties were altered by the heat."* The properties of the metal in the HAZ are hard for prediction; mostly the metal in the HAZ becomes brittle which shows less extensibility than the normal. Therefore, the HAZ will cause decreasing in the fatigue ability of ship sections. Furthermore, some lifting lugs are welded on the hull of the ship; HAZs around these lifting lugs become a potential hazard to the ship and be harmful to the safety.

The second damage is the residual stress; it is created after the welding work. The most direct influence of the residual stress is the metal plate's deformation. To the appearance, the metal plates become curved and unsmooth, the ship's exterior is influenced. Figure1.1.2 shows the deformation caused by residual stress after welding.

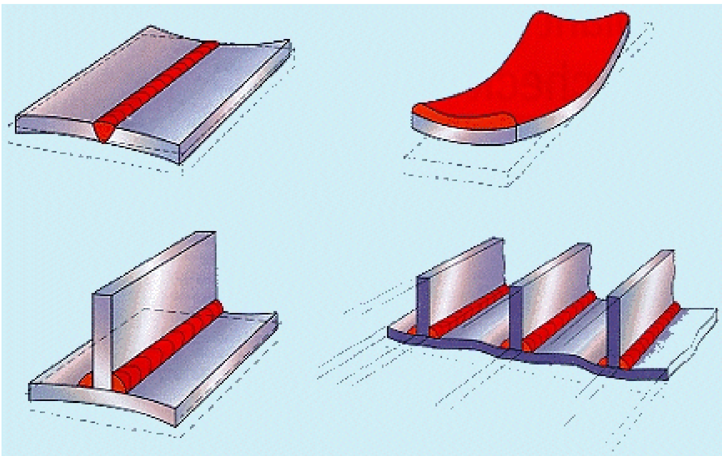


Figure 1.1.2 Deformation caused by residual stress (TWI Group websites [5])

To the interior, the residual stress decreases the mechanical behaviors of the base metal, such as decreasing the stiffness, the stabilities of components and the fatigue ability.

The third damage relates to the coating. Lifting lugs are generally installed on places where the panting work is finished; when the lifting lugs are welded, the coating on the welding joint should be removed to ensure the quality of the welding. In addition, coating around the welding joint is destroyed by the high temperature created in the welding work. The damaged coating needs to be re-painted so that the work load in the building process is increased.

1.1.2 Advantages of adhesive bonding joints

Adhesive bonding joints are widely used in the fabrication industry and different types of adhesively bonding joints are used to connect components for producing machines, vehicles and aircrafts. Adhesive bonding joints show some unique and outstanding advantages in some aspects comparing with other connecting methods.

Different with welding, adhesive bonding can avoid the defects of welding in the operating process. Firstly, adhesive bonding does not produce large amount of heat in the operating process; so no HAZ is produced. Secondly, welding residual stress in the base metal is also avoided because adhesive bonding does not influence the base metal. Thirdly, adhesive bonding is slightly destructive to the coating comparing with welding. The coating may also be removed for bonding but no heat will be produced to destroy the coating around the bonding joints.

Besides the characteristics listed above, adhesive bonding has other characteristics that benefit for installing lifting lugs; such as easy to bond dissimilar materials and remove. Firstly, because an adhesive bonding joint uses adhesive's viscosity to connect components; the components' materials are not required such severe like welding. Secondly, most adhesives become poor in strength performances when the temperature increases above 100℃; which make the bonded components easy to disassemble and the lifting lugs needs to be removed after lifting will be benefit from this characteristic.

1.1.3 Sub conclusion

Comparing with welding, adhesive bonding cannot provide same mechanical properties for the connecting joints but adhesive bonding does not influence the steel negatively; therefore, it has potentials to be used for temporary structures during the ship building process, such as lifting lugs or structures. In the ship building process, installing and cutting welded lifting lugs on ship sections or some facilities causes troubles for base metals used in building. While adhesive bonding joints are harmless to the base metal and more easily removed; therefore, using adhesively bonded joints for fixing lifting lugs is a good attempt in the ship production process. **As a result, it can be hypothesized that**

adhesive bonding joints can replace welding joints in installation of lifting lugs to some extent. In the next part, questions for the research are given.

1.2 Define questions

Even adhesive bonding joints have been successfully applied in other fabrication industries, whether it can be used for connecting lifting lugs and sections in ship building industry is still uncertain. Analysis and investigation need to be processed, and main questions are defined as:

1. Whether adhesively bonded lifting lugs can be applied in ship building?

2. If it is applied, what are the rules for the application?

To solve the main question, several sub-questions are defined and shortly explained below.

A. What kinds of adhesives will be feasible for bonding lifting lugs?

Adhesives are the main medium connecting two components in a bonding joint, so their performances become factors need to be considered. Mostly, the ship sections and lifting lugs are made of metal; so kinds of adhesives for metal to metal bonding are needed in the application and the adhesive should also has enough strength to carry the load in the building process.

B. What types of bonding joints can be used?

As most adhesives perform better in defensing shear strength than normal strength, the bonding joints need to be designed to make adhesives sustain loads in the shear direction. For selecting bonding joints, it should also consider the shape of positions for installation on the ship sections. A good bonding joint can completely use adhesives' advantages to make the bonding joints have high strength and feasible for operation and production.

C. How to define the shape and geometrical attribute of lifting lugs?

The area of the bonding joints will determine the load a bonding joint can bear. So an appropriate shape for a bonding joint will make it have enough strength. To analyze the shape aims to decrease the stress concentration in the joints to avoid too high stress in a point so that the reliability of the bonding joints can be increased. The research will find out requirements (e.g. size of lifting lugs) constrain the shape and formulas to calculate the stresses with given geometries.

D. What is the state of stress of the bonding joint with load?

After setting the shape and theoretical formulas for calculating critical stresses for bonding joints, the performances of the bonding joints needs to be known. For some unregularly shape joints, theoretical formulas hardly give exactly results for the stresses. To simulate the real situation of bonding joints to see the value, direction and description of stresses will help to find the defects of designs; and modifying them to get a better application.

E. Where is the optimal position for installing lifting lugs?

After solving the strength problems, the next step turns to installing lifting lugs on sections in appropriate places. A place suitable for fixing lifting lugs is the main issue needs to be solved for this part of research. To give a reasonable solution, there are sub problems need to be considered, such as which places have enough strength for fixing and lifting lugs, which places are able to use the selected bonding joints and what are the influences of the structures in the fixing position.

F. How to evaluate the feasibility of the application?

After a serious of research for the application of adhesively bonded lifting lugs, plans for the application are given and their feasibility needs to be evaluated. So evaluation methods are needed in the research as well as criterion used for evaluation.

G. How bonding joints perform in turning?

Lifting work is one part of the lifting lugs' function; the other part is the turning work. The main difference between turning work and lifting work is the change of the load; both value and direction. To find out performances of bonding joints in turning work is important for judging whether adhesively bonded joints can be applied in ship building.

1.3 Research plan

Based on the "sub research questions **A** to **F**" listed above, eight topics about the research are concluded and they are listed in table 1.3.1.

Table 1.3.1 Topics concluded from sub questions

Number of sub research questions	Topics
A	Adhesive
B	Adhesive bonding joint
C	Geometry
D	Load, Stress
E	Position
F	Simulation, Strength

Based on the topics, a "research spiral" is designed and it is used to guide the research;

the “research spiral” is shown in Figure 1.3.1.

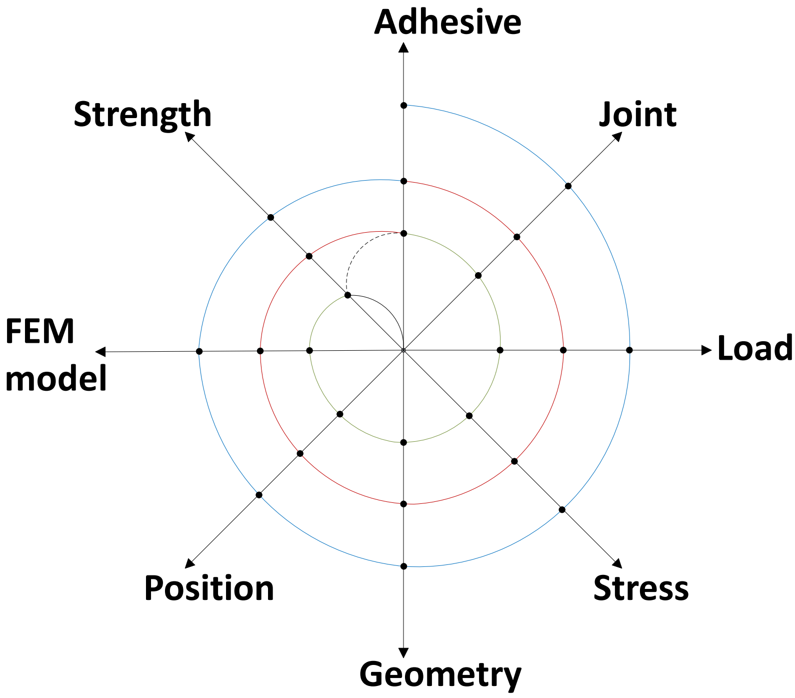


Figure 1.3.1 Research Spiral

There are three research circles in the research spiral and they are in different colors. The first research circle is colored in blue and knowledge about the research is going to be set up; sub questions “**A** to **F”** will be answered globally. The work will be done in the first research circle is listed below:

(1) Collecting information about metal to metal adhesive and adhesive bonding joints

(2) Understanding rules of welded lifting lugs in ship building

(3) Defining methods for evaluation

Then in the second research circle, sub questions “**A** to **F”** will be answered further. The rules of welded lifting lugs are going to be adapted to rules of adhesively bonded lifting lugs. In the adaption work, requirements about load, stress, geometry and position for installing lifting lugs will be given combining with characteristics of adhesive bonding; and adapted rules should be given. After that, the application based on the adapted rules of adhesively bonded lifting lugs will be evaluated by some methods to see the feasibility and defects.

In the last research circle, the aim of the work is to make the application feasible and sub questions “**A** to **F”** will be answered adequately. According to the defects found in the second research circle, the adapted rules of adhesively bonded lifting lugs will be improved and new plans for the application will be given. And then verification about the new application plans is going to be processed to check the feasibility. In the real-life research, the improvement for making the application feasible may take several turns of research, so a dashed line to stand for several times of improvement is added in the end of the third research circle before the conclusion.

The application of adhesively bonded lifting lugs contains two processes: “lifting process” and “turning process”. The research starts with the “lifting process”, which means the “transportation work” in the building; useful information and feasibility of part of the application are concluded from the first part of research. Then the “turning process” is researched in the seconded part of the research; useful information and data can be used from the conclusions in the “lifting process” research. After the second part of the research, sub question “**G**” will be answered adequately; and final conclusions can be given.

II. Setting up the knowledge stage

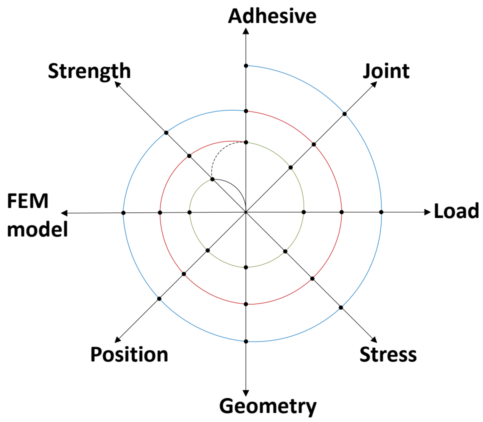


Figure 2.0.1 Research Spiral

In the first research circle, shown in Figure 2.0.1 in blue, “literature study” will be done in this part and sub questions “**A** to **F**” will be answered globally. By answering the questions, kind of adhesive using in the application should be found, current rules of welded lifting lugs should be concluded and criterion for evaluation should be given.

2. Introduction of basic knowledge

Firstly, basic knowledge about adhesive will be introduced. Application of adhesive in the fabrication industries will be introduced as well as the adhesive bonding joints.

Then, rules of welded lifting lugs should be studied and they are given after the introduction of adhesives. Because it should consider both the adhesives’ properties and the characteristics of ship building to apply adhesively bonded lifting lugs.

Lastly, methods for evaluation will be discussed briefly.

2.1 Introduction of adhesives

2.1.1 Structural adhesive

Firstly, a kind of adhesive which can bond metal to metal joint with high strength should be selected and “structural adhesive” is the kind of adhesive that has potential to be used; and the potentials are shown in the following introduction.

Bolger pointed that there is no there is still no universally accepted definition of the term "structural adhesive"; and he proposes the definition: thermosetting resin compositions used to form permanent, load-bearing, joints between two rigid, high-strength, adherends[6]. The ASTM[1] defines structural adhesive as: “a bonding agent used for transferring required loads between adherends exposed to service environments typical for the structure involved”. And the characteristics of structural adhesives are calculated by Hartshorn[7] in his book, and they are listed below.

1. High-strength adherends are involved (metal, wood, ceramic, reinforced plastic).
2. The adhesive is capable of transferring stress between the adherends without loss of structural integrity, within the design limits for the bonded structure.
3. The bonded structure maintains integrity over long periods of time in typical service environments.

Hartshorn studied the structures further and he listed the advantages and limitations of structural adhesive bonding in his book and shown in table 2.1.1 [8].

Table 2.1.1 Advantages and limitations of structural adhesive bonding

Advantages	**limitations**
1. Outstanding fatigue resistance. 2. Light-gauge materials may be joined. 3. Suitable for dissimilar materials. 4. Integrity of materials maintained. 5. Joints are completely sealed. 6. Only practical method for certain applications. 7. Provides thermal and electrical insulation. 8. Smooth surfaces obtained. 9. Can reduce manufacturing costs.	1. Joints must be designed to eliminate peel and cleavage stresses. 2. Careful surface preparation often required. 3. Performance may be degraded by hostile environments. 4. Simple nondestructive test methods are not available. 5. Limited high-temperature resistance. 6. Equipment costs can be high.

The research of Bolger and Hartshorn can show the potentials to apply structural adhesives preliminary and the application of structural adhesives in fabrication industries will explain the potential further.

Structural adhesives have been applied successfully within many sectors of industry, such as automobile and aerospace industries [9], which have similar situation with ship building industry for bonding metal components; and the application in those industries can provide reasonable help and experiences for applying adhesively bonded lifting lugs.

For producing automobiles, adhesives with high strength were produced in 1990s and they started to be used for bonding structure elements of automobiles [10]. Firstly, manufactures glued windscreens and rear windows; then components like front bonnet, boot lid or roof were bonded with adhesives. In recently years, adhesive bonding plays a more important role in automobile industry because multi-material design becomes

[1] American Society for Testing and Materials

popular. *R. D. Adams* gives examples in his book, the new S-Class Coup6 of DaimlerChrysler has more than 100 m of structural bonds in body in white applications; in the “series 7 BMW” have more than 10 kg of structural adhesives applied.

In the aircraft industry, the application of adhesively bonding can date to the time in WW II; “de Havilland” used epoxy adhesives to bond the wooden structures for warplane “Mosquito” (*Dan Gleich, 2002*). This application fully proves that structural adhesives have enough strength, even for weapons in the war; Figure 1.1.3 shows the warplane “Mosquito”.

Figure 1.1.3 “de Havilland Mosquito war plane” (fennerschool [12])

The techniques for bonding aluminum was fully developed in 1950s and adhesive bonding becomes the more favoring joining option because the development of composite materials [13]. Adhesive bonding joints are also used to bond components such as control surfaces, tail structures and fuselages. Other aircraft companies such as “SAAB”, “Fokker” and “Cessna” also used adhesive bonding in their aircraft widely; “SAAB” has made a type of aircrafts using adhesive bonding with the properties of the structure cannot be achieved with conventional riveted structures [14]. The application of structural adhesives in automobile industry and airplane industry can further prove that structural adhesive bonding has great potential for bonding lifting lugs.

Weitzenbock showed some current application of structural adhesive in ship building, such as “joining lightweight structures made of composite or aluminium to the steel hull [15]”; the application shows that adhesive bonding make it possible to bond lifting lugs and sections made of different materials. Weitzenbock also showed that adhesive bonding is needed by the ship building industry in the future. He said that multi materials or lightweight materials are required for joining to build ships such as “low energy ship”, “green-fueled ship” and “The Arctic ship” which are needed in the future; and adhesive bonding is relevant for the connecting of the materials used in those ships [16]. So the application of adhesively bonded lifting lugs can solve both the defects of the current welded lifting lugs and it will also help build ships with new materials in the future.

Then the concentration moves to select specific structural adhesives that can be used in the application. Based on the chemical composition, adhesives are separated as five categories [17]: Epoxy, Phenolic, Acrylic, Cyanoacrylate, and Urethane (or Polyurethane). Their performances for bonding are concluded in table 2.1.2.

For bonding lifting lugs for ship sections in current ship building industry, the basic requirement is that the adhesive should have high performance for bonding metal substrates. According to this requirement, the Polyurethane adhesive and Cyanoacrylate adhesive are excluded from the application.

Table 2.1.2 Performances of kinds of adhesives

	Available bonding substrates
Epoxy	Metal, glass, wood
Acrylic	Metals, wood, organic glass
Polyurethane	Wood
Cyanoacrylate	Wood and medical
Phenolic	Wood, metal, glass

Bouwman did further research on application of adhesives in shipbuilding [18]. He tested kinds of adhesives in the view of their appropriate substrates, strength and operation conditions. In his test, an important factor is considered; that is the performance of adhesives bonding substrates with premium painting. The results shows that the epoxy adhesives are the most appropriate structural adhesives for bonding metal with or without premium painting and the acrylic adhesive works a little worse but still acceptable. Therefore, the adhesives used as specimen for calculation are selected from structural epoxy adhesives and structural acrylic adhesives.

From main adhesive manufactures, two kinds of structural adhesives are selected as specimen for calculation. They are “Epibond 100 A/B High-temperature Epoxy Structural Adhesive [19]” from Company Huntsman and “3M Scotch-Weld™ Acrylic Adhesives DP8410NS Green [20]” from Company 3M. Some basic data of their properties are shown in table2.2.2.

Table 2.2.2 Properties of the two selected adhesives

Category	Type	Lap shear strength for bonding metal	Young’s modulus	Poisson’s ratio
Epoxy	Epibond 100	34.5 mpa	2178.7 mpa	0.22
Acrylic	DP8410NS Green	24.6 mpa	1301.5 mpa	0.3

2.1.2 Bonding joints

Adhesive bonding joints have been studied for a period of time and a certain number of books and researches have introduced them. Adams and Wake [21] and Straalen [22] described kinds of adhesive bonding joints in detail. Hartshorn [23] generalized bonding joints into three main categorizes: “Butt joints”, “Lap joints” and “Scarf and Modified Joints”.

"Although the butt joint has a simple design, it is probably one of the least popular", says in Hartshorn's research.

In butt joints, contact area of the adhesive and substrates are small and it is determined by the cross-sectional area of the adherends; furthermore, butt joints will produce tensile stress and peel stress in large values, which are the weak points of adhesively bonding joint. Even increasing the area of the joint can increase the strength; the application for carrying large mass ship sections is difficult. Therefore, butt joints will not be selected for analyzing in the thesis.

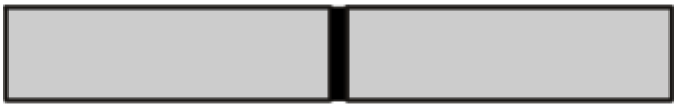


Figure 2.1.1 Butt joint

Lap or overlap joints are the most common bonding type and there are many variations of overlap joints, such as single lap joints and double lap joints.

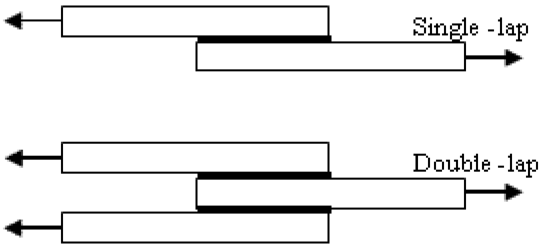


Figure 2.1.2 A single lap and a double Lap joint

Single lap joint is the simplest type of overlap joint; stress concentration will occur in the edges of the joints, however, by increasing the joints' width and overlap length will make the strength higher. Double lap joint is another useful type of lap joint. Comparing with single lap joint, it can significantly decrease stress concentration and increase the strength; but the application condition is more complicated. Both single lap and double lap joints can have high strength for connection, so they should be options for the application.

Scarf joint is similar with lap joint in the connection form; both of them have overlap area in the joint. However, scarf joint works better than lap joint; it is even regarded as the most efficient joint design.

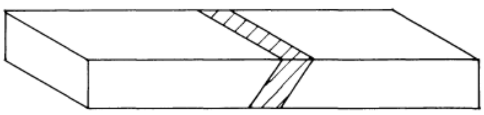


Figure 2.1.3 Scarf joint [24]

There are other types of joints design such as tapered, stepped and joggle lap joint, all of them have improved performance, but the complicated shape makes them more difficult to be applied for connecting lifting lugs.

To sum up, lap joints are the most appropriate types of joints for the lifting lugs connection work in ship building. In the thesis, both single lap joints and double lap joints will be analyzed for the application; and a serious of modification will be processed for the joints contrary to the characteristics in ship building.

At last, other types of bonding joints are shown in Figure2.1.4. Some of them may be feasible for some special conditions. The joints are concluded by Dan Gleich in the research [25].

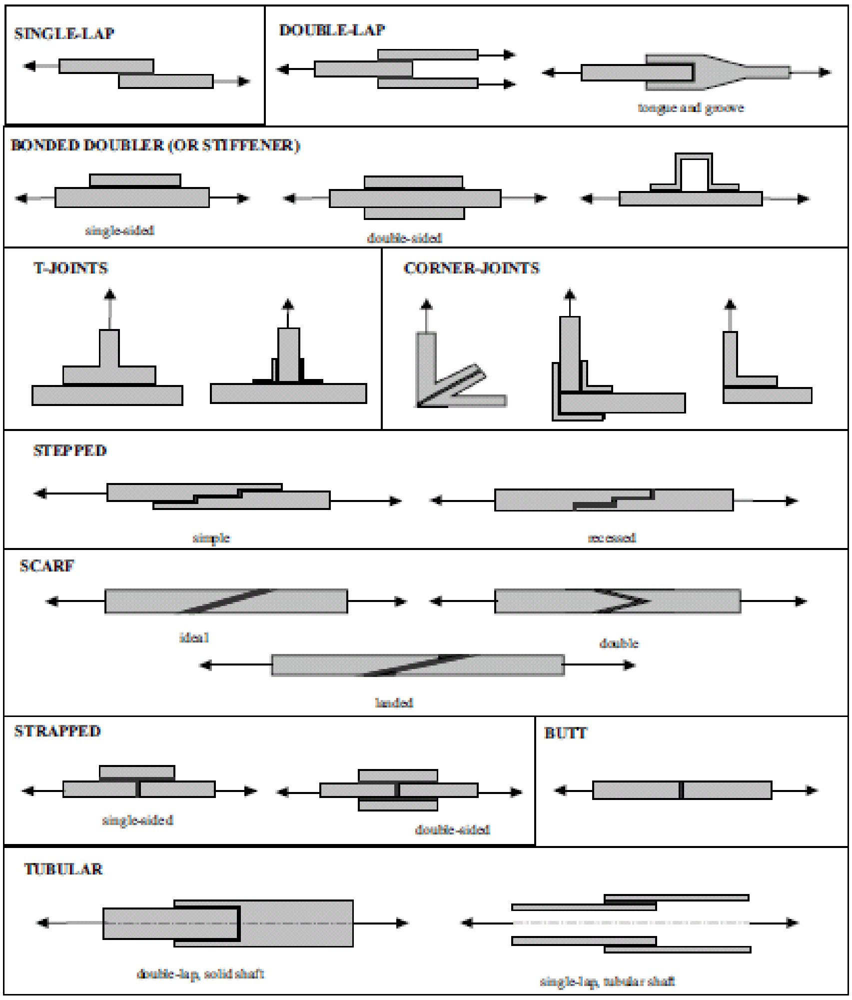


Figure 2.1.4 Kinds of bonding joints [25]

2.2 Introduction rules for welded lifting lugs

The rules for welded lifting lugs [26] are provided by IHC ship yard; it describes critical factors for welded lifting lugs in the lifting work in detail. The documents introduce rules in two parts; the former part mainly talked about lifting lugs in lifting process and the turning process is given in the second part. The basic requirements for lifting work, requirements of lifting lugs' strength and geometries and critical stress calculation are introduced in the first part; in the second part, the load analysis and requirements for turning sections are provided. All the requirements and precautions are concluded and listed in the following parts.

I. Components in the lifting process

Components for lifting a section include steel cable, shackle, green pin and lifting lugs. Steel cable is the link between crane and section, in the end near the section it is connected with the shackle. The shackle connects the lifting lug with the green pin which is a steel stick inserts through a hole (named “padeye”) on the lifting lug. The green pin and the shackle’s sizes influence the dimensions of the lifting lug; the details will be given later.

II. Classification for lifting lugs

The lifting lugs are classified into three categories according to the load they carry; the categories are “less than 20ton”, “between 20ton and 30ton” and “more than 30ton”. Except the difference in the dimensions, lifting lugs in each level have different requirements for installation modes and positions, they are listed below:

A. Lifting lugs carrying load less than 20ton do not need to pierce the plate of the structure
B. Lifting lugs carrying load from 20ton to 30ton need to pierce the plate, but can be welded against a bulkhead or web frame
C. Lifting lugs carrying load more than 30ton must pierce the plate and need to be integrated into the bulkhead or web frame

III. Position for installation

The positions for fixing lifting lugs should fulfill some requirements. As mentioned before, kinds of components are used in the lifting process; when installing lifting lugs on sections, there should be enough space for fixing lifting lugs and arranging the other components that connected with lifting lugs. The arrangement of lifting lugs should also consider the stabilities when the section is moving, which means the lifting lugs need to be bilateral symmetry; it relates to the load calculation.

IV. Load calculation

The load on each lifting lug should be kept under the strength requirements, however, loads on each lifting lug may not be separated averagely, their values depends on the mass distribution of a section. The method to calculate the load is shown with an example below.

Example:

The total load for lifting is given as F_t, the number of lifting lugs is set as 4 (the load on 2 lifting lugs in one symmetry side is $\frac{F_t}{2}$), and it is assumed that "$F_1 = F_3, F_2 = F_4$". The load on each lifting lug depends on the shape of the section and the position of the gravity center.

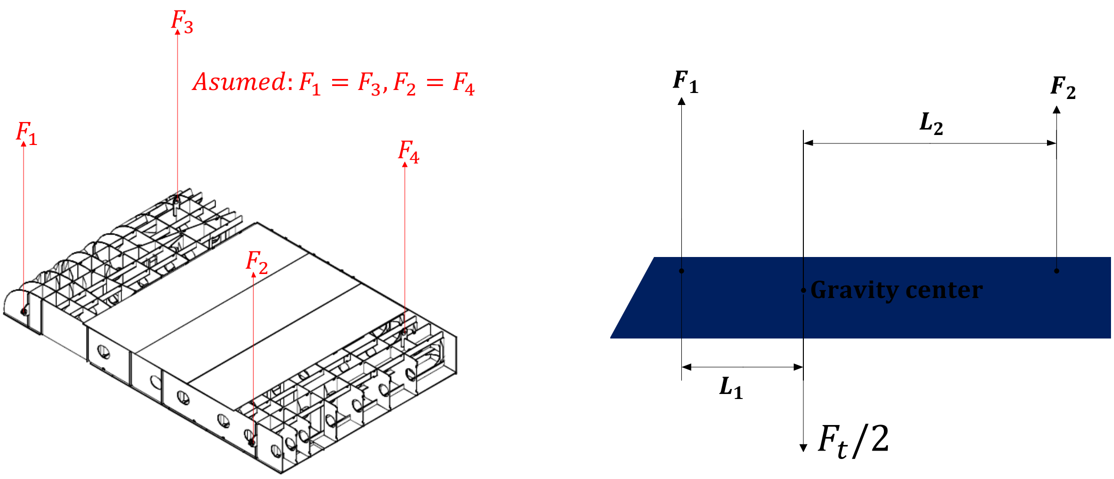


Figure 2.1.1 A brief view for calculating loading in lifting

$$\begin{cases} F_1 \cdot L_1 = F_2 \cdot L_2 \\ F_1 + F_2 = \frac{F_t}{2} \end{cases} \qquad (2.1.1)$$

$$\begin{cases} F_1 = \frac{F_t \cdot L_1}{2(L_1 + L_2)} \\ F_2 = \frac{F_t \cdot L_2}{2(L_1 + L_2)} \end{cases} \qquad (2.1.2)$$

V. Strength and shape of the lifting lug

The shape of a lifting lug depends on the load it bears and the dimensions of lifting accessories it connects with; a lifting lug's shape (the joint part is not in) is shown in Figure2.1.2.

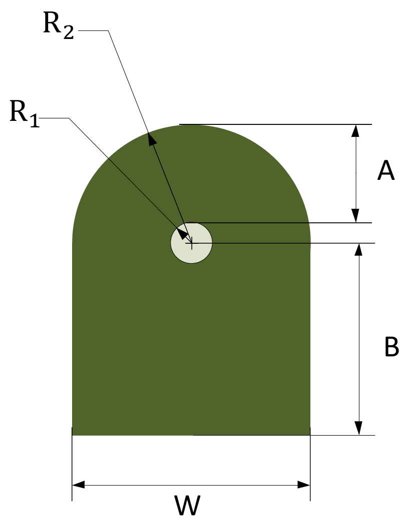


Figure 2.1.2 A brief view of the top part of a lifting lug

The hole in the lifting lug is used to assemble with a green pin; the green pin will be inserted through the hole and connected with the shackle. The Diameter of the hole in a lifting lug is generally 3mm larger than the Diameter of the green pin. The green pin's radius is set as “r”, and then the diameter of the hole on the lifting lug will be:

$$R_1 = r + 1.5\ (mm) \tag{2.1.3}$$

The radius of the lifting lug is influenced by the radius of the hole, the thickness of the lifting lug and the load. The requirement is the stress in the area (perpendicular to the shown surface in Figure 2.1.2) above the top point of the “pad eye” should be smaller than $1\text{ton}/cm^2$.

