ADHESION: LESSONS LEARNED ABOUT ADHESIVE BONDING IN SHIP STRUCTURES

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SUMMARY

A joint research program called ADHESION, consisting of 13 different stakeholders, has led to a structured acquaintance of the Dutch shipbuilding industry with adhesive bonding. The project goal was to gain information and implement technology for certified adhesive joints in shipbuilding practice.

A large number of specimen tests were performed to test the applicability of various adhesives systems on (coated) shipbuilding materials. The test results showed that for high strength adhesives failure occurs in the coating/primer, which means the full capacity of the adhesive is not used. However, the test results did show that coatings are required to prevent corrosion of metals underneath the bondline.

Besides specimen testing, four case studies into typical ship structural components were carried out, which indicated bonding of ship structures is feasible. An important result that followed from the cases is that stress values attained in practice are a factor 2 lower compared to values attained in specimen tests. The biggest remaining challenge after this cooperative research project is to predict the service life of an adhesive joint. This challenge needs to be addressed before “standard” certified adhesive joints in shipbuilding will become common practice.

1. INTRODUCTION

Traditionally the shipbuilding relies almost exclusively on welding to assemble metal structures and to install equipment. However, under the pressure to produce lightweight and cost effective structures, plate material of which ships are constructed becomes thinner, and composite materials are increasingly applied. This creates situations in which welding is no longer possible or has negative impact on aesthetics. Adhesive bonding could provide a cost effective solution for these joining problems, but questions exist about the long term durability and mechanical strength of adhesive joints.

To implement adhesive bonding technology in shipbuilding practice a research project ‘ADHESION’ was initiated within the Netherlands Maritime Innovation Program. Among the project participants were shipyards (Damen, classification societies, engineering firms, an adhesive supplier and knowledge institutes. The objectives of the projects were as follows:

- To develop and provide knowledge in the field of adhesive bonding that can be used by engineers to design maritime structures
- To determine the effect of the shipyard production environment on the quality of the adhesive bond
- To transfer know how of bonding procedures to shipyard and service employees
- To identify the technical and economic potential of large scale bonding applications in light weight maritime structures

This paper presents a brief overview of the results of the ADHESION project. Section 2 describes the challenges the maritime sector is facing in the field of bonding and those are related to bonding practices in other industries. The third section focuses on the mechanical aspects of bonded joints and presents the results of the case studies. Section 4 describes durability related issues of adhesive joints in a maritime environment. The road forward towards certified adhesive joints in shipbuilding practice is described in Section 5. The paper ends with the conclusion in section 6.

2. UNIQUE CHALLENGES OF BONDING IN THE SHIPBUILDING INDUSTRY

With the exception of composite ship building. adhesive bonding is not yet widely applied in maritime engineering. Adhesive technology has found its way in furnishing of yachts and other specific applications such as window bonding. However, as of today bonding is not yet used in primary structural joints in metal ships. There have been research efforts in the field of adhesive bonding for maritime applications before of which BONDSHIP is the most noteworthy. One of the main achievements of BONDSHIP was the publications of a set of guidelines that can be used for designing adhesive bonds (Weitzenböck J. , 2010). The authors argued that the next step was to move from precompetitive research to product development. A critical mass of users of bonding technology in shipbuilding is required to make bonding a widely accepted technology.

Examples of industries where bonding technology is more widely accepted are the aerospace- and automotive industry. Adhesive bonding literature is full of references to the aerospace industry as an example of an industry where bonding is already widely applied (Kinloch, 1987; Kwakernaak, Hofstede, Poulis, & Benedictus, 2010; Weitzenböck J. , 2012). However, a critical review of the bonded applications in the aerospace industry indicates this is only partly true. Structural bonding in aircraft structures is limited mainly to secondary applications. Aerospace manufacturer Fokker from the Netherlands is one of the few exceptions in the aerospace industry who widely applies bonding. Fokker has been bonding stringers to metal wing skins for over 80 years now, leading to metal structures with excellent fatigue life (Kwakernaak, Hofstede, Poulis, & Benedictus, 2010).

