Report No.	D1.2.1	
Title of Report:	**Model predicting the mechanical performance of the joint, based on loading and environmental input.**	

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EXECUTIVE SUMMARY

There is a great interest in designing and building lighter, more stable and cost-effective maritime vessels. One of the ideas developed for this purpose is to employ composites and subsequently adhesively bonded joints instead of welding and bolts. Adhesives are under study to be used in primary structures of the ship such as in the connections of a composite superstructure to the steel deck.

The previous investigations and load analysis on full ship model done by a partner of the project (BV), showed the different loading on the whole ship due to sea wave. Those analysis indicates that the adhesives are under shear loading and the range of loading is determined. Hence, our study is focused on the mechanical behaviour and fracture properties of these adhesives under shear.

In this report, we propose a modelling approach to predict the mechanical properties of adhesives under shear. Moreover, we look at the effect of different dimensional parameters, as well as size, location, and types on the joint performance throughout its lifetime. A physically based constitutive model for the adhesive, including failure, is generated. The effect of environmental factors is seen in the mechanical properties of adhesives. The joint performance throughout its lifetime (considering fatigue and aging) can be predicted by changing the inputs of the model. The results of experiments such as tensile testing on adhesives at room and elevated temperature as well as single-edge notch bending test will be used in the model predicting the mechanical behavior and fracture properties of the adhesives.

In order to gain knowledge on mechanical response of the adhesive under shear, and to validate the proposed models, a Thick-Adherend-Shear-Test configuration is designed and studied.

SUMMARY

TABLE OF FIGURES

1. INTRODUCTION

1.1. QUALIFY project

The advantages of composites are encouraging ship building industries to use these materials in maritime structures. Weight reduction and subsequently lower transport costs for structures and increased range/payload capacity for ships, as well as reduction in corrosion problems are among the most important advantages of these materials. Figure 1 shows the reference vessel used in this project. Main characteristics of this vessel are listed below:

Dimensions:

Overall Length = 90.71 m

Moulded breadth = 13.02 m

Draught scantlings = 3.85 m

Performance:

Speed= 27.1 knots

Figure 1: The QUALIFY reference vessel

Historically, in hybrid structures of metal and composite, mechanical joints such as bolts and rivets were being used, however, bonded joints offer benefits such as reduced weight, reduced through life maintenance, and removal of the stress concentrations which result from holes and mechanical fasteners. One of the examples would be joining a steel hulled ship with a composite superstructure which is the main focus of this research.

A number of European research projects have previously investigated bonded composite to steel joints (EUCLID, CONVINCE, BONDSHIP) with focus on optimizing joint designs. The goal of QUALIFY is to evaluate the performance of adhesives in the designed joints. Moreover, the effect of fatigue and other environmental factors such as aging are critical to understand the performance and resilience of designed bonded joints through their life. The purpose of this project is to identify a qualification procedure for bonded composite to steel joints to provide classification societies with a means to approve such bonded joints. A common set of requirements and loading conditions are being defined together with BV. For the reference vessel a 3D finite element model of a hybrid structure, consisting of a composite superstructure on a steel hull structure has been created and shared between BV and DSNS. This model is then combined by an analysis software developed by BV in order to determine a realistic set of loading conditions considering fatigue loading and global bending.

The main limitation in advancing this technology on maritime industry is the lack of acceptance of adhesive. The main goal of this project is to overcome this lack of confidence in adhesives by considering all the aspects and covering all the safety issues. Nowadays, in critical-load-bearing structures, fasteners are always included along the bond-lines, as “back-up” in case the bond fails. These fasteners are fixed by drilling holes into composites. Moreover a large extra weight is introduced since holes are cut through the load carrying fibers and destroy the load path. This results in an inefficient composite structures.

Both industrial Partners, DSNS and BAE Systems have identified and documented an application case, representing two realistic scenarios for use of composite-to metal hybrid structures with an adhesively bonded connection. The two demonstrator cases represent the broad scope of typical adhesively bonded hybrid joints considering:

• BAE demonstrator consists of a thin adhesive laminated joint of composites to steel, representing a typical thin adhesive joint, created by integrating a steel connection into the composites structure during manufacturing of the composite module.

• DSNS demonstrator consists of a thick adhesive joint by injecting an adhesive after positioning the composite modules in the steel sill channel, dealing with typical steel yard conditions and tolerances. For both cases the configuration and set of requirements have been defined. Both demonstrator cases are merged into a single platform, being a DAMEN Offshore Patrol Vessel, for reasons of comparable load cases; and a common set of requirements. The geometry of these joints are shown in Figure 2.

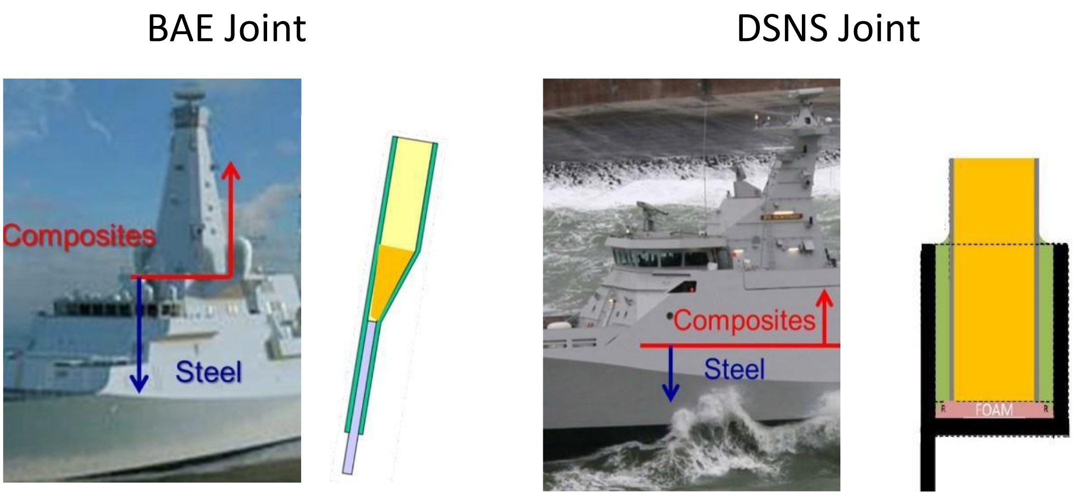


Figure 2: BAE and DSNS joint configurations

1.2. Background on adhesive joint design

There is currently an increasing interest in employing advanced composites in different structures such as shipbuilding and automotive industries due to their light structure and high durability. On the other hand, metals are still the most used materials in these industries. Hence, hybrid metal and composite structures (such as a steel hulled ship with a composite superstructure) are being more developed. These structures require a method for joining metals and composites. So far, the main method of joining metals to composites are mechanical joint such as bolts or rivets. The disadvantages of this method can be listed as stress concentration due to the holes in the structures and high weight of these joints. For this reason, bonded joints are being developed and designed in order to reduce the weight of the joint and also increase the durability of the joint by decreasing the corrosion possibility and removing stress concentration. The purpose of this project is to identify a qualification procedure for bonded composite to steel joints to provide classification societies with a means to approve such bonded joints.

