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Specialization: Transport Engineering and Logistics

Report number: 2010.TEL.7480

Title: **The potential of adhesive bonding in shipbuilding**

Author: P.C. Bouwman

Title (in Dutch) Het potentieel van lijmen in de scheepsbouw

Assignment: Masters thesis

Confidential: no

Initiator (university): prof. ir. J.C. Rijsenbrij

Initiator (company): D.C.P. van Tol (IHC Beaver Dredgers B.V.)

Supervisor: ir. J.F.J. Pruyn

Date: 1 July 2010

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Supervisor (Company):	D.C.P. van Tol	Specialization:	TEL
		Report number:	2010.TEL.7480
		Confidential:	No

Subject: **Investigating the possibilities of using adhesives in shipbuilding**

A combination of Dutch shipyards is interested in the potentials offered by the use of adhesives instead of welding for the installation of small non structural elements on board of vessels. The goal is to limit the period of hot work (welding, burning, etc.) in the outfit phase of the project. Hot work limits the progress of other work not only within the section or space it is performed, but also in the adjacent one. Painting is the most important example of work influenced by hot work, especially with forgotten items, there can be much rework due to restoration of paint in 2 compartments.

Your assignment is to investigate which elements in the production process could be installed using adhesives. You are expected to quantify the benefits of the use of adhesives in the regular process and in the special case (e.g. forgotten or late delivered items). While potential is large, regulation is tight and an investigation of the regulation is necessary. Will Classification allow the use of adhesives and if they do, under what circumstances? The last element in your research should be the acceptance of this method, by the shipyard and possibly also by the future owner and the subcontractors.

This project is a cooperation between Delft University of Technology and several companies in the Dutch Maritime Sector. The graduate student is expected to spend 3-4 days a week at least at the shipyard.

The report should comply with the guidelines of the section. Details can be found on the website.

The professor,

Prof. J.C. Rijsenbrij

Summary

A combination of Dutch shipyards is interested in the possibility to use adhesive bonding instead of welding to attach steel parts. The use of adhesives instead of welding in shipbuilding could prevent heat processing or finish heat processing earlier in the outfit phase of a section or area. This heat processing restricts the work to be done in the area, but also in the room to the other side of the wall where heat processing occurs. Damage to paintwork (on both sides of the wall) and the additional repairs are a clear example of these restrictions. However, at this stage, the knowledge of adhesive bonding within shipbuilding is limited. The main objective of this report is to analyze if adhesive bonding can and should be applied for the assembly of steel parts, instead of the current joining method (welding). The application of adhesive bonding is examined through literature research, interviews with stakeholders (employees shipyards, adhesive suppliers, researchers, customers), experiments (adhesive tests) and practice research.

This research took place in the production department of IHC Beaver Dredgers B.V. IHC Beaver Dredgers specialises in the design and construction of standard and custom built cutter suction dredgers. Potential applications for adhesive bonding are selected by analyzing the production process on site during the period of research. In order to make a distinction in potential applications, the selected components are categorized by risk and strength as a first step. Adhesive bonding applications should always favor shear and compressive loads, while excessive peel and cleavage loads should be avoided. After possible components are selected, the process centers around the requirements which are favorable or which adhesives must fulfill. This includes identification of possible alternative substrates, joint designs, and available processing facilities. The environmental conditions and types of loading that the joint must resist are determined as well. The influence of the most commonly substrate surfaces used in shipbuilding on the strength of a joint is quantified by performing adhesive tests. From the adhesive tests, two different types of adhesive are chosen to be applied in shipbuilding; epoxy adhesive and MS Polymer. Subsequently, the potential of adhesive bonding is determined by establishing rough pre-designs for each component, and by determining the possible savings in production costs per item and on yearly base compared to welding. Based on this analysis, a ship's nameplate is chosen as best application and further elaborated by joint design and cost-price analysis as an example for all other applications. Potential implementation problems with this application and requirements for production, fire-safety and in-service conditions are evaluated compared to welding as well.

It may be concluded that, based on numerous preconditions, it is possible to use adhesive bonding successfully in shipbuilding. The selected items in this report are representative for a wider range of products at IHC Beaver Dredgers and shipbuilding in general. From the performed adhesive tests, it appeared that adhesive bonding to the most commonly substrate surfaces (steel, shop-primer and coating) used in shipbuilding is possible. Two types of adhesives were selected for appliance in shipbuilding; epoxy adhesive (for local attachments) and MS Polymers (large areas with large tolerance requirements). Using degreasing as a simple surface preparation is sufficient to obtain a proper adhesive bond for both types of adhesive. In total, annually cost-savings of €146.000 can be realized when applying adhesive bonding instead of welding for the selected applications. This corresponds with a reduction of on average 65 % in cost price for using adhesive bonding instead of welding the selected items. The highest average reduction in cost-price compared to welding is obtained for adhesive bonding items in a special case (e.g. forgotten or late delivered items); 80% vs. 57 % for adhesive bonded items in the regular process. Adhesively bonding of the ship's nameplates provides most cost-savings annually (around € 39.000), per item (around € 2800) and reduces the production costs to 93% compared to the current design of this item. Taken into account production requirements, fire safety requirements and in- service requirements, the implementation of an adhesively bonded ship's nameplate is relatively simple and technical feasible without significant chances on the shipyard process.

To obtain a more complete overview of adhesive performance, testing of full scale joints and simulation of environmental and in-service conditions (temperature, salt water, different types of load) during the test program is recommended. As an alternative to these time-consuming and expensive tests the stresses in the selected applications may be analyzed by FEA (Finite Element Analysis) As a verification of the performed analytical analyses in this report it is recommended to analyze the obtained results by numerical methods using FEA (Finite Element Analysis) in future research. Additionally, the selected applications with more complex geometry, boundary conditions and load transfer mechanisms (category C) can be analyzed using FEA (Finite Element Analysis) as well.

However, for a successful introduction of adhesive bonding in shipbuilding reserve of local staff should be overcome and adhesive bonding should first be introduced in less critical areas (based on risk and strength) and increasingly also in more critical areas as service experience is gained and confidence in the long term performance is built.

Summary (in Dutch)

Een combinatie van Nederlandse scheepswerven is geïnteresseerd in de mogelijkheid om lijmen te gebruiken in plaats van lassen voor het bevestigen van stalen onderdelen. Het gebruik van lijmen in plaats van lassen in de scheepsbouw kan hittebewerkingen voorkomen of eerder beëindigen in de outfit fase van een sectie of ruimte. Deze hitte bewerkingen beperken de te verrichten werkzaamheden in de ruimte zelf, maar ook in de ruimte aan de andere kant van de wand waar de hitte bewerking plaatsvindt. Schade aan verf (aan beide zijden van de wand) en de bijkomende reparaties zijn een duidelijk voorbeeld van deze beperkingen. Echter, op dit moment is de kennis binnen de scheepsbouw op het gebied van lijmen beperkt. De belangrijkste doelstelling van dit verslag is om na te gaan of lijmverbindingen kunnen en moeten worden toegepast in plaats van de huidige verbindingsmethode (lassen), voor de montage van stalen onderdelen. De toepassing van lijmverbindingen is onderzocht door middel van literatuuronderzoek, interviews met betrokken partijen (werknemers op de werf, lijm leveranciers, onderzoekers, klanten), experimenten (lijm tests) en praktijk onderzoek.

Dit onderzoek is uitgevoerd op de productie afdeling van IHC Beaver Dredgers BV. IHC Beaver Dredgers heeft zich gespecialiseerd in het ontwerpen en bouwen van standaard en custom-built snijkopzuigers. Potentiële toepassingen van lijmverbindingen zijn geselecteerd door tijdens onderzoeksperiode het productieproces op de werf te analyseren. Om een onderscheid te maken in potentiële toepassingen worden, als eerste stap, de geselecteerde componenten ingedeeld op basis van risico en sterkte. Lijmverbindingen dienen bij voorkeur te worden belast op schuif- en drukkrachten, terwijl overmatige afpel- of scheurbelasting moet worden vermeden. Na de selectie van potentiële componenten, draait het selectieproces om de eisen waaraan de lijm moet voldoen en de criteria die gunstig zijn voor een lijmverbinding. De identificatie van mogelijke alternatieve ondergronden, vormgeving van de verbinding, en de beschikbare productie faciliteiten zijn hierbij meegenomen. De omgevingscondities en de soort belasting die de lijmverbinding moet weerstaan worden eveneens bepaald gedurende het selectieproces. De invloed van de meest voorkomende ondergronden binnen de op de sterkte van een lijmverbinding zijn gekwantificeerd door het uitvoeren van lijmtesten. Vanuit de lijmtest, zijn twee verschillende soorten lijm gekozen voor de toepassing binnen de scheepsbouw; epoxy lijm en MS Polymeer. Vervolgens kan het potentieel van lijmen worden bepaald door ruwe ontwerpschetsen voor elk onderdeel uit te werken, en de mogelijke besparingen op de productiekosten per stuk en op jaarbasis te bepalen in vergelijking met lassen. Het verlijmen van een naambord van een schip is op grond van deze analyse gekozen als beste lijmtoepassing en verder uitgewerkt op het gebied van constructieve vormgeving en kostprijs als een voorbeeld voor alle andere geselecteerde

toepassingen in het rapport. Tevens zijn potentiële implementatie problemen voor deze lijmtoepassing en de eisen met betrekking tot de werkplaats, brandveiligheid en 'in-service' condities in vergelijking tot het lassen geëvalueerd.

Er kan worden geconcludeerd dat, op basis van verschillende randvoorwaarden, het mogelijk is om lijmverbindingen succesvol toe te passen binnen de scheepsbouw. De geselecteerde onderdelen in dit rapport zijn representatief voor een verscheidenheid aan producten bij IHC Beaver Dredgers en daarmee de scheepsbouw. Uit de lijmtesten blijkt dat de toepassing van lijmverbindingen op de meest voorkomende ondergronden binnen de scheepsbouw (staal, shop-primer en coating) mogelijk is. Er zijn twee soorten lijm geselecteerd voor de toepassingen binnen de scheepsbouw; epoxy lijm (voor lokale bevestigingen) en MS Polymeer (grote gebieden met ruime maattoleranties). Voor beide lijmen is het toepassen van ontvetten als oppervlakte voorbehandelingsmethode voldoende voor het verkrijgen van een goede lijmverbinding. In totaal kan een jaarlijkse besparing van € 146.000 worden gerealiseerd door de geselecteerde onderdelen te verlijmen in plaats van lassen. Dit komt overeen met een vermindering van gemiddeld 65% in de kostprijs ten opzichte van het lassen van de geselecteerde onderdelen. De grootste besparing in kostprijs in vergelijking met lassen kan worden verkregen door lijm toe te passen in speciale gevallen (bijvoorbeeld vergeten of te laat geleverde onderdelen); 80% versus 57% voor het lijmen als regulier proces. Het verlijmen van het naambord van een schip biedt de meeste kostenbesparingen per jaar (ongeveer € 39.000), per stuk (ongeveer € 2800) en de productie kosten worden tot 93% verminderd ten opzichte van het huidige ontwerp. Wanneer er rekening wordt gehouden met de eisen ten aanzien van de werkplaats, brandveiligheid en de in-service omgeving, is de toepassing van een verlijmd naambord van een schip relatief eenvoudig en technisch haalbaar zonder aanzienlijke veranderingen van het productieproces op de werf.

Voor het verkrijgen van een completer overzicht van de prestaties van een lijm is het testen van lijmverbindingen op ware grootte en het simuleren van omgevings- en in-service condities (temperatuur, zout water, verschillende soorten belasting) tijdens het test programma aanbevolen. Als alternatief voor deze tijdrovende en dure testmethoden kunnen de spanningen in de lijmverbindingen van de geselecteerde toepassingen worden geanalyseerd met behulp van EEM (Eindige Elementen Methode).

Om lijmen in de scheepsbouw succesvol te kunnen introduceren, zal terughoudendheid vanuit het personeel doorbroken moeten worden. Tevens dienen lijmverbindingen eerst in minder kritieke gebieden (gebaseerd op risico en sterkte) te worden toegepast waarnaar, wanneer praktijk ervaring is opgedaan en het vertrouwen in de prestaties op lange termijn verder is uitgebreid, het toepassingsgebied uitgebreid kan worden naar meer kritieke gebieden.

List of symbols

A	Bonding Area	mm^2
b	Width of joint	mm
d	Thickness adhesive	mm
E_1	Young's modulus adherend 1	MPa
E_2	Young's modulus adherend 2	MPa
F	Force	N
f_{Df}	Dynamic load, Fatigue factor	
$f_{Df,M,T}$	Dynamic load, Fatigue, Moisture, Temperature factor	
f_i	Knock-down factor	
f_M	Humidity, moisture factor	
f_S	Surface preparation factor	
f_T	Temperature factor	
G	Shear modulus adhesive	MPa
k	Bending moment factor	
l	Length of overlap region	mm
l_0	Overlap length of joint	mm
s	Thickness adherend	mm
S	Safety factor	
q	Maximum admissible deformation	mm
x	Length of sample	mm
γ	Shear strain	
δ	Adherend stiffness ratio	
ν_1	Poisson's ratio adherend 1	
ν_2	Poisson's ratio adherend 2	
σ_{10}	Tensile stress adherend 1	N/mm^2
τ	Shear strength	N/mm^2
τ_a	Allowable shear strength	N/mm^2
$\tau_{a,dry}$	Allowable shear strength, dry conditions	N/mm^2
$\tau_{a,humid}$	Allowable shear strength, humid conditions	N/mm^2
τ_f	Shear strength adhesive	N/mm^2
τ_{max}	Maximum shear strength	N/mm^2

List of abbreviations

AA	Adhesive failure Adhesive
AP	Adhesive failure Primer
ASTM	American Society of Testing and Materials
CA	Cohesive failure Adhesive
CC	Cohesive failure Coating
CP	Cohesive failure Primer
EAB	European Adhesive Bonder
EAS	European Adhesive Specialist
EEM	Eindige Elementen Methode
EWF	European Welding Federation
FEA	Finite Element Analysis
FTP	Fire Test Procedures
IACS	International Association of Classification Societies
ISO	International Organization for Standardization
IPA	Isopropyl Alcohol
MMA	Methyl Methacrylate Adhesive
MSP	Modified Silane Polyether
NDT	Non Destructive Testing
PU	Polyurethane
Sa	Sand
SMAW	Shielded Metal Arc Welding
SOLAS	International Convention for Safety of Life at Sea
SP	Shop-primer
SWOT	Strengths, Weaknesses, Opportunities, Strengths
UV	Ultra Violet
VHB	Very High Bond

Contents

1 Introduction

A combination of Dutch shipyards is interested in the possibility to use adhesive bonding instead of welding to attach steel parts. In the present situation, steel parts are mainly joined by welding. Generally, welding of small steel parts is carried out at a late stage in the outfit phase of a section or area. This heat processing not only restricts the work to be done in the area, but also in the room at the other side of the wall where heat processing occurs. Damage to paintwork and the additional repairs due to welding are a clear example of these restrictions.

The use of adhesives instead of welding in shipbuilding could prevent heat processing or finish heat processing earlier in the outfit phase of a section or area. At this stage, the knowledge of adhesive bonding within shipbuilding is limited. Therefore, it is important to further investigate the feasibility of applying adhesives instead of welding in shipbuilding.

The main objective is to analyze if adhesive bonding can and should be applied for the assembly of (steel) parts in shipbuilding, instead of the current joining method (welding). Therefore, this report focuses on the following question:

To what extent can and should the current method of joining steel parts (welding) within a yard be replaced by adhesive bonding?

The application of adhesive bonding is examined through literature research, interviews with stakeholders (employees shipyards, adhesive suppliers, researchers, customers), experiments (adhesive tests) and practice research. The application of adhesive bonding instead of welding will primarily be judged on effectiveness, technical feasibility and cost reduction.

In chapter 2 the problem is defined more extensively and specific objectives and boundary conditions are determined in order to formulate a clear approach. Before the aspects from this approach are elaborated, an introduction to shipbuilding is given in chapter 3 to indicate the environment were this research took place. Subsequently, a comparison between the current bonding method (welding) and adhesive bonding is made in chapter 4. Based on this comparison a clear picture of starting points for research is obtained to select potential applications for adhesive bonding in chapter 5. The requirements which are favorable and which adhesives must fulfill are discussed in chapter 6 to make a first basic selection in suitable adhesives. Next, the test program in which the previously selected adhesives are tested in adhesion strength when applied to different substrates is discussed in chapter 7. Based on this test program a final adhesive selection is made to apply in shipbuilding practice. In chapter 8 the potential of adhesive bonding for each previously selected component in combination with the previously selected adhesives is determined and one best application is chosen. In the same chapter the effect on the shipyard process and the required conditions of this 'best application' are discussed. Finally, chapter 9 contains conclusions about the potential of adhesive bonding in shipbuilding and recommendations for further research.

2 Problem definition

2.1 Why adhesive bonding?

Shipyards are specialized in processing large quantities of steel, joined by welding. By using welding as a joining method for the assembly of steel parts, some disadvantages are involved.

First of all, welding causes deformation of structures by heat input. Welding is also limited to join similar materials (steel) and requires an exhauster because of the production of harmful welding fume. Furthermore, welding may only be performed by well trained personnel and requires a significant amount of electricity capacity on site.

However, the major disadvantages of welding in shipbuilding practice take place when the assembly of steel parts, due to forgotten or lately delivered components, is carried out at a late stage in the outfit phase of a section or area. This heat processing restricts the work to be done in the area, but also in the room to the other side of the wall where heat processing occurs. Damage to paintwork (on both sides of the wall) and the additional repairs due to welding are a clear example of these restrictions. Examples of damage to paint work due to welding are represented in Figure 1.

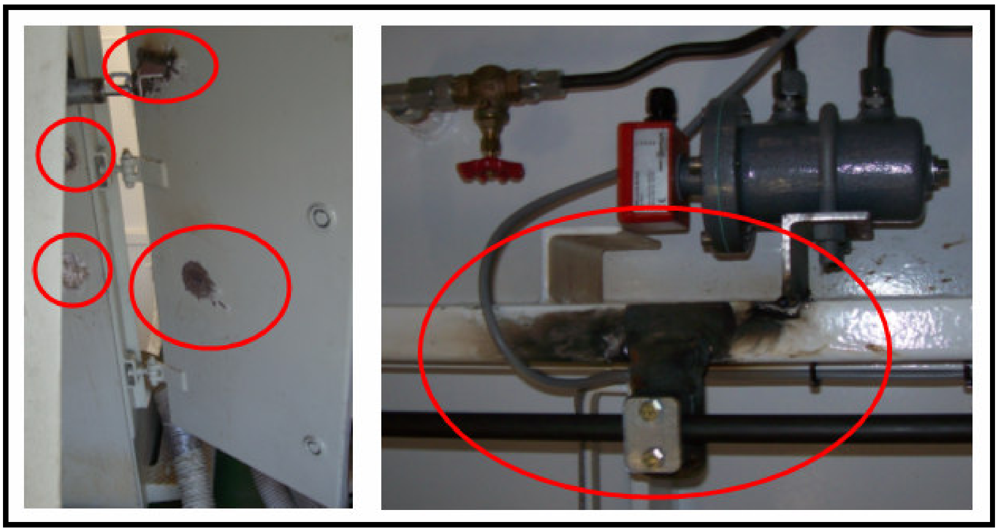


Figure 1 Damage to paint work due to welding at IHC Beaver Dredgers

Hence, welding a (e.g. forgotten or lately delivered) component in a later stadium of the building process may lead to a wide range of additional activities and costs compared to an 'ideal' situation. In this way, welding of steel parts contribute to a significant proportion of the total man hours and cost of ships, not only by direct cost but also by nonproductive work operations due to heat processing. The use of adhesive bonding in shipbuilding could solve the problems involved with welding by preventing heat processing or finish heat processing earlier in the outfit phase of a section or area. In addition, adhesive bonding in the pre-outfit phase of a ship may lead to a decrease in lead time and construction cost too. Therefore, the potential of adhesive bonding in shipbuilding should be reviewed by both application of adhesive bonding in the outfit phase and in the pre-outfit phase of a ship. However, at this stage, the knowledge of adhesive bonding within shipbuilding is limited.

2.2 Objective

The main objective is to analyze if adhesive bonding can and should be applied for the assembly of (steel) parts in shipbuilding, instead of the current joining method (welding). For this analysis the shipbuilding industry is represented by the shipyard of IHC Beaver Dredgers as a special case. Therefore, this report focuses on the following question:

To what extent can and should the current method of joining steel parts (welding) within a yard be replaced by adhesive bonding?

In order to provide an answer to this question, the following more specific objectives have been formulated:

- Identify potential adhesive bonding applications in shipbuilding
- Determine the criteria which adhesives must fulfill
- Determine the influence of different surfaces (steel, shop primer, coating) on the strength of adhesives
- Identify the technical and economical potential of adhesive bonding applications in shipbuilding
- Determine the effect of the most appropriate bonding application on the shipyard process and required conditions

Analysis of the appliance of adhesive bonding at one specific yard has been chosen to achieve the above mentioned objectives. The selected adhesive bonding applications at the shipyard of IHC Beaver Dredgers will represent a variety of applications which fulfills a combination of functions and is applied on diverse ship types in shipbuilding industry.

2.3 Boundary conditions

In order to implement technology of adhesive joints in shipbuilding practice several boundary conditions should be considered. In the following the boundary conditions for this research are pointed out and shortly clarified.

The objective of this report is marked by the following boundary conditions:

Current location, area and layout of the yard should remain the same

The current production environment on the shipyard is mainly focused on the welding process. It is expected that, although adhesive bonding can offer great benefits, will not replace welding in total.

Selected applications should mainly be loaded in shear and / or compression

Adhesive bonding is especially suited for the transfer of shear or compressive loads. According to the general design rules and the mechanical strength of adhesives any peel load should be avoided.

The new joining method must meet the quality requirements of the yard

The application of adhesive bonding has to meet the agreed specifications, should be reliable, should be of good quality and should operate or produce as expected.

Level of training of staff and willingness to complete knowledge

Approval bodies demand the appropriate qualification of the personnel employed in the execution of adhesives subject to approval. At the same time, knowledge of adhesive bonding increases the acceptance of employees on site for this new technology.

Availability of information about production process

In order to determine the effect of adhesive bonding on the shipyard process and the required conditions specific knowledge of the production process at a shipyard is necessary.

Prior art: knowledge and possibilities

A successful implementation of adhesive bonding also depends on the available knowledge and experience with adhesive bonding from the adhesive supplier and the possibility in the yard to gain knowledge.

Financial resources (staff training, investment)

Financial resources should be available to invest in adhesive materials, equipment and training of personnel. To be profitable, the investment in adhesive bonding must be earned back.

2.4 Approach

In this paragraph an approach is formulated in order to answer the main research question and to achieve the objectives as described in paragraph 2.2. Before the aspects from this approach are elaborated, firstly an introduction to shipbuilding is given to indicate the environment were this research took place. The company IHC Beaver Dredgers is described briefly to provide some background information about the organization, history and products and market of this company. Subsequently, the production process of a shipyard is discussed for a general shipyard and for IHC Beaver Dredgers in specific.

Next, the current situation in the field of adhesives, the factors affecting successful implementation and the objectives of adhesives are researched by literature (Appendix B) and interviews (Appendix D) with involved parties and employees on site.

From this research the strengths, weaknesses, opportunities and threads of using adhesive bonding in shipbuilding are extracted. With the results of this SWOT analysis in mind, an approach is formulated in order to answer the main research question and to achieve the objectives as described in paragraph 2.2.

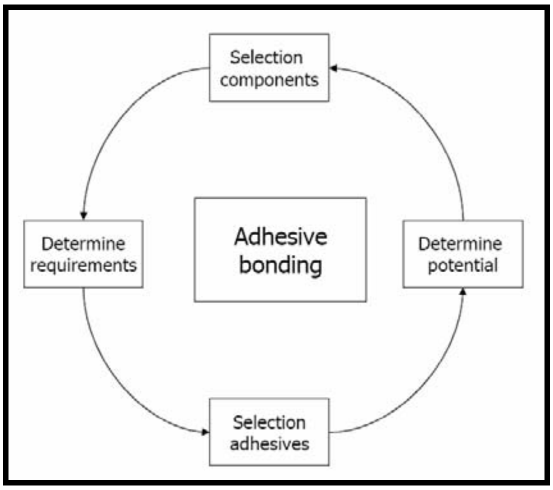


Figure 2 Schematic representation of approach

In the process of choosing a final 'best application', there are several critical decisions that need to be made as shown in Figure 2. Each of the steps, need to be analyzed and optimized with respect to their influence on the final, desired result. A significant problem is that each of these decisions cannot be made independently. The component selection, for example, may influence the processing conditions that are required and the joint design that is necessary.

Therefore, the selection of adhesive bonding applications must be made considering all of the parameters involved in the bonding process. After this analysis, if the estimates of strength, durability, and cost do not appear to provide an adequate safety margin, then one must go back through the entire process, making refinements where they can be made to end with a truly optimized result.

Selection of components

In order to select possible candidates firstly the production process on site is analyzed during the period of research. Furthermore, employees from various departments within IHC Beaver Dredgers are interviewed with respect to possible application of adhesive bonding within shipbuilding. This includes interviews with work preparation, order coordinators, welders, iron workers, painters, drawing office, production managers etc. In this way all of the information possible about the product being bonded and the processing capabilities that are available is gathered.

This is a fact-finding step to accumulate critical information on the application and the restrictions that may be placed on the bonding process. The parameters that are gathered during this fact-finding may need to be reconsidered and compromised as the adhesive selection process proceeds and various adhesive systems are matched to the list of requirements.

Determine requirements

Once possible components are selected, the process centers around the requirements which are favorable or which adhesives must fulfill. This will include identification of possible alternative substrates, joint designs, and available processing facilities. The environmental conditions and types of loading that the joint must resist are determined as well.
These criteria will be derived by survey based on literature, interviews with involved parties (adhesive suppliers, employees of IHC Beaver Dredgers, companies which currently use adhesive bonding, etc.), adhesive supplier data sheets and analysis of the production process on site.

