Investigation of change in strength of Double Cantilever Beam Adhesive Joints under Mode I failure by addition of Cork Particles

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ABSTRACT

Crack propagation in a double cantilever beam is evaluated by experiment on the Universal Testing Machine. The main assumption on which the experiment is based is that the beams deform as shear beams. Tensile testing is done on the double cantilever beam of stainless steel 210 with specific dimensions. Pre crack was initially developed at a fixed distance and in this problem, crack growth is studied using Araldite 2011 adhesive between the beams.

Pre crack length is 70mm and overall length of the beam is 200mm. It is showed that this model calculates crack motion, which is qualitatively constant with the results of more detailed numerical analyses of the problem and with experimental results. Cork powder with the mesh size of 80 is mixed in the adhesive and DCB is studied at different cork ratios. Crack speed was constant from the point of initiation to the crack arrest. Cork powder is mixed in Araldite 2011 in the ratio of 0.25%, 0.5% and 0.75%.

Variation in crack propagation is obtained with inclusion of cork powder and without the cork powder. No direct relation has been observed. Moreover Optical Microscope is used to check the type of failure exhibited whether failure was cohesive failure or adhesive. Comparison has been made between the different cork ratios. Results show that there is no specific behavior or variation with and without mixing of cork powder in the adhesive.

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1. INTRODUCTION

1.1 Background

Currently there has been considerable attention put into the adhesive joints for structural models and applications. However, no extensively accepted failure criterion is currently available .The existing approach go down as into continuum mechanics (CM) or fracture mechanics (FM).The CM based approach is currently quite popular, in spite of its significant limitations, e.g. it is based on simplified stress analyses and peel stresses are ignored, as well the strengthening effect of adhesive fillets at the joint ends. In the FM approach, a pre-existent crack is assumed and the conditions for crack growth are usually determined comparing strain energy release rates with their critical values.

Double cantilever beam (DCB) is the most commonly used method for measuring the initiation and propagation values of Mode I fracture energy G_I under static and cyclic loading conditions. DCB consists of two beams having same length, width and thickness. A pre-crack is initiated by inserting a thin film between the two beams which are required to be bonded. Tensile loading is applied normal to the crack in the universal testing machine (UTM). Crack length can be measured by using the video camera or crack gauge.

This is the best method used to evaluate the properties of adhesives in extreme environment. It is used in marine industry and aerospace industry extensively.

1.2 Aims and objectives of the research

The aim of this project is to evaluate the crack growth in the double cantilever beam (DCB) and then the bond strength of the adhesive Araldite (2011) by tensile shearing. In addition effect of cork powder is also observed under different ratios on the bond strength of the adhesive.

1.3 Scheme of the thesis

Following are the chapters which will be discussed in detail

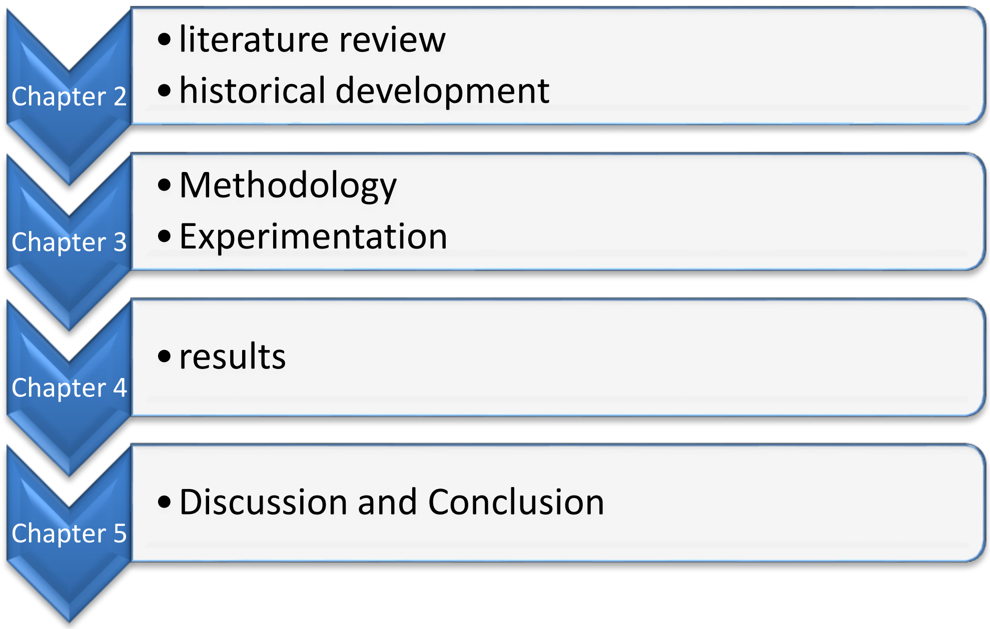


Figure 1-1: Scheme of thesis

2. LITERATURE REVIEW

2.1 ADHESIVES

Structural adhesives have been used for centuries. Adhesives are used to join two surfaces. Adhesives offered a lot of advantages when methods for joining different materials are considered. They provide more benefits as compared to traditional methods of joining such as welding, brazing, bolting and fasteners etc **(1).** In order to understand the science and to excel in this technology inputs from the mechanical engineer, surface chemist, polymer chemist and material engineer were required because of following nature of adhesives.

- Adhesive has to be in liquid form when it spreads and makes contact with substrate.
- In order to bear the load, adhesive has to be hardened.
- Load carrying ability of the adhesive depends upon the design of joint, loading condtions and the environment in which the adhesive joint will operate during its service time.

Adhesives and adhesion is a multidiscipline subject. Application of fracture mechanics to adhesive joints has resulted in enhanced understanding of the basic concepts of adhesion and faster development in technology for the advanced engineering applications.

It has been seen that fracture mechanics approach had led to

- Better understanding of many industrial test methods that commonly used adhesive joints.
- Developing methods to increase the service life of adhesive joints when they had to be exposed to unfavorable environment.

- Design and predict the mechanical performance and durability of adhesive joints when exposed to adverse environment.

