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MECHANICAL ANALYSIS OF ADHESIVE SOLUTIONS IN AUTOMOTIVE MANUFACTURING: A STUDY ON LOCTITE ADHESIVES

THESIS

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- ε - Strain
- σ - Stress
- σ_e- The engineering stress:
- σ_t- The true stress:
- A_0- original cross-sectional area
- A_i- instantaneous cross-sectional area
- ε_{eng}- Engineering Strain:
- l_f- final elongation/length
- l_0- initial elongation/length
- ε_t- true Strain:
- L_i- instantaneous length
- F - Force
- A – Cross Sectional Area
- A_s- Shear Area
- MPa - Mega pascals
- mm - millimeters

Introduction

Now a days, It is difficult to imagine the development of vehicle production without the use of adhesive bonding technology, because it provides great opportunities for the assembly process and ensures improvement of vehicle safety and durability, as well as enhancing various aspects of performance. Instead of the old mechanical fastening method like welding and riveting, adhesive bonding has its own merits. These are better stress management, lightened weight and better look. Adhesives in automotive manufacturing processes more and more widely utilized, having changed the established joining methods instead of improving upon them and leading to highly innovative solutions and kinds of production.[1]

The lap shear strength is one of the most fundamental factors that influence the adhesive bonding performance, a critically important parameter to know how well the adhesive can withstand the tensile forces or in other words that is its ability to resist against the forces trying to pull it down or off of the two surfaces. This particular strength measure contributes in a significant way to the dependability as well as the integrity of adhesive bonds in automotive the applications.[2]

This study intends to examine the strength characteristics of two well-known adhesive formulations: Loctite 402 and Loctite 406. The need of adhesive technology is steadily increasing and drawing the attention of automotive industry. The objective of this study is to establish the mechanical characterization describing the behavior of these adhesives through the tensile mode by using an Instron instrument for conducting tensile testing on single-lap joints while following the guidelines laid down in ISO 4587.

There are various objectives of this research. This first part will shed more light on how adhesives are used in automotive manufacturing (to reveal the extent of significance of these adhesives in modern vehicle design and construction). The second step shall include explaining the materials and methods used in the tensile strength measurement of Loctite adhesives 402 and 408 and this will be the basis for experimental testing that will serve to standardize research. Thirdly, in terms of characterization and quantification of the forces of these adhesives, breaking stress, and such aspects can be investigated to get an idea of the capabilities. For the last step, compare the acquired findings to industrial standard and literature data, which can be a great assistance for indepth evaluation of the effectiveness of these adhesive formulations in automotive usage.

The purpose of this study is to identify the final mechanical characteristics of Henkel Loctite adhesives 402 and 408. This will be carried out through the evaluation of tensile and lap-shear strength evaluation and an analysis of the factors that affect their behavior and thus the quality of the bond. Furthermore we aim to identify connections, among the composition of adhesives methods for preparing surfaces and the effectiveness of bonding to enhance bonding procedures, in the industry.

1 Literature Review

1.1 Adhesives

An adhesive is a substance that can be employed to cover the surfaces of objects in order to permanently bond them together by an adhesive bonding method. It is a kind of material that is capable of making bonds to each of the two components when the final object is made up of two pieces that connect together. The fact that adhesives are utilized in relatively tiny amounts compared to the weight of the finished product is one of their characteristics. It's challenging to define adhesion, but Wu's suggestion was found useful. “When two dissimilar bodies are bonded together by close interfacial contact, mechanical force or work can be transmitted across the interface. This is referred to as adhesion. Electrostatic attraction, chemical bonding, or van der Waals forces are all possible sources of the interfacial forces that hold the two phases together. The mechanical features of the interfacial zone and the two bulk phases, in addition to the interfacial forces, define the system's mechanical strength [3].”

1.1.1 Adhesion and Cohesion

The main mechanism by which adhesives and sealants work is adhesion, which refers to the attraction between two distinct components caused by intermolecular interactions. It differs from cohesion, which solely concerns the attractive forces present within a single substance. Van der Waals forces are mostly responsible for adhesion and cohesion. Consider the failed joints shown in Fig.1 to have a better understanding of the distinction between adhesion and cohesion [4].

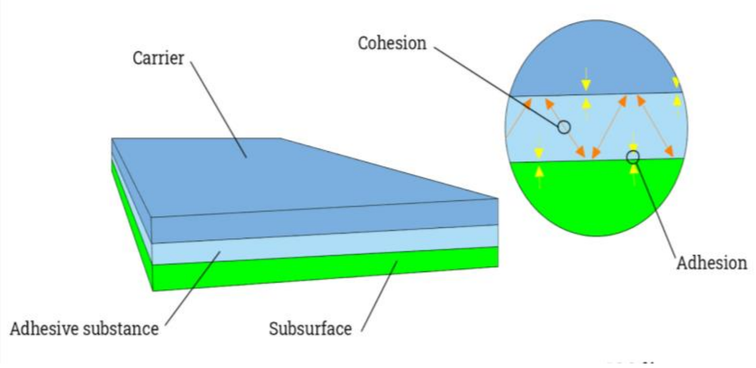

Figure 1: Understanding Adhesion and Cohesion with Adhesive [5]

Cohesive failure, adhesive failure, or a mix of the two are all possible causes of joint failure. Cohesive failure can happen within the adhesive substance or the adherend, whereas adhesive failure happens when the connection between the adhesive and adherend fails. When the adhesive fails cohesively, a layer of adhesive still remains on both substrates due to stress fracture in the adhesive substance. Cohesive failure of the adherend occurs when the adherend breaks before the adhesive, leaving the joint area unaffected [4].

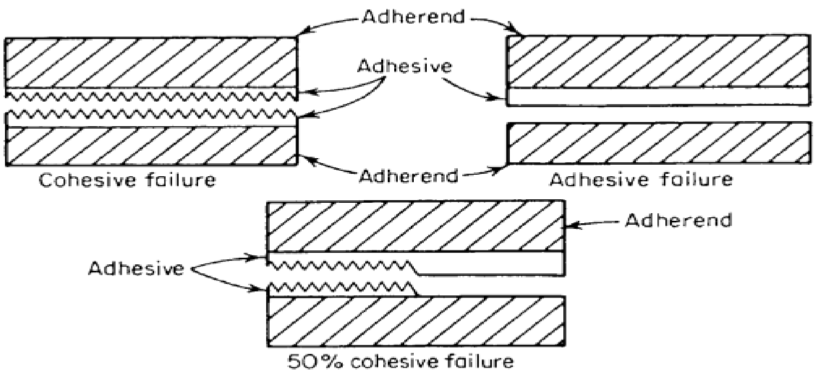

Figure 2: Cohesive and adhesive failure cases [4]

Adhesive Bonding:

Adhesive bonding is a flexible procedure that may be employed to connect various materials, such as magnesium alloys and other metals, by applying an adhesive component through surface attachment, making it appropriate for any shape and size. Smooth surface joints and large-area connections are possible with adhesively joined structures. After sufficient surface preparation, adhesives can be used to link magnesium alloys with other substances such as metal, plastic, ceramics, cork, and rubber. Large stress-bearing surfaces and consistent stress distribution can be achieved using adhesive bonding. Magnesium alloy adhesive bonding requires attention to corrosion difficulties, but it can be protected from the atmosphere by a nonconductive adhesive layer [6].

Adhesive bonding can be divided into two categories: structural and non-structural. It is necessary for structural adhesive bonding to be able to withstand stress without losing integrity within design parameters because the adherends (the materials being joined together) may be subjected to significant stresses up to their yield point in these applications. In addition to possessing a significant resistance to aging, a structural bond has been characterized as having a shear strength of .7 MPa. Non-structural adhesives are only used to hold lightweight components in place; they are not needed to sustain heavy loads. Sometimes, this kind of adhesive is referred to as a "holding adhesive." Non-structural adhesives include things like package adhesives and pressure-sensitive tapes. It might be difficult to tell the difference between structural and non-structural bonds. For instance, is a warm-melt adhesive that is utilized to retain the plies of a fabric structural or non-structural? Such an adhesive may theoretically fall under either category, according to some. Superglues (cyanoacrylates), although having poor resistance to heat and moisture, are still categorized as structural adhesives [3].

1.1.2 Conditions for a Strong Adhesive Bond:

Increasing the adhesive bond's capacity and resilience when it is subjected to service environmental conditions is the goal of any surface treatment process.

However, there are other factors to consider building a strong adhesive bond. The following are the prerequisites for a solid adhesive bond [7]:

- choosing the right adhesive
- excellent joint design
- the condition of the surfaces
- adhering surfaces are wetted before being glued together.

The design of an adhesive joint

An adhesive joint is made up of two substrate surfaces with a space between them that is filled with adhesive material. The adhesive layer is not uniform, though. There are two boundary layers in addition to the portion of the adhesive layer whose characteristics are unaffected by the substrate due to impurities and reaction products at the substrate surfaces. [8]

The adhesive layer's boundary layer is the area next to the substrate surface.