The main focus of this project is on shipbuilding industry. The primary material used in this industry is steel. Before the World War II, riveting was the main method of joining metals, however, after that welding was introduced and become the most common method [1]. In shipbuilding industry, two important changes has happened through the time: 1) using thinner metal plates, 2) using composites instead of metals [2]. In joining composite parts to each other and to metal parts, adhesives is the main solution. In the recreational boating industry, composites parts and, subsequently, employing adhesives is already common, however, in large shipbuilding industries, it is still not well established.

Previous research performed in Cambridge University on adhesive joints and the performance of adhesives and the effect of geometrical effect provide essential insight on this project [3, 4]. It has been shown that adhesives behave tougher and stronger in shear loading. This was used to propose a more effective interface design for adhesive joints. In this project, the joints are designed in a way to apply shear loading on the adhesives rather than tensile loading.

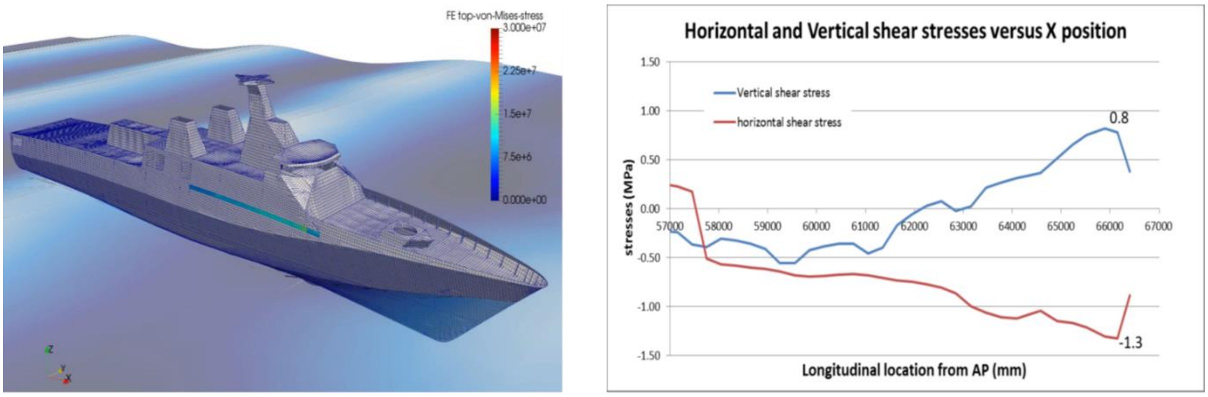
1.2.1. Adhesive selection

One of the most important challenges in designing hybrid joints in shipbuilding industry is to find a suitable adhesive. There are four general types of structural adhesive used for joining load-bearing elements of a structure: epoxies, polyurethanes, cyanoacrylates, acrylics, and methylmethacrylates (MMAs). There are several important factors need to be considered for adhesive selection, among which we can list: 1) type and nature of the substrates, 2) curing and adhesive application method, and 3) the expected stresses that the joint will face during service life. The appropriate selection is critical for the durability of the joint design [5].

In this project two adhesive are chosen and their behaviour on different test setups are evaluated. After numerous mechanical and corrosion tests, one of these two candidates will be the final choice of adhesive for shipbuilding industry application.

1.2.2. Load analysis on the joints

Bureau Veritas Marine & Offshore (BV M&O) analysed the adhesive, i.e. the bonded joint, in the junction between superstructure and hull, respecting operational conditions provided by DAMEN SCHELDE NAVAL SHIPBUILDING (DSNS) and requirements established by BV M&O on this type of vessel. The published document defines the loading conditions to be applied for the adhesive joint of the QUALIFY research project. Several methods have been performed in order to assess their accuracy in view of future design review. The details of the analysis can be found in the submitted document. Figure 3 shows some of the important results of the analysis.



(a) (b)

Figure 3: (a) Modelling of the full ship design considering the adhesive joint, (b) most severe cases of loading on the adhesive joint

1.3. Objectives

The main purpose of QUALIFY research is to help adhesive bonding technique to establish in shipbuilding industry and provide the necessary knowledge on mechanical behaviour of adhesives in harsh marine environment. The main objective of the research is to study the bonding of composite superstructure to the steel deck in naval ships and evaluate the effect of various design parameters and flaw sensitivity. There are many questions need to be answered in this project such as: For a 25-year service life, how reliable are the hybrid joints? What type of adhesive is more suitable for this application? What is the optimal thickness of the adhesive?

Extended report of the outcome of the research work developed towards the modelling of mode II fracture experiments on adhesive joints. The goal of this document is to provide a detailed description of the theoretical and numerical frameworks developed and report the results obtained along the project. A model predicting the mechanical performance of the joint, based on loading and environmental input, is proposed. The model, expanding a previous research result at Cambridge in collaboration with DAMEN and M2i, will allow to simulate the synergistic effects environmental conditions and be transferred in the concept of a failure map to be applied in the numerical simulations of realistic structures.

2. ADHESIVES UNDER SHEAR: LITERATURE REVIEW

Different loading modes (and their mixtures) may be applied to the adhesive joint during its life: Tensile (or compressive) stresses, Peel loads, Cleavage loads, Shear stresses produced by tensile, torsional or pure shear loads. The nature of loading depends on many factors such as geometry of the joints, mechanical properties of the adhesive and adherends as well as the loading on the whole full structure. In order to have a clear idea about the performance of adhesive joints, these loadings should be simplified. In other words, in early stages of the research, the performance of joints under single mode (or a mixture of two modes) of loading will be evaluated and analysed.

For the application of adhesive joints in shipbuilding and the designed configuration, shear loading is one of the dominant modes of loading on the adhesive. Hence, we mostly focus on the mechanical properties of the adhesives and their flaw sensitivity. Many studies carried out by focusing on the shear behaviour of adhesives. Different testing configurations have been used in the literature among them we can mention: Single-lap shear test, double-lap shear test, Thick-adherent shear test.

Single-lap shear tests are relatively very common because of their easy manufacturing [6, 7]. Literature points out that not only shear stresses, but also peel stresses arise in the bonded region. The single lap joint geometry inherently has a certain non-linearity in its geometry. This nonlinearity causes an eccentricity in the applied load path, leading to out-of-plane bending moments. Elevated peel stresses are the result. These peel stresses are particularly important in joints containing composite adherends due to their low strength in the through-thickness direction. Hence, these peel stresses can lead to premature failure of the joint. The problem of eccentricity in loading, is solved in double-lap shear tests and thick-adherend shear tests.

2.1. Cohesive Zone Modelling

One of the methods of predicting mechanical behaviour of adhesive joints is using cohesive zone modelling. The advantage of this method is that the interface characteristics is considered despite most of the conventional methods which perfect bonding between adhesive and adhered is assumed. Hence, in cohesive zone modelling both adhesive properties and interface characteristics play roles in predicting the mechanical response of the adhesive joint. Therefore interfacial failure or partial cohesive failure. However, one of the challenges in this method is determining the interface properties.

Energy release rate and fracture are key parameters in a Cohesive Zone Model (CZM). Assigning a cohesive law to a layer of element can predict the progressive failure of the layer. The failure in CZM is expressed by a bilinear traction-separation law which is defined by three parameters: the initial stiffness, the critical strength and the fracture toughness. A schematic of this behaviour is shown in Figure 4.