If the load is set as “T ton”, then the area (perpendicular to the shown surface in Figure 2.1.2) above the top point is $\frac{\mathrm{T}}{\frac{1\text{ton}}{cm^2}} = \mathrm{T}\ cm^2$. And if the thickness of the lifting lug is set as “t”, then the height above the top point is $\mathrm{A} = \mathrm{T}/\mathrm{t}$, so the radius of the lifting lug

$$R_2 = R_1 + A \tag{2.1.4}$$

The width of the lifting lug is twice as the radius of the semi-circle in the top, that is:

$$\mathrm{W} = 2R_2 \tag{2.1.5}$$

The height above the bottom board and the circle of the hole is influenced by the width of the lifting lug. It is:

$$\mathrm{B} = \mathrm{W}/2 + 50(mm) \tag{2.1.6}$$

The area of the cross section is also required; the stress in the area cannot be larger than $1cm^2/ton$. So $\mathrm{t} \times \mathrm{W} \geq \mathrm{T}/1cm^2/ton$.

VI. Stress and strength of the joint

There are two kinds of welding joints introduced in the rules, butt welding joint and lap welding joint. For a welded lifting lug with a butt welding joint, the bending stress and a composite stress (formed by a bending stress and a shear stress) are required. The maximum bending stress should be smaller than 2.4 ton/cm^2 and the composite stress should be smaller than 1.2 ton/cm^2. An example of a butt welded lifting lug is used to show critical stresses and the calculation methods.

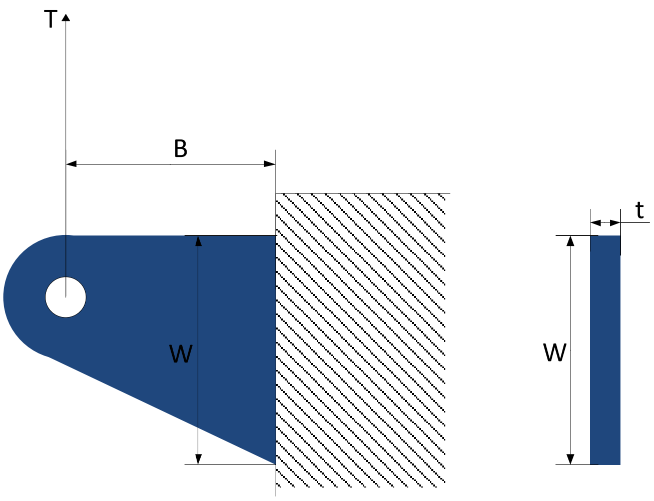


Figure 2.1.3 A brief of a welded lifting lug with butt joint

As shown in Figure2.1.3, the lifting lug is welded on the side surface of a section with a butt welding joint, the load “T” acts on the lifting lug in vertical direction. Therefore, in the joint there will be shear stress and normal stress caused by a bending moment. The normal stress is calculated firstly.

The bending moment$M_{bending}$:

$$M_{bending} = \mathrm{T} \times \mathrm{B} \tag{2.1.7}$$

The moment of resistance$M_{resistance}$:

$$M_{resistance} = \frac{1}{6} \times t \times W^2 \tag{2.1.8}$$

Then the maximum bending stress $\sigma_{max}$is:

$$\sigma_{max} = \frac{M_{bending}}{M_{resistance}} = \frac{\mathrm{T} \times \mathrm{B}}{\frac{1}{6} \times t \times W^2} \tag{2.1.9}$$

Then the shear stress is calculated and it is used to calculate a composite stress which is used to judge the strength of the joint.

The shear stress τ:

$$\tau = \frac{T}{A} = \frac{T}{W \times t} \tag{2.1.10}$$

"A" is the area of the cross section of the lifting lug

Then the composite stress δ:

$$\delta = \sqrt{{\sigma_{max}}^2 + \tau^2} \tag{2.1.11}$$

Then turns to the lap welded lifting lug; Figure2.1.4 shows a welded lifting lug with lap joint.

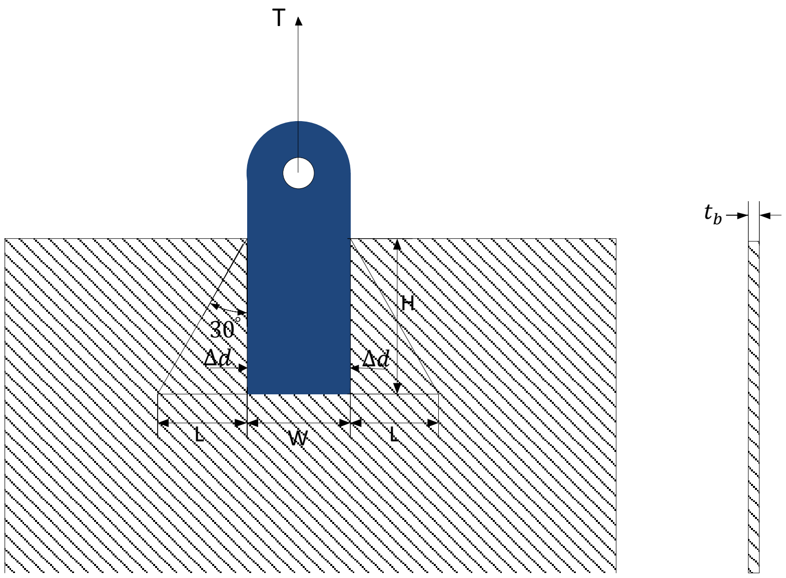


Figure 2.1.4 A brief view of a welded lifting lug with lap joint

In a lap welding joint, the shear stress is required. The width of the welded seam is "d" per side and the length is "H"; so the welding area per side A_0 is: $A_0 = H \times d$

The load on the lifting lug is "T", and then the shear stress per side is :

$$\tau_0 = \frac{T/2}{A_0} = \frac{T}{2 \times H \times d} \tag{2.1.12}$$

The shear stress should be less than 1ton/cm^2.

There is also a requirement for the width of the lifting lug. When the lifting lug is lap welded on the plate of a section, the stress transfers from the top of the welding seam with an angle of 30° till the end creating a distance “L” per side. The stress acts on the line is required and it should be less than 1ton/cm^2. If the thickness of the plate is defined as “t_b”, the stress “σ_b” is:

$$\sigma_b = \frac{T}{(0.577\times H\times 2+W)\times t_b} \tag{2.1.13}$$

And σ_b should be less than 1ton/cm^2.

2.3 Discussing evaluation methods

In the research, evaluation needs to be processed to discover defects of the adapted rules for applying adhesively bonded lifting lugs and check the feasibility of the specific application after improvements; therefore, criterion and methods for evaluation should be given.

Same with rules of welded lifting lugs, the strength of adhesive bonding joints is used as the criterion for evaluation; when an adhesively bonded lifting lug is carrying load, the stress in the bonding joint should be no more than the strength of the bonding joint can provide. The strength of the bonding joint relates to adhesives’ properties in specific kinds of bonding joints. In the research lap joints are used; so the adhesives’ overlap strength and strength in the normal direction should be used as the criterion. Shear stress and normal stress need to be calculated.

The stress can be calculated from two ways; one is test and the other is FEM simulation. Bouwman introduced tests for measuring strength of adhesive bonding joints in the research [27]; which can be also used for measuring stress in bonding joints. This method needs severe requirements for laboratory equipment and specimens which are hard to be processed in the current situation; so FEM simulation should be the evaluation method used in the research. In the FEM simulation, models are built based on the specimens and simulated with the same situation in the real-life. By using FEM simulation software, the needed results, such as stress, can be read. FEM simulation have been used and discussed in lot of research about adhesive bonding joints, such as Yuping Yang’s research [28] about “Composite-to-Steel Adhesive Joints” and Dan Gleich’s research [29] about “Structural Bonded Joints”. For the selection of specific FEM software, it will be given in Chapter 5.

2.4 Summary and finding

2.4.1 Summary

Sub questions A to F (listed below) can now be answered globally.

A. What kinds of adhesives will be feasible for bonding lifting lugs?

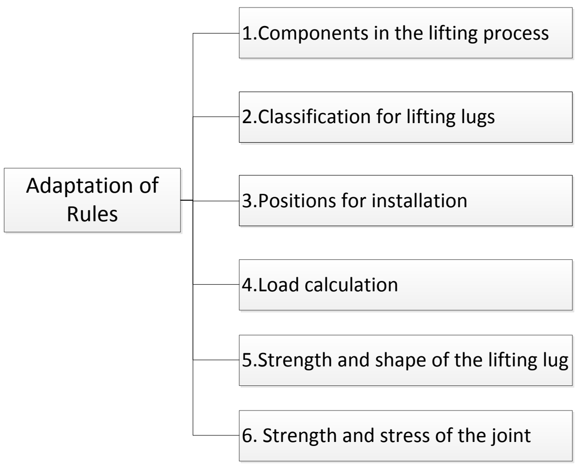
Epoxy structural adhesives and Acrylic structural adhesives are selected for bonding adhesively bonded lifting lugs; Epoxy adhesives “Epibond 100” and Acrylic adhesives “DP8410NS Green” are selected as specimens in the research.

B. What types of bonding joints can be used?

Lap joints, contains both single lap joints and double lap joints are selected as the joints’ type in the application; but which ones performs better will be analyzed in the following parts.

C. How to define the shape and geometrical attribute of lifting lugs? D. What is the state of stress of the bonding joint with load? E. Where is the optimal position for installing lifting lugs?

Rules of welded lifting lugs are introduced in the 2.2; shape and geometry of lifting lugs, load, stress and positions for installation are introduced. The rules can be concluded in six aspects shown below.



F. How to evaluate the feasibility of the application?

The strength of the adhesive bonding joint is used as the criterion for the evaluation and to make the application feasible the stress in the joint should be no more than the strength. FEM simulation is used as the method to calculate the needed stress.

2.4.2 Finding

The strength of adhesives is used for the adaptation and evaluation, such as defining the original dimensions of lifting lugs and checking whether a bonded lifting lug is feasible for application; so the strength should be given. In the research, the focus is put on shear strength and normal strength regarding to the characteristics of lifting lugs' fixing type. It is found that in a data sheet provided by an adhesive manufacture, shear strength is easily got but it is hard to get information of normal strength. So a method to calculate the normal strength should be defined.

Before calculating the normal strength, the method to define shear strength is introduced. For lap joints with two metal substrates, the shear strength of an adhesive is got from a test named "ASTM D1002". In the test, specimens are tested on a "tensile testing machine" which is shown in Figure 2.3.1. The specimen is pulled from its two sides by the tensile testing machine; and when the specimen is broken, the force is recorded and defined as breaking load. Then the break load is divided by the value of the bonding area, the result is the shears strength of the adhesive. And the data provided by the manufactures are usually measured from this test.

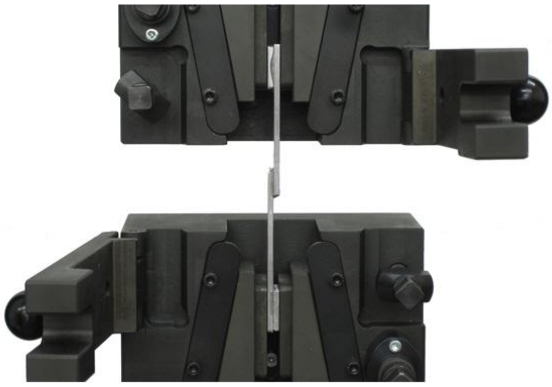


Figure2.3.1. A tensile testing machine and a specimen (ADMET [30])

If the shear strength is known, the breaking force can be calculated; and the normal strength for lap joints is also calculated by using bending moment and modulus of the bonding area. Figure 2.3.2 shows a specimen with parameters of its size.

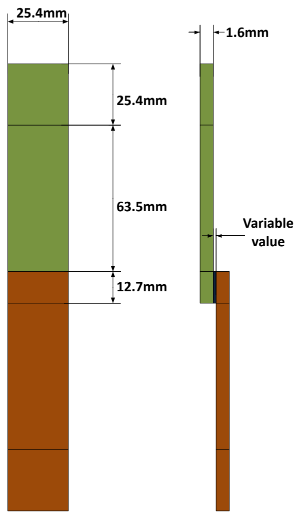


Figure 2.3.2 Shape of a specimen used in ASTM D-1002

All the dimensions of a specimen is ruled in “ASTM D1002” data sheet [31]; while the thickness of the bonding layer can be a variable value and in the theoretical calculation it is set as a very small value which can be neglected in the calculation; and the thickness of the adhesive will be analyzed in Chapter 6. The maximum normal stress is produced in the area circled with red in Figure 2.3.3. Then formulas for calculating the normal strength can be given and it is shown in formula (2.3.1).

$$\sigma_{max} = \frac{M_{bending}}{Modulus} = \frac{M_{bending}}{{}^{1}/_{6}wl^2} \tag{2.3.1}$$

For adhesives used in the thesis, their shear strength and normal strength are listed in the table below after calculation.

	Shear strength	Normal strength
Epibond 100	34.5 mpa	13 mpa
DP8410NS Green	24.6 mpa	9.3 mpa

This method just briefly calculated the normal strength; regarded the normal strength value as an average stress and stress concentration same as the way to calculate shear strength in “ASTM D1002”. For the specific application, new tests need to be processed.

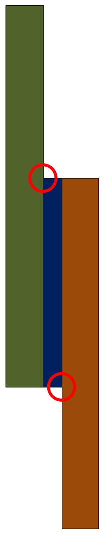


Figure 2.3.3 Maximum normal stress in a specimen used in ASTM D-1002

In the “data sheet” provided by manufactures, peel strength are often given to reflect the ability of an adhesive to defense normal stress; but the peel strength cannot stand for the normal strength in the lap joint in ASTM D-1002. The definition of “peel stress” in “*Standard Test Method for Peel Resistance of Adhesives*” is: “the average load per unit width of bond line required to separate progressively a flexible member from a rigid member or another flexible member.” From the definition it can be seen that when peel occurs, one or two of the adherends should be flexible; but for the lap joints connecting lifting lugs and sections, both of the adherends are rigid. So for the exact real strength of adhesives, some tests like ASTM D-1002 need to be processed, and the tests should be more close to the real condition. Bouwman (2011) did a serious of this kind of tests in his research and he got some reasonable data for some adhesives' performance. Therefore, in the future research the tests for measuring adhesives' strength can use both theoretical calculation like ASTM D-1002 or tests same as Bouwman did.

III. Adaptation rules and Evaluation

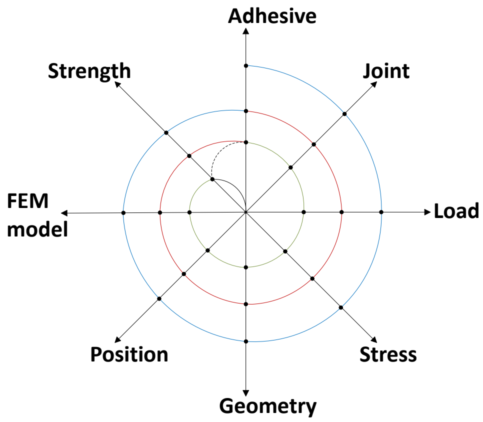


Figure 3.0.1 Research Spiral

In the second research circle, shown in Figure 3.0.1 in red, the rules of adhesively bonded lifting lugs will be adapted and evaluated; sub questions “**C**, **D, E** and **F**” will be answered further. Stress in bonding joint will be calculated and methods for define geometry of adhesively bonded lifting lugs and bonding joints will be given; positions for installation lifting lugs are going to be discussed. After the adaptation, evaluation will be done for the adapted rules.

When adapting rules for adhesively bonded lifting lugs, the rules are separated into two groups and more detailed classification is used; one is still usable and the other needs to be redefined. They are concluded and shown in Figure 3.0.2. Redefined rules 1 to 3 will be given in Chapter 3 and rule 4 will be given in Chapter 4.

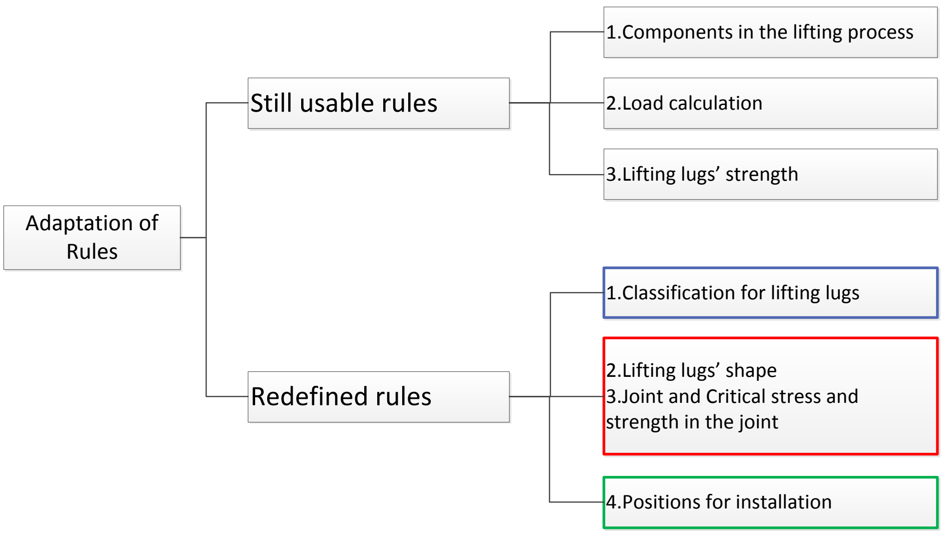


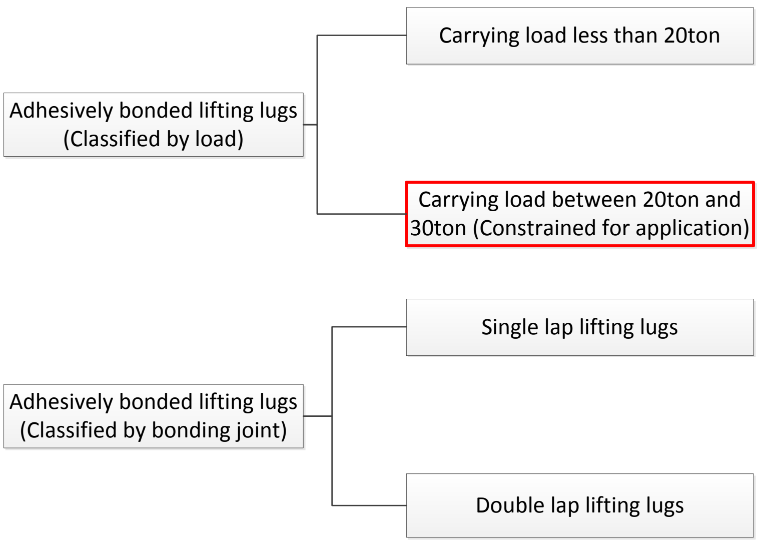
Figure 3.0.2 Rules of lifting lugs

3. Adaptation: Dimensions definition and stress calculation

This chapter aims to translate the rules for welded lifting lugs to rules for adhesively bonded lifting lugs; such as define preliminary shape and dimensions of lifting lugs and bonding layers. Firstly, the shape and dimensions of lifting lugs are given; and then the concentration is moved to the bonding joints. Secondly, the stress in the bonding layer is going to be calculated with theoretical formulas. At last, the method to define the shape and dimensions of the bonding layer will be given.

3.1 Classification and Load analysis

In the rules of welded lifting lugs, lifting lugs carrying load more than 20ton need to be inserted into the structures when they are installed; while those carrying load less than 20ton are not required. So lifting lugs carry load less than 20ton are able to use adhesive bonding for installation. For lifting lugs carry load between 20ton and 30ton, to avoid damaging the section, they can only be used when no plate is above the installation structures; the application of adhesively bonded lifting lugs is further limited. For lifting lugs carrying load above 30ton, they need to pierce the plate and be integrated with the structures for installation; which means adhesive bonding cannot be used for their installation. So 20ton is defined as the optimal load for applying adhesively bonded lifting lugs and the thesis will concentrate on lifting lugs with capacity less than 20ton; lifting lugs with capacity from 20ton to 30ton are not ideal for using adhesive bonding joints and less attention is paid on them in the research.
Except load, the adhesively bonded lifting lugs can be classified according to the bonding joint, “single lap joint” and “double lap joint”; and the classification is shown below.



The method for calculating load on adhesively bonded lifting lugs is the same with that for welded lifting lugs which is given in Chapter 2; but there is something should be taken attention. For welded lifting lugs, the essential is calculating load they carrying on; while for adhesively bonded lifting lugs, the essential should be changed to control the load on each lifting lug under the requirement (optimal maximum load: 20ton, maximum load with constrains: 30ton). For example, if a section uses 4 adhesively bonded lifting lugs in the lifting process, and the structures for installation have plates on them. If the whole mass of the section is set as 80ton, so each lifting lug carry no more than 20ton load and the 80 ton load must be distributed to every lifting lug averagely. The discussion for the positioning will be discussed in the chapter 4.

Because the poor performance for defensing normal stress of bonded lap joints, the direction of the load should be kept vertical to the ground and parallel with the adhesive layer to avoid producing normal stress. In the real-life situation, when ship sections are transported, the steel cables are difficultly to be kept vertical and angle exists between the steel cable and the vertical line; and the direction of the load changes with the steel cable which causes extra normal stress or torque. Figure 3.1.1 shows the situation.

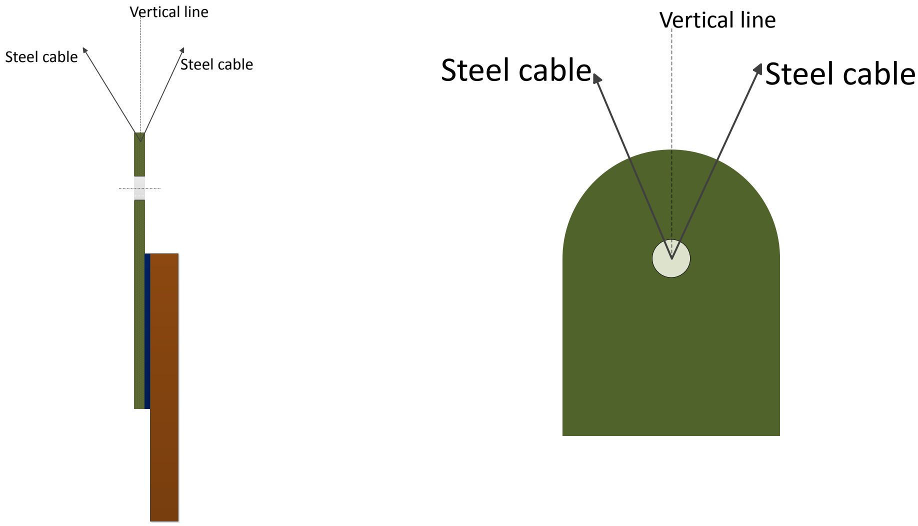


Figure 3.1.1 Situations of load directions in the transportation process

The situations shown above should be avoided in the building process. To ensure the strength of the bonding joints when the situation happens, safety factor are used in the stress calculation and lifting lugs design process; the safety factor is talked in 3.3 in this chapter. In the research, steel cables on lifting lugs are hypothesized vertical to the ground to stand for the ideal situation.

3.2 Stress calculation

3.2.1 Failure mode introduction

Figuring out the failure modes in a lap joint is necessary because it prevents wrong application and operation; and it is discussed in this part. A basic adhesively bonded single lap joint is composed by two adherends and an adhesive bonding layer, Figure3.2.1 shows the composition of a lap joint with the names of parts mentioned in the introduction of failure modes.

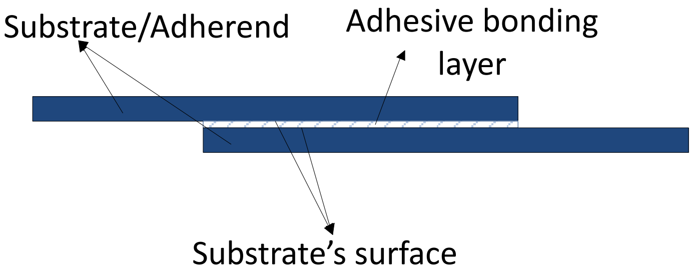


Figure 3.2.1 components in a bonded lap joint

The failures occur in a bonded lap joint happen in three places, the adherends, the bonding layer and the substrates. The failure modes for adhesively bonded joints are calculated in researches and Hartshorn's (1986) concluded three basic failure modes [32] in his book: "adhesive failure" "cohesive failure" and "substrate failure". They are defined as:

"Cohesive failure" occurs when the specimen fails within the adhesive layer;

"Adhesive failure" occurs when the specimen fails at the interface between the adhesive and adherend;

"Substrate failure": refers to the damages appearing in the substrate or adherend.

Figure3.2.2 explains how the failures occur in adhesive bonding joints. These three kinds of failure modes are also used by manufactures for giving the properties of adhesives in data sheets. In the research, the "substrate failure" is about the strength of lifting lugs which is introduced in Chapter 2; while "cohesive failure" and "adhesive failure" are about the adhesive bonding layer which are the concentration in this chapter.

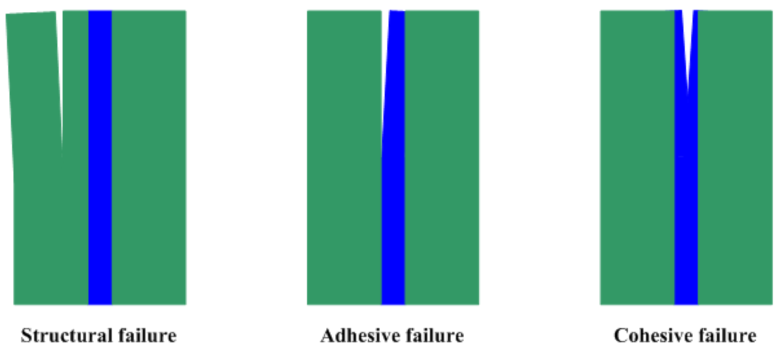


Figure3.2.2 Failure modes in bonded lap joints (SubsTech [33])

Bouwman (2011) gave the differences between "Cohesive failure" and "Adhesive failure" in detail in his research [34] and Figure3.2.3 shows it.

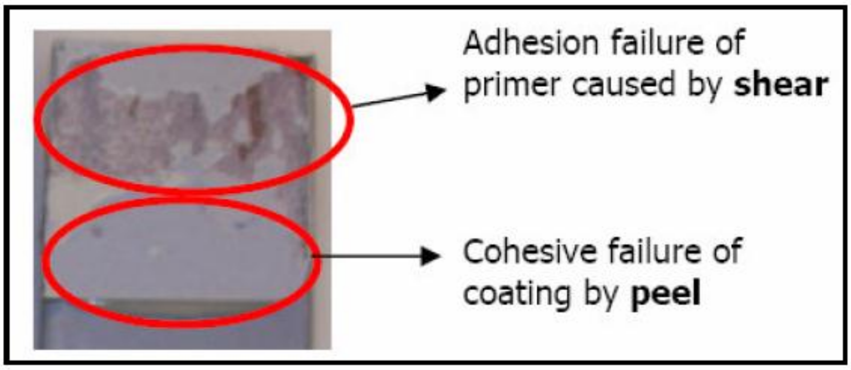


Figure3.2.3 Failure modes in tests [34]

Therefore, combining with the characteristics of a lap bonding joint, the critical stresses can be pointed: the shear stress in the adhesive layer and the interface between substrate and adhesive layer, the normal stress in the adhesive layer and the interface between substrate and adhesive layer. These stresses are going to be analyzed in the following part.

3.2.2 Theoretical calculation of stresses in bonding joints

Shear stress and normal stress in the bonding joint are the stresses need to be calculated in the application. And for lap joints, shear stress should be taken attention in the first place; then is the normal stress. Figure3.2.4 shows a single lap bonding joint with dimensions used for calculating shear and normal stresses.

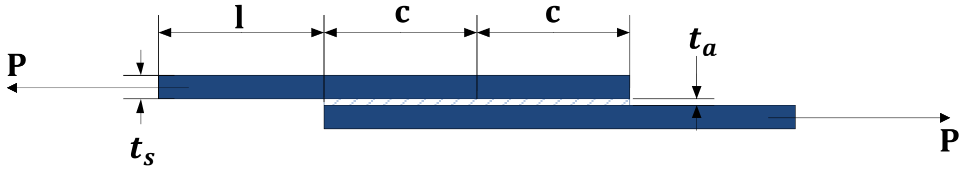


Figure 3.2.4 A Lap joint with dimensions

For the average shear stress in a lap bonded joint, the formula for calculating can be given as:

$$\tau_{ave} = \frac{P}{A} = \frac{P}{2c \cdot w} \quad (3.2.1)$$

P-the load acts on the joint
A-the bonding layer's area
2c-length of the bonding layer
w-width of the bonding layer
τ_{ave}-the average shear stress

But in this formula, the result only shows the average stress which cannot reflect the real situation of an adhesively bonded lap joint; because the uniform distribution shear stress occurs only when the adherends are rigid and the adhesive deforms only in shear [35]. For the real distribution of shear stress in a bonded lap joint, both Hartshorn (1986) and Adams gave their views; the difference between their views is the decrease speed of the stress from the edge to the middle, but they both believed that stress concentration occurs in the edge of the bonding layer [36].

