Joining Of Dissimilar Materials By Different Techniques

A MAJOR PROJECT REPORT

Submitted in partial fulfillment of the

requirements for the award of the degree

of

BACHELOR OF TECHNOLOGY

in

MECHANICAL ENGINEERING

By

Abhishek Dixit (BT20MEC007)

Satyam Singh Gurjar (BT20MEC008)

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, UTTARAKHAND

SRINAGAR (GARHWAL) – 246174 (INDIA)

May 2023

CANDIDATE'S DECLARATION

We**,** hereby declare that the work carried out in this project entitled '**Joining Of Dissimilar Materials By Different Techniques**, is presented on behalf of partial fulfillment of the requirements for the award of the degree of Bachelor of Technology in Mechanical Engineering submitted to the Department of Mechanical Engineering, National Institute of Technology, Uttarakhand, under the guidance of **Dr. Pawan Kumar Rakesh, Assistant Professor,** Department of Mechanical Engineering.

We have not submitted the record embodied in this report for the award of any other degree or diploma to any other institute or university.

Abhishek Dixit (BT20MEC007) Satyam Singh Gurjar (BT20MEC008)

Date: 02/05/2023

Place: Srinagar (Garhwal)

CERTIFICATE

This is to certify that the above statement made by the candidates is correct to the best of my knowledge and belief.

Dr. Pawan Kumar Rakesh

Assistant Professor

Department of Mechanical Engineering

NIT Uttarakhand

ACKNOWLEDGEMENT

I am highly grateful to **Dr. Lalit Awasthi**, Director, National Institute of Technology Uttarakhand for providing this opportunity to carry out the major project on the topic Joining Of Dissimilar Materials By Different Techniques.

The constant guidance and encouragement received from **Dr. Hitesh Sharma** course Coordinator, NIT Uttarakhand has been of great help in carrying out the project work and is acknowledged with reverential thanks.

The help and guidance rendered by **Dr. Pawan Kumar Rakesh**, (Supervisor) (Department of Mechanical Engineering, NIT Uttarakhand) during the course of the major project is greatly acknowledged.

I express gratitude to other faculty members of the Mechanical Engineering Department of NIT Uttarakhand for their intellectual support throughout the course of this work.

Finally, I am indebted to all whosoever have contributed to this report work.

ABSTRACT

This study aimed to investigate the feasibility of joining coir composite, galvanized iron sheet, and aluminum sheet using both mechanical fastening and adhesive bonding techniques. Tensile, Shear, and thermal tests were conducted to evaluate the joint strength, and Structural analysis was performed to examine the interface between the materials.

Results showed that both mechanical fastening and adhesive bonding techniques were effective in joining the three materials, with the strength of the joints varying depending on the specific technique used. The mechanical fastening technique produced higher tensile and shear strength compared to the adhesive bonding technique.

Microstructural analysis revealed that the adhesive bonding technique produced a uniform and continuous interface between the materials, while the mechanical fastening technique showed some surface irregularities and deformation.

Overall, the study demonstrated that joining coir composite, galvanized iron sheet, and aluminum sheet using both mechanical fastening and adhesive bonding techniques was feasible and could result in strong and durable joints. The specific technique used would depend on the specific application requirements and material properties, with the mechanical fastening technique being preferred for applications requiring high strength and durability.

Keywords: Composite materials • Composite joining • Bolted composites • Adhesive joined composites.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The awareness of climate change is increasing worldwide, putting pressure on the vehicle industry to minimize emissions. Vehicle manufacturers are constantly looking for ways to decrease the emissions from their products. One way of doing this is by reducing the weight of the vehicles. Although, this has to be done at the same time as acceptable mechanical and comfort properties are maintained. Manufacturers today are trying to solve this by using lightweight materials such as high-strength steel to create vehicles with increased crash safety and decreased weight. Others are looking at fiber composites, aluminum, or magnesium, which also are materials with a high strength-to-weight ratio [1]. However, joining these dissimilar materials can prove to be a challenge. Different material combinations can be difficult to join because of either their individual chemical compositions or large differences in physical properties. Considering high-strength steel and fiber composites with their distinct chemical composition difference and the fact that there are also many different variations of these materials, the creation of a sound joint can be an issue [2]. Joining dissimilar materials refers to the process of connecting two or more materials with different physical, chemical, or mechanical properties. The technique used to join these materials is critical in ensuring that the joint is strong, durable, and suitable for the intended application.

Materials such as aluminum alloys, composites, and GI sheets have different properties, making it difficult to join them together using traditional techniques. As a result, various techniques have been developed to join dissimilar materials, including welding, adhesive bonding, mechanical fastening, riveting, and friction stir welding.

Each technique has its own advantages and disadvantages, and the choice of technique will depend on the application's specific requirements. For example, welding provides a strong, permanent bond but may not be suitable for all materials, while adhesive bonding offers versatility but may not provide the same level of strength as welding.

The joining of dissimilar materials is a critical step in many industrial processes and applications [Fig 1, Fig 2], and the choice of technique will depend on the application’s specific requirements.