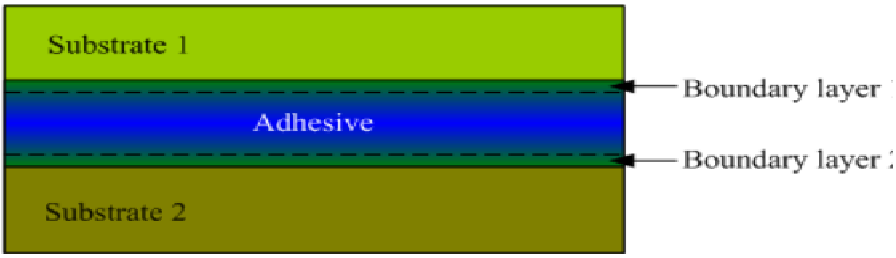

Figure 3: Design of adhesive junction[8]

Glass, epoxies, photoresists, or other polymers can be employed as the intermediate layer in adhesive bonding, based on the substrate components and purposes. Silicon wafers can be thermally bonded using a thin intermediate glass layer. For adhesive bonding, epoxies, UV-curable epoxies, and photoresists can also be utilized. Because of their low process temperature and capability to link various kinds of substrate substances, polymers are suitable as an intermediate layer [9].

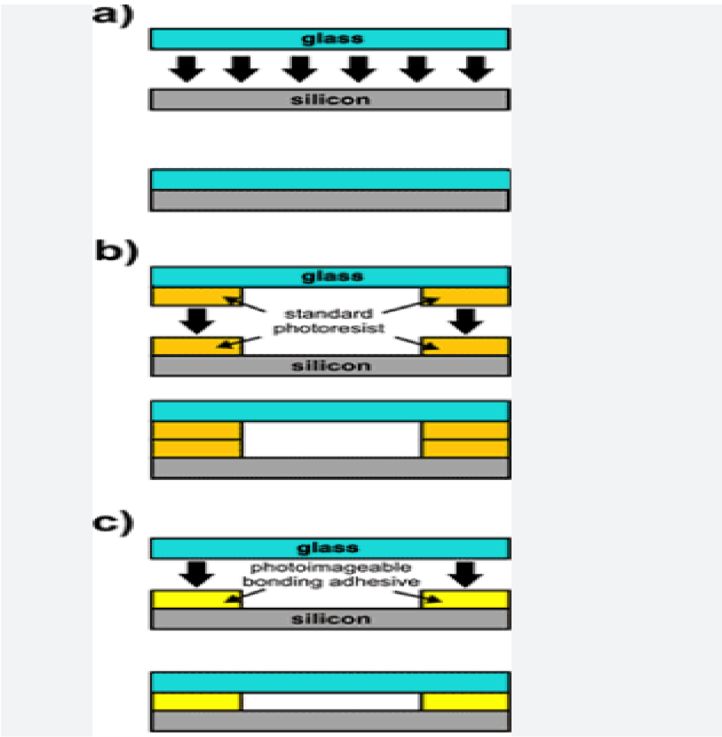

Figure 4: Multiple strategies for silicon/glass bonding: [10].

Due to its many benefits, adhesive bonding is becoming more and more common in the automotive sector. One of these benefits is its capacity to link various materials, such as high-strength steel with aluminium or magnesium panels, without being concerned about temperature distortions, compatibility, or galvanic corrosion difficulties. This capability has made it easier to use lightweight materials in car body structures. Adhesive bonding also has other advantages, such as its strength and durability, which makes it possible to automate at a cheap cost and integrate it into the body-weld manufacturing process. To increase overall rigidity and crash resistance, adhesively bonded constructions are frequently hemmed. Formulations for adhesive bonds can be modified to enhance their functionality and make application easier. Because the adhesive bonding is invisible, it has no detrimental effects on the look or design of the panels and can be applied to Class A surfaces. When compared to fusion welding techniques, it facilitates modular designs, a greater use of platform solutions, and has less of an impact on the body-in-white's overall dimensional conformity [11].

1.1.3 Adhesive bonding breakdown:

There are three potential reasons why an adhesive bonding fail:

1. Internal substrate component breakdown in a location close to the joint is referred to as structural failure.

2. One of the substrates became separated from the adhesive layer due to interfacial failure caused by adhesive failure.
3. Cohesive failure is an interior sticky layer failure.

Cohesion, the internal intermolecular attraction force keeping the material in a unified condition, determines the mechanism of cohesive breakdown [8]

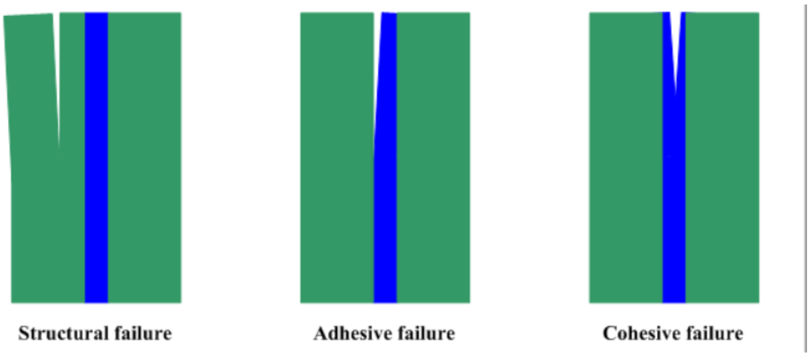

Figure 5: Adhesive bonding break-down process [8].

1.1.4 Adhesive final-use procedures

An adhesive joint's success is influenced by the manufacturing processes that were utilized to create the assembly as well as the adhesive itself. Decisions made in one process segment may have an impact on those made in other process segments as well. For instance, the substrate choice has an impact on the technique used for surface preparation, and the adhesive choice has an impact on the amount of surface preparation necessary. The kind of adhesive that can be used and the kind of substrate that can be taken into consideration for the application depends on the processing tools and time needed. As a result, there are connections between and dependencies among the processes used in adhesive bonding. The user must identify the best processing techniques for the particular application and regularly apply them if they are to produce satisfactory results [4].

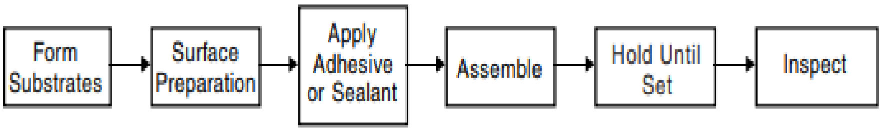

Figure 6: fundamental phases in the adhesive bonding, sealing procedure [4].

1.1.5 Mechanical benefit of Adhesive bonding:

Adhesive bonding offers mechanical advantages over other attachment techniques like welding, brazing, and mechanical fasteners. Adhesives can bond materials with different elastic moduli or coefficients of thermal expansion and resist thermal cycling and crack propagation. Bonded structures are often stronger or on par with structures made using traditional assembly techniques. Adhesive joints offer greater fatigue resistance by dispersing stress evenly throughout the overlap region. Adhesives eliminate the need for holes, which can cause stress concentrations and compromise structural integrity. All things considered, adhesives provide a low-temperature, highly effective, and economical solution for combining materials in the automotive industry [4].

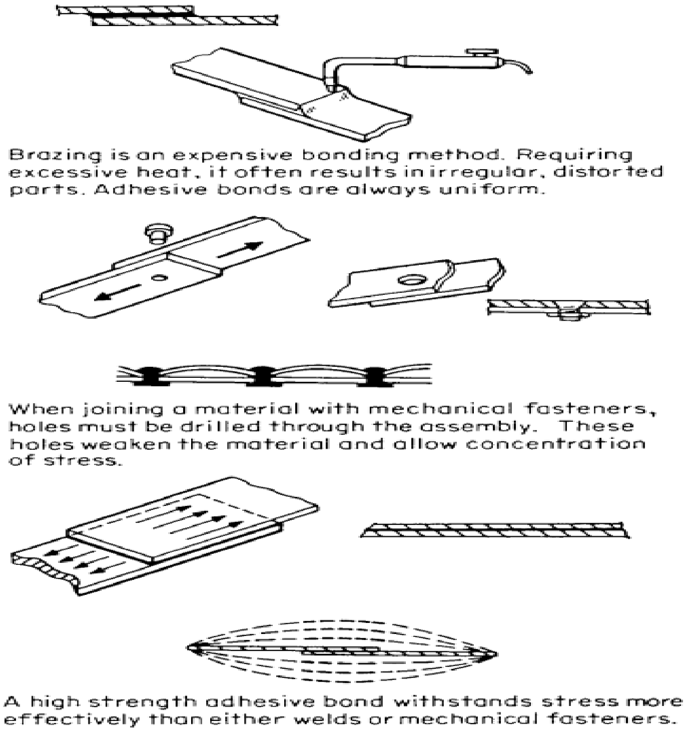

Figure 7: Typical techniques for structural fastening [4].

1.1.6 Economic Advantages of using Adhesive bonding:

Adhesive bonding can be both faster as well as cheaper than traditional fastening techniques when large, bonded regions are needed. The time and labour savings from utilizing adhesives instead of mechanical fasteners rise as the area to be joined expands because the entire joint area can be bonded in a single operation. Although adhesive bonding may be more expensive than other attaching techniques, the overall cost of the finished product may be lower since less material is needed, less weight is added, drilling and welding are not necessary, and the assembly process is made simpler. It might be less expensive to use related production techniques to cure the glue, like a paint-drying oven [4].

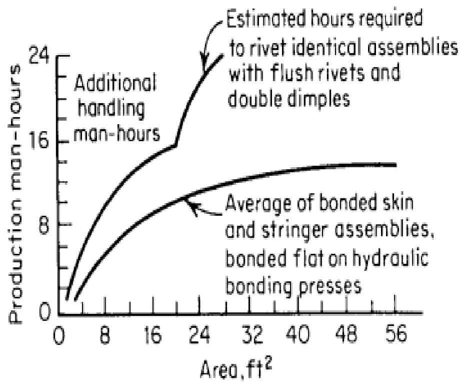

Figure 8: The cost savings of adhesive bonding over traditional rivets [4].