Selection of adhesives

Based on the determined requirements a basic selection for possible adhesive candidates for the appliance in shipbuilding will be made. A final selection of appropriate adhesives will be made in cooperation with an adhesive supplier and, additionally, by performing a testing program. Goal of this testing program is determining the characteristic strengths of the different adhesive and the influence of different substrates (steel, shop-primer and coating) on the strength of the selected adhesives.

Determine potential of applications

This report will conclude with an economic evaluation of each component taking into account life cycle aspects and the impact of the adhesive bonding process on the existing shipbuilding process. From this analysis, one 'best application' will be chosen and further elaborated. Potential implementation problems with this application, requirements for construction, logistics, layout, workload, safety, etc. will be evaluated compared to welding.

3 Introduction to shipbuilding

In order to collect the correct information and to measure the effect of adhesive bonding, specific knowledge of the production process at a shipyard is necessary. Therefore, this research took place in the production department of IHC Beaver Dredgers B.V. In this chapter the company IHC Beaver Dredgers will be described briefly (paragraph 3.1) to provide some background information about the organization, history and products and market of this company. Subsequently, the production process of a shipyard will be discussed for a general shipyard and for IHC Beaver Dredgers in specific.

3.1 The company IHC Beaver Dredgers

3.1.1 IHC Merwede B.V.

IHC Beaver Dredgers is part of the company IHC Merwede. IHC Merwede is focused on the continuous development of its design and construction activities for the specialized shipbuilding sector, in particular the dredging and offshore industries. IHC Merwede has a staff of approximately 2,800 at its locations in the Netherlands. There are also branches in China, India, the Middle East, Nigeria, Russia, Singapore, Slovakia, the United Kingdom and the United States of America.

The IHC Merwede units have been grouped together in three divisions: Dredging & Mining, Offshore & Marine, and the group of sector-related products and services. Because of the technological expertise it brings together, this division is now known as Technology & Services. IHC Beaver Dredgers takes part in the dredging & mining division of IHC Merwede, see Figure 3.

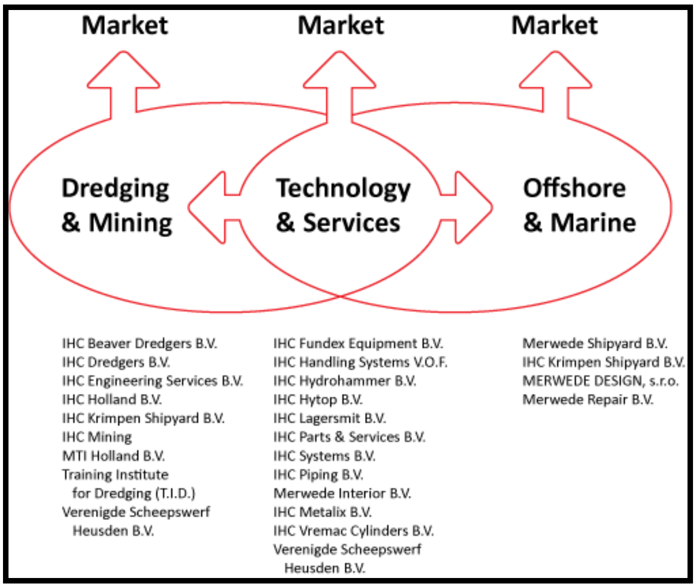


Figure 3 IHC Merwede divisions [1]

3.1.2 History of IHC Beaver Dredgers

IHC Beaver Dredgers B.V. at Sliedrecht resulted from the merging of two shipyards, IHC De Klop and Werf Van Rees both established at Sliedrecht, which had been the cradle of dredging, for many decades. When the two companies were merged, in 1980, a new complex was constructed at the Molendijk, the site of the former Werf Van Rees.

3.1.3 Products and markets of IHC Beaver Dredgers

IHC Beaver Dredgers at Sliedrecht specialises in the design and construction of cutter suction dredgers. These can be divided into two main categories: Custom-built vessels and those built to a standard design, with optionals or customised to the clients specifications. The standardised cutter suction dredgers are marketed under the name IHC Beaver Dredger. In Figure 3 a standardized cutter suction dredger is represented. The encircled components in Figure 3 are types of equipment which are also separately fabricated for the dredging and alluvial mining industries by IHC Beaver Dredgers.

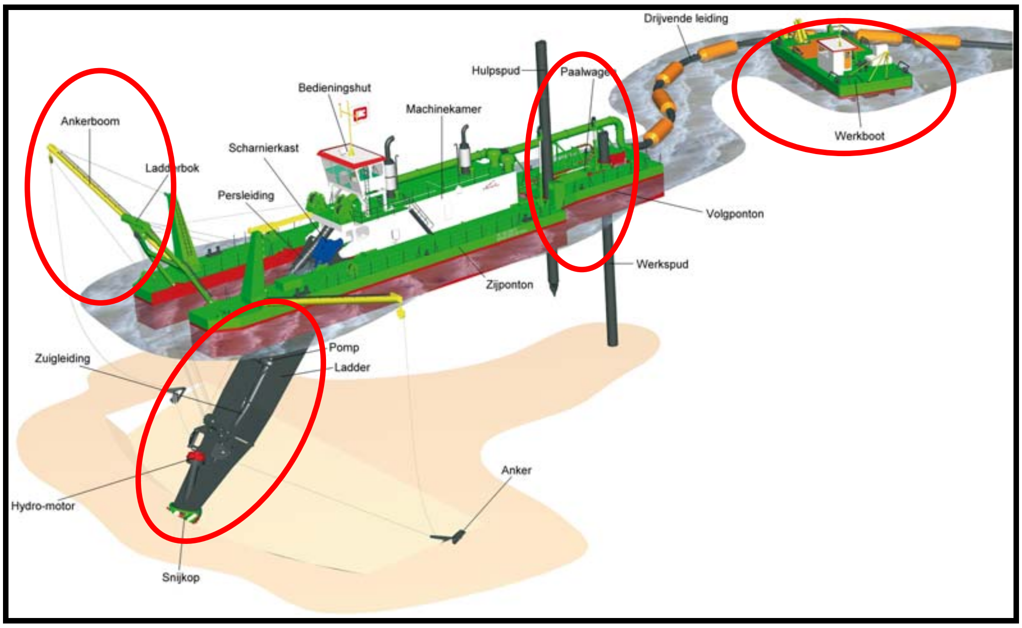


Figure 4 Standardized cutter suction dredger [1]

The Beaver Dredger range comprises different types with varying dimensions, dredging depths and draughts. The most commonly produced types of Beavers and their principal particulars are represented in Table 1. The first 4 types in Table 1 are named by the power output range in horse power (300 – 1600 horse power) while the last 3 types are named by the diameter of the delivery pipeline in cm (50 – 65 cm).

Table 1 Principal particulars of the Beaver Dredger range

Type	Length (m)	Breadth (m)	Depth (m)	Draught (m)	Cutter: Power at shaft (kW)	Dredging depth (m)
B300	12	4.05	1.3	0.88	30	6
B600	12.5	5.75	1.51	1.10	52	8
B1200	16.5	6.96	1.87	1.25	110	10
B1600	22	7.95	2.46	1.50	170	14
B50	21.65	7.87	2.44	1.45	170	14
B50c	23.5	9.50	2.46	1.50	170	14
B65c	32.5	12.44	2.97	2.05	585	18

In addition to cutter suction dredgers, IHC Beaver Dredgers constructs other types of equipment for the dredging and alluvial mining industries (see red encircled components in Figure 3), such as:

Booster stations

In order to increase the pumping distance, booster stations can be placed in the discharge pipeline of the Beaver dredger. These booster stations are designed as a floating self-supporting unit containing a dredge pump with a diesel engine.

Workboats

Workboats are used for a wide range of marine operations in sheltered and shallow waters, including pushing/pulling, dredging support work, fuel oil and water supply.

Cutter ladders

Cutter ladders are of a rigid steel construction, easily capable of handling the forces induced by the dredging operations. The ladder is provided with the suction line, and the ladder front part.

Spud carriages

A spud carriage is used to move the cutters suction dredgers forward by pushing against the working spud.

Anchor booms

Anchor booms are designed to reposition the side anchors of the dredger without assistance of a work boat.

3.2 Production process on a shipyard

3.2.1 General characteristics

In general, the basic classification used in manufacturing includes the following categories: unique- , batch-, mass- and flow production. The manufacture of ships is characterized as unique production. Unique production and the production of smaller series are characterized by [2]:

- Small numbers of identical products
- A high number of man-hours per unit of product (labor intensive)
- A high level of craftsmanship on the floor

Due to the small numbers of products and labor-intensive character a high flexibility in production and the organization is required. This creates an image as shown in Figure 5.

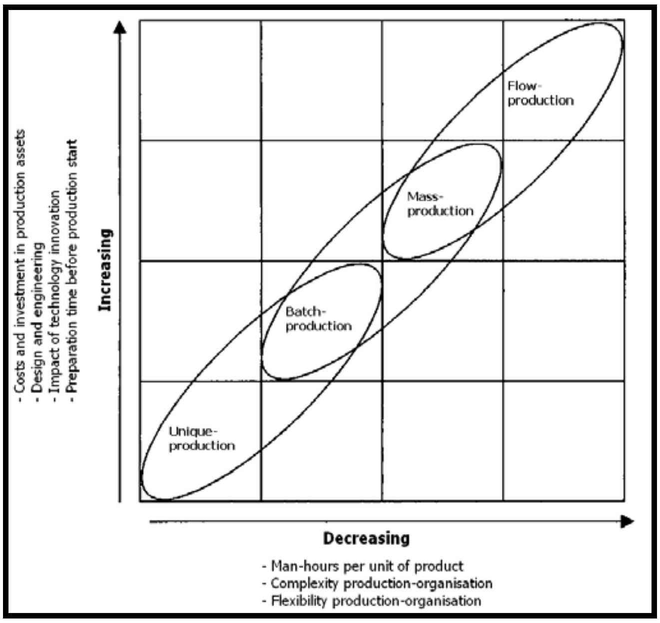


Figure 5 Characteristics of production processes [2]

Building a ship, according to the characteristics of unique production, is a process of successive and related activities in a logical sequence. Figure 6 gives a schematically representation of the production process on a shipyard.

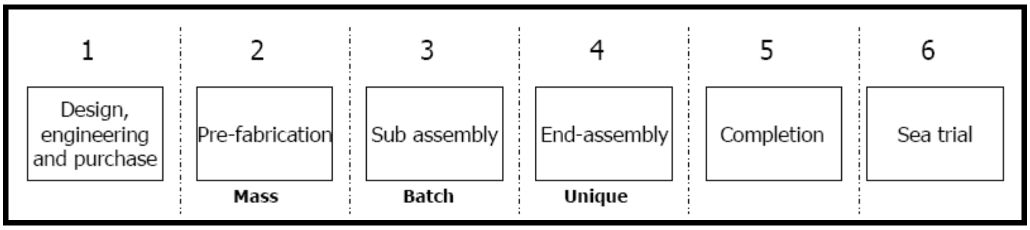


Figure 6 Production process on a shipyard [2]

Because the various stages in the production of a vessel overlap, many activities are started with incomplete information. Although the overall production process is characterized by unique production, the pre-fabrication (phase 2 in Figure 6) is characterized by mass production and the sub assembly (phase 3 in Figure 6) by batch production. A description of the different phases in shipbuilding, as represented in Figure 6, can be found in literature [2,3]. This report will mainly focus on phase 3, phase 4 and phase 5 as represented in Figure 6; the sub- assembly, end-assembly and completion of a ship.

3.2.2 Production process IHC Beaver Dredgers

The operations within IHC Beaver Dredgers are subdivided into managing processes, the primary process (obtaining the order), and supporting processes [4]. The primary process is central to this: everything is aimed at transferring the client's order into a product (and associated services) that meets client's requirements and expectations. The primary process at IHC Beaver Dredgers is comparable to the processes as described in literature [2,3] and is illustrated in Figure 7.

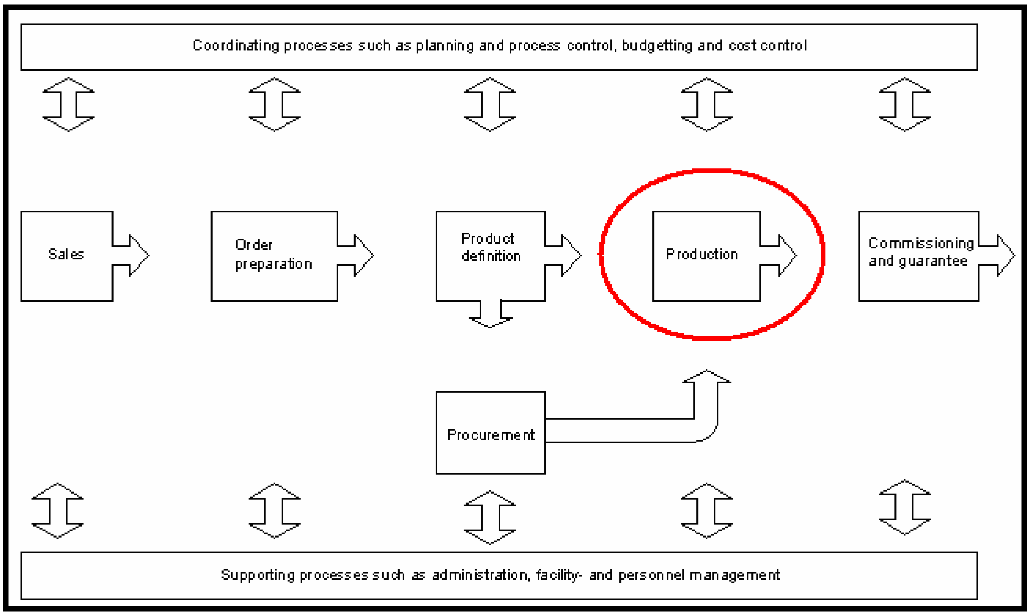


Figure 7 Primary process of IHC Beaver dredgers [4]

The equipment is produced in close cooperation with specialised and qualified suppliers and subcontractors. The production and assembly activities are carried out by a number of functional departments. Good coordination and direction of all parties involved is therefore increasingly important.

In the production phase, prior defined quality inspections, measurements, tests and trials are carried out. For a number of delivery types the presence of the client and the inspection body is required by the contract and/or the regulations. The production process of IHC Beaver Dredgers is schemattically represented in Figure 8. An important sub-process in the production process is welding. In order to make a good comparison between adhesive bonding and the welding process the welding process will be more detailled described in the next chapter.

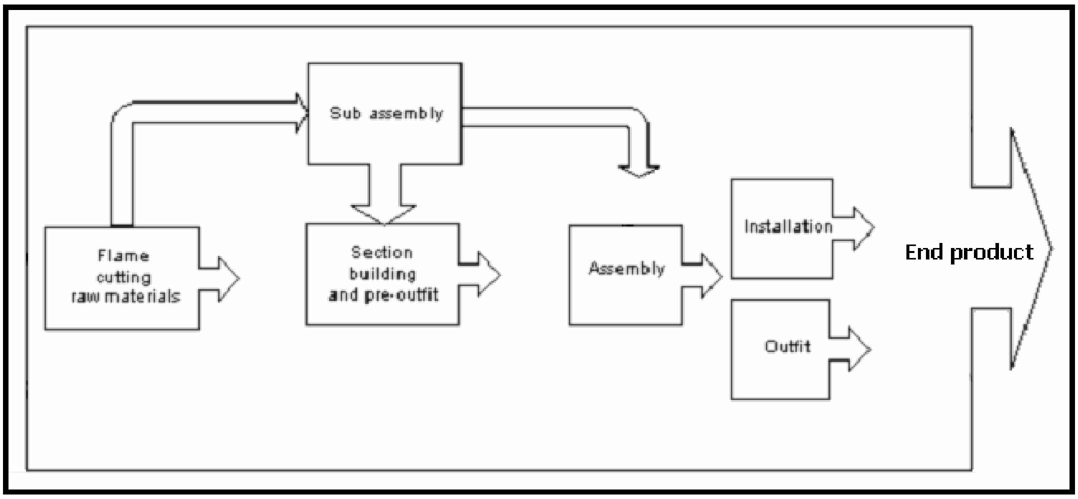


Figure 8 Production process of IHC Beaver Dredgers [4]

4 Introduction: adhesive bonding vs. welding

A variety of joining methods can be used to provide the assembly function. In this chapter a general comparison between adhesive bonding and welding will be made. Firstly, an introduction to adhesive bonding will be given in paragraph 4.1. The working principle of welding will be briefly described in paragraph 4.2. A general comparison of both characteristics is made in paragraph 4.3. To create an image of the starting points before research a SWOT analysis is performed based on (paragraph 4.4) based on the strengths, weaknesses, opportunities and threads of adhesive bonding compared to the current joining method (welding).

4.1 Introduction to adhesive bonding

Adhesive bonding is a modern assembly technique where two similar or non-similar materials (metals, plastics, composites, etc.) are joined using an adhesive. Adhesion is the attraction of two different substances resulting from intermolecular forces between the substances. Both adhesive and cohesive forces are the result of forces existing between atoms or molecules [5]. The strength of an adhesive bond depends on:

- Adhesive strength: adhesive forces hold two materials together at their surfaces
- Cohesive strength: cohesive forces hold adjacent molecules of a single material together

Joints may fail in adhesion or cohesion or by some combination of the two, see Figure 9:

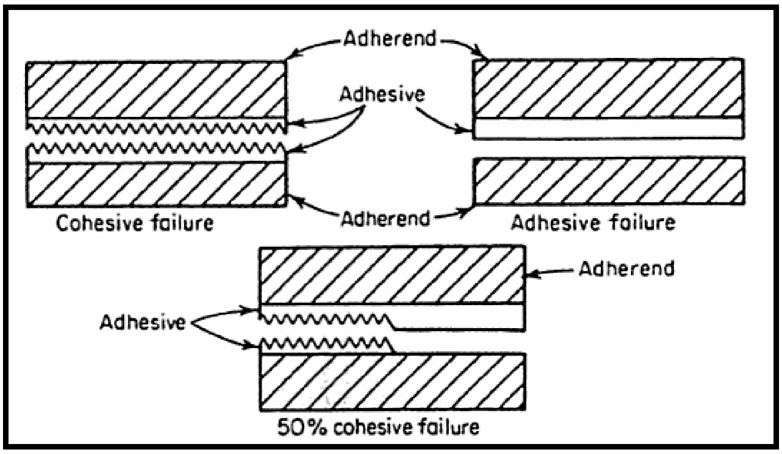


Figure 9 Examples of cohesive and adhesive failure [5]

Adhesive bonding is used in a variety of industries; construction, packaging, textile, aircraft, automotive and many others. A full literature research to the main markets and applications of adhesive bonding is represented in appendix B.

4.2 Introduction to welding

Welding is a fabrication process that joins materials, usually metals, by causing coalescence. This is often done by melting the work pieces and adding a filler material to form a pool of molten material (the weld pool) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld [6]. One of the most popular welding methods is Shielded Metal Arc Welding (SMAW), frequently referred to as 'stick' or 'covered electrode' welding [7]. The principle of SMAW welding is represented in Figure 10.

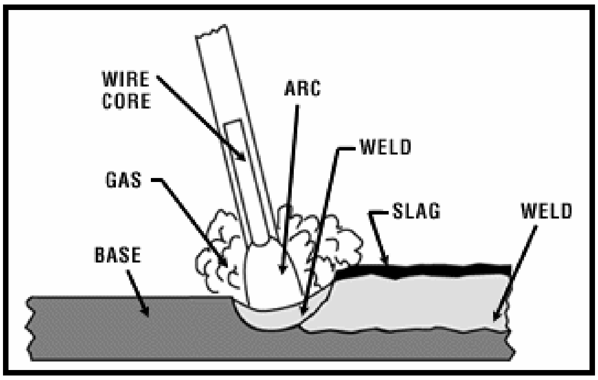


Figure 10 Principle of SMAW welding [7]

Welding techniques are employed in the construction of numerous products; ships, buildings, bridges are fabricated by welding processes.

4.3 General comparison

In many applications, both welding and adhesive bonding are possible. Each joining application must be considered with regard to its specific processing and performance requirements. There are times when adhesives may be a better option for joining two substrates, and there are times when adhesives may be the worse alternative [9]. In Table 2, a general comparison between welding and adhesive bonding is provided as to their joint characteristics and their production features.

Table 2 General comparison of joining characteristics [8]

	Welding	Adhesive Bonding
Joint Features		
Permanence	Permanent joints	Permanent joints
Stress distribution	Local stress points in structure	Good uniform load distribution over joint area **(except in peel)**
Appearance	Joint appearance usually acceptable. Dressing necessary for smooth surfaces	No surface marking. Joint almost invisible
Materials joined	Only similar material groups	Ideal for joining most dissimilar materials
Temp. resistance	Very high temperature resistance	Poor resistance to elevated temperatures
Mechanical resistance	Special provision often necessary to enhance fatigue resistance	Excellent fatigue properties. Electrical resistance reduces corrosion
Production Aspects		
Joint preparation	Little or none on thin material. Edge preparation for thick plates	Cleaning often necessary
Post Processing	Heat transfer sometimes necessary	Not often required
Equipment	Relatively expensive, bulky and often required heavy power supply	Only large multi-feature, multi-component dispensers are expensive
Consumables	Wire, rods, etc., fairly cheap	Structural adhesives somewhat expensive
Production rate	Can be very fast (minutes, < 1 hour)	Seconds to hours, according to type
Quality assurance	NDT methods applicable	NDT methods limited

Table 2 shows that adhesive bonding is, at times, less faster than welding. The production rate for adhesive bonding depends merely on the curing time that has to be observed. According to the type of adhesive used, this curing time can be very fast (seconds) to very slow (hours to days). Moreover, the resistance of adhesives to elevated temperatures is poor and surface preparation is often required. Chemical environments and outdoor weathering (rain, UV light) also degrade adhesives. The rate of strength degradation may be accelerated by continuous stress or elevated temperatures. The combination of continuous stress along with high moisture levels is of special concern [9]. On the other hand, adhesives provide a low temperature, high strength, joint with many different substrates. They thereby avoid the problem of distortion of materials by heat, commonly encountered with welding. The inspection of finished joints for quality control is very difficult. Non-destructive test techniques cannot quantitatively predict joint strength. This necessitates strict control over the entire bonding process to ensure uniform quality.

4.4 SWOT analysis

In the previous paragraphs welding and adhesive bonding have been compared by their general characteristics. Additionally, with information based on interviews with involved parties to both adhesive bonding as welding (see Appendix D), informal conversations with employees and literature [9,10,11,12] a SWOT analysis is performed in this paragraph.

The main goal of this SWOT analysis is to create a clear picture of starting points before further research. This SWOT analysis is based on the strengths, weaknesses, opportunities and threads of adhesive bonding compared to the current joining method (welding). The SWOT analysis is based on **relative** strengths, weaknesses, opportunities and threats. That is, the point is strong or weak compared to the current joining technique (welding). This applies less for the opportunities and threats, because they often affect the entire production process. The most important aspects of the SWOT analysis are shown in *italics* in Table 3.

Table 3 SWOT analysis; adhesive bonding compared to welding

Strengths: *Joins dissimilar (thin) materials* Minimizes or prevents corrosion *No heat processing required; prevents distortion and change of structure of materials* Creates an uniform load distribution *No heat processing required; prevents damage to paintwork, isolated walls and potable water tanks* No electricity required No release of welding fume No slag and weld spatter	**Weaknesses:** May only be loaded by shear or compression Less strength and stiffness of the joint Poor rate of strength development Joint is as strong as the weakest link in the joint *Quality depends on environmental conditions (humidity, temperature, dirt)* *Quality depends on surface preparation* *Quality depends on curing conditions (temperature, time)* Jigs and fixtures may be needed *Poor resistance to elevated temperatures* Modification current design may be required to increase bonding area
Opportunities: *Assembly later in production process possible: > flexibility, > production capacity / throughput* *Cost reduction in repair: < cost-price* Design options can be extended Good health and safety conditions General aspects: improved management, good public relations impact, environmentally friendly	**Threads:** *Environmental conditions at a shipyard* *Little interest in adhesive bonding* *Little experience in adhesive bonding* Few process support from adhesive suppliers Work is outsourced on regular base *No guarantee for durability and quality of a joint by adhesive suppliers* *Absence of theoretical base of joint strength* Large dimensional tolerances in shipbuilding Difficult to control obtained adhesion non-destructive

The aspects which are considered as most important, shown in *italics* in Table 3, are briefly discussed below.

As can be seen in Table 3, adhesive bonding has many strengths and opportunities compared to welding. One of the main strengths of adhesive bonding compared to welding is the prevention of heat processing. By preventing this heat processing, time consuming and costly repairs can be avoided. For this research it is of special interest to take a closer look at the costs and specific problems involved with these repairs. Furthermore, if adhesive bonding could be applied to coated surfaces, assembly of components can take place later in the production process creating more flexibility and an increasing production capacity. However, little is known at this stage about the influence of a coated surface on the strength of an adhesive bond. Therefore, one of the main points of interest would be, to quantify the influence of a coated surface on the strength of a joint, by performing adhesive tests.

However, from this SWOT analysis also some bottlenecks can be selected which are of special concern for this report. One of the major issues about adhesive bonding, compared to welding, is the possibility to guarantee the quality of an adhesive joint. A lack of knowledge is available and a clear theoretical base to predict the strength and lifetime of a bonded joint is absent.

Moreover, at first sight, the shipbuilding industry does not offer good conditions for the application of adhesive bonding. In both the production environment as in the 'in service' environment, many parameters which may influence the quality of a bonded joint are involved. From these parameters (e.g. temperature, humidity, dirt) criteria which an adhesive should fulfil have to be derived and quantified in order to make a selection in possible adhesive candidates for shipbuilding. By using these criteria, particularly important for shipbuilding, also some specific production considerations can be further examined. Questions to be asked are for example; which methods are available for positioning or clamping of bonded assemblies? And; which surface preparation is to be used?