To calculate the value of the stress concentration, stress concentration factor *n* is used to explain the relationship between the maximum stress τ_{max} and the average shear stress τ_{ave}.

$$\tau_{max} = \mathrm{n} \cdot \tau_{ave} \tag{3.2.2}$$

τ_{max}- maximum stress in the bonding layer

n-stress concentration factor

In the calculation of the stress concentration factor, "*Volkersen's theory "* and "*Goland and Reissner's (1944) theory"* are recognized; both Hartshorn and Adams used their theory in their books. "*Volkersen's theory"* does not consider the bending of the adherends from the eccentricity of the loading path, so "predictions based on Volkersen's work is more valid for double-lap joints where bending is minimized [37] (Hartshorn, 1986)". Volkersen's work of stress concentration factor is shown below.

$$\mathrm{n} = \frac{\tau_{max}}{\tau} = \frac{\delta}{\varepsilon}\left(\frac{2\varepsilon^2 - 1 + \cosh 2\varepsilon\delta}{\sinh 2\varepsilon\delta}\right) \tag{3.2.3}$$

$$\tau_{max} = \mathrm{n} \cdot \tau = \frac{\delta}{\varepsilon}\left(\frac{2\varepsilon^2 - 1 + \cosh 2\varepsilon\delta}{\sinh 2\varepsilon\delta}\right) \cdot \tau \tag{3.2.4}$$

δ and ε are factors which are calculated in formulas (3.2.5) and (3.2.6).

$$\delta^2 = \frac{2c^2 G_a}{E_{s2} t_{s2} t_a} \tag{3.2.5}$$

$$\varepsilon^2 = \frac{E_{s1} t_{s1} + E_{s2} + t_{s2}}{2 E_{s1} t_{s1}} \tag{3.2.6}$$

t_{s1} and t_{s2}- the thickness of the two adherends

t_a- the thickness of the bonding layer

E_{s1} and E_{s2}- the Young's modulus of the two adherends

G_a- the shear modulus of the adhesive

While *Goland and Reissner* considered bending in their work, and the results are given as:

$$\mathrm{n} = \frac{\tau_{max}}{\tau} = \frac{1+3K}{4}\left(\frac{\beta c}{t_s} \cosh \frac{\beta c}{t_s}\right) + \frac{3}{4}(1 - K) \tag{3.2.7}$$

$$\tau_{max} = \tau \cdot \left[\frac{1+3K}{4}\left(\frac{\beta c}{t_s} \cosh \frac{\beta c}{t_s}\right) + \frac{3}{4}(1 - K)\right] \tag{3.2.8}$$

β, K, u_1 and u_2 are factors and they are listed in formulas (3.2.9) to (3.2.12).

$$\beta = 2\sqrt{2}\left(\frac{G_a t_s}{E_s t_a}\right)^{1/2} \tag{3.2.9}$$

$$\mathrm{K} = \frac{\cosh u_2 c \sinh u_1 l}{\sinh u_1 l \cosh u_2 c + 2\sqrt{2} \cosh u_1 l \sinh u_2 c} \qquad (3.2.10)$$

$$u_1 = \frac{2}{t_s}\left[3(1-\nu^2)\frac{P}{E_s t_s}\right]^{1/2} \qquad (3.2.11)$$

$$u_2 = \frac{\sqrt{2}}{4} u_1 \qquad (3.2.12)$$

ν- the Poisson's's ratio of the adhesive

For the normal stress in a single lap joint, the simplified calculation of maximum normal stress can use the formula same with the welded joint, they are shown below:

$$\sigma_0 = \frac{M_{bending}}{I_R} = \frac{(\frac{t_s}{2}+t_1)\times P}{\frac{1}{6}W\times(2c)^2} \qquad (3.2.13)$$

In *Goland and Reissner's* theory, the normal stress is got in the process when they calculated the stress concentration factor, it is shown in formula.

$$\sigma = \frac{Pt_s}{c^2\Delta}\left[\left(R_2\lambda^2\frac{K}{2} + \lambda K' \cosh\lambda\cos\lambda\right)\cosh\lambda\frac{x}{c}\cos\lambda\frac{x}{c} + \left(R_1\lambda^2\frac{K}{2} + \lambda K' \sinh\lambda\sin\lambda\right)\sinh\lambda\frac{x}{c}\sin\lambda\frac{x}{c}\right] \qquad (3.2.14)$$

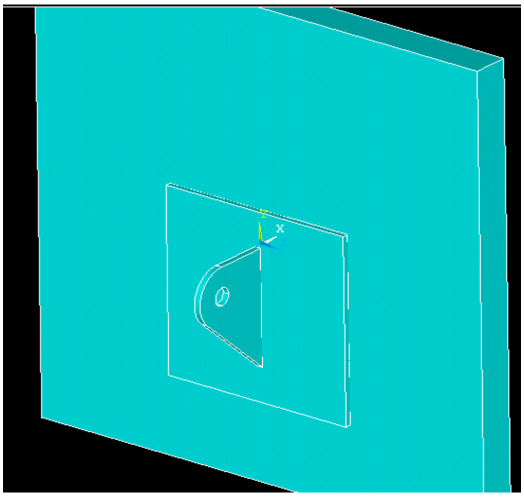
For lap joints, the calculation for normal stress contains more factors and more steps than the calculation for shear stress; and the formulas are more appropriate for calculating regular lap joint specimens. In the real application, the situation will become more complicated such as the shape of lap joint becomes irregular and the properties of adherends may not the same; therefore, calculating theoretical normal stress becomes difficult based on the pure formula. However, the theory for calculating normal stress "using bending moment" and "modulus" is used again for calculating the normal stress and the next part (3.3, chapter 3) will show the method in detail.

In conclusion for the stresses calculation for bonded lap joints:
In the shear direction, "*Goland and Reissner's theory*" is used for single lap joints and *"Volkersen's theory"* theory is used for double lap joints to calculate the stress concentration factor. And in the normal direction, the situation becomes more complicated and the theoretical calculation formulas are hard to be applied and the results may become unreliable; the calculation formulas provided in the rules of welded lifting lugs are used as a primary method. To get the exact results, using software to do FEM simulation is a good method; and in the FEM software the distribution of the stresses can be shown as well. So FEM simulation is chosen as the method to measure the stress in the bonding joint and it is talked in Chapter 5 of the thesis.

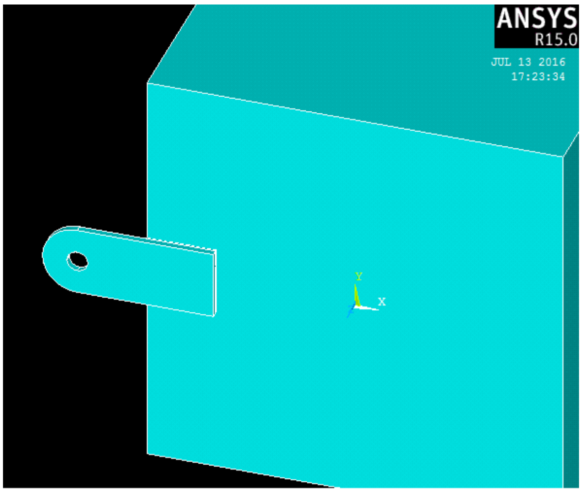
3.3 Designing lifting lugs and Define original dimensions

3.3.1 Selecting installation type

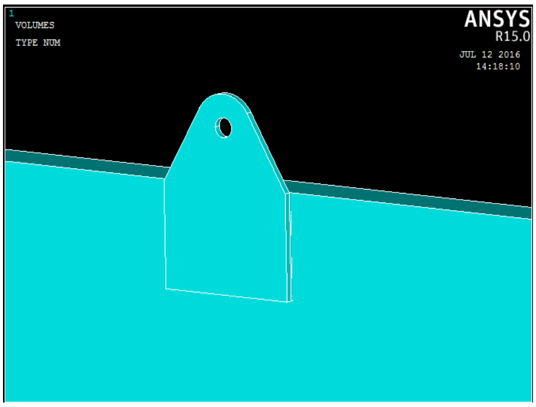
Firstly in the design of adhesively bonded lifting lugs is to ensure the installation type. As lap joints are decided to be used for the application, several plans arranging lifting lugs are provided and they are shown in Figure3.3.1.



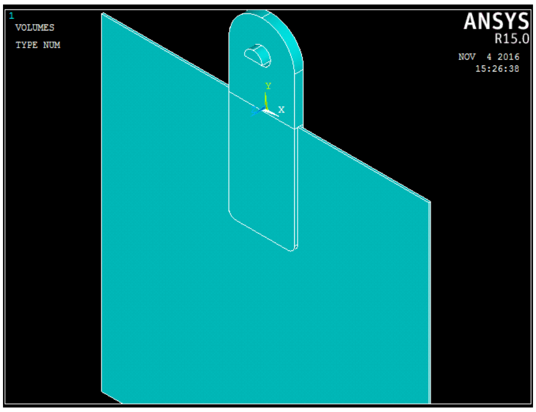
Plan 1



Plan 2



Plan 3



Plan 4

Figure 3.3.1 pictures of different lap bonding plans

The plans given above all have potentials to be applied for the lifting lugs installation, but the lifting lugs' design should be processed based on the lap joints' properties; so some of them should be abandoned. Bouwman (2011), Hartshron (1986) and also Adams(1984) said in their researches, the lap joints design should avoid peel and cleavage stress to increase the strength of the joint; Bouwman also gave a picture for explain it.

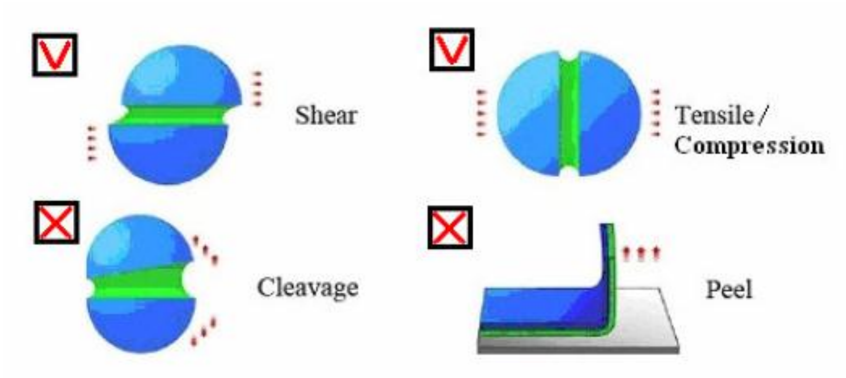


Figure 3.3.2 Types should be avoided and applied for bonded joints (Bouwman 2011)

Based on the view given by the authors, the first plan should be canceled, because cleavage stress is created. Then comparing with the last three plans, the second plan will have a shear stress in the vertical direction and another stress caused by a bending moment in horizontal direction; while the third and fourth plan only have shear stress in the perpendicular direction. And normal stress in the horizontal direction perpendicular to the adhesive layer exists in all plans. Therefore the second plan's strength is lower than the third and fourth; the third and fourth plan will be chosen for the lifting work during the production process. Actually, the second plan is a transformation of the third plan which can be used in the turning process; and it will be analyzed in the chapter about turning process.

3.3.2 Define Dimensions

The first thing for design a bonded lifting lug is to guarantee the lifting lug's strength for its self; which means the lifting lug should not be broken under the maximum load it can carry. This problem mainly relates to the area above the pad eye in the lifting lug which is talked in 2.1.1, chapter 2; Figure 3.3.3 shows a lifting lug in the front view and the dimensions of it has been talked in 2.1, Chapter 2.

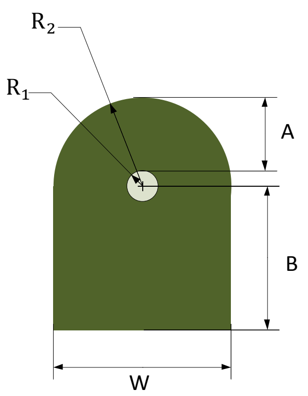


Figure 3.3.3 Top part of a single lap lifting lug

In the requirement, the stress in the area (perpendicular to the papaer) above the hole for inserting the green pin must be smaller than 1ton/cm^2; so when the thickness is given, a minimum width of the bonding layer can be got.

For example (this example will be defined as example 1 and continued using in the following part), the optimal maximum load a bonded lifting lug can carry is 20ton; the radius of the green pin hole is 27mm and the thickness of it can be set as 25mm (There is no exact requirement for the thickness of the lifting lug, choosing 25mm as the thickness is because in the welded lifting lug's rule it is also used as an example). So the minimum length of "A" is 80mm and "R_2" is 107mm; so the minimum width is 214mm. For easily modeling FEM models in the following part and feasible production in the real situation, the width is set as 220mm or a value larger than 220mm.

Then detailed calculation for the stresses is processed based on the properties of the specified adhesives; and in the calculation, the safety factor cannot be neglected. The safety factor in the welded lifting lugs can be got from the rules and for adhesively bonded joints it can be a reasonable reference. The shear stress requirement in the welded lap joint is set as 1ton/cm^2 and the shear strength of 45 steel is 178MPa; so the safety factor equals to$\frac{178\text{MPa}}{\frac{1\text{ton}}{cm^2}} = 1.81$. Meanwhile, in Bouwman's (2011) research, the safety factor is set as 2. Therefore, in conclusion, the safety factor applied for bonding joint can be set as 2. Then the maximum "applied shear strength" used for defining bonding layer's shape is equal to the "shear strength provided by the manufacture" divided by the safety factor. For instance, the shear strength of "Epibond 100A" provided in the data is 34.5MPA, then the "applied shear strength" equals to$\frac{34.5\text{Mpa}}{2} \approx 17\text{Mpa}$. The rule for calculating applied strength is also used for calculating normal strength in the following part.

In section 3.2, two formulas are given for restrain the dimensions of the bonding layer; one is about the shear stress and the other is the stress transferred in the base plate and are given below.

$$\tau_{ave} = \frac{P}{A} = \frac{P}{2c \cdot w} = \frac{P}{l \times w} \tag{3.3.1}$$

"l" is the length of the bonding layer and it equals to "2c"

$$L_{min} = w + \frac{2}{\sqrt{3}} l = \frac{load = 20ton}{1ton/cm^2 \cdot t_{ad}} \tag{3.3.2}$$

t_{ad} is the thickness of the base plate

The width of the bonding layer equals to the width of the lifting lug, and it is also written as "w". Using formula (3.3.1), the minimum bonding area can be got. The "τ_{ave}" is replaced by the shear strength of a kind of adhesive and "P" will be substituted by the maximum load carrying by bonded lugs of "20ton". Then the formula can be rewritten as an inequality using the width and length of the bonding layer as parameters:

$$l \times w \geq \frac{P}{\tau_{ave}} \geq \frac{20ton}{shear\ strength} \tag{3.3.3}$$

Then using formula (3.3.2), another relation between the length and width can be got. A new inequality is given below:

$$w + \frac{2}{\sqrt{3}} l \geq \frac{load=20ton}{1ton/cm^2 \cdot t_{ad}} \quad (3.3.4)$$

Using inequalities (3.3.3) and (3.3.4), a smaller range for measuring the shape of the bonding layer can be got; and example is shown below.

Continue using the example 1 given in PART A, even there is no parameter that has been given will influence inequalities (3.3.3) and (3.3.4). The “Epibond 100” epoxy adhesive is chosen for calculating and the applied shear strength after dealing with safety factor is defined as 17mpa; and the thickness of base plate is defined a 8mm (the thickness can be adjusted according to the real situation). Then new inequalities for the example are given:

$$l \times w \geq \frac{P}{\tau_{ave}} \geq \frac{20ton}{17mpa} = 11765mm^2 \quad (3.3.5)$$

$$w + \frac{2}{\sqrt{3}} l \geq \frac{load=20ton}{\frac{1ton}{cm^2} \cdot 8mm} = 250mm \quad (3.3.6)$$

Thirdly, for the normal stress, the theoretical calculation method is two complicated and it needs to define other unknown parameters in the formula; that causes it is not suitable for restricting the bonding layer’s dimensions. While, for general calculation, it can refer the method using in the welded lifting lug’s rule-using “bending moment” and “modulus (Dutch: weerstands moment tegen buiging)”. Figure3.3.4 shows the parameters for calculation.

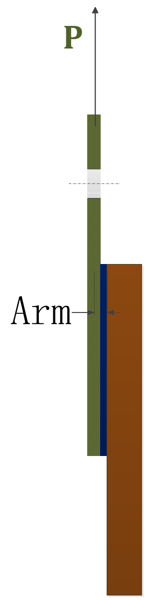


Figure3.3.4. Shape for calculating normal stress

Then the calculations for them are given:

$$M_{bending} = P \times arm \quad (3.3.7)$$

$$arm = 0.5thickness + bonding\ layer\ thickness \quad (3.3.8)$$

$$\text{Modulus} = \frac{1}{6} \times w \times l^2 \quad (3.3.9)$$

$$\sigma_{max} = \frac{M_{bending}}{\text{Modulus}} = \frac{P \times arm}{\frac{1}{6} \times w \times l^2} \quad (3.3.10)$$

σ_{max} is the normal stress, it can also stand for the normal strength

Transferring formula (3.3.9) to an inequality to restrict the shape, the new inequality can be got and shown below.

$$w \times l^2 \geq \frac{P \times arm}{\frac{1}{6} \times normal\ strength} \quad (3.3.11)$$

Then use inequality (3.3.11) in example 1. The normal strength of "Epibond 100" epoxy adhesive is 6.5mpa; the thickness of the bonding layer is set as 1mm. A new inequality with the given parameters can be given:

$$w \times l^2 \geq \frac{20\text{ton} \times (12.5\text{mm}+1\text{mm})}{\frac{1}{6} \times 6.5\text{mpa}} = 2492307mm^3 \quad (3.3.12)$$

3.3.3 Sub conclusion

With inequalities (3.3.3), (3.3.4) and (3.3.11), using width "w" and length "l" as axis of a coordinate, three curves can be drawn to give a range for defining shape. And the rules for measuring the minimum width can also be seen as a restricting condition and the description in inequality is:

$$w \geq 2R_{2min} \quad (3.3.13)$$

And in example 1 it is:

$$w \geq 214\text{mm} \quad (3.3.14)$$

If maximum values of the width and length are ruled based on the feasible fixing position can provide, the range for defining the bonding layer's dimensions can be got.

Then moving to example 1, if the feasible position can provide 400mm×400mm area, and using inequalities (3.3.5),(3.3.6),(3.3.12) and (3.3.14), a range is got; shown in Figure 3.3.5 (a).

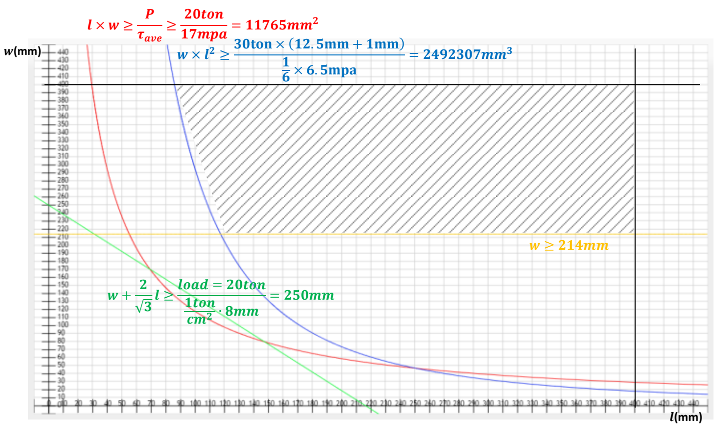


Figure3.3.5 (a) Range in a coordinate for defining dimension with 20ton load

So the width and length of the bonding layer can be chosen from the shadowed area in the coordinate shown in the Figure 3.3.5 (a). For the example 1, the final width is chosen as 220mm, and the length is 330mm. The shape is set bigger than the theoretical one for against the stress concentration, so the length is chosen much bigger than the theoretical. Figure 3.3.5 (b) shows the coordinate for defining dimension when the load increases to 30ton; the area for available value becomes smaller.

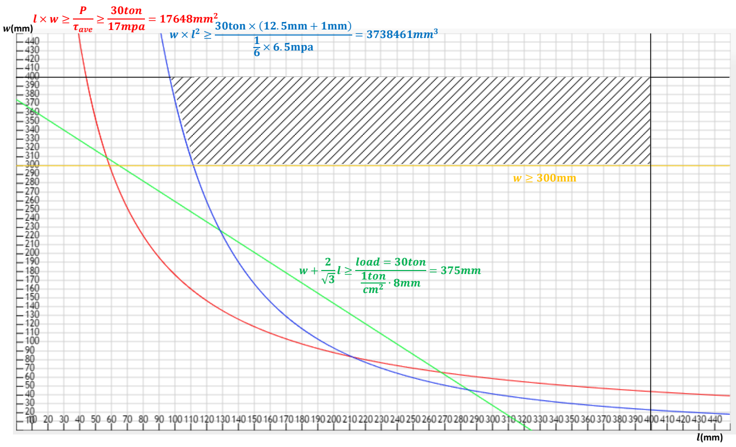


Figure3.3.5 (b) Range in a coordinate for defining dimension with 30ton load

In example 1, all the basic dimensions are guaranteed; and two fillets are set to decrease the stress concentration in the two bottom corners, as the radius of the fillets, it is analyzed in chapter 6, and it is set as 50mm firstly. Figure3.3.6 shows the basic design of a single lap bonded lifting lug, in the following part it will be modified if defects appear or the performance cannot fulfill the requirements.

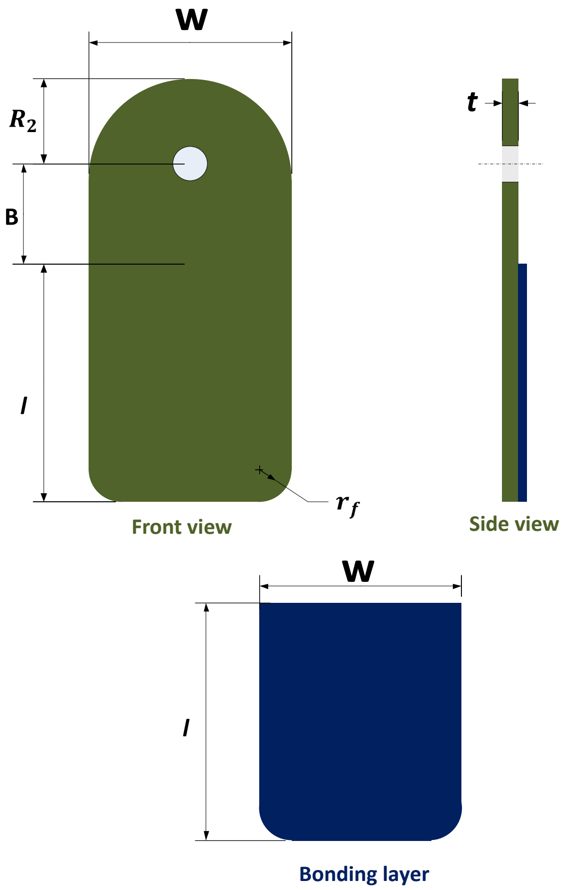


Figure3.3.6. A single lap lifting and its dimensions

So the final dimension for the basic single lap is given as:

Width: w=220mm

Length of bonding layer: l=330mm

Length: L=l+B+R2=330+160+110=600mm

Thickness: t=25mm

Radius of each fillet: $r_f = 50mm$

This example of basic single lap lifting lug model will be used as an original model for setting FEM model in following parts, monitoring the stress distribution, value and stress concentration in the bonding layer.

3.3.4 Double lap lifting lugs dimensioning

For double lap lifting lugs, the thought for define bonding layer's dimensions is same with that of single lap lifting lugs; while there is one thing different and should be taken care of for guarantee the self-strength.

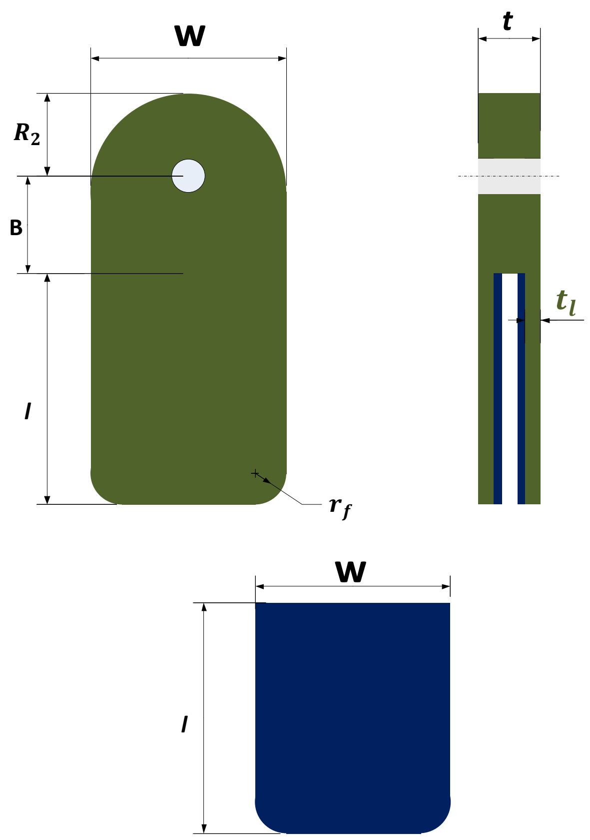


Figure3.3.7 A double lap lifting lug

Figure3.3.7 shows the shape of a double lap lifting with a basic design, the thing should be concerned is the thickness of the lifting lug for two side parts, the thickness is defined as t_l. Following the requirements of welded lifting lug, the stress in the cross section are of the side parts of a double lap lifting lug should be less than 1ton/cm^2; which means:

$$t_l \times \mathrm{w} \geq \frac{10ton}{\frac{1ton}{cm^2}} = 10cm^2.$$

For example, if the width of the lifting lug uses the same width with example 1, the minimum t_l is $\frac{10cm^2}{220mm} = 4.55mm$.

In the thesis, the general shape of a model of a double lap lifting lug is set as the same as a single lap one; The occupied volumes on the section for fixing the two kinds of lifting lugs are the same; then comparison between the two kinds of lifting lugs is processed.

So example 2 will provide dimensions of a basic double lap lifting lug:

Width: w=220mm

Length: L=l+B+R2=330+160+110=600mm

Thickness in the top part: t=25mm

Side part thickness: $t_l = \frac{1}{2}(t - base\ plate\ thickness - bonding\ layer\ thickness \times 2) =$

$0.5(25 - 8 - 1 \times 2) = 7.5mm > 4.55mm$

Radius of each fillet: $r_f = 50mm$

The double lap lifting lug provided in example 2 is also used for building original FEM model in following chapters.

3.4 Summary

In Chapter 3, the sub questions “**C**” and “**D**” are primarily and partially answered:

C. How to define the shape and geometrical attribute of lifting lugs?
Based on the theoretical calculation formulas, the method for defining primary shape and dimensions of lifting lugs and bonding layers is given. The dimensions of the bonding layer and lifting lug must fulfill the stress requirements firstly; and all the limitation factors can be transferred into mathematical formulas and given in a coordinate as a “selection Figure”. Dimensions are defined with the “selection Figure” combining other requirements, such as easily production and installation position.

D. What is the state of stress of the bonding joint with load?
Stresses are not distributing averagely in the bonding layer and stress concentration occurs in the edge of the bonding layer; formulas for theoretically calculating shear and normal stress are given.

The discussion of installation position is given in Chapter 4.

4. Adaptation: Feasible fixing position selection

After the design of the shape and dimensions of adhesively bonded lifting lugs, the places to install them will be discussed in this chapter. In the thesis, the positions that have potentials to be used for bonding lifting lugs are defined as “potential positions”; but not all the potential positions can be used for the installation. The feasible fixing positions are selected from potential positions; and there are several levels for the selection. In the chapter, differences between kinds of potential positions are talked; and the final fixing positions are selected after the analysis.

4.1 Analyses for position requirements

In the first part of this chapter, the requirements for the potential positions on sections are translated from the rules of welded lifting lugs or drafted based on the properties of adhesive bonding. The positions for fixing lifting lugs influence the performances of the bonded lifting lugs in both macro and micro aspects; and both aspects should be considered in the selection. The macro view refers to “how the whole section mass distributes on each lifting lug”, “whether the potential position is strong enough” and “whether the area is suitable for adhesive bonding”. The micro view refers to how the stresses and the stress concentration are produced in the joint. The selection for potential positions will be processed in several levels from macro view to micro view, progressively.

In the first level for selecting potential positions, the task is to find positions that can distribute the whole section mass to each lifting lug under their carrying capacities. As required in the former chapter, the load acts on each lifting lug should be less than 20ton; and the calculating method is given in chapter 2. In the rules for welded lifting lugs, lifting lugs carrying load less than 20ton need not to be inserted into the skin of the section but only bulkheads or web frames can be the positions for fixing. So in the first selecting level, bulkheads and web frames that distributes load on each lifting lug under their carrying capacity are selected as the potential positions.

In the second level, requirements about bonding area are considered. The requirements relate to both the shape and the value of the area for bonding. For the adhesively bonded joints, the bonding plane needs to be kept as flat as possible to ensure the strength and the surface for bonding joints should have no protrusion; such as welding seam is allowed in the region in the bonding joint. Then the value of the surface used for the bonding should be large enough for the bonding joint needs and fulfill the requirements for both the length and width. Therefore, in the second level, the potential positions are re-defined as: “appropriate bulkheads and web frames with flat plane and enough bonding area for the bonding joints but without any protrusions that obstruct the lugs’ installation”.