Strength of adhesive can be increased in a number of ways such as by adding foreign particles such an example is shown in the figure 1.1

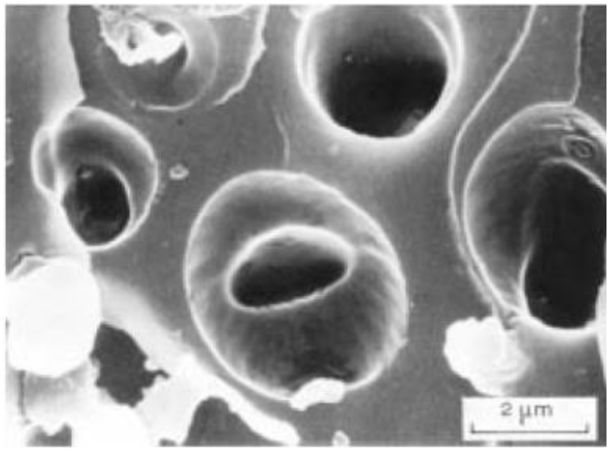


***Figure 2-1*:** Scanning Electron micrograph of rubber toughened epoxy adhesive showing cavitated rubber particles and plastic hole growth in epoxy

Researchers carried out an experimental study on the strength of adhesively bonded stainless steel joints **[2]**, prepared with two epoxy and one acrylic adhesive. In double cantilever beam (DCB) tests mode I critical strain energy release rate were determined, GIc. On different types of single-lap and double-lap joints shear tests were executed. Joint strength results were explained by using finite element analysis. It was established that the strength of adhesive joints depended mostly on the level of peel stresses near the bondline edges. Joint strengths were generally insusceptible to the existence of defects formed at the overlap ends.

Investigation on the strengths of stainless steel joints which were bonded together with two epoxy (AS and L3450) and one acrylic (L330) adhesives was studied in this paper. The critical energy release rate, GIc; of the joints were measured by Mode 1 fracture double cantilever beam. The highest strengths were acquired with the AS adhesive in thin plate single lap joint. Such results were similar with the significant peel stresses inborn to this specimen and with the good GIc results. Strength values for the very tough L330 adhesive joints were also relatively high, considering the low strength of this acrylic adhesive. FE analyses were utilized to attain the strength results. Joint strengths were observed to depend essentially on the intensity of peel stresses near the bondline edges where epoxy adhesives were concerned. The L330 adhesive joint strengths were susceptible to both peel and shear near-the-edge stresses because of its high toughness and low strength. The effect of defects at the overlap ends of single lap joints

and double lap joints specimens was also calculated. If expressed in terms of effective overlaps, joint strengths were generally unaffected by the presence of such defects.

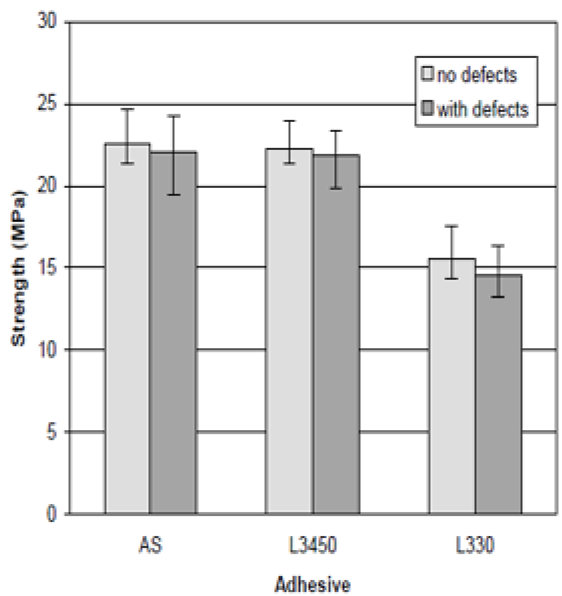


Figure 2-2: Influence of defects on joint strength of DLT specimens

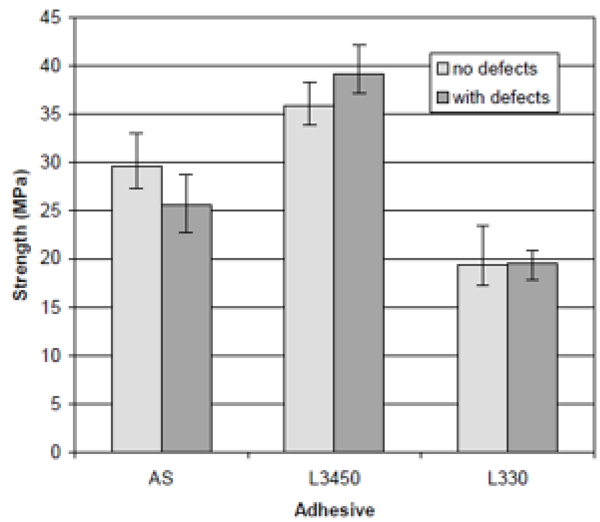


Figure 2-3: Influence of defects on joint strengths of SLT specimens

[3] presented numerical analyses of crack propagation in double cantilever beam (DCB) tests of multidirectional laminates. Function of the virtual crack closure technique and for simulation of crack growth with a progressive damage model three dimensional finite element techniques were employed. The analyses were concerned with three features that may affect the measurements of the

- mode I critical strain energy release rate GIc
- residual stresses
- modemixity
- curved delamination fronts.

The results showed that the effects of those features could be decreased by a appropriate choice of specimen stacking sequences. The suitability of other DCB specimens proposed in the literature to stay away from intralaminar damage and crack jumping was also assessed.