Another bottleneck of using adhesive bonding in shipbuilding is the poor heat resistance of adhesives. One can imagine that limitations in possible applications of adhesive bonding may occur because of this weak characteristic. For this reason, the existing classification rules in fire safety should be investigated. The possibilities of 'in service' inspection and 'in service' repair of finished joints should be investigated too.

Since adhesive bonding does not enjoy the same status in comparison to the current joining technique (welding) reserve of local staff is expected, after all; unknown, unloved. The acceptance of local staff for adhesive bonding as a new joining technique is a critical factor in a final implementation of adhesive bonding in shipbuilding and should be realised by providing well-founded knowledge of adhesive bonding.

5 Potential applications for adhesive bonding

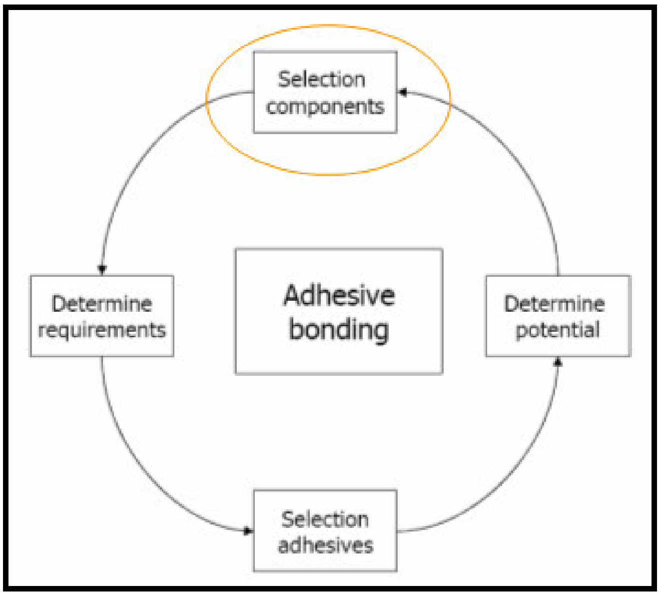


Figure 11 Step 1: identifying possible candidates for research

First step chosen in determining the aim for the use of adhesive bonding in shipbuilding is identifying possible candidates for research. The selection of possible candidates begins with an analysis of the production process on site during the period of this research. As the production process on site is largely standardized, the various models Beavers usually have similar characteristics. This allowed the construction process to be followed at several stages simultaneously.

Beside analysis of the production process, employees from various departments within IHC Beaver Dredgers have been interviewed with respect to possible application of adhesive bonding within shipbuilding. This includes interviews with work preparation, order coordinators, welders, iron workers, painters, drawing office, production managers etc. Some interviews are represented in Appendix D, however, information is also gathered by informal conversations.

Finally, interviews with other companies (e.g. Damen Shipyard, Click Bond) and institutes (TU Delft) are used to obtain information about existing applications of adhesive bonding in shipbuilding (see Appendix D).

5.1 Classification of components

In order to make a distinction in potential applications, the selected components are categorized by risk and strength. Although there are exceptions (see item 8 in Figure 12), in general, with applications requiring a high strength, high risks are involved and vice versa. Although this is a relatively broad and subjective interpretation, it is a sufficient way to indicate the potential of the selected components as a first step. In this way the selected components are divided into 3 different categories, see Table 4 and Figure 12.

Table 4 Classification of components

Category A:	**Category B:**	**Category C:**
Strength: Weight of component 0-5 kg Static load	**Strength:** Weight of component 5 – 50 kg Intermittent loads	**Strength:** Weight of component > 50 kg Intermittent loads
Risk: Simple geometry Low chance of failure Low impact on failure	**Risk:** Medium complexity of geometry Medium chance of failure Medium impact on failure	**Risk:** Complex geometry High chance of failure High impact on failure

Using the conditions as represented in Table 4, the selected components can be schematically represented as in Figure 12. The numbers as represented in this figure are referring to the numbers in the table as represented in Appendix E.

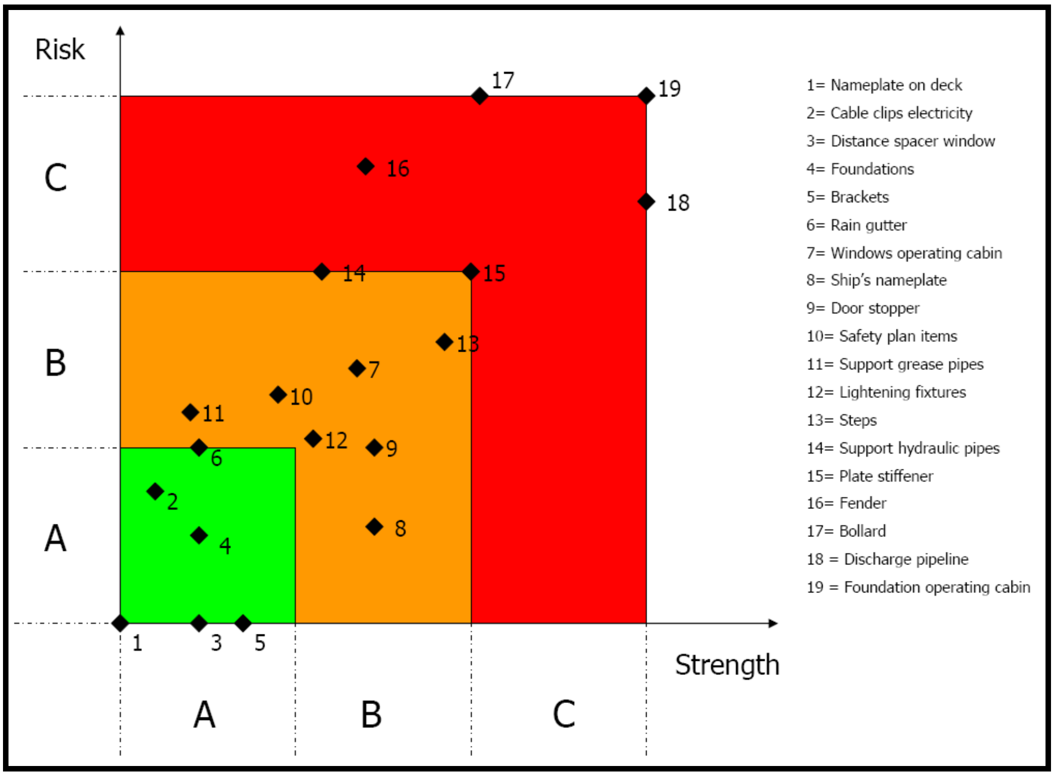


Figure 12 Possible adhesive applications

In Figure 12, every component is marked by a number and placed in one of the categories A, B or C based on the conditions from Table 4. This way of classifying only intents to give a rough idea about the risk and strength involved with the use of adhesive bonding for attachment of a specific component.

Additionally to the conditions from Table 4, the risk and strength factor is also influenced by other conditions such as environmental conditions (temperature, humidity) and type of substrate to be bonded (e.g. bonding to steel or coating). For this reason, more specific information about such conditions per item, as represented in Figure 12, is given in Appendix E and Appendix F.

As an example, one potential adhesive bonding application is represented and further elaborated as example for the other items as represented in Appendix E. In this case, component 1 is selected.

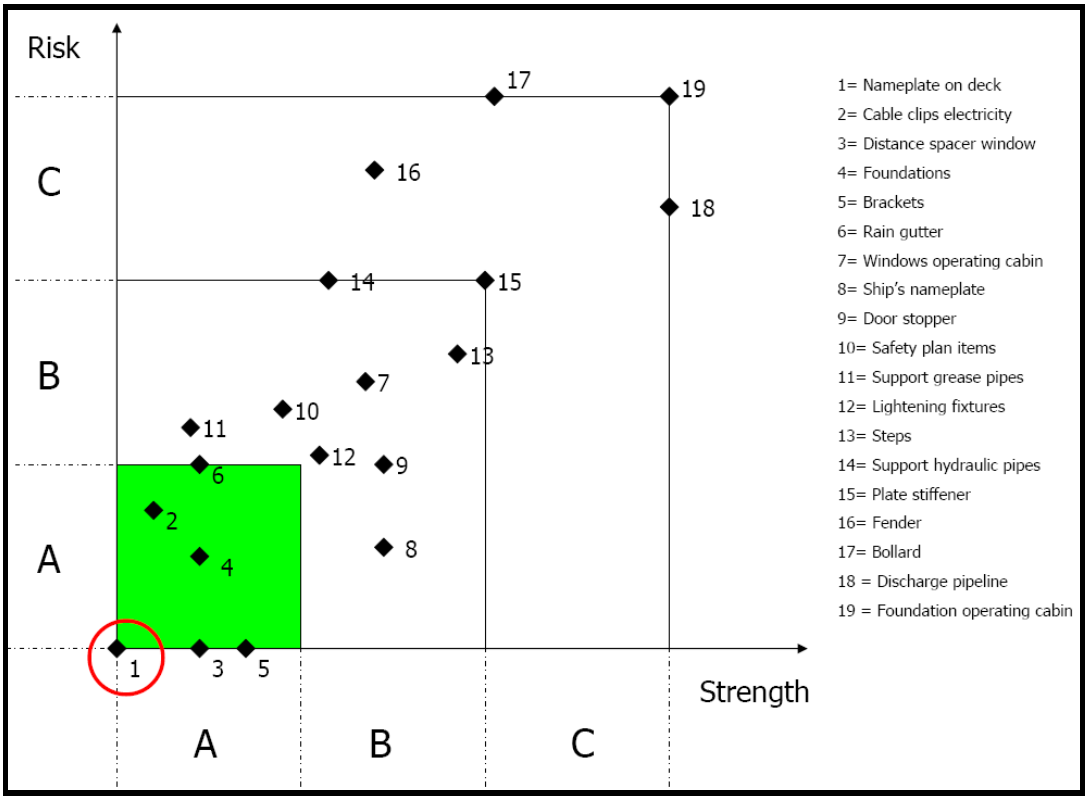


Figure 13 Category A; directly achievable

1	Nameplate on deck 	Nameplates are used to identify the type of pipeline on deck. In the current situation disproportionate time and materials is spent on fixing nameplates on the deck. By using adhesives, nameplates could be directly bonded on a coated surface. In 2009, 1300 of this nameplate brackets were mounted on the deck of both Beaver and custom-built ships.

In a similar way all other potential applications for adhesive bonding have been selected and described in Appendix E. Based on these descriptions appropriate adhesives have to be selected. Appropriate adhesives are selected also using a list of criteria which will be described in the next chapter.

6 Criteria for selecting possible adhesives

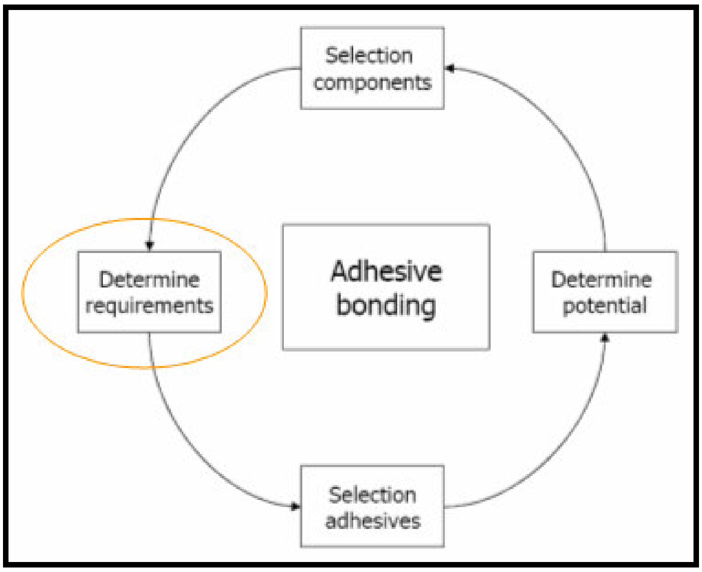


Figure 14 Step 2; determine requirements

Because of the wide range of commercially available adhesives a basic selection of a few possible candidates is necessary. In order to make this basic selection, in this chapter requirements for possible adhesive candidates for the testing program and use in shipbuilding practice are determined.

The adhesive selection process is difficult because many factors must be considered, and there is no universal adhesive that will fulfill every application [13]. It is usually necessary to compromise when selecting a practical adhesive system. Some properties and characteristics that are desired of the adhesive will be more important than others, and a thoughtful prioritization of these criteria will be necessary in selecting an adhesive. One must first find an adhesive that will satisfy the high priority requirements of the application. The lower priority 'requirements' may then need to be compromised to find the best fit.

From the previous survey (literature, interviews, and product data sheets) the following criteria are formulated for selecting an adhesive:

- High priority requirements: criteria the candidate adhesive **must** fulfill in order to be applied in shipbuilding practice (paragraph 6.1)
- Lower priority requirements: requirements which are favorable for appliance in shipbuilding practice (paragraph 6.3)

After the high priority requirements are determined, a first basic selection in possible adhesives can be made by using a questionnaire as tool to identify the lower priority requirements in addition. An example of such a questionnaire is represented in paragraph 6.2.

6.1 High priority requirements

In this paragraph the criteria a candidate adhesive **must** fulfill, in order to be applied in shipbuilding practice, are discussed. From the previous survey (literature, interviews, and product data sheets) the following high priority requirements are formulated for selecting an adhesive:

- Joint design: lifetime of adhesive should be at least 25 years
- Substrate to be bonded: the adhesive must be able to bond to steel
- Service requirements: adhesive should be water resistant
- Production processes: curing should be possible in a temperature range of 10°C - 30 °C

Service life

The service life of a joint should be at least equal to the service life of the product. A service life of 25 years is taken into account for a Beaver. Adhesives which are characterized by a service life of at least 25 years are [5]:

- Structural adhesives, including thermosetting- and hybrid adhesives
- High-performance sealants, with (semi) structural adhesive properties

In accordance to these criteria the adhesives as represented in Figure 15 may be possible candidates for application in shipbuilding. The encircled adhesives in Figure 15 are both (semi) structural adhesives as high-performance sealants.

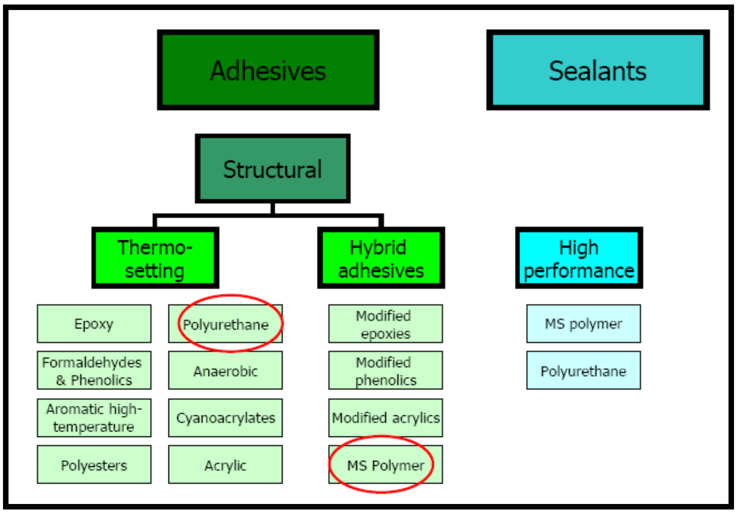


Figure 15 Selection of adhesives and sealants by service life and function

Substrate to be bonded

The following types of substrate are presented in shipbuilding practice:

- Metallic surface
- (Shop)primed surface
- Coated surface

The adhesive should be able to, at least, **bond to metallic surfaces.** A shop-primed or coated surface can, although not favorable, be reduced to a steel surface by grinding or sand blasting. Therefore, bonding to (shop) primed surfaces and coated surfaces is considered as a lower priority requirement in this report.

Water resistance

Because of the environment the adhesive will see in service, the adhesive **must be** water resistant.

Curing conditions

Because of the production environment in shipbuilding practice, with ambient temperatures as low as 0°C, the adhesive should be able to **cure in a temperature range of 10°C - 30 °C.**

The selection of candidate adhesives by the previously described high priority requirements is represented in Table 5. As a first selection, the adhesives must meet the requirement of a lifetime of at least 25 years. The type of adhesives which meet this specific requirement are represented in the first column of Table 5. By meeting this criterion, as a logical consequence, all these adhesives are indicated by 'yes' in the second column (lifetime > 25 year) of Table 5. Subsequently, the adhesives are judged by the other high priority requirements as well. In this way, the adhesives as represented in the first column of Table 5 are narrowed down to a few possible candidates who meet all the previously described high priority requirements. The adhesives which meet all high priority requirements are indicated by a green area while adhesives which do not meet all high priority requirements are indicated by a red area (see Table 5). Finally, this results in a few possible adhesive candidates which could be used in shipbuilding as represented in the last column of Table 5.

Table 5 Selection of candidate adhesives by high priority requirements

Type of adhesive	Fixed criteria					
	Lifetime > 25 years	Bonding metal	Water resistant	Curing in range of 10°C-30°C		Possible candidates
Epoxy	yes	yes	good	yes		Epoxy
Modified epoxies	yes	yes	good	yes		Modified epoxies
Formaldehyde & Phenolics	yes	**no**	good	yes		
Modified phenolics	yes	yes	good	**no**		
Aromatic high-temperature	yes	yes	good	**no**		
Polyester	yes	yes	**fair**	yes		
Anaerobic	yes	yes	**poor**	yes		
Cyanoacrylates	yes	yes	**poor**	yes		
Modified acrylics	yes	yes	good	yes		Modified acrylics
MS polymers	yes	yes	good	yes		MS polymers
Polyurethane	yes	yes	good	yes		Polyurethane

As can be seen in Table 5, possible adhesive candidates to be used in shipbuilding are [5]:

Epoxy: epoxy adhesives consist of an epoxy resin plus a hardener. They allow great versatility in formulation since there are many resins and many different hardeners. They form extremely strong durable bonds with most materials. Epoxy adhesives are available in one-part or two-part form, however, only 2 component types cure at ambient temperatures.

Modified epoxy: a variety of polymers can be blended and co-reacted with epoxy resins to provide certain desired properties. The most common types of modified epoxies are epoxy resins that are **toughened**. Tougheners improve impact, peel, and fatigue properties of the normally brittle epoxy without a corresponding decrease in other properties.

Acrylic: this type of adhesive is particularly noted for its weather and moisture resistance as well as its fast cure at room temperature. Acrylics are often used as pressure sensitive adhesives in the form of a tape.

Modified acrylics: these adhesives are fast-curing and offer high strength and toughness. Supplied as two parts (resin and catalyst), they are usually mixed prior to application. They tolerate minimal surface preparation and bond well to a wide range of materials.

MS polymer: Silyl terminated Modified Polymer also known as Modified Silane Polyether prepared from high molecular weight polypropylene oxide. MS polymers are one part moisture curing adhesives which also provides sealant properties.

Polyurethane: Polyurethane adhesives are commonly one part moisture curing or two-part. Since the two-part type has poor moisture resistance, only the 1 component moisture curing type is considered. They provide strong resilient joints, which are resistant to impacts.

> Note: Additionally, the main characteristics of all types of adhesives available on the market can be found in Appendix I: Adhesives

6.2 Questionnaire

A simple questionnaire such as illustrated in Figure 16 can be used as a tool to select adhesive candidates for testing. The shaded requirements in Figure 16 are the previously discussed high-priority requirements.

1 What materials are being joined?

A The application is to bond ______________ to:

- ☐ Steel
- ☐ Shopprimed steel
- ☐ Coated steel

B The desired surface preparation is: Basic

2 Joint design

A The required service life of the adhesive joint is: ________ years

3 What are the end-use service requirements?

The assembly will be expected to withstand:

A Temperature extremes of: ________ °C ☐ Continuously ☐ Intermittently

B These chemicals or solvents: ______________

☐ Immersion ☐ Vapour ☐ Continiously ☐ Intermittently

C These conditions: ☐ Moisture ☐ Sunlight ☐ Outdoor weathering

D These loads:

- ☐ Shear ________ MPa
- ☐ Peel ________ MPa
- ☐ Impact ________ MPa

4 Which production method will be used?

A The following form of adhesive is preferred:

☐ Liquid ☐ Paste ☐ Film ☐ Powder

B This will be: ☐ Hand application ☐ Machine application

C Desirable equipment:

- ☐ Brush
- ☐ Extruder
- ☐ Knife or trowel
- ☐ Manual dispenser
- ☐ Spray
- ☐ Roll coater
- ☐ Other: ________

D These are the application requirements:

- Viscosity desired ________
- Drying time required ________
- Curing temp. available ________
- Curing time available ________
- Pressure available ________
- Thickness required ________

E If necessarry a 2-part adhesive ☐ can ☐ cannot be used

Figure 16 Questionnaire as a tool for the selection of adhesive candidates

As can be seen in Figure 16, the selection of an adhesive depends primarily on the:

- Substrate to be bonded
- Joint design
- Service requirements
- Production conditions

By using these factors as an addition to the previously described fixed criteria, the many commercially available adhesives can be narrowed down to a few possible candidates for appliance in shipbuilding. In the next paragraph these factors (lower priority requirements) will be further discussed.

6.3 Lower priority requirements

By using the high priority requirements as criteria for selection, the many commercially available adhesives are narrowed down to a few possible candidates for appliance in shipbuilding. However, the final adhesive selection for a specific application must be made considering all of the parameters involved in the **entire bonding process.** Considerations need to be given at the same time to substrates, joint design, surface pretreatment, quality control, application and curing methods and other sub-processes [13, 5]. These lower priority requirements may need to be compromised to find the best adhesive for a specific application.

Although not all data of the different sub-processes is available at this stage, some important considerations were made to further elaborate the basic selection of adhesives at this stage.

6.3.1 Substrates and surface treatments

The nature of the substrate surface is critical for the success of any bonding operation since adhesives must function by surface attachment. By using adhesives as bonding mechanism many different substrates can be bonded. However, in the shipbuilding industry the most commonly substrate surfaces to be bonded are:

- Metallic surfaces (structural steel)
- (Shop) primed surfaces
- Coated surfaces

Metallic surfaces

The ‘surface’ of metals, such as shipbuilding steel, might consist of several, not always homogeneously distributed, regions as shown in Figure 17.

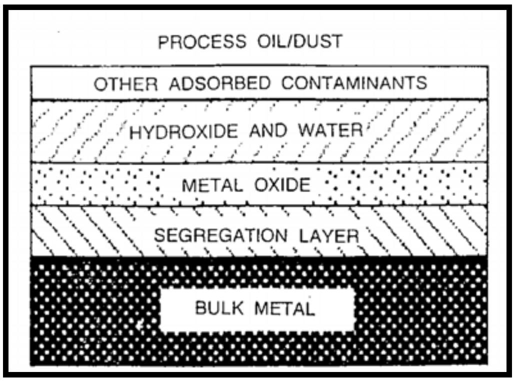


Figure 17 Metal substrate surface regions [5]

Outside the bulk metal, there will likely be a segregation layer of alloying elements. Furthermore, virtually, all metal surfaces are coated with transparent metal oxides that bind at least one layer of water. The nature of the oxide layer depends on the metal beneath the surface and the conditions that caused the oxide surface to grow. Certain adhesives will interact more effectively with certain oxide layers. However, in general it is desired to remove the substrate surface regions and expose the adhesive to the pure bulk adherend material to create an optimal adhesion.

Shop-primed surfaces

For short to medium-term protection of abrasive blast cleaned steel plates and other structural steel during the storage, fabrication and construction periods often a shop-primer is used. These primers provide a degree of corrosion protection to enhance environmental protection.

Coated surfaces

For protection in severely corrosive environment a coating is applied to structural steel. However, bonding to painted parts is not recommended because the resulting bond is usually only as strong as the adhesion of the paint to the base material.

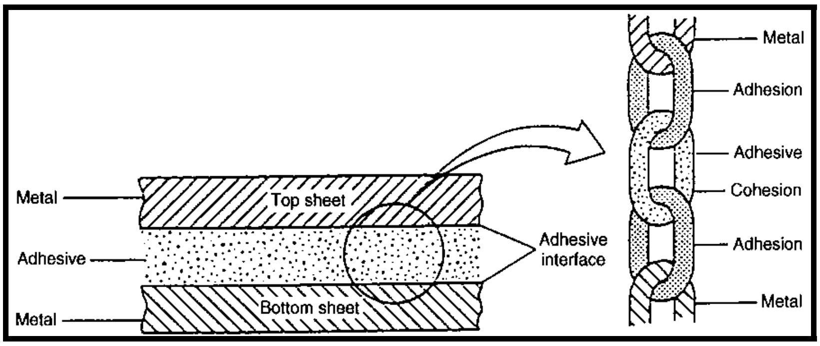


Figure 18 Representation of adhesive joint as a chain [5]

An adhesive joint can be divided into at least five regions that are similar to the links in a chain, see Figure 18. In general, an adhesive joint is as weak as the weakest link in the chain. Therefore, the influence of shop-primer and coating on the strength of a joint should be investigated. It is assumed that bonding directly to steel is recommended.

Surface preparation

The main purpose of surface preparation is to ensure that adhesion develops to the extent that the weakest link in the joint is either the adhesive or the adherend. With optimum surface treatment, failure should not occur at the interface because of a weak boundary layer or insufficient wetting [5,14]. An example of insufficient wetting respectively sufficient wetting of an adhesive is represented in Figure 19.

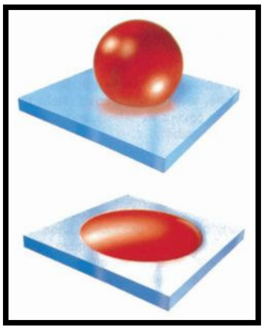


Figure 19 Wetting [15]

Any surface treatment used for bonding requires the completion of one or more of the following operations; cleaning, degreasing, mechanical abrasion or active surface modifications [5]. The cost and quality related to these surface treatments is schematically represented in Figure 20.

Surface treatment	Cost	Quality
None	Inexpensive	Poor
Cleaning	↓	↓
Degreasing		
Mechanical abrasion		
Active surface modifications	Expensive	Excellent

Figure 20 Surface treatment related to cost and quality

The chosen adhesive should bond well to substrates with minimal surface treatment (because of the environmental conditions at a yard):

- Degrease only
- Degrease, abrade and remove loose particles

Abrasion treatment, if carried out, must be followed by a further treatment (repeat degreasing operation, light brushing or air-blasting) to ensure complete removal of loose particles.