In the third level, the space requirements are considered. In this level, the coordination between lap joints’ type and potential position is discussed. The single lap joint and the double lap joint are different in the bonding requirements; the single lap joint needs one surface for bonding while the double lap joint needs two symmetrical surfaces. Furthermore, the single lap joint causes bigger bending moment than the double lap joint because its asymmetry structure; and the bending moment causes bending deformation in both the lifting lug and the base plate which increases the normal stress. While, the double lap joint is a symmetry structure which causes no bending for the adherends; so it can decrease the normal stress caused by bending. Besides of that, double lap joint distributes the total loads to both of the two bonding layers which decrease the value of stress. Therefore, it can be regarded that the double lap joint is more reliable than the single lap joint; the priority of applying double lap joints should be higher than single lap joints. For applying double lap joints, the potential positions should have two symmetrical surfaces for bonding and there should be spaces on the top surface. While, for single lap joint, one appropriate bonding surface in the potential position is needed. Except for the number of bonding surfaces, the space provided by the potential position for the accessories combined with a lifting lug should be enough. A lifting lug in lap joint needs to have a part (shown in Figure 2.1.2) higher than the top surface of the section to be assembled with other lifting accessories; therefore, there should be no obstacles influencing the accessories during the lifting process. So in the third level, the potential positions are defined more detailed as: “Appropriate bulkheads and web frames with flat plane and enough bonding area for the bonding joints but without any protrusion that obstruct the lugs’ installation; the bulkhead or web frames should have enough bonding surfaces for the applied lap joints and enough space for other lifting accessories”.

In the fourth level, the concentration moves to factors in the micro view; such as the deformation of bending. Compared with the shape of a section, the deformation produced in the lifting process can be seen as micro changes; and it influences the joints’ strength, considerably. As Hartshorn (1986) said in the book, the adherends’ bending will influence single lap bonding joints’ strength []; the different stress concentration factors calculated by “Volkersen” and “Goland and Reissner” also explains it. The bending of the adherends increases the shear stress concentration and the normal stress; even peel can be caused in the metal to metal bonding joint. Therefore, potential positions that have small deformation of bending should be selected preferentially. Finally, the definition of the potential positions can be given as: “Appropriate bulkheads and web frames with flat plane and enough bonding area for the bonding joints but without any protrusion that obstruct the lugs’ installation; the bulkhead or web frames should have enough bonding surfaces for the applied lap joints and enough space for other lifting accessories; the potential position should make the deformation of bending as small as possible”. Feasible fixing positions are selected from the potential positions referring some specific requirements, such as which type of lap joints is used or operation requirements.

An example is shown below to explain how to select potential positions in a section based on the “4 levels requirements” given above; the example can show the former three levels and the last level selection will be discussed in 4.2.

A sectional view of a section provided by IHC Ship Yard is shown in Figure 4.1.1 (lifting plan 1301 [39]); it shows the overview of the lifting plan using welded lifting lugs which are highlighted in red circles. Six lifting lugs are arranged in the top side, the bottom side and one of the flank sides of the section, and all of them are welded on frames.

Firstly, appropriate bulkheads or web frames will be found. In the top side, the plate has been welded and bonded lifting lugs cannot be applied. Therefore, bonded lifting lugs can only be fixed on the other side, choosing frames that no plates welded on the frames. The selected frames are the same as the frames used in plan for welded lifting lugs; shown in Figure 4.1.2 highlighting with blue blocks.

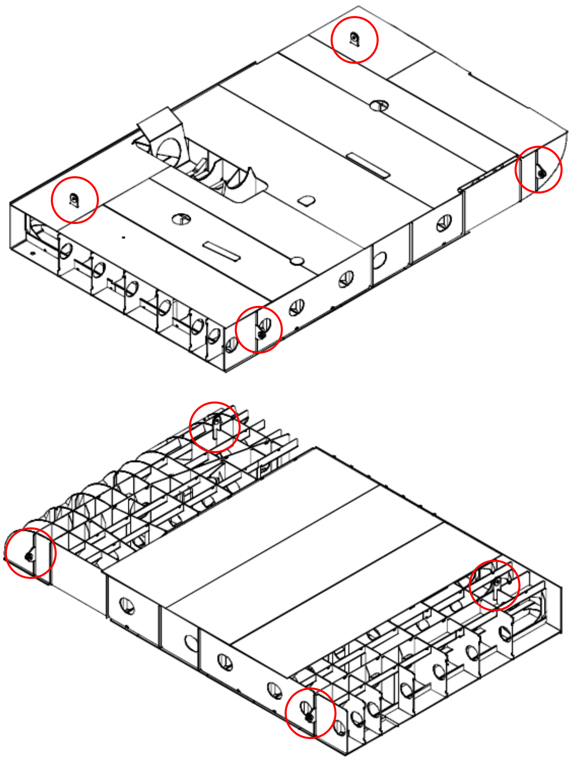


Figure 4.1.1 Overview of the lifting plan

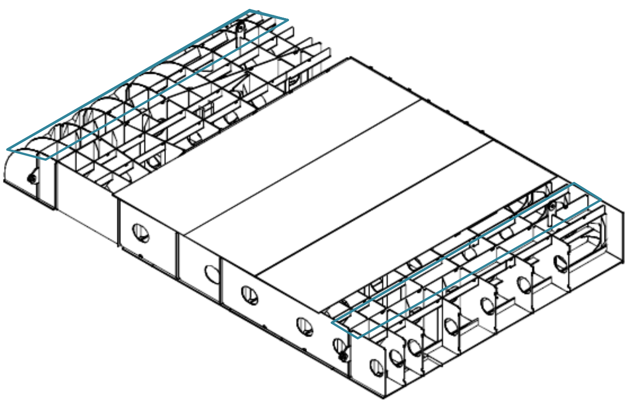


Figure 4.1.2 Frames for bonded lifting lugs

Then appropriate area on the frame will be selected. Figure 4.1.3 shows the front view of the frame selected in the frame. The areas in the green blocks are not welded with stiffeners or other longitudinal structures, so it can be regarded as flat area which is suitable for bonding. And the areas' length and width restrain the bonding joints' size, such as the length and width, shown with black lines in Figure 3.3.5, Chapter 3. If the values of the areas are assumed big enough for the bonding joints' requirement, the areas for bonding are got.

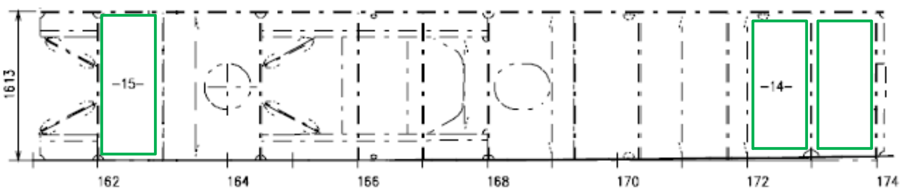


Figure 1.1.3 Front view of the web frame

Then the process comes to judge the space requirement. Combining with Figure 4.2 and 4.3, there is no top plate on the selected areas on the web fame so both single lap and double lap joints can be applied. And also there are no obstacles to the lifting work around the selected areas; so the final area for bonding is chosen from them.

At last, the ability for defense bending deformation is analyzed. FEM models for the selected structures and lifting lugs will also be built in "Part III" to simulate the influences in the micro view and the results will show the exact strength of the bonding joints. The explanation of the influences in the micro view is discussed in the section 4.2.

4.2 Influences of strength in potential positions

The performance of the bonding joints is influenced by some factors form the micro view; deformation of bending is the main reason for decreasing the joints' strength. In the potential positions, the support structures assembled on the bonding plates will influence the deformation of bending. Combining with the characteristics of ship sections, different kinds of support structures are discussed.

The bending in the potential positions mainly influences single lap joints, because the load acts on the lifting lug is eccentric; while the double lap joint distributes load to each side equally, bending does not occur in the base plate during the lifting process if the load is kept vertical. So the analysis focuses on positions for installing single lap joints.

A bonded lifting lug with single lap joints is fixed on one surface of the structure in sections; and the structure must be selected from bulkheads or web frames which are made of plates. The properties of plate structures provides one big area surface to for bonding and other surfaces are welded on the section or other structures, or become free surfaces. According to the ship sections' structural characters, several scenarios can be given for analyzing the influences to the strength of bonding joints.

The most common one is the model shown in Figure 4.2.1. A bonded lifting lug is fixed in the middle area of a base plate which is used to build bulkhead or web frame; and each flank side is welded with structures perpendicular to the bonding surface. And the base plate is usually welded with the section in the bottom surface; the top surface is a free surface. The scenario is named as "Scenario 1" shown in Figure 4.2.1.

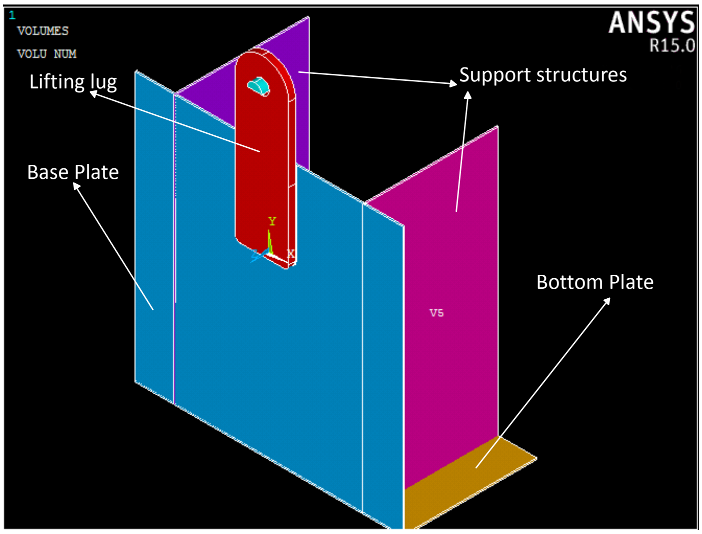


Figure 4.2.1 Base plate with support structures in flank sides

Then Figure4.2.2 shows another scenario. Based on "Scenario 1", a support structure, such as a gird, is welded on the back surface in the middle of the base plate. The plate is supported in the middle, so the anti-bending modulus of the base plate is increased and the deformation of bending is decreased. The scenario shown in Figure 4.2.2 is named as "Scenario 2".

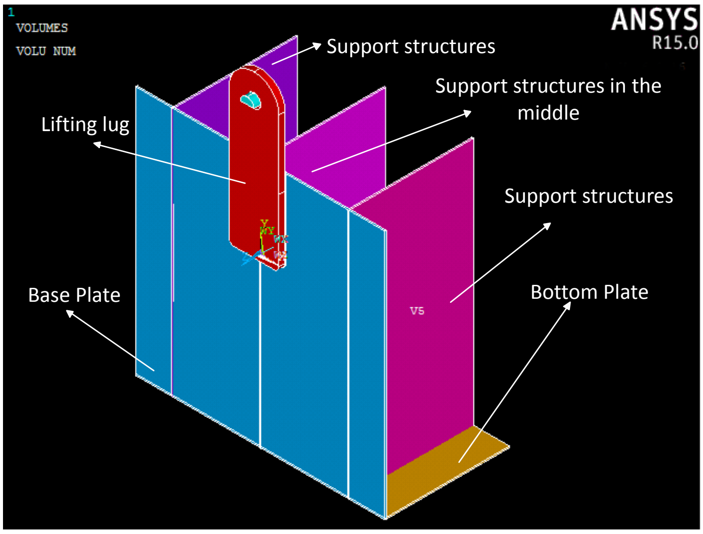


Figure 4.2.2 Base plate with middle support structure

In Figure 4.2.3, a more complicated scenario named "Scenario 3" is shown. Different with "Scenario 2", the support structure in the middle is instead by several stiffeners. The stiffeners are distributed in the whole area of the base plate in the back surface; the stiffeners increase the stiffness of the whole base plate.

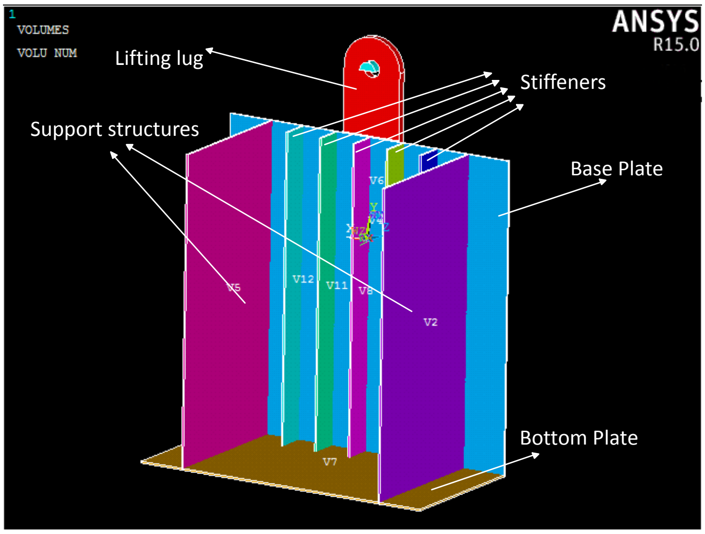


Figure 4.2.3 Base plate with stiffeners

The first scenario experiences the largest bending among the three scenarios; while the second and third scenario make the base plate have higher stiffness to defense bending. The exact results will be simulated in FEM models and the differences between each scenario can be given; by comparing the differences the priority to select positions for bonding lifting lugs can be got. Chapter 5 will introduce FEM simulation and the results.

4.3 Summary

The chapter concludes requirements for positions for fixing lifting lugs; and sub question "**E**" is answered further:

E. Where is the optimal position for installing lifting lugs?
the potential fixing positions with requirements can be concluded as "Bulkheads and web frames with flat plane and enough bonding area for the bonding joints but without any protrusion that obstruct the lugs' installation; the bulkhead or web frames should have enough bonding surfaces for the applied lap joints and enough space for other lifting accessories; the potential position should make the deformation of bending as small as possible".

The selection of potential positions with macro view requirements is explained by an example; and the micro view is talked in the second part. The support structures on the potential positions' structures are the main factors influencing the performance for defensing bending; three kinds of scenarios are given and they will be simulated by FEM models in Chapter 5.

5. Evaluation: Building and simulating FEM models

In this chapter, items of FEM simulation are introduced. Firstly, the basic FEM model of bonded lifting lug's system is given. Then boundary conditions for different kinds of the potential positions are discussed, corresponding to the scenarios given in 4.2, chapter 4. Lastly, the results of the FEM simulation will be analyzed and discussed to Figure out probable defects.

5.1 Introduction of FEM model

5.1.1 Software selection

In the finite element analysis simulation, the software ANSYS is used; the mode "mechanical APDL" for solving structure problems in the software is used. For analyzing finite element problems, FEM software such as ANSYS and ABAQUS are both suitable for dealing with problems about adhesive bonding joints; and they have been already used for analyzing bonding joints in lectures by lots of researchers. Fan-rong Kong [40] (2006) introduced some methods for analyzing cleavage stress in lap bonded joints using ANSYS; the specimens have commons with bonded lifting lugs structures in the research. So ANSYS will be selected to be applied in the thesis for the FEM simulation.

The official website of ANSYS introduce the software for structure calculation as: "*The strength of components is a key requirement in understanding a product's performance, lifecycle and possible failure modes. Mechanical loading, thermal stress, bolt tension, pressure conditions and rotational acceleration are just some of the factors that will dictate strength requirements for materials and designs. ANSYS Mechanical ensures your product's viability and safety by predicting the strength required for the loads your design will experience in service* [41]*.*" And combined with the research results of FEM analysis, it can believe that ANSYS provides reasonable solutions for problems about adhesively bonded joints. Then FEM models are gonging to be built based on "ANSYS".

The general process for FEM simulation with ANSYS in this research is concluded as eight steps shown in Figure 5.1.1. The first five steps in the box are steps for building the basic model which will be used for the calculation later; they will be introduced in part 5.1.2. Then in the sixth step, boundary conditions are set based on the scenarios provided in 4.2, chapter 4; and it is discussed in section 5.2. The last two steps will deal with the results and they will be given in section 5.3.

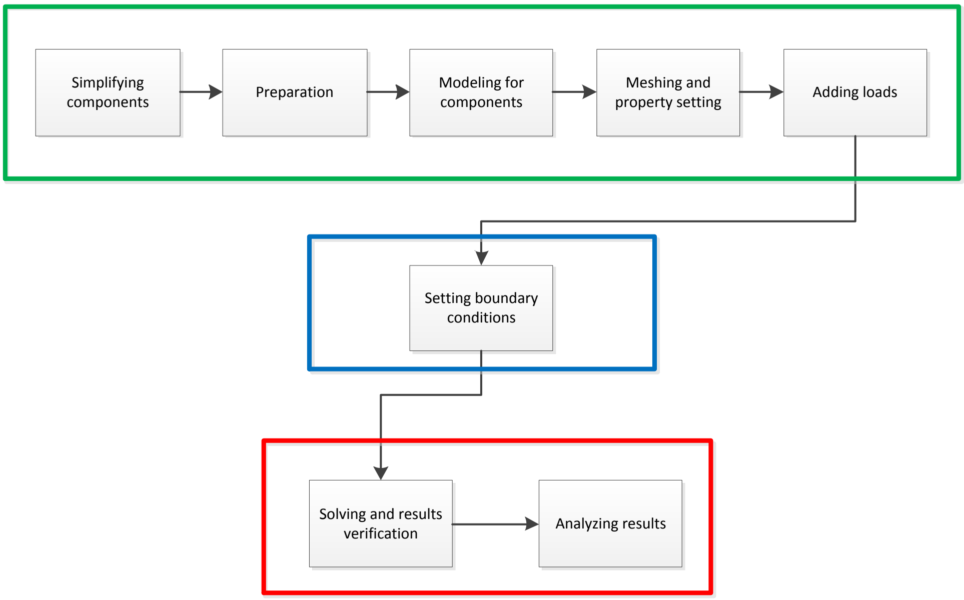


Figure5.1.1 Steps for FEM simulation

5.1.2 Building FEM models

I. Simplifying components in a bonded lifting lug system

An adhesively bonded lifting lug system contains components as the following: a section, a lifting lug, a bonding layer and other lifting accessories. While in the FEM simulation, building the whole system will occupy too much resource. Therefore, some parts are selected and simplified from the whole system. The main simplification will focus on the section and the lifting accessories. A part of plate or plate with support structures is intercepted from the potential position on a section for fixing lifting lug, it is named "base plate" in the thesis; and only the green pin from lifting accessories will be used in the model. While lifting lug and the bonding layer are kept without any changing. So in a basic FEM model, the components will be a base plate, a lifting lug, a bonding layer and a green pin; and support structures models are added in the following FEM models.

II. preparation

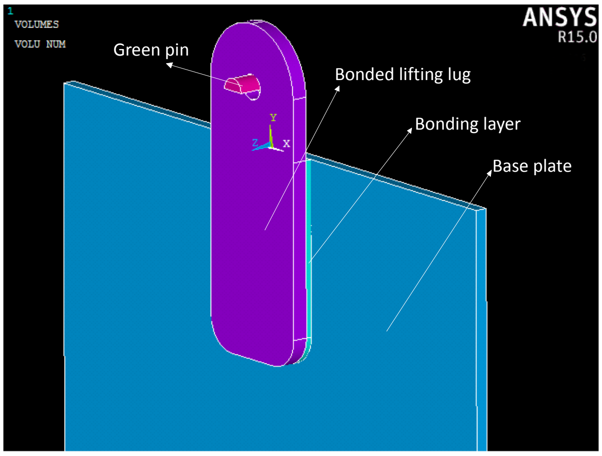
Before modeling, some parameters need to be set for the model. Kong's research [42] can help with the preparation work as well as the building work in the "part C". Firstly, the "element" is set as "Solid 185". Then the properties for the materials are given, the applied parameters are shown in Table 5.1.1.

Table 5.1.1 parameters used in FEM model

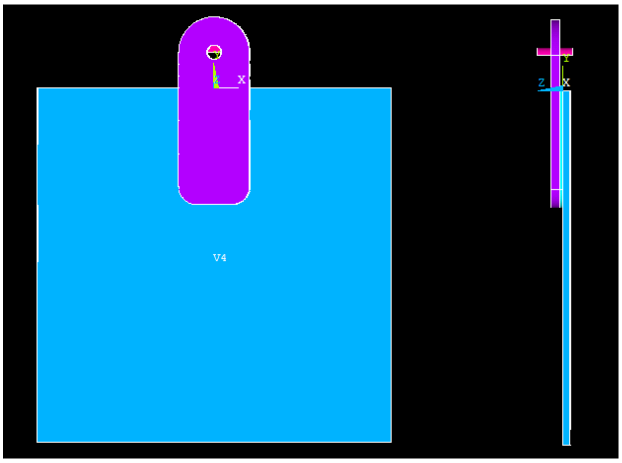
	Poisson's ratio (mpa)	Young's modulus
Metal	2e11	0.3
Epoxy adhesive "Epibond 100"	2.18E9	0.22
Acrylic adhesive "NS8410"	1.3E9	0.3

III. Modeling

The FEM model starts with a single lap bonded lifting lug; the FEM model contains an adhesively bonded lifting lug, a bonding layer, a base plate and a green pin; Figure 5.1.2 shows it with an overview in picture (a) and “front and side view” in picture (b).



(a)



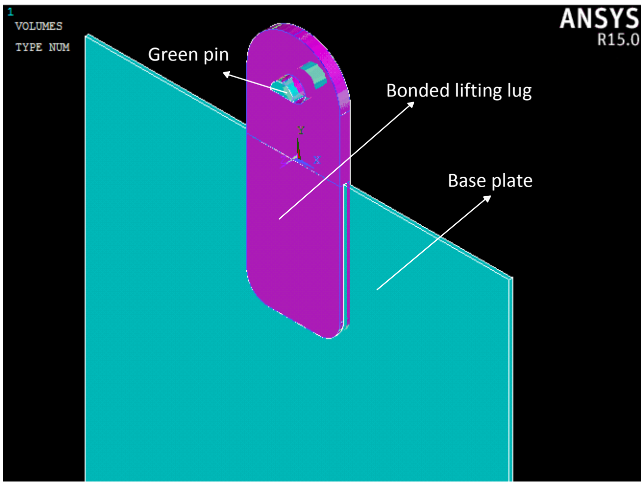
(b)

Figure5.1.2 FEM model of a single lap lifting lug

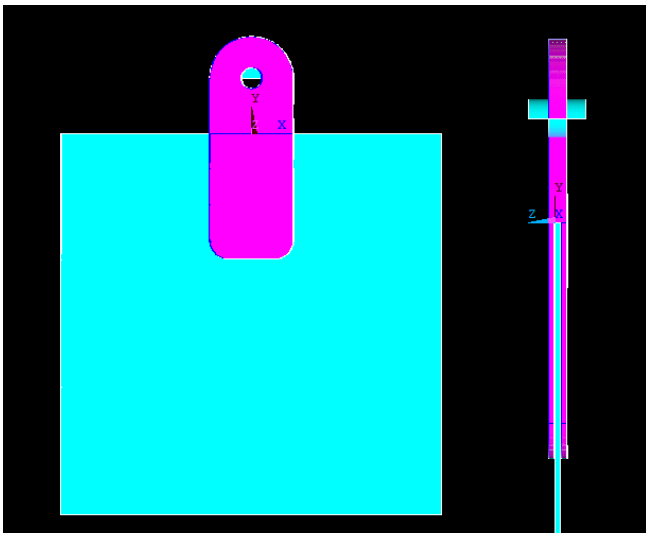
All components in the model are built as “VOLUME” in ANSYS. The base plate is simplified with dimension of 1m × 1m in length and width, 8mm in thickness. The dimension of the base plate uses data from the “liftingplan 1301” and values of the dimension are simplified to make the model to be built. In the future research, the base plate can be built with other dimensions to make the simulation more close to specific applications. The lifting lug’s and bonding area’s dimensions are used data calculated before in “example 1”, section 3.3, Chapter 3; and they are placed in the middle of the plate. The green pin is cut in the middle and deleted the lower half part, this measurement aims to make the load easily added on and exactly simulate the force transferring. The lifting lug, bonding area and the base plate are connected using the operation “glue” in ANSYS to simulate adhesive bonding.

Similar with the single lap lifting lug, the FEM model of a double lap lifting lug is shown in

Figure 5.1.3; dimensions are used data from “Example 2” provided in section 3.3, Chapter 3.



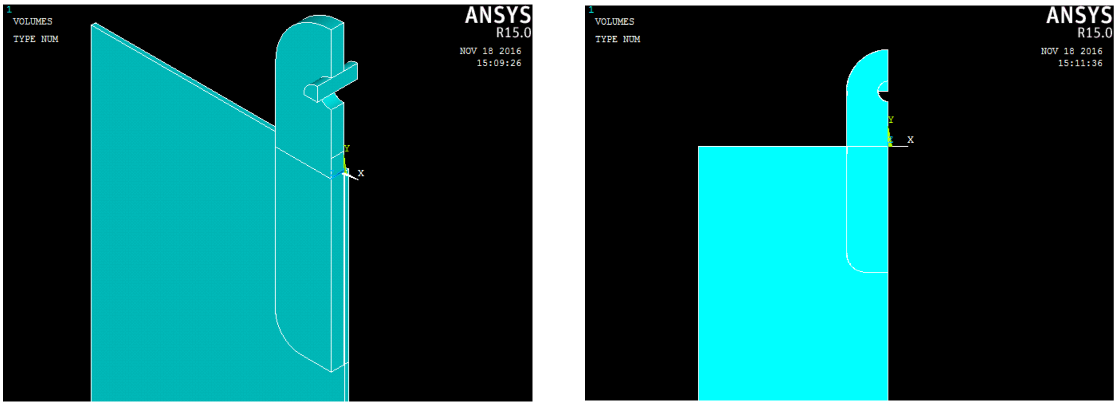
(a)



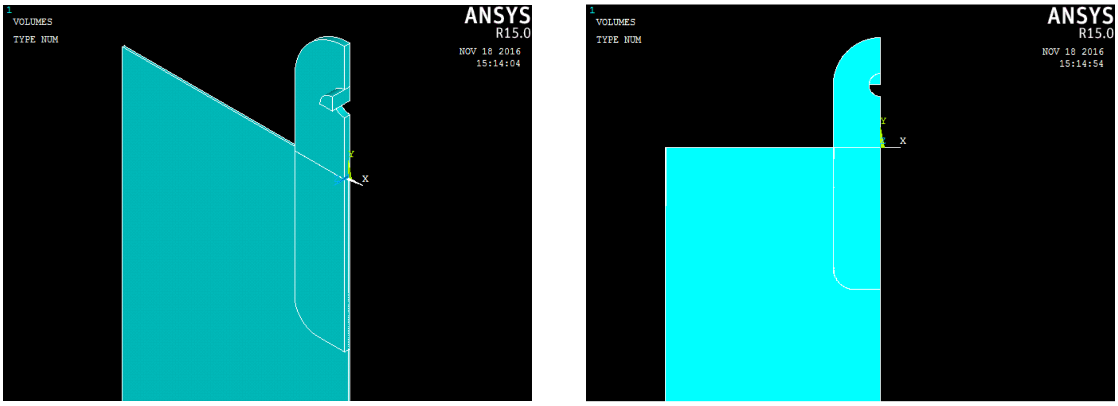
(b)

Figure 5.1.3 FEM model of a double lap lifting lug

Then for decreasing the calculation burden for the computer, the FEM models are further simplified; because they are both in symmetry structures. And ANSYS can provide a function that using a symmetry part of the model to simulate a complete system by setting appropriate boundary conditions. The single lap lifting lug model is symmetry to the middle plane perpendicular to the bonding layer; so half of the whole model will be used. While double lap lifting lug model is symmetry to both the middle plane perpendicular to the bonding layer and the middle plane parallel to the bonding layer; and finally a symmetry structure of 1/4 of the whole model is used. Figure 5.1.4 shows and briefly explains the further simplified model.



(a) Further simplified single lap FEM model



(b) Further simplified double lap FEM model

Figure5.1.4 Further simplified FEM models

IV. Meshing and properties setting

In this step, mesh will be set to the model. To ensure the accuracy of the calculating results, elements are defined as “hexahedral” for all the components. The mesh density is set as an appropriate number at first and then they will be arranged to make the results accurate; the discussion will be introduced in the third section in this chapter.

Then the components in the model will be defined with different properties based on their own properties. The bonding layer is defined with properties of selected adhesives and the lifting lug, base plate and green pin are defined with properties of metal.

V. Adding load

The load added on the model is 20ton, the maximum value an adhesively bonded lifting can carry. The load is added on the bottom surface of the green pin in pressure; to transfer load to pressure, the formula is given in Formula (5.1.1).

$$Pressure = \frac{Loads}{r \times l_{gp}} \qquad (5.1.1)$$

And the dimensions of the area for adding load of a 20ton-green pin is 54mm in width and

80mm in length, then the pressure is calculated as:

$$\text{pressure} = \frac{20ton}{0.054m \times 0.08m} = 4.63 \times 10^{7} pa \qquad (5.1.2)$$

So the pressure applied in the FEM is 4.63$\times$ 10^{7}Pa.

5.2 Discussing the boundary conditions

Boundary conditions are something to constrain the FEM model that make the model can simulate the real situation, and they will influence the results. Because the FEM model used in the research is cut from the whole system, setting correct boundary conditions to make the model have the same situation with the original system is important. For FEM models used in the research, the support structures on the base plate are the main factors influence the setting of boundary conditions, and several different boundary conditions are discussed based on the scenarios provided in chapter 4.