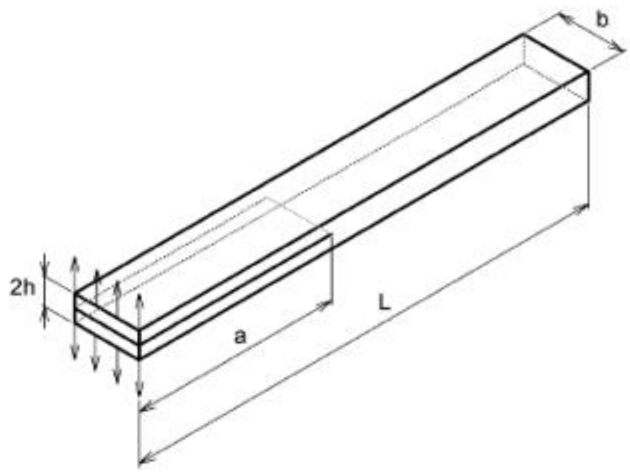


Figure 2-4: Double Cantilever Beam specimen

[4] studied that the inclusion of foreign particles (nano or micro) is a technique to improve the mechanical properties, such as toughness and impact resistance of structural adhesives. Structural adhesives are known for their low ductility and toughness but also high strength and stiffness. Toughness can be increased by a number of ways according to the literature, one of the most known being the use of rubber particles. In the present study, natural micro particles of cork were used with the goal to increase the impact resistance of a brittle epoxy adhesive. The idea was for the cork particles to act like crack stoppers and absorb impact leading to higher absorption of energy. The influence of the cork particle size and amount were studied. In the epoxy adhesive Araldite1 2020 from Huntsman particles of cork ranging from 38 to 250 mm were mixed. The amount of cork in the adhesive was varied between 1 and 5% by weight. Surface treatment (low pressure plasma) was utilized to the cork powder to evaluate the effect of the interaction adhesive-cork with several degrees of adhesion. This evaluation was made using impact tests and it was evident that impact absorption was related to the size. Density of the treated and untreated cork particles was shown in figure.

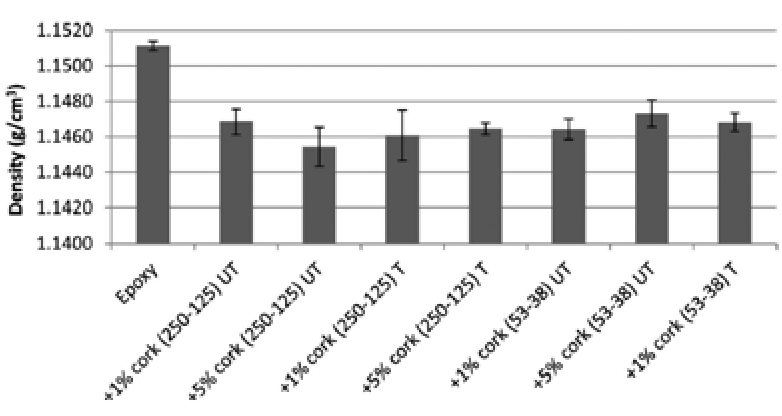


Figure 2-5: Density of composite specimen with different surface treatments, amount and cork particles size.

The beginning tests made of the surface of the cork board showed that Plasma treatment increased the surface energy of the cork board. However, atmospheric plasma treatment demonstrated a greater enhancement in the polar component of surface energy. Low pressure plasma must be utilized to avoid the dispersion of particles in the chamber for the treatement of cork particles. The contact angle was decreased and increased the wettability of cork by low density plasma treatment. There was an erosion of the face which increased roughness, increasing adhesion between cork and adhesive. In cork particles, this surface treatment must be optimized. Impact tests were used to evaluate the effect of the size and amount of cork particles on the impact toughness of a structural brittle adhesive . The following conclusions can be drawn

- SEM and OTM analysis showed that most cells of the big particles (125– 250 mm) were not filled with resin.
- The amount of cork, size of particles, and surface treatments result in different fracture behaviours and morphology.
- Small amounts of cork particles with a structure composed of a limited number of cells (1–5 cells) integrated in a brittle resin display a good impact energy absorption than large amounts or small particles.

Due to the improvement in adhesive properties and the continuous development observed in bonded joints there were an increase of the bonded joint applications. Two highly relevant methods are Fracture Mechanics and Cohesive Zone Models (CZM) concerning the strength prediction of adhesive joints **[5]**. CZM facilitated the simulation of initiation of crack and propagation and in Fracture Mechanics, this was usually carried out by an energetic analysis. One of the most important parameters for calculating the joint strength was the tensile critical strain energy release rate (GIc) of adhesives. Double Cantilever Beam (DCB) and the Tapered Double Cantilever Beam (TDCB) were the two most important methods. This study goal was to assess the capability of the DCB and TDCB test to predict the value of GIc of adhesive joints. To learn the correctness of the typical data reduction methods under situations that are not always constant with Linear Elastic Fracture Mechanics (LEFM) principles three types of adhesives with different levels of ductility are used. For both test protocols, methods that do not require measurement of the crack length (a) during the test are evaluated. In the DCB test, these are the

- Compliance Calibration Method (CCM)
- Corrected Beam Theory (CBT)
- Compliance Based Beam Method (CBBM)

The methods used in the TDCB test are the

- Simple Beam Theory (SBT),
- CCM
- CBT

The results were almost consistent between the different methods considered for each test with few exceptions .The inconsistency of results was greater when comparing the two types of tests, except for the brittle adhesive. It was concluded that the data reduction methods for the TDCB test were too conventional to measure GIc of ductile adhesives.

The selected adhesives were the Araldites AV138, the Araldites 2015 and the Sikaforces 7752, which showed brittle, moderately ductile and ductile behaviors respectively. In this study value of GIc of three adhesives was estimated by DCB and TDCB tests. The Araldites AV138 displayed unstable crack propagation because of its brittleness in the DCB test. This performance was not examined for the TDCB specimens, or for all the DCB R-curves of the Araldites 2015 and the Sikaforces 7752. In these cases, the evolution of GI with a or a eq was smooth, although in some conditions with minor fluctuations because of the experimental measurement of **a**. Stress strain curve for different adhesive used is shown in figure 2.6

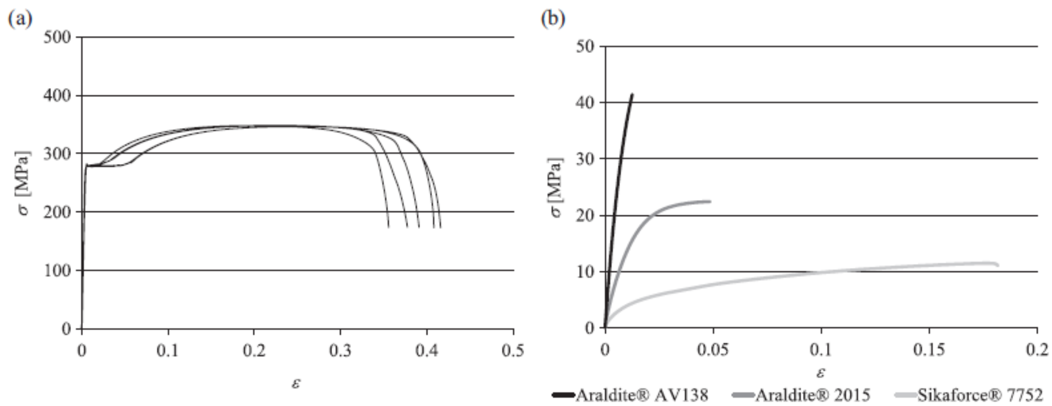


Figure 2-6: Strain curves for different adhesives

The comparison between data reduction methods for each test configuration showed that, for the DCB test, the CBBM was the most reliable as it accounts for the FPZ effects and it did not require the measurement of **a**. Due to similar testing and curing conditions and also failure modes, it can be concluded that the suggested data reduction methods for the TDCB were not the most appropriate to include the adhesives' ductility and to predict GIc under conditions that did not agree with LEFM.