In Appendix H, all types of surface treatment methods are described.

A new trend in surface treatments is the use of laser cleaning. With this surface treatment a shop-primed or coated surface can be removed without inserting any heat in the surface. In this way an optimal bonding surface (steel) could be obtained in a simple manner. However, disadvantages are involved in this method either. More information about laser cleaning can be found in Appendix D.

6.3.2 Joint design

Any combination or variation of the stresses, illustrated in Figure 21, may be encountered in an application. As can be seen by the red marks in Figure 21, shear and tensile/compression are favorable stresses for adhesively bonded joints and cleavage and peel stresses should be avoided.

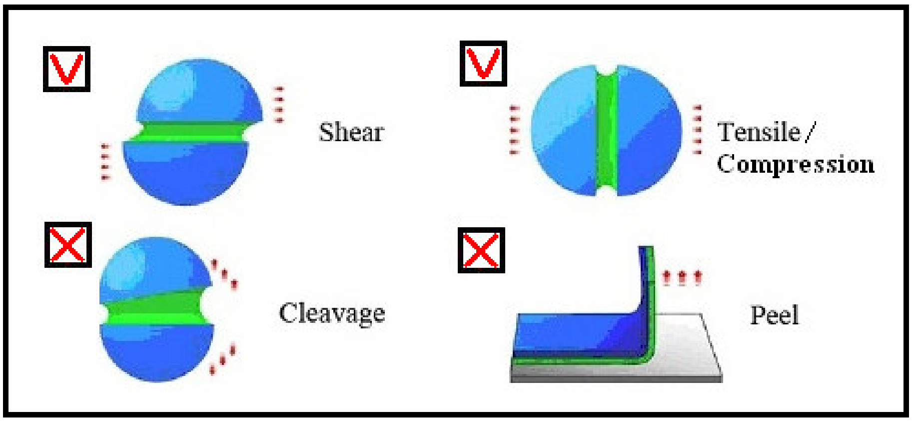


Figure 21 basic types of stress common to adhesives [16]

The basic principles for the design of adhesive joints are general design principles for structures. Consequently, in many cases where adhesive joints shall be used, the surrounding structure has to be designed for adhesive bonding. Sometimes this may require significant changes to structural geometries that were originally designed for welding. Using adhesive bonding, re-design of current components, like shape, materials and finishing, may be required. An example of re-designing is the increase in bonding area as represented in Figure 22.

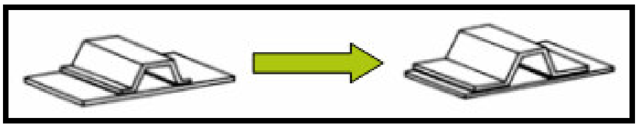


Figure 22 Increased bond area [11]

In general, adhesives have a lower strength than the strength of metallic adherends. In order to reach the strength of a metallic structural joint, the joint should be loaded in shear or compression and the size of the bonding area should be sufficiently large. According to the general design rules and the mechanical strength of adhesives **any peel load should be avoided.**

To obtain a proper joint design, several variables are taken into account by the design of adhesive joints. The rules which form the basis for common adhesive joint designs are described in Appendix C.

6.3.3 Service conditions

Loads

The type of stress loading will have a significant effect on the strength of a joint. As mentioned before, shear forces are best for an adhesive joint and peel and cleavage forces should be avoided. The required shear strength for the selected adhesives should be > 15 MPa for structural adhesives and > 2 MPa for high-performance sealants with semi-structural properties. As an indication, 15 MPa shear strength is comparable with bonding the weight of 300 elephants on a bonding surface area of 1 square metre (see Figure 23).

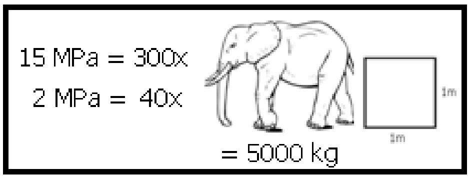


Figure 23 Illustrated indication of shear strength

However, in practise not all applications will be loaded in 100% shear and some degree of peel forces may occur. In order to resist these peel forces, toughness of the adhesive is required. Additionally, toughness is required also to resist impact loading which may occur during the operational status of the ship.

Resistance to environmental conditions

The operating temperature range is an important issue in selecting a proper adhesive. The adhesive should have a temperature range above the normal operating temperatures.

Therefore, a temperature range of -20°C to 80 °C is required. Because of the application in a marine environment, it is important that the selected adhesive provides a good chemical resistance (resistance to gasoline, lubricating oils, acids etc.) as well.

In addition to the 'in service' temperatures and the required chemical resistance, weather conditions are an important factor in the durability of the adhesive bond as well. For metallic joints the most common mode of failure in outdoor environments is corrosion of the substrate and resulting weak boundary layers at the interface due to moisture penetrating the adhesive and adsorbing on substrate surface. Therefore, as mentioned before, the selected adhesive **must** be water resistant (high priority requirement). In order to properly resist outdoor weathering the adhesive should, besides moisture or humidity, withstand UV radiation as well.

6.3.4 Production conditions

The conditions under which the adhesive is to be bonded are important parameters in choosing the right adhesive. Certain circumstances (temperature, dimensional tolerances, etc.) on a yard restrict the type of adhesives that can be considered. The most important production considerations are the method chosen for application of the adhesive and the curing conditions such as temperature and pressure.

Application of the adhesive

The method chosen for the application of an adhesive to the work piece is determined by the size and shape of the parts being bonded and the number of components to be bonded. Because of the high costs to mechanise or robotize a bonding operation and the pre set boundary condition of a remaining layout of the yard, a manual bonding process is desired. Moreover, in shipbuilding practise, it is more convenient to carry a (lightweight) handheld gun, especially during outfitting.

Figure 24 Handheld dispensing gun

Because of hand application a low viscosity or thixotropic form of the adhesive is desirable. This form of adhesive provides an easy coverage of the bonding area and minimizes spillage of adhesive during the bonding operation. Shipbuilding is characterized by large dimensional tolerances. In the quality acceptance standard of IHC beaver Dredgers the flatness of constructed panels is described according to IACS (International Association of Classification Societies) [17]. The maximum admissible deformation of a constructed panel is indicated in Figure 25 as q. The maximum value for q is 8 mm per 1000 mm, i.e. an admissible deformation of 0, 8 % of the length. Therefore in some cases adhesives with gap filling properties up to 8 mm are desired.

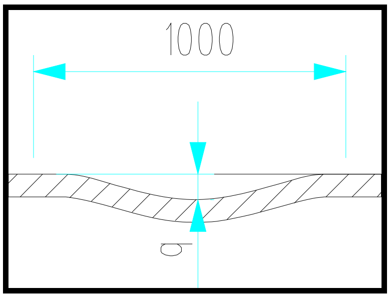


Figure 25 deformation q

Curing conditions

As already mentioned, the available curing temperature on a yard can be as low as 0 °C. Therefore, the adhesive **must** be able to cure in a temperature range of 10 °C – 30 °C. The available curing temperature influences the curing time of an adhesive. As a rule of thumb, for each degrease in temperature of 10°C, the curing time of the adhesive may be doubled. From production point of view a fast curing process is desired. Therefore, an adhesive should be cured in less than 8 hours to reach handling strength.

A fast curing adhesive, in turn, is characterized by a fast processing time. For some Methacrylate adhesives the processing time may be only 3 minutes. Because a manual bonding process is desired, a longer processing time is required. A processing time of 10 – 60 minutes is held as requirement for IHC Beaver Dredgers.

During the curing of an adhesive, a low toxicity of the adhesive is desired to provide a safe and healthy environment for the employees on site. Finally, the use of jigs and fixtures should be minimized or avoided if possible. No fixation or a short fixation is desired.

Cost

Although not decisive, a low price of adhesive material costs is desired. However, a final application of adhesive bonding will be mainly judged on the cost-price compared to welding. It is evident that the cost price for adhesive bonding should be lower than the cost price for welding.

6.4 Sub conclusion: selecting adhesives for testing

Choosing an adhesive is an iterative process and the final adhesive selection for a specific application must be made considering all of the parameters involved in the **entire bonding process.**

However, by using the high priority requirements and the lower priority requirements from paragraph 6.1 and 6.3 and the questionnaire as represented in paragraph 6.2, a selection of adhesives for the testing program can be made as shown in Table 6. Each requirement is rated by a number in the range of 1 to 5, representing a very poor characteristic respectively a very good characteristic of the adhesive. Subsequently, the score for each requirement is multiplied with a weigh factor of 1 to 3, depending on the level of priority. Finally, these values are added together to a final score.

Table 6 Adhesive selection for testing program by high- and lower priority requirements

	Weigh factor	Epoxy (2C)	Modified epoxy	Acrylic	Modified acrylic	MS polymer	Polyurethane (1C)
Substrates and surface preparation							
Bonding to:							
Steel	3	5	5	5	5	5	5
Various substrates	2	4	4	4	4	4	4
Surface preparation							
Tolerance to poor surface preparation	2	2	5	3	5	5	4
Joint design							
Service life 20-25 year	3	5	5	5	5	5	5
Service conditions							
Loads							
Resistance to shear	2	5	5	4	5	3	3
Peel strength	2	2	4	2	4	4	4
Impact	2	2	4	2	4	4	4
Environmental conditions							
High temperature resistance	2	4	4	3	4	3	2
Low temperature resistance	2	3	4	3	4	4	4
Chemical resistance	2	4	4	4	4	3	3
Water resistance	3	4	4	4	4	4	4
Weather resistance	2	4	4	4	4	4	3
Production considerations							
Application of the adhesive							
Thickness; gapfilling	2	1	3	3	3	5	5
Curing conditions							
Curing at ambient temperatures (≤ RT)	3	5	5	5	5	5	5
Fast curing	2	4	4	4	5	3	1
Safety and health							
Low toxicity properties	1	3	3	3	3	4	2
Cost							
Adhesive material cost	1	3	3	3	2	4	4
Total		133	153	135	154	149	137

Notes: Shaded requirements are high priority requirements
Rating: 1 = very poor, 2 = poor, 3 = medium, 4 = good, 5 = very good
Weigh factor: 1= low priority, 2= medium priority, 3= high priority

The red encircled adhesives in Table 6 represent the adhesives with the highest score. Since the selection of adhesives for the testing program is based on the highest scoring adhesives, the following adhesives are selected for the testing program (red circles in Table 6):

- Epoxy versus modified epoxy: modified epoxy (toughened)
- Acrylic versus modified acrylic: modified acrylic (toughened)
- MS Polymer versus Polyurethane: MS Polymer

The benefits of toughened structural adhesives are apparent compared to conventional rigid adhesives. Tougheners improve impact, peel, and fatigue properties of thermosetting adhesives without a corresponding decrease in other properties.

The type and nature of the substrate to be bonded and the required surface preparation are prime factors in determining which adhesive to use.

It may be concluded that certain components should be re-designed (shape, material, finishing) before adhesive bonding can be applied successfully.

The adhesive selection is mainly based on general factors such as the anticipated service environment and manufacturing requirements. However, not all requirements can be monitored properly by a score. For example, a good adhesion to various substrates does not ensure a good adhesion to a shop primed or coated surface. Therefore, testing is required to determine these adhesion properties.

7 Testing adhesives

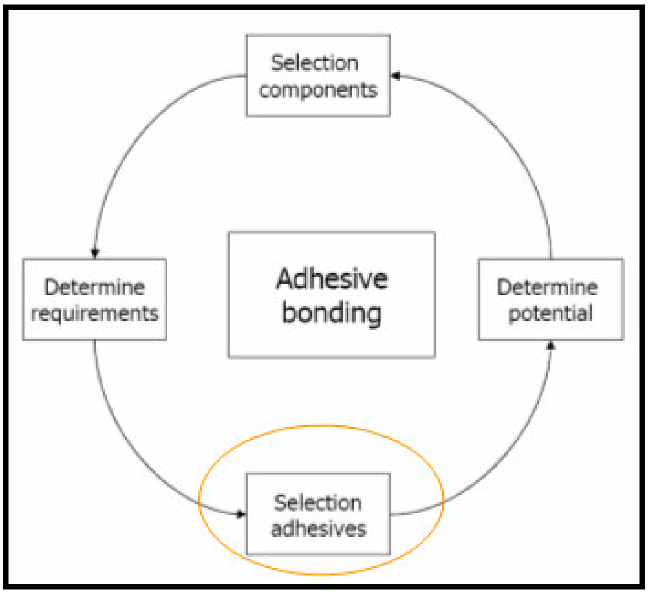


Figure 26 Step 3; selection of adhesives by testing

The information provided by adhesive suppliers, is just an indication of the strength of the adhesive. These tests are usually performed under controlled conditions. Moreover, no information regarding to the adhesion capacity to the specific substrates (shop-primer, coating) used at the yard of IHC Beaver Dredgers is available at this moment. Therefore, testing of the previously selected adhesives is required to determine these adhesion properties.

In the performed tests the shear strength of the selected adhesives on different substrates (steel, shop primer, coating) is tested with single-lap-joint adhesively bonded specimens by tension loading. The method of testing is described in paragraph 7.1, the results of the performed test program are represented in paragraph 7.2.

Although laboratory test results cannot be readily translated into specific strength values for an actual production joint, the performed tests can give an indication of the variation in adhesion strength of the adhesives when applied to different substrates. The obtained test results are evaluated in paragraph 7.3, followed by a sub conclusion in the final paragraph of this chapter.

7.1 Test program

The adhesives are tested by a lap-shear method. This is the most commonly used test as the specimens are inexpensive, easy to fabricate, and simple to test. The test is carried out by pulling the two ends of the overlap in tension with a 3-tons static test machine causing the adhesive to be stressed in shear (see Figure 27).

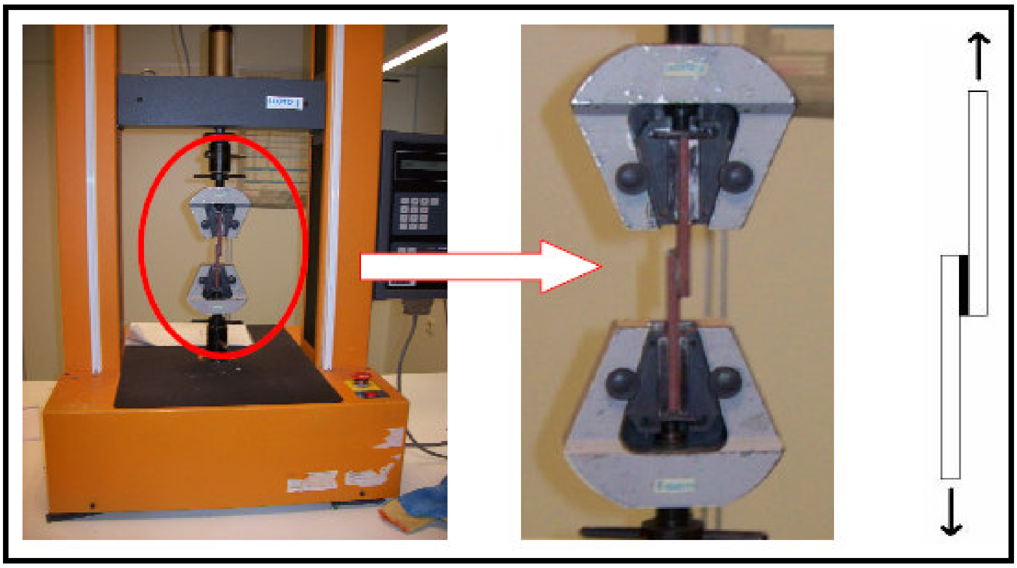


Figure 27 3-tons static test machine

> Note: It is difficult to minimize or eliminate bending stresses in common shear joint specimens. Because the standard lap shear tests introduce some degree of peel into the adhesive joint, lower and less realistic strength values are obtained than with modified lap shear tests as described in Appendix G: Test methods.

The lap shear tests are performed in order to determine the strength of the selected adhesives in combination with a selected pre-treatment and substrate. The selected adhesives are shortly described in subparagraph 7.1.1. Each of these adhesives is tested in combination with three types of substrates (steel, shop-primer, and coating). The exact composition of these substrates is described in subparagraph 7.1.2. For all tests, specimens with similar geometry are used, which is represented in subparagraph 7.1.3.

7.1.1 Selected adhesives

In the previous chapter a modified epoxy (toughened), modified acrylic (toughened) and a MS Polymer adhesive were selected for the testing program. Although the types of adhesives to be tested were known, still a wide range of adhesives to choose from were available. Therefore, an adhesive supplier, VIBA [18], was contacted to help to narrow the choice of adhesives. The following adhesives were selected in cooperation with the adhesive supplier:

- Araldite 2048: two component toughened methacrylate adhesive system
- Araldite 2022: two component toughened methacrylate adhesive system
- Araldite 2015: two component epoxy (toughened) paste adhesive, **Lloyd's approved**
- 3M VHB Tape 5952: modified acrylic adhesive on both sides of very conformable foam
- Puraflex 6006: one-component moisture curing MS polymer

As can be noticed, two MMA adhesives were selected for the test program; araldite 2048 and araldite 2022. Araldite 2048 is slightly faster curing, characterized by higher shear strength and has got better gap filling properties compared to Araldite 2022. On the other hand, Araldite 2022 is better resistant to petrol and oils. The possible differences in adhesion between both MMA adhesives to a shop-primed or coated surface are unknown and should be further investigated by the test program.

Additionally to the adhesives as selected in chapter 6, a 3M VHB (very high bond) industrial tape is selected. This tape can be used in shipbuilding practice to fulfill the function of:

- A **positioning tool** during the curing of another adhesive
- A **distance spacer** to create an optimal bond line thickness

Application of adhesives

Before the adhesive is applied, firstly the environmental conditions are reported. Key parameters are temperature, time and humidity. The dew point depends on the relative humidity and the surrounding temperature. To prevent condensation and the associated decrease in adhesion strength of the adhesive the material temperature should be at least 3 °C above the dew point. As can be seen in Table 7, this applied for all performed tests.

Table 7 Environmental conditions during tests

Lijm	Omgevingsomstandigheden						
	Datum	Tijdstip	Temp. (°C)	% Relatieve vochtigheid	Materiaal temp. (°C)	Dauwpunt	Dikte d (mm)
MMA 2048	18-2-2010	11:30	21	33	19	9,61	0,1
MMA 2022	18-2-2010	12:00	21,9	32	21,5	10,24	0,1
Epoxy 2015	18-2-2010	12:25	22,4	32	22,5	10,80	0,1
VHB 5952	18-2-2010	13:45	21,2	32	21,6	9,44	1,1
MSP 6006	18-2-2010	13:10	21,3	32	21,8	9,56	1

Subsequently all surfaces are pre-treated using **IPA (Isopropyl Alcohol) as a cleaner.** The surfaces are wiped off with a series of straight, light strokes applied using a paper towel.

After cleaning the bonding surfaces the adhesive can be applied. To prevent the bond surfaces from moving relative to one another during the curing process and to ensure a controlled thickness of the adhesive clamps are used. The method used for clamping the test specimens is represented in Figure 28.

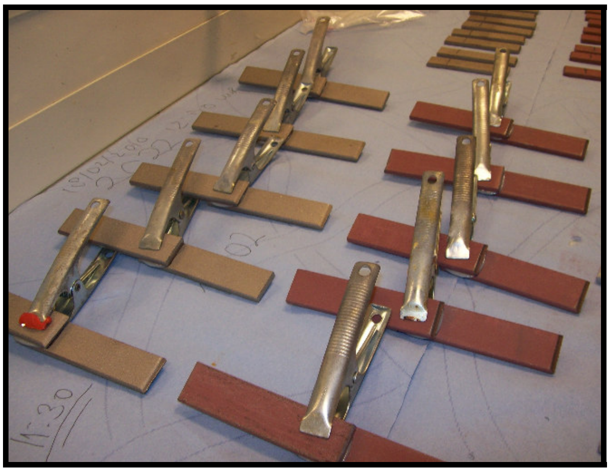


Figure 28 Clamping method

7.1.2 Substrates to be bonded

The main goal of the test program is to determine the adhesion capacity to the specific substrates (steel, shop-primer, coating) used at IHC Beaver Dredgers. Therefore, a total amount of 150 samples were fabricated at IHC Beaver Dredgers, as shown in Figure 29.

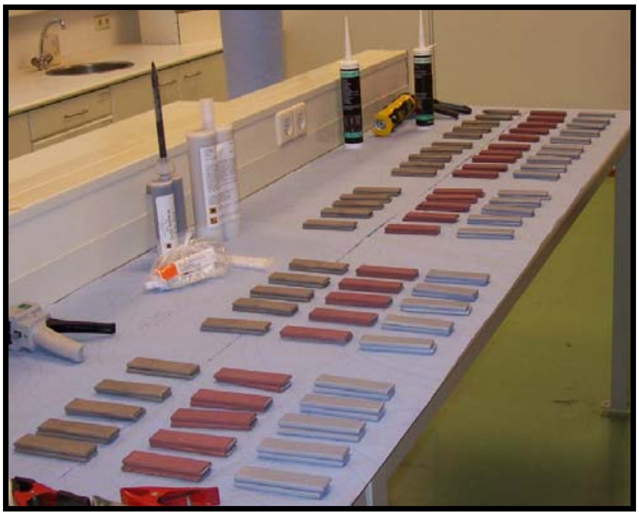


Figure 29 Fabricated samples

Three types of samples are fabricated, as shown in Figure 30. Fifty samples are blast cleaned to remove rust and millscale till SA 2.5, fifty samples are shop-primed and fifty samples are coated with a coating system.

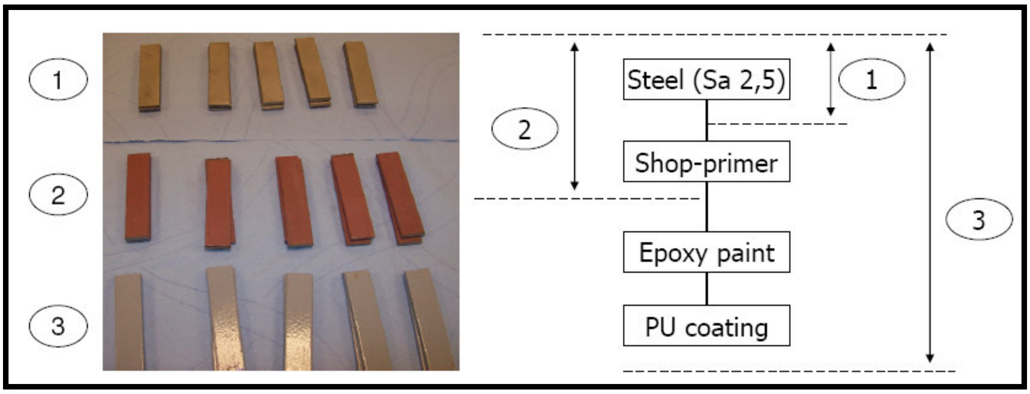


Figure 30 Substrate compositions

The numbers in Figure 30 correspond with the following substrates:

1. Blast cleaned steel till SA 2.5
2. Blast cleaned steel treated with one coat of low zinc (ethyl) silicate prefabrication primer (Sigmaweld MC) of about 15 µm thickness
3. Coating system:

- 1 x 15 µm shop-primer (Sigmaweld MC)
- 1 x 100 µm two-component epoxy paint (Hempadur 15570)
- 1 x 50 µm two-component polyurethane coating (Hempathane topcoat 55210)

The composition of the coating system is chosen in cooperation with the painter (de Koning) and forms a representation of the coating systems used in shipbuilding at IHC Beaver Dredgers. The coating system for the test specimens is applied by the painter on location at the yard of IHC Beaver Dredgers.

It should be noticed that in practice there are a lot of variables that influence the adhesion of coatings [19]. For example, for the tested coating system the polyurethane coating is applied within a few days on the epoxy paint. In practice this is often done after a much longer time resulting in a lower adhesion capacity and quality of the coating system. Furthermore, the coating system of the test samples is applied at the same time. However, in practice different areas and parts of a ship are painted at different times by different painters. This results in inconsistency of the film thicknesses of the coating system, adhesion capacity and quality of the coating system too.

7.1.3 Test specimens

The geometry of the test specimens are determined in cooperation with an adhesive supplier (VIBA), they all have the same dimensions. The geometry parameters of the test specimens are represented in Figure 31.

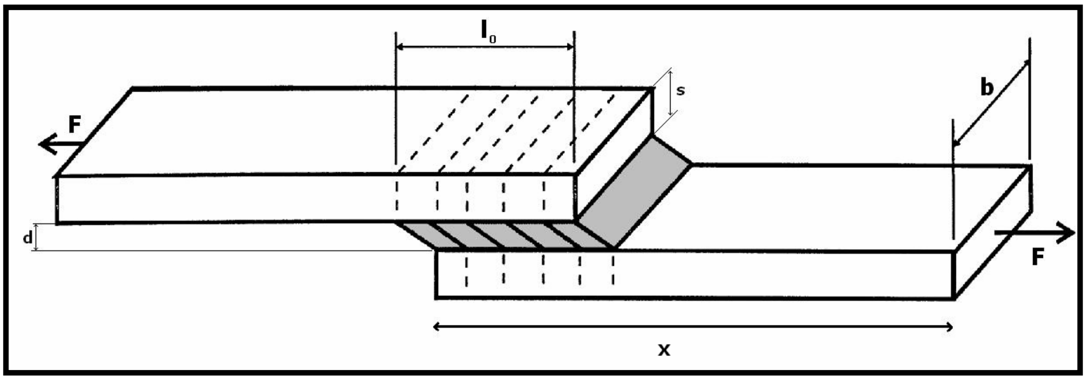


Figure 31 Geometry of test specimen

Length of the overlap region:	l_0 = 25 mm
The width of the joint:	b = 25 mm
Length of the sample:	x = 100 mm
The thickness of the adherend:	s = 5 mm
The thickness of the adhesive layer:	d = 0.1 - 1.1 mm (depends on type of adhesive)

The geometrical parameters as represented in Figure 31 have the following values:

An overlap length, l_0, of 25 mm and a width, b, of 25 mm create a total bonding area, A, of 25 mm x 25 mm = 625 mm^2.