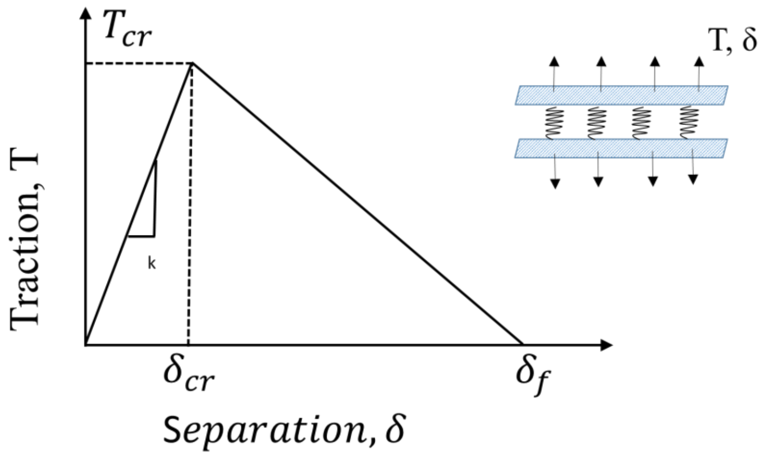


Figure 4: Bilinear model of the traction-separation law

There are experimental methods to determine the fracture toughness, however, the initial stiffness and critical strength are usually determined iteratively by adjusting the simulation results to the experimental data. The allowed dissipation energy of the cohesive law is limited to the intrinsic fracture energy (Γ) which represents the energy of the crack to propagate. Therefore, the interface energy and material energy of the adhesive and adherend are embodied into the cohesive zone.

In a study done by Lee et al. [8], Single Leg Bending (SLB) joints with mode I and mode II-dominant configurations were used. Then, through a systematic numerical procedure, cohesive parameters were found. The obtained cohesive parameters were used in a finite element model and the results were compared to the experimental data.

3. MICROMECHANICAL MODELLING

3.1. Basics of fracture mechanics

Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. It uses methods of analytical solid mechanics to calculate the driving force on a crack and those of experimental solid mechanics to characterize the material's resistance to fracture. There are three ways of applying a force to enable a crack to propagate:

- Mode I fracture – Opening mode (a tensile stress normal to the plane of the crack),
- Mode II fracture – Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front), and
- Mode III fracture – Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front).

The dominant loading mode in the QUALIFY project (BAE and DSNS joints) is determined to be Mode II of loading. We are employing fracture mechanics in this problem in order to provide answers to the following questions:

- What is the strength of the component as a function of crack size?
- What crack size can be tolerated under service loading, i.e. what is the maximum permissible crack size?
- How long does it take for a crack to grow from a certain initial size, for example the minimum detectable crack size, to the maximum permissible crack size?

Linear Elastic Fracture Mechanics (LEFM) field was founded by Griffith who was trying to explain the low failure stress of glass comparing to its theoretical strength [9]. With modifications by Irwin, the fracture mechanics theory for a crack in an infinite plate under a remote stress (shown in Figure 5) formulised in the following equations [10]:

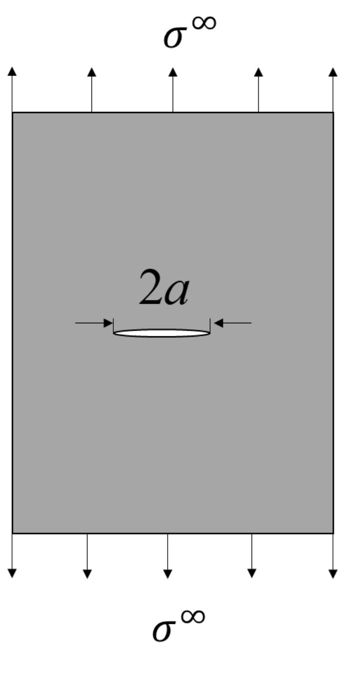


Figure 5: Schematic of a pre-cracked plate under tension

The stress intensity factor is defined as:

$$K \equiv \sigma^{\infty}\sqrt{\pi a}$$

and fracture occurs when K attains the fracture toughness, K_{IC}, of the material. Hence,

$$K_{IC} = \sigma_c\sqrt{\pi a}$$

where σ_c is the failure stress, a is the flaw size (crack size), E is the materials Young's Modulus. So,

$$\sigma_c = \frac{K_{IC}}{\sqrt{\pi a}} = \sqrt{\frac{EG_c}{\pi a}}$$

where $G_c = \frac{K_{IC}^2}{E}$, defined as the toughness of material (fracture work per unit area).

In basic calculations of strength and fracture of materials usually the complicated material behaviour in the process zone near the crack tip is being avoided. This approach is acceptable as long as the process zone is small compared with the specimen dimensions, and a clear zone of K-dominance is established around the crack tip. In Linear Elastic Fracture Mechanics, the failure strength for a finite plate can be written as:

$$\sigma_c = \frac{K_{IC}}{\sqrt{\pi a}} Y(\frac{a}{W})$$

where $Y\left(\frac{a}{W}\right)$ is called the geometric K-calibration factor and for a/W= 0.05 is 1.0012 [11].

3.2. Problem Statement: Fracture mechanics of adhesives under shear and defect sensitivity

Defects in the adhesive bondline such as porosities can lead to premature failure of the joint. It is almost impossible to produce specimen without any defects in the bonded layer. This applies especially for high viscosity adhesives. Some adhesives such as methyl methacrylates (MMAs) exhibit exothermic reactions during curing of the bond. If the temperature gets too high, overheating can result in material degradation. Increasing the adhesive thickness in these types of adhesives, increases the heat is trapped within the bulk of the bond and pronounce this problem. For application of these adhesives in shipbuilding industry, thick flexible joints are desired, hence the effect of defects on the strength of these joints is significantly important.

A recent experimental study done by Heidarpour et al. [12] investigated the effects of both debonding between adhesive and adherend, as well as a cavity that stretches from one interface to another in all three dimensions on the single lap joint mechanical performance are investigated. The results implicated that ultimate strength is more severely impacted by cavities rather than debonding in the interfaces. The analysis on samples containing cavities showed an approximately linear decrease in strength as the defect area increased, while for debonding defects a non-linear trend was observed. As stated earlier [3], peel and shear stresses are higher at the edge zone than in the mid-thickness of the adhesive layer. Enlarging the size of the 2D defect into these high stress concentration edge zones makes the effect of the defect more severe.

The goal of this study is to investigate the effect of dimensional and material parameters in a bi-material system on its fracture strength. We aim to determine the fracture shear strength of the adhesively bonded joints with different modulus mismatch and geometries. The study is focused on the following overall geometry (Figure 6).