1.1.7 Advantages and disadvantages of adhesive bonding

Advantages:

- Greater stress-bearing surface and uniform stress distribution
- Join components of any shape, whether they are thin or thick.
- join components that are different or similar.
- sustain cyclical loads and wear.
- Offer joints rounded outlines.
- Joints should be sealed against various environments.
- Typically, the heat needed to establish the joint is too small to significantly decrease the strength of the metal components.
- Give a good strength-to-weight ratio.
- cheaper or more quickly formed than mechanical fastening [3].

Disadvantages:

- Unless the adherends are visible, the bond does not allow for a visual inspection of the bond region.
- To achieve permanent bonding, careful surface preparation is necessary, frequently using corrosive chemicals.
- Holding fixtures, presses, ovens, and autoclaves are necessary for adhesive bonding even if they are not often needed for other attaching methods, especially where high cure temperatures are not used.
- Although special adhesives, which are typically more expensive, are only available for limited use up to 371ºC, upper service temperatures are typically confined to 177 ºC or less.
- Most adhesives need strict process control, with an emphasis on cleanliness.
- The surroundings to which the adhesive junction is exposed determine its useful life [3].

1.1.8 The Purpose of using Adhesives.

Adhesives are employed to connect pieces together by distributing stresses more uniformly from one component to another than can be accomplished with mechanical fasteners. Adhesive bonding frequently produces constructions that are less expensive and heavier while being structurally equivalent to or stronger than conventional assembly. When a structure is fastened mechanically, the portions of the components that come into touch with the fasteners are where the structure's strength is restricted. However, it is not that difficult to gain powerful adhesive bonds than those of the strength of adherends [7].

If the appropriate surface treatments are applied, adhesives can be used to join various materials, including plastics, metals, ceramics, cork, rubber, and mixtures of materials. Additionally, conductive adhesives can be formulated. Adhesives also serve another important purpose when working with items made of various substances and exposed to changes in temperatures. In order to avoid damage from rigid fastening systems, flexible adhesives can handle variations in the thermal expansion coefficients of the adherends. [7].

Adhesive bonding is an important process to reduce the amount of stress concentration in small areas in structures and products. In contrast to mechanical attachment systems, this method offers the built-in benefit of having smooth surfaces, which prevent exposed surfaces from degrading and shapes from being altered. This characteristic is crucial for aircraft constructions since they need smooth exteriors to reduce drag and maintain cool temperatures. Adhesive bonding allows for the use of lighter materials because of the joint's consistent stress distribution. Furthermore, adhesive bonding offers significantly broader areas for stress transfer across the part, reducing the distribution of stress in small regions [7].

Another significant purpose of adhesive connecting is sealing. Gases and liquids that won't harm the adhesive (or sealant) remain sealed out by the continuous bond. Solid or cellular gaskets are frequently replaced with adhesives or sealants. Adhesives/sealants can offer mechanical damping that are frequently utilized in place of solid or cellular gaskets. Adhesives that are capable of tolerating cyclic strains and shock loads without cracking can be employed to enhance the fatigue resistance. Adhesive bonds also have the potential to join thin or delicate pieces. Due to the absence of significant stresses on the adherends and the relative absence of heat-induced deformation, adhesive junctions often fail before the adhesive itself [7].

1.2 Types of Adhesives

Adhesives can be categorized in a variety of ways, such as according to their chemical makeup or functionality. They can be divided into two categories: natural and synthetic. Animal glue, casein- and protein-based adhesives, and adhesives made of natural rubber all fall within the natural category. The synthetic group, however, is further broken down into two subcategories: industrial compounds (such as silicones, epoxies, and acrylics) and specialty compounds. The specialty group includes things like pressure-sensitive adhesives [3].

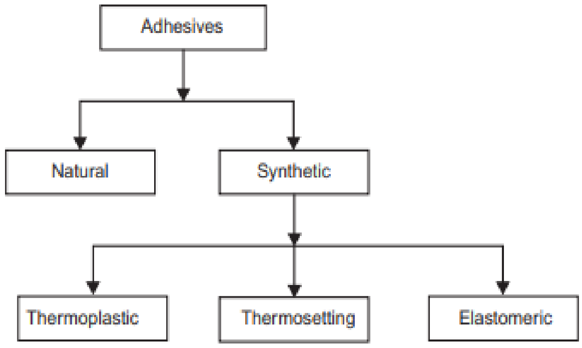

Figure 9: A basic source and polymer classification system [3].

There are many different classification systems for adhesives, frequently with hierarchical levels. Differentiating between adhesives produced from synthetic materials and those generated from natural sources is one general strategy. Natural adhesives are made from naturally occurring materials like animal or agricultural byproducts, whereas synthetic adhesives are often generated using man-made compounds like polymers [4].

There are adhesive systems that are generated from substances that are inorganic, while the majority of adhesives are made of organic polymers. The first adhesives utilized historically were made of natural polymers. Even though they have less strength and processing flexibility than synthetic polymers, naturally occurring adhesives have a large market in certain applications, such as joining paper and wood, where biodegradability or recyclability is desirable. Modern adhesives, such as epoxies, urethanes, acrylics, and other cutting-edge solutions, frequently apply synthetic polymers for demanding structural applications [4].

For practical purposes, classifying adhesives purely as synthetic or naturally occurring is frequently too wide. As a result, the industry has developed several standard classification systems for adhesives, which have a variety of uses. These classes are as following depending on:

- the adhesive's purpose,
- chemical structure,
- its application or reaction process.
- physical characteristics,
- price,
- and intended use. It is significant to notice that these categories and classifications sometimes overlap [4].

1.2.1 Natural vs. Synthetic Adhesives

Adhesives play a crucial role in bonding the coating to the paper or board and pigments in the coating formula, typically constituting 10-20% of the formula. Based on the source**,** there are two types of adhesives: natural and synthetic. The categorization is made on the basis of whether the adhesive is made from natural resources or synthetically from simple hydrocarbons [12].

1.2.2 Natural Adhesives

A variety of materials, including protein and starch, are used as natural adhesives. There are two types of industrial-grade soy protein: unmodified and modified, with varying degrees of hydrolysis and viscosity. Defatted soybean flakes are a source of soy protein. Several substances, such as corn, wheat, potatoes, and waxy maize, are sources of starch, which is a high molecular weight polymer. For specialized uses in coatings, surface sizing, or paper machine processes, starches can be chemically altered. To enable starch's adhesive characteristics, it must be gelatinized, which is accomplished by heating a mixture of starch and water [12].

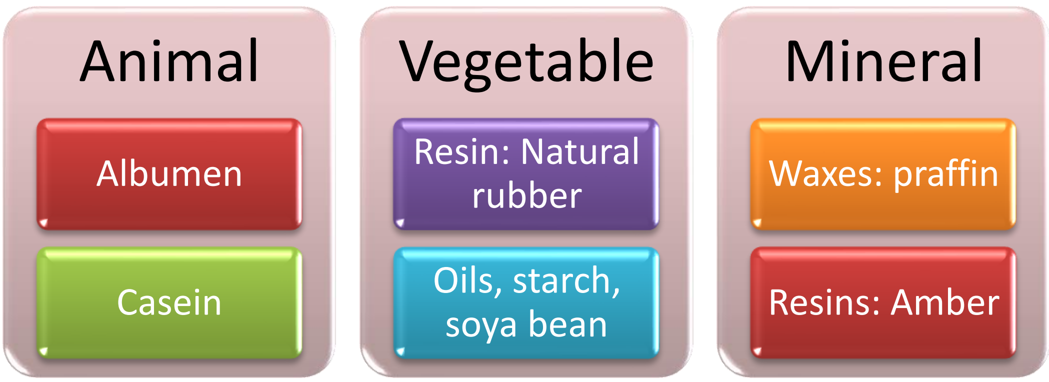

Figure 10: Classification of natural adhesive[7].

Since ancient times, natural adhesives including starch, animal glues, and plant resins have been utilized extensively for packing and bonding wood. The initial use of rubber-based adhesives in the footwear and tire industries occurred near the end of the nineteenth century, however, the development of contemporary structural adhesives is widely credited to the invention of phenol-formaldehyde resins at the beginning of the twentieth century. The performance of natural adhesives has improved during the last four to five decades [7].

Detailed descriptions of various commercial natural adhesives are provided: [10]

Starch and dextrin are polysaccharides that, when hydrolysed, produce long-chain units of glucose, and are obtained from cereals or roots like corn, wheat, tapioca, and sago. For applications like multiwall bags and corrugated paper, these substances are frequently employed in the paper industry. A dry roasted starch called dextrin is used in remoisten able adhesives [3].

Gelatine (Animal, Fish, Vegetable glue) is a substance made up of proteins that are formed through the hydrolysis of collagen, soy flour, or the decomposition of casein from skim milk. It includes animal, fish, and vegetable glues [3].

- In textiles, bookbinding, case-making, gummed tape, and other products, **animal glues** from bones and hides are used.
- Rubber gaskets and paper have been adhered to steel using fish glues made from fish skins.
- **Soya bean glues** are employed in paperbacks,
- **Caseins** made from skim milk are predominantly used in wood bonding.
- **Blood glues** are frequently utilized in plywood and veneering.

Bitumen and asphalt, both heavy in crude oil components, are primarily utilized as sealants instead of adhesives. In order to create waterproof building papers, they serve a purpose in the bonding of coarse-grade papers [3].

Natural rubber is sticky and is derived as latex from the rubber tree. It is utilized in pressure-sensitive applications, tapes, ceramic tile adhesives, and flooring adhesives because it has a high degree of stickiness and tackiness.

