BONDSHIP: developing guidelines for adhesive bonding in shipbuilding

Jan R. Weitzenböck, Det Norske Veritas AS, DNV Research, Veritasveien 1, 1322 Høvik, Norway, Jan.Weitzenboeck@dnv.com

Introduction

European shipyards are facing considerable pressure to remain competitive as they are competing for new orders on a world-wide basis. There is a constant need to reduce production costs while introducing novel materials and structural designs [1]. This has lead to an increased interest in adhesive bonding for use in application areas such as:

- To join different materials, e.g. an aluminium deckhouse to a steel deck.
- To reduce cost or weight: lack of heat distortion eliminates the need for rework, reduces the time spent on surface finishing, and allows the use of thinner plating.
- When welding is not practical, e.g. the surfaces are already painted or electrical cables are adjacent to the joint.

The BONDSHIP - *Bonding of lightweight materials for cost effective production of high speed craft and passenger ships* project was started in 2000 to develop adhesive bonding as a standard joining process in shipbuilding. One of the main results emerging from this project are the BONDSHIP project guidelines [2]. The objective of the guidelines is to provide guidance and examples on how to design, produce and inspect adhesively bonded joints. The guidelines are split into two parts. Part one is the Code part setting safety relevant requirements for the approval of joints. The second part is a collection of recommended practices - how to e.g. select adhesives, design and analyse joints. Furthermore it shall provide the basis for meeting the general requirements laid out in the Code document. The BONDSHIP guidelines apply to all types of adhesively bonded joints in ships. The bonded joints can be either structural or non-structural. The document encompasses the design, manufacture and use of bonded joints. Figure 1 shows a summary of the total process for new building and in-service. This diagram is not meant as a complete description of how to design and build a ship structure. Its aim is merely to highlight the adhesive-specific aspects. In the remainder of this paper the approval process is described which is followed by a brief discussion of the main chapters of the BONDSHIP guidelines.