Composite materials have recently become more desirable for use in mechanical and structural components due to their relatively high specific strength and stiffness-to-weight ratios. Composites can also be designed and optimized to meet different strength and stiffness requirements in various directions as dictated by the design and performance of a structural component. Unlike metallic structures, the modeling and analysis of composite structures is a fairly challenging task. The load-carrying capacity of the composite material continues to be severely limited by the reduced load carrying capacity at the joint or attachment locations to the main structure. Due to anisotropy and inhomogeneity of composites, their response to loading is more complex, as compared to metallic structures. For a reliable design of composite structures, it is essential to thoroughly understand their behavior under static and dynamic mechanical and thermal loading under various environmental scenarios during the life of the component. The development of such design methods must be based on test data, analytical and computer modeling as well as numerical models using Finite Elements techniques. The fastening and joining of composite materials mainly consist of the bonding and mechanical fastening. The main objective of bolted joints is to transfer applied load from one part of the joint structure to the other through fastener elements. However, bolt holes cause a stress concentration in the composite joint plates, which can severely reduce the mechanical strength and fatigue life of the joined structures. There are several possible joint failure modes in composites and three of the common ones are bearing, net tension and shear-out. Among them, bearing failure is often considered as the "desirable" mode because it usually gives a higher strength and the failure is less brittle. Other modes are often considered as "premature" failures which should be avoided through proper design of the joint geometry and the composite material itself. Referring to the geometric dimensions such as specimen width, hole diameter and hole-to-edge distance, Collings [4] proposed ultimate bearing strength, net ultimate tensile strength, and ultimate shear strength based on average stresses at failure, and the actual failure mode and load are associated with the one with the lowest load value among them.[7]

Fatigue damage around bolt holes consists of three types: hole wear, damage in the contact surface of the composite, and the growth of delamination around the bolt holes induced by the drilling. The hole wear is caused by the erosion of material around the bolt hole as a result of the friction forces. Damage at the contact surfaces is induced by bolt bending under loading. This would result in hole elongation during fatigue loading. It was found that the growth of delamination around bolt holes results in a decrease in the fatigue life of bolted joints. The failure load and pattern of composite bolted joints wosly depend on the bolt preload level and distribution, orientation of layer reinforcing fibers, the ratio of bolt diameter to specimen width, bolt type, ratio of hole diameter to laminate thickness, number of bolts, and bolt arrangement. Two problems should be addressed in the design of composite structures with joints that have multiple bolts. Firstly, it is necessary to adequately understand the behavior, strength, failure modes, and failure criterion of single-bolt joints. Secondly, it is necessary to accurately evaluate the loading magnitude and distribution. The strength prediction methods developed from single-bolt joints can also be utilized for determining the maximum failure load and the corresponding failure mode. The loading proportion is not generally equal for each fastener in the same joint. Therefore, the determination of the ratio of loading proportion for each element becomes an important problem in the optimal design of joints with multiple threaded fasteners. Because this is mostly a highly statically indeterminate mechanical problem, FEA modeling is used for the determination of the loading ratio. Catastrophic failure modes such as tension, shear,-out and cleavage-tension failures are avoidable through proper design of the joint geometry and the composite material itself. Most bolted composite structures are primarily designed to avoid bearing failure; investigating the effect of various joint parameters on bearing failure in a joint is of fundamental importance. Adhesive joints increase structural efficiency and weight savings. They also minimize the potential for stress concentration within the joint, which cannot be achieved with mechanical fasteners. However, because of the lack of reliable, economical, and feasible inspection methods and due to the requirement for close dimensional tolerances in fabrication, designers have generally avoided bonded construction in primary structures. For bonded composite joints, the non-uniform stress distribution along the bonding surface should always be accounted for. The peak stress is mainly dependent on the bonding pattern of the joint, bonded length, adhesive thickness, joint geometry, adherend stiffness imbalance, ductile adhesive response, and the composite adherents.

1.1. Applications

Aerospace and Defense: In the aerospace and defense industries, dissimilar materials are commonly used in the construction of aircraft, spacecraft, and defense equipment. Welding and adhesive bonding are commonly used to join these materials, providing strong and durable bonds that can withstand the harsh conditions and high stresses of aerospace and defense applications.[1]

Automotive: The automotive industry uses dissimilar materials in the construction of vehicles, including the body, chassis, and suspension components. Mechanical fastening and riveting are commonly used in the automotive industry, as they provide a strong and durable bond that can withstand the demands of automotive applications.

Construction: Dissimilar materials are often used in the construction industry, particularly in the construction of buildings, bridges, and other structures. Adhesive bonding and mechanical fastening are commonly used to join these materials, providing a strong and durable bond that can withstand the demands of construction applications.

Electronics: The electronics industry uses dissimilar materials in the construction of various devices, including smartphones, laptops, and other electronic devices. Adhesive bonding and mechanical fastening are commonly used to join these materials, providing a strong and durable bond that can withstand the demands of electronic applications.

Medical: In the medical industry, dissimilar materials are commonly used in the construction of medical devices, including implants, prosthetics, and surgical instruments. Adhesive bonding and mechanical fastening are commonly used to join these materials, providing a strong and durable bond that can withstand the demands of medical applications.