The challenge for the shipbuilding industry is that the manufacturing standards from aerospace engineering are not easily transferred into the shipbuilding industry. For example, for bonding aluminum Fokker uses a chromic acid anodizing pretreatment and primes the surfaces with a heat curing epoxy primer. The anodizing process improves the strength of the adhesive joint and also creates a very stable oxide layer (Kinloch, 1987). Such extensive pretreatment requires significant investments in chemical pretreatment machinery and leads to high manufacturing costs, which makes these processes not suitable for the shipbuilding industry.

Another industry which is often referenced in bonding literature is the automotive industry (Habenicht, 2008). For example, adhesive bonding has been extensively used for over 30 years in the elastic bonding of windshields. Also truck trailers are increasingly assembled relying solely on adhesive bonding technology. Accelerated aging test are widely used by automotive manufacturers for assessing the durability of adhesive systems. All automotive manufacturers have their own test cycles, but usually they involve cycles of about 7-10 days with temperatures ranging between -30°C and +70°C, UV radiation and humidity levels up to 100% (Kinloch, 1987). Although these testing conditions are severe and seem to give reliable results for the automotive industry, their applicability to the maritime industry are questionable. Take for example the environmental conditions in Singapore, where temperatures of 30°C and higher are reached on a daily basis, in which surfaces can heat up to 80°C. In combination with high humidity levels and a saline environment, these conditions can form a much higher loading for the adhesive system than a common accelerated aging test. This means the shipbuilding industry has to develop its own standards for accelerated test that yield representative results for the service life of a bonded joint.

A final challenge that the maritime industry has to address before adhesive bonding can be readily applied is the influence of the production environment and the influence of the "bonder" making the adhesive joint. In theory a dirty production environment could negatively influence the quality of an adhesive joint. Oil and dust particles in the air can deposit on the substrate leading to a lower adhesive strength. The bonder is another contributing factor, because the quality of the joint is determined by how carefully the bonder follows the prescribed manufacturing procedure. The quality assessment is complicated because it is difficult to inspect adhesive bonds using non-destructive testing methods.

Both manufacturing aspects described above were briefly addressed during ADHESION. For this purpose a series of samples was made under different circumstances: clean laboratory conditions, "clean" shipyard conditions and "dirty" shipyard conditions. No trend followed from the destructive tests that were carried out on the samples (Bosman, 2012). A large spread was present in the data, which indicates the bonder seems to have a large influence on the quality of the joint. To get a better idea of the influence of the shipyard environment on the bonding process a more thorough test setup is required: eliminate the effect of the bonder, by letting 1 person make samples under the 3 different conditions.

An important lesson that can be learned from the effect of the production environment and the bonder on the quality of the joint is that one has to take these effects into account for the serviceability of adhesive joints. An adhesive joint does not only need to be achievable under shipyard conditions, but here should also be a solution to service the joint in the field by a service engineer.

3. MECHANICAL TESTING OF ADHESIVE BONDS

During ADHESION 4 different cases were studied which represented typical ship structures. The goal of the case studies was to evaluate the suitability of adhesive joints for primary structural joints. Practical tests were performed on 2 different levels of the so called testing pyramid (Figure 1): at coupon level and at component level. The testing pyramid is commonly applied in aerospace engineering for describing the process through which a technology develops up to a point where it can be readily applied in the industry (Beumler, 2004). When a technology is still relatively new, tests are performed at a coupon level, because at this level testing is still relatively cheap. Afterwards the higher levels of the testing pyramid are filled by performing test at component and full scale level. The latter is not applied in shipbuilding because it would simply make the development process too costly. By testing at multiple levels knock down factors can be set that can be used during the design phase.