Each combination of adhesive and surface has been tested with a sample population of five specimens. As mentioned previously, 5 adhesives and 3 different substrates were selected for the test program. Hence, a total amount of 75 tests is performed during the test program.

7.2 Results of tests

From the performed tests the shear strength, τ, of the selected adhesives on different substrates (steel, shop primer, coating) can be determined by dividing the applied tension load at failure by the bonding area of the test specimen. For example, if a tension load until failure of 11670 Newton is measured, the corresponding shear strength can be determined by:

$$\tau = \frac{F}{b \cdot l_0} = \frac{11670\,N}{25\,mm \cdot 25\,mm} = 18{,}67\ \text{N/mm}^2 = 18{,}67\,MPa$$

In a similar way the shear strengths for all performed tests are determined. Subsequently, from each sample population of five specimens the mean shear strength value is calculated for each combination of adhesive and substrate. This results in a graph as represented in Figure 32.

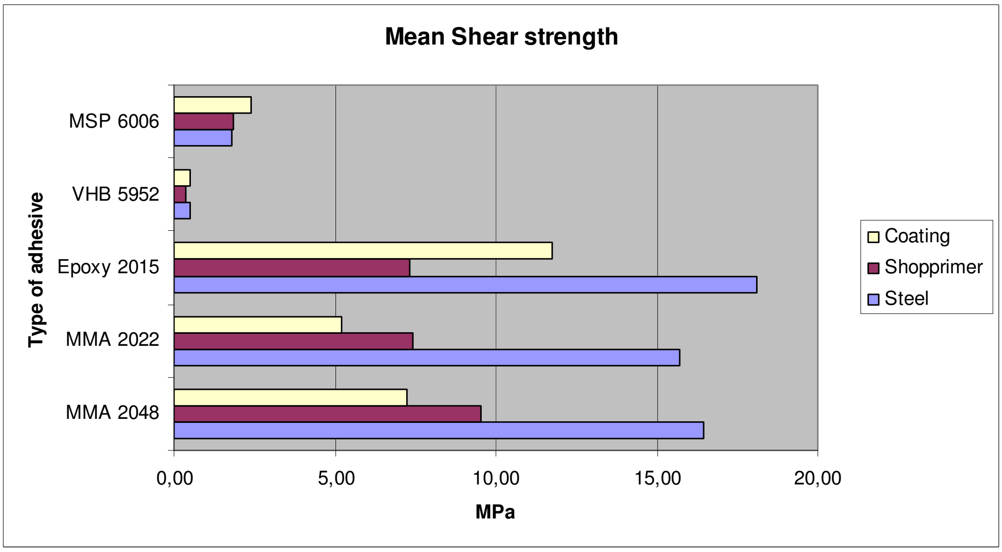


Figure 32 Mean shear strength of adhesives on different substrates

As can be seen in figure 32, adhesion to steel provides the highest bond strengths for structural adhesives (MMA 2022, MMA 2048, Epoxy 2015). Semi structural adhesives (MSP 6006, VHB 5952), on the other hand, provide better adhesion to coated surfaces than to steel. The difference in adhesion capacity of the tested adhesives to a shop-primed or coated surface compared to the adhesion capacity to blast cleaned steel is represented in Figure 33. In this graph the difference in shear strength compared to steel is expressed in a percentage. A negative percentage, e.g. -60%, represents a reduction in adhesion compared to steel while a positive percentage, e.g. 10 % represents an increase in adhesion compared to steel.

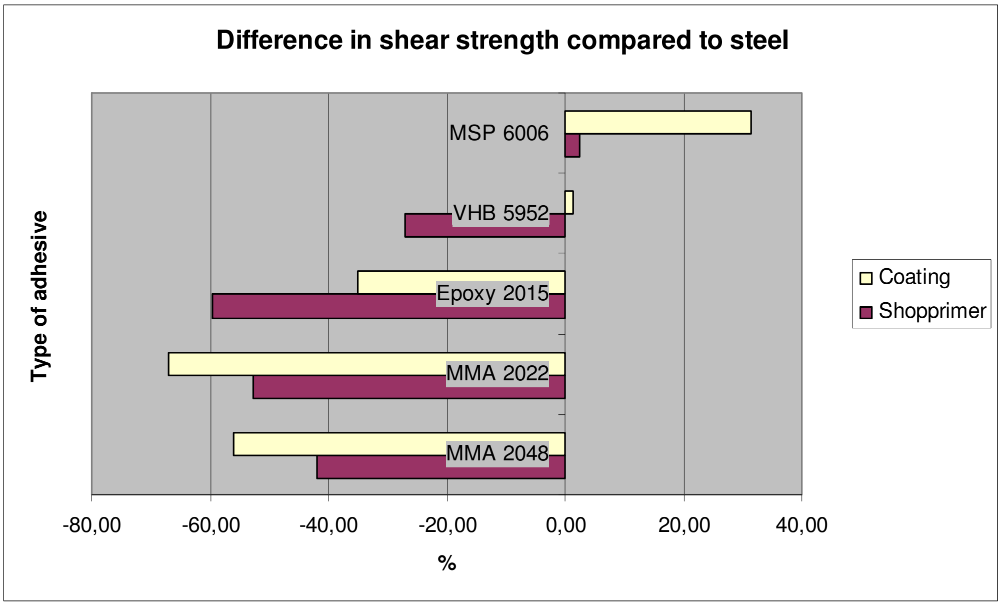


Figure 33 Difference in shear strength compared to steel

In Figure 33, one can see that bonding to a coated surface is preferable for the semi-structural adhesives. However, for the structural adhesives (MMA 2022, 2048 and Epoxy 2015) bigger differences in adhesion to the different substrates compared to steel can be seen in Figure 33. The main differences in adhesion between the **structural adhesives**, regarding to the bonded substrate, are described below.

Adhesion to steel: as mentioned previously, adhesion to steel provides the highest bond strengths for all structural adhesives tested. However, the strongest bonds to steel are provided by epoxy adhesive (Epoxy 2015).

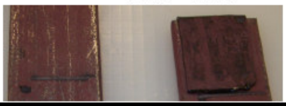
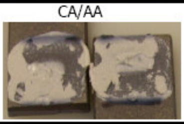
Adhesion to shop-primer: bonding structural adhesives to shop-primed surface results in a significant reduction, 40 - 60 %, in adhesion compared to adhesion to steel. The adhesion to shop-primed surfaces is for both MMA adhesives and Epoxy comparable.

Adhesion to coating: although both epoxy (35%) and the MMA adhesives (±60%) show a reduction in strength compared to steel, the tested epoxy adhesive provides significant better adhesion to a coated surface than both MMA adhesives.

The differences in test results regarding to shear strength on different substrates, as represented in Figure 32 and Figure 33 is further evaluated in paragraph 7.3.

In the testing of adhesive joints, not only the strength properties but also the appearance of the fracture are decisive. For each sample, the relationship between adhesive failure and cohesive failure must be specified, because only then can the influence of substrates on the bond be specified. A representation of the type of failure for each sample population (5 samples) on the different substrates is represented in Table 8. The type of failure is illustrated by a picture and described by an abbreviation. A clarification of the used abbreviations is presented in Table 8 too.

Table 8 Types of failure

Adhesive	Types of failure		
	Steel (A)	Shop-primer (B)	Coating (C)
MMA 2048 I	CA/AA 	AP/CP 	CC 
MMA 2022 II	CA/AA 	AP/CP 	CC 
Epoxy 2015 III	CA/AA 	AP/CP 	CC/AP 
VHB 5952 (1,1mm) IV	CA 	AA/AP + AA/CA 	CA 
MSP Puraflex 6006 V	CA/AA 	CA/AA 	CA 
	AA= Adhesion failure Adhesive AP= Adhesion failure Primer	CA= Cohesion failure Adhesive CP= Cohesion failure Primer	CC= Cohesion failure Coating

Evaluating the type of failure in the semi structural adhesives (MSP 6006 and VHB 5952) it can be seen that failure is mainly caused by cohesive failure of the adhesive (indicated as CA in Table 8).

In general the types of failure of the structural adhesives, represented by the MMA adhesives and Epoxy adhesive, are similar. However, looking more closely one obvious difference can be noticed between the epoxy adhesives and both MMA adhesives in adhesive failure. When bonded to coating, the type of failure which occurs using a MMA adhesive is caused by cohesion failure of the coating (CC) while a combination of adhesive failure of the primer and cohesion failure of the coating occurs (AP/CC) using epoxy adhesive. As mentioned previously, the corresponding shear strength for the MMA adhesives on coating is significant lower than with epoxy adhesive. Therefore, a relationship between the type of failure and the difference in shear strength on coating between MMA adhesives and epoxy adhesive might be assumed. In paragraph 7.3 hypotheses are formulated and verified to explain this difference in shear strength and type of failure between both type of adhesives.

7.3 Interpretation of test results

As mentioned previously, some differences in strengths and type of failure can be noticed between the test results for the different adhesives. Therefore, the obtained test results are evaluated in this paragraph. Additionally, a safety factor is determined for the use in the design of bonded joints.

7.3.1 Difference in shear strength on coating

Main goal of the test program was the determination of the adhesion capacity to the specific substrates (shop-primer, coating) used at the yard of IHC Beaver Dredgers. The most striking results can be seen in the difference in shear strength on coating between epoxy and MMA adhesive as represented by the red marked areas in Figure 34.

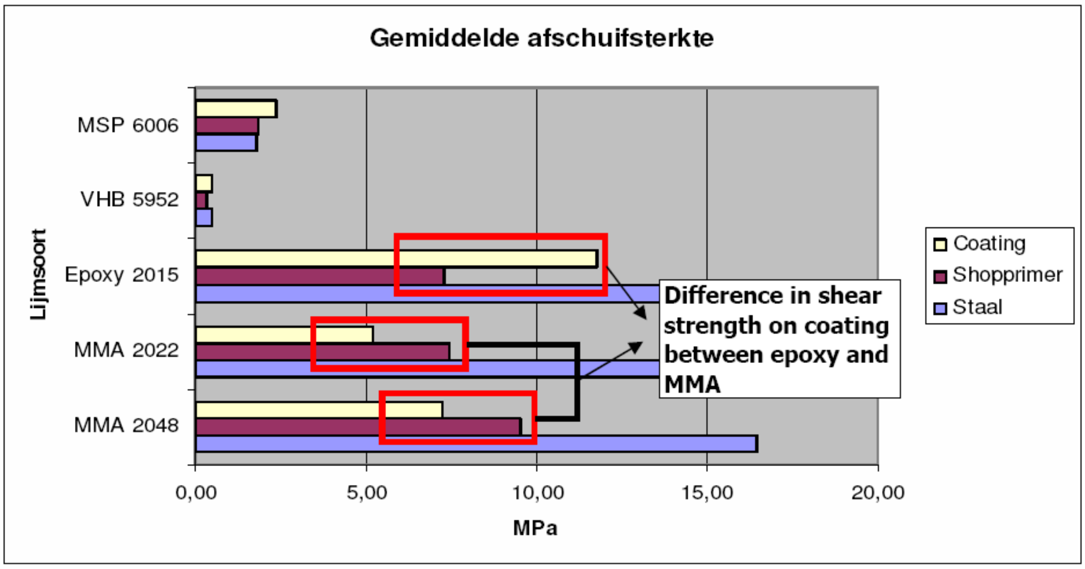


Figure 34 difference in shear strength on coating

As shown in the red marked areas in Figure 34, adhesion of the tested epoxy adhesive to a coated surface is much higher than the adhesion of a MMA (Methyl Methacrylate) to a coated surface. Remarkably, the value of adhesion of the epoxy to a shop-primed surface is comparable to the value of adhesion of MMA to a shop-primed surface. Although these values are comparable for both types of adhesives, the adhesion to shop-primed surface relative to the adhesion to a coated surface shows a major difference between both adhesives again.

Adhesion of the epoxy to a shop-primed surface is lower than the adhesion to a coated surface while for MMA adhesives the adhesion to a shop-primed surface is higher than the adhesion to a coated surface.

In order to formulate an explanation for these differences, interviews were performed with coating specialists and adhesive suppliers [19]. In cooperation with these specialists the following **hypotheses** were formulated:

A. Difference in wetting ability

B. Weakening of coating by solvents/plasticizers in MMA

C. Additional reaction to steel while bonding to shop-primer

A. Difference in wetting ability

In Figure 35 the different regions of an adhesive joint are schematically represented for bonding an epoxy to a coated surface (marked by **a**) and a shop-primed surface (marked by **b**).

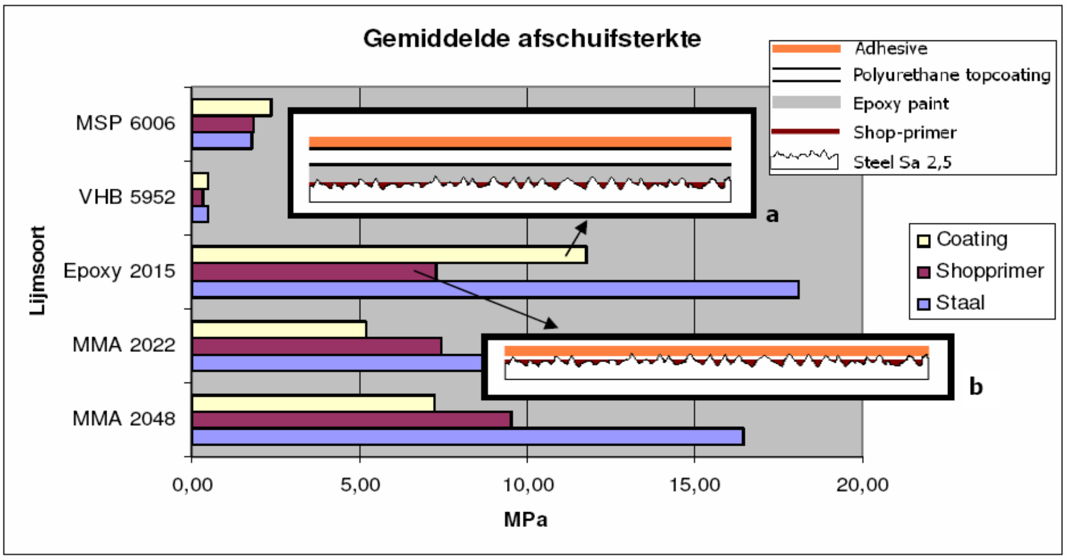


Figure 35 Difference in wetting ability epoxy paint versus epoxy adhesive

Better surface wetting ability of an epoxy paint is likely to result in better penetration of the epoxy paint into the porous zinc silicate shop primer and thus likely to also bond to the steel substrate whilst altering the cohesion properties of the zinc silicate shop primer (see Figure 35a). An epoxy adhesive is not expected to penetrate the porous zinc silicate shop primer to the same degree and it is therefore less likely to obtain the same bond strength compared to the epoxy paint (see Figure 35b). As an epoxy paint does not have the undesirable porosity and cohesion properties of the zinc silicate, this may explain why the bond between epoxy adhesive to the epoxy paint (top coated with polyurethane) shows higher values than the bond strength of epoxy adhesive applied to zinc silicate shop primer.

B. Weakening of coating by solvents/plasticizers in MMA

From the test results a relationship between the occurring type of failure and the difference in shear strength on coating between MMA adhesives and epoxy adhesive might be assumed. The cohesive failure of the coating may be caused by plasticizers or solvents in MMA adhesives which deteriorate the coating system and causing low shear strength values. The shear strength of MMA adhesives to a coated surface is even lower than to a shop-primed surface (see Figure 36). The deterioration of the coating by solvents/plasticizers is schematically represented by the highlighted picture in Figure 36.

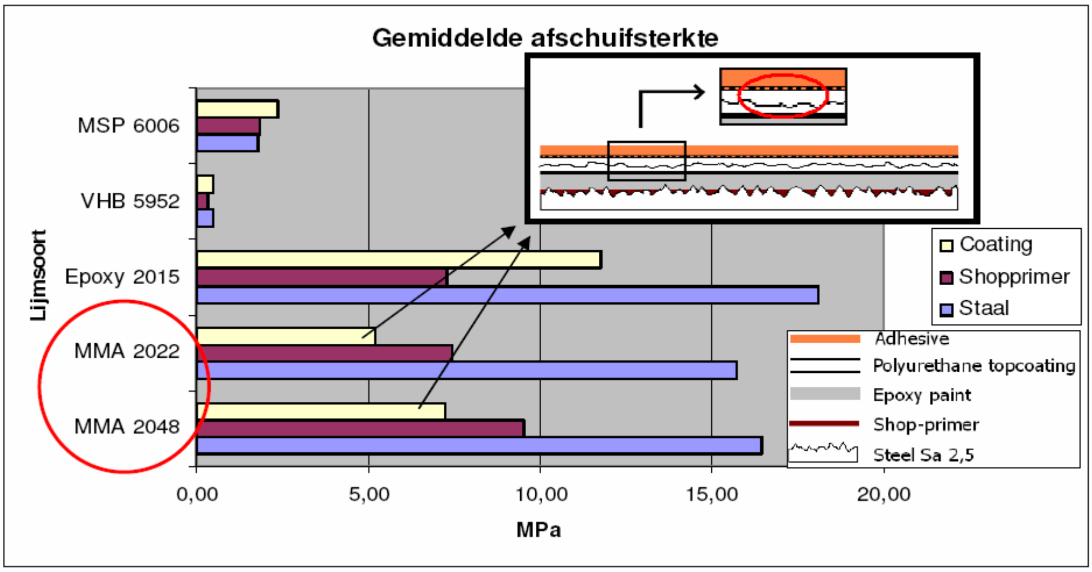


Figure 36 Solvents or plasticizers causing cohesive failure in coating

In the highlighted picture in Figure 36, intrusion of plasticizers or solvents is represented by the orange dots between the adhesive and polyurethane top coating layer (red encircled in highlight). The jagged black line in the polyurethane top coating layer represents the fracture in the coating layer caused by these solvents/plasticizers.

C. Additional reaction of adhesive with steel while bonding to shop-primer

As represented in Figure 37, higher shear strength values for bonding MMA adhesives to shop-primer, compared to bonding to coating, are obtained. It might be possible that bonding to shop-primer results in a stronger bond because the adhesive may not only bond to the shop-primer but also reaction between adhesive and steel may occur due to porosity of the zinc silicate shop-primer and the roughness of the steel surface. This principle is schematically represented in the highlighted picture in Figure 37. In this image, it can be seen that both adhesive (orange layer) as shop-primer (red layer) are in contact with the steel surface (jagged line).

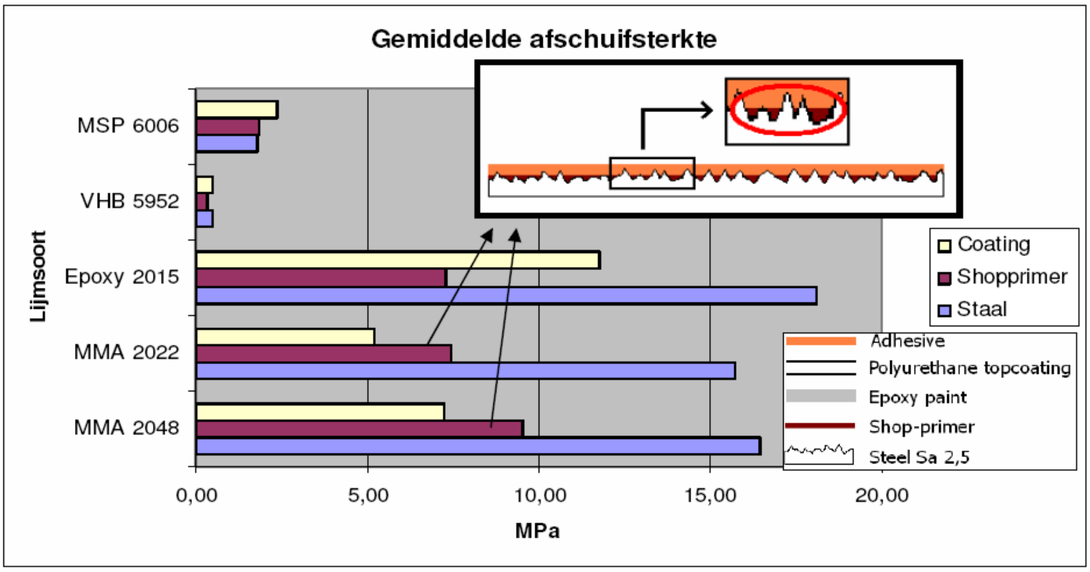
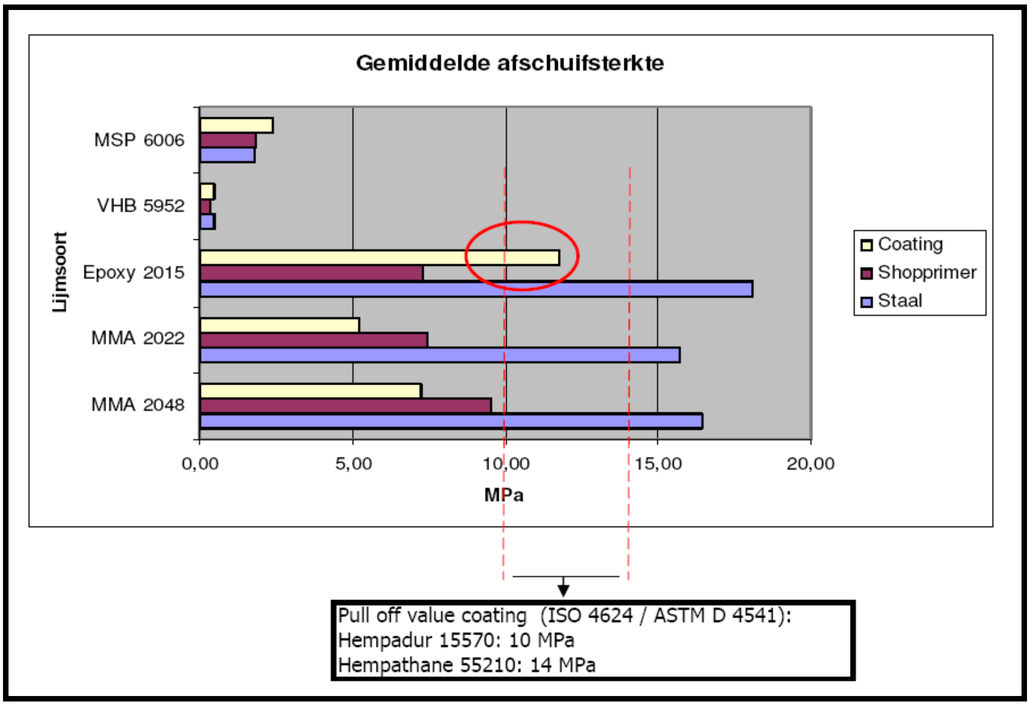


Figure 37 Additional reaction of adhesive with steel while bonding to shop-primer

As can be seen in Figure 37 too, the adhesion of epoxy adhesive to coating is higher than the adhesion to shop-primer. Assuming theory C to be true, a contradiction appears when one looks at the adhesion of epoxy adhesive to shop-primer compared to coating. Therefore, theory C is unlikely to appear in practice.

Conclusion

As an additional verification the pull off values for the coating system as used in the test program, provided by the coating supplier of IHC Beaver Dredgers (Hempel), are used too. The range of the pull of values for the coating system is indicated in Figure 38 by the dotted lines. Looking at these pull off values, in the range of 10 MPa to 14 MPa, the bonding strength of the epoxy on coating shows the most similarity (see the red circle in Figure 38).



Note: the pull off value is obtained by another test method (ASTM D 4541) as the test method used in this report for the testing of adhesive strength. For this reason the pull off value is only used as a basic comparison between the adhesion strength of the coating and adhesion strength of the adhesives to the coating.

Figure 38 Pull off value coating (ISO 4624 / ASTM D 4541)

MMA's do have much lower adhesive strengths on coating than epoxy adhesive. However, the values for adhesion to shop-primer for both epoxy adhesive as MMA adhesive are comparable to one another. Although these values are comparable for both types of adhesives, adhesion of the epoxy to a shop-primed surface is lower than the adhesion to a coated surface while for MMA adhesives the adhesion to a shop-primed surface is higher than the adhesion to a coated surface.

Thus, it is assumable a combination of the **hypothesis A and B** has occurred:

- The difference in wetting ability of the epoxy paint compared to the wetting ability of the adhesives resulted in a better adhesion to coating than to shop-primer.
- Solvents or plasticizers in MMA have weakened the cohesion of the coating resulting in lower bond strength.

7.3.2 Average by mean or median

The obtained measurements from the testing program are represented as a mean value in Figure 34 to Figure 38.

Additionally, as verification, also the median of the test results have been taken. The median can be found by arranging all the observations from lowest value to highest value and picking the middle one.

Table 9 Mean versus median

Adhesive	Shear strength (MPa)					
	Steel		Shop-primer		Coating	
	Mean	Median	Mean	Median	Mean	Median
MSP 6006	1,81	1,78	1,86	1,99	2,38	2,28
VHB 5952	0,49	0,50	0,36	0,37	0,50	0,50
Epoxy 2015	18,09	17,49	7,31	7,39	11,77	11,88
MMA 2022	15,70	16,74	7,43	7,44	5,19	5,60
MMA 2048	16,44	16,51	9,54	9,52	7,23	7,39

As can be seen in Table 9, the differences in mean value and median are negligible. Therefore, only the mean values are reproduced to use for the evaluation of bonding strengths.