Similar with the former parts, the discussion starts with the simplest single lap bonded lifting lug. The whole model can be regarded as being fixed on the ground and a force acts on the lifting lug, this can simulate the balance situation of the whole system. In Figure5.2.1, it shows how the base plate is cut and simplified from its original structure in a ship section. It can be seen that the two flank surfaces are not exist in the reality; they are abstracted after the simplification. Therefore, these two surfaces should be constrained with totally fixed in x, y and z directions. The bottom surface is welded with the bottom plate of the section and it is not pulled to separate from the bottom plate of the section; the bottom surface is not moved in the directions in the horizontal plane. So the boundary condition set on the bottom surface should be in x, y and z directions. In sum, the boundary conditions for the basic FEM model used in the research is set by constraining the surfaces' displacement; the surfaces which are constrained by other structures based on the real condition are selected.

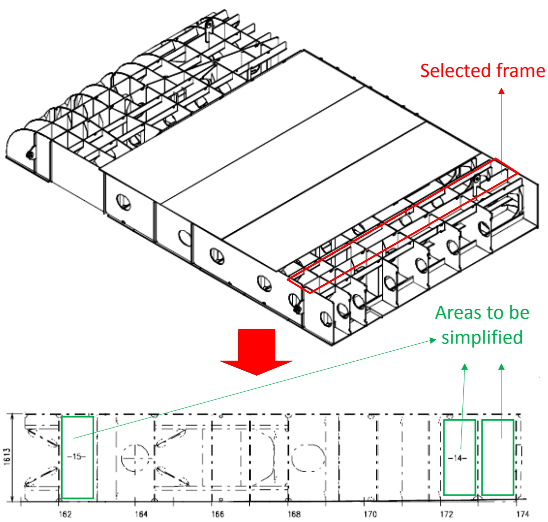


Figure 5.2.1 Selection of simplified base plate

For the lifting lug with double lap joint, the situation of the base plate experiences the same with the simple single lap lifting lug. So boundary conditions are also the same.

Then the discussion moves to the setting for different scenarios of lifting lugs with single lap joints. “Scenario 1” (shown in Figure 4.2.1) has the same boundary conditions with the basic single lap lifting lugs.

In Scenario 2 (shown in Figure 4.2.2), the situation becomes different from the basic one. In Scenario 2, there is a support structure in the middle of the base plate. The support structure can increase the stiffness of the base plate; the middle area will have the largest stiffness in the whole base plate and bending in this area will be effectively defensed. While the two areas besides the support structure in the base plate will experience larger bending deformation with the increasing of the distance away from the support structure. So for setting boundary conditions for Scenario 2, the support structure will be totally fixed and the base plate is the same with that in the simple single lap lifting lug. Figure5.2.2 shows the setting of the boundary condition for Scenario 2.

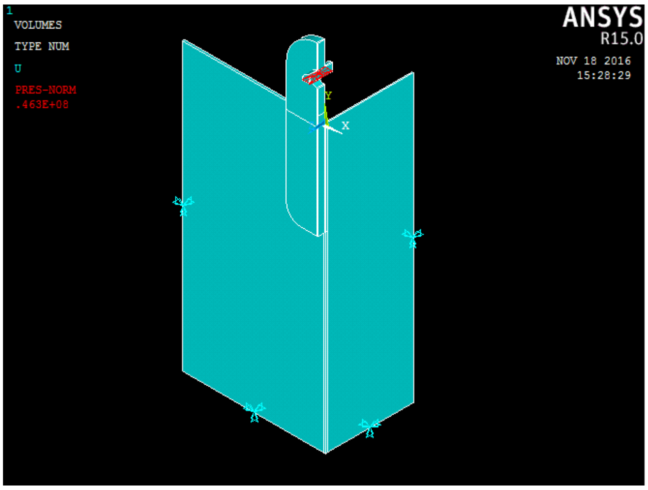


Figure5.2.2 Boundary condition for Scenario 2

In Scenario 3, the support structures become stiffeners distributing averagely on the back side of the base plate. The stiffness of the whole base plate is increased largely and bending of the base plate is decreased significantly. So it can be assumed that a base plate with a serious of stiffeners will not experience bending in the lifting process; and the FEM model for Scenario 3 can use the same with the basic single lap lifting lug; but different in the setting of boundary conditions. Then in the setting of the boundary conditions for the model, the back surface of the base plate is set with fixed in the direction perpendicular to the back surface; and the other surfaces’ displacements are the same with the basic single lap model. Figure 5.2.3 shows the conditions in detail.

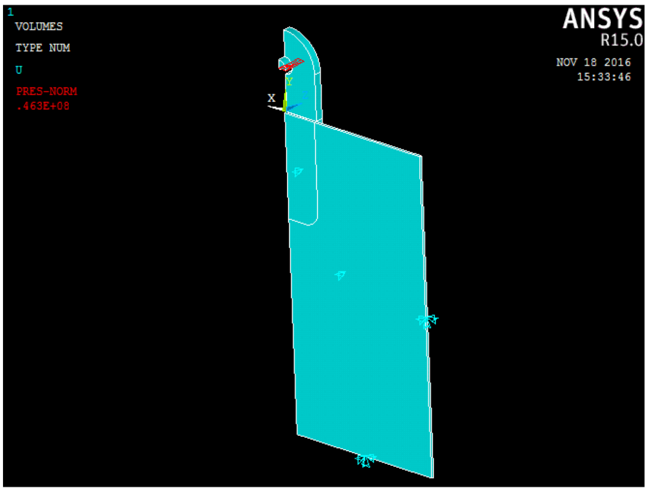


Figure5.2.3 Boundary condition for Scenario 3

5.3 Discussing the results

The FEM model will be solved after the preparation work being finished in the former part; and the results of stresses in the bonding joints will be analyzed. Before the analysis of the stress results, the accuracy of the results will be discussed firstly.

For calculation FEM model with ANSYS in the solution part, the density of the mesh on the model is one of the factors that influence the accuracy of results. The density of the mesh influences the number of the elements used for calculation in the FEM model. The results' accuracy will increase with the increase of the density of mesh and number of elements; and the accuracy will be stable when the density increases to a value. Because the performance of adhesively bonded joints using for fixing lifting lugs is the focus for the investigation in the research; the concentration of the mesh density should be on the bonding layers in the FEM models.

In the operation of setting mesh density in the FEM models, the mesh density is controlled by dividing the sides on the bonding layer and mapped mesh method is applied for the meshing to get regular hexahedral elements.

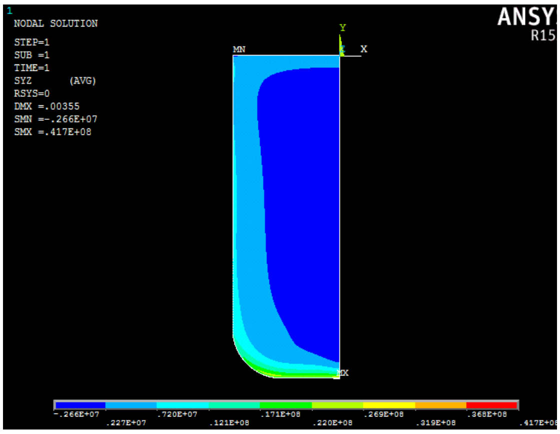
The original mesh density starts with dividing each side on the bonding surface into 50 parts; which means the elements' size of the bonding layer is $\frac{220}{50} = 4.4mm$ in width and $\frac{330}{50} = 6.6mm$ in length; and the thickness was divided into 5 parts averagely. Then the elements' size in the bonding surface of the bonding layer will be decreased to increase the mesh density to check whether the elements' size is small enough to provide accuracy results. Simulation will be repeated until reasonable results are got; the shear stress and deformation in the shear in the direction same with the load in the concentration part will be monitored as factors for judging. In table 5.1, a serious of simulation results of the basic single lap model with epoxy adhesive joints in different mesh density are shown.

Table 5.3.1 Results of simulations with different mesh densities

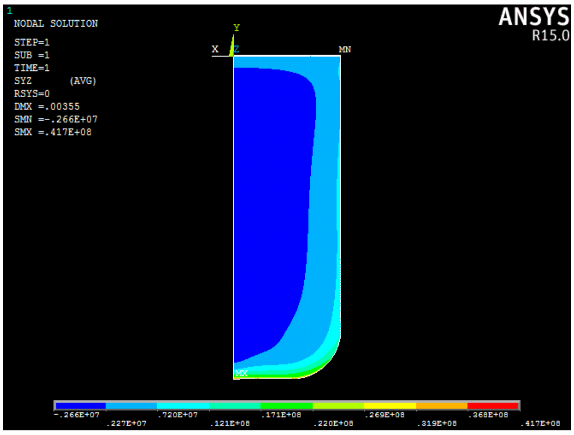
Element size of bonding surface (width*length, mm)	Deformation in the direction same with the load (10^{-3}mm)	Changing ratio	Maximum shear stress (Mpa)	Changing ratio
4.4*6.6	1.67	-	30.5	-
2.2*3.3	1.94	13.9%	51.9	41.2%
1.1*1.65	1.71	-13.5%	41.7	-24.5%
0.55*0.825	1.72	0.58%	43.8	4.8%

Comparing with results shown in table 5.3.1, when the element size is controlled around 1.1~1.6mm, changings of results become smaller and results become stable; so this element size will be used in the following simulations.

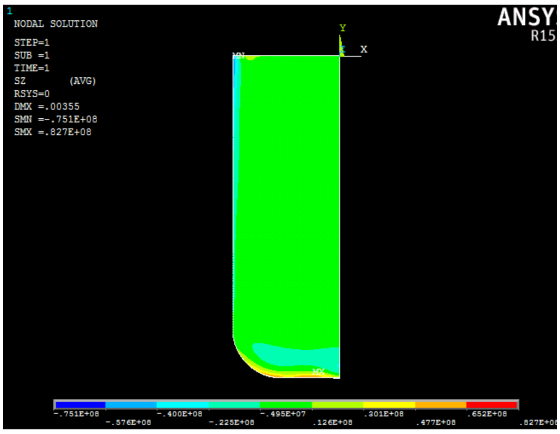
The simulation results can be got after the system running in the software; the results show the values of different stresses exist in the bonding layer and their distribution. Then a group of simulation results are given in Figure 5.3.1.



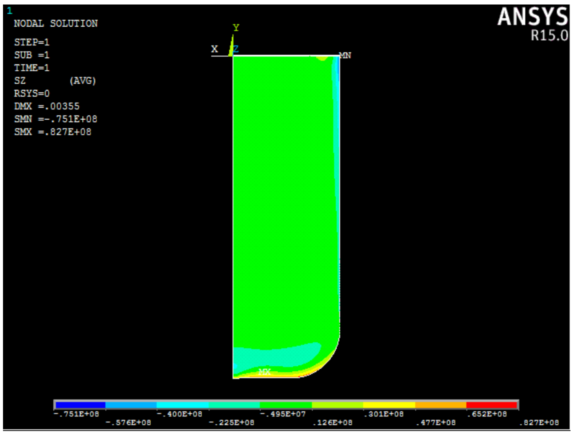
(a) Front side of shear stress



(b)Back side of shear stress



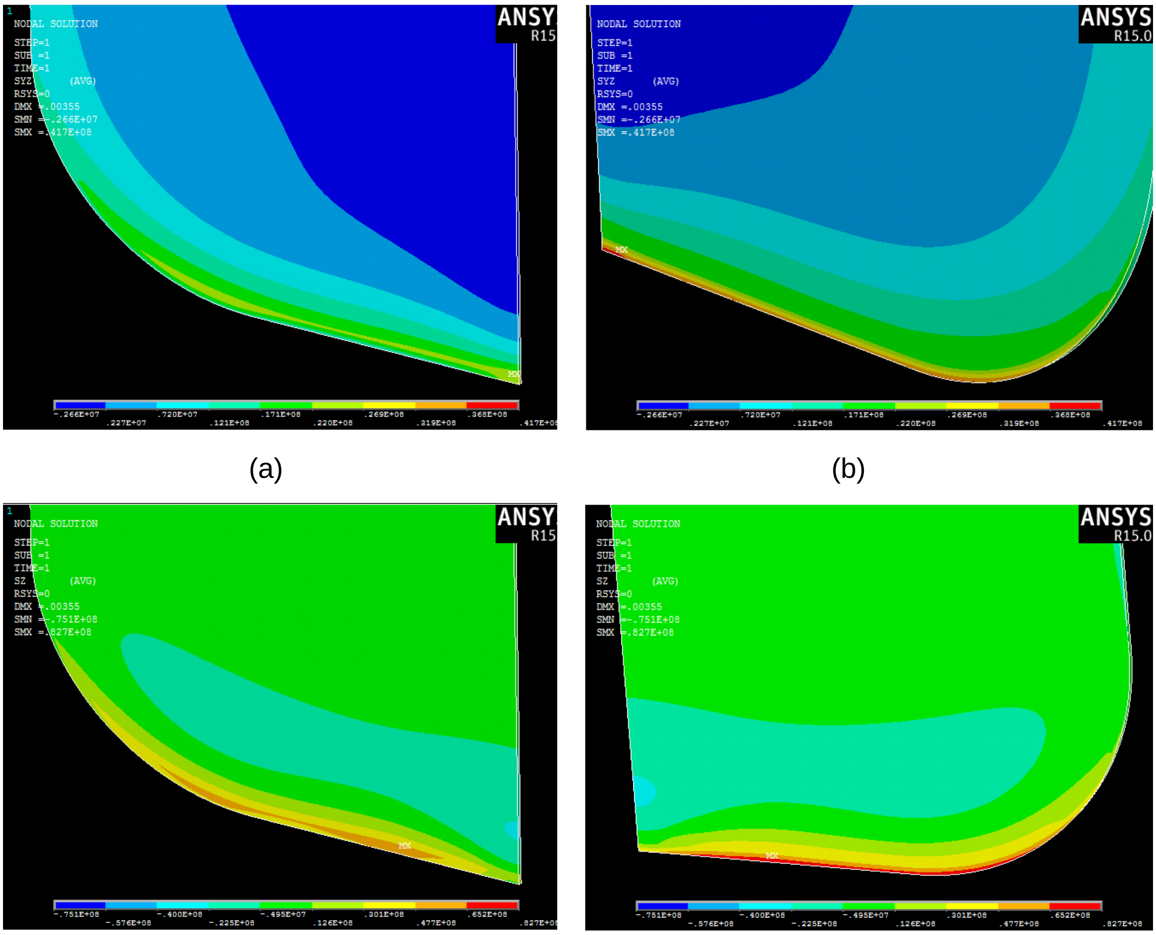
(c) Front side of normal stress



(d) Back side of normal stress

Figure5.3.1 stresses' distribution in a lap bonded joint in "Scenario1"

In Figure 5.3.1(a) and 5.3.1(b), the distribution of the shear stress in the bonding layer is given; and in Figure 5.3.1(c) and 5.3.1(d), distribution of the normal stress is given. It can be seen that, in general view, the distribution of the stresses doesn't change a lot through the thickness of the bonding layer; but in the edge of the bonding layer, there exists severe stress concentration. Then Figure 5.3.2 gives the zoomed in picture of the bonding layer.



(a) (b)

(c) (d)

Figure 5.3.2 Zoomed in pictures of stress distribution in the bonding layer

Figure 5.3.2(a) and 5.3.2(b) gives the zoomed in view from the front side and back side of the shear stress around the edge of the bonding layer; it can be seen that the concentration stress is increasing from the front surface to the back surface through the thickness and the maximum stress appears in the bottom edge of the back side. Figure 5.3.2(c) and 5.3.2(d) shows the zoomed in views of normal stress concentration in the bottom edge; the stress is also increasing from the front surface to the back surface through the thickness. From Figure 5.3.1 and 5.3.2, the values of the stresses can be read and they will be recorded.

And then the other FEM simulations results are monitored and recorded same with the example shown above. And in table 5.3.2, results of different FEM models are listed; and they are used to compare with the adhesive's strength to judge the feasibility for applying bonded joints. The strength of the selected adhesives is shown in Table 5.3.3.

Table 5.3.2 Results in different FEM models after simulation

	Single lap joints						Double lap joints	
	Scenario 1		Scenario 2		Scenario 3		-	
Adhesive	EP	AC	EP	AC	EP	AC	EP	AC
Shear concentration stress	41.7mpa	32.5mpa	12.9mpa Fillet corner 8.98mpa	10.5mpa Fillet corner 8.9mpa	16.8mpa	12.00mpa	18.8mpa	12.7mpa
Location description	At the fillet Corner and the bottom edge	At the fillet Corner and the bottom edge	At the middle of the bottom edge and two top edge corners	At middle of the bottom edge and two top edge corners	At the top edge	At the top edge	At the top corner of two edges	At the top corner of two edges
Max Normal stress pull	82.7mpa	65.4mpa	27.4mpa	19.0mpa	15.0mpa	10.1mpa	17.5mpa	11.6mpa
Max Normal stress compress	75.1mpa	58.9mpa	15.6mpa	12.9mpa	16.4mpa	11.7mpa	16.6mpa	11mpa

Tips for table 5.2: EP=epoxy adhesive "Epibond 100" AR=acrylic adhesive "DP8410NS Green"

Scenario 1: Base plate without any support structures.

Scenario 2: Base plate with a support structure in the interior area.

Scenario 3: Base plate with a strong support structures such as a serious of stiffeners.

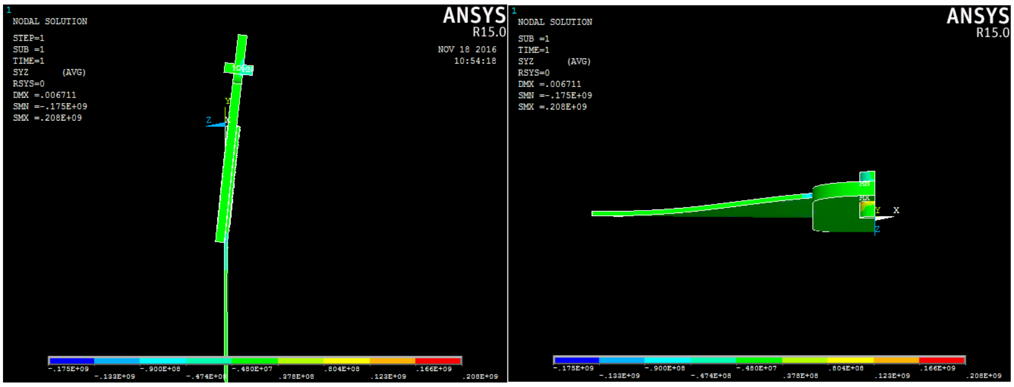
Table 5.3.3 Strength of selected adhesives

Adhesive name	Category	Shear strength	Normal strength
Epibond 100	Epoxy	34.5 mpa	13 mpa
DP8410	Acrylic	24.6 mpa	9.3 mpa

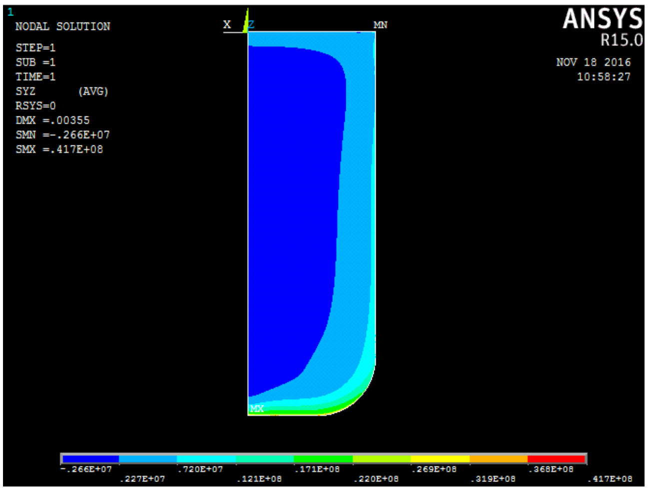
From the table it can be seen that adhesively bonded lifting lugs in Scenario 1 suffers the largest concentration shear stress among all scenarios. The base plate in Scenario 1 will suffer the most serious bending because there is no anti-bending structure; the simulations are same with the theories given in Hartshorn's (1986) book. Figure 5.8 uses Epoxy adhesive's joints' performance in Scenario 1 to show the situation of the lifting lug and the base plate. In Figure5.3.3 (a) the general deformation of the whole model is shown[2], the base plate suffers a large bending; the deformation in with is much larger than that in length which means the width of the base plate influences the stress more and in

[2] The deformation is zoomed by a scale factor of 4.65 for monitoring it clearly

the future the width of the base plate should be taken more concentration to be researched. Figure5.3.3 (b) gives the distribution of the shear stress in the bonding layer. In sum, the shear stress concentration is much larger than the adhesive's strength and the joints in Scenario 1 cannot be used.



(a)

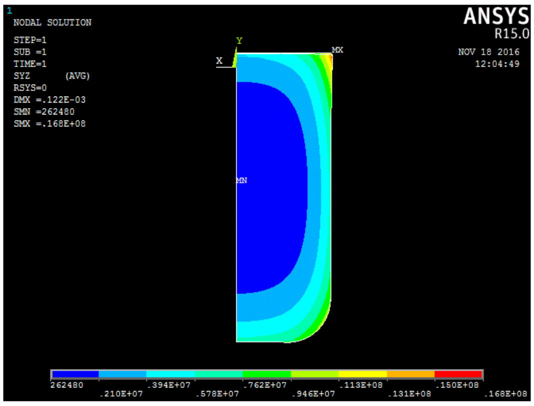


(b)

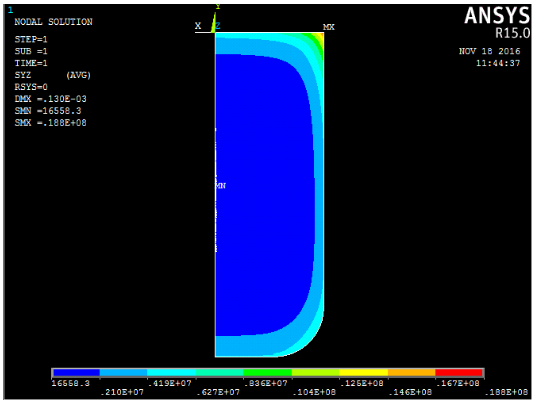
Figure 5.3.3 Results in Scenario 1

Results in Scenario 2 and Scenario 3 show smaller shear stress concentration compared with Scenario 1; and their shear stress concentration are similar and both of the maximum shear stress can be accepted by the requirements of the strength. Scenario 2 suffers a much larger normal stress; because the supporting structures in Scenario 2 provide fewer efforts against bending than those in Scenario 3.

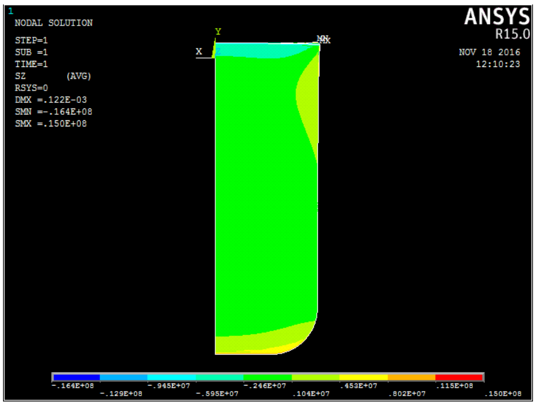
In the double lap joints' simulation, there will be no bending in the base plate; the shear stress concentration is a little larger than that in Scenario 3 which also suffers no bending in the base plate, but the area with concentration stress becomes smaller. Figure 5.3.4(a) and 5.3.4(b) show the distribution of shear stress in Scenario 3 and the Scenario of double lap. While the area that carrying loads in the double lap bonding layer is smaller than that in Scenario 3, because double lap joint separates the total load into two bonding layers.



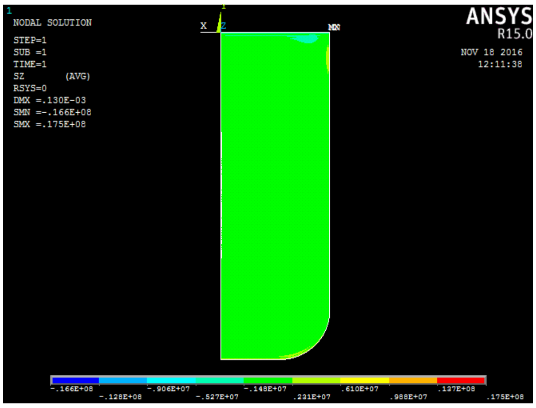
(a) Distribution of shear stress in Scenario 3



(b) Distribution of shear stress in a double lap scenario



(c) Distribution of normal stress in Scenario 3



(d)Distribution of normal stress in a double lap scenario

Figure 5.3.4 Distribution of stresses in Scenario 3 and double lap scenario

Figure 5.3.4(c) and 5.3.4(d) gives the distribution of the normal stress in the two scenarios. The values of the maximum normal stresses are similar, but the average normal stresses (stresses not in the concentration areas) are much different in the two scenarios; the value in the double lap layer is nearly half of that in Scenario 3 with single lap joint.

5.4 Summary

The adapted rules are evaluated in this chapter and sub question "**F. How to evaluate the feasibility of the application?**" can be answered. FEM models are built and simulated in software "ANSYS"; values and distribution of shear stress and normal stress in the bonding joints are read from the simulation results. The stress is compared with the selected adhesives' strength to check the feasibility.

From the FEM simulation results, It can conclude a rule for choosing fixing positions for lifting lugs with single lap joints: lifting lugs with single lap joints should be placed in positions that have supporting structures for defensing bending and they can never be placed in the interior area of a base plate without any support structures.

Then for the stresses, it can be seen that bending is the factor that will cause a sharp increase in stress concentration and areas that suffer stress concentration. Scenario 1, Scenario 2 and Scenario 3 can show that decreasing the bending deformation can contribute to decrease the stress concentration in both value and area. Shear stress can be decreased within allowable value in the area suffering stress concentration of shear stress; but the normal stress cannot fulfill the strength requirements. Therefore, the modification will be processed in the next chapter to make the normal stress concentration allowable. Because in Scenario 3, the bonding joint performs the best with stress concentration, so the focus of the modification will be put on Scenario 3 for single lap; and "Scenario for double lap" will be used continually for lifting lugs with double lap joint.

IV. Improvement and verification

The third research circle is shown in green in Figure 4.0.1. In the third research circle, the application of adhesively bonded lifting lugs based on adapted rules in “Part III” will be improved and the improved application will be verified.

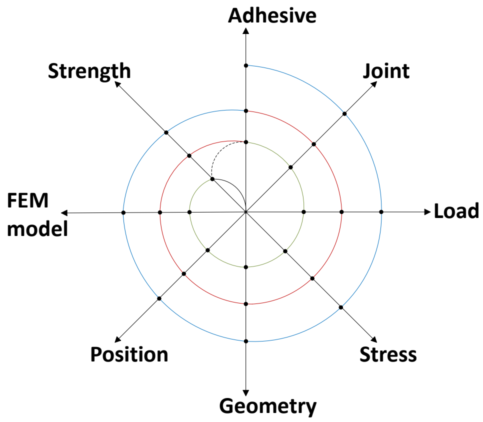


Figure 4.0.1 Design Spiral

After the researches in this part, sub questions “**C, D** and **E**” will be answered fully; the final answers to these sub questions can be given based on the results shown in FEM simulations.

6. Improving lifting lugs and verification of improvements

The FEM simulations in Chapter 5 show shear stress and normal stress in the bonding layers in different situations; and in most part of a bonding layer, stress can fulfill the requirements. But there is still area experiencing stress concentration with much larger stress which may cause failure in the bonding layer. Firstly, investigation of modifying “the shape and dimensions of the bonding layer” and “fixing methods” will be processed to decrease the stress concentration. Then performances of different adhesives are researched to discover the influences caused by different adhesives’ properties. Finally, there provides a feasible plan for bonded lifting lugs.

6.1 Adjusting bonding layer’s shape

First in this chapter, shape of the bonding layer will be analyzed. Shape such as the bonding area size, the thickness of the bonding layer and the fillet’s radius size are defined as critical factors that will influence the performance for resisting stress concentration. They will be verified in a serious of values in FEM models to monitor how they influence concentration stresses in the bonding layer; and the results are used for modifying the bonding layer. The Single lap simulation with "Scenario 3" is used for analyzing in this part, because Scenario1 and Scenario2 are proofed not suitable for adhesive bonding.

6.1.1 Influences of bonding area

Increasing the bonding area is the most direct way to decrease the average stress in the bonding layer; and according to the theoretical calculating formula $\tau_{max} = n \cdot \tau_{ave}$, it is also useful for decreasing concentration stresses.

To increase the bonding area, it can be achieved by increasing only the width or length of the bonding layer, or increasing both of them; and in this analysis, it will analyze the width or length separately. The new models will be increased with bonding area, in each model only the width or the length is going to be changed to increase the bonding area; Figure 6.1.1 shows what is changed in the bonding layer.

In Chapter 5, the results show that stress concentration appears in two parts in a bonding layer; one is the edge of the fillet in the bottom side, another is the corner in the top side. Figure 6.1.2 shows the areas with highlighted in red circles in a picture of the bonding layer in front view. So the monitored results from the simulations are maximum shear and normal stress in both the top corner and the filet in the bottom; the stresses are recorded separately and compared with the same results simulated in "Scenario 3"; epoxy adhesive "Epibond 100" is used for building the bonding layer. Table 6.1.1 gives the data.