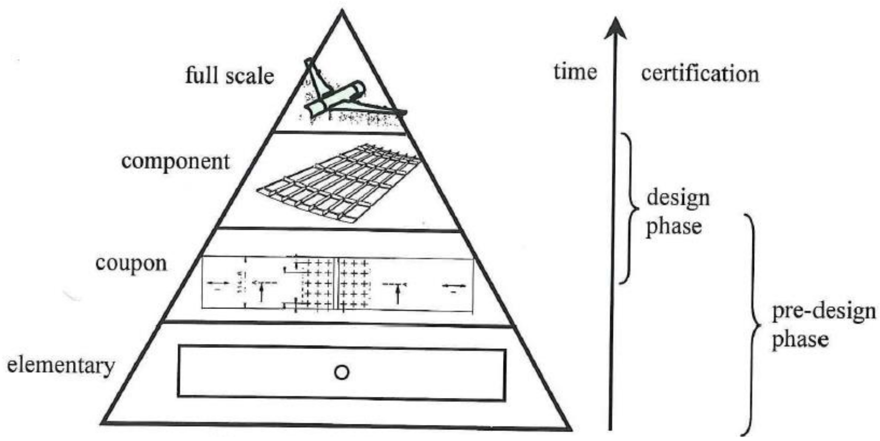


Figure 1: Testing pyramid during the development of an aircraft (Beumler, 2004)

During the ADHESION the following 4 cases were selected to be investigated, which are listed below (see Figure 2). In each case specific properties regarding the performance of the adhesive joint were required such as fatigue resistance, underwater bonding and different substrate material.

1. Mast-Superstructure connection
2. Stainless steel bow plate
3. Foundations for rotating machinery
4. Streamline fairing

The case studies performed during ADHESION did not result in certified adhesively bonded solutions for the structural elements that were under investigation (Bosman, 2012). For achieving this too many question marks remain, such as the durability of the joint and the way to inspect the joint by means of non destructive inspection. The main lesson learned was that the joint geometry has a large influence on the strength values that are achieved. The strength values that resulted from ASTM standards were roughly a factor 2 higher compared to the stress values that were obtained in the actual application. This implies two things: first of all, alternative testing standards compared to ASTM standard D1002 have to be used to produce engineering values that can be used during the design phase. Secondly, accurate FEA methods are required to calculate stresses in bondlines to avoid preliminary failure.


Figure 2: cases that were studied: left, stainless steel bow plate (source: Amels); right, composite streamline fairing bonded to steel or aluminum hull

4. DURABILITY OF ADHESIVE BONDS

This chapter describes durability aspects of adhesive joints in maritime environments. Sub-section 4.1 describes adhesive forces on a molecule level and how these forces are affected by the maritime environment. Sub-section 4.2 presents the durability results that were obtained during the ADHESION project and what the results imply for design practices of adhesive bonds in shipbuilding practice.

4.1 Physical and chemical principles at a molecule level

Substrates like metal, glass, wood and fiber reinforced composites all have a similar surface topology when it comes to bonding: they all have (at least some) hydroxyl groups and double bonded oxygen molecules at the surface. The precondition for a strong adhesive bond is that the adhesive molecules come in close contact with the substrate (Kinloch, 1987). Close molecular contact is only achieved when the adhesive wets out properly on the surface. Proper wetting is achieved when the attractive forces of the substrate on the liquid adhesive are higher than the attractive forces in the liquid itself.