7.3.3 Types of failure

As mentioned before, bending forces occur with the simple specimens used in the single lap shear test causing peel at the edges of the lap. This deformation is represented in Figure 39:

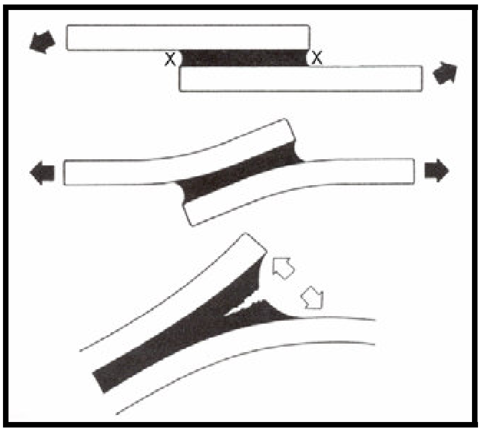


Figure 39 Deformation of single lap joint [20]

Besides the influence of peeling on the obtained shear strength value, also the obtained type of failure is affected. The combination of adhesion failure of the primer and cohesive failure of the coating as test result for bonding an epoxy to coating is taken as an example, see Figure 40. As can be seen in Figure 40, the type of failure is mainly (approximately 60 %) characterized by adhesion failure of the primer by shear. However, because of the deformation of the test specimen a peeling force is introduced at the end of the overlap, leading to cohesive failure of the coating either.

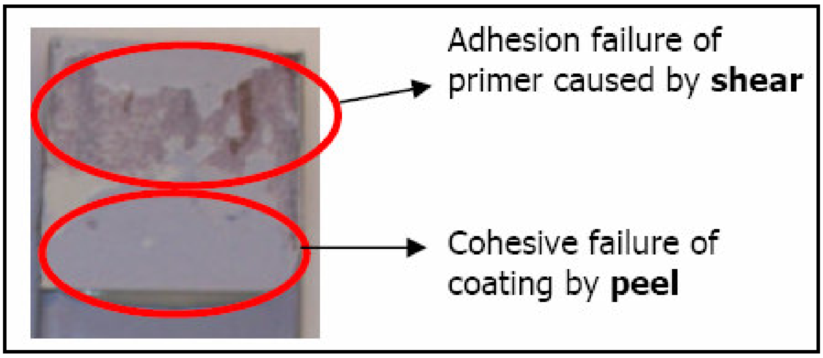


Figure 40 Influence of peeling on type of failure

If another joint design would have been applied, e.g. a double lap joint (see Appendix C and Appendix G), the chances of deformation as represented in Figure 39 are lessened and as a consequence more realistic types of failure are obtained.

7.3.4 Safety factor

Little information is available about a general safety factor to use for the design of adhesive joints. In this test program only the strength of the adhesives on different substrates is tested without considering environmental and in-service conditions. Therefore, an additional safety factor should be used in order to obtain a proper design of the joint.

In order to determinate a reliable safety factor to use in the design of bonded joints, knock-down factors as obtained during the BONDSHIP project [10] are used. These knock-down factors were obtained by ageing and fatigue tests.

Knock- down factors for designing adhesive joints [10]:

$$\begin{aligned} f_T &= Temperature \\ f_{Df} &= Dynamic\ load, fatigue \\ f_M &= Humidity, moisture \\ f_S &= Surface\ preparation \end{aligned}$$

For the remaining uncertainties an additional safety factor S=2 is included.

For dry conditions:

$$\tau_{a,dry} = \tau_f \cdot \frac{f_t \cdot f_{Df} \cdot f_S}{S} = \tau_f \cdot \frac{0.7 \cdot 0.5 \cdot 0.7}{2} = \tau_f \cdot 0.1225$$

For humid conditions:

$$\tau_{a,humid} = \tau_f \cdot \frac{f_{Df,M,T} \cdot f_S}{S} = \tau_f \cdot \frac{0.2 \cdot 0.7}{2} = \tau_f \cdot 0.07$$

Where:

$$\begin{aligned}
&\tau_a = allowable\ shear\ stress \\
&\tau_f = shear\ strength\ adhesive\ (from\ lap-shear\ test) \\
&f_i = knock-down\ factor \\
&S = safety\ factor
\end{aligned}$$

The result for both dry conditions and humid conditions seems quite low. Therefore, a proper joint design is required to obtain higher strength values. As example, increasing a bonding area by a factor 2 will indirectly decrease the effect of the safety factor by a factor 2 either. In the design of bonded joints, the stresses a joint will see in service should always be below the allowable stresses as calculated by using the formulae above. How this effects the design of adhesive joints will be further elaborated in the next chapter.

7.4 Sub conclusion: adhesion properties

From the obtained test results it may be concluded that bonding directly to steel is recommended. This provides the highest bond strength and avoids failure by a weakest link (i.e. shop– primer or coating). For the application in shipbuilding, the use of **Epoxy 2015** adhesive is recommended. This adhesive provides the best adhesion to both steel and coating and is already Lloyd’s approved too. However, taken into account the gap filling possibility and tolerance to bond line thickness variation of the tested MS Polymer, this adhesive will be preferred in applications requiring these specific characteristics. To obtain a more complete overview of adhesive performance, simulation of environmental and in-service conditions during the test program is recommended. However, these more extensively test methods are generally time-consuming and very expensive.

8 Best application

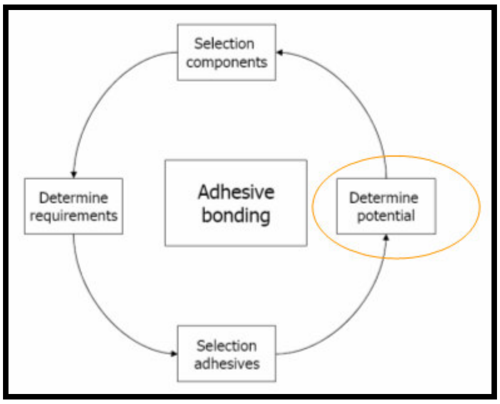


Figure 41 Step 4: determine potential

In the previous chapters the general joint requirements were specified (Chapter 6) and adhesives for the designs of bonded joints were selected by tests (Chapter 7). In this final chapter the potential of adhesive bonding for each component, as selected in chapter 5, is determined.

Firstly, a summary table of the general characteristics of each component and the maximum cost-savings per item is presented in paragraph 8.1. From this summary table one 'best application' is chosen and further elaborated. This elaboration serves as an example for all components described in appendix F. The main characteristics of the 'best application' are described in paragraph 8.2. Subsequently, possible joint designs are established and evaluated according to strength requirements and cost-price in paragraph 8.3.

The impact of the adhesive bonding process in the existing shipbuilding process is evaluated in paragraph 8.4, 8.5, and 8.6.

8.1 Selection of best application

To determine the potential of adhesive bonding for each component, as represented in appendix F, rough pre-designs are sketched and evaluated economically by determining the possible savings in production costs per item and on yearly base compared to welding in appendix F. This evaluation is performed with input of welders and a welding engineer, an adhesive supplier, designers, and sub-contractors (e.g. painter), etc. and is summarized in Table 10.

Table 10 Summary table of potential applications

#	Description	# of items		Pre-outfit	Load description		Substrates		Adhesive	In-service condition	Cost savings [€]		
		Per ship	Annual		[N]	Type	1	2			Per item [€]	Annual [€]	%
	Category A												
1	Nameplate deck	35-65	1287	yes	0	Compression	Brass	Coating	VHB tape	Humid	28,75	37001,25	67
2	Electricity cable	25	75	no	< 10	Shear	Steel	Coating	Epoxy	Dry	23,00	1725,00	69
3	Distance spacer	24-40	994	yes	25	Shear	Steel	SP	Epoxy	Humid	13,42	13336,17	56
4	Horn foundation	1	27	yes	<50	Compression	Steel	Coating	Epoxy	Humid	13,42	362,25	56
5	Manometer plate		100	yes	<50	Shear	Steel	Coating	Epoxy	Dry	13,42	1341,67	56
6	Rain gutter	2 to 34	66	yes	<50	Shear	Steel	Coating	MSP	Humid	2,87	189,75	9
	Total cost savings category A [€]											**53956,09**	**62**
	Category B												
7	Windows	10	90	no	310	Shear	Glass	Coating	MSP	Humid	9,58	862,50	25
8	Ship's nameplate	4 to 6	14	no	1500	Shear	Plastic	Coating	MSP	Humid	2807,92	39310,83	93
9	Door buffer	88		no		Tens./compr.	Steel	Coating	Epoxy	Humid	13,42	1180,67	40
10	Fire extinguisher	16 to 54	87	no	140	Shear	Steel	Coating	Epoxy	Humid	42,17	3668,50	80
11	Clamp grease line	20 to 220	1860	yes	<20	Shear	Steel	Coating	Epoxy	Humid	8,63	16042,50	45
12	Lightening fixture	3	9	no	<60	Shear	Coating	Coating	MSP	Humid	3,83	120,75	35
13	Anti slip bars	1 to 189	654	yes	800	Compression	SP	SP	MSP	Immersion	23,00	15042,00	60
14	Clamp hydraulic	20 to 100	700	no	<32	Shear	Steel	Coating	Epoxy	Dry	23,00	16100,00	69
	Total cost savings category B [€]											**92327,75**	**67**
	Category C												
15	Plate stiffener			yes	27000	Shear	SP	SP	Epoxy	Dry			
16	Fender	96		yes		Peel/compr.	SP	SP	MSP	Humid			
17	Bollard	2	32	yes	20000	Peel	SP	SP	MSP	Humid			
18	Discharge pipeline	1	27	yes		Compression	Plastic	SP	Epoxy	Humid			
19	Foundation cabin	1	27	yes	10000	Compression	SP	SP	MSP	Humid			
	Total cost savings category A and B [€]											**146283,84**	**65**

Note: Category C is in this report mainly evaluated in order to determine the boundaries of strength and design options using adhesive bonding within shipbuilding. For this reason a cost-price analysis for the components represented in category C is of less importance and is not evaluated in this report, as also shown in Table 10.

As shown in table 10, every item is indicated by a number and a description of the item. The number corresponds with the number as represented in Figure 12 in chapter 5. The same figure is represented for each category (A, B and C) in appendix F too. In the following the data represented in each column of Table 10 is shortly discussed.

Number of items

The number of components as represented in Table 10 is based on the production in the year 2009 and by evaluating the production process on site. In 2009, 24 standard Beavers (in different ranges) and 3 custom built ships were fabricated at IHC Beaver dredgers. The number of items are indicated in Table 10 **per** ship and annually. In some cases the number of components has been estimated in consultation with involved parties (subcontractors, designers, etc.).

Assembly stage

A distinction in the use of adhesives in the regular process and in the special case (e.g. forgotten or late delivered items) is made either. Whether a component is assembled in the pre-outfitting phase or the outfitting phase is indicated in a separate column. Welding in outfitting often interferes with other work operations and can destroy paint and outfitting elements. The costs involved with repair (mainly painting) due to attachment of these components in the final assembly stage will be evaluated in the cost-analysis in order to identify the benefits of the use of adhesives in the special case (e.g. forgotten or late delivered items). This cost-analysis, as represented in paragraph 8.3.2 and appendix F, is evaluated in cooperation with involved parties (sub contractors, welders etc.).

Load description

The loads conditions per item are described in Table 10 by the amount and the type of load. As reported previously, those items were selected which favor shear and compressive loads.

Substrates

The selected item is indicated as substrate 1 and the surface the item is to be bonded to is indicated as substrate 2. For example item 1, a brass nameplate, is bonded to a coated deck (substrate 2). The substrates as represented in Table 10, are the substrates to be bonded for the best design option chosen (see appendix F). Other design options for this component, as presented in appendix F, might differ regarding to the substrates to be bonded.

Adhesive

Except item 1, for all items the choice between MS Polymer and Epoxy adhesive have been made. Depending on the re-design options, required bond line thickness and the size of the area to be bonded adhesives are chosen. Therefore, design options as presented in appendix F might differ regarding to the represented type of adhesive in Table 10.

In-service condition

For each item the conditions the item will experience in-service is determined. A distinction is made between humid and dry conditions. For both in-service conditions a previously determined (paragraph 7.3.4) safety factor is taken into account for the joint design.

Cost savings

In the last column of Table 10 the **maximum** cost-savings are represented compared to welding. A distinction is made between the cost savings per item, the annual cost savings and the cost-savings in percentage. These cost-savings are obtained by a comparison between the current designs (welding) and designs wherein adhesive bonding is used. The percentage of cost-savings represented in Table 10, indicates the reduction in cost-price compared to welding. This percentage may also be used to give an indication of the possible cost-savings of an item to be bonded which is not specified in this report.

Conclusion

From this analysis, the adhesive bonding of **component 8; Ship's nameplate** is chosen as 'best application' to be further elaborated in this chapter. This component is yellow highlighted in Table 10. Adhesively bonding of the ship's nameplates the most cost-savings annually (€ 39.310, 83), per item (€ 2807, 92) and reduces the production costs to 93%. Moreover, the impact of the adhesive bonding of a ship's nameplate in the existing shipbuilding process is higher than most other applications. For example, although item 1 (nameplate on deck) provides high cost-saving, this item is very small and non-loaded. Item 8 provides the opportunity to perform a design method for adhesive bonding as an example for the other items as represented in appendix F.

In the next paragraphs **component 8; Ship's nameplate** is further elaborated regarding to joint-design, cost-price and the impact of the adhesive bonding process on the existing shipbuilding process. This elaboration represents the method of joint design and cost-price analysis for both **category A and category B** as described in appendix F. As previously discussed category C is, because of higher risk and strengths requirements, not analyzed in a similar way (see appendix F).

8.2 Main characteristics

Every custom built ship is indicated by nameplates on board. These nameplates are produced by welding steel symbols to a steel plate (2-3 m^2), a very labor-intensive job. Additionally, because of heat input, the nameplate deforms and has to be rolled before attachment on board. The nameplate is attached to welded threaded cams on the wall. Adhesive bonding offers the opportunity to prevent deformations and to use dissimilar materials. A picture of a ship's nameplate is represented in Figure 42.

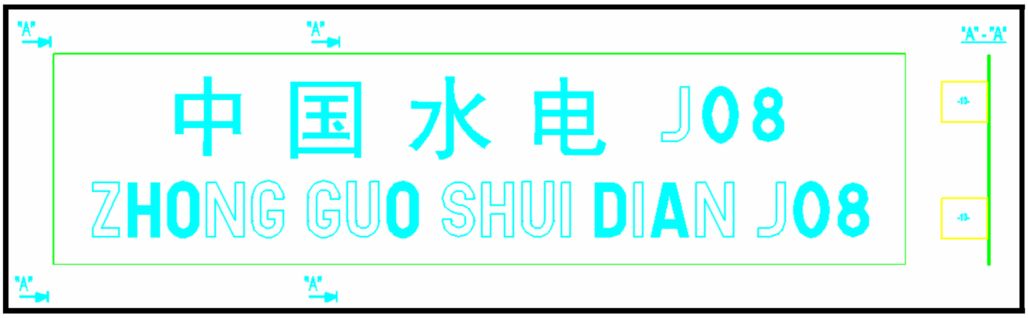


Figure 42 Item 8: Ship's nameplate

The main characteristics for this item are represented in a table, as shown in Table 11. The data in this table is almost similar to the data shown in the previous summary table (Table 10). However, additionally to the previous table, the geometry of the item is represented in the last column of the table.

Table 11 Main characteristic features of item 8; Ship's nameplate

#	# of items		Pre-	Load description		Substrates		Adhesive	In-service	Geometry [mm]			
	Ship	Annual	outfit	[N]	Type	1	2		condition	Length	Width	Height	Thickness
8	4 to 6	14	no	1500	Shear	Plastic	Coating	MSP	Humid	780	3000		8

8.3 *Joint design and analysis*

As concluded in chapter 6, for the joint design of all applications two types of adhesives might be used; MS Polymer or Epoxy 2015. Although the nature, the load carrying capacity and the application areas of MS polymer joints might differ considerably from those of epoxy adhesive joints, the main elements in the design procedure for both types of joints are similar. The general design procedure followed in this report is illustrated graphically in Figure 43 by different phases. This general design procedure is derived from the BONDSHIP project [10]. However, a cost-price analysis of the optional designs is added as an extra phase in the design procedure.

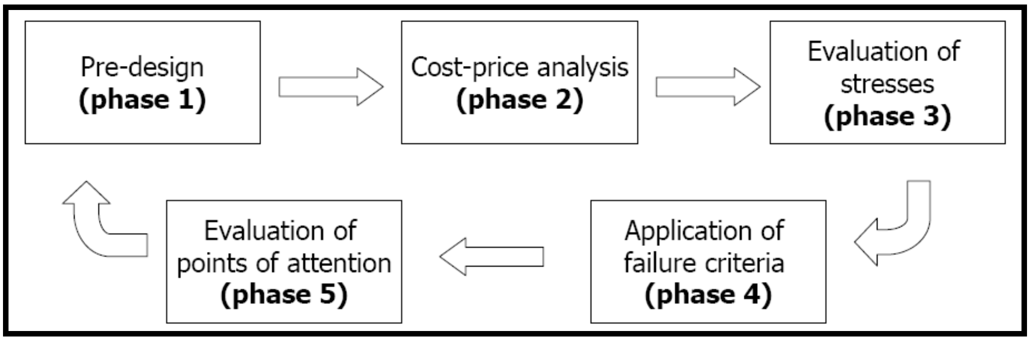


Figure 43 General design procedure for adhesive joints

One typically starts with determining a basic configuration of the joint (phase 1). These pre-designs are evaluated economically by a cost-price analysis (phase 2). From phase 1 and phase 2 one 'best design' is chosen to be analyzed by stresses (and strain for MS Polymer) in the joint when subjected to the design load as specified in Table 11 (phase 3). Then, the obtained stresses are inserted in the failure criteria applied for the joint (phase 4). From the application of failure criteria, critical parameters might be detected (phase 5). If such points are observed, the design of the joint must be modified (return to phase 1). Thus, by following this trial and error process, a convenient and safe joint design is obtained. Each phase illustrated in Figure 43 is described more extensively in the next subparagraphs.

8.3.1 Pre-design (phase 1)

The first phase in the general design procedure is to establish possible designs of the assembly. This pre-design is based on general considerations as described in chapter 6 and in paragraph 8.2. Four options of redesign are described below:

Option 1: the current design remains. In this design letters are welded on the nameplate and the nameplate is mounted on the wall with welded threaded cams.

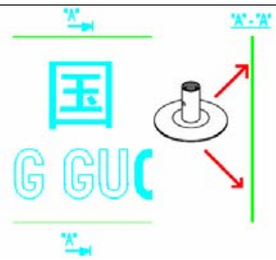
Option 2: welding the letters on the nameplate remains, but the nameplate is mounted on the wall with adhesively bonded stand offs. Damage to paint work can be avoided and the nameplate is still removable.

Option 3: to avoid deformation of the nameplate by heat input and the additional repair activities (rolling, grinding letters before painting) the letters are adhesively bonded to the nameplate. The threaded cams are still welded to the wall.

Option 4: to avoid all welding activities a plastic nameplate can be adhesively bonded directly to the wall. Because of the large area to be bonded, the admissible deformation can be as large as 6 mm [17]. Therefore, an MS Polymer should be used as adhesive.

These four options of possible redesigns are sketched, as shown in Table 12:

Table 12 possible redesigns of item 8; Ship's nameplate

Option 1: Current design	Option 2: Adhesive bonding of threaded cams (epoxy), nameplate welded	Option 3: Welding threaded cams, adhesive bonding letters (epoxy)	Option 4: Direct adhesive bonding of plastic nameplate with MSP
Fastening with welded threaded cams on wall Welding nameplate letters	Threaded cams can be mounted with click bond adhesively bonded stand offs	Possibility to use letters of dissimilar material	Tape to be used as fixture Large bonding area
			

8.3.2 Cost-price analysis (phase 2)

In this phase of the design procedure the four options of possible redesign as sketched in Table 12 are economically evaluated by cost-price. In order to determine the time required for all activities this evaluation is performed with input of welders and a welding engineer, adhesive suppliers, designers, sub-contractors (e.g. painter, electrician), outsourcing and calculation department etc. Although a high amount of usable information is provided by these parties to determine reliable production times, economical evaluation by cost-price is still a broad and objective approach.

For category C, the determination of a cost-price is not sufficient because many additional production costs and adjustments to the current production process are required when using adhesive bonding. These adjustments to the production process go against the preset boundary condition; **current location, area and layout of the yard should remain the same.**

However, for category A and B a cost-price analysis is regarded to be a sufficient method for an economical evaluation of adhesive bonding compared to welding. In general the activities described in the cost-price analyses in appendix F can be subdivided in the following **activities:**

Steelwork: a steelworker is responsibly for the sub-assembly of components by tack welding. Before a component is tack welded, the component has to be measured for attachment on the right place. Because welding requires two hands, one for holding the welding torch and one for holding the face shield, tack welding and positioning a component at the same time is almost impossible. Therefore, 2 men are required for the main steelwork activities.

Welding: after the component is tack welded the component can be welded. Because the components are already tack welded only one worker is required for welding the component. The most components in category A and B are relatively small parts and for this reason the time required for **welding only** is often very low. However, there are many activities involved with welding. One can think of installation and replacement of welding equipment, installation of exhaust systems, pulling welding cables, replacement of welding consumables, etc. The resulting working time, finally, is determined by additional activities such as walking, waiting, consulting, and personal care for people.

Painting: as mentioned previously, in the selection of components a distinction has been made between attachment in the pre-outfitting phase or the final assembly stage (outfitting). Welding in outfitting interferes with other work operations and can destroy paint and outfitting elements. For repair of damaged paint the most time-consuming activity is the surface preparation by mechanical tool cleaning. Next step is applying the multi layered coating system. Each layer should be cured properly before applying the next layer. This increases the total production time, moreover because for each layer, painting equipment has to be brought to the deck again.

To gain more insight in the main problems causing the damage to paint work and the problems involved with damage to paintwork an interview with the painter at the yard of IHC Beaver Dredgers is represented in appendix D: Interviews. However, for the purpose of this cost-analysis only minimal damage to paintwork is taken into account without considering additional costs for interferences and delay in other working activities.

Adhesive bonding: the main activities of adhesive bonding are surface preparation, bonding, and clamping of the joint (if necessary). Depending on the type of joint, whether or not clamping is required, and the method of clamping, etc. 1 or 2 workers are required for the bonding operation. Using the appropriate clamping method, e.g. click bond system (see appendix D), which combines thickness control and fixation of the joint, the required time for clamping activities decreases significantly. All activities involved, including appropriate clamping methods, for producing a joint are described more extensively in 8.4.2.

Although a high amount of usable information is provided by welders, sub-contractors, engineering, adhesive suppliers etc. to determine reliable production times, still **assumptions** have been made:

Hourly rates of personnel: In practice, many production activities at IHC Beaver Dredgers are performed by subcontractors (electrician, painter) which apply another hourly rate than IHC Beaver Dredgers. However, in the performed cost-price analyses for all workers, regardless to their working field (e.g. painter or welder), the hourly rate is kept similar: **€ 57, 50**. This is similar to the hourly rate at IHC Beaver Dredgers applied for welders and steelworkers.

Hourly rate is all-in: in the applied hourly rate of € 57, 50 all indirect costs are included. These costs may vary in depreciation of welding equipment, costs for electricity, adhesive materials, costs for redesign, paint and painting equipment, etc. Therefore, the material costs, e.g. because of redesign, are not taken into account separately in this cost-analysis. In the hourly rate for the employees at IHC Beaver Dredgers an all-in hourly rate is applied too. However, for the subcontractors an all-in hourly rate is often not applied and costs for materials are declared separately.

Similar working time for all activities (20%): As discussed previously, the resulting working time, is determined by additional activities such as, measuring, installation and replacement of equipment, waiting, consulting, etc. Although it is presumed that some activities require more working time than the other, the working time for all activities is kept similar for all activities. The working time is assumed to be similar to the working time as applied for welding at IHC Beaver Dredgers; **20%**. Hence, if in the cost-price analysis 10 minutes are determined for welding a component, the effective time of welding (in practice) is only 20% of 10 minutes (2 minutes).

Number of workers per activity: For some activities, e.g. tack welding in combination with positioning a component, 2 workers is required. The number of workers per activity is indicated separately in the cost-price analysis and included in the required time for the specific activity.

Taken into account the activities and the assumptions as described above a cost-price is determined for every option as sketched in Table 12 and described in 8.3.1 (phase 1). The cost-price analysis for item 8; ship's nameplate is represented in Table 13:

Table 13 Cost-price analysis of item 8; a ship's nameplate

Component 8				
	Option 1	**Option 2**	**Option 3**	**Option 4**
Man hours [hours]				
Steelwork:				
Positioning and tack welding letters	8	8		
Stretching nameplate	2	2		
Tack welding threaded cams (8x) (2 men)	2	2	2	
Welding:				
Welding letters	20	20		
Grinding letters	8	8		
Welding threaded cams (8x) (1 man)	0,67		0,67	
Grinding (8x)	0,67		0,67	
Other:				
Transportation to roll	1	1		
Rolling	6	6		
Fastening nameplate (2 men)	4		4	
Adhesive bonding:				
Cleaning surfaces		1	1	1
Positioning and bonding letters			8	
Bonding threaded cams		2		
Removing adhesive residue		1	1	0,5
Bonding nameplate				1
Clamping				1
Total amount of hours	52,33	51,00	17,33	3,50
Production costs [€]				
57,50 [€/h]	3009,17	2932,50	996,67	201,25
Cost savings [€]				
Per item	**0,00**	**76,67**	**2012,50**	**2807,92**
Annual (14 x)	**0,00**	**1073,33**	**28175,00**	**39310,83**

As can be concluded from the cost-analysis as represented in Table 13, option 4 is the best economically solution. This option provides annual cost savings of € 39310, 83 and reduces the production costs to as high as 93%. However, to illustrate the difference in stress calculation of MS Polymer bonded assemblies and epoxy adhesive bonded assemblies option 3 will be considered too in the following. Both option 3 and option 4 are marked in Table 13 and will be further elaborated in the following subsections.

8.3.3 Evaluation of stresses in the assembly (phase 3)

Next to phase 2, the selected options from the cost-price analysis are evaluated by stress analysis in phase 3. Although the main elements in the design procedure, as illustrated in Figure 43 in paragraph 8.3, for both types of adhesives are similar, the analysis of stresses differs considerably from each other. However, for both adhesives (MS Polymer and Epoxy) analytical analysis methods are used.