1.2.3 Synthetic Adhesives

The expression "Synthetic Adhesive" is typically referred to every kind of adhesives other than natural adhesives (e.g., elastomeric, thermoplastic, thermosetting, and alloys). Synthetic adhesives, as opposed to natural adhesives, are **structural adhesives** [4]. Prepolymers, or polymers, created from petrochemicals, are the basis for synthetic adhesives. To apply these polymers, they must first be melted, dissolved in water, or emulsified in water. The solvent is either eliminated by evaporation or adsorption, or the melted polymer solidifies through cooling as the glue sets. Synthetic adhesives are categorized after solidification according to the type of polymer used.

Synthetic Adhesives	
Thermoplastic**: poly (vinyl acetate), polystyrene, poly (cyanoacrylate)s, poly (vinyl alcohol), polyurethanes, etc.**	**Thermosetting**: amino plastics, phenol-formaldehydes, epoxy-polyamide, poly epoxides, epoxy-bitumen, etc.

Table 1: Classification of Synthetic Adhesives[7]

Polymers known as thermoplastic resins are soluble and soften when heated and solidify when cooled. In this group, PVAc is frequently used as a wood adhesive. EVA is an example of a hot-melt thermoplastic used for wood bonding that has a lower molecular weight and viscosity. Thermosetting resins produce polymers that cross-link throughout the curing process, become insoluble, and do not soften under heat. Amino resins, phenolic resins, epoxy resins, and isocyanates are a few examples of this group [7]. Since elastomeric adhesives have low yield stresses, they are appropriate for detachable and repositionable applications. High fracture toughness is required for stable and semi-structural connections, and it can be attained by creating significant damage zones during debonding. It is necessary to precisely manage the adhesive's viscoelastic characteristics, and different molecular weight fractions—such as high molecular weight fractions or light cross-linking—play distinct parts in this process[7].

1.3 Chemical structure-based categorization

The Synthetic Adhesives can be categorized as **thermosetting, thermoplastic, elastomeric, or alloys (hybrids)** depending on their chemical structure.

1.3.1 Thermosetting adhesives

Thermosetting adhesives are substances that, after curing through an irreversible chemical reaction known as crosslinking, establish insoluble and infusible linkages. These adhesives cannot be continuously heated or softened after they have dried or hardened. Two linear polymers are linked together during the crosslinking process, creating a hard three-dimensional chemical structure. Thermosetting adhesives, which can be purchased in single or multi-part solutions, include epoxy and urethane adhesives. These adhesives exhibit negligible elastic deformation under load at high temperatures and are resistant to heat and solvents. Structural adhesives are frequently made with polymeric resins with thermosetting molecular structures to ensure strong bonding [4].

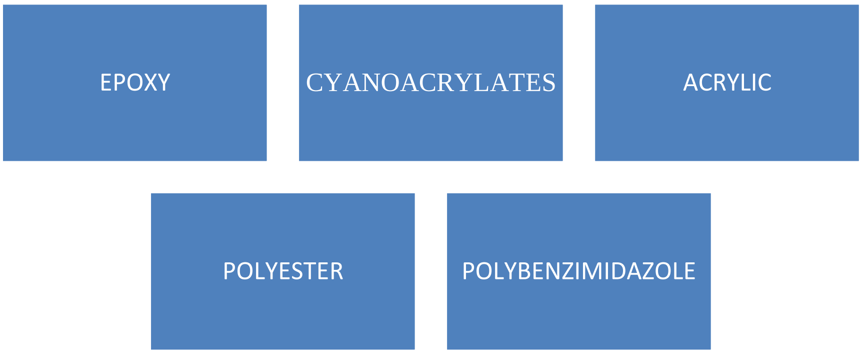

Figure 11: Major Thermosetting Adhesives [3]

1.3.2 Thermoplastic

Thermoplastic adhesives are adhesives that do not cure and are categorized into three types. When applied to substrates, hot melts like EVA must first be heated to a liquid condition because they are solid at ambient temperature. When contact adhesives are applied, such as rubber cement, the solvent evaporates before the coated substrates are joined. In the same way that unreacted acrylic monomers are applied to one substrate, usually a flexible substrate known as the backing, pressure-sensitive adhesives (PSAs) are applied to another substrate to produce the tape. The PSA then interacts with the surface through secondary chemical interactions to form a connection, and the tape is then adhered to another surface by applying pressure. The composition of thermoplastic adhesives can be changed to customize their characteristics. Thermoplastic adhesives are frequently utilized in tapes and labels and are frequently employed in applications where a temporary or semi-permanent binding is required. They are typically not as strong or long-lasting as thermosetting adhesives, which go through a chemical curing process to provide a more robust connection [13].

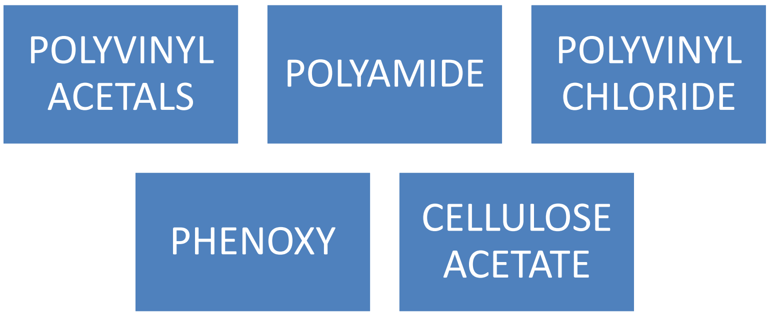

Figure 12: Major Thermoplastic Adhesives [3]

1.3.3 Elastomeric Adhesives

Elastomeric adhesives, which are often made of rubber-based materials (natural or synthetic), have good peel strength but poor shear strength. With the exception of silicone, which has great temperature resistance, they are resilient and offer strong fatigue and impact qualities, but their application is often restricted to temperatures between 66 and 93 °C. Elastomeric adhesives are offered as pressure-sensitive tapes, latex, types of cement, and solvent-based solutions. Prior to bonding, the solvent must be removed from latex cement and solvent solutions, whereas rubber-based adhesives that are stronger or more ecologically friendly may require an elevated-temperature cure. Pressure-sensitive adhesives offer close contact with the adherend surface while just requiring a little pressure to bond. Neoprene and recycled rubber mastics, for example, are made of elastomers and are used in the construction industry to connect plywood and gypsum board floors to wood framing components. Due to the requirement for antioxidants and tackifiers, the elastomer-adhesive composition is complicated [13].

Figure 13: Major Elastomeric Adhesives [3]

1.3.4 Hybrid Adhesives (Adhesive alloys)

Adhesive alloys are created by mixing resins from various chemical classes, such as thermosetting, thermoplastic, or elastomeric. The second resin's toughness and flexibility combine with the thermosetting resin's high strength to increase the alloy's impact resistance. These adhesives are offered as films and solvent-based solutions and make the most of each component's greatest qualities. Since the majority of alloy adhesives are solvent-based dispersions or 100% solids, curing is normally accomplished using heat and pressure. They are often stronger over greater temperature ranges than other adhesives and have a well-balanced combination of characteristics. When the toughest end-use requirements must be met, regardless of cost, adhesive alloys are employed in military applications and are suited for structural applications [3].

Figure 14: Major Alloy Adhesives [3]

According to me, in general, both natural and synthetic adhesives have their benefits and uses, but synthetic adhesives are typically seen to be better suited for the automotive sector. This is due to the fact that synthetic adhesives, especially thermosetting adhesives, provide more substantial and longer-lasting bonding, which is crucial in automobile applications. Thus, my research will be conducted mainly with cyanoacrylates adhesives (Loctite 402 and 408) which is a kind of thermosetting adhesives.

At high-temperature conditions, synthetic adhesives like epoxy and urethane adhesives exhibit negligible elastic deformation under stress and are heat- and solvent-resistant. They are therefore perfect for the demanding circumstances encountered in the automotive industry. In addition, thermosetting adhesives go through a chemical curing process, producing a stronger and more durable bond.

Although the performance of natural adhesives has improved over time, they still frequently fall short of the strength, toughness, and heat resistance needed for automotive applications. As a result of their higher performance qualities and capacity to satisfy the industry's high demands, synthetic adhesives are favored in automotive manufacturing.

Few More categorization and their examples depending on various factor are discussed below:

Depending on function: **Structural adhesives and Non-Structural**. It will be discussed later.

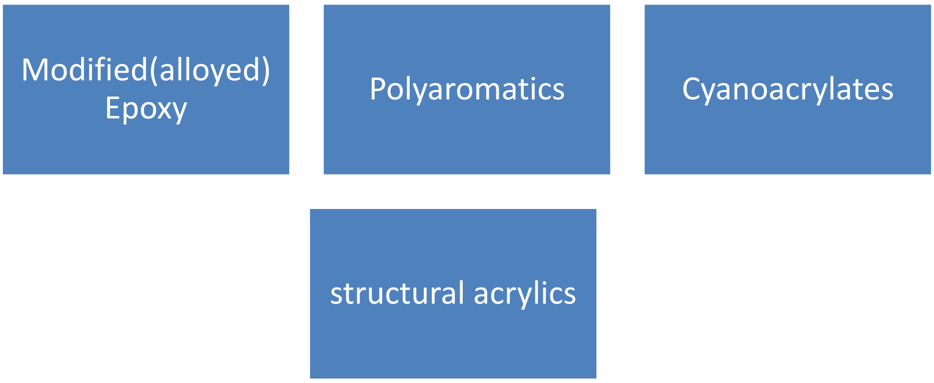

Figure 15: Stuctural Adhesives [14]

Figure 16: non-structural Adhesive [14]

2 Application of Adhesives in Automotive Industry

2.1 Inroducing Adhesives in the Automotive Industry

Adhesives have been used in the automotive sector for almost as long as the industry itself. Earlier bonding agents composed of wood and canvas have been superseded by formulas that are able to connect to a number of materials, including metal, glass, plastic, rubber, and a wide range of fabrics. In the automotive sector, adhesives are utilized for **structural, holding, and sealing** applications. Automotive adhesives have improved in sophistication and capability over the past 20 years as a result of the necessity to join novel components that are corrosion- and weight-resistant while also taking into account cost and health issues. Higher consumption of plastics and galvanized steel, the robotic application of adhesives and sealants, nondestructive testing, and statistical quality control methods are a few significant industry trends [15].