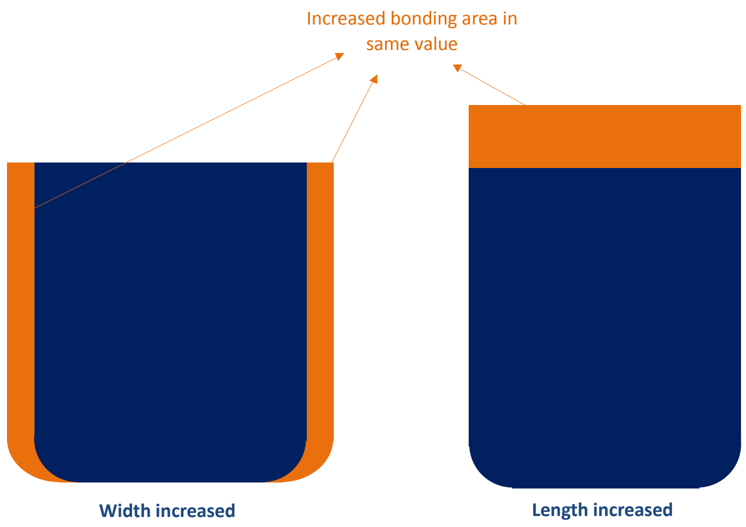


Figure 2.1.1 Different ways of increasing bonding area

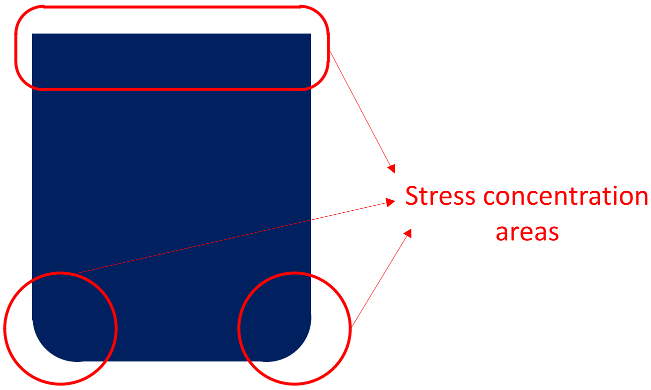


Figure 6.1.2 Bonding layer and its stress concentration areas

From the results shown in Table 6.1.1, by changing the size of the length to increase the bonding area is more efficient than changing the width to decrease “shear and normal stress concentration” in fillet area and “normal stress concentration” in the top corner area; but by only changing the length cannot decrease the shear stress in the top corner efficiently. The phenomenon is caused by the transfer of the force. When the force transferring from the top to the bottom, the area carrying load is a triangle, shown in Figure 6.1.3; the stress starts from a point and then spread to the two sides of the bonding layer. The angle between the vertical and the spreading direction should be30°; and the value of the angle can be predicted from the rules for lap welded lifting lugs, given in Figure 2.1.4, chapter 2. So increasing the width makes the bonding area carry more loads in the top area.

Another thing should be taken care is that only the shear stress concentration can be controlled in the range of the strength requirements by increasing the bonding area; the normal stress concentration is still much larger than the requirements. Therefore, new methods need to be found out to control the normal stress.

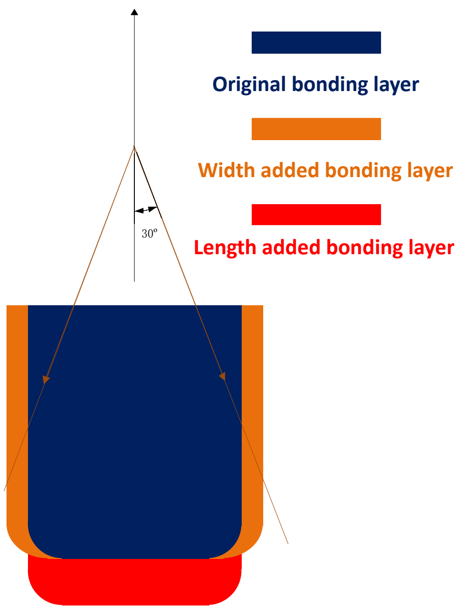


Figure 6.1.3 Load transferring in the bonding layer

Table 6.1.1 Changed parameters and stresses

	Increased bonding area	10000mm^2		20000mm^2		Original results	
Increasing width	Size value(mm)	250×330		280×330		220×330	
	Shear stress(mpa)	Fillet	Top corner	Fillet	Top corner	Fillet	Top corner
		10.5	15.5	9.9	14.5	11.1	16.8
	Normal stress (mpa)	Fillet	Top corner	Fillet	Top corner	Fillet	Top corner
		12.3	14.3	11.6	13.8	13.1	15
Increasing length	Size value(mm)	220×375		220×420		220×330	
	Shear stress(mpa)	Fillet	Top corner	Fillet	Top corner	Fillet	Top corner
		10.2	16.3	9.41	16	11.1	16.8
	Normal stress (mpa)	Fillet	Top corner	Fillet	Top corner	Fillet	Top corner
		12.1	14	11.1	13.5	13.1	15

6.1.2 Thickness influences

The bonding layer's thickness has been discussed in some literatures; but the literatures show different opinions about it. In a theoretical research processed by *PK Shaoo (2006)* using FEM analysis, the thickness of the layer is set as 0.0126 inch [43] (0.32004mm); while in another research of a real application simulation processed by *Yang (2011)*, the thickness of the bonding layer is set from 2mm to 4mm [44]. There is a big difference between the two analyses for the bonding layer's thickness, and it is hard to judge which one can help the analysis of this thesis. So for this research, the appropriate value of bonding layer's thickness is given by processing a serious of FEM simulations.

The thickness analysis in this part will use the model of a lifting lug with single lap joint with boundary conditions in "scenario 3" as the basic model and epoxy adhesive "Epibond 100" will be used for building the bonding layer. New simulations with different bonding layer's thickness are processed and the thickness is set as 0.5mm, 2mm, 3mm and 4mm in new FEM models. Maximum shear stress and normal stress in the concentration areas (shown in Figure 6.1.2) are monitored.

After processing the simulation, results in FEM models with different thickness of bonding layers are listed and compared in table 6.1.2.

Table 6.1.2 stresses in bonding layer with different thickness

Stress / Thickness	Shear concentration (MPa)		Normal concentration (MPa)	
	Top corner	Fillet	Top corner	Fillet
0.5mm	26.7	14.8	12.8	14.2
1mm	16.8	11.1	15	13.1
2mm	11.3	8.44	13.0	13.2
3mm	8.86	7.24	11.6	12.9
4mm	7.58	6.54	10.8	12.6

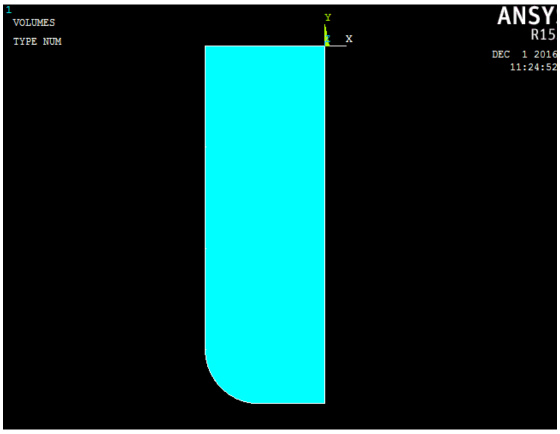
From the table, it can be seen that the shear stress concentration decreases with the increasing of the thickness; while after 2mm thickness; the changes in shear stress become smaller, both in the fillet and the top corner. The normal stress starts to decrease from thickness of 1mm in the top corner and 2mm in the fillet; but it doesn’t change a lot with the thickness increasing after 2mm. Though bonding layer with 0.5mm thickness can decrease normal stress concentration but the shear stress concentration is enlarged several times comparing with bonding layers of other thickness.

With the increasing of bonding layers’ thickness the difficulty for producing perfect bonding layer is increased, air bladders may exist with larger probability. After 2mm thickness, the shear stress concentration fulfills the strength requirement and doesn’t change a lot; so 2mm for the bonding layer thickness is used in the modification. But the normal stress concentration still cannot be solved by increase thickness; researches need to be continued.

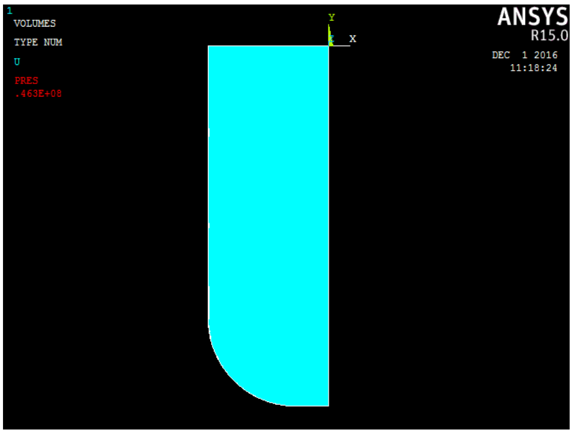
6.1.3 Fillet radius’ influences

Fillets are used to eliminate corners in structures for decreasing stress concentration; and they are also used in the thesis for eliminating stress concentration in the bonding layer. The radius of the fillets becomes a critical factor for decreasing the stress concentration and several simulations are processed to monitor changes in fillets with different radius.

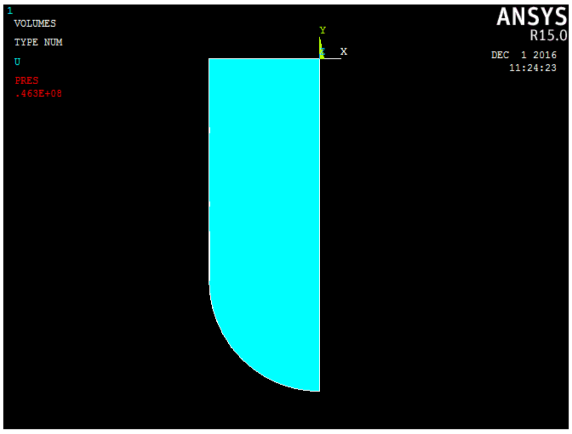
In the former research, the fillet radius was set as 5cm and simulation results have been got. And the new simulation model will increase the radius to 8cm, monitoring the stressed around the fillet; and then another new model will be built with a semi-circle bottom line to stand for the maximum fillet radius can be, stresses are monitored in the bottom line. All the models will set the bonding layer thickness at 2mm. Figure 6.1.4 shows the different bonding layers in front view. There is one thing should be noticed, the larger the radius, the more area will be decreased from the whole bonding area. In table 6.1.4 the bonding decreased area is listed with the changing of stresses.



(a) Bonding layer with 5cm fillet



(b) Bonding layer with 8cm fillet



(c) Bonding layer with circle bottom line with 11cm radius

Figure 6.1.4 Bonding layers with different fillet radius

Table 6.1.3 stresses and decreased bonding area in models with different fillet radius

	Shear concentration stress (mpa)	Normal concentration stress (mpa)	Area decreased(mm^2) Comparing with 50mm
50mm	8.44	13.2	-
80mm	8.12	11.4	838.5
110mm(semi-circle)	8.02	11.7	2064

The data in Table 6.1.3 shows that increasing the fillet radius can decrease shear stress concentration in small extend; while the normal stress decreasing ratio is a little higher, and a semi-circle bottom line cannot decrease the normal stress concentration efficiently, it is caused by the large decreased bonding area. So increasing the fillet radius can be defined as an inefficient method to decrease stress concentration for the optimization, and change the whole bottom line of the bonding layer to a semi-circle is not advised for the modification.

In sum, to decrease the stress concentration by arranging the shape of bonding layer: the bonding area should be increased by increasing both the width and length; the bonding layer’s thickness should be arranged to an appropriate value (that depends on the specific requirement and production process); radius of fillet in the bottom corner should be big enough to resist stress concentration.

6.2 Arrange position

Except the shape and dimensions of the bonding layer, the bonding position (the places for bonding on potential position) also influences stress concentration in the bonding layer. The top corner is the most severe part experiences stress concentration in the bonding layer and by adjusting the bonding layer’s shape it is hard to decrease the stress concentration under the strength requirement; because the top corner locates in the area where sudden change in shape happens. Different with the bottom corner which can be transferred in fillet to eliminate stress concentration; the shape of the bonding layer and the lifting lug in the top corner cannot be changed. So changing the bonding position to make the bonding layer avoid to be positioned at the edge is a method for eliminating stress concentration in the top corner.

Then the new modified plan can be given and Figure 6.2.1 shows it briefly. Firstly, the bonding layer’s position on the base plate is moved, the top edge of the bonding layer is lower than the top edge of the base plate; therefore the sudden change in the top edge can be avoided. Secondly, the bonding layer’s position in the lower part of the lifting lug is also changed; it is moved to the middle area of the lower part of the lifting lug so the sudden change caused by other edges are avoided. Lastly, the top corners of the bonding layer are transferred into fillets to eliminate stress concentration.

In this plan, a modification of the lifting lug is added to help solve bending problem. Figure 6.2.2 shows the plan in zoom. For single lap joint, when the load is added on the lifting lug, because there is a distance between the load and the bonding area, a bending moment “$M_{bending}$” is provided and the lifting lug is bent. So in the new plan, a metal gasket is added in the new created gap between the base plate and the lifting lug to decrease the influence of bending. The gasket is fixed on the lifting lug by welding or other method but not fixed with the base plate.

Then FEM model for the new single lap lifting lug is built and the exact shape and dimensions are given in Figure 6.2.3. The new FEM model will also be simplified into a symmetry model and its boundary condition of the base plate is the same with “Scenario 3”; Figure 6.2.4 shows the FEM model.

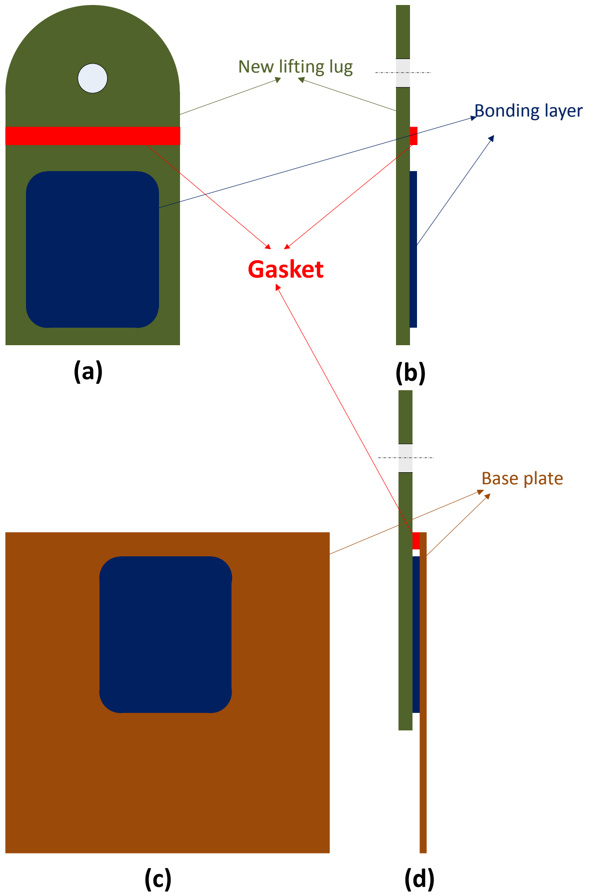


Figure 6.2.1 Modified lifting lugs installation plan

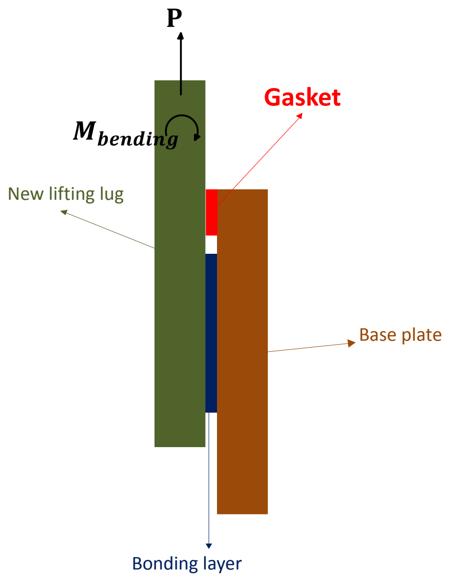


Figure 6.2.2

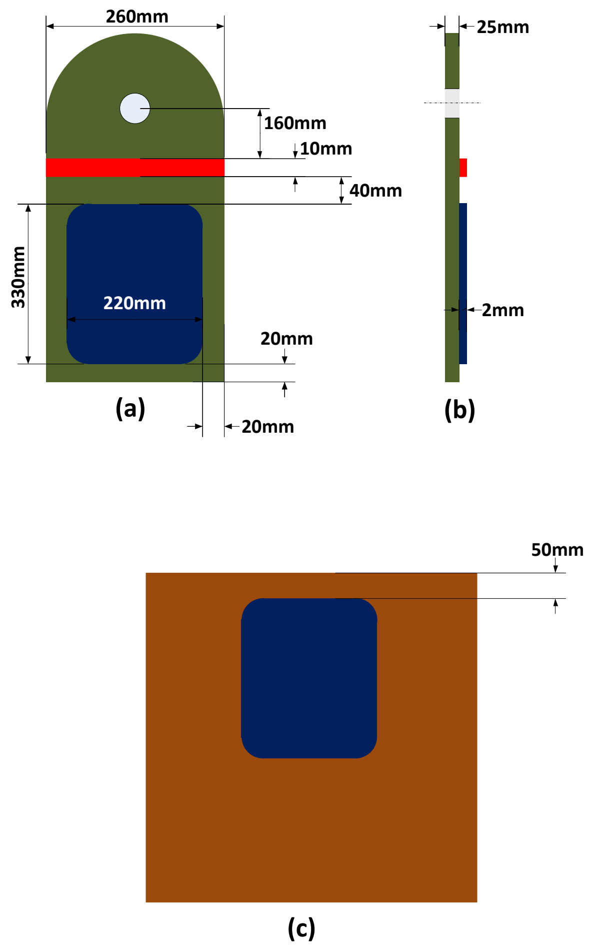


Figure 6.2.3 New single lap lifting lug with shape

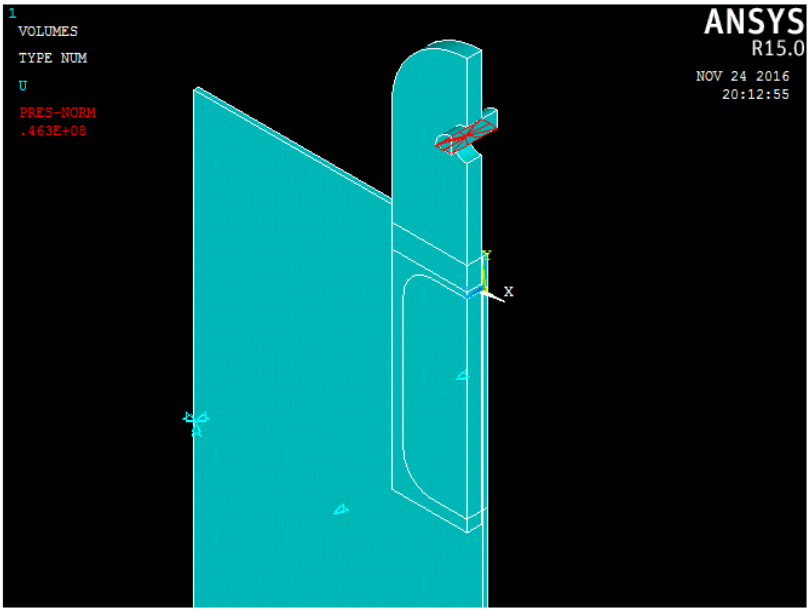
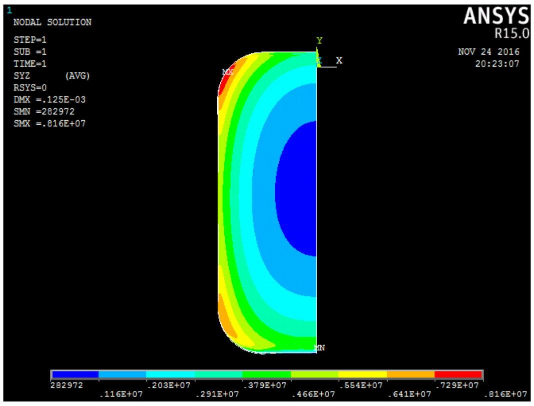
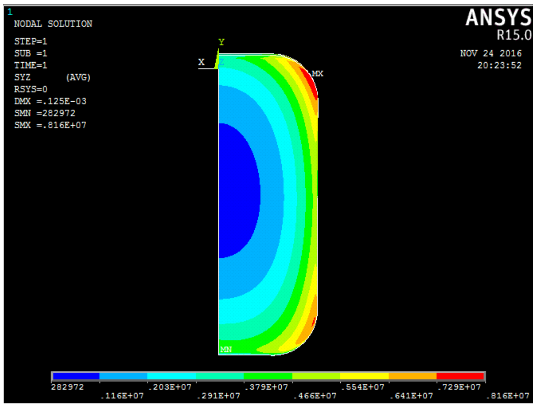


Figure 6.2.4 FEM model in ANSYS

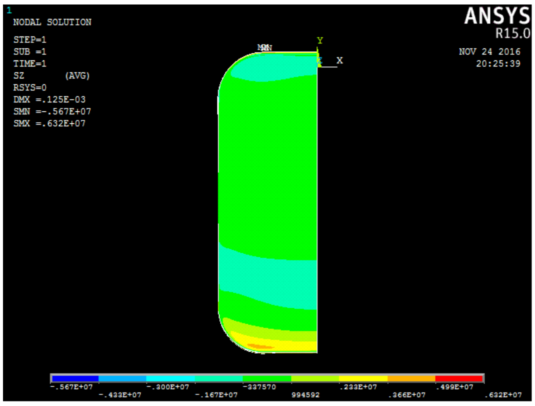
Then the simulation is processed. The distribution of stresses is shown in Figure 6.2.5 and the exact value is shown in table 6.2.1.



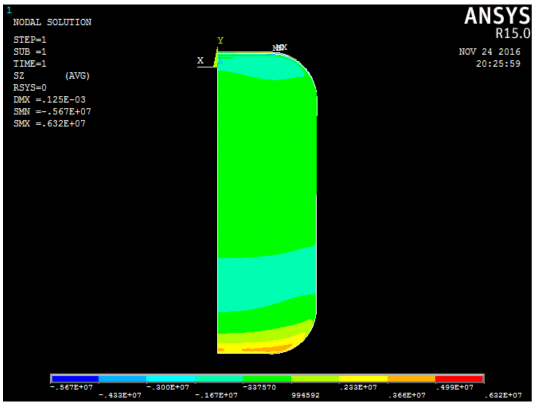
(a) Shear stress distribution in front side



(b) Shear stress distribution in back side



(c) Normal stress distribution in front side



(d) Normal stress distribution in back side

Figure 6.2.5 stresses distribution in the bonding layer

From the distribution of stresses in the bonding layer shown in Figure 6.2.5 (a) and (b), the shear stress concentration locates in the top and bottom fillets; and the value of the stress listed in Table 6.2.1 indicates that they are all less than 9 Mpa which is less than the applied shear strength of 17Mpa. Figure 6.2.5 (c) and (d) gives the normal stress distribution in the bonding layer, it can be seen that the normal stress in most of the area is in low value and in the bottom fillet there appears stress concentration. When zooming in the top fillet, it can be seen that there still exists stress concentration in the edge of the bonding layer, shown in Figure 6.2.6. The maximum value of normal stress concentration is under the applied normal strength. So it can be concluded that the new plan for single lap lifting lugs can decrease the stress concentration and control the maximum stresses under the strength requirements.

Table 6.2.1 stresses in the bonding layer of a single lap lifting lug

	Shear stress (mpa)	Normal stress (mpa)
Top fillet	8.16	6.32
Bottom fillet	7.34	5.16

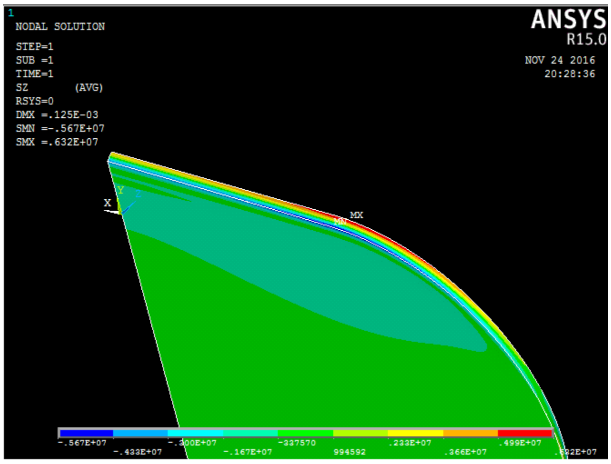


Figure 6.2.6 zooming in view of the stress distribution

The thought for modifying single lap joints is also helpful for the optimization for double lap lifting lugs. In the new plan for a double lap lifting lug, the bonding area is also moved both in the lifting lug and the base plate same as what is done in a single lap lifting lug; because bending does not influence double lap joint, the gasket is canceled. The brief view of a modified double lap lifting lug is shown in Figure 6.2.7 with shape.

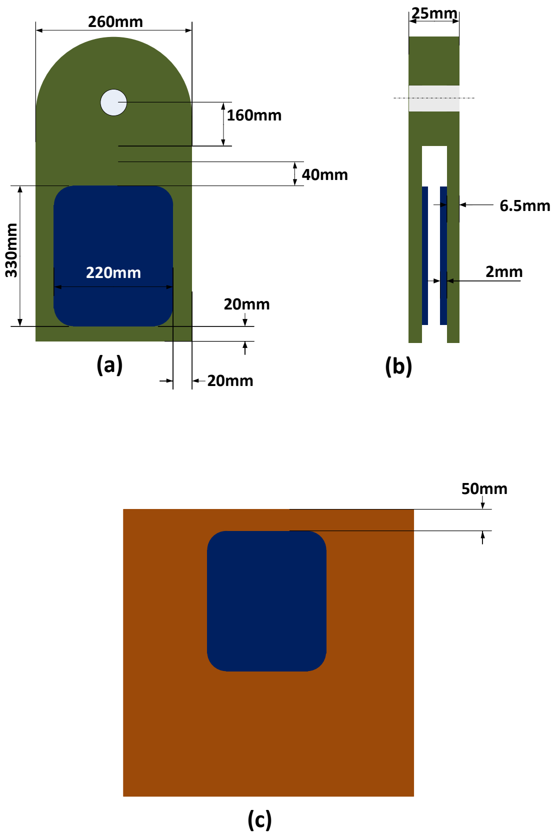
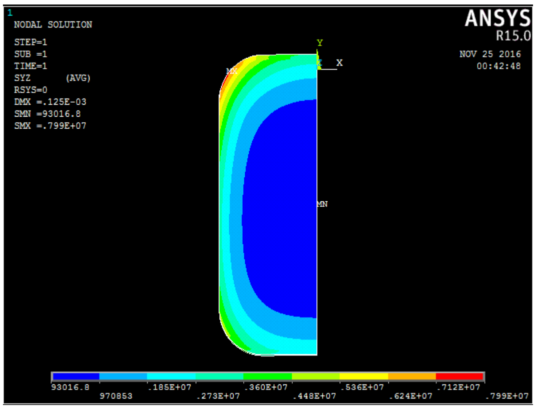
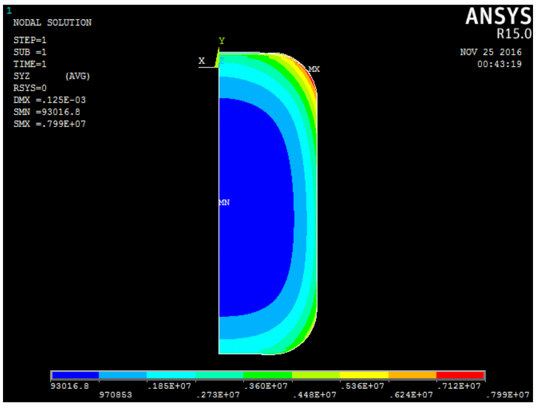


Figure 6.2.7 New double lap lifting lug with shape

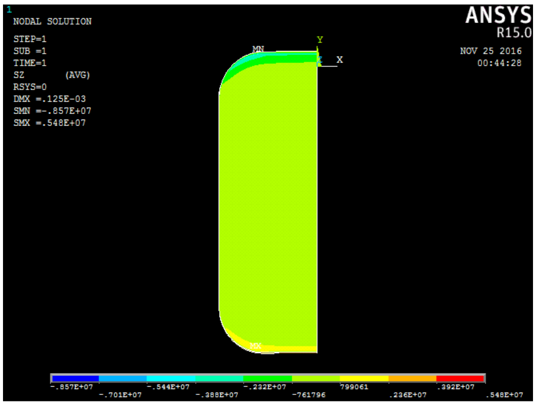
Then simulation is processed to see the results. The stress distribution is shown in Figure 6.2.8; and the stress values are shown in Table 6.2.2. The shear stress distribution in the bonding layer is similar with that in single lap joint; but the stress concentration area become smaller as well as the maximum value. The normal stress concentration appears around the top and bottom fillet. Comparing with the single lap, the stress concentration area around top fillet increases in area value but decreases in stress value; while the normal stress around the bottom fillet decreases in both area and stress value. All stresses are controlled under the applied strength so the new plan of double lap fulfills the strength requirement.