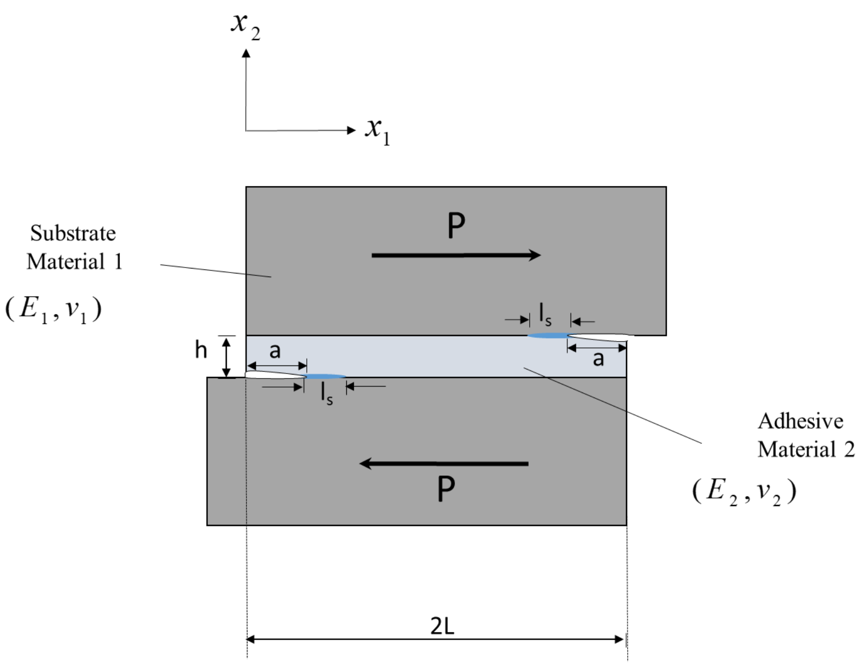


Figure 6: Schematic of the adhesive and defects under shear

The mechanical response of the adhesive is considered to be linear elastic with shear modulus of μ. Same analysis presented for the adhesive under tension can be applied to the adhesive under shear.

In order to systematically analyse the fracture properties of this system, first, the effective non-dimensional groups need to be determined. Based on the geometry and the effective properties, the non-dimensional strength $\bar{\tau}$ can be defined as:

$$\bar{\tau} = \frac{\tau^{\infty}\sqrt{h}}{\sqrt{G_{II}\overline{E_2}}} = f(\frac{a}{h}, \frac{l_s}{h}, \frac{h}{L}, \frac{E_2}{E_1}, \nu_1, \nu_2)$$

In order to approach the problem, first we assume $l_s = 0,$ which changes the schematic setup to schematically shown figure 7.

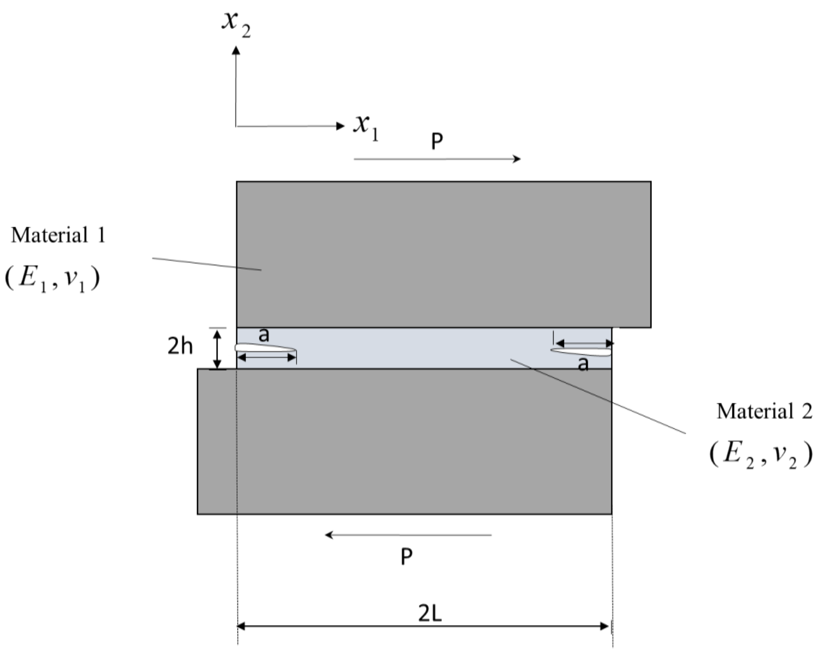


Figure 7: Adhesive layer under shear

Analysing this structure can be performed by considering the following general equation:

$$BG_{II} = \frac{1}{4}P^2\frac{\partial C}{\partial a}$$

where B is the thickness of the structure (into the page), GII is the toughness of the material under shear, P is the shear force applied to the structure, C is the compliance which is defined as $C = \frac{u}{P}$.

We can solve the problem by superposition of compliance of the different cases. Figure 8 shows the schematic of different cases.

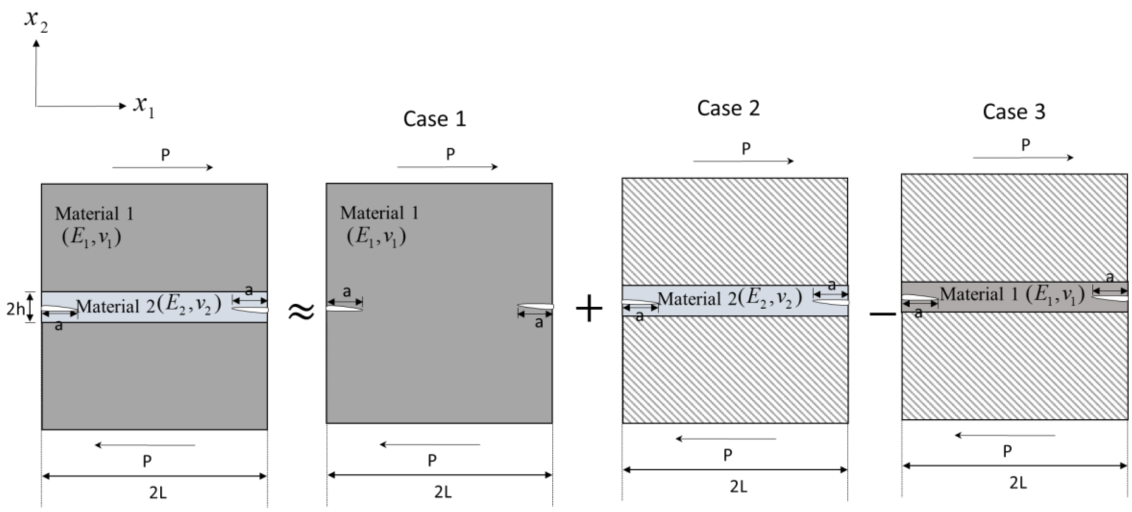


Figure 8: Superposition of cases that result in the final real case

$$C \approx C_1 + C_2 - C_3$$

Case one is considering a block of material 1 (substrate) with 2 edge cracks and under shear loading. Case 2 is assuming the substrates to be a rigid materials attached with the adhesive. Case 3 is for subtracting the extra substrate from the superposition analysis. For each of these cases, the compliance variation with respect to crack length change will be found, then, using superposition, the compliance various to crack length change of the main configuration will be determined. Later on, the Griffith's energy balance equation will be used to obtain the strength of bi-material setup.

Case 1:

First the case of thick sample of material 1 (substrate) with two edge notches is considered. Figure 9 is shown the schematic configuration of this case.

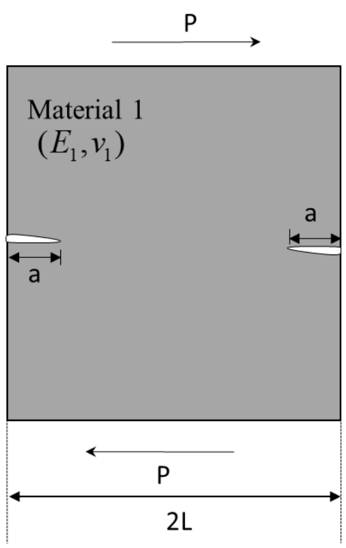


Figure 9: Schematic of case 1. The whole section is made of material 1 (substrate) and it is under shear.