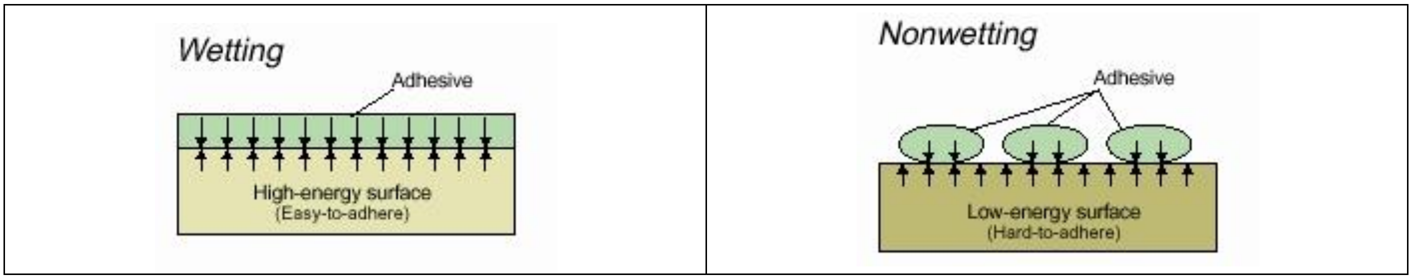


Figure 3: left, proper wetting in case of a clean and high energy surface; right, poor wetting in case of a low energy surface (source: machinedesign.com)

The same molecule structure that improves wetting characteristics of adhesives also makes them vulnerable to environmental attack: adhesives often have polar groups to improve wetting and adhesion characteristics, but as a result water also diffuses more easily into the bulk adhesive (Burchardt, 2010). Water and Oxygen diffuse into the adhesive and attack an adhesive joint on multiple places: in the cohesive zone, the adhesive zone and the substrate itself (Figure 4). However, the diffusion of moisture into the adhesive is not always an unwanted side effect; elastomers like MS polymers and 1 component PU adhesives, require moisture to cure.

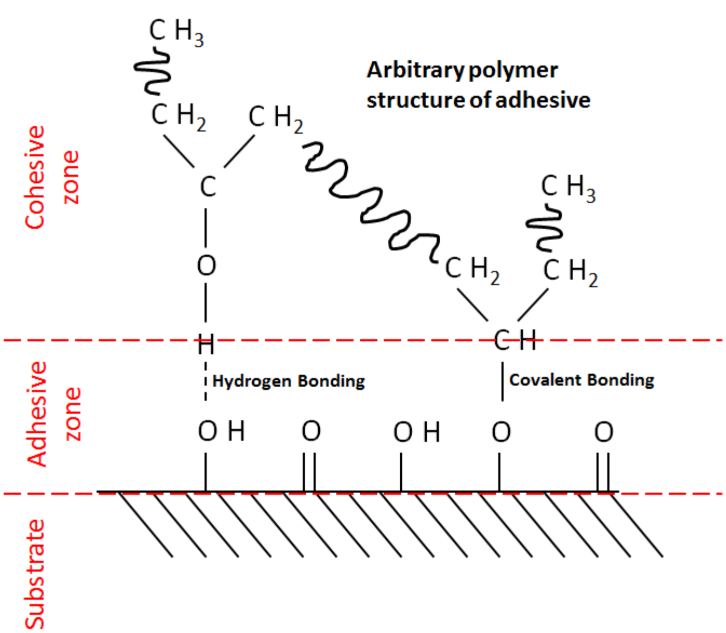


Figure 4: Different areas of an adhesive joint where the environment can attack

Below the mechanisms by which the maritime environment can attack an adhesive joint are listed. The list is limited to the contribution of water, oxygen, UV and heat, while other substances such as alkaline and acid solutions (gasoline, cleaning agents, etc.) can reduce the strength of an adhesive joint as well. However, the mechanisms by which this attack occurs are similar to the ones described below. It is important to understand the processes by which adhesive joints age in a marine environment, because failures that occur in practice can be recognized and appropriate countermeasures to increase joint durability can be taken.