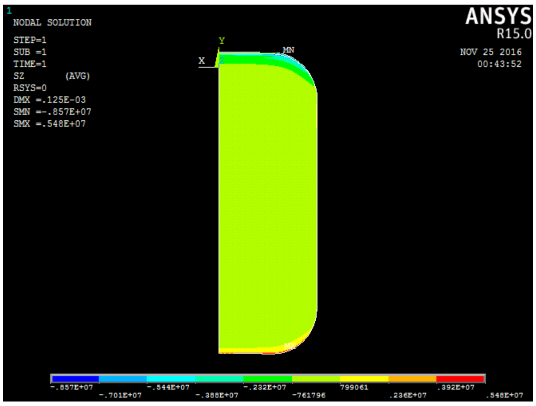
(a) Shear stress distribution in front side



(b) Shear stress distribution in back side



(c) Normal stress distribution in front side



(d) Normal stress distribution in front side

Figure 6.2.8 stresses distribution in the bonding layer of a double lap lifting lug

Table 6.2.2 stresses in one of the bonding layer of a double lap lifting lug

	Shear stress (mpa)	Normal stress (mpa)
Top fillet	7.99	4.86
Bottom fillet	5.37	5.48

From now on, lifting lugs using epoxy adhesive “Epibond 100” are modified to fulfill the strength requirements and another selected adhesive’s performance needs to be tested. So in the next part, adhesives with different properties are discussed with their performance.

6.3 Adhesive properties

According to the research in Chapter 5, the performances of the two selected adhesives are different in the same bonding joint, see Table 5.2. The acrylic adhesive make the maximum stress value less than the epoxy adhesive in the bonding joint; the young's modulus and the Poisson's ratio may be the reasons for this phenomenon. Therefore, the influences caused by these two factors (young's modulus and the Poisson's ratio) are going to be analyzed in this part. Then some advises for selecting adhesives are concluded.

6.3.1 Simulations for different young's modulus and Poisson's ratio

In the results provided in table 5.2, with FEM models in same shape and boundary conditions, the acrylic adhesive bonding layer has stresses in smaller value than the epoxy adhesive layer. The main differences between the two adhesives are their strength, young's modulus and Poisson's ratio; and the young's modulus and Poisson's ratio may be critical factors that influence stresses in the bonding layer. But there is one thing should be taken care, the bonding joints is carrying load in the shear direction, so the shear modulus must be considered. The shear modulus is a value relates to the young's modulus and Poisson's ratio; and formula (6.3.1) gives the relation. So a calculation form between the two adhesives' properties can be given in table 6.3.1. These properties show the factor (or factors) influences the stress value in the bonding joint.

$$G = \frac{E}{2(1+\nu)} \tag{6.3.1}$$

Table 6.3.1 properties of selected adhesives

	Young's modulus	Poisson's ratio	Shear modulus
EP	2178.7 mpa	0.22	892.9 mpa
AC	1301.5 mpa	0.3	500.6 mpa

The epoxy adhesive has higher Young's modulus and Poisson's ration than the acrylic adhesive; so the shear modulus is also higher. But only the two selected adhesives cannot show all the influence caused by adhesive's properties; it needs 4 comparisons to see the of the adhesive's properties influences.

1. Adhesives with same Poisson's ratio and different Young's modulus, and adhesive "A1" is supposed.
2. Adhesives with same Young's modulus and different Poisson's ratio, and adhesive "A2" is supposed.
3. Adhesives with same shear modulus and different in Young's modulus and different

Poisson's ratio, and adhesive "A3" is supposed.

4. Adhesives with different shear modulus, Young's modulus and different Poisson's ratio, the two selected adhesives can do this test.

If epoxy adhesive "Epibond 100" is selected as the basic specimen in the comparison tests and other specimens' properties are set based on the "Epibond 100". The first comparison test is about different Young's modulus, the comparison is between "Epibond 100" and a supposed adhesive named as "A1"; "A1" has the same Poisson's ratio but different Young's modulus with the epoxy adhesive. The second comparison test is about different Poisson's ratio and the comparison is between "Epibond 100" and a supposed adhesive named as "A2"; "A2" has the same Young's modulus but different Poisson's ratio with the epoxy. In the third comparison test, the comparison is between "Epibond 100" and a supposed adhesive named as "A3"; "A3" has the same shear modulus with the epoxy adhesive; the Young's modulus and Poisson's ratio are both increased. At last the fourth comparison test is about different young's modulus and Poisson's ratio which can use the selected epoxy adhesive and acrylic adhesive as the two specimens. All the properties of the supposed adhesives are listed in Table 6.3.2.

Table 6.3.2 properties of supposed adhesives

A1	1301.5 mpa	0.22	533.4
A2	2178.7 mpa	0.44	756.5 mpa
A3	2571.5 mpa	0.44	892.9 mpa

6.3.2 Results analyzing

The new simulation models will use the same with Scenario 3 in shape and boundary conditions, but different in property setting of bonding layers. Then new simulations are processed and results are collected. To simulation results and the stresses used for comparison, only the maximum stresses in the fillet area are concerned; the stresses in the corner are neglected because the corner is changed into fillet in the new plan given in 6.2. Figure 6.3.1 shows which area in the bonding layer is concerned with pointing in red circle; and Table 6.3.3 lists the exact values of shear and normal stresses for both the selected adhesive and the supposed adhesives.

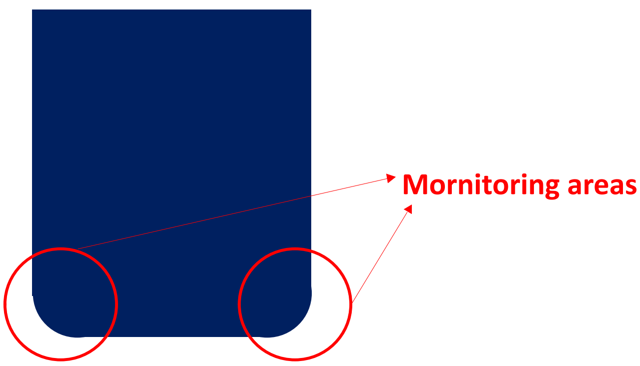


Figure 6.3.1 monitoring areas

T6.3.3 stresses in the comparison models

I.

	Normal stress (MPA)	Shear stress (MPA)
EP	13.1	11.1
A1	10.2	8.78

II.

	Normal stress (MPA)	Shear stress (MPA)
EP	13.1	11.1
A2	13.1	12.4

III.

	Normal stress (MPA)	Shear stress (MPA)
EP	13.1	11.1
A3	14.2	13.3

IV.

	Normal stress (MPA)	Shear stress (MPA)
EP	13.1	11.1
AC	10.1	8.87

From the results of the first two comparison tests (see Table 6.3.3-I and 6.3.3-II), it can be concluded that: high value of Young's modulus will increase the normal stress; while Poisson's ration do not influence the normal stress, it will decrease the shear modulus as well as the maximum shear stress. Then in the fourth comparison (Table 6.3.3-IV), the results show that high modulus will cause high stress to both normal and shear. In the second comparison test (Table 6.3.3-II), the two specimens have the same shear modulus but different in the results in shear stress; the supposed adhesive with higher Young's modulus experiences higher normal and shear stress than the selected epoxy adhesive. So the young's modulus should be the main factor which influence the maximum stresses in the bonding joint.

It can be concluded that maximum stress in both shear and normal directions is decreased by decreasing the young's modulus and shear modulus, but young's modulus is the main factor that influences the maximum stresses.

While, small value of modulus causes large strain in the bonding layer which causes failure to the bonding joint. In the report provided by U.S. Department of Transportation (2002), it gives Figures of some structural adhesives' stress-strain curves; which shows the adhesives can only keep their ideal modulus in small strain and after a specific point their modulus decreases obviously. Figure 6.3.2 gives a curve of a kind of structural adhesive from the report.

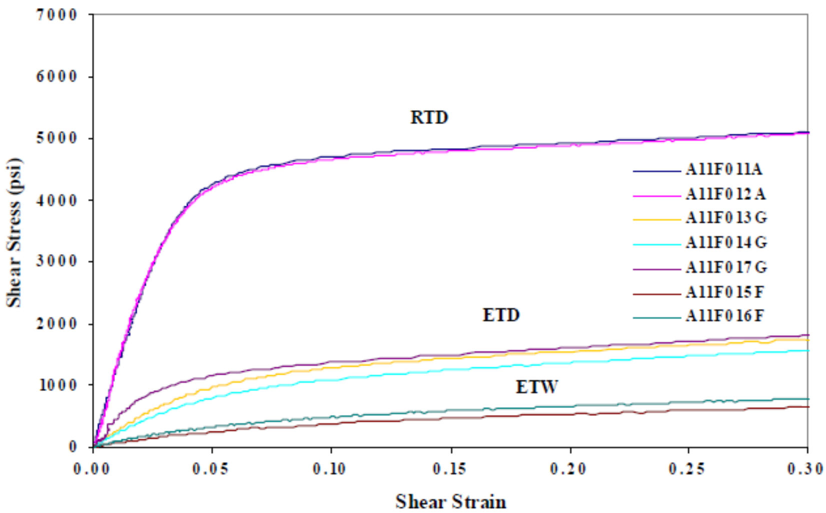


Figure 6.3.2 shear stress and strain curves [45]

So the properties of failure in the bonding layer are increased. So when selecting adhesives, the Young's modulus should be considered to control the strain in the range which the adhesive can perform its ideal properties.

6.4 Improvement summary

After analysis and modification in the former part, a brief summary for them will be given in this part.

Firstly, the bonding joints will be talked. For applying adhesively bonded lifting lugs, it should use lifting lugs with double lap joints as possible as it can. It is hard to say whether single lap joint or double lap joint lifting lugs are better for the application in ship building. They both have requirements of the fixing structures: single lap lifting lugs need base plate with supporting structures that can resist bending; while double lap lifting lugs need the base plate has two available surfaces. However, if the fixing structures can fulfill the requirements, both the two kinds of lifting lugs can be used in theory.

Secondly, the modification plans are given. Applied thickness of the bonding layer is set at 2mm and all the corners of a rectangle bonding layer are changed into fillets. Then the lifting lugs shape are increased to make the bonding layer can be moved in the middle range of it to avoid sudden change in shape; the bonding layer's position on the base plate is also moved to avoid sudden change in shape and a gasket is added in the gap between the lifting lug and base plate to resist bending.

Thirdly, properties of adhesives are discussed to give some advises for selecting appropriate glues. Young's modulus will be the main critical factor influence stress concentration in the bonding layer; small modulus produces small stress concentration but large strain. And in the application of adhesives, the strain should be controlled in the range which the adhesives can show their best properties. So in the selection of adhesives, the first thing is to choose one with high strength in both shear and normal;

then coordinate the stresses and strain with appropriate modulus and Poisson's ratio.

At last the performances of the two selected adhesives in the modified single lap and double lap lifting lugs are listed in the Table 6.4.1 and strength of selected adhesives is shown in Table 6.4.2. Because the results in the models provided in 6.2 can fulfill the requirements, the final models will continue using the same shape provided in Figure 6.2.3 and 6.2.7. Strain in the bonding layer is added in the table as well.

Table 6.4.1 Results in the modified lifting lugs for lifting process

		Epibond 100	DP8410NS Green
Shear stress	Top fillet (mpa)	8.16	6.06
	Bottom fillet (mpa)	7.34	5.86
Normal stress	Top fillet(mpa)	6.32	2.18
	Bottom fillet (mpa)	5.16	5.22
Strain	Shear	3.75E-4	3.94E-4
	Normal	2.28E-3	2.87E-3

(a) Single lap lifting lug

		Epibond 100	DP8410NS Green
Shear stress	Top fillet (mpa)	7.99	6.08
	Bottom fillet (mpa)	5.37	4.11
Normal stress	Top fillet(mpa)	4.86	3.77
	Bottom fillet (mpa)	5.48	4.2
Strain	Shear	3.8E-4	3.9E-4
	Normal	2E-3	2.3E-3

(b) Double lap lifting lug

Table 6.4.2 Strength of selected adhesives

Adhesive name	Category	Shear strength	Normal strength
Epibond 100	Epoxy	34.5 mpa	13 mpa
DP8410	Acrylic	24.6 mpa	9.3 mpa

From the results given in 6.1 to 6.3, it can be predicted that lifting lugs with capacity from 20ton to 30ton can be applied with adhesive bonding joints; the bonding layer should have large enough bonding area, appropriate shape and be built with appropriate adhesive. The improvement of the bonding layer should be researched in further research.

6.5 Summary

To sum up the results in this part, the application of adhesively bonded lifting lugs based on the adapted rules is improved and results shows the improved plans for application are feasible for applying. Sub question "**C**, **D** and **E**" are fully answered.

C. How to define the shape and geometrical attribute of lifting lugs?

The final plans of the shape and geometry of adhesively bonded lifting lugs are given in 6.2 in this chapter; examples are used to shown the feasibility.

D. What is the state of stress of the bonding joint with load?

The values of stress in the bonding joints in improved plans are shown in Table 6.4.1 and the distribution of the stress is shown in Figure 6.2.5 and Figure 6.2.8.

E. Where is the optimal position for installing lifting lugs?

The positions for installation should be kept the same with that concluded in “Part III”; but the bonding layer is moved to the interior area on both the base plate and the lifting lugs to avoid sudden change of shape and stress concentration.

V. Turning analysis

7. Lifting lugs in turning

Turning work in the production process is another important task of lifting lugs except lifting work; in this chapter the analysis of turning will be researched. The steps of researching lifting lugs' performance in turning work is similar with those in lifting work; and the analysis steps will be more simplified because some main analysis about adhesives and lifting lugs have been discussed in the former part.

The analysis starts with introducing some rules used for welded lifting lugs and then load analysis in the turning work will be given. Secondly, advice for selecting potential positions suitable for fixing lifting lugs in the turning work will be given after the discussion. Thirdly, stresses in the bonding joints are going to be calculated; dimensions and shape for the new lifting lugs will be defined. At last, FEM simulation will be processed to see stress concentration and distribution; after the modification work it will give a conclusion whether the bonded lifting lugs can be used for turning work.

In this part, the sub problem "**G**" about "turning work" will be answered.

7.1 Load analysis for turning

Different form lifting work, the load acts on the lifting lug in the turning work keeps changing during the process. In the rules of welded lifting lugs, the load calculation method in the initial state is given firstly; it is the same with the calculation method in the lifting work, Figure 7.1.1 shows the initial state of an example used in the welded lifting lugs' rules; and formula 7.1.1 and 7.1.2 give the method for calculating loads.

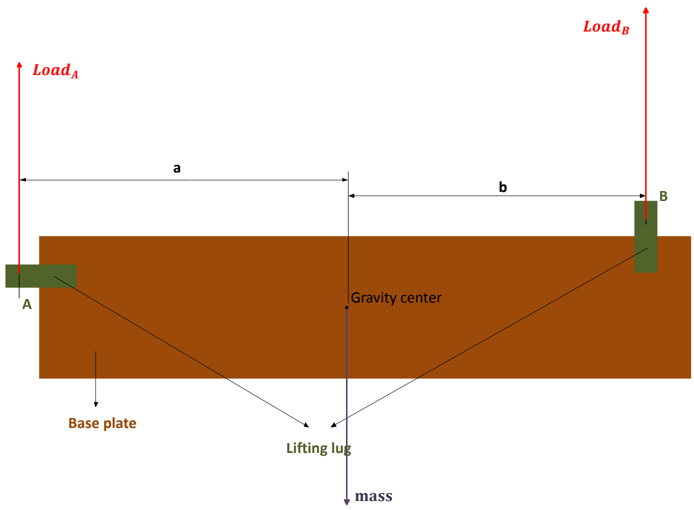


Figure 7.1.1 Initial state of a section in turning process

$$Load_A = \frac{b}{a+b} mass \tag{7.1.1}$$

$$Load_B = \frac{a}{a+b} mass \tag{7.1.2}$$

Then the rules show the state when the optimal load acts on a lifting lug; the state will happen when the direction of the load moves and coincides with the line of the gravity of the section. Figure 7.1.2 shows the state using the same example shown in Figure 7.1.1; in this situation, the whole load is concentrated on the lifting lugs on the top. In the former part, the optimal load a bonded lifting lug can carry is defined as 20ton, therefore, if a section uses four lifting lugs in the production process and only two of them will carry load in the situation shown in Figure 7.1.2. As a result of that, the optimal maximum mass of a section adhesively bonded lifting lugs can carry is limited as 40ton in theory; much less than 80ton, the theoretical optimal maximum load for lifting.

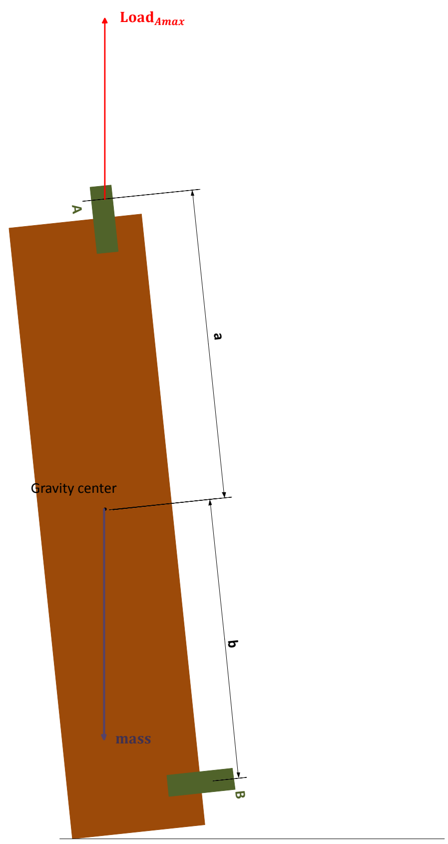


Figure 7.1.2 The state lifting lug A hold the whole section's mass

From Figure 7.1.2, it can be seen that the state the maximum load appears on the top two lifting lugs are influenced by some factors of the section, the gravity center and position of the lifting lugs; Figure 7.1.3 gives the shape of these factors.

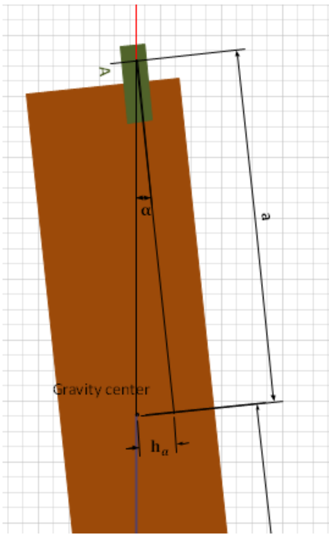


Figure 7.1.3 Shape of factors

So the angle when maximum load appears is related to the length and height between the lifting lug and the gravity center; and the formula to calculate the angle is given below.

$$\tan\alpha = \frac{a}{h_a} \qquad (7.1.3)$$

For finding a suitable value of α, some supposed situations are given; and the calculation and discussion of the stresses is given in 7.3.

However, the rules for welded lifting lugs don’t give how the load on each lifting lug changes from the initial state to the maximum load appears on the top lifting lugs; but changes should be noticed. Figure 7.1.4 shows a section and related shape in a state during the turning process and calculation formulas are given from 7.1.4 to 7.1.7.

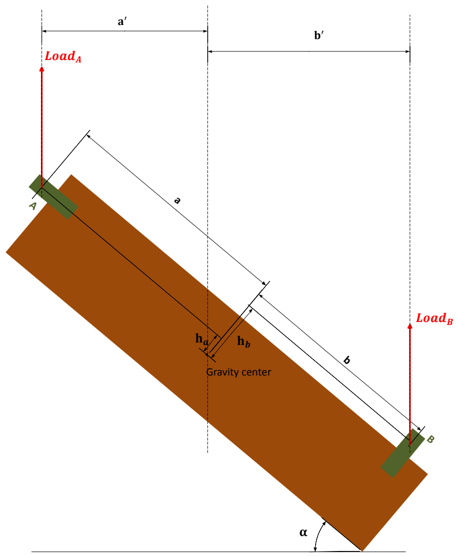


Figure 7.1.4 A state during the turning process

$$a' = a\cos\alpha - h_a \sin\alpha \tag{7.1.4}$$

$$b' = b\cos\alpha + h_b \sin\alpha \tag{7.1.5}$$

$$Load_A = \frac{b'}{a'+b'} = \frac{b\cos\alpha + h_b\sin\alpha}{(a+b)\cos\alpha + (h_b - h_a)\sin\alpha} \times \frac{mass}{2} \tag{7.1.6}$$

$$Load_B = \frac{a'}{a'+b'} = \frac{a\cos\alpha - h_a\sin\alpha}{(a+b)\cos\alpha + (h_b - h_a)\sin\alpha} \times \frac{mass}{2} \tag{7.1.7}$$

The value of the load a lifting lug carries in the initial state relates to the position of the gravity center, but the exact value is influenced by shape of a specific model; the only thing that can be determined is that the maximum load is not beyond 20 ton for a bonded lifting lug. For adhesively bonded lifting lugs, the whole mass should be separated on each lifting lug averagely to avoid the load concentrating on one or some of them; so in the calculation below, the gravity center of section is set in the middle of the section. Then in the initial state, the load on each lifting lug is 10ton.

7.2 Position selection

For selecting position for adhesively bonded lifting lugs in turning process, it is similar with that in the lifting process. Firstly, structures with potential positions are selected, and then they are judged which kind of bonding joint they are suitable for. In the former parts, the requirements were given in 6.4, chapter 6. While, in the turning process there are some differences for selecting fixing positions.

In the initial state during the turning process, lifting lugs cannot be all fixed in one surface; they need to be fixed in three surfaces on a section. There should be three lifting lugs installed on the section in three different surfaces; in the first stage for turning, the section is turned from the initial state by hoisting lifting lug A; when the direction of the load acts on A coincides with the gravity line of the section, lifting lug A will carry the whole mass and lifting B starts contributing nothing to the turning. Then in the second stage, a cable is linked with lifting lug in the opposite surface with Lifting lug B and the section continues turning until it is turned 180 degrees. If the lifting lugs are still distributed in same type with the lifting process, the second stage cannot be processed.

So in turning process, the selection for fixing positions should obey the rules given in Chapter 4 firstly; and then they should be positioned in three different surfaces on the section.

7.3 Stress calculation and shape definition

7.3.1 Stress calculation and joints design

The change of load acts on lifting lugs causes change of the stresses produced in the bonding layer during the turning process. And in the whole process, the load acts on the lifting lug changes in two states; one is the initiate state shown in Figure 7.1.1 and another is the state during turning, shown in Figure 7.1.4.

In the state during turning, the load on lifting lug A keeps increasing and load on lifting lug B keeps decreasing; so lifting lug A will be the critical lifting lug of the analysis and the following research focuses on lifting lug A. From Figure 7.1.4, the load on lifting lug A can be separated into two directions, one is perpendicular to the lifting lug and the other is in the axis line of the lifting lug; the perpendicular will produce a moment and the other one produces shear stress in the axis direction.

To define the shape and calculate the theoretical stresses, it starts with the initial state. In the initiate state, the load is perpendicular to the lifting lug and a moment is provided; while in the bonding joint there will appear a torque to defense the moment. Figure 7.3.1 shows a lifting lug in the initial state with shape.

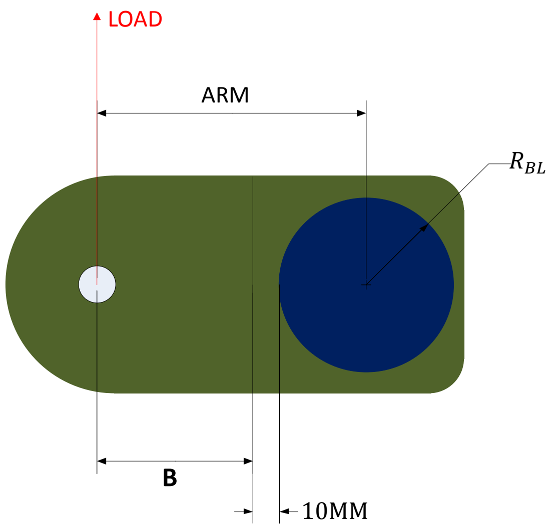


Figure 7.3.1 A lifting lug in the initial state with shape

The bonding layer is designed as a circle which is the best shape to defense torque and it is arranged in the middle part of the lifting to avoid sudden change in shape in the edge; 10mm is set from the edge of the bonding layer to the edge of the base plate. The bonding layer's radius is R_{BL} and the distance between the center of the lifting eye and the center of the bonding layer is defined as the arm.

So the torque in the section cross section of the bonding layer is:

$$\text{Torque} = \text{Load} \times \text{Arm} = \text{Load} \times (\text{B} + R_{BL} + 10\text{mm}) \qquad (7.3.1)$$

The "polar moment of inertiaI_p" of the bonding layer is:

$$I_p = \frac{\pi}{2} {R_{BL}}^4 \tag{7.3.2}$$

The maximum shear stress appears in the edge of the bonding layer which is:

$$\tau_T = \frac{Torque \times R_{BL}}{I_p} = \frac{\mathrm{Load} \times (\mathrm{B} + R_{BL} + 10\mathrm{mm})}{\frac{\pi}{2} {R_{BL}}^3} \tag{7.3.3}$$

Then an example is shown to discuss how to define the radius of the bonding layer in the initial state; and this example is named "example 3". In example 3, a 40ton section is given; the shape of the section is similar to a cuboid. In the cross section fixing with lifting lugs of the section, the distance between two lifting lugs is 10m and the height is 1.6m and it is supposed that the distances between the gravity center to the two lifting lugs are equal and the gravity center is in the middle of the height. Figure 7.3.2 shows a brief view of it.

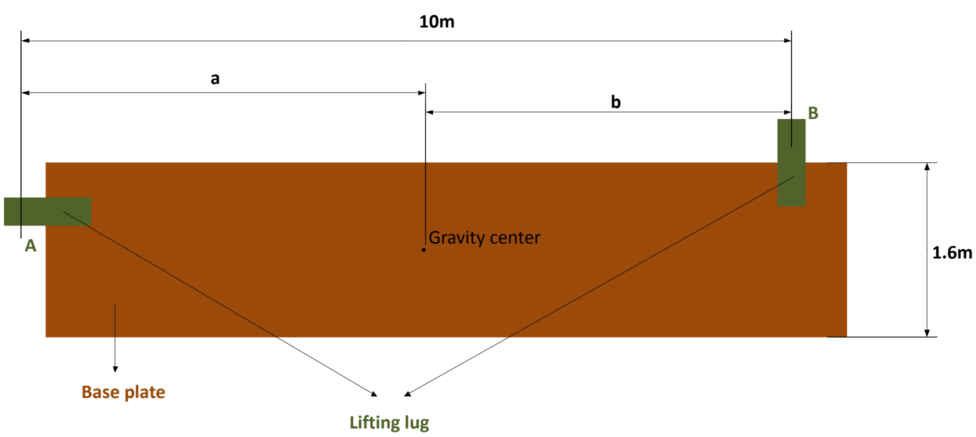


Figure 7.3.2 Brief view of a cross section from a section

It is set "a=b", so the load acts on lifting lug A is 10 ton. In the former part, the value of "B" in the lifting lug is calculated as 160mm, so the "Arm" is "170mm+R_{BL}". Then substituting exact value, the formula can be written as:

$$\tau_T = \frac{10\mathrm{ton} \times (170\mathrm{mm} + R_{BL})}{\frac{\pi}{2} {R_{BL}}^3} \tag{7.3.4}$$

Then a curve about τ_T and R_{BL} can be given and it is shown in Figure 7.3.3.

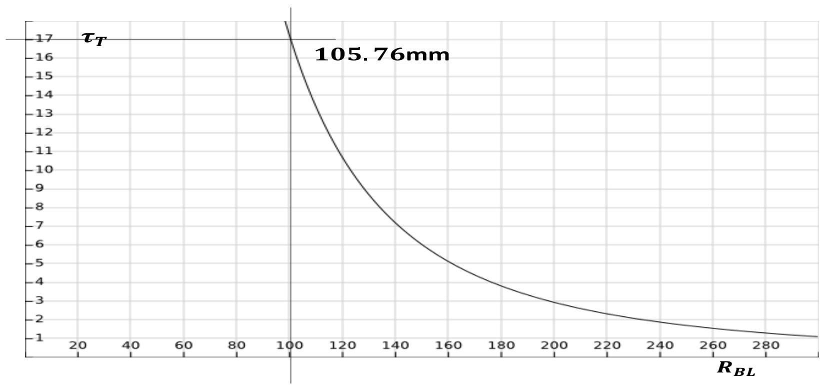


Figure 7.3.3 Curve for τ_T and R_{BL}

From the curve, it can be seen that the shear stress decreases with the increase of the radius of the bonding layer; the speed for decreasing becomes slow with the increase of the radius. The shear stress decreases 70% when the radius increases to 160mm and 82% when the radius increases to 200mm. The shear strength of Epoxy adhesive "Epibond 100" is 17Mpa, so the maximum radius of the bonding layer is 105.76mm. As the experience in the former part, the stress concentration is much higher than the theoretical value; so in the example the radius can be selected as 200mm.

Then the stresses during the turning process will be analyzed and defined shape of the bonding layer is checked if it can fulfill the requirements in the process. A brief view of the cross section from a section during the turning process is shown in Figure 7.3.4 with shape.