For this case, the Griffith's energy balance equation can be written as:

$$BG_{II} = \frac{1}{4}P^2\frac{\partial C_1}{\partial a}$$

Hence,

$$\frac{\partial C_1}{\partial a} = \frac{4BG_{II}}{P^2} = \frac{4B\frac{K_{II}^2}{\overline{E_1}}}{4(\tau^\infty)^2L^2B^2} = \frac{B(\tau^\infty)^2\pi aF^2(\frac{a}{L})}{\overline{E_1}(\tau^\infty)^2L^2B^2} = \frac{\pi a}{L^2\overline{E_1}B}F^2(\frac{a}{L})$$

$$\frac{\partial C_1}{\partial a} = \frac{\pi a}{L^2\overline{E_1}B}F^2(\frac{a}{L})$$

Where,

$$F\left(\frac{a}{h}\frac{h}{L}\right) = [1 - 0.025\left(\frac{a}{h}\frac{h}{L}\right)^2 + 0.06\left(\frac{a}{h}\frac{h}{L}\right)^4]\,(\sec\left(\frac{\pi}{2}\frac{a}{h}\frac{h}{L}\right))^{\frac{1}{2}}$$

and,

$$\bar{E}_1 = \frac{E_1}{1 - \nu_1^2}$$

Case 2:

In the second case, the substrates are assumed to be rigid and jointed by a layer of material 2 (adhesive) with thickness of 2h.

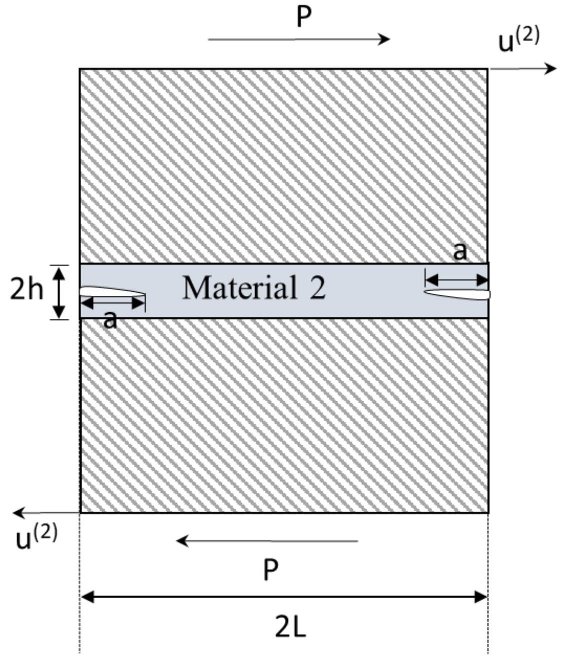


Figure 10: Schematic of case 3, the substrates are assumed to be rigid materials and the material between them is Material 2.

For this configuration, the toughness can be obtained from the following equation:

$$C_2 = \frac{u^{(2)}}{P} = \frac{2\gamma h}{P} = \frac{h}{B\mu_2 L(1-\frac{a}{L})}$$

Hence,

$$\frac{\partial C_2}{\partial a} = \frac{h}{B\mu_2 L^2(1-\frac{a}{L})}$$

Case 3:

This case is similar to Case 2. The only change is that the middle layer is replaced by material 1 properties.

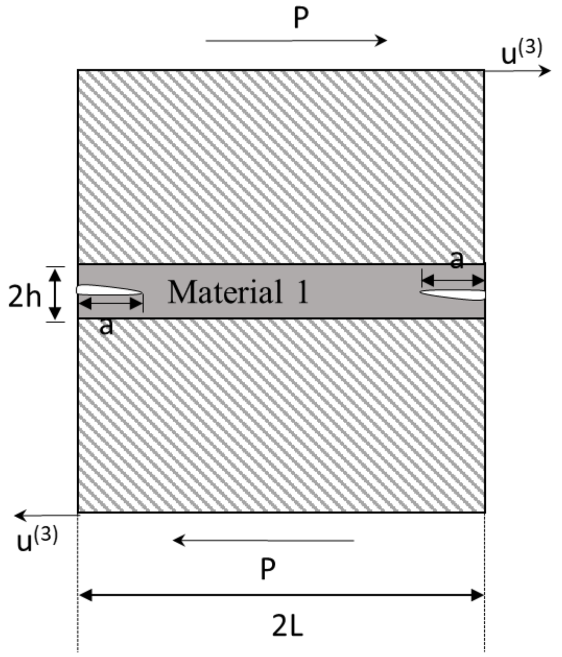


Figure 11: Schematic of case 3, the substrates are assumed to be rigid materials and the material between them is Material 1.

Analogous to case 2, we have the following set of equations.

$$C_3 = \frac{u^{(3)}}{P} = \frac{2\gamma h}{P} = \frac{h}{B\mu_1 L(1-\frac{a}{L})}$$

Hence,

$$\frac{\partial C_3}{\partial a} = \frac{h}{B\mu_1 L^2(1-\frac{a}{L})}$$

Hence, for the final configuration, we can write:

$$\frac{\partial C}{\partial a} \approx \frac{\partial C_1}{\partial a} + \frac{\partial C_2}{\partial a} - \frac{\partial C_3}{\partial a}$$

$$BG_{II} = \frac{1}{4}P^2\frac{\partial C}{\partial a} = \frac{1}{4}P^2\left[\frac{\pi a}{L^2\overline{E_1}B}F^2\left(\frac{a}{L}\right)\right] + \frac{1}{4}P^2\left[\frac{h}{B(L-a)^2\mu_2}\right] - \frac{1}{4}P^2[\frac{h}{B(L-a)^2\mu_1}]$$

Assume that failure occurs when energy release rate attain the fracture toughness of the adhesive, $G_{II} = G_{IIC}$, the failure load can be written as:

$$P = P_c = 2LB\tau_c^{\infty}$$

Where τ_c^{∞} is the remote stress at failure. Then, by considering $\nu_1 = \nu_2 = \nu$, we can write:

$$\bar{\tau} = \frac{\tau_c^{\infty}\sqrt{h}}{\sqrt{G_{IIC}\overline{\overline{E}}_2}} = [\pi\left(\frac{a}{h}\right)\left(\frac{E_2}{E_1}\right)F^2\left(\frac{a}{h}\frac{h}{L}\right) + \frac{1}{\left(1-\frac{a}{L}\right)^2}\left(\frac{1+2\nu}{1-\nu^2}\right)\left(1-\frac{E_2}{E_1}\right)]^{-\frac{1}{2}}$$

Assuming that the adhesive joint length is much bigger than the other dimensions ($\frac{a}{L} \rightarrow 0$), the equation simplifies to:

$$\bar{\tau} = [\pi\left(\frac{a}{h}\right)\left(\frac{E_2}{E_1}\right) + \left(\frac{1+2\nu}{1-\nu^2}\right)\left(1-\frac{E_2}{E_1}\right)]^{-\frac{1}{2}}$$

Figure 12 can be obtained from the obtained equation.