1. Water, Oxygen, heat and UV attack the adhesive itself in the cohesive zone:
    a. Moisture can plasticize adhesive (intercalation of water): water molecules that diffuses into the adhesive displace polymer chains, this increases the distance between the polymer chains and thereby they slide easier along each other plasticizing the adhesive.
    b. Acid hydrolysis of adhesive: polymer chains are broken by water molecules (Figure 5)
    c. Migration of molecules such as plasticizers, stabilizers or catalysts, which is caused by an intrinsic instability in the adhesive
    d. Oxygen can scission polymer chains under the influence of UV light
    e. Heat can break chemical bonds in the adhesive
2. Water, Oxygen, heat and UV attack the chemical and physical bonds between adhesive and substrate in the adhesive zone
    a. moisture can displace adhesive (intercalation of water) at the adhesive substrate interface (see 1a)
    b. Oxygen and/or water can scission chemical bonds between substrate and adhesive
    c. Heat can break chemical bonds at the adhesive substrate interface
3. Water and Oxygen can attack the substrate:
    a. Water and oxygen can attack metal oxide layers, creating a weak interface which easily breaks away. Salt water can considerably speed up this process
    b. Fiber reinforced polymers can be weakened by moisture ingress, oxygen, UV and heat

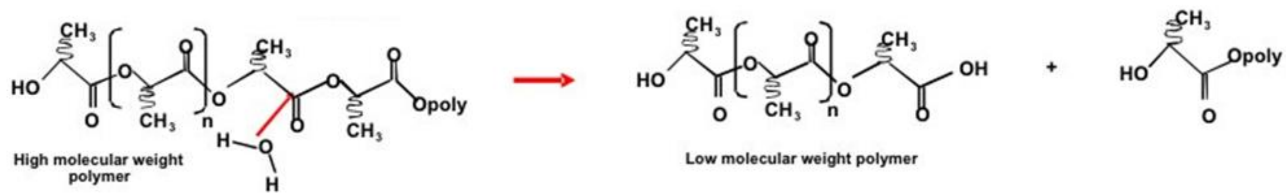


Figure 5: Hydrolysis and cleavage of the ester linkage in a polymer (source: http://www.uweb.engr.washington.edu/)

From the overview of failure modes it becomes obvious that if one would like to model or predict the long term durability of adhesives in a maritime environment, one needs to have a thorough understanding of the above described mechanisms. The overview of failure modes does not take the effect of cyclic loading into account, while it is known that adhesive joints are sensitive to fatigue (Kinloch, 1987). The fatigue life of a joint can be expressed by $N \cdot S^m = C$, in which N is the number of cycles, S the stress amplitude and C is a material constant. The variable m is a measure which indicates how sensitive the material is for the stress range. For welded details in metals a common value for m equals 3. During the fatigue tests that were performed as part of ADHESION, m-values in the range of 8-10 were found (Bosman, 2012). This indicates the stress amplitude affects the fatigue life of adhesive joints, but they perform better compared to welded or mechanically fastened joints. This essentially arises from a better stress distribution in the joint, since adhesive joints do not lead to stress concentrations (Kinloch, 1987).

Most of the progressive damage models for disbond growth in adhesive joints under the influence of cyclic loading that are currently available are based on empirical models (Pascoe, Alderliesten, & Benedictus, 2013). These empirical models work relatively well under well-defined laboratory conditions, but are of little use for predicting service life in practice. Therefore, models on a more physical and chemical basis are required to make accurate service life predictions for bonded joints.

4.2 Increasing the durability of adhesive joints

To create a durable bond one has to create a stable interface between the adhesive and the adherent (Kinloch, 1987). The oxide layer of steel is known to be very unstable and easily breaks away. The oxide layer of aluminum is much more stable as the layer passivates by itself. However, under the influence of water molecules, the aluminum oxide can hydrate leading to a weak layer that can easily break away (Kinloch, 1987). During the ADHESION project the durability of uncoated steel and aluminum surfaces was tested. The result was that uncoated metals did indeed not result in durable bonds. Figure 6 shows two examples of specimen after aging and destructive testing. In the left side of the figure is clearly visible that edge-corrosion occurs at the steel-adhesive interface. In the right side of the figure the white layer after aging indicates hydrolysis of the aluminum oxide layer, leading to a reduction in adhesive strength.