[6] An experimental attempt was made to study the extent of crack propagation in the conducted DCB test for mode-1 fracture in the adhesive joints. The DCB tests were conducted incorporating adhesive composition variation as an investigating parameter which had a significant influence over crack propagation. The characteristics of crack propagation, in both the experimental and numerical realms were analyzed. The correlation of the results from ANSYS and the experiments was also found to converge to a particular extent as revealed from the plots.

DCB tests were conducted to measure fracture toughness in different types of adherends bonded with a two-part acrylic-based adhesive, i.e., aluminum alloy, GF/PP, and CF/EP **[7]**. The values of fracture toughness for the aluminum alloy, GF/PP, and CF/EP specimens were 1071, 1438, and 1652 Jm^{-2}, respectively. It was confirmed by investigating the fracture surfaces that the fractures of the aluminum alloy specimens occurred mainly between the aluminum alloy and the adhesive. Relatively poor bonding between the GFs and PP caused delamination of the adherends in the GF/PP specimens. The fracture surfaces of the CF/EP specimens were cohesive failures. It can be concluded that the fracture toughness of the specimens is closely related to the fracture morphology of the fracture surfaces. Future work includes an investigation of proper surface treatments and modification of the adhesive to improve the fracture toughness.

[8] Fracture mechanical tests subjected to mixed-mode I+III loading has been applied on elastic-plastic adhesive joints using the Mixed-Mode-Controlled DCB (MC-DCB) test. For this test, ratio of mode-mixity has been defined on contributions of J-integral. A test control on those contributions has been successfully realized. Several tests have been considered under constant and variable mode-mix-ratios. Unintended contributions to Jintegral caused by support/loading conditions has been examined and turned out to be in negligible order of magnitude for nearly the entire experiment. By considering the intended contributions, a fracture envelope has been evaluated on mode-mixity I+III and subsequently compared to results from literature of Mixed-Mode-Bending (MMB) tests. A coherence of both fracture envelopes could not be clearly observed due to different adhesive layer thicknesses.

Figure 2.7 presents a detailed view of typical surface morphologies of the DCB joints as a function of the adhesive thickness **[9]**. A visual analysis of these surface morphologies shows that topographic marks were developed on the failure surfaces. The formation of these marks might be explained by the presence of secondary micro cracks ahead of the main crack, which grow and eventually link up with the main crack. Due to the presence of large damage zones, the secondary cracks do not always nucleate in the plane of the main crack. This is specific of modern toughened adhesive joints where fracture occurs by the development and propagation of a damage zone, rather than a single sharp crack. From Fig. 2.7 it can be noted that the dimensions of the marks and the deformation level gradually increased with the adhesive thickness. These differences mainly depend on the energy dissipating mechanisms (plasticity and damage development). The physical constraint of the adherends and the nature of the crack-tip stress field in an adhesive joint alter the size and shape of the deformation zone, and this in turn changes the fracture behavior. Moreover, these morphological variations might be associated with the corresponding variation in fracture toughness.

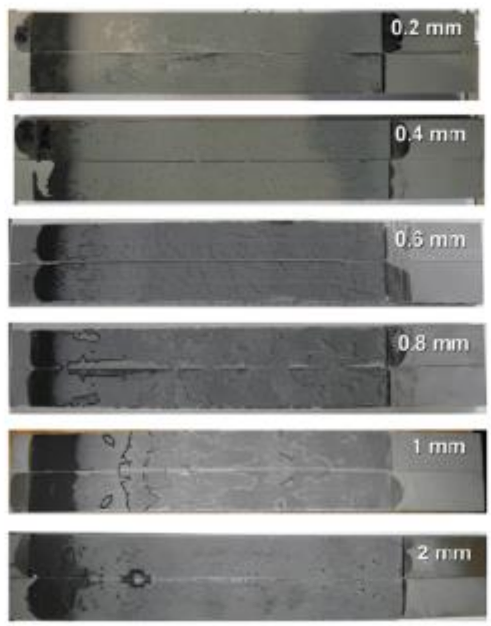


Figure 2-7: DCB failure mode as a function of adhesive thickness

Structural adhesives are progressively replacing conventional bonding methods, being constantly adopted for new applications **[10]**. The most commonly used structural adhesives are epoxies due to their good mechanical, thermal and chemical properties, having a wide range of application. Epoxies are recognized for their high stiffness and strength, induced by their high degree of crosslinking. While the densely cross-linked molecular structure is responsible for the excellent properties of these materials, it also makes them inherently brittle, resulting in low ductility and toughness. Several researchers have, in the past decades, found necessary to mitigate this effect and developed new methods to increase the toughness of structural adhesives. There are many processes depicted in the literature on how to increase the toughness of adhesives. For example, the inclusion of particles (of nano or micro scale) is a successful technique to improve the toughness of structural adhesives. Natural micro particles of cork are used with the objective of increasing the toughness of a brittle epoxy adhesive. The fundamental basis of this concept is for the cork particles to act like crack stoppers, leading to more energy absorption