Figure 1.1.1: In Aerospace field [2]

Figure 1.1.2: In Defense Field [1]

1.2. Coir Composite

Coir is a hard and stiff biodegradable lignocellulosic fiber that is obtained from the fibrous mesocarp of coconut fruits and makes up about 25% of the nut [4,5]. Coconut (cocos nucifera) is cultivated extensively in tropical countries such as Thailand, India, Lanka, etc. [3]. Due to the high lignin content of coir fibers, they are durable, weather resistant, relatively waterproof, and chemically modified [6,9,11]. The fibers also have high elongation at break i.e. they can also be stretched beyond the elastic limit without rupture [8,9]. A detailed study of the structural, morphological, mechanical, and thermal properties of coir fibers was reported in the literature [4]. To improve the overall properties of the composites, studies have reported the hybridization of coir fiber composites with other fibers such as kenaf [4], bamboo [9], rice straws [6], and glass fibers [6] among others [6,15,7–9]. Many authors have given an overview of the production process and mechanical properties of various fiber composites such as but less effort has been focused on coir fiber composites alone. This work provides an overview of coir fiber composites.

1.2.1. Composition and properties of coir fibers

Coir fibers possess several advantageous properties such as low cost, high lignin content, low density, availability, high elongation at break, and low elastic modulus [21]. An understanding of this composition is important in the development of fiber-reinforced composites. In this section, the chemical, physic mechanical, thermal, and microstructural will be discussed.

1.2.2. Physical and mechanical composition

Composite properties largely depend on the characteristics of their constituent materials and the interaction among them [12]. The physical properties of a material refer to the diameter, density, and weight gain by water absorption of that material while the mechanical properties include the tensile, flexural, and impact strengths. The value of selected physical and mechanical coir fibers as analyzed and Coir fibers can be said to have 1.1–1.5 g/cm3 density, 2–8 GPa Young's modulus, and 105–593 MPa tensile strength. 10–180% water absorption and 15–51% elongation at break. The variation of these properties may depend on the source of the fiber, pre-treatment, and extraction methods [14]

Table 1: Chemical composition of coir composite

Cellulose	Hemicellulose	Lignin	Origin	Reference
43.4	0.25	45.8	-	[22]
46	21	31	-	[21]
47	15	31	-	[12]
47.7	25.9	17.8	-	[3]
64	-----	-----	India	[17]
----	-----	27.2-33.8	-	[19]
33.3-35.5	16.8-18	33.6-36.6	Philippines	[24]
36.3	-----	31.9 (AIL)	Philippines	[20]
		0.8 (ASL)	Philippines	[11]
43.4±1.2	4.0±0.3	48.3±1.9	Brazil	[13]

1.3. Aluminum Alloy

The most commonly used aluminum alloys for construction and manufacturing applications are 6061-T6 and 6063-T5. These alloys have good mechanical properties and are relatively easy to fabricate, making them ideal for a variety of applications. 6061-T6 is used for this project.

Table 2: Mechanical properties of Aluminum Alloy 6061-T6 [19]

Properties	Metric	Imperial
Tensile strength	310 MPa	45000 psi
Yield strength	276 MPa	40000 psi
Shear strength	207 MPa	30000 psi
Fatigue strength	96.5 MPa	14000 psi
Elastic modulus	68.9 GPa	10000 ksi
Poisson's ratio	0.33	0.33
Elongation	12-17%	12-17%
Hardness, Brinell	95	95

1.4. Galvanized Iron (GI) Sheets

GI sheets are typically made of cold-rolled carbon steel that has been coated with zinc to protect against corrosion. The most common type of GI sheet is hot-dip galvanized steel, which is produced by immersing the steel in a bath of molten zinc.

Table 3: Mechanical properties of Galvanized Iron (Grade 33) [14]

Mechanical Properties	Metric	English
Modulus of Elasticity	200 GPa	29000 ksi
Bulk Modulus	160 GPa	23200 ksi
Poissons Ratio	0.29	0.29
Shear Modulus	80.0 GPa	11600 ksi

1.5. Literature Review

The main purpose of an adhesively bonded joint and mechanical fastening is to transfer loads reliably under various environmental conditions throughout the entire service life of the joint and the parent structural component. The joint interfacial stresses introduced by those loads must remain an essential part of the design, analysis, testing, and validation process. Much of the current methodologies used in the design and analysis of adhesive joints in composite structures are based on the approach developed by L. J. Hart-Smith in a series of NASA-Langley-sponsored contracts [3, 4] during the early 1970s. Some of the key principles on which that effort was based include (1) the use of simple 1-dimensional stress analysis of generic composite joints wherever possible [5]; (2) the need to select the joint design to ensure failure in the adherend rather than the adhesive, so that the adhesive is never the week link; (3) a recognition that the ductility of adhesives is beneficial in reducing the stress peaks in the adhesive; (4) careful use of such factors as adherend tapering to reduce or eliminate peel stresses from the joint; and (5) recognition of slow cyclic loading, corresponding to such phenomena as a major factor controlling durability of adhesive joints, and the need to avoid the worst effects of this type of loading by providing sufficient overlap length. This ensures that some of the adhesive is so lightly loaded that creep was not significant under the most severe scenarios of extreme humidity and temperature over the component service life. After Volker Sen's work [6] on the stress analysis of a single lap joint, many analytical models have been proposed for the stress analysis of various adhesively bonded joints. Sample 3-D analytical models for interfacial stress are developed by Ma-et-al. [7]. Most recently, several investigational studies have been carried out by Nasser et al. at the Fastening and Joining Research Institute-Oakland University, on various fastening and joining aspects of advanced composite materials. Experimental and analytical techniques, as well as FEA simulation, are used to study bolted joint behavior and failure modes in different loading and temperature conditions. That includes deformation, NDE and preload control, Tribology of threaded fasteners, vibration and impact-induced loosening of preloaded threaded fasteners, elastic interaction, loss of preload, creep relaxation modeling, and hole and washer variables.