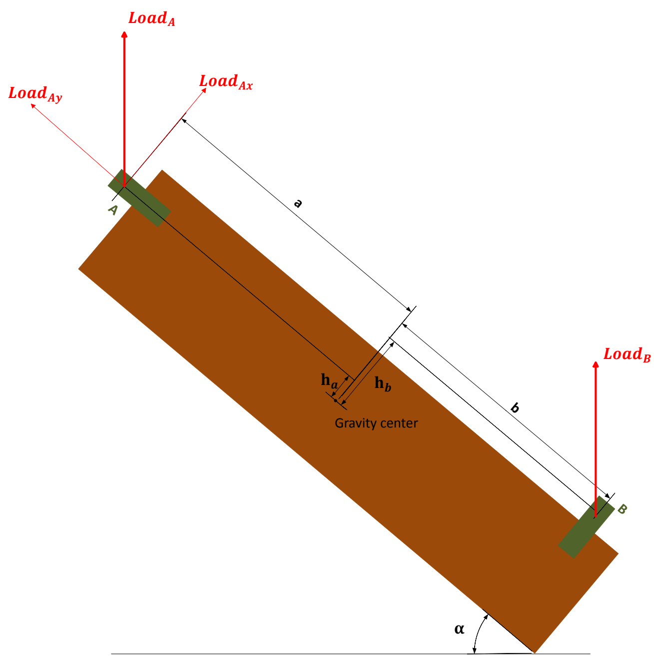


Figure 7.3.4 the cross section from a section during the turning process

When the section is in the turning process, the load keeps in the vertical direction; and it can be separated into two sub loads, $Load_{Ax}$ and $Load_{Ay}$; shown in the Figure. $Load_{Ax}$ is in the axis direction of the section which will produce shear stress; and $Load_{Ay}$ is perpendicular to the lifting lug which will produce torque to the bonding layer. The maximum stress in this phenomenon is the composite stress of the shear stress produced by $Load_{Ay}$ and the shear stress provided by the torque, the maximum composite shear stress will in the axis direction of the section which is same with$Load_{Ay}$. Then the calculation formulas are given below.

$$Load_A = \frac{b\cos\alpha + h_b \sin\alpha}{(a+b)\cos\alpha + (h_b - h_a)\sin\alpha} \times \frac{mass}{2} \qquad (7.3.5)$$

$$Load_{Ay} = \frac{b\cos\alpha + h_b \sin\alpha}{(a+b)\cos\alpha + (h_b - h_a)\sin\alpha} \times \sin\alpha \times \frac{mass}{2} \qquad (7.3.6)$$

$$Load_{Ax} = \frac{b\cos\alpha + h_b \sin\alpha}{(a+b)\cos\alpha + (h_b - h_a)\sin\alpha} \times \cos\alpha \times \frac{mass}{2} \qquad (7.3.7)$$

$$\tau_y = \frac{Load_{Ay}}{A_{bl}} = \frac{Load_{Ay}}{\pi {R_{BL}}^2} \qquad (7.3.8)$$

$$\tau_T = \frac{Torque \times R_{BL}}{I_p} = \frac{Load_{Ay} \times \mathrm{Arm}}{\frac{\pi}{2} {R_{BL}}^3} \qquad (7.3.9)$$

$$\tau_{com} = \tau_y + \tau_T \qquad (7.3.10)$$

Then use “example 3” to discuss the trend of the stress changing during the turning process. In example 3, a 40ton section is given; the shape of the section is similar to a cuboid. In the cross section fixing with lifting lugs of the section, the distance between two lifting lugs is 10m and the height is 1.6m and it is supposed that the distances between the gravity center to the two lifting lugs are equal and the gravity center is in the middle of the height. Figure 7.3.2 shows a brief view of it.

From Figure 7.3.4 and 7.3.6 it can be inferred that the value of h_b is a constant value which equals to “$0.5\mathrm{height} + 10\mathrm{mm} + \mathrm{B}$” and in the example it is 970mm; while the value of h_a is a variable value which can change between 0 to 600mm. The value of h_a will also influence the maximum angle a section can be turned in the first stage as well as the maximum stress when the whole load acts on lifting lug A. Therefore, several values of h_a are set and the values are 0, 300mm and 600mm. Then inferring exact value to the formula for calculating the maximum composite shear stress, three formulas with different h_a value can be got.

$$\tau_{com} = 1.59\left(\frac{\cos\alpha + 0.194\sin\alpha}{2\cot\alpha + 0.074}\right) + 5.89\left(\frac{\cos\alpha + 0.12\sin\alpha}{2\cot\alpha + 0.074\tan\alpha}\right) \qquad (7.3.11)$$

$$\tau_{com} = 1.59\left(\frac{\cos\alpha + 0.194\sin\alpha}{2\cot\alpha + 0.134}\right) + 5.89\left(\frac{\cos\alpha + 0.06\sin\alpha}{2\cot\alpha + 0.134\tan\alpha}\right) \qquad (7.3.12)$$

$$\tau_{com} = 1.59\left(\frac{\cos\alpha + 0.194\sin\alpha}{2\cot\alpha + 0.194}\right) + 5.89\left(\frac{\cos\alpha}{2\cot\alpha + 0.194\tan\alpha}\right) \qquad (7.3.13)$$

Figure 7.3.5 shows the curves for the three formulas shown above.

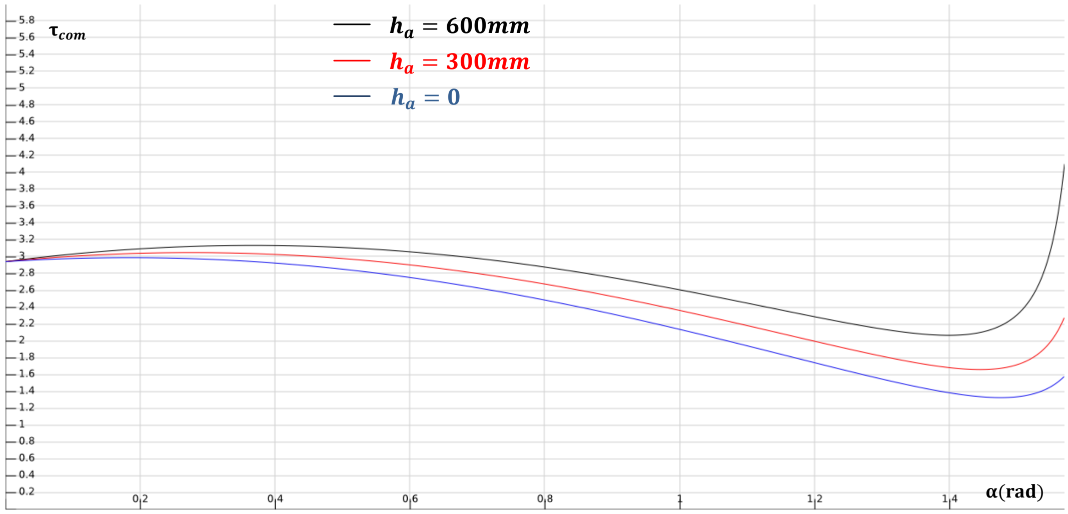


Figure 7.3.5 curves for different value of h_a

From the three curves' trend in the coordinate; smaller value of h_a makes the composite stress smaller during the whole turning process until the load coincides with the gravity line. And the curves also show that the smaller h_a is, the lower shear stress there will be in the state when the section stops turning. Therefore, it can be concluded that lifting lug in the side surface should be fixed to make the distance between it and the gravity center in the vertical direction as small as possible.

Then in "example 3", the lifting lug in the side surface is fixed in the same horizontal plane with the gravity center, which means h_a equals to 0 and the blue curve in Figure 7.3.7 shows the trend of stress' variation. The general trend of the blue curve shows that the shear stress will not higher than 3.2mpa in theoretical, so the radius defined in the initial state can fulfill the requirements during the turning process. The curves also show that the shear stress increases when the section starts turning and reach a maximum value at an angle; after that the shear stress starts decreasing. The value of the angle create the maximum shear stress can be read and this state in the turning process is defined as the "critical state", and this state will be simulated in the FEM software to monitor the stress concentration for judging feasibility. And the initial state is also selected for FEM simulation.

7.3.2 Lifting lug design

In the previous part, new bonding joint type is given for turning and the shape and shape of the new bonding joint is quite different from the one used in the lifting process; therefore the lifting lug used in the lifting work needs to be modified to adapt the new bonding joint and turning work.

There will be some modifications in the new lifting lugs. Firstly, the area of the lower part of the lifting lug for arranging bonding layer should be increased; as the new bonding layer is a circle, the lower part will be redesigned as a square. The length of the sides of the square is a little longer than the diameter of the bonding layer to avoid sudden change in shape.

Secondly, because a torque is created in the bonding layer during the turning process, the lifting lug should be modified to decrease the value of the torque. The torque equals load times arm in theoretical calculation, the load can't be changed, so to decrease the torque the "arm" should be decreased. In the modified lifting, the distance between the top point of the bonding layer to the edge of the base plate is decreased to 10mm; and the gasket is cancelled to save the distance.

The upper part of the lifting lug is kept the same with the one using in the lifting process. Figure 7.3.6 shows a brief of the modified lifting lug with shape.

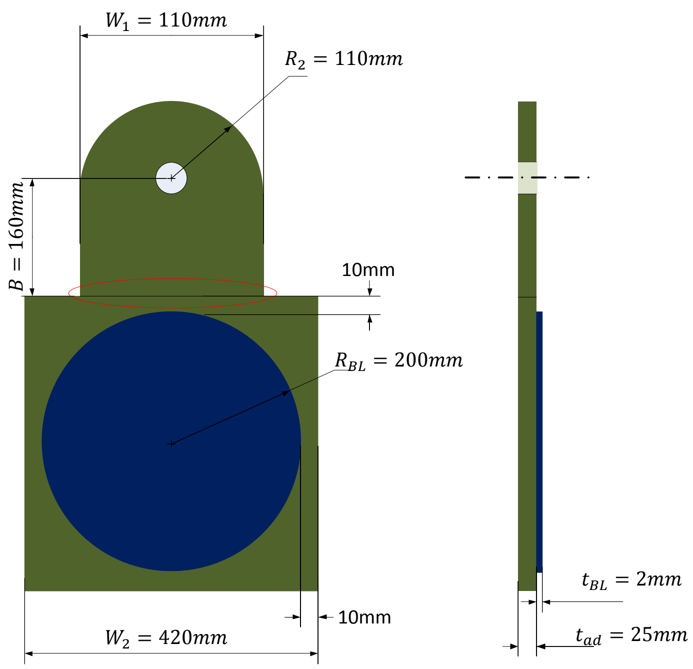


Figure 7.3.6. A brief view of the modified single lap lifting lug for turning

In Figure 7.3.8, the modified lifting lug is shown and there is a part circled with red in the Figure; this part should be taken care and checked with bending. The applied modulus of that part is:

$$22\text{cm} \times 22\text{cm} \times 2.5\text{cm} \div 6 = 201.7cm^3$$

While the minimum modulus the part needs to have is :

$$10\text{ton} \times 16\text{cm} \div \frac{1\text{ton}}{cm^2} = 160cm^3$$

The applied modulus is bigger than the minimum modulus, so the modified lifting lug fulfills the strength requirement for itself.

Then base on the single lap modified lifting lug, a double lap modified lug for turning is given and its brief view is shown in Figure 7.3.7 with shape. The thickness of the side plate of the lifting lug is increased to 10mm to defense bending which is different from the double lifting lug used for lifting work; and total thickness of the lifting lug is increased to 32mm.

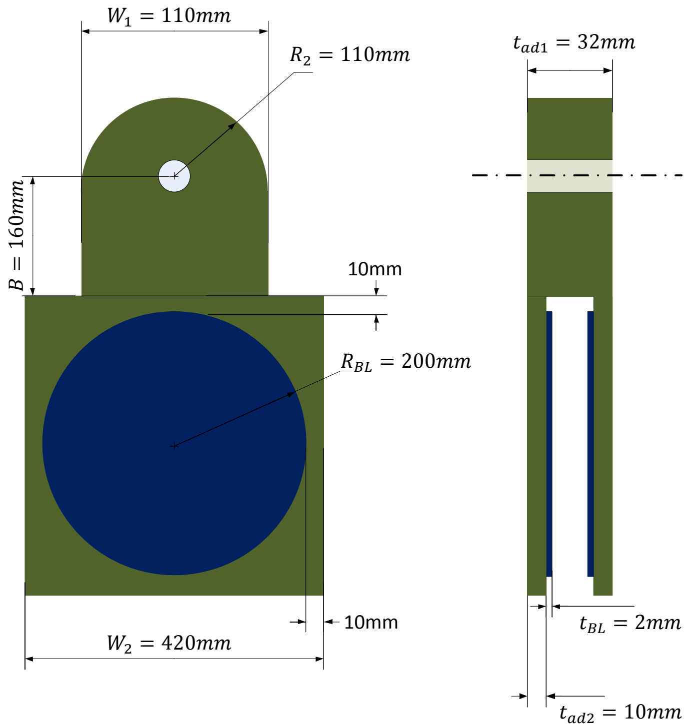


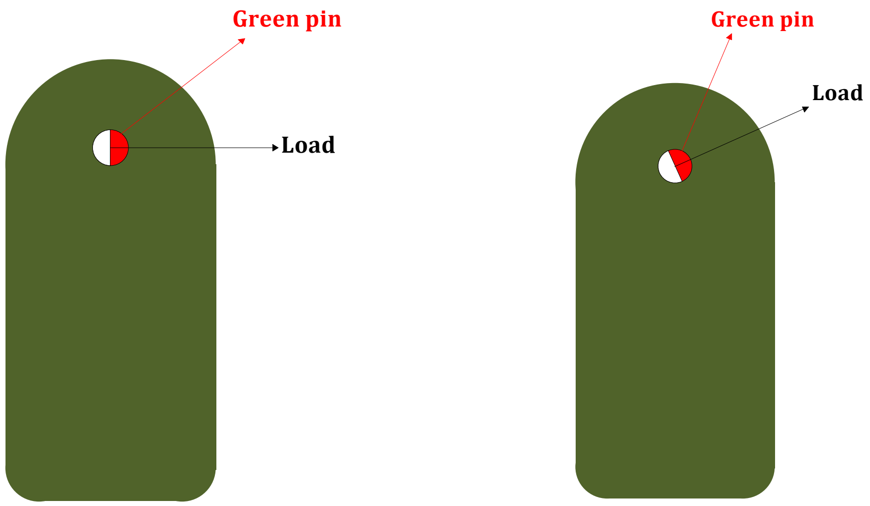
Figure 7.3.7 A brief view of the modified double lap lifting lug for turning

With the given new modified lifting lug, the FEM simulation can be processed in the next part.

7.4 FEM simulation and results discussing

FEM simulation for the modified lifting lugs will be processed in this part. Two selected adhesives used for building the bonding layer and both single lap and double lap lifting lugs will be simulated. The “example 3” is used for simulating the turning process and the simulated critical lifting lug is positioned within the same horizontal plane with the gravity center. The “initial state” and “critical state” are simulated; by reading the results from Figure 7.3.7 in the blue curve, the angle α when critical state appears is 11.5°.

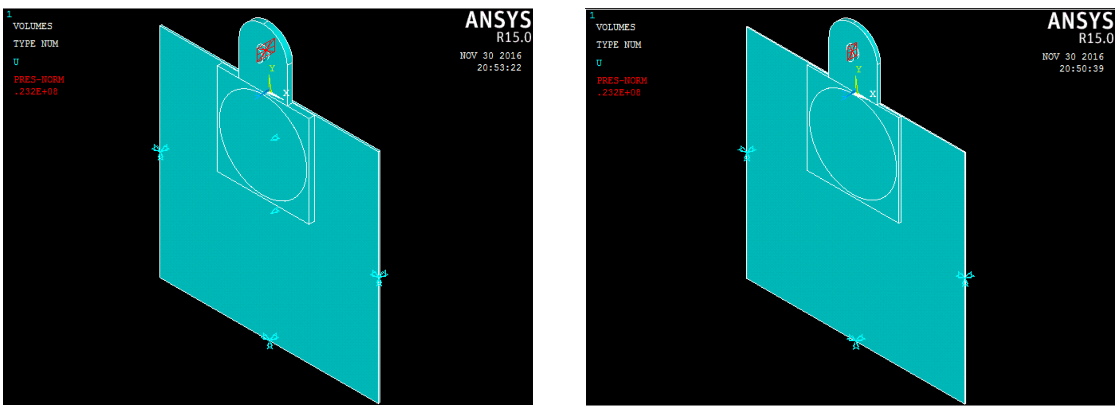
For building the FEM model, the thought and method are the same with what have been talked in chapter 5. The single lap lifting lug will use the same boundary conditions with “Scenario 3”, given in 5.2 chapter5; and for double lap lifting lug, the boundary condition for the base plate will be the same with that in “Scenario 1”. In these simulations, the single lap lifting lug model uses a whole size model; while the double lap model uses a symmetric model. The green pin will be turned based on its axis to simulate the direction change of the load and Figure 7.4.1 explains it. Then the FEM models are built and shown in Figure 7.4.2.



(a) Position of green pin in initial state

(b) Position of green pin in state during turning

Figure 7.4.1 Green pin's position in the turning process

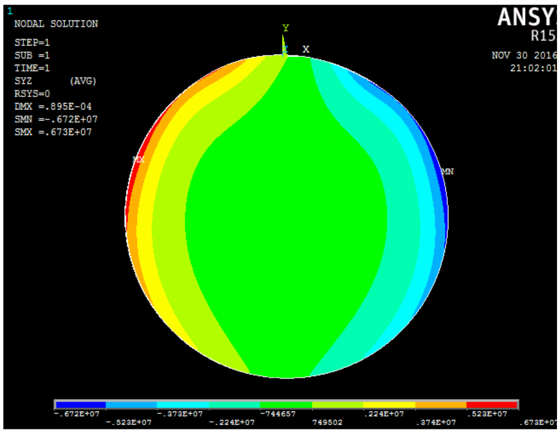


(a) Single lap lifting lug

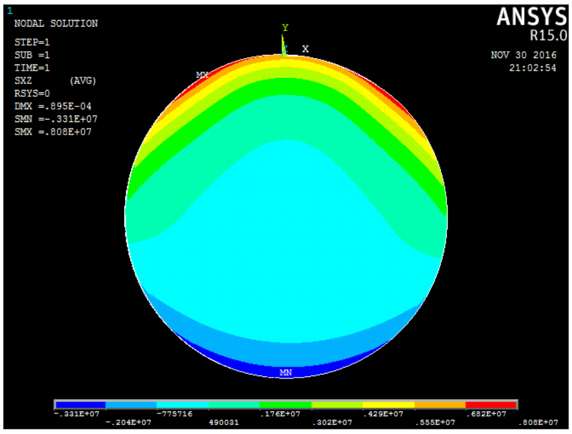
(b) Double lap lifting lug

Figure 7.4.2 FEM model of lifting lugs and base plates

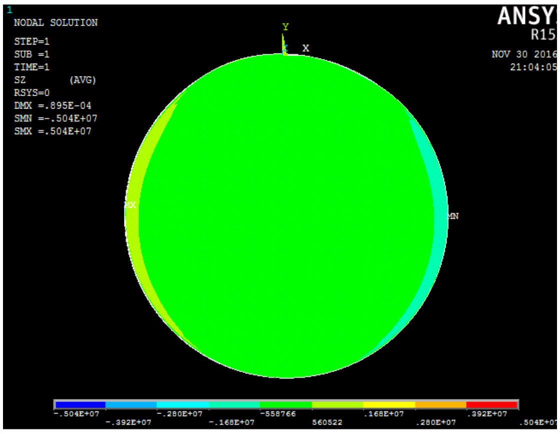
Then the results in a single lap lifting lug are shown in Figure 7.4.3 to explain the stress distribution. In Figure 7.4.3(a) and (b), shear stress caused by the torque, the distribution basically meets the theoretical distribution. In the edge of the bonding layer the value of the shear stress is bigger than that in the inner area; and the value of the shear stress near the load is bigger than that far from the load, because the stress weakens through the bonding layer. Figure 7.4.3 (c) shows the normal stress, it can been seen in most of the bonding layer the normal stress is in small value; when zooming in the edge, shown in Figure 7.4.3(d), it can been seen there still exists stress concentration in some areas.



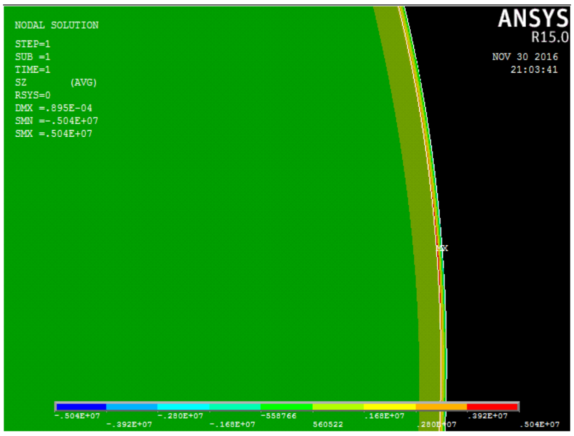
(a) Shear stress in the axis direction (yz)



(b) Shear stress in the perpendicular axis direction (xz)



(c) Normal stress distribution



(d) Zoom in the edge for normal stress

Figure 7.4.3 Stress distribution in a modified single lap lifting lug's bonding layer

In table 7.4.1(a) and 7.4.1(b), all values of results in different models are listed; it contains models with two selected adhesives used in single and double lap lifting lugs in the "initial state" and "critical state" during the turning process. Strength of selected adhesives is shown in 7.4.2.

Table 7.4.1(a) results in the initial state

		Epibond 100	DP8410NS Green
Single lap	Shear stress in axis (mpa)	6.73	5.41
	Shear perpendicular to axis (mpa)	8.08	6.36
	Normal stress (mpa)	5.04	4.25
Double lap	Shear stress in axis (mpa)	4.94	3.81
	Shear perpendicular to axis (mpa)	5.89	4.56
	Normal stress (mpa)	4.17	2.88

Table 7.4.1(b) results in the critical state

		Epibond 100	DP8410NS Green
Single lap	Shear stress in axis (mpa)	7.25	5.81
	Shear perpendicular to axis (mpa)	8.41	6.58
	Normal stress (mpa)	5.18	4.36
Double lap	Shear stress in axis (mpa)	5.14	3.95
	Shear perpendicular to axis (mpa)	6.4	4.88
	Normal stress (mpa)	3.47	2.55

Table 7.4.2 Strength of selected adhesives

Adhesive name	Category	Shear strength	Normal strength
Epibond 100	Epoxy	34.5 mpa	13 mpa
DP8410	Acrylic	24.6 mpa	9.3 mpa

From the results, it can be seen that the stresses in the bonding layer are controlled under the strength requirements; which can prove that the adhesively bonded lifting lugs have the abilities for being applied in the turning process.

7.5 Summary

To conclude the analysis processed in this chapter: adhesively bonded lifting lugs and can be used in the turning process, but the bonding joint are different from that used in the lifting process; limitations also exists for application. The sub question **"G. How bonding joints perform in turning?"** is answered.

Firstly, the total mass of the section is limited; because the optimal maximum load a bonded lifting lug can carry is 20ton and only two lifting lugs hold the whole mass of the section in a state during the turning process. Secondly, the positions for fixing lifting lugs are difficult to find, the skins welded on the frames are obstacles for the installation; and the requirements for value of area is increased. Thirdly, the bonding layers are difficult to be produced; a round bonding layer make the production more complicated than a rectangle bonding layer. The discussion of producing the bonding layer will be given in the last part.

Therefore, even the bonded lifting lugs are proved feasible for turning sections; several limitations restrict its application in the real production. For the real application, problems still need to be solved.

VI. Conclusion

8. Conclusion and further research

In the end of the research, conclusions of the analysis are summarized and advice for the further research is also listed.

8.1 Conclusion

Then the sub questions asked in the beginning of the thesis will be answered.

A. What kinds of adhesives will be feasible for bonding lifting lugs?

In general, structural adhesives should be used for bonding lifting lugs in the application; “epoxy structural adhesives” and “acrylic structural adhesives” are suitable for the application. Requirements for selecting appropriate adhesives are also concluded: firstly, the adhesive should have enough strength to hold the loads, usually the higher the better; secondly, the Young’s modulus and the Poisson’s ratio should be considered to control the strain of the adhesive in adhesive elastic deformation under the applied load.

B. What types of bonding joints can be used?

“Lap joints” are the best adhesively bonding joints for installing lifting lugs in the application; both “single lap joints” and “double lap joints” can be used. “Single lap joints” need the fixing positions supported with structures to decrease bending; while “double lap joints” need the fixing structures with two available bonding surfaces for arranging bonding joints. Both of the joints can make the adhesively bonded lifting lugs feasible for the application with enough supporting structures and appropriate bonding layers. “Double lap joints” are advised for application because it can release the bending in minimum level.

C. How to define the shape and geometrical attribute of lifting lugs?

To define the shape and dimension of bonded lifting lugs, it is processed in two parts. The first part is to ensure the strength of the lifting lug itself, it relates to the load and other accessories used in the lifting process; the detail methods are given in 2.1, Chapter 2. 20ton is defined as the optimal maximum load a lifting lug carries because minimal installation requirements are required with this load.
The second part is to make the bonding layers performances fulfill the strength requirements. The bonding layers are different in lifting process and turning process. In the lifting process, bonding layers are designed as a rectangle with fillets in four corners

and located in the inner area of the lifting lug; details for defining the original shape are given in 3.3, Chapter 3; and the improvements are provided in 6.1 and 6.2, Chapter 6. In the turning process, the bonding layer is redesigned as a circle to defense torque and value of the area are increased; details are provided in chapter 7.

D. What is the state of stress of the bonding joint with load?

"Shear stress" is the main stress in the bonding joints and large in value; normal stress also exists in the bonding layer. Stress concentrations appear in the edges of the bonding layer and they are sharply increased by bending of the base plate. For calculating shear stress and normal stress theoretically, formulas are given in 3.2, Chapter 3 and 7.3, Chapter 7; while FEM simulations are provided in part III and part IV. In the FEM models, the stress concentration values are got, and the value is several times higher than the theoretical average values of the stresses. After modification, the value of concentration stresses can be controlled within the strength requirements of the selected adhesives in specific applications.

E. Where are the best places for fixing lifting lugs on a section?

Generally, the bonded lifting lugs can only be fixed on structures of web frames or bulkheads which have enough value of available area for bonding in sections; the requirements for fixing single lap bonding joints and double lap joints are also different. For single lap joints, the fixing structures should have enough modulus to defense bending; while double lap joints need two surfaces available for bonding. Details about requirements are talked and given in Chapter 4.

F. How to evaluate the feasibility of the application?

The strength of the bonding layer and bonding joint is used as a criterion for evaluation and verification. Adhesively bonded lifting lugs are designed based on the rules adapted from rules of welded lifting lugs; shear stress and normal stress in the bonding joint are calculated and in feasible applications they cannot be larger than the strength of the bonding joint. FEM is chosen to simulate for calculating stress in the bonding joints and software "ANSYS" is used in the research.

G. How bonding joints perform in turning?

In the turning process, the load causes torque in the bonding layer and stress distribution is different from that in the lifting process; the changes in the distribution cause the stresses increasing in value and stress concentration increasing. Therefore, the bonding layer used in lifting process cannot be continually used in the turning process; a round bonding layer with larger bonding area is provided to instead the rectangle bonding layer. With the new bonding layer, shear stress and normal stress can be controlled within the adhesives' requirements as well as the stress concentration. However, in the turning process, the maximum mass of a section are decreased to 40ton, because of the applying limitation of bonded lifting lugs; Chapter 7 gives the details.

After answering the sub questions, the final conclusions are given.
The main questions of the investigation are:
1. Whether adhesively bonded lifting lugs can be applied in ship building?
2. If it is applied, what are the rules for the application?

And the final conclusions are shown below:

Adhesively bonded lifting lugs can replace welded lifting lugs when the capacity of the lifting lugs is lower than 20ton.
The application of the adhesively bonded lifting lugs should consider the defined calculations for: "the load a lifting lug can carry", "the strength of adhesives", "the positions of installation", "the shape of bonding layer" and "stress in the bonding layer".

8.2 Further research

The thesis processes some basic investigation for the feasibility of applying adhesively bonded lifting lugs in ship building; the results show the application is able to use theoretically, but for the further application, more researches should be processed and practiced. In this part, some advice for the further research is given.

Firstly, the research for the lifting lugs with capacity from 20ton to 30ton should be processed in the future. In the research, lifting lugs with capacity from 20ton to 30ton are not regarded as ideal subjects for investigation because they have more requirements for installation and suffer higher risks; the concentration for the research is put on lifting lugs with capacity of 20ton. While, making adhesively bonded lifting lugs carry heavier load can expand the application of adhesively bonded lifting lugs and solve more problems in the ship building process; research needs to be taken to optimize the application of adhesively bonded lifting lugs with capacity from 20ton to 30ton.

Secondly, the data about the adhesives information should be completed. In the thesis, the applied strength of adhesives is calculated from the data sheet provided by manufactures and standard test ASTM D1002 is also used for calculation. The data can show some properties of the adhesives, but they are more close to theoretical results. For the real production, tests like what Bouwman (2011) did in his researches should be advised to be processed in the further research; giving exact estimation for adhesives using in condition close to real production.

Thirdly, the production of the bonding layer should be analyzed. In the research, the bonding layers are designed smaller than the lifting lugs and with special shapes. So in the production it is hard to operate. To solve this problem, molds should be used in the production process to help the adhesive curdle into specific shape; then the molds can be moved. Another advice is to use adhesive films to produce bonding layer, but it is the work more related to adhesive manufactures.

Lastly, the economy problems should be analyzed. The adhesively bonded lifting lugs can help improve the performances of the ship, but whether the costs deserve the benefits may be different in views among shipyards, ship owners and ship designers. While for some non-metallic materials ships, adhesively bonded lifting lugs is a good choice; but for traditional steel structure ships the application’s benefit-cost ratio deserves to be analyzed.

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