Because of their many advantages, adhesively bonded joints are intensively used in many engineering fields. Therefore, the mechanical research of the adhesively bonded joints is very important to use these joints safely. There are many studies performed by researchers to investigate the mechanical properties of the adhesive joints. There has been a considerable interest in nanoparticles added to structural adhesives recently because nanoparticles improve the mechanical properties of adhesives and joints. Different nanoparticles reinforced by epoxy adhesive, and neat adhesive were used to produce single lap joints **[11]**. The static and fatigue strengths of single lap joints incorporating nanoparticles were compared to those without nanoparticles. Experiments were performed at 20 mm overlap length. DP460 epoxy was used as the adhesive material, and nano-Al_2O_3, nano-TiO_2 and nano-SiO_2 were used as the nanoparticles; and AISI 304 stainless steel plates were used as the adherents. The results of the experimental research revealed that average failure load increased significantly in nanoparticle-reinforced adhesive joints. The highest average failure load was obtained with 4 wt% nano-Al_2O_3 in epoxy adhesive. Fatigue tests were performed at 10 Hz frequency, and 0.1 loading ratio (R). When the fatigue test results were examined, it was observed that the addition of the nano-Al_2O_3 and nano-SiO_2 to the adhesive increased fatigue strength of the adhesive joints, on the other hand, the addition of the nano-TiO_2 to the adhesive reduced fatigue strength of the adhesive joints.

A tri-layer sandwich structure of SS316L/PU/SS316L was produced by the warm roll bonding method **[12]**. With the penetration of polyurethane in the semi-molten state into the scratches and irregularities of the substrate, mechanical locks were created and a direct adhesion between steel and polymer was established. By determining the appropriate preheat temperature range for polyurethane, the effects of change in the processing parameters of roll bonding on the bond strength were measured. These parameters included preheating temperature, the rolling speed, thickness reduction, and surface preparation conditions, including surface roughness and the orientations of the surface scratches.

By enhancing the thickness reduction up to 40%, the contact pressure and the contact time were increased; thus, the bond strength was also increased, but in the higher thickness reduction, the excessive exiting of polyurethane from between layers caused cavities and imperfections and as a result the bond strength was reduced.

[13] In recent years so many methods are being used to modify substrate by adding microfibers, micro particles(MPs) and nanoparticles(NPs). This improvement has been studied and reviewed by (**Nemati Giv, Ayatollahi, Ghaffari, & da Silva, 2018).** They investigated how these additions effect the mechanical properties of adhesives and adhesive joints. Some salient features of this research papers are

- Characteristics and applications of additions.
- The effects of several parameters on the strength, stiffness and fracture toughness improvement of polymeric materials are reviewed for reinforcements.
- Damage mechanisms involved in increasing or decreasing the mechanical properties are reviewed.

Double Cantilever beam specimen using two different adhesives were prepared. The specimens were subjected to different ageing environments **[14]**. They were fully degraded that means they were tested until their toughness stabilized. Hence it has been experimentally proved that the diffusion of water into the adhesive joints was faster than to bilk adhesive alone.

[15] studied that the size of particles also matter. It should be in-between 4 and 100 micrometer. Similarly, use of biological reinforcements such as Cork particles plays an important role because of its properties such as light in weight, elastic and also impermeable to gas and liquid.

[16] Researched on the inclusion of Nano silica particles to rubber toughened adhesive and experimentally proved that it helped in increasing the toughness of adhesive, glass transition temperature and single lap shear strength.

[17] Studied the effect of aligning Multi walled carbon nanotubes and graphene oxides nanoplatelets on the fracture behavior of glass-epoxy nanocomposite adhesive joints. The results showed that there was 82% and 155% increase in fracture energy as well as improvements of 19% and 69% in the maximum load.

2.2 My Research Work

My research work comprises of crack propagation in double cantilever beam DCB on Stainless Steel 210. Specifications of the specimen are according to the ASTM standards. A lot of work had been done in this specific area of research but DCB testing with inclusion of Cork particles (Amber tree) in adhesives has never been done before. In our thesis we are going to investigate the effect of cork particles at different ratios by using Araldite (2011). As we studied that how mechanical properties of adhesive and adhesive joints increased with the inclusion of microparticles, nanoparticles and microfibers, Let's see the effect of addition of cork particles in DCB test. Different ratios of cork powder has been taken 0.25%, 0.5% and 0.75%.

3. Material and Experimental Methods

Double cantilever beam (DCB) specimen were prepared with and without adding cork particles to determine the effect of secondary particles on DCB adhesive joint strength for to measure the crack propagation at atmospheric conditions**.**

3.1 Material

The material of adherends was Stainless Steel 210. It has wide range of applications, such as food and indoor equipment as well as in automotive industry. In automotive industry main application of stainless steel is in exhaust system manufacturing: for these components high temperatures and corrosive gases demands the use of tough and corrosion resistant materials to prevent rust and creep. To make the bond between adherends Huntsman Araldite 2011 as an adhesive was used.

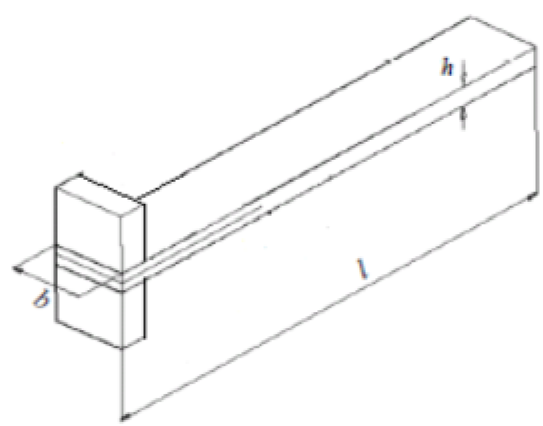


Figure 3-1: Sketch of Double Cantilever Beam (DCB)

The Dimensions of specimen are as follows:

Total length of specimen "l":	200 mm
Thickness of specimen "h":	5 mm
Width of specimen "b":	25mm

Specimen without adhesive layer: 70 mm (From L-joint end)

Specimen with adhesive layer: 130 mm

L-Joint overlapping SS strips: 70 mm

3.2 Araldite Adhesive 2011

Araldite 2011 adhesive was used in this project for adhering Stainless steel adherends. This adhesive was selected because of its good adhesive properties with metal. The properties of Araldite Huntsman 2011 are shown in Table 3.3.