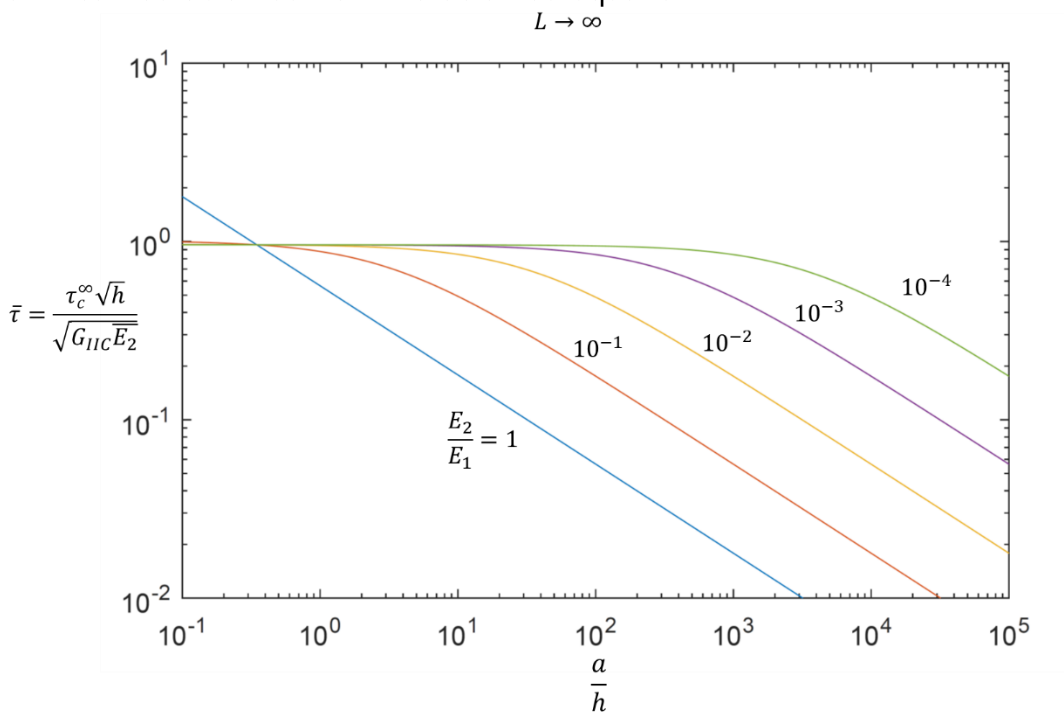


Figure 12: This figure shows how strength vary by the crack length for different modulus mismatches. For a large modulus mismatch, the strength is independent of crack lengths for long cracks.

This figure shows that:

1- For large modulus mismatch($\frac{E_2}{E_1} \rightarrow 0$), and large cracks, the strength is independent of crack length.

2- For systems with analogous dimensions, increasing modulus mismatch between substrate and adhesive increases the strength of the joint.

Moreover, Figure 13 shows the effect of bondline thickness for joints with finite length. The graphs are obtained for modulus mismatch of 0.01.

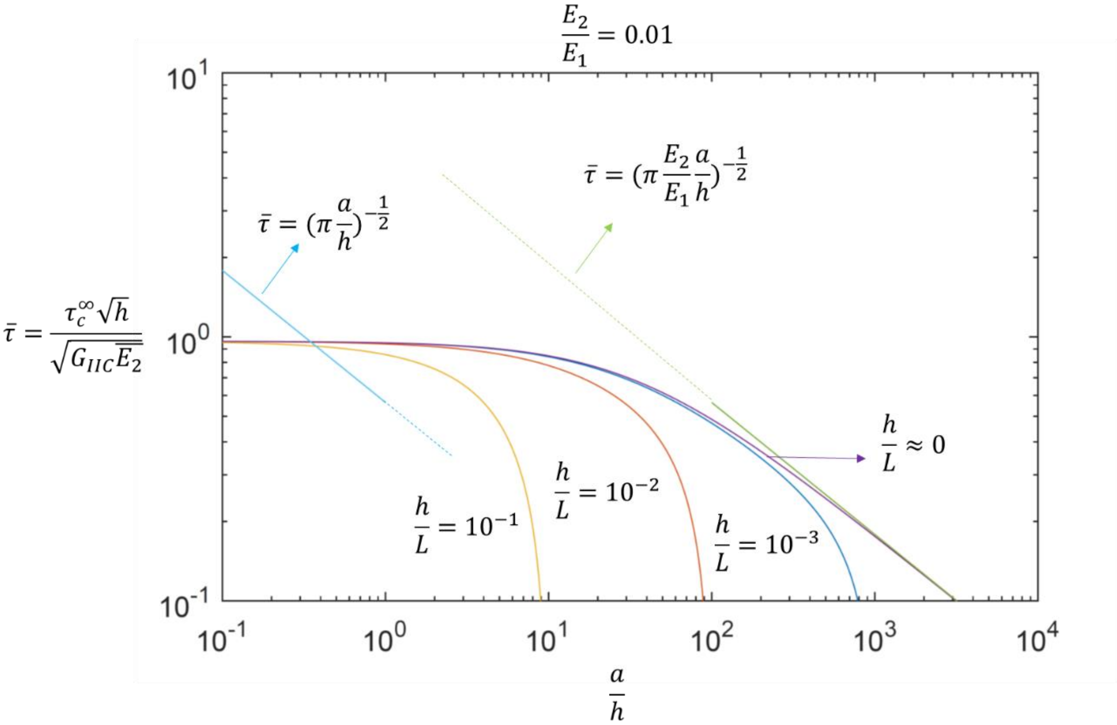


Figure 13: This graph shows how strength depends on the crack length for modulus mismatch of 0.01 and different adhesive thicknesses. The linear lines in the graph shows the Dugdale analysis results (explained in the future sections).

The results show that for a similar crack length to bondline thickness ratio, increasing adhesive thickness to bondline length increases the strength of samples. More studies are needed assuming elastic-plastic behaviour for the adhesive, however, the essence of analysis would be very similar.

3.3. Effect of environmental factors and cyclic loading

In the presented theory, the effect of environmental factors such as humidity and temperature as well as effect of fatigue are embodied in mechanical properties, fracture toughness of adhesives, and the interfacial characteristics of adhesive and adherend. In particular, as the elastic modulus and interfacial fracture toughness changes in harsh environments, the value of the non-dimensional strength would change. Hence, these effects can be evaluated by considering the experiments and may be implemented by a coefficient in the corresponding equations.

3.4. The role of yielding of the adhesive:

Da Silva et al. [13] have studied single lap shear test setup and the effect of adhesive thickness on the lap shear strength for different types of adhesives. In their analysis, a steel with high stiffness and strength was selected as an adherend so that the steel stays in the elastic range and does not deform significantly. Their experimental results show that increasing adhesive thickness decreases the shear strength. Da Silva argues that three main theories are able to plausibly explain this exhibited behaviour. One of the simplest justifications for this phenomenan presented by Adam et al. [14] argues that thick adhesive bondlines inherently contain more defects like microcracks and voids, leading to lower strengths.

In another paper, Crocombe et al. [15] present a theory that explains this phenomenon by plasticity of the adhesive. He believes that increasing the adhesive thickness, the “plastic spreading” of the adhesive occurs faster than in thinner bondlines. This is because of more uniform stress distribution in samples with higher adhesive thickness. For thin bondlines, the stresses are more concentrated near the ends of the overlap, so the adhesive yielding happens in lower loads. However, when yielding happens, it does not spread to other parts of the adhesive as fast as in thick bondlines. Hence, the overall failure strength for samples with higher adhesive thickness is lower than of samples with smaller adhesive thickness. Gleich et al. [16] employed finite element method to find the peel and shear stresses in the interface of adhesive and adherent. Using this analysis they found out that the stresses at the interface of adhesive and adherend are higher in samples with thick bondlines. Assuming that final failure occurs in the vicinity of the adhesive-adherend interface, this theory explains why thinner bondlines are stronger than thicker ones.