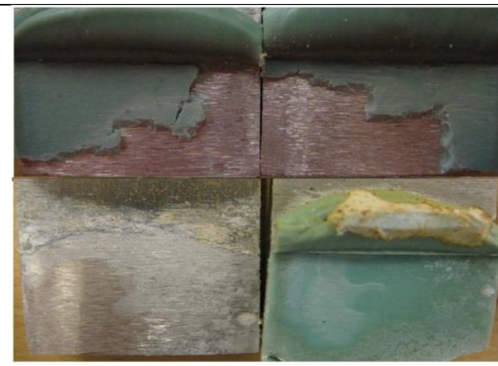
Steel samples bonded with Teroson MS-9380 adhesive, subjected to salt spray testing at 35°C		Aluminium samples bonded with Loctite UK1366B10/UK5452, subjected to deionized water	
	unaged		unaged
	6 weeks salt spray testing		10 weeks of deionized water

Figure 6: Left, uncoated steel samples subjected to salt spray testing; right, Aluminium samples subjected to deionized water

During the ADHESION project commonly applied ship building primer systems were investigated as an interface for bonding. These primer systems normally form the basis of a paint system that protects the metal surface from corroding. The results of the test performed during ADHESION are twofold (Bosman, 2012):

1. Shipbuilding primer systems make adhesive bonds durable in corrosive environments
2. When shipbuilding primers systems are used in combination with structural adhesives, failure occurs in the primer layer

Although the first result is promising the second result poses a major design challenge. The primer failure is a brittle failure and difficult to model during joint design. In a bonded joint one generally aims for a cohesive failure, because this yields a more predictable failure mode during the design process. Shipbuilding primers did turn out to be a suitable substrate for low strength elastic adhesives, such as MS polymers and 1 component PU adhesives. These adhesive have considerably lower strength and therefore fail before the primer layer fails.

For durable bonds which do use the full potential of the adhesive, leading to cohesive failure, a different primer system than the currently applied paint primers needs to be identified. Silane primers have been successfully applied in the past for creating durable adhesive bonds (Kinloch, 1987). To what extent these systems are applicable to ship building requires more testing. There is already experience with Silane primer in composite patching of metal ship structures (Karr, 2014). Alternatively the adhesive can be applied directly to the bare metal but then the joint needs to be protected from the corrosive environment by a coating or sealing on top of the bonded joint.

5. TOWARDS PRIMARY STRUCTURAL BONDING IN SHIP STRUCTURES

The ADHESION project did not lead to a large breakthrough in adhesive bonding of ship structures, but it did create the required knowledge base to increase the number of applications of adhesive bonding in the industry. At multiple shipyards that participated in the ADHESION project engineers continue to design bonded solutions to joining challenges. Due to the limited experience with the durability of adhesives, the applications should be limited to low risk applications for the moment. In case more critical components are bonded, one can opt for a hybrid solution, where mechanical fasteners are used in combination with the adhesive. This way trust can be built in this promising technology. Best bonding practices need to be secured in hand books and applications need to be monitored to gain knowledge about the long term performance of adhesives in a maritime environment. This way adhesive bonding can find its way in the industry as a cost effective alternative to welding and mechanically fastening.

6. CONCLUSIONS

This paper described the key results of the research project ‘ADHESION’ which focused on adhesive bonding in the maritime industry. The project goal was to gain information and implement technology for certified adhesive joints in shipbuilding practice. The project resulted in a firm knowledge base about requirements that a bond needs to fulfill, to survive in a marine environment. The conditions at the shipyard proved to be suitable for bonding and employees from the yard were trained in bonding practices. A large number of specimen tests were performed, which showed metals need to be protected against corrosion prior to bonding. A corrosion resistant primer system that is strong enough to result in cohesive failure has not been identified yet. The biggest challenge that remains is to develop adhesive bonds that survive the marine environment and to make accurate predictions about the service life. To tackle this challenge it necessary to gain experience with bonding by means of low risk applications. This process has been started at some of the shipyards that participated in ADHESION.

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