Figure 3-2: *Araldite 2011 (Huntsman)*

Table 3-1: Properties of Huntsman Adhesive Araldite 2011

Property	Araldite 2011 A	Araldite 2011 B
Appearance	Neutral	Pale Yellow
Density, g/cm^3	~1.15	~0.96
Viscosity at 25 ^oC, cP	30, 000 – 50,000	20, 000 – 35, 000

3.3 Cork Powder

Cork particles are used in this research as a reinforcement. **Figure 3.2** shows the cork particles used. It is obtained from bark of tree (Amur). It is also environmental friendly. The particle size is 177 microns. These partciles are added in the adhesive to measure the crack length as well as measure the overall strength of Double Cantilever Beam (DCB).

Figure 3-3: Cork Particles

3.4 Joint Manufacturing

Stainless Steel adherends and dimensions are shown in **Figure 3.1.** Two long strips SS were used to make one sample. The composition and properties of SS are shown in **Table 3.1** and **Table 3.2** respectively.

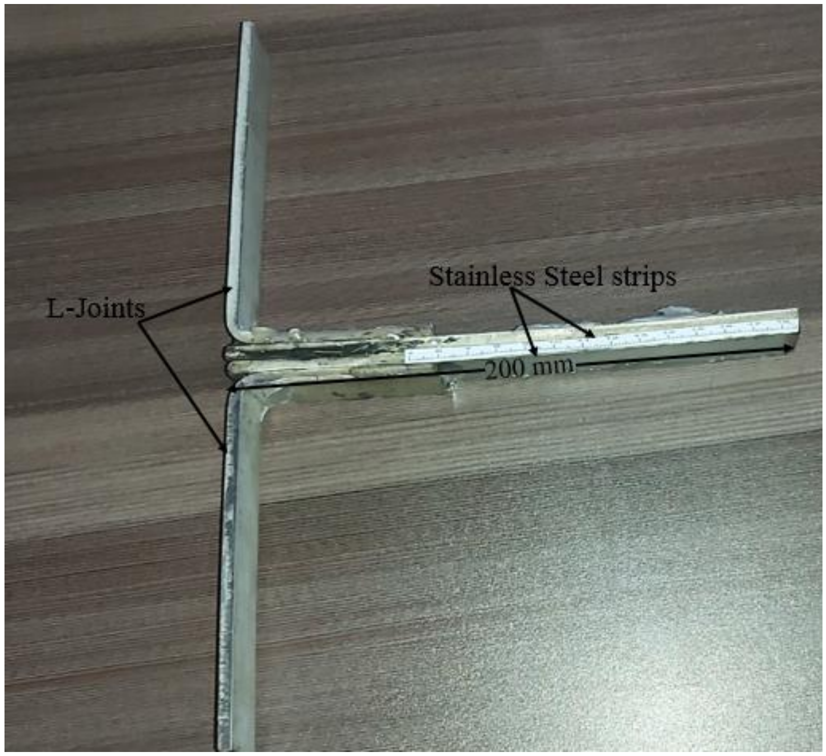


Figure 3-4: Dimensions of Double Cantilever Beam

Table 3.2: Composition of SS 210

Component	Wt%
Fe	98.6
C	0.27
Mn	0.93
Si	0.1
S	0.035
P	0.035

Table 3.3: Mechanical and Physical properties of SS 210

Mechanical Properties	**Value**
Tensile Strength	470 MPa
Fatigue Strength	230 MPa
Shear Strength	320 MPa
Physical Properties	**Value**
Density	7.9 g/cm^3

Stainless Steel L-joints were also used to grip the specimen in the jaws of Universal Testing Machine consequently measuring crack length.

For the preparation of Double cantilever Beam adhesive joints adhesive was applied upto length of 130mm while 70mm of surface was without adhesive. After careful application of Adhesive-particles mixture, joint were held at their position with the help of clips. As, due to viscosity of adhesive the adherends slips. Afterwards, the joints were kept for 24hrs for curing to ensure proper bonding between adhesive and adherends.

Adhesive thickness is very important to maintain. The thickness maintained was 0.33 mm. The total thickness including adherends was 10.33 mm. The thickness was checked with digital Vernier caliper as shown in Figure 3.2

Figure 3-5: Overall thickness of Double Cantilever Beam joint

3.5 Surface Treatment

Stainless Steel adherends were cleaned first with acetone. As the material contains unwanted particles on its surface, which effect the strength of adhesive bonding, hence surface has to clean. After washing with acetone the Stainless Steel long strips were rubbed with grit paper. After that, the adherends were bonded together with Araldite 2011 adhesive.

3.6 Adhesive-Cork Powder Mixture

The two components involved in Mixture are: 1) Adhesive, 2) Cork powder. Different solutions were prepared with different cork powder ratios.

Firstly, adhesive was added into the beaker and then required percentage of cork particles were added. Then the initial mixture was stirred under mechanical stirred for about 20-25 mins. After that, the mixture was placed into ultrasonic bath as shown in figure 3.3 and kept there for 25mins. At the end, hardener was added and then again stirred under mechanical stirrer. After the final mixing of solution it was then applied onto the adherends to measure adhesive strength in Double Cantilever Beam.

Figure 3-6: Sonicator

Figure 3-7: Mechanical Stirrer

After the mixture was prepared it was applied on the surfaces of adherend up to the length of 130mm. L-joints were also attached to grip the specimen and further measure the crack length. Measuring tpe was attached with the joint to measure the length or crack propagation. The adhesively bonded specimen after curing is shown in **figure 3.2.** The curing time set for each of the specimen was 24 hrs at room temperature.

Figure 3-8: Specimen after curing

3.7 Tensile Shear Testing

Universal Testing Machine (SHIMADZU) was used to measure the crack length of SS specimen with and without the inclusion of cork particles. The strain rate kept was 1.5mm/min. The specimen under testing is shown in **Figure 3.3.**

Figure 3-9: Specimen under testing

The standard followed to make DCB adhesive joint was ASTM D5528. The initial crack length maintained was 70mm. The 70 mm length was maintained by placing thin material in between the adherends so that adhesive doesn't follow beyond this limit.

4. Results and Discussions

After preparing and testing the specimen under UTM machine results were plotted between cork powder ratio and different quantities. Adhesive and cohesive failure was also measured using digital microscopy. Crack length was also measured with and without the inclusion of cork particles.