1.6. Preparation of Coir composite

At first, a Coir composite is prepared by the hand-lay technique. To prepare a coir composite sample, the Followings materials and equipment are used:

- Coir fibers
- Epoxy (Araldite® LY 556)
- Hardener (Araldite® LY556 hardener)

Equipment:

- Mixing container (such as a plastic cup)
- Stirring stick or tool
- Brush or roller
- Mold or surface to apply the composite to

Here are the general steps [9] to prepare a coir composite sample:

- Cut the coir fibers to the desired length and shape. You can use scissors or a cutting tool for this.
- Mix the epoxy and hardener in a ratio of 1:10. Stir the mixture thoroughly.
- Apply a release agent to the mold or surface you will be used to prevent the composite from sticking.
- Dip the coir fibers into the resin mixture or apply the resin mixture to the coir fibers with a brush or roller. Make sure the fibers are well-coated with resin.
- Arrange the coated fibers into the desired shape and place them onto the prepared mold or surface.
- Apply pressure to the composite to ensure good adhesion and remove any air bubbles. You can use a roller or a similar tool for this.
- Allow the composite to cure for 24 hours.
- Once the composite has cured, remove it from the mold or surface and trim any excess material.

Prepare three coir composites of dimension 200*200*3 $mm^{\wedge 3}$. Then, cut the sample of dimension into 200*25*3 mm^3 with the grinder of blade 10 inches. Here, figure 3 shows the coir composite sample.

Figure 1.6.3: Coir Composite

Figure 1.6.4: Layout of Coir composite

1.7. Preparation of Aluminum Sheet and Galvanized Iron Sheet

Cut the Aluminum and Galvanized Iron sheets into dimensions of 200*25 mm^2 with a snipping tool. The thickness of the Aluminum sheet is 0.3 mm and that of Galvanized sheet is 0.6 mm. Then, prepare 18 samples of Galvanized Iron and 36 Aluminum sheets because to maintain uniformity in the thickness of both sheets, so take we used two aluminum sheets, one coir composite sample, and one galvanized iron sheet. Figure 4 shows the samples of Aluminum sheets and galvanized sheets.

So, the total thickness of the combined sample is 4.2 mm.

Figure 1.7.5: Aluminum Sheets and Galvanized Iron Sheets

1.8. Joining through mechanical fastening and adhesive techniques

Joining the samples by two different techniques:

1. Mechanical Fastening

- Nut and bolts
- Riveting

2. Adhesive joining

1.8.1. Mechanical Fastening

Nuts and Bolts

For joining aluminum alloys, stainless steel nuts and bolts are typically used to ensure corrosion resistance. In some cases, aluminum nuts and bolts may also be used, but it is important to ensure that they are of the correct grade and strength for the application. We used a 3.5mm diameter [5]. For joining GI sheets, carbon steel nuts, and bolts may be used, but it is recommended to use a corrosion-resistant coating such as yellow zinc chromate or a galvanized coating to ensure long-term performance.

For joining composite, stainless steel nuts and bolts or nuts and bolts with a protective coating are recommended to ensure corrosion resistance. The strength requirements for the application must also be considered when selecting nuts and bolts for composites, as they have lower tensile strength compared to aluminum alloys and GI sheets [8].

The diameter varies with the size of the screw and the depth of the hole is about 3.5 mm.

Riveting

For composite, stainless steel pop rivets or solid stainless steel rivets are typically used to ensure resistance to corrosion. It is important to consider the strength requirements for the application when selecting rivets for composite, as the composite material has lower tensile strength compared to aluminum alloys and GI sheets [12].

Three samples from each method will prepare for testing. Three samples from the Adhesive technique using epoxy as an adhesive and three samples from the Mechanical Fasteners technique and three from the Single rivet lap joint, three from the double rivet lap joint, and three from the triple-rivet lap joint.

Figure 5 shows the dimension of the sample and the dimension of the hole through which mechanical fastening joining will be done.