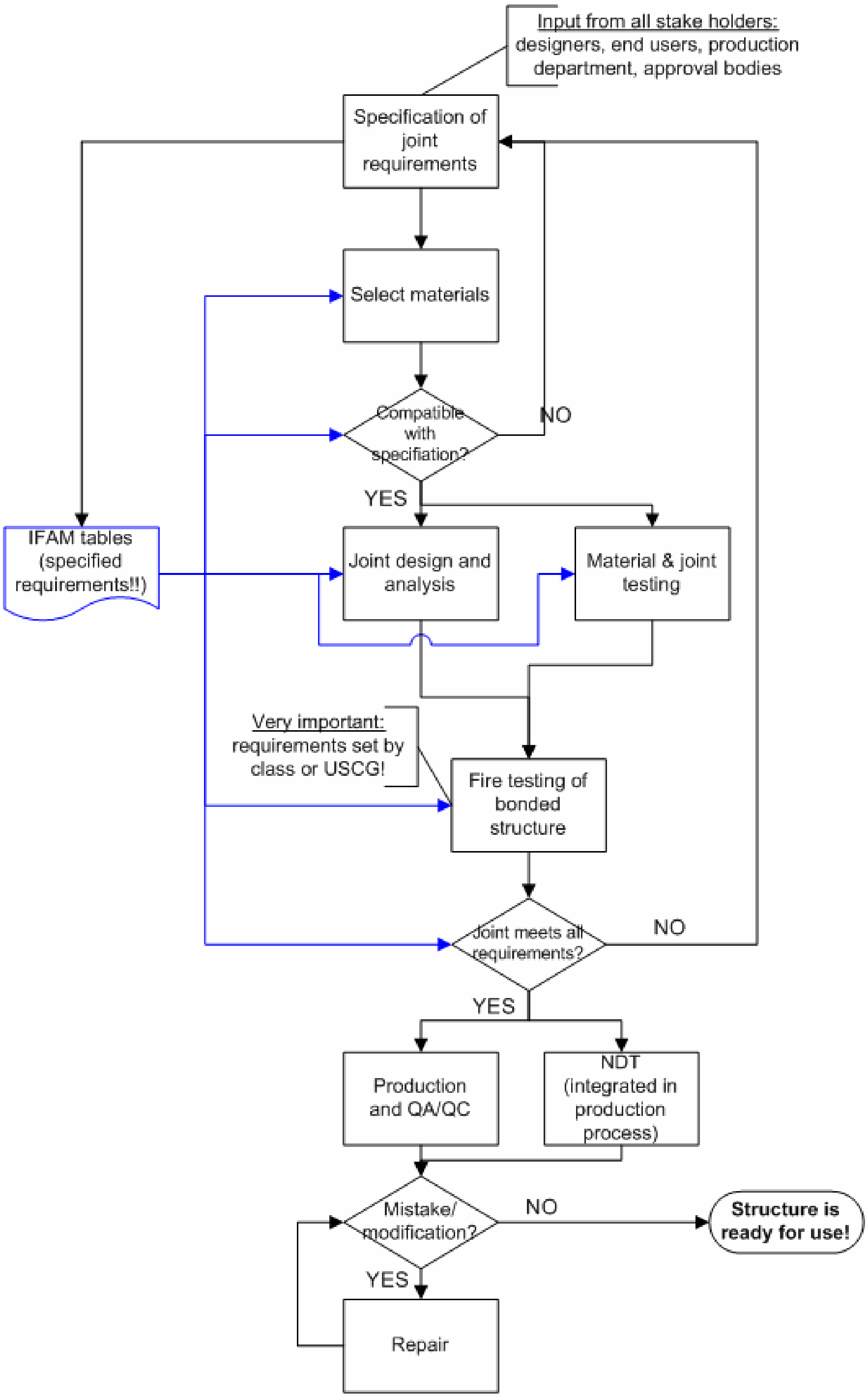

Figure 1: Outline of the design and production process for bonded joints

Approval of bonded joints

Adhesive bonding is faced with a dilemma: there is virtually no documentation of the long-term performance of bonded joints in a marine environment. Hence, it is not straightforward to demonstrate, say, a 25 year lifetime for a new joint design. One therefore needs to find an alternative way for obtaining acceptance and approval of bonded joints. The alternative approach developed in BONDSHIP [3] uses well established principles of risk-based design.

Formal hazard identification is used to identify possible causes and consequences of long-term degradation and possible consequential damage. The identified hazards are reviewed and assessed. The following risk control measures are used to control the associated risks:

1. Use best practice in material selection, joint design and production technology: The BONDSHIP guidelines [2] provide examples of this. Best practice is used in materials selection to eliminate unsuitable combinations of adhesives and adherends. Best practice in production is used to establish robust processes with minimal variability. Furthermore it is used to ensure tight quality control of each production step as it is not possible today to check the quality of a finished joint non-destructively.
2. Ensure that the design allows detection of damage before ultimate failure: The joint is e.g. starting to leak or develops visible cracks. To ensure that joint failure or the onset of failure does not affect overall safety requires that the structure is designed with sufficient redundancy and reserve strength so that detectable damage in a joint is tolerable (at least until it can be repaired).
3. Develop and demonstrate a repair procedure for the joints to be able to repair damage: These repair procedures are to be developed by the shipyard or subcontractor responsible for the bonding operation in consultation with the ship owner and e.g. the adhesive supplier.

Definition of requirements

The first step in the design of adhesively bonded joints is to work out a detailed list of requirements to determine all features that could affect the behaviour and performance during the lifetime of the joint. The definition of the requirements and their main features in the list below are not always strictly correct in the sense of their physical meaning, but they have to be understood in a more general sense with the purpose to cluster the requirements and to gain a full set of information:

- Geometry: including all geometric data of the structure around the adhesive joint.
- Kinematics: including all accelerations and deformations of the structure which might create forces in the joint.
- Forces: all forces and loads at the joint including the stiffness of the surrounding structure.
- Energy: influence of temperature which might directly change any material properties or generate strain due to different thermal expansion factors of materials.

- Material: including physical, mechanical and chemical properties and any change of these properties due to ageing.
- Verification: any testing and design methods like numerical and analytical methods, standards and regulations.
- Maintenance: including protection against possible damage and applicable repair methods.

Material selection

The main instrument for selecting the materials used in the design of bonded joints is the screening test. Screening tests are usually carried out at the beginning of the design process. The screening test programme is used to reduce the vast number of possible combinations of adhesives, primers, paints and other surface preparations available for different adherend materials such as steel, aluminium and composites. Tests are chosen to obtain relevant test data for selecting materials in a cost and time efficient manner. Common to all tests is that the specimens are simple and cheap to produce. The test programme is usually divided according to the type of adhesive: (1) rigid and (2) flexible adhesives. The main reason for this is that many tests only work with a certain type of adhesive due to their specific mechanical properties.

Modelling

The objective is to provide a guideline for designing adhesive joints in shipbuilding, starting from collecting information for the design process to using analytical approaches and finite element analysis for the design. The main focus is on obtaining procedures that are practicable, pragmatic and safe from the point of view of the shipbuilding industry. Thus, in addition to being conservative the methods should be easy-to-use. On the other hand academic completeness is not the most important factor. The different approaches are discussed with their limitations due to mathematical assumptions or the grade of implementation in standard commercial finite element codes. Most of the proposed design methods have been thoroughly verified through comparison with experiments performed in the BONDSHIP project.

It is important to note that a design procedure is not necessarily suitable for all kinds of adhesive joints. For certain simple joints of low utilisation a loads methods based on nominal stresses and strains may be applied. Early analytical solutions, like the approach of Volkersen or Goland and Reissner, may be used for some further aspects: Here, stress concentrations at the ends of the joints are taken into account, and approximations on the peel stresses may be obtained. These methods are suitable to get a first estimate of the overlap-length of adhesively bonded joints. A more recent and more comprehensive analytical solution method, derived by Bigwood and Crocombe, has also been thoroughly investigated during the project work [4]. The relatively involved analytical expressions arising from this method have been implemented in an Excel worksheet. The method works well for certain application cases. However, procedures based on linear and non-linear finite element calculations might be the most suitable methods for more general and complex joint design problems. Thus, it turns out that the term *easy-to-use*-design-rule is not necessarily identical to *simple* analytical approach [4]. In many cases linear or non-linear finite element analysis may be the most efficient and suitable way to approach a design of a bonded joint in a structure [5-7].