Additionally, adhesives help automakers streamline their assembling procedures. Bonded parts don't require drilling or punching holes, and assemblers don't need to measure torque or double-check fastening procedures. Eliminating fasteners also reduces the weight of the car, which is an important factor for automakers looking to enhance fuel efficiency. According to one estimate, 200 pounds of mechanical fasteners can be replaced with 70 pounds of adhesive [16].

2.1.1 Specifications/Requirements for automotive application

Automotive adhesives are required to follow a number of specifications that are mostly unrelated to joint performance. They must be functional in the following circumstances: [15]

- a workforce that is primarily unskilled and frequently has a high turnover rate.
- High manufacturing rates, with short, constant periods between operations (some lines are built to handle 100 automobiles per hour).
- Only little cleaning of surfaces that could become contaminated overnight or over time.
- Lack of tolerance for risks to one's health and safety.
- The adhesives also need to be free of complex measurement and mixing procedures and have variable cure times, pressures, and temperatures that may be used with paint bake schedules or low material heat distortion temperatures.
- A desire to avoid difficult weighing and combining.

Once these prerequisites have been accomplished and the joint has been created, adhesive bonding must continue to hold under challenging circumstances for the whole life of the car. A modern automobile is intended to perform from -40°C to over 90°C , withstand exposure to fluctuating temperatures, sea water, fuel, oil, high humidity, vibration, impact, detergents, and dust. No other mass-produced product comes close to matching the complexity of a modern automotive. It is a true testament to the automotive and adhesives industries that adhesives have been able to achieve these requirements and do so with durability throughout the life of the car [15].

As we have discussed above that **structural adhesives** are mostly utilized in transportation, industrial assembly thus the application of its is discussed below:

2.2 Application of Structural Adhesives in Automotive Industry

Basic Ideas of Structural Adhesives:

Structural adhesives refer to those kind of adhesives that can carry decent-sized mechanical loads and are often made of thermosetting substances like epoxies, phenolics, polyurethanes, cyanoacrylate, polyesters, or certain plastisols. They essentially act as a "high-strength glue," that joins the constituent parts of a load-bearing structure. These adhesives are frequently the sole accessible, reasonably priced means of structural assembly and are used to decrease stress concentrations, produce smooth curves, and boost service life or performance. The structural adhesives used may be changed in accordance with the supplier's or user's requests, as shown in Table 1 [15].

2.2.1 Uses of Structual Adhesives

One of the first applications of structural adhesives in the automotive industry was to join the inner and outer sections of hoods to prevent "oil canning" or fluttering at high speeds, which can be fixed by adding an inner reinforcing element. To minimize unattractive weld traces on the hood, the interior parts are adhesively attached with plastisol adhesive in "Hershey drops." Plastisols are not thermosetting, but they can still be used as structural adhesives since they can attach huge regions with small forces, withstand no peel or cleavage stress, and have cyclic rather than static tensile loads, which eliminates the importance of the cold flow problem [15].

Epoxies are frequently used in the automotive sector to join body panels for cars and trucks. The four-second induction heat cycle is used to quickly set these adhesives, and the paint oven is used for the final curing step. Plastisol adhesive is effectively used to enable the double shell method of roof building, which requires fewer metal stampings than conventional welded assembly. This glue produces a durable, vibration-free structure with little surface preparation and flexibility in bond line thickness [15].

Application	Resin/Adhesive	Comments
Disc Brake pads.	phenolic urethane,	Heat resistant
FRP body panels (for trucks and sports cars)	Polyester	used over twenty-five years
PVC bumpers	Urethanes	improves performance
Atomizer (Radiator)tanks	Epoxy	replaces solder

Table 2: Typical Automotive Structural Adhesive Usage [15].

2.2.2 Growth of usage of structural adhesive

According to Frank Billotto, an expert in adhesives and the Americas Strategic Market Manager for DuPont Transportation & Industrial, structural adhesive usage in automobiles has grown dramatically. In comparison to 2014, when 69 meters of adhesive were used on average per car, 90 meters were used on average in 2019. Anywhere there is a structural connecting with a weld or rivet, such as on the body-in-white or closure panels, the adhesive can be placed. The capacity of structural adhesives to combine various materials, such as steel, aluminum, magnesium, composites, polymers, and glass, is one of their amazing qualities. It's important to note that the Dow adhesives portfolio has been incorporated under DuPont Transportation and Industrial [17].

Can Welding be Avoided?

When questioned if structural adhesives could substitute conventional welding, Frank Billotto responds that it would be extremely difficult due to the curing time needed for adhesives, whether by chemical curing at ambient temperature or warming for curing and bonding. The BMW i3 composite substructure, which uses a two-component adhesive without welds or fasteners, serves as an example of how structural adhesives can be utilized alone in some circumstances. In this instance, the glue is placed and infrared heat-staked selectively to fast increase strength [17].

Non- Structural Adhesives:

Non-structural adhesives are employed to temporarily join objects or to glue lightweight components with lower stress levels together. They are made to support stresses less than 1000 psi. They are frequently used to hold substrates in place before fastening them with bolts or screws because they are not designed for bearing heavy loads. Non-structural adhesives are also employed for veneers, trim, gaskets, and light-duty packing. They are frequently produced from rubber, acrylic, or hot-melt adhesives and are primarily one-part, solvent-based polymers that are sticky. In certain situations, tape or film forms may also be employed [18].

The benefit of structural adhesive:

Because of their tremendous strength, structural adhesives are frequently employed for long-term, permanent connection. Structural adhesives are used by the automotive, aircraft, consumer appliance, construction, electronics, medical device production, and other industries, primarily as a substitute for mechanical fasteners.

Features consist of:

- reduced weight and size of the assembly
- less components per assembly
- the capacity to combine disparate materials
- Easily fill up spaces between substrates to prevent exposure to the environment
- ability to adapt to automated operations
- Gains in productivity from fast-setting formulas
- A more attractive design
- Low price

Therefore, Structural adhesives are more frequently applied in the automotive industry than non-structural adhesives. This is due to the fact that structural adhesives may connect materials with high-strength needs, such as metals, composites, and polymers because they have a higher load-carrying capacity. Additionally, they can be utilized in place of welding, a more difficult option when working with mixed materials or intricate geometries. Additionally advantageous are structural adhesives' enhanced crashworthiness, less weight, and decreased noise and vibration (NVH). Non-structural adhesives are used for lighter-duty applications, which are less frequent in the automobile sector, despite the fact that they offer their own benefits such as ease of use and affordability [18].

2.3 Adhesive Bonding Technology in Automotive Industry

Adhesive joints and adhesive bonds are terms used to describe an assembly created using an adhesive. The mechanical characteristics of the adherends and adhesive play a major role in determining the actual strength of an adhesive junction. Practical adhesion is the phrase we use to describe the quantified physical strength of an adhesive connection [19].

Reasons of using Adhesive Bonding in Automotive Industry:

In comparison to welding, which might be challenging, adhesive bonding can be an easier alternative when joining different substances like steel and aluminum. The adhesive is a better choice because it creates a corrosion barrier because fastening these materials together can cause galvanic corrosion at the interface. The Polestar 1's body is bonded together with about 50 meters of glue, which reduces mass and lessens noise, vibration, and harshness (NVH). The body of the TX5 cab from the London EV Company is made of bonded aluminum, with the chassis, brackets, posts, roof, fixed glass, and SMC body panels all adhering together [17].

In addition, adhesive bonding is a valuable technique for combining particular substances because it enables the assembly of shock-sensitive materials without the application of mechanical force. However, adhesion, a surface phenomenon that is influenced by the condition of the adherend's surface, is what is necessary for load transmission in adhesive bonding. Due to this, joint strengths may be less than those expected by the mechanical characteristics of the adhesive and adherend. In comparison to mechanical fastening, adhesive bonding provides benefits including the capacity to seal the assembly in a single step and the ability to allow materials that are galvanically incompatible to adhere without causing corrosion. Since polymeric adhesives are non-ionic and electrical insulators, a strong adhesive bond can unite two galvanic couple members physically while electrically separating them [19].

Welded Joint	Adhesive Bond
Permanent	Permanent (with proper surface preparation)
Local stress points	Predominantly uniform stress distribution
Joints often have to be “dressed” for aesthetics	No surface markings
Useful only for identical materials	Dissimilar materials are easily joined
High temperature resistance	Low to moderate temperature resistance
Poor fatigue resistance	Excellent fatigue resistance

Figure 17:Welded Joints vs. Adhesive Bonds [19].