3.5. Model for an Elasto-Plastic Adhesive:

In this study, energy release rate (J) would be used to evaluate the effect of bondline thickness on the adhesive. We assume that the elastic energy release rate would be acceptable to obtain the peak load applies on the adhesive. Consider the configuration shown in figure 14:

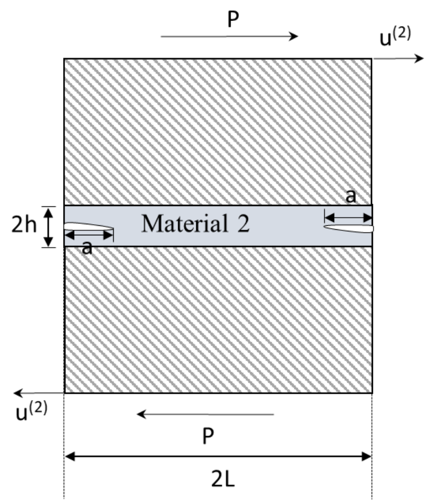


Figure 14: Schematic configuration for studying adhesive thickness

If we assume the following shear stress-shear strain curve for the adhesive:

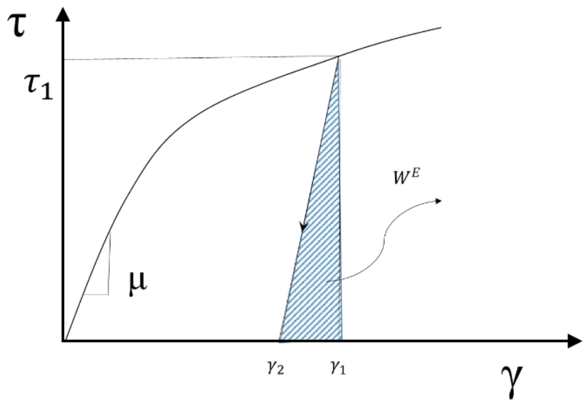


Figure 15: Adhesive shear stress-shear strain behaviour and elastic energy release at each point

In this system, the elastic energy released at the failure can be written as (the shaded area shown in Figure 15):

$$W^E = \left(\frac{1}{2}\frac{\tau_1^2}{\mu}\right)(2L - 2a)(hB)$$

Also, we know that:

$$J = -\frac{\partial W^E}{B\partial a}|_u = \frac{\tau_1^2 h}{\mu} \Longrightarrow \tau_1^2 = \frac{\mu J}{h}$$

Hence,

$$P = B(2L - 2a)\tau_1$$

$$\Longrightarrow\ P = 2B(L - a)(\frac{\mu J}{h})^{\frac{1}{2}}$$

Implying that the final force decreases by increasing the adhesive thickness. Hence, if we assume all other parameters remain same, the following relationship can be found:

$$\frac{P_2}{P_1} = (\frac{h_1}{h_2})^{\frac{1}{2}}$$

This equation shows that if we only change the adhesive thickness by a factor of n (bondline and crack length are fixed), the final load on the joint decreases by a factor of $\sqrt{n}$.

4. FUTURE WORKS: VALIDATION OF THE THEORY

In order to validate our models and have a better understanding of the mechanical behaviour of adhesives under shear, a Thick-Adherend-Shear-Test is designed. We aim at designing, modelling and conducting tests with a device that is able to prescribe shear loading with the pins aligned with the centre point of the adhesive specimen - see Figure 16.

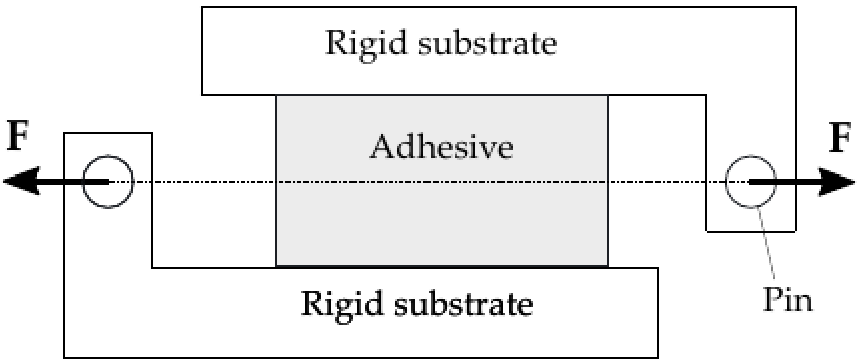


Figure 16: Sketch of the experimental device

Consider the notation of Figure 17. Force equilibrium dictates,

$$T_M = T_r = T$$

$$F_M = F_r = F$$

$$M_M = M_r + F_r h + T_{rl}$$

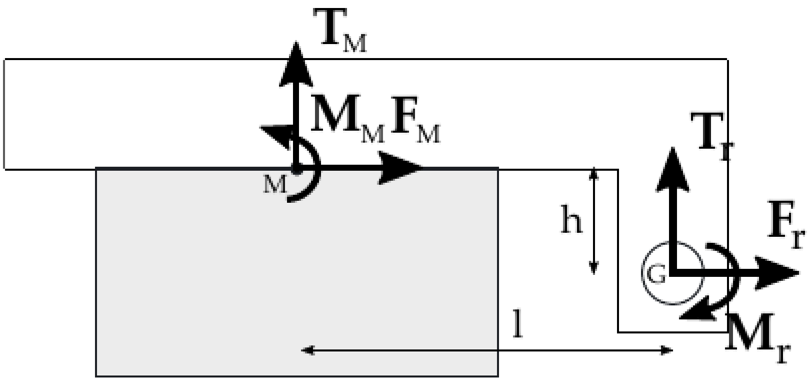


Figure 17: Sketch of forces and moments acting on the right grip and on a middle point in the interface between the adhesive and the substrate

Denoting the rotation as "w" and the horizontal and vertical displacements with, respectively, u and v, the kinematics read:

$$u_r = u_m + wh$$

$$v_r = v_m + wl$$

And we choose to prescribe the following grip constraint conditions

$$M_r = 0$$

$$v_r = 0$$

Implying:

$$wl = v_m$$

And additionally we will have T_r=0, and consequently there will be a moment acting on the middle point,

$$M_M = F_r h$$

The analysis can be easily extended to the entire device. Figure 18 shows the non-zero forces acting on the top and bottom middle points.

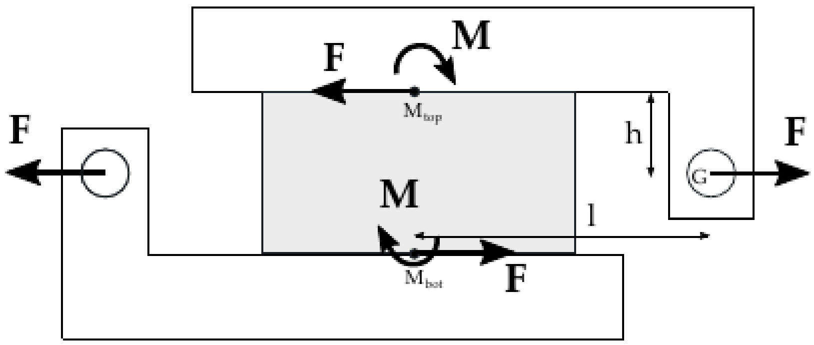


Figure 18: Sketch of forces and moments acting on the grips and on the middle points (top and bottom) in the interface between the adhesive and the substrates

The moment is now M=Fh. Given that, $F \sim \tau_y l$, then,

$$M \sim \tau_y lh$$

Such that the shear stresses will not be uniform over the top and bottom, and tension and compression tractions will be seen in the edges, over a region of h.