Two main types of analytical approaches exist. The first and simplest approach is used for all applications using MS polymer as adhesive and is based on nominal stresses and strains in the adhesive. The second approach is based on solutions of differential equations to evaluate the considerable stress peaks at the ends of the joints which occur in epoxy adhesives.
Both methods of stress analysis will be described separately in this subparagraph. These methods of stress analysis are representative for all components of **category A and B** in appendix F (depending on the type of adhesive used).

However, for joints with more complex geometry, boundary conditions and load transfer mechanisms, as represented in **category C** in appendix F, numerical methods using FEA (Finite Element Analysis) should be applied. Since category C is mainly evaluated to determine the boundaries of strength and design options of adhesive bonding in shipbuilding, these methods are not taken into account in this report. Nevertheless, it is recommended to take a close look at these types of numerical methods in future research. The information provided in [10] could be useful for using numerical methods.

MS Polymer: Analysis using nominal stresses and strains
In some applications MS Polymers might be subjected to relatively high load levels, while the external loads are small in other cases. In the latter estimates based on nominal stresses and strains might be sufficient. On the other hand, for joints exposed to high level of loads an accurate resolution of stresses and strains is of great importance [10]. In the BONDSHIP project four main joint categories are introduced (see Table 14) in order to be able to make the proper choice for analysis method.

Table 14 Recommended analysis methods for (flexible) MS Polymer adhesive joints [10]

Joint Geometry / Utilization of load	Simple	Complex
Low	Analytical, nominal stresses and strains (constant stress/ strain distribution) **Category 1**	Numerical, linear FEA **Category 2**
High	Numerical, materially and geometrically non-linear FEA **Category 3**	Numerical, materially and geometrically non-linear FEA **Category 4**

As shown in Table 14, for MS Polymer adhesive joints subjected to a relatively high level of applied loads finite element analysis (FEA), taking both material and geometrical non-linearity into account, should be applied regardless of the complexity of the joint. Since the applications as represented by **category C** in appendix F are subjected to high loads, it is recommended to evaluate these applications by the analysis methods of category 3 and 4 as represented in Table 14 in future research.

However, for this report only the analysis for **simple** joints of **low utilization of load** is selected. For these applications the load-carrying capacity is of no major concern and they can be classified in **category 1**, as marked in Table 14 by the red circle.

Application example: option 4

The present subsection offers an example on a general analysis of the stresses and strains within the MS Polymer adhesive layer of a component (mainly) loaded in shear. This example is representative for all applications bonded with MS Polymer adhesive as represented by category A and B in appendix F.

In 8.3.1 (phase 1), the preliminary design of the joint is specified by **option 4**. A plastic nameplate is used instead of a steel nameplate as used in the current design to reduce the weight of the ship's nameplate significantly. Consequently the applied load in shear is reduced from 1500 N to 200 N. The plastic nameplate is bonded directly to the coated wall with a MS Polymer, using tape as positioning tool and distance spacer. The geometry of the nameplate remains the same compared to the current design. The main characteristic features of this redesign are represented in Table 15.

Table 15 Main characteristic features of option 4

#	Load description		Substrates		Adhesive	In-service	Geometry [mm]			
	[N]	Type	1	2		condition	Length	Width	Height	Thickness
8	200	Shear	Plastic	Coating	MSP	Humid	780	3000		8

It is well-known that joints with MS Polymer do not show considerable stress peaks at the ends of the joints like joints with more rigid (e.g. epoxy) adhesives. Therefore, the assumption of constant stress and strain distributions can be used for components bonded with MS Polymer [10]. Since the MS Polymer is used to compensate relatively large deformations, both stresses and strains should be considered during design.

The nominal adhesive shear stress, τ, for the joint is given by:

$$\tau = \frac{F}{l \cdot b}$$

Applying the correct data from Table 15 gives:

$$\tau = \frac{200N}{780\,mm \cdot 3000\,mm} \approx 0\,MPa$$

Assuming linear elastic adhesive behavior the relation between the shear stress and shear strain reads

$$\tau = G \cdot \gamma$$

G is the shear modulus of the adhesive and γ the shear strain in the adhesive.

$$\gamma = \frac{\tau}{G} = \frac{8.55 \cdot 10^{-5}\,MPa}{0.68\,MPa} \approx 0$$

Epoxy adhesive: Analysis using analytical linear methods

Compared to MS Polymer the stiffness and strength of epoxy adhesive is much higher. Consequently, the failure strain is considerably smaller, and the gap filling properties are less. In contrary to MS Polymer adhesive, a joint with epoxy adhesive show considerable stress peaks at the ends of the overlap which should be taken into account in the evaluation of stresses of epoxy adhesives. The analysis used in this report is based on the approach as described in the BONDSHIP project [10]. For a wide variation of applications of epoxy adhesive, six main categories are introduced in [10] as represented in Table 16.

Table 16 Recommended analysis methods for (rigid) epoxy adhesive joints [10]

Joint Geometry / Utilization of load	Simple	Complex
Low	Analytical, nominal stresses and strains (constant stress/strain distribution) **Category 1**	Numerical, linear FEA **Category 2**
Medium	Analytical, linear methods **Category 3**	Numerical, linear FEA **Category 4**
High	Numerical, materially and geometrically non-linear FEA **Category 5**	Numerical, materially and geometrically non-linear FEA **Category 6**

Note: Compared to the analysis methods of MS Polymer adhesives (Table 14) an additional utilization of load category (Medium) is represented in the analysis methods for epoxy adhesive joints represented by category 3 and category 4 in Table 16. Therefore, the analysis methods of MS Polymer adhesive as represented by Category 3 and Category 4 in Table 14, are represented by Category 5 and Category 6 in Table 16.

Since analysis of joints with simple geometry and low utilization of load, represented as category 1 in, is similar to the analysis of MS Polymer adhesive this analysis is not described in the present subsection. If the joint geometry is complex (category 2) it is recommended to apply linear finite element calculations.

For epoxy adhesive joints subjected to a higher level of applied loads (category 3 in Table 16) analyses using nominal stresses are not applicable [10]. Although not loaded to their upper limits, non-uniform stresses in the joint should be taken into account. The maximum stress peaks can be determined by linear analytical methods (category 3). Because the validity of these methods is restricted to a simple geometry of the joint, for complex joints (see category 4 Table 16) linear finite element methods should be applied.

Highly loaded joints should be analyzed numerical, materially and geometrically regardless of the complexity of the joint geometry and are classified by category 5 and category 6 in Table 16.

The components representing **category A and B** in appendix F are **simple** joints with **low or medium utilization of load**. However, in order to obtain conservative results for the evaluation of stresses in the joint, analytical linear methods are used both for applications with low and medium utilization of load. These methods are classified by **category 3** which is marked by a red circle in Table 16.

<u>Application example: option 3</u>

The present subsection offers an example on a general analysis of the stress distribution within the adhesive layer of a component (mainly) loaded in shear based on analytical expressions arising from analytical solution methods. This example is representative for all applications bonded with epoxy adhesive as represented by category A and B in appendix F.

In 8.3.1 (phase 1), the preliminary design of the joint is specified by **option 3**. Similar to the current design, threaded cams are welded to the wall to attach the nameplate. Instead of welding the letters, the shop-primed steel letters are adhesively bonded to a shop-primed steel plate by weight. In this way, deformations of the nameplate involved with the current design can be avoided. For the stress evaluation one letter is selected as example for all letters on the nameplate. The weight of this letter is approximately 0.5 kg, corresponding to a load in shear direction of 5 Newton. The main characteristic features of the adhesively bonded letter are represented in Table 17.

Table 17 Main characteristic features of option 3

#	Load description		Substrates		Adhesive	In-service	Geometry [mm]			
	[N]	Type	1	2		condition	Length	Width	Height	Thickness
8	5	Shear	SP	SP	Epoxy	Humid	200	100		6

As mentioned previously, for epoxy adhesives the stress distribution is usually highly non-uniform and the maximum shear stress occurs at the ends of the overlap length. The presence of non-uniform stresses is taken into account by several analytical solution methods, e.g. Volkersen, Goland and Reissner and Bigwood and Crocombe. A more detailed discussion of these theories is presented in literature by [10,11, 21].

However, for shipbuilding industry it is desirable to use basic and at the same time reliable design rules. Therefore, in this report simple analytical formulas are used based on the main conclusions of the analysis of Wiedemann as discussed in [10]. Wiedemann has derived 'easy to use' analytical formulas taken into account the overlap length of the joint and the thickness of the adhesive. This analysis is based on the following assumptions regarding the deformation pattern and the material behavior of the joint [10]:

- Axial deformations in the adherends
- Shear deformations in the adhesive
- Linear elastic behavior of adherends and adhesive

Before these easy-to-use solutions of differential equations are discussed, typical parameters required in the analysis of single-lap joints are introduced first. These parameters are represented in Table 18.

Table 18 Specified parameters for option 3

Material parameters		
Young's modulus of adherend 1	E1	215000 MPa
Young's modulus of adherend 2	E2	215000 MPa
Poisson's ration adherend 1	v	0,33
Poisson's ration adherend 2	v	0,33
Shear Modulus adhesive	G	667 MPa
Geometrical parameters		
Thickness of adherend 1	s1	6 mm
Thickness of adherend 2	s2	6 mm
Thickness of adhesive layer	d	0,15 mm
Overlap length of joint	l	200 mm
Width of joint	b	100 mm

For the determination of the shear modulus (G) the typical material parameters for the epoxy adhesive are used from reference [10]. For option 3 both adherend 1 and adherend 2 are shop-primed steel with a thickness of 6 mm and a Young's modulus of 215.000 MPA.

Due to this specific stress distribution in the joint there is a maximum overlap length above which no further load capacity can be reached. The design value of the overlap length for a single-lap joint can be estimated by:

$$l \geq 2 \cdot 5 \cdot \sqrt{\left(\frac{E_1 \cdot s_1 \cdot d}{G \cdot (1+\delta)}\right)}$$

Where δ is the adherend stiffness ratio defined by

$$\delta = \frac{E_1 \cdot s_1}{E_2 \cdot s_2}$$

The factor 2 is introduced to take peel stresses and additional stresses due to the bending moment in account. The values for E and s of the adherends have to be selected in a way to ensure $\delta \leq 1$.

Using the parameters from Table 18, the maximum overlap length above which no further load capacity can be reached is:

$$l \geq 120\ mm$$

Hence, the strength of the final joint, after the appliance of failure criteria in phase 4, should be sufficient for an overlap length, l ≤ 120 mm.

Note: The value of the maximum overlap length, above which no further load capacity can be reached, is only used as a verification method during the pre-design of the joint. Although taken into account during the performed stress analyses and applications of failure criteria in appendix F, the calculation as discussed above will not be represented separately in appendix F.

The ratio of the maximum shear stress at the ends of the joint and the mean (nominal value) is given by:

$$\frac{\tau_{\max}}{\tau} = \frac{1}{4}\left[(1+3k)\cdot\rho\cdot\coth\rho + (3-3k)\right]$$

Where the parameter ρ, which is characteristic for the specific joint, is

$$\rho = l\cdot\sqrt{(1+\delta)\frac{G}{E_1\cdot s_1\cdot d}}$$

And the bending moment factor may be expressed as:

$$k = \left[1+2\sqrt{2}\cdot\tanh\left(\theta / 2\sqrt{2}\right)\right]^{-1}$$

Here, θ is defined by

$$\theta = 1\sqrt{\frac{3\cdot F\cdot(1-\nu^2)}{b\cdot E\cdot s^3}}$$

Using the parameters as represented in Table 18 the ratio of the maximum shear stress at the ends of the joint and the nominal adhesive shear stress is:

$$\frac{\tau_{\max}}{\tau} = 16{,}48$$

With the parameters as represented in Table 17, the nominal adhesive shear stress, τ, for the joint is given by:

$$\tau = \frac{F}{l\cdot b} = \frac{5\,N}{200\,mm\cdot 100\,mm} \approx 0$$

Since, the nominal adhesive shear stress, τ, is approximately equal to zero, the maximum shear stress at the ends of the joint is approximately equal to zero too:

$$\tau_{max} = \tau \cdot 8{,}28 \approx 0 MPa$$

According to the applied load F (5 Newton) in shear direction, a tensile stress in adherend 1 is applied. This (nominal) tensile stress in the adherend is denoted by:

$$\sigma_{10} = \frac{F}{b \cdot s_1} = \frac{5N}{100mm \cdot 6mm} = 0.01 MPa$$

8.3.4 Application of failure criteria (phase 4)

In this report it is assumed that the failure criterion can be expressed in terms of a single allowable strength value. This allowable strength value depends on the intended service environment. The representative tests to obtain these values are not included in this report. However, an appropriate safety factor for the intended service environment, as obtained in paragraph 7.3.4 previously, is applied.

Failure criteria MS Polymer

For qualifying the MS Polymer adhesive joint the following set of failure criteria is applied:

- $\tau_{a,humid} \geq \tau$

Where $\tau_{a,\,humid}$ is the allowable shear stress at humid conditions and τ is the maximum predicted stress in the joint in response to the environmental conditions (see phase 3).

- $\gamma_{a,humid} \geq \gamma$

Where $\gamma_{a,\,humid}$ is the allowable shear strain at humid conditions and γ is the maximum predicted shear strain in the joint in response to the environmental conditions (see phase 3).

The value for $\tau_{a,\,humid}$ is obtained by multiplying the shear strength of the adhesive obtained from the lap-shear test, τ_f, with the safety factor obtained in paragraph 7.3.4:

$$\tau_{a,humid} = \tau_f \cdot \frac{f_{Df,M,T} \cdot f_S}{S} = \tau_f \cdot \frac{0.2 \cdot 0.7}{2} = \tau_f \cdot 0.07$$

The shear strength of the adhesive obtained from the lap-shear test, τ_f, while bonding to coating is marked by a red circle in Table 19.

Table 19 Measured shear strength at fracture from test program

	Steel [MPa]	SP [MPa]	Coating [MPa]
MSP	1,81	1,86	2,38

Using the measured shear strength at fracture from the test program, gives:

$$\tau_{a,humid} = \tau_f \cdot 0.07 = 2.38\ MPa \cdot 0.07 = 0.17\,MPa$$

The predicted shear stress in the joint is (see phase 3):

$$\tau \approx 0\,MPa$$

Hence,

$$\tau_{a,humid} \geq \tau$$

From the obtained value for $\tau_{a,\ humid}$, the allowable shear strain at humid conditions, $\gamma_{a,\ humid}$, is calculated:

$$\gamma_{a,humid} = \frac{\tau_{a,humid}}{G} = \frac{0.17\,MPa}{0.68\,MPa} = 0.25$$

The predicted shear strain in the joint is (see phase 3):

$$\gamma \approx 0$$

Hence,

$$\gamma_{a,humid} \geq \gamma$$

Failure criteria Epoxy

For qualifying the epoxy adhesive joint the following set of failure criteria is applied:

- $\tau_{a,humid} \geq \tau_{\max}$

Where $\tau_{a,\ humid}$ is the allowable shear stress at humid conditions and τ_{max} is the maximum predicted stress in the joint at the end of the overlap (see phase 3).

- $\sigma_{10} \leq 2 \cdot \tau_f \cdot \sqrt{\dfrac{(1+\delta) \cdot E_1 \cdot d}{s_1 \cdot G}}$

Where σ_{10} is the tensile stress in adherend 1 and τ_f is the shear strength of the adhesive obtained from the lap-shear test.

The value for $\tau_{a,\ humid}$ is obtained by multiplying the shear strength of the adhesive obtained from the lap-shear test, τ_f, with the safety factor obtained in paragraph 7.3.4:

$$\tau_{a,humid} = \tau_f \cdot \frac{f_{Df,M,T} \cdot f_S}{S} = \tau_f \cdot \frac{0.2 \cdot 0.7}{2} = \tau_f \cdot 0.07$$

The shear strength of the adhesive obtained from the lap-shear test, τ_f, while bonding to coating is marked by a red circle in Table 20.

Table 20 Measured shear strength at fracture from test program

	Steel [MPa]	SP [MPa]	Coating [MPa]
Epoxy	18,09	7,31	11,77

Using the measured shear strength at fracture from the test program, gives:

$$\tau_{a,humid} = \tau_f \cdot 0.07 = 11.77\ MPa \cdot 0.07 = 0.82\,MPa$$

The predicted maximum shear stress at the end of the joint is (see phase 3):

$$\tau_{\max} \approx 0\,MPa$$

Hence,

$$\tau_{a,humid} \geq \tau_{\max}$$

Using the measured shear strength at fracture from the test program, τ_f, and the parameters as represented in Table 8, gives:

$$2 \cdot \tau_f \cdot \sqrt{\frac{(1+\delta) \cdot E_1 \cdot d}{s_1 \cdot G}} = 0.10\,MPa$$

The predicted tensile stress in adherend 1 is (see phase 3):

$$\sigma_{10} = 0.01\,MPa$$

Hence,

$$\sigma_{10} \leq 2 \cdot \tau_f \cdot \sqrt{\frac{(1+\delta) \cdot E_1 \cdot d}{s_1 \cdot G}}$$

8.3.5 Evaluation of points of attention (phase 5)

Although option 3 is analyzed by bonding shop-primed steel letters to a shop-primed steel plate, also the possibility exists to use other materials, e.g. aluminum, to bond the letters. The letters can also be bonded to a previously painted steel plate to provide higher strengths. Option 4 is economically the best choice, but the use of plastic instead of steel should be classified by the classification society. Since a large margin is provided in strength requirements from the stress analysis, using aluminum could be a serious option as well. When bonding directly to the wall with adhesive (option 4) the nameplate is not that easy removable compared to the current design. A disadvantage of using MS Polymer as adhesive is the relatively slow curing time when bonding a large area such as a ship's nameplate (2-3 m^2). A large area decreases the amount of moisture intrusion, required for the MSP to cure.

It should be noticed that in this analysis no damage to paintwork is taken into account. However, previously, this situation occurred due to attachment of a nameplate in the final assembly stage. In this situation adhesive would provide even more cost-savings than analyzed in this report.

8.4 Production requirements

In the previous section of this chapter the joint is specified in a design process. The base materials and the geometry with tolerances (e.g. bond width and length, bond line thickness with tolerances) are chosen. The next step is to produce the joint and to identify possible implementation problems which may occur during the bonding operation (clamping, curing time). In the following sections an example of a quality plan for the bonding operation will be specified in detail for the 'best application'.

8.4.1 Receipt and storage

The first step in the production procedure is the receipt and storage of the materials. Before bonding, the correct adhesive and equipment for mechanical surface preparation has to be present in-house [10]. For the required (easy) surface preparation IPA (Isopropyl alcohol) is used as a cleaner. Additionally, before using IPA, the surface might be prepared by using Scotch-Brite surface conditioning products [22] to lightly abrade or brush the surface to be bonded depending on the application.

As adhesive, either the epoxy adhesive Araldite 2015 or the MS polymer Puraflex 6006 is used. The product specifications and the manufacturers or 3rd party certificates should be verified before storage. Additionally, the shelf-life of the adhesive should be verified, registered and marked before storing.

The range of acceptable storage temperatures is between 5 and 25°C [28]. Stored dry and cool, the (unopened) MS Polymer is storable for 12 months. Araldite 2015 may be stored for up to 3 years at room temperature provided the components are stored in sealed containers

[23]. The packages should be well closed to avoid moisture intrusion. This applies especially for the Puraflex 6006 MS polymer, since this adhesive is moisture curing.

The adhesives should be stored in a clean area and (opened) packages should be handled with care. When adhesives are taken from storage, acclimatization of the adhesive is recommended before use. How to handle the adhesives during fabrication is described in the next subparagraph.

8.4.2 Bonding operation

Before starting the bonding operation an acceptable working environment must be ensured. The appropriate working temperatures and humidity must be available for both sufficient surface preparation and the final application of the adhesive. The main issues to consider during the bonding operation itself are described below.

Working environment and handling

At temperatures below 10°C, the curing process of the adhesive is so slow that this temperature can be regarded as the lower limit. The upper temperature limit is mainly determined by the available pot time of the adhesive. Therefore, during fabrication the acceptable working temperatures should be in the range of 10°C to 30°C. This means that in some periods, e.g. a cold winter's day, the situation may occur that adhesive bonding can not be applied.

A relative humidity of more than 70 percent should be avoided during fabrication of the bond [24]. For this value the danger that the dew point is reached is still sufficiently low. Because Puraflex 6006 (MS Polymer) is a moisture curing adhesive, a relative humidity of at least 30 percent must be ensured. Hence, the acceptable working humidity during fabrication should be in the range of 30 to 70 percent. To assure a high level of quality of the finished joint, the climate prevailing during both the bonding process and the curing period should be measured and recorded. The temperature, relative humidity and the resulting dew point can be measured by easy to use meters available on the market [25,26, 27]. An example of a tool for measuring and recording all climate parameters required for adhesive bonding is shown in Figure 44.

Figure 44 Dew check tool

During or after the surface preparation no dust-producing processes should be carried out in the vicinity to assure a clean workspace.

Both Puraflex and Araldite 2015 are, provided that certain precautions normally taken when handling chemicals are observed, generally quite harmless to handle [23,28].
The uncured materials must not, for instance, be allowed to come into contact with foodstuffs or food utensils, and measurements should be taken to prevent the uncured materials from coming in contact with the skin, since people with particularly sensitive skin may be affected.

The wearing of impervious rubber or plastic gloves will normally be necessary; likewise the use of eye protection [29]. In Figure 45 the gloves used during the test program is shown.

Figure 45 Rubber gloves

The skin should be thoroughly cleaned at the end of each working period by washing with soap and warm water. The use of solvents is to be avoided. Disposable paper - not cloth towels - should be used to dry the skin. Adequate ventilation of the working area is recommended. These precautions are described in greater detail in the Material Safety Data sheets for the individual products and should be referred to for fuller information [23,28,29].

Surface preparation

As previously described, at the very least, the joint surface is cleaned with a good degreasing agent such as acetone, Iso - Propanol (IPA) or other proprietary degreasing agents in order to remove all traces of oil, grease and dirt [23].

Figure 46 IPA cleaner

Application is done by a white linen cloth or, better still, by a paper towel. The cleaner is applied sparingly to the cloth or towel, and then wipe off the surface with a series of straight, light strokes. A rotary polishing action is not recommended [10]. If surfaces are with dust or rust deposits they must be cleaned by mechanical abrasion with an abrasive pad. Abrading should be followed by a second degreasing treatment always.

Good ventilation of the workspace is required and a heat source or dust-producing processes close to the cleaning area should be avoided. In addition, the use of protective gloves and glasses is recommended to avoid skin and eye contact with the cleaner. As an additional controlling step the pretreated surfaces may be inspected by the methods as described in Appendix H. Once treated, the nameplate will be bonded to the substrate within a suitable period (< 1 hour), so as no degrading or oxidizing of the substrates surface occurs.

Application of the adhesive

If possible, the adhesive should be applied to the joining surfaces immediately after the pre-treatment has been concluded. As previously reported, the acceptable working temperatures during fabrication should be in the range of 10°C to 30°C.

Before the adhesive is applied, the manufacturer's specification of shelf-life and open time should be verified and recorded. The 2 component epoxy adhesive is mixed by a handheld gun using a static mixer (see Figure 47). This ensures that the two components are always mixed at the same ratio. The mixing tip is discarded after use. However, for a MS Polymer no mixing is required and a handheld gun for a single cartridge is used. For bonding of a large bonding area a spatula may be used to apply the adhesive and a tooth comb to spread the adhesive.

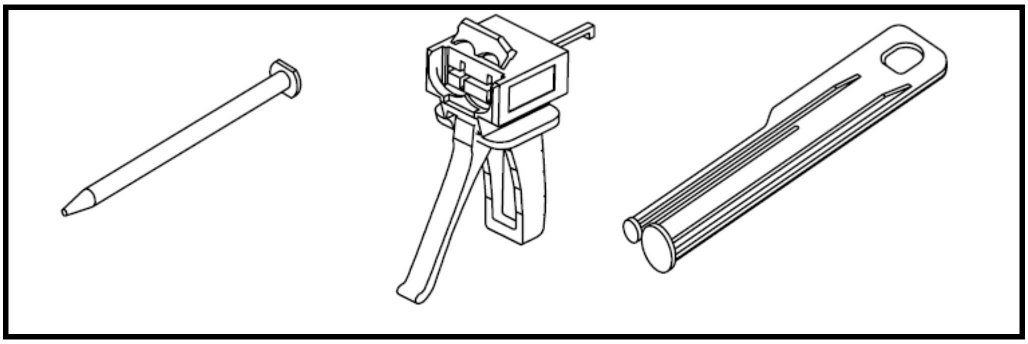


Figure 47 Mixing tip, manual dispenser, ratio slide [30]

All tools should be cleaned with hot water and soap before adhesives residues have had time to cure. The removal of cured residues is a difficult and time-consuming operation.
It is of major importance that the open time of the adhesive is taken into account. During the bonding process, the processing time of the adhesive (open time/pot life) specified by the manufacturer shall not be exceeded. The processing time for the epoxy adhesive is 40 minutes and for the MS polymer 10 minutes, both at room temperature.

It must be ensured that dust-producing or hot work is not performed at the same time as the bonding activities. Furthermore, processes generating a large amount of heat, such as cutting and welding, must not be performed near the adhesive joints; otherwise there may be irreversible damage to the bond [24].

Fit up

From the previous joint design a bond line thickness is determined. In general, the bond line thickness of a joint can be controlled in different ways depending on the application. Although both MS Polymer and Epoxy do not require pressure to cure, jigs and fixtures may be needed to maintain the target bond line thickness and to prevent the bond surfaces from moving relative to one another during the curing process. In order to reduce the processing time, methods based on a combination of positioning and bond line thickness control are favorable. Such methods are represented by the Click Bond system and VHB tape as described in appendix D: Interviews. The use of Click Bond ensures a uniform bond line thickness for each application by the 'click system' as represented in Figure 48. Moreover, the fixture keeps the bonded component at its place during curing of the adhesive.