2.3.1 Structural Adhesive bonded joints

The variables that influence the reliability of adhesive joints include adhesion properties the thickness of the adherent the design of the adhesive joint the shape and size of the adherend and the adhesive the surface preparation of the adhesive and adherend and operating and service conditions composite parts are joined by a number of joint configurations shown in fig 20 including scarf joints butt joints single and double strap joints stepped lap and single double and tapered lap joints those adhesive joints to be designed for high load transfer must be properly considered taking into account the factors discussed earlier in this section. [20]

Adhesives are widely used in the vehicle industry, as illustrated in Figure 22, which depicts the numerous places where adhesives are used. For instance, the stiffener and top panel of a vehicle hood are attached with anti-flutter adhesive, allowing the hood to maintain its shape even when subjected to severe loads and wind shear. In more recent cars, the windshield is affixed to the frame with adhesives, and the doors are attached with adhesives using the hem-flange assembly method. Adhesive bonding is used to reduce noise and vibration in the vehicle chassis, together with spot welding (sometimes referred to as "weld-bonding"). The potential weight reductions of adhesive bonding are a significant factor for its expanding application in vehicle technology [19].

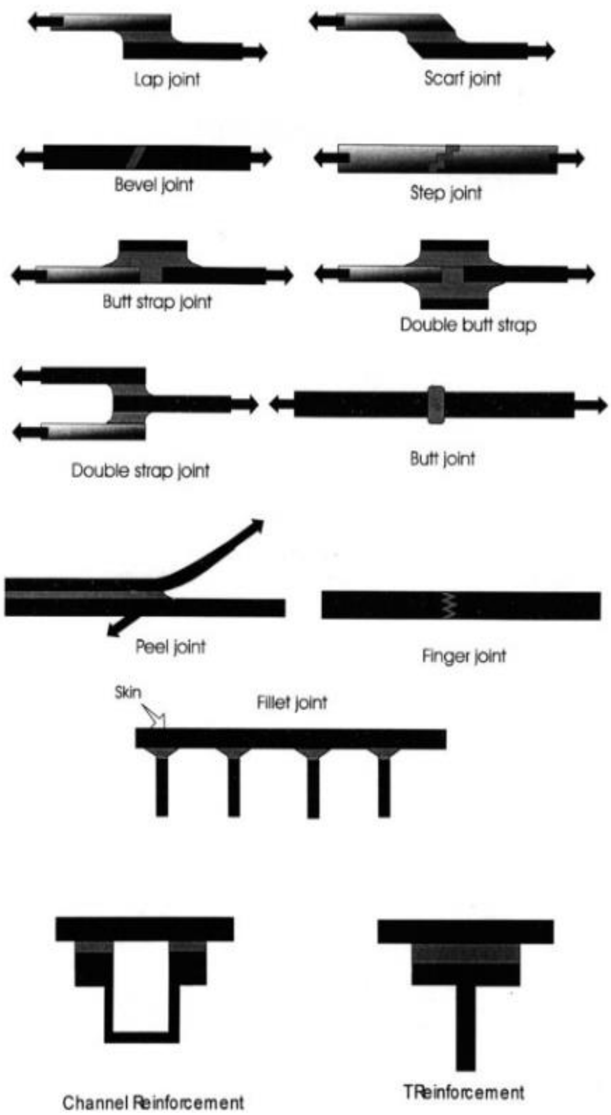

Figure 18: regular bonds present in composite structures [20].

A joint consists of two parts:

1. **the substrate—adherent:** The adherent might break in a junction with optimum strength in metal joints, however, exposure to moisture can weaken either the adhesive or the adherent. Due to the similarities between the adhering and adhesive in composites, it is more challenging to forecast the locus of failure, and failure frequently begins in the substrate [20].
2. **The Adhesive**: Typically, a thermosetting polymer—which can be made tougher by adding rubber particles or a thermoplastic polymer—serves as the adhesive in an adhesive joint. The intended application determines which adhesive should be used [20].

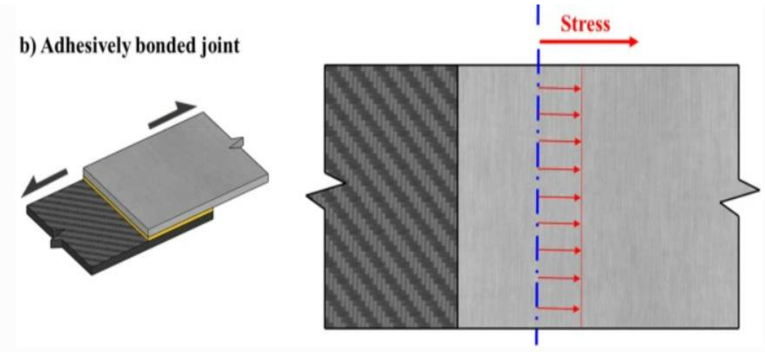

Figure 19: Adhesive bonded joint and its stress distribution [21].

2.3.2 Application of Testing of Adhesive Bond Strength [3]

Every area of materials science and engineering requires testing, but adhesives require testing above all else. These tests assess the adhesive's inherent strength, the bonding method, surface cleanliness, curing cycle etc.

Adhesive tests are conducted for multiple purposes. Such as: Evaluation of characteristics (such as durability, environmental resistance, conductivity, tensile, shear, peel strength etc.) Examinig the quality of each batch of adhesives to ensure that they still meet standards Observing the impact of surface and/or other preparation. Anticipation of performance for identification of parameters that can be applicable. Such as, cure conditions, drying conditions, bond-line thickness, etc.

Adhesive Bonding Strength is measured using various tests. However, based on my experiment, Tensile and Shear strength test are discussed here.

Tensile Test

Tensile test is one of the most common tests applied for evaluating adhesives. In Pure tensile tests the load is applied normal to the bond line's plane and aligned with the center of the bond regions. Here, Tensile strength is determined by pulling apart two sample substrates that are joined with the adhesive. [1]

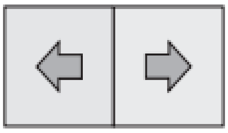

Figure 20: Tension applied to material [3]

Tensile strength is measured by including the adhesive's peak tension force and dividing it by the adhesive's cross-sectional area. The result is the adhesive's maximum tension force that it can withstand. This estimation is commonly used for adhesive strength and expresses how well the adhesive can withstand loads under stress without breaking. [1]

Shear Test [3]

Shear tests are frequently performed because the samples are easily constructed and closely resemble the geometry and operating conditions of a wide range of structural adhesives. Pure shear stresses are applied in its plane and parallel to the bond. Despite being useful and reasonably easy to prepare, single-lap shear specimens cannot accurately represent pure shear. However, they can be used in the test to determine the strength of the adhesive easily. [1]

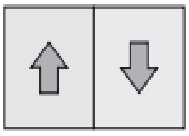

Figure 21: Shear stress in the joint [3]

Shear strength can be determined by sliding and pulling two sample substrates bonded together (making a single lap joint) with adhesive in opposite directions. The shear strength of the adhesive is then calculated by dividing the maximum shear force that is sustained prior to failure by its cross sectional area.

2.3.3 Importance of Adhesive Strength Testing

While analyzing an adhesive solution, finding its strength through one of the testing is one of the key factors to focus on. To make an informed decision about whether an adhesive is "strong" or not, it is essential to understand adhesive strength. To achieve that, we must stop referring to adhesives as "strong" and instead use the term "strong enough." [22]

This is because adhesive strength can describe the adhesive's capacity to maintain the position of the substrate. Two things will determine this ability:

1. The amount of force it must bear.
2. The area that can be bonded.

Testing and determining adhesive strength are crucial for quality assurance. This is for not only to follow industry standards but as well as customer specifications. One of the most crucial elements of a successful bond is adhesive strength. The physical stability of the product is greatly dependent on the adhesive strength of the bonded materials in numerous industrial applications.[22]

For instance, adhesives are used by manufacturers in the aerospace sector to join the various parts of an aircraft. For operations to be safe, these bonds must be strong. Similarly, adhesives are utilized by manufacturers in the automotive industry for a variety of purposes. There are two typical applications: bonding body panels and windshield glass. [22]

On the other hand, Adhesion failures can be financially expensive and potentially damage a company's reputation. During the design process, adhesive bond strength evaluation and other inspections can help prevent these problems.

In conclusion, the adhesive strength plays a crucial role in maintaining a strong bond due to which adhesive strength testing becomes an important element of quality assurance and product in the automotive industry due to its simple experimental procedure and low-cost and the other important environmental factors. in some applications, strong bonds are essential to life safety. [22]

3 Materials and Methods

3.1 Slection of Material

The selection of appropriate materials is crucial for the success of any engineering As my research focuses on examining the tensile strength of adhesive bonds the choice of suitable materials is essential for the success of any engineering application especially in adhesive bonding processes where the relationship between the substrate material and the adhesive is critical. Here, rigid aluminum alloys are the selected material for the substrate.

Figure 22: selection of rigid alloy material

3.1.1 Properties of Alloys

As we've described, a crucial component of automotive engineering that ensures the safety and structural integrity of automobiles is adhesive bonding strength. To accurately measure the adhesive bonding strength, the specimens must be made of appropriate materials. This chapter explains why aluminum alloys were chosen for automotive applications over steel while testing adhesive bonding strength. The properties listed below illustrate the advantages of aluminum alloys.

Reduced Density: The density of aluminum alloys is **2.7 g/cm3**, while that of steel is 7.87 g/cm3. This allows for a considerable reduction in weight for vehicle components.

Better Thermal Conductivity: The increased thermal conductivity of Aluminum alloys makes them appropriate for use in heat exchanger applications, which helps automobiles manage their temperature more effectively.