4.1. Dugdale Analysis

In some structures, however, the materials are so tough and ductile that the plastic zone near the crack tip is large and comparable to specimen dimensions. In these cases, LEFM cannot be always used. Instead, frameworks based on plastic solutions to crack tip fields need to be adapted. One of the frameworks is developed by Dugdale and Barenblatt [17]. In order to predict the fracture in these materials, first the size of plastic zone need to be calculated. Among all the developed methods, the simplest estimate of the size of the plastic zone at a crack tip can be obtained using Dugdale & Barenblatt's cohesive zone model.

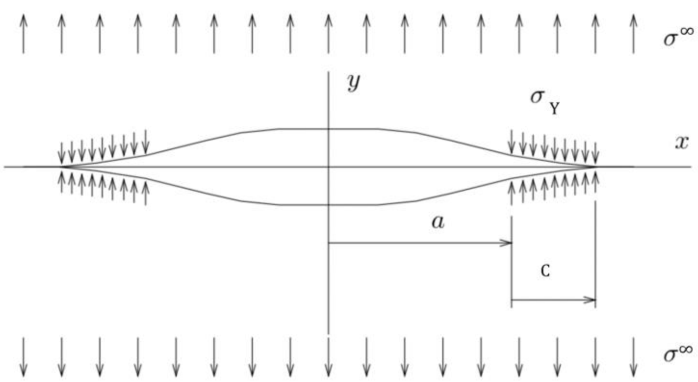


Figure 19: : Illustration of plastic zone size in Dugdale analysis

Using this method the plane stress plastic zone size at the tip of a crack can be written as:

$$c \sim \frac{\pi}{8}\left(\frac{K_{IC}}{\sigma_Y}\right)^2 = \frac{\pi}{8} l_s$$

where $l_s \equiv \frac{EG_c}{\sigma_Y^2}$ and σ_Y is the material yield strength. Moreover, G_c is the toughness of material (fracture work per unit area). The failure stress is dictated by crack length as shown in Figure 20.

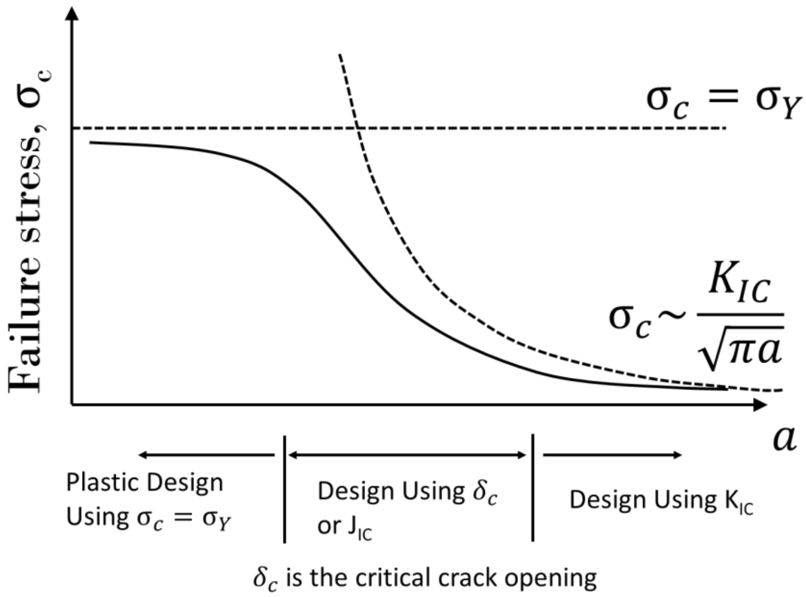


Figure 20: Dugdale analysis design map for crack under tension loading

When the flaw (crack) size is much bigger than the plastic zone size, linear elastic fracture mechanics can be applied to predict the failure stress.

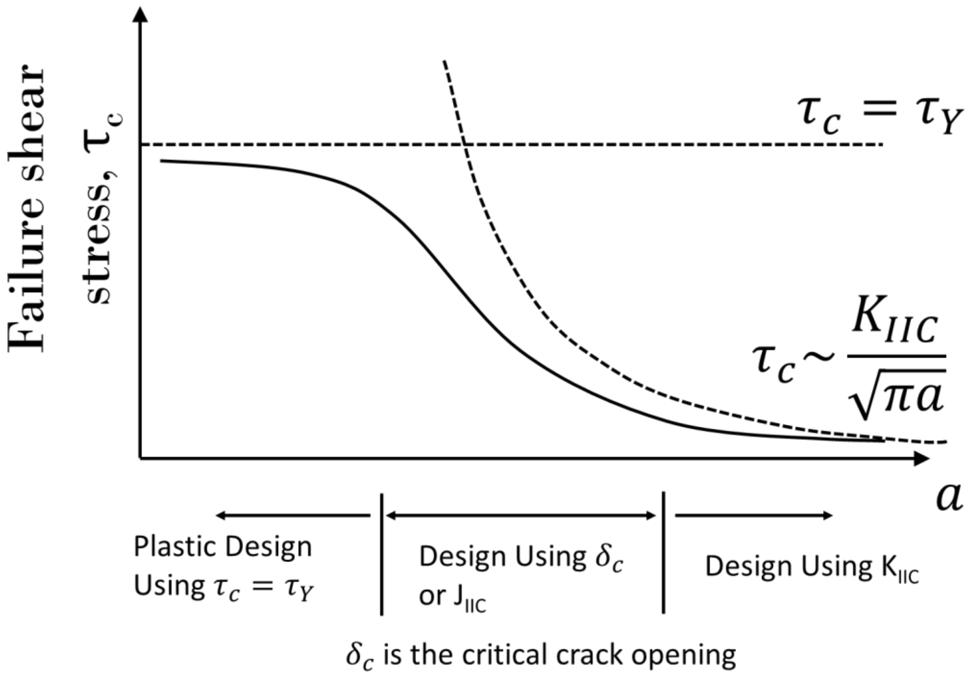


Figure 21: Dugdale analysis design map for crack under shear

However for our problem we need to do the K-calibration. The geometries of our problem is as following.

5. CONCLUSIONS

Adhesive joints are not well-established in ship-building industry and the main reason behind this issue is the lack of knowledge on the performance of adhesive joints under harsh environment and different loading conditions. The purpose of this study was to shed light on some basic aspects of adhesive fracture under shear loading.

In this report, the strength of adhesive joints are investigated. A new approach is proposed to study the effect of adhesive thickness, crack length, and modulus mismatch on the fracture properties of adhesives under shear. The results obtained from this study show that for high modulus mismatch between adhesive and substrate and large cracks, the length of crack does not affect the strength of adhesive joints. Moreover, it has been shown that, for a constant value of crack length and bondline length, the strength increases by decreasing the adhesive thickness.

Moreover, an experimental setup is designed for evaluating the flaw sensitivity and effect of thickness on adhesives under shear loading. These experiments along with finite element simulations will be used to validate the proposed model.

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