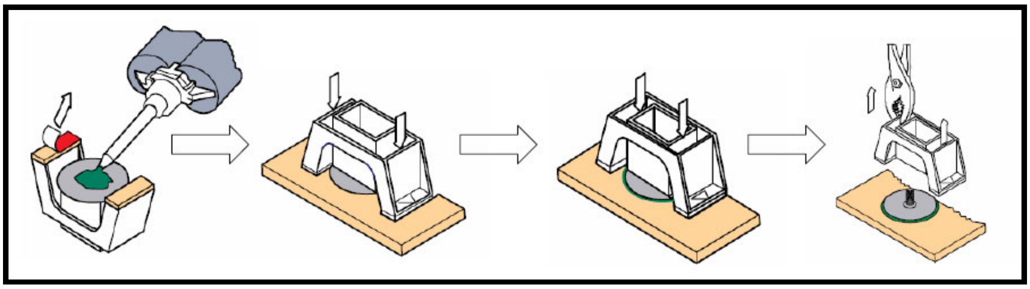


Figure 48 Click Bond system [30]

The Click Bond system is mainly designed to use in combination with structural adhesives such as MMA and epoxy. Because the typical adhesive thickness of MS polymer (3 to 15 mm) is much higher than the thickness of an epoxy adhesive, the use of the click bond system for a MS Polymer is not recommended. However, the use of VHB tape, with a thickness similar to the desired thickness for the bonding application, may offer a good alternative by providing a combination of positioning and bond line thickness control too (Figure 49).

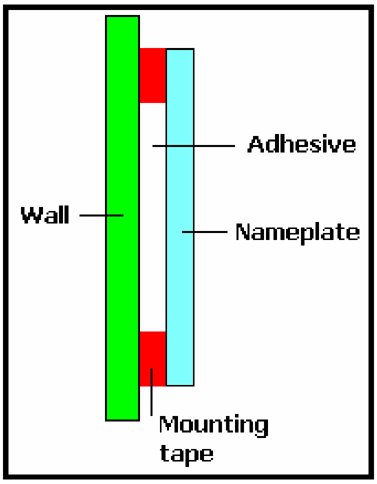


Figure 49 Tape as distance spacer

Other alternatives, for the control of bond line thickness are the use of glass beads as spacer in the adhesive (Appendix D) or the use of special features in the adherends such as grooves or ridges [10].

As mentioned in the interviews in Appendix D, the main clamping method for components mounted in horizontal compression position is the use of weights. A common method for components to be mounted in vertical position is the use of 'C' clamps. C clamps are desired to be resilient, to avoid decrease, or even loss, of pressure during solidification because of the flowing of the adhesive [12]. An example of a resilient C clamp is represented in Figure 50.

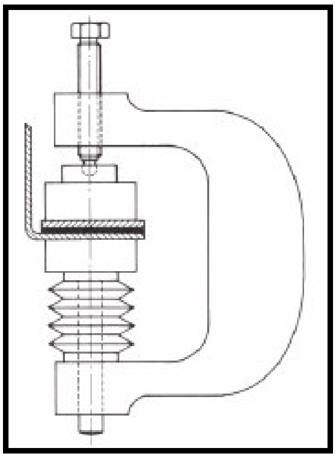


Figure 50 C-clamp with disc springs [12]

In some cases clamping by C-clamps is not possible, particularly when adhesive bonding is applied on a large area such as a vertical wall. In this case from interviews (see Appendix D) other methods of positioning the adhesive assembly are available; simple nylon-reinforced packaging tape, or, as shown in Figure 51, the component can be positioned by using magnets.

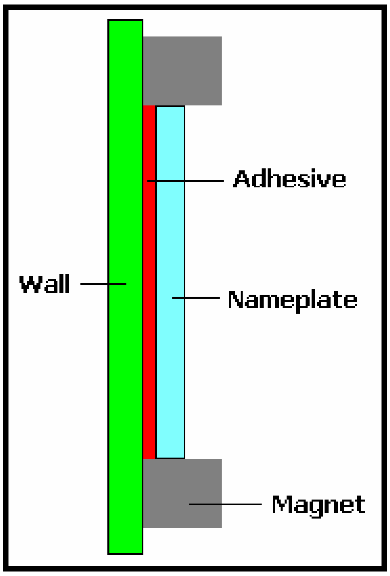


Figure 51 Using magnets as fixation tool

Excessive (uncured) adhesive should be removed by using a cleaner. The used clamps can be removed after the open time of the adhesive is expired. The open time depends on the used adhesive and the environmental temperature. At room temperature the open time is 10 minutes for the MS Polymer and 40 minutes for the Epoxy adhesive. Higher temperatures lead to faster curing and as a consequence lower processing times.

Curing

Curing time is mainly depending on the type of adhesive and the available curing temperature. As previously reported, the environmental temperature should be at least 10°C. To accelerate the curing process, heating of the workspace or the adhesive joint itself can be applied. When the humidity curing MS Polymer adhesive is used, it is of major concern that moisture can reach the adhesive sufficiently. The curing times must be taken into account for the production planning to avoid dust-producing or hot work activities during the bonding activities.

Safety and Health

Adhesives and cleaners require careful handling. However, if provided precautions are taken they are safe to use. The main safety precautions to be taken are [10]:

- Follow safety data sheets provided by the adhesive suppliers [23,28]
- Follow regulatory requirement regarding maximum allowable concentration of volatile gasses
- Provide protection to workers for skin, eyes and inhalation

A major advantage of adhesive bonding compared to welding is the prevention of released welding fume.

8.4.3 Personnel qualification

Although adhesive bonding seems to be easy and requires a low level of craftsman's skill compared to welding, appropriate qualification of personnel is required [24]. Errors must be avoided from the start or at least detected as soon as they originate. Especially, because errors in bonding lead to failure of the joint after a long interval. For this reason, failure of the joint after weeks or months is often blamed on the adhesive (see also interviews in Appendix D). However, this judgement only applies in very few cases and is usually caused by insufficient knowledge of personnel in the field of surface treatment and the handling of adhesives.

As mentioned in the interviews in Appendix D, training of personnel is mainly provided through suitable (theoretical and practical) training by the adhesive supplier or by study courses of institutes. Bonding does not yet enjoy the same status in comparison to other joining methods such as welding and this reflects in the low level of well-founded knowledge of bonding technology within shipbuilding. However, a qualification programme, structured in a similar way to that of welding, is available and even partly required by the approval body Germanischer Lloyd [24]. This qualification scheme, provided by the EWF (European Welding federation) shall contain the following elements [10]:

- Theoretical training
- Practical training
- Qualification exams, test etc.
- Certification schemes
- Methods and requirements to maintenance of qualifications:
    - Training
    - Qualification exams
    - Operator joint logbook

Although sufficient knowledge can be provided through suitable training by the adhesive manufacturer, in conjunction with a test conducted by a recognized testing institute or under the supervision of the approval body it is highly recommendable that workers responsible for the bonding operation are qualified to European Adhesive Bonder standard (EAB). Supervisors shall meet the requirements of European Adhesive Specialist (EAS). As mentioned in the interviews in Appendix D, these trainings are available in the Netherlands at 'Stichting Mikrocentrum Nederland' [31]. These trainings are provided in cooperation with Adhesion Institute TU Delft (specialist in adhesives and bonding technology). Recently, the Adhesion Institute received the certificates to become 'approved training body' for EAB and EAS from the European Welding federation [32].

8.5 Fire safety requirements

As pointed out earlier, adhesives have a poor resistance to high temperatures compared to welding. The temperature resistance is 100°C for the epoxy adhesive and 120°C for the MS Polymer [23,28]. Above these temperatures the adhesives are flammable and therefore the aspect of fire protection must be taken into account using adhesive bonding instead of welding. However, in the rules and codes, for adhesives no general requirements or guidelines are given for adhesive bonding explicitly [10,24].

Therefore, adhesives should be treated as part of materials which are classified into various fire classes such as fire-retardant and non-combustible. Requirements for fire safety on board are described in various rules an codes, dependent on the type of ship and operational profile [24]. However, the governing rules for fire safety are described according to SOLAS ('The International Convention for Safety of Life at Sea') [33]. In this code materials are classified into load carrying and non-load carrying fire divisions. Non-load carrying divisions or elements should maintain structural strength without the adhesive joint and/or the structural strength of the bonded elements for the required time. Moreover the division should remain smoke and flame tight for the required time [10]. For structural (load-bearing) adhesive joints a detailed load analysis has to be carried out in order to qualify the joint. The qualification of the bonded joints is obtained by performing (full scale) tests according to the FTP code (International Code for Application of Fire Test Procedures).

The fire reaction (heat release, smoke and toxicity) properties of adhesives are also tested by the FTP code [10,24], but in general, do not represent any decrease in fire safety level. This is because only a small amount of adhesives is used compared to other combustible materials, e.g. paint, and only small areas of adhesive is exposed to fire.

Hence, as the current experience with adhesive bonding within shipbuilding is marginal, it is of major importance that the designer works in close cooperation with the classification society from the beginning. However, from interviews (see Appendix D) with shipbuilding companies it appeared that within the production of the smaller types of ships no classification societies are involved. For this type of ships, e.g. the standard range of Beavers, adhesive bonding could be applied in an easier way.

8.6 In-service requirements

In order to detect errors in the adhesive during the in-service operation bonded joints should be inspected by NDT (Non Destructive Testing). Any damage needs to be repaired using an approved repair method.

8.6.1 NDT inspection

The main non-destructive inspection method is **visual inspection** [5, 11, 10]. Each NDT inspection begins with a visual inspection. Bonded joints should be checked for corrosion of the adherend along the bond line, cracks in the adhesive and whether or not leakage is observed on the other side of the joint. Then, depending on the demands of the adhesive joints, possibly even an instrumental methodology can be applied to investigate critical or suspect areas more thoroughly. A review of currently available relevant NDT techniques is provided in appendix G. The NDT methods as represented in appendix G give an appreciation of the technologies that could be employed for adhesive bonding.
However, there are no non destructive testing (NDT) methods available to measure *reliable* the adhesion strength of a finished joint currently [10, 24, 34]. Therefore, in practice, adhesive joints are designed in such a way (e.g. by using sufficient safety factors) that joints can be produced reliably and consistently.

8.6.2 Repair

The need for repair can occur directly after the bonding operation to correct mistakes or in-service, e.g. as a result of wear or accident damage. However, from the interviews with yards currently applying adhesive bonding and with adhesive suppliers it may be concluded that joints repair of bonded joints is not considered as a major point of concern. For the repair of MS Polymer adhesive joints in some cases one can bond onto the existing adhesive. An epoxy adhesive on the other hand, requires complete removal of the old bond line and proper surface preparation. Most commonly used methods, mentioned in the interviews in appendix D, are:

- **Heating:** one of the most commonly used method to remove an adhesive joint is heating the adhesive to can be heated to temperatures above 120°C by a heating gun
- **Refrigerating:** under cooling of smaller surfaces and parts down to -45°C by refrigerating spray.
- **Cutting:** Using a knife, vibration cutter or wire to cut the adhesive
- **Induction:** for the Click Bond system (see appendix D) induction is introduced as a removal tool. This induction tool removes anything that has been bonded to steel or aluminum with adhesive.

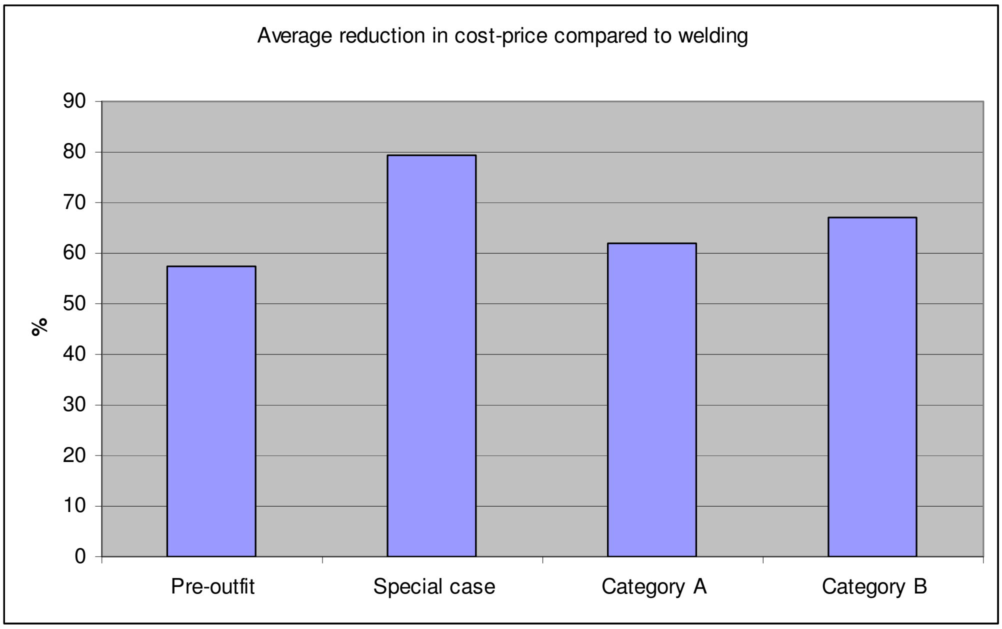
8.7 Sub conclusion: potential and requirements

Economical potential

In total, annually cost-savings of €146.000 can be realized when applying adhesive bonding instead of welding for the selected applications. This corresponds with a reduction of on average 65 % in cost price for using adhesive bonding instead of welding the selected items. However, these items only form a representation of a wider range of possible applications. For this reason, in practice, much higher cost-savings could be provided by using adhesive bonding. The percentages of possible cost-savings provided in this report may be used to give an indication of the possible cost-savings of an item to be bonded which is not specified in this report.

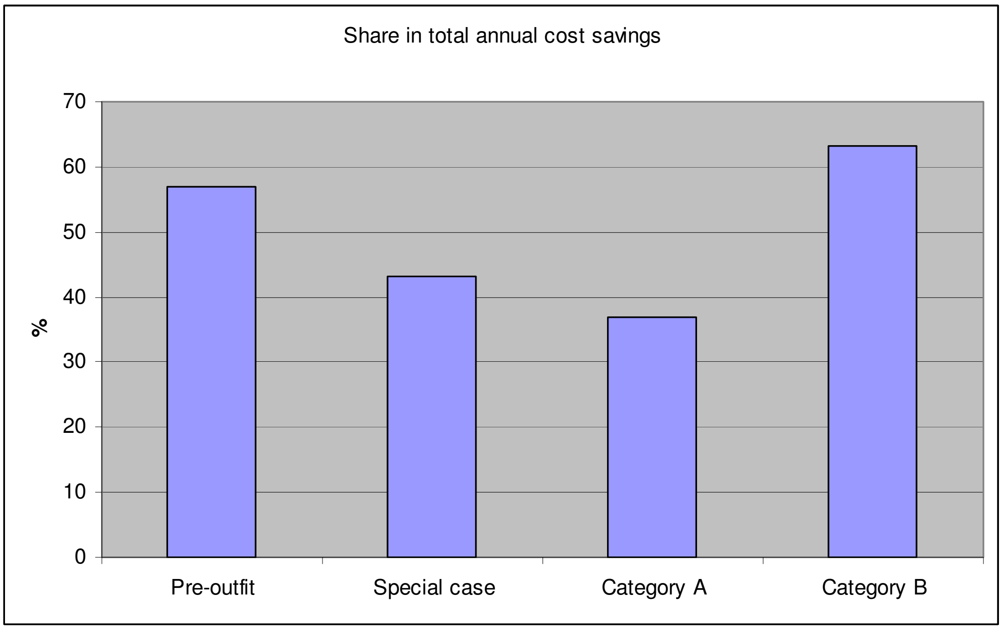
In Table 21, the average reduction in cost-price compared to welding is represented for adhesively bonded items for the use of adhesive bonding in the regular process (pre-outfit) and in the special case (e.g. forgotten or late delivered items). Additionally, the average cost-price reduction for both category A and category B is represented too.

Table 21 Average reduction in cost-price compared to welding



In the summary table (Table 10 of paragraph 8.1) total annual cost savings of € 53.956,08 for category A and € 92.327,75 for category B were obtained. This corresponds with a share in total annual cost savings of 37% and 63 % respectively (see Table 22). The share in total annual cost savings are represented for adhesively bonded items in the pre-outfit (57 %) and for special cases (43 %) too.

Table 22 Share in total annual cost savings



By analyzing both Table 21 and Table 22 the following conclusions may be drawn about the potential for the specific categories:

1. The highest average reduction in cost-price compared to welding is obtained for adhesive bonding in the special case (e.g. forgotten or late delivered items); 80% (vs. 57 % for pre-outfit), see Table 21. However, the share in total annual cost-savings (43%) for adhesive bonding in the special case is less than for adhesive bonding in the pre-outfit phase (57%), see Table 22.

2. Adhesive bonding of the items represented by category B provides a (much) larger share (63% vs. 37%) in total annual cost-savings than for category A (see Table 22), while the average reduction in cost-price compared to welding is almost similar for both categories (62 % category A and 67 % category B), see Table 21.

Technical potential

Although the theoretical determinations applied during the design phase are common, still verification by test and/or FEA (Finite Element Analysis) is required. The discussed stress analyses are not suitable for joints with complex geometries, boundary conditions and/or load transfer mechanisms as represented in Category C.

Best application

A ship's nameplate is the 'best application' to replace the current design by adhesive bonding. Taken into account production requirements, fire safety requirements and in- service requirements, the implementation of adhesive bonding of a ship's nameplate, is relatively simple and technical feasible without significant chances on the shipyard process. Adhesively bonding of the ship's nameplates provides most cost-savings annually (around € 39.000), per item (around € 2800) and reduces the production costs to 93% compared to welding.

Requirements

For successful processing and curing of the adhesive the ambient temperature is a critical factor (should be >10°C). Due to the lack of non destructive tests and fire safety requirements, classification societies have to be involved in the structural design and the manufacturing process. Additionally, personnel at the yard should be trained and educated, to realize acceptance of the new joining method and thereby ease the implementation of adhesive bonding.

9 Conclusions and recommendations

The central question of this report was; to what extent can and should the current method of joining steel parts (welding) within a yard be replaced by adhesive bonding? From this report it may be concluded that, based on numerous preconditions, it is possible to use adhesive bonding successfully in shipbuilding. For a successful introduction of adhesive bonding in shipbuilding, adhesive bonding should first be introduced in less critical areas (based on risk and strength) and increasingly also in more critical areas as service experience is gained and confidence in the long term performance is built up.

9.1 Conclusions

Potential adhesive bonding applications in shipbuilding
Adhesive bonding applications should always favor shear and compressive loads, while excessive peel and cleavage loads should be avoided. Despite this requirement still a significant amount of items can be adhesively bonded in shipbuilding. In this report 19 items, categorized by risk and strength, were presented as possible adhesive bonding applications. These items are representative for a wider range of products at IHC Beaver Dredgers and shipbuilding in general. Hence, the total amount of bonding applications in shipbuilding will be much higher in practice.

Criteria for selecting adhesives
In both the production environment as in the 'in service' environment, many parameters which influence the quality of a bonded joint are involved. From these parameters (e.g. temperature, humidity) criteria which an adhesive should fulfil were derived and quantified in order to make a selection in possible adhesive candidates for shipbuilding. In order to be applied in shipbuilding practice an adhesive should at least fulfill the following criteria:

- Lifetime of adhesive should be at least 25 year
- The adhesive must be able to bond to steel
- The adhesive should be water resistant
- Curing should be possible in a temperature range of 10°C - 30°C

As an addition to these fixed criteria, also lower priority requirements which are valid for appliance in shipbuilding practice were determined. This includes identification of possible alternative substrates, joint designs, and available processing facilities. These lower priority requirements were applied and compromised in order to select proper adhesive candidates for shipbuilding. Depending on the application, a distinction in suitable adhesives for shipbuilding can be made between toughened structural adhesives (toughened epoxy and toughened acrylic adhesive) and high-performance sealants with (semi) structural adhesive properties (MS Polymer adhesive). The type and nature of the substrate to be bonded and the required surface preparation were prime factors in determining which adhesive to use.

Influence of different substrates on the strength of adhesives

The adhesion capacity to the specific substrates (steel, shop-primer, coating) used at IHC Beaver Dredgers by simple surface preparation (degreasing only) was investigated for five different adhesives by performing lap-shear tests. From the obtained test results it may be concluded that, for the application in shipbuilding, the use of epoxy adhesive is recommended. This adhesive provides the best adhesion to both steel and coating. A reduction in adhesion capacity of 35% occurs when bonding the epoxy adhesive to coating instead of steel. When bonding to a shop-primed surface the reduction in adhesion capacity compared to steel is even higher; 60%. Therefore, bonding directly to steel is recommended. From the obtained test results it appeared that the adhesion capacity of MMA adhesives (Methyl Methacrylate) to the coating system of IHC Beaver Dredgers was poor. Therefore, this adhesive is not suitable for appliance at IHC Beaver Dredgers. For applications requiring gap filling properties and tolerance to bond line thickness variation, the epoxy adhesive is less suitable and MS Polymer should be used. The obtained difference in adhesion capacity to steel, shop-primer and coating for this type of adhesive is negligible.

Technical and economical potential of adhesive bonding applications in shipbuilding

To determine the potential of adhesive bonding, for each component rough pre-designs were established and evaluated economically by determining the possible savings in production costs per item and on yearly base compared to welding. From this analysis, the adhesive bonding of **a Ship's nameplate** is chosen as 'best application'. Adhesively bonding of the ship's nameplates provides most cost-savings annually (around € 39.000), per item (around € 2800) and reduces the production costs to 93% compared to welding.

In total, annually cost-savings of €146.000 can be realized when applying adhesive bonding instead of welding for the selected applications. This corresponds with a reduction of on average 65 % in cost price for using adhesive bonding instead of welding the selected items. However, these items only form a representation of a wider range of possible applications. For this reason, in practice, much higher cost-savings could be provided by using adhesive bonding. The percentages of possible cost-savings provided in this report may be used to give an indication of the possible cost-savings of an item to be bonded which is not specified in this report.

The highest average reduction in cost-price compared to welding is obtained for adhesive bonding in the special case (e.g. forgotten or late delivered items); 80% (vs. 57 % for pre-outfit). However, the share in total annual cost-savings (43%) for adhesive bonding in the special case is less than for adhesive bonding in the pre-outfit phase (57%). Adhesive bonding of the items represented by category B provides a (much) larger share (63% vs. 37%) in total annual cost-savings than for category A, while the average reduction in cost-price compared to welding is almost similar for both categories (62 % category A and 67 % category B).

Two main types of analytical approaches were used to determine the strength requirements of the selected applications. For MS Polymer the analysis using nominal stresses and strains has proven to be sufficient while for the analytical analysis of epoxy adhesive joints analytical linear methods should be used to obtain sufficient results. However, for joints with complex geometries, boundary conditions and/or load transfer mechanisms it is difficult or impossible to derive suitable analytical methods for both types of adhesives. These highly loaded joints should be analyzed numerically, materially and geometrically regardless of the complexity of the joint geometry.

Effect of 'best application' on the shipyard process and required conditions

Based on numerous preconditions, the implementation of adhesive bonding of the chosen 'best application'; a ship's nameplate, is relatively simple and technical feasible without significant chances on the shipyard process. In general, epoxy adhesive should be used for local attachments and MS Polymers should be used bonding larger areas with large tolerance requirements. Easy surface preparation (degreasing only) is sufficient to provide a strong bond and bonding to coating is possible for both adhesives. By bonding to coating, damage to paintwork is avoided and assembly of a component later in the production process is possible. In this way the flexibility of the production process on the shipyard is increased and interference with other work operations can be avoided. Furthermore, the selected epoxy adhesive is approved by a classification society to use in shipbuilding. However, when using adhesive bonding instead of welding numerous influencing factors have to be taken into account. Although the theoretical determinations applied during the design phase are common, still verification by test is required. Due to the lack of non destructive tests and fire safety requirements, classification societies have to be involved in the structural design and the manufacturing process. Furthermore, although adhesives were selected with low curing temperatures, successful processing and curing of the adhesive is still depending on available working temperatures (> 10°C) and humidity at the moment of application. Finally, for successful implementation of adhesive bonding the personnel at the yard should be trained and educated and approvals for the production facilities are required.

9.2 Recommendations

Tests

In the performed test program only the strength of the adhesives on different substrates was tested without considering environmental and in-service conditions. Moreover, the adhesives were only tested by shear strength properties using a simple lap-shear sample. To obtain a more complete overview of adhesive performance, testing of full scale joints and simulation of environmental and in-service conditions (temperature, salt water, different types of load) during the test program is recommended. Although a favorable adhesion capacity of the epoxy adhesive to a coated surface was obtained from the test program, in practice there are a lot of variables that influence the adhesion of coatings. Therefore, it is recommendable to further investigate the influence of inconsistency in adhesion properties of the coating system on the adhesive joint strengths.

Surface preparation

Although, easy surface preparation during the test program provided sufficient adhesion strengths on the different substrates it is recommended to further investigate the possibility of applying laser cleaning. With this surface treatment a shop-primed or coated surface can be removed without inserting any heat in the surface. In this way an optimal bonding surface (steel) could be obtained in a simple manner.

Strength calculations

As a verification of the performed analytical analyses in this report it is recommended to analyze the obtained results by numerical methods using FEA (Finite Element Analysis) in future research. Additionally, the selected applications with more complex geometry, boundary conditions and load transfer mechanisms (category C) can be analyzed using FEA (Finite Element Analysis) as well.

Implementation

Since adhesive bonding does not enjoy the same status in comparison to the current joining technique (welding) reserve of local staff should be overcome. The acceptance of local staff for adhesive bonding as a new joining technique is a critical factor in a final implementation of adhesive bonding in shipbuilding and should be realised by providing well-founded knowledge of adhesive bonding. It is recommended to introduce adhesive bonding first in less critical areas to gain service experience and built up confidence in the long term performance. In this way a 'snowball effect' could be created and adhesive bonding could be applied increasingly in more critical areas.

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