Properties Relevant to Adhesive Bonding Strength

Aluminum alloys have several characteristics that are essential for testing adhesive bonding strength and provide flexibility in manufacturing and design procedures. The yield strength of aluminum alloys typically falls **between 100 to 400 MPa.** This means that even under intense impact conditions, aluminum remains steadfast and doesn't buckle under pressure.

Design characteristics: When it comes to material selection for engineering applications, the modulus of a material plays an important role in determining its suitability for a specific use case. In the case of aluminum and steel, the modulus of aluminum is significantly lower than that of steel, coming in at 70 GPa compared to 207 GPa, respectively.

Because of this modulus difference, an aluminum component must be 43.5% thicker than a steel component to have the same bending stiffness. This difference means that in order to achieve equal bending stiffness, an aluminum component will need to be 43.5% thicker than the steel. While aluminum is lighter than steel, the weight reduction achieved by using aluminum will not be directly proportional to the density ratio between the two materials. Practically, this means that substituting a steel body panel with an aluminum one will result in almost a 50% weight saving. This weight saving can have significant implications for industries improve fuel efficiency, reduce emissions, or increase payload capacity.

Joining Methods: When it comes to joining techniques for aluminum alloys, adhesive bonding stands out as a crucial method worth considering, especially in the realm of automotive applications. The strength of adhesive bonding plays a key role in ensuring the structural integrity of components.

Surface Characteristics: Aluminum alloys have good surface energy and roughness characteristics, making their surfaces ideal for adhesive bonding. These characteristics enable the adhesive and alloy substrate to form strong and long-lasting bonds, offering the best possible adhesion and bond strength.

Additionally, a remarkable **resistance to corrosion** is observed in aluminium alloys. There are other variety of properties that made aluminium superior than the other materials for specimen perparation while bonding with adhesives.

In summary, the choice to employ aluminum alloys in the adhesive tensile test experiment was made after giving careful thought to their special qualities, which will help us determine their effectiveness in a variety of situations. These alloys have been chosen because they are suitable for applications involving adhesive bonding, which shows how innovative they can be in the engineering and automotive sectors. The investigation of aluminum alloys in this work represents an important step toward expanding our understanding and optimizing the adhesive bonding procedures for improved outcomes and developments across a range of industries. [23] [24]

3.2 Selection of Adhesives

3.2.1 Cyanoacrylates Adhesives

As we previously discussed, cyanoacrylates are one kind of structural adhesive. They are commonly referred to as instant adhesives or super glues due to their ability to cure quickly at room temperature. To initiate and begin the polymer reaction, cyanoacrylate adhesives require surface moisture. The rate of reaction decreases with decreasing humidity on the surface of the bonded material. Lower temperatures also cause a slowdown in reaction and curing. All adhesive curing speed parameters are measured at 21°C, every adhesive curing speed parameter is measured. Loctite 402 and Loctite 408 are the adhesives I've selected for my experiments. [25] [26]

Figure 23: selected adhesives

Charecteristics:

For my experiment, I decided to use cyanoacrylate adhesive to bond the alloy specimens for the following reasons: [25] [26]

High Joint Strength: Cyanoacrylate adhesives, such as Loctite's Super Bonder 400 series instant adhesive, generate extremely strong joints while bonding alloys to one another and other materials. This implies that strong, long-lasting bonds can be formed using cyanoacrylate adhesives. For example, the adhesives Loctite 402 and 408 are made to provide strong tensile bonding between rigid components. This shows that they can withstand pulling forces, which is crucial for automotive parts that must withstand tensile loads while being used.

Rapid Cure Time: Cyanoacrylate adhesives cure fast at room temperature, this usually takes 30s to 2 minutes for metals and plastics. Due to the adhesive-bonded alloy specimens' quick curing time, testing and analysis can be completed effectively, which gives me access to the results in time for my thesis research.

Wide Compatibility: Adhesives made of cyanoacrylate work well on a variety of surfaces, including rubber, wood, plastic, and metal. This compatibility is useful when bonding specimens made of alloys because it ensures that the adhesive will be able to successfully bind the alloy surfaces together, increasing the overall tensile strength of the joints.

Minimal Shrinkage: Cyanoacrylate adhesives exhibit minimal shrinkage during curing, leading to uniform bond lines and a reduced probability of stress concentrations affecting tensile strength. Because it confirms that the adhesive bonds will stay strong and intact over time that has a positive impact on my work.

Ease of Application: Cyanoacrylate adhesives are suitable for my thesis experiments because they are simple to use and require little surface preparation.

All the above properties of the adhesives with their simplicity of application allow us to concentrate on testing and analyzing the adhesive-bonded alloy specimens. Thus, Loctite 402 and 408 adhesives were selected for my research.

3.2.2 Loctite 402

LOCTITE 402, the newest product that Henkel has developed is a combination of ethyl and allyl cyanoacrylate monomers. Its patented technology allows it to perform better than standard ethyl cyanoacrylates. This instant adhesive offers exceptional performance at elevated temperatures, combining rapid curing and stability and enhanced environmental durability. [27] [28]

As demonstrated in Table 2, LOCTITE 402 exhibits rapid fixture speed on a variety of substrates, including metals, polymers, rubbers, and porous materials like paper and wood.

Component	Loctite 402
Mild Steel	< 5 s
Aluminum	< 5 s
Stainless Steel	30 to 45 s
PVC	10 to 20 s
Paper	5 to 20 s

Table 3: Fixture Speed of LOCTITE 402[27]

LOCTITE 402 provides high bond strength and also has excellent **lap shear strength** on all plastics tested on a wide range of metals and plastics (see Figure 27).

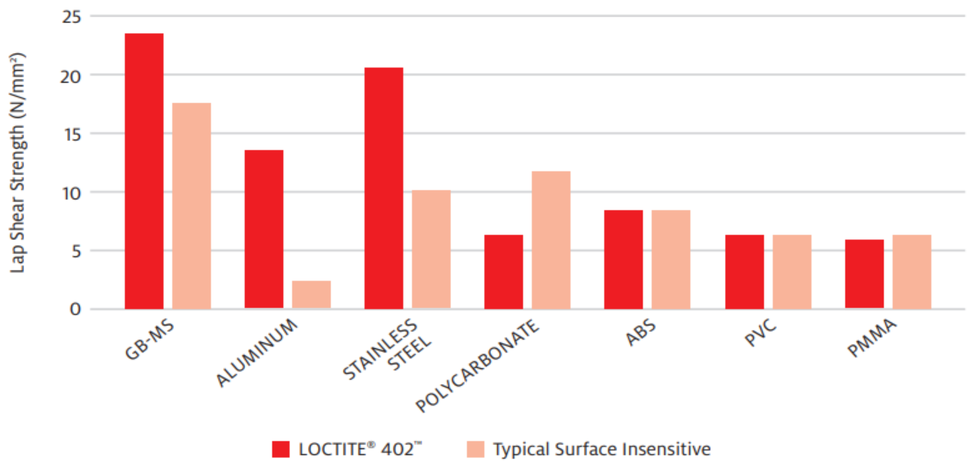

Figure 24:Lap shear strength of LOCTITE 402[28]

The product's fundamental properties are provided in Table No. 3 (LOCTITE 402). [27]

Technology	**Cyanoacrylate**
Chemical Type	Ethyl / allyl Cyanoacrylate
Method of Curing	Humidity
Appearance (uncured)	Transparent, colorless
Specific Gravity (at 22°C)	1.1
Viscosity (at 25°C)	(Low) 110 mPa·s (millipascal-second)
Curing Speed (at 23°C / 50% relative humidity)	Aluminum: 5 seconds
Curing time	Relatively short, at least 24 hours
(Cured for 72 hours @ 23°C) Tensile Lap Shear Strength ISO 4587 (Aluminum)	20 N/mm2/ (2,900 psi)

Table 4:Technical data of LOCTITE 402 adhesive[27]

3.2.3 LOCTITE 408

LOCTITE 408 is especially well-suited for applications where vapor control is challenging because of its low odor and low blooming characteristics. This product is useful for quick bonding of a variety of materials, such as elastomers, metals, and polymers. [29]

According to Table 4, LOCTITE 408 exhibits quick fixture speed on a variety of substrates, including metals, polymers, rubbers, and porous materials like paper and wood.

Material	Loctite 402
Steel	20-30 s
Aluminum	< 5 s
Wood (pine)	10 to 20 s
PVC	30 to 45 s
Paper	< 5 s

Table 5:Fixture Speed of LOCTITE 408 [29]

Table No. 5 shows the important properties of the product (LOCTITE 408).

Technology	Cyanoacrylate
Chemical Type	Alkoxyethyl Cyanoacrylate
Method of Curing	Humidity
Appearance (uncured)	Transparent, colorless
Density (at 25°C)	1.1 g/cm³
Viscosity (at 25°C)	(Low) Cone & Plate: 4 to 10 mPa·s (millipascal-second)
Curing Speed (at 23°C / 50% relative humidity)	Aluminum: <5 seconds
Curing time	Relatively short, at least 24 hours
Tensile Lap Shear Strength (Cured for 72 hours @ 22°C) ISO 4587 (Aluminum)	17.3 N/mm² (2500 psi)

Table 6:Technical data of LOCTITE 408 adhesive [29]

3.3 Equimpment used for Tensile strength Experiment:

I utilized a Universal Testing Instron 6800 series for my research due to its reliability, accuracy, compatibility, and ease of use. These devices are renowned for their adaptability and ability to carry out a wide variety of mechanical tests, such as tests of tensile strength after adhesive bonding. Because of these qualities, adhesive bonding processes and product performance can be enhanced by manufacturers, engineers, and researchers using them as necessary resources.