First graph shown in **Figure 4.1** is plotted is between cork powder ratio and Force. Average of values is taken in order to minimize the error. It is shown that when samples were tested with 0% of cork powder the specimen shoed tensile shear strength of 632 N. With 0.25% the strength falls to about 500 N. Furthermore, when samples were tested with 0.5% ratio of cork pwder the average firce specimen withstood was 614N i.e. little less than with 0% cork powder ratio. With 0.75% it again fell down to about 579 N.

Hence it has been concluded that Double cantilever beam with Stainless Steel material shows maximum strength at 0% cork powder ratio and minimum shear strength at 0.25%

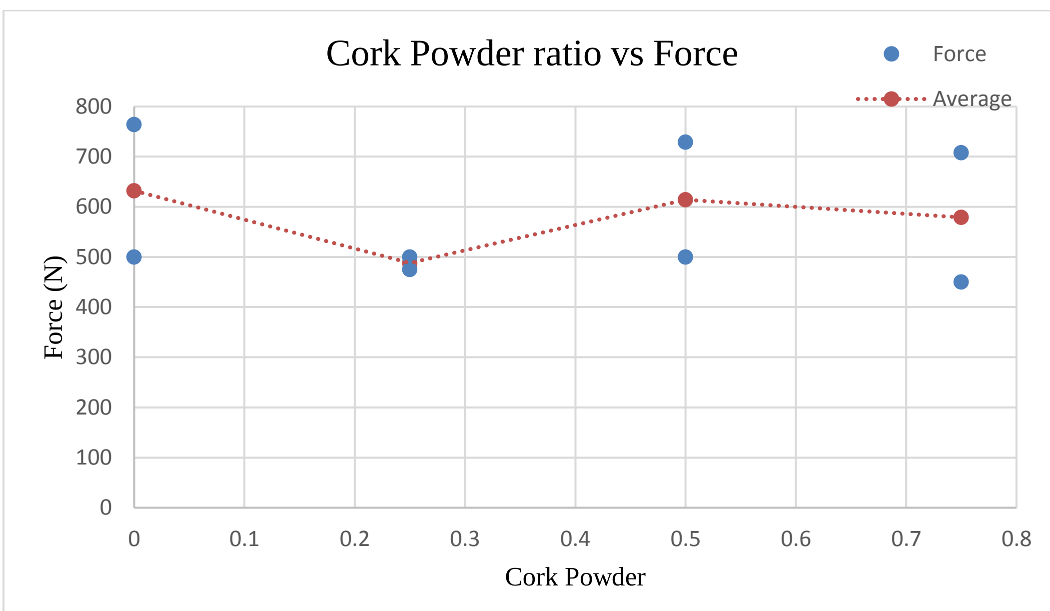


***Figure 4-1**: Cork powder ratio vs Force*

Displacement of failure means how much specimen has moved from its mean position before failure. It can be seen in Figure 4.2 that maximum displacement of failure is in the samples prepared with 0.75% cork powder ratio. The reason behind it is that at 0.75% adhesive started to act as ductile due to addition of cork particles. Whereas, in other cork powder ratio it is less as compare to 0.75% and least in the samples prepared without cork powder ratio which is 1.5mm.

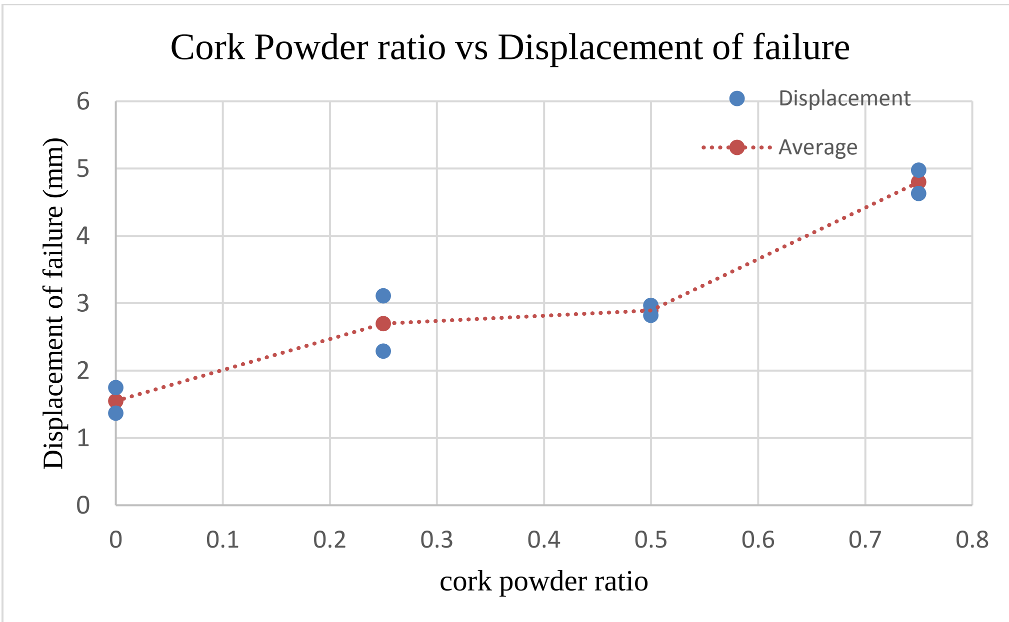


Figure 3-2: % Cork powder Vs Displacement of failure

4.1 Digital Microscopy

Digital microscopy was also performed on the tested samples. In order to identify the type of failure in DCB specimen. **Figure 4.3** shows without any inclusion of cork powder at 50 times magnification under optical microscope.