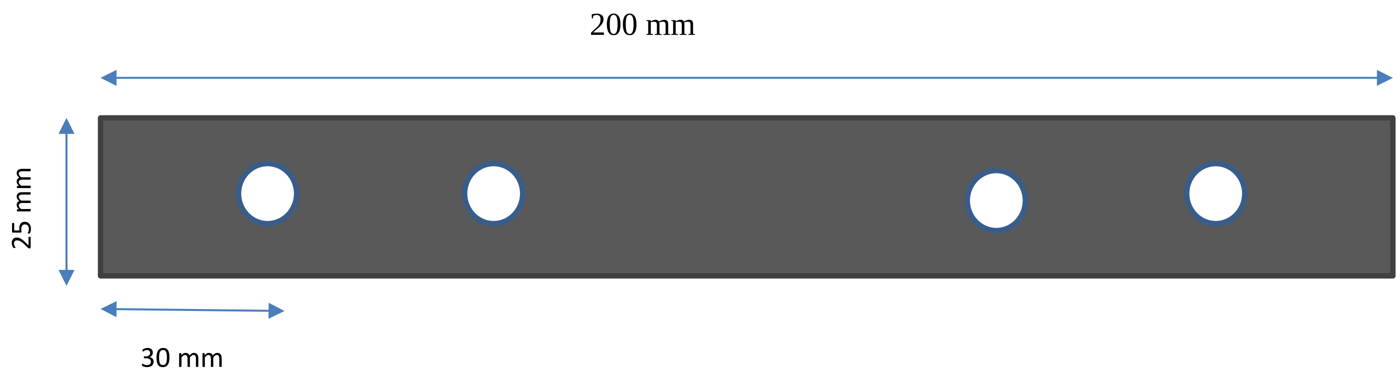

Figure 1.8.6: Dimension of sample for joining

Figure 1.8.7: Joining through Nut Bolt technique

Figure 1.8.8: Joining through rivet technique

1.8.2. Adhesive Joining

When joining metal and composite materials together, it's important to select an appropriate adhesive that will bond to both materials and provide a strong, durable joint. Here are some general steps to follow for the adhesive joining of metal and composite materials:

- Clean and prepare the surfaces of both materials that will be bonded together. The surfaces should be free of dirt, grease, and other contaminants that could interfere with bonding.
- Select an adhesive that is suitable for bonding both metal and composite materials. Epoxy is used with a hardener in a ratio of 1:10.
- Apply the adhesive to one of the surfaces.
- Press the two surfaces together firmly. Use clamps or other methods to apply pressure and hold the surfaces in place until the adhesive cures.
- Allow the adhesive to cure for 24 hours. The curing time may vary depending on the type of adhesive used and the environmental conditions.
- After the adhesive has cured, test the strength of the bond to ensure it is strong enough for the intended use. If necessary, make adjustments or apply additional adhesive to strengthen the bond.
- When joining metal and composite materials, it's important to select an adhesive that is compatible with both materials and provides a strong, durable bond.

Here, we use Epoxy (Araldite® LY 556) and hardener (Araldite® LY556 hardener) for joining metal and composite.

Table 4: Properties of Epoxy (Araldite® LY 556) [15]

Product Type	Epoxies-Bisphenol-A based
Chemical composition	Bisphenol-A-based epoxy resin
Aspect	Clear, pale yellow liquid
Density at 25 C	1.15-1.20 g/cm^3
Viscosity at 25 C	10000-12000 m Pa s

Table 5: Properties of Hardener (Araldite® LY556 hardener) [15]

Specific gravity at 20 C	0.95-1.05 g/cm^3
Viscosity at 25 C	10-20 mPa s

Figure 1.8.9: Adhesive Joining

The mechanical properties of composite materials have great importance in the field of using these materials. The static structural analysis of the joining of aluminum sheet, galvanized Sheet, and Coir composite through mechanical fastening by applying 100 MPa load in one direction and the other end is fixed is shown in Figure (11,12,13).