Testing

Experimental testing of bonded joints and their materials is carried out for various purposes during design and qualification of the joints:

- Screening tests are carried out in order to establish the basis for selecting suitable materials and manufacturing procedures.
- Material characterisation tests are carried out in order to characterise the properties of the materials present in the joint for input to theoretical models.
    - Thick adherend shear test (TAST)
    - Simple shear strength test
    - True stress / true strain behaviour, E–Modulus, Poisson's ratio
    - Compression Tests – Rhagava equivalent stress
- For joint strength prediction, tailor made tests are sometimes used together with theoretical models to establish critical strength parameters. Some examples were presented in [4].
- For qualification of the joints, dedicated qualification tests of the full-scale joints are sometimes required.
- Ageing and fatigue tests: Qualification must be based on a joint strength estimate that is representative for the whole intended lifetime of the joint. To the extent the service environment may affect the joint strength, this must be accounted for.

Fabrication

Fabrication of bonded joints and the required quality control features are governed by the production rate (joints per hour) and level of mechanisation:

- High level of mechanisation: pre-qualified procedures, on-line measurement and process control
- Low level of mechanisation: training, inspection, pre-qualified procedures

A quality plan for the bonding operation(s) shall be prepared by the yard/fabricator specifying working procedures, check points, tests, inspections etc.. Once the materials for the adherends and the adhesive(s) have been selected the manufacturing process is mostly defined. The BONDSHIP guidelines provide checklists for preparing production procedures [8]. The main steps are:

- Joint specification
- Receipt and storage of materials
- Bonding operation
- Storage of finished bonds
- Health and safety

Furthermore information is provided for selecting the most suitable manufacturing route. Specifically the dispensing of adhesives, manual and mechanised/robotised adhesive processing and cure of adhesives are discussed.

Fire protection

For joints that have to carry load during fire, adhesive systems with heat resistance of less than 80-100°C is not recommended, as this will require excessive amount of fire insulation. There are no technical problems connected to fire protection of the bonded joints to any target value, but the thickness of insulation needed can in some cases be in conflict with volume or area requirements, and of course weight and cost requirements. In order to assess the requirements of a bonded joint in a fire, a detailed load analysis has to be carried out in each case. The key questions are:

- What does happen if the joint fails during fire?
- Does this have any impact on the fire safety of the vessel?
- How can this be avoided by other means than structural strength of the adhesive during fire?

Flaming or smoke from the adhesive joint was not a problem for any of the tested cases. Even if the joints had been unprotected, the fire reaction (heat release, toxicity) properties of the adhesive did not represent any decrease in fire safety level. This is due to the small areas of adhesive exposed to fire, but also the small amount used compared to other combustible materials used on a ship (paint, decorative surfaces, deck covering). The load carrying bonded joints failed at relatively low temperatures (between 40 and 80°C). None of the adhesives tested in BONDSHIP had been selected for optimum temperature resistance, and were not post-cured at elevated temperatures. Increasing the temperature limit from 40 to 120°C for the adhesive would have a major impact on structural lifetime of a joint during a fire, or on the amount of insulation needed to meet a given requirement.

Non-destructive testing

The research reported in the BONDSHIP project guidelines has shown the applicability of NDT techniques to support production and in-service monitoring of adhesively bonded marine structures. The suitability of ultrasound as an inspection technique was demonstrated for most of the proposed materials and joint designs considered for the application cases. Novel use of experimental data and modelling techniques enabled the simulation of many of the inspection prior to the construction of test assemblies and the application case structures. Inspection strategies were developed for each of the application cases based on the joint designs and measurements of the adhesive and adherends. In some cases new inspection methods utilising lower ultrasound frequencies or large areas scanning techniques were employed. Close working and consultation with the manufacturers of the application cases enabled the key requirements for future NDT inspection of commercial structures to be identified and the role of NDT for production monitoring and assessment of the joining process to be assessed.

Summary and conclusions

The BONDSHIP guidelines present methods and, where possible, actual examples for the design, production and in-service phase of adhesively bonded joints. The following topics are discussed:

- Specification of bonded joints
- Materials selection
- Failure criteria and characteristic strength values

- Design and analysis of bonded joints
- Testing of materials and structures
- Fire safety
- Production and repair of bonded joints
- Non-destructive inspection

Significant progress was made in BONDSHIP. However, most designers, builders and owners of ships and marine structures are not aware of the possibilities (and limitations) that adhesive bonding offers. The BONDSHIP guidelines provide a framework for the safe introduction of bonded joints, first in less critical areas and increasingly also in more critical areas as service experience is gained and confidence in the long term performance is built.

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