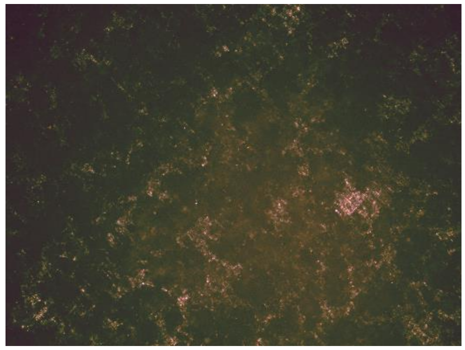
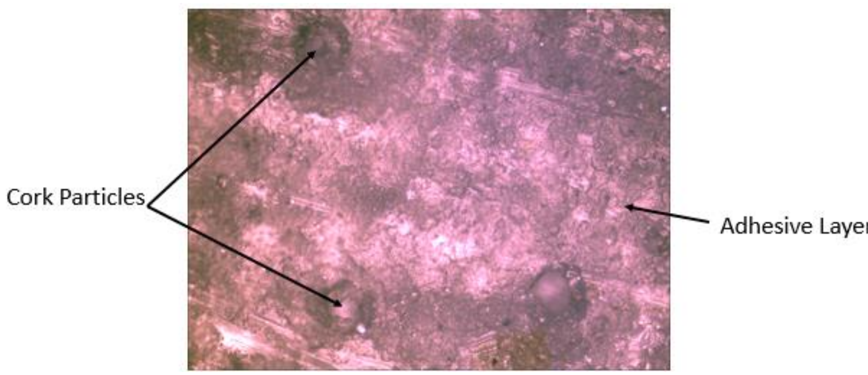
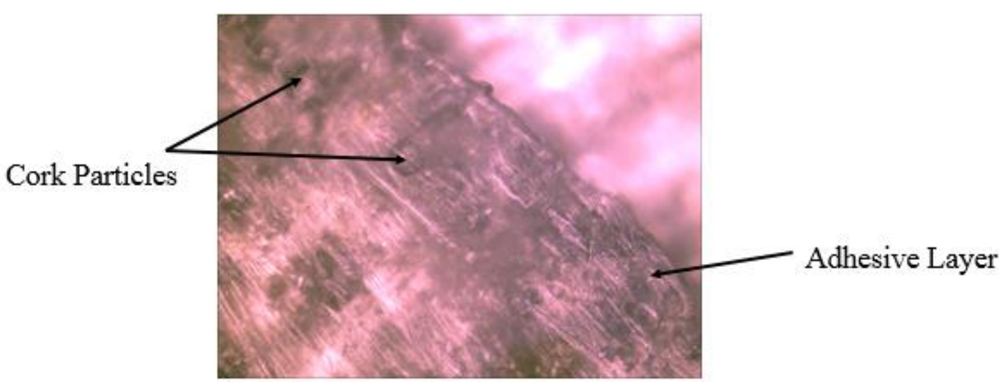


Figure 3-3: Specimen under Optical microscope with 0% cork particles (x50)



(a)



(b)

(c)

Figure 3-4: Specimen under optical microscope : (a) with 0.25% cork particles (x200); (b) with 0.75% cork particles (x200); (c) marked areas are observed under microscope

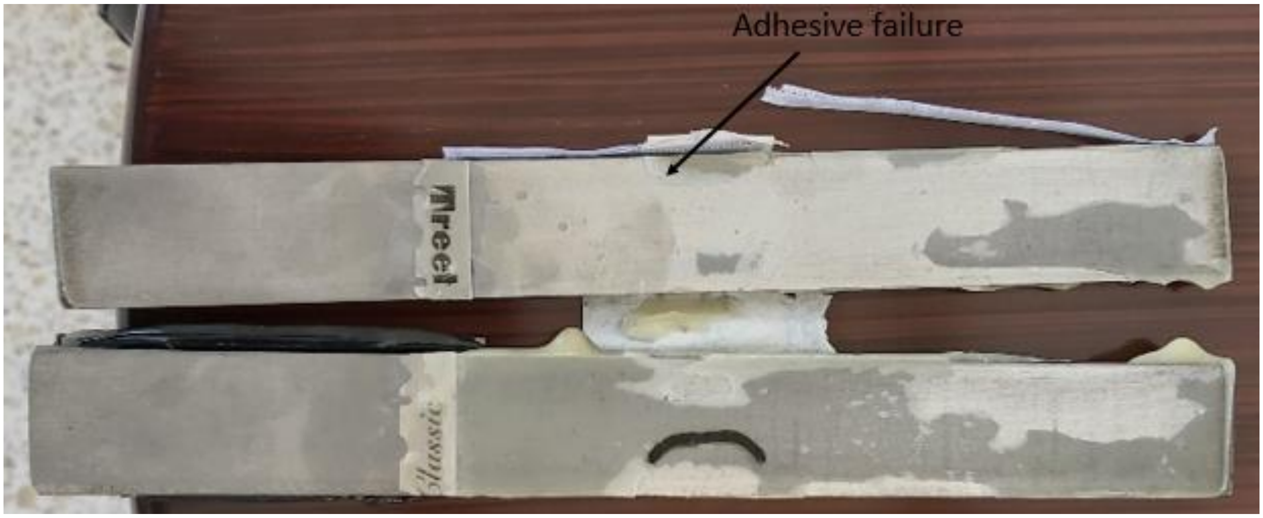
Table 4.1: Type of failure surface

Cork Powder (%)	**Type of Failure Adhesive failure (AF) / Cohesive failure (CF)**	**Av. Force (N)**	**Av. Displacement (mm)**
0	AF and CF both	632	1.55
0.25	CF	488	2.7
0.50	CF	614	2.895
0.75	AF and CF both	579	4.80

(a)

(b)

(c)



(d)

Figure 3-5: Type of failure with 0, 0.25, 0.50 and 0.75% of cork powder: (a) Cohesive and Adhesive both type of failure; (b) Cohesive failure; (c) Cohesive failure; (d) Cohesive and Adhesive both

4.2 Conclusions

- Double cantilever beam showed average load of 632N when samples are tested without adding cork powder under mode-I loading conditions.
- Maximum displacement failure is 4.80 mm when 0.75% of cork powder is added by weight in Araldite 2011.
- Under mode-I loading conditions, addition of cork powder doesn't provide any significant change in the strength of the DCB adhesive joints.
- Under mode-I loading conditions, addition of cork powder improved the displacement at the failure with increase in cork powder ratio. Thus, the ductility of the joint was increased.
- The change in the failure response of the DCB adhesive joints showed that joint can absorb more energy during the plastic deformation as crack propagation is hindered by cork powder when crack grows in a direction parallel to the adherends.
- Cohesive failure occurred in most of the samples, but adhesive failure was also observed in samples with 0% and 0.75% of cork particles.
- The change in the failure response of the DCB joints showed that joint can absorb more energy during the plastic deformation as crack propagation is hindered by the cork powder when crack grows in a direction parallel to the adherends.

However, the added cork powder particles have no significant effect on the peel strength of the joint that is mainly responsible for the failure of the joint under mode I loading conditions.

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