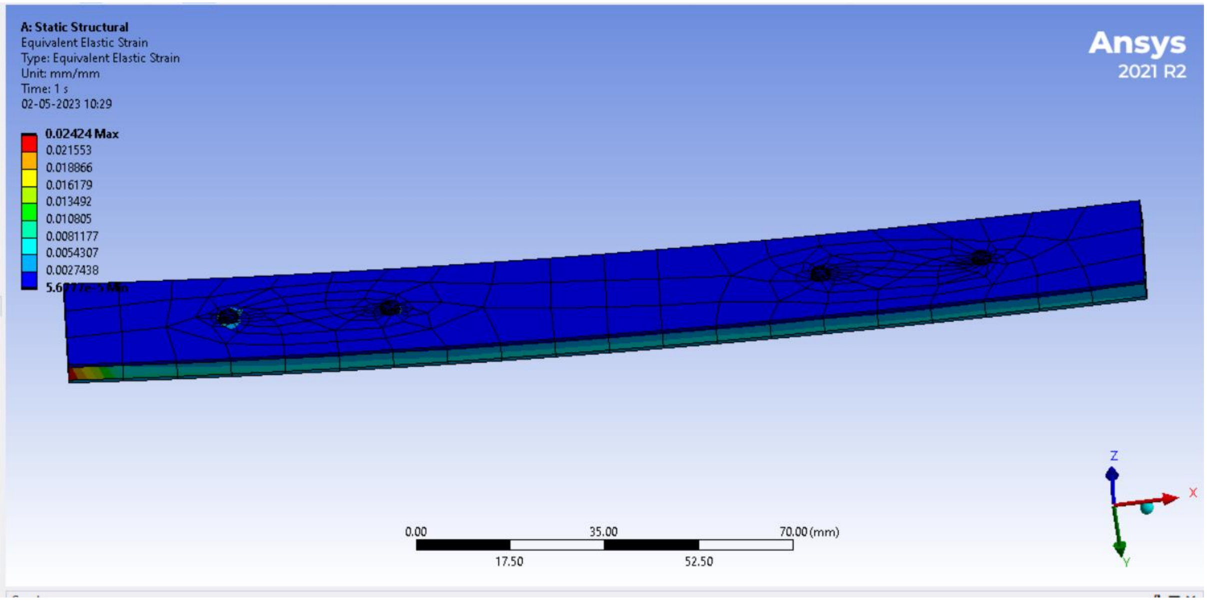

Figure 10: Equivalent Elastic Strain

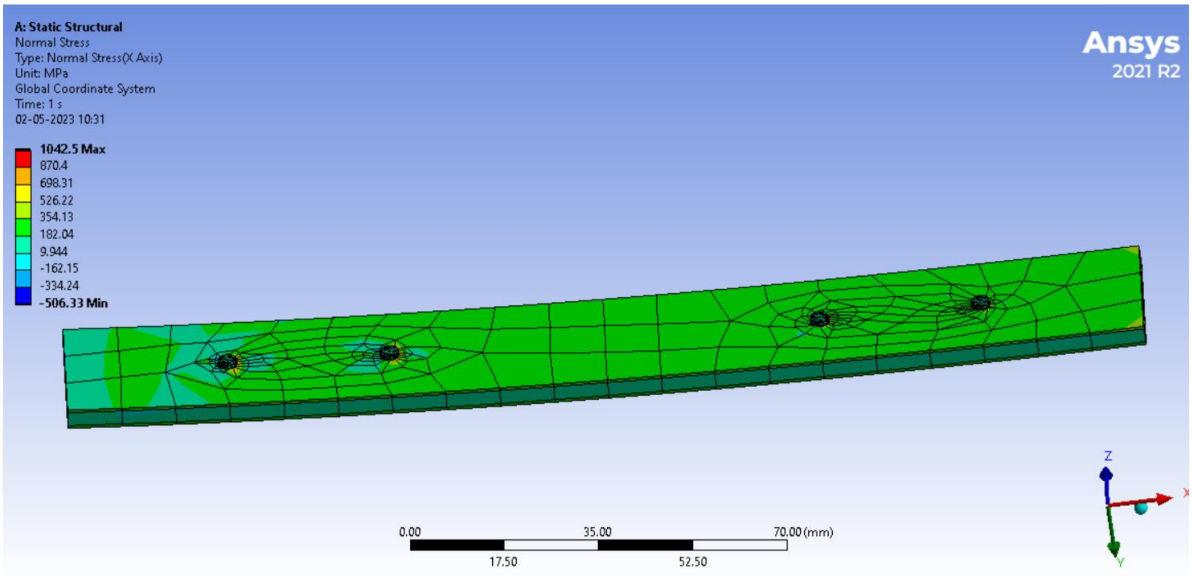

Figure 11: Normal Stress Analysis

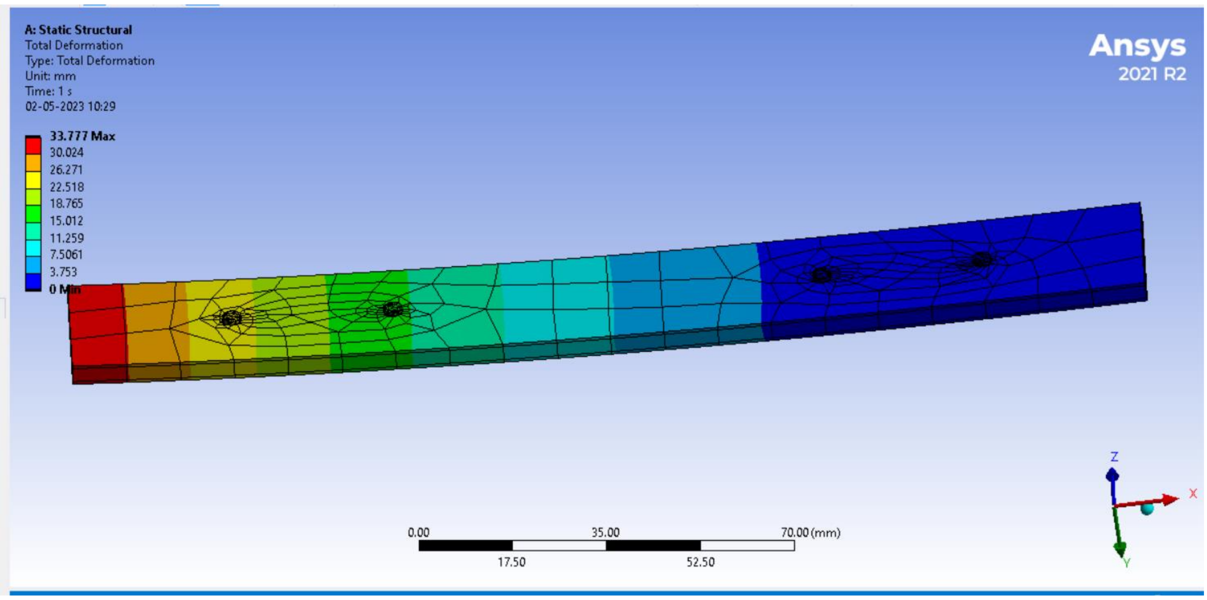

Figure 12: Total deformation

Now, Here Static Structural analysis of joining of Aluminum sheet, Galvanized Iron and coir composite by Adhesive technique by applying load of 100 MPa in unidirectional. The Static Structural properties as shown in Figure (13, 14).

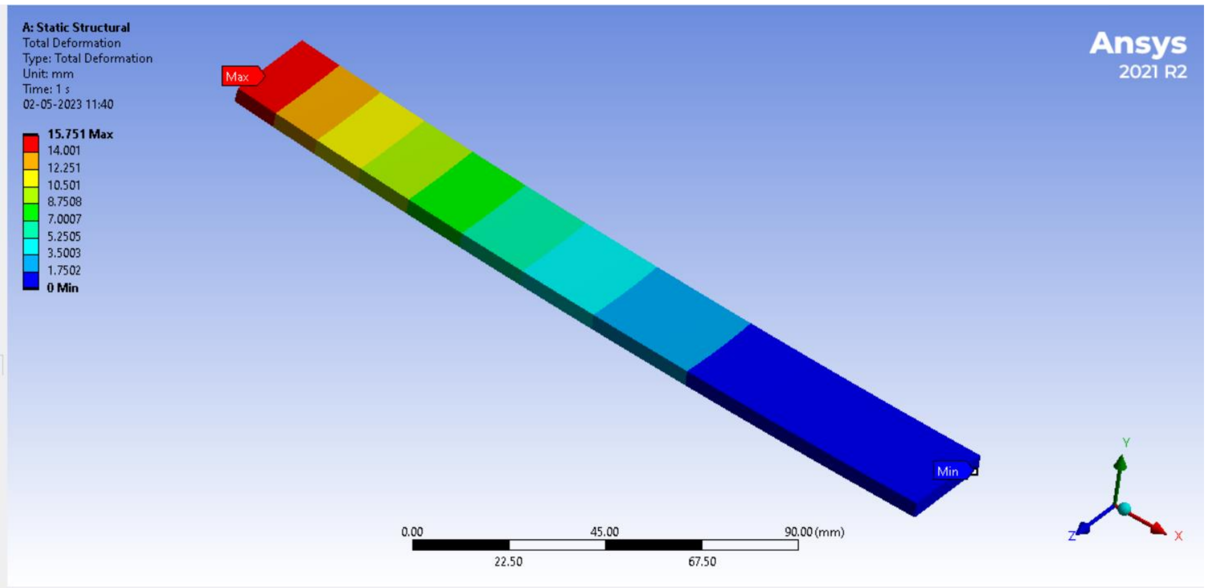

Figure 13: Total deformation

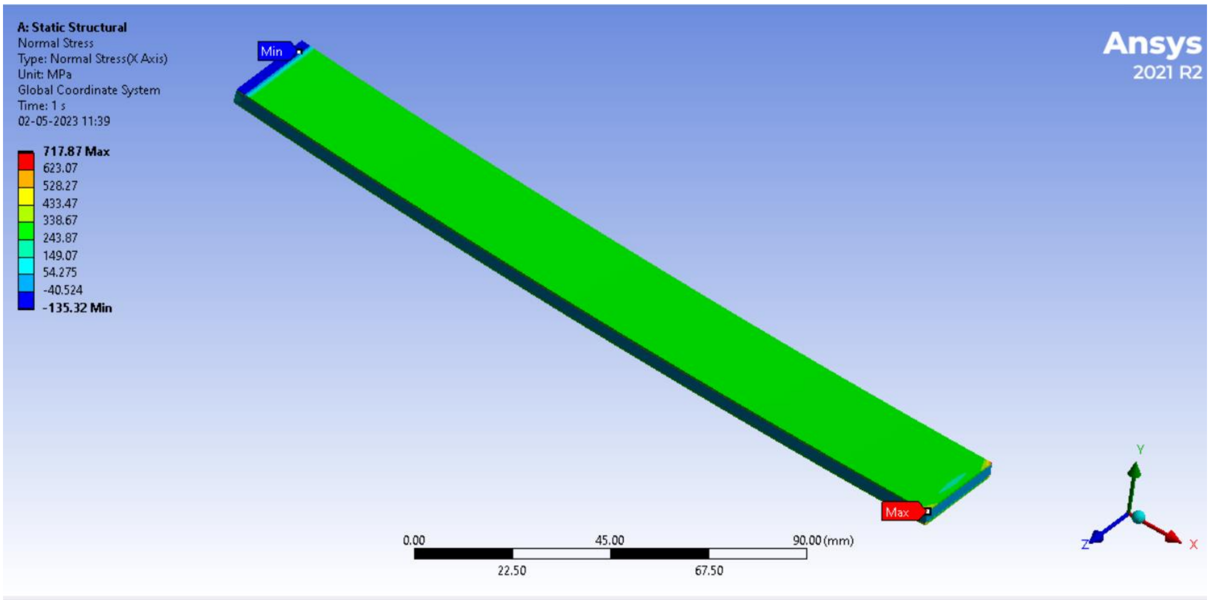

Figure 14: Normal Stress

Conclusion

As the analysis of adhesive and mechanical fastening techniques, the deformation is more in joining through mechanical fastening rather than adhesive joining because, in mechanical fastening, the maximum deformation is 33.77 mm while in adhesive joining it is 15.751 mm. So, adhesive joining is best for joining dissimilar materials. However, adhesive joining also has some limitations. Adhesives require clean and properly prepared surfaces for bonding, which can be time-consuming and require special equipment or techniques. Adhesives can also be affected by temperature, moisture, and chemicals, which can weaken the bond or cause failure over time. Additionally, adhesives may not provide the same level of strength and durability as other joining methods in certain applications. In conclusion, adhesive joining can be a viable option in many cases, but it is not always the best choice. The suitability of adhesive joining depends on the specific requirements and constraints of the project, and a careful evaluation of the advantages and limitations of adhesive joining should be conducted before making a final decision.

References

1. S. Jayavani, H. Deka, T. Varghese, S. Nayak Recent development and future trends in coir fiber-reinforced green polymer composites: review and evaluation Polym Compos, 11 (37) (2016), pp. 3296-3309
2. N.A.S. Priya, P.V. Raju, P. Naveen Experimental testing of polymer reinforced with coconut coir fiber composites Int J Emerg Technol Adv Eng, 4 (12) (2014), pp. 453-460
3. S.K. Saw, G. Sarkhel, A. Choudhury Surface modification of coir fibre involving oxidation of lignins followed by reaction with furfuryl alcohol: characterization and stability Appl Surf Sci, 257 (8) (2011), pp. 3763-3769
4. S. Bettini, A. Bicudo, I. Augusto, L. Antunes, P. Morassi, R. Condotta, B. Bonse Investigation on the use of coir fiber as an alternative reinforcement in polypropylene J Appl Polym Sci, 118 (5) (2010), pp. 2841-2848
5. E. Zainudin, L.H. Yan, W. Haniffah, M. Jawaid, O.Y. Alothman Effect of coir fiber loading on mechanical and morphological properties of oil palm fibers reinforced polypropylene composites Polym Compos, 35 (7) (2014), pp. 1418-1425
6. H. Essabir, R. Boujmal, M.O. Bensalah, D. Rodrigue, R. Bouhfid, A. el kacem Qaiss Mechanical and thermal properties of hybrid composites: oil-palm fiber/clay reinforced high density polyethylene Mech Mater, 98 (2016), pp. 36-4
7. M. Gupta, R. Singh PLA-coated sisal fibre-reinforced polyester composite: water absorption, static and dynamic mechanical properties J Compos Mater, 53 (1) (2019), pp. 65-72
8. J. Naveen, M. Jawaid, P. Amuthakkannan, M. Chandrasekar Mechanical and physical properties of sisal and hybrid sisal fiber-reinforced polymer composites Mechanical and physical testing of biocomposites, fibre-reinforced composites, and hybrid composites, Elsevier (2019), pp. 427-440
9. S. Abdulkareem, A. Adeniyi Production of particle boards using polystyrene and bamboo wastes Niger J Technol, 36 (3) (2017), pp. 788-793
10. N. Venkateshwaran, V. Santhanam, A. Alavudeen Feasibility study of fly ash as filler in banana fiber-reinforced hybrid composites Processing of green composites, Springer (2019), pp. 31-47

11. M.S. Islam, N.A.B. Hasbullah, M. Hasan, Z.A. Talib, M. Jawaid, M.M. Haafiz Physical, mechanical and biodegradable properties of kenaf/coir hybrid fiber reinforced polymer nanocomposites,Mater Today Commun, 4 (2015), pp. 69-76
12. V.K. Bhagat, S. Biswas, J. Dehury Physical, mechanical, and water absorption behavior of coir/glass fiber reinforced epoxy based hybrid composites Polym Compos, 35 (5) (2014), pp. 925-930
13. H.U. Zaman, M.A. Khan, R.A. Khan Comparative experimental measurements of jute fiber/polypropylene and coir fiber/polypropylene composites as ionizing radiation Polym Compos, 33 (7) (2012), pp. 1077-1084
14. M. Sakthivel, S. Ramesh Mechanical properties of natural fiber (banana, coir, sisal) polymer composites Sci Park, 1 (1) (2013), pp. 1-6
15. S. Siddika, F. Mansura, M. Hasan physico-mechanical properties of jute-coir fiber reinforced hybrid polypropylene composites Eng Technol, 73 (2013), pp. 1145-1149
16. S.K. Saw, G. Sarkhel, A. Choudhury Preparation and characterization of chemically modified Jute–Coir hybrid fiber reinforced epoxy novolac composites J Appl Polym Sci, 125 (4) (2012), pp. 3038-3049
17. M. Zin, K. Abdan, M. Norizan, N. Mazlan The effects of alkali treatment on the mechanical and chemical properties of banana fiber and adhesion to epoxy resin Pertanika J Sci Technol, 26 (1) (2018)
18. Bragancxa IMF, Silva CMA, Alves LM, et al. Joining sheets perpendicular to one other by sheet-bulk metal forming. Int J Adv Manuf Tech 2017; 89: 77–86.
19. Bragancxa IMF, Silva CMA, Alves LM, et al. Lightweight joining of polymer and polymer-metal sheets by sheet bulk-forming. J Clean Prod 2017; 145: 98–104.
20. Merklein M, Allwood JM, Behrens BA, et al. Bulk forming of sheet metal. CIRP Ann: Manuf Techn 2012; 61:725–745.
21. Alves LM, Nielsen CV and Martins PAF. Revisiting the fundamentals and capabilities of the stack compression test. Exp Mech 2011; 51: 1565–1572.
22. Silva DFM, Bragancxa IMF, Silva CMA, et al. Joining by forming additively manufactured ‘mortise-and-tenon’ joints. J Eng Manuf. Epub ahead of print 27 July 2017. DOI: 10.1177/0954405417720954.
23. Alves LM, Silva CMA, Nielsen CV, et al. Pressure-assisted forming of non-concentric tubular cross sections with solid medium. J Eng Manuf 2017; 231: 2123–2132.

24. Alves LM, Afonso RM, Silva CMA, et al. Joining sandwich composite panels to tubes. J Mater Design Appl. Epub ahead of print 27 March 2018. DOI: 10.1177/1464420718763463.
25. Nielsen CV, Zhang W, Alves LM, et al. Modeling of thermo-electro-mechanical manufacturing processes with applications in metal forming and resistance welding. London: Springer, 2013.