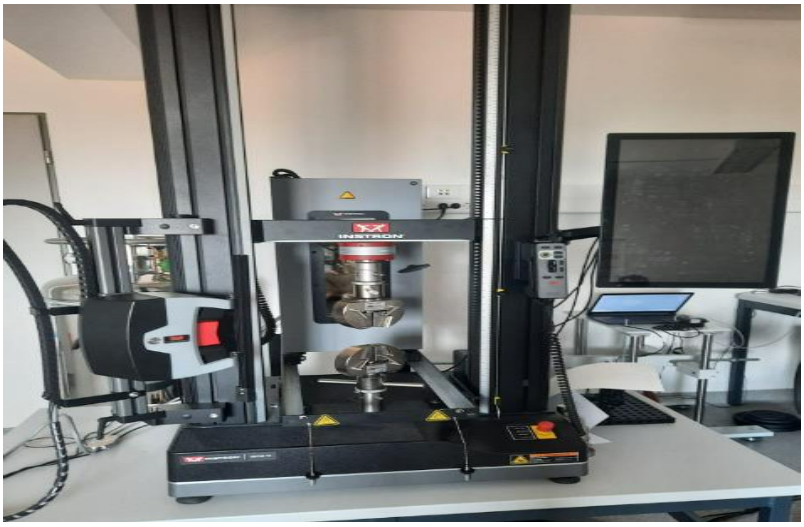

Figure 25:Instron 6800 for tensile strength experiment

3.3.1 Shear Testing in Tension with single lap joint:

After the specimen is created using a single lap joint (SLJ) due to its manufacturing simplicity, the tensile lap-shear test will be conducted to find out the strength of bonds using the Instron machine.

This single lap joint has been extensively researched in the literature, both theoretically and experimentally. The single-lap test has the following benefits: it is easy to use, inexpensive, and can be conducted with a standard tensile testing apparatus, where a bunch of data is available for comparison.

In this kind of joint, combined tensile and shear stress typically occur. In this case, the entire bonded surface experiences an uneven stress distribution. Adhesive deformation is caused by adhesive layer thickness, because of non-uniform deformation. Maximum stress is generated at the ends of the lap, which are the most deformed, which is shown in figure 27. This leads to an approximate hyperbolic stress distribution over the entire lapping length. [30][31]

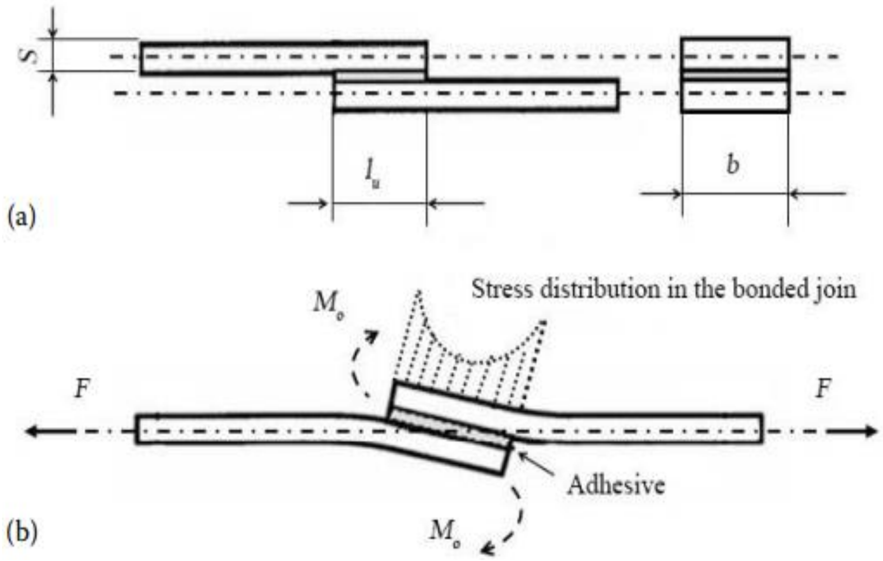

Figure 26: Single Lap joint structure and stress distribution after load[2]

The results demonstrated that, as the adhesive layer thickness increased, it also raised the bending moment. As a result, the adhesive bond strength is decreased.

In addition to increased bonded material strength and thickness, different construction arrangements can also help reduce the stress level caused by the bending moment. As a result, the bonded lap joint design needs to be modified according to the bonding technology for which we are going to follow the dimensions provided by ISO 4583 for the better strength result.

After proper selection, I will use the Instron machine to perform lap shear testing for my experiment.

One common method for evaluating adhesives is lap shear testing, also known as shear testing in tension. A material specimen is pulled apart when tensile force is applied from opposite sides in a parallel plane, stressing the material in a sliding motion. Lap shear tests are particularly helpful for assessing adhesive bonds between flat surfaces.

These surfaces can be one, two, or more in number. In a single-lap shear test, one component is pulled across the other. The strength of a lap joint depends on several factors, including the materials used, how well they mate with the adhesive, how elastic they are, and how cohesive the adhesive is.

Analyzing test results carefully is necessary, especially when shear failure may impact the bonding material, the bonded layers, or both. Lap shear measurements are typically expressed in MPa or N/mm² units, which are computed by dividing the applied load by the bonded overlap area.

4 Evaluation of Tensile Strength

4.1 Experimental Setup:

The following steps are taken to prepare the specimen for conducting the Tensile test.

4.1.1 Preparation of Specimen:

The alloys we chose mentioned in Fig 22 is used to make our desired specimen.

Dimensions and Parameters of Specimens: [32]

Specimen Standards: We already have found that the Rigid alloys have been selected for the lap-shear testing according to the standards ISO 4587. The dimensioning for the better results given by the standards is shown below that I made in Autocad software.

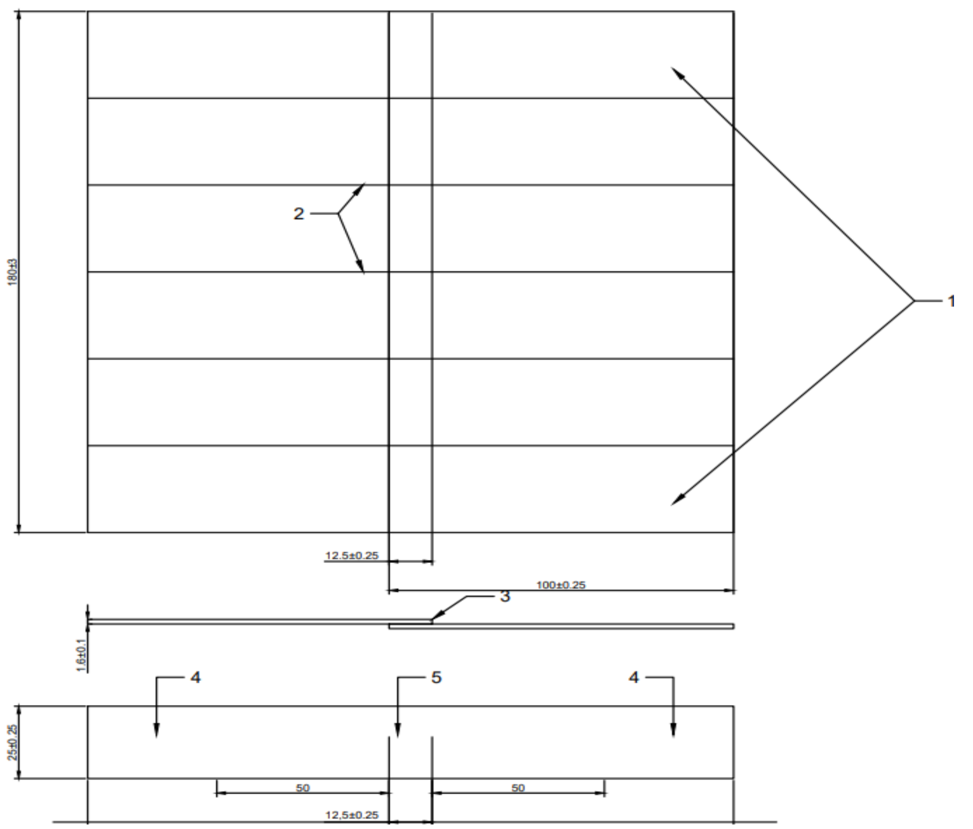

Figure 27: Designs and measurements of the specimen and test panel

1 discard
2 Generally 90° ± 1°
3 adhesive bond
4 Region placed in grips
5 shear area

Parameters	Dimensions (mm)
Length of adherends	100 ± 0.25
Width of adherends	25 ± 0.25
Thickness	1.6 ± 0.1
Overlap Length	12.5 ± 0.25
Adhesive Thickness	0.2

Table 7:Parameters and dimensions of Specimen based on ISO 4587[32]

The preparation steps for the aluminium specimen are mentioned below:

4.1.2 Cutting of Adherends

Adherends are the materials being bonded together through the adhesives. Using the proper cutting instruments, such as precision cutters, the adherends are first cut to the required size and shape to prepare the specimen with proper dimensions.

In this case, exact cutting is necessary to ensure the dimensions so that the adherends fit together perfectly and without any gaps that could affect the bonding strength. [33]

Now, we Cut adherends from the selected alloys by a Manual Sheet Cutting Metal Tool given in the following figure according to the dimensions specified in the standard from fig. 28.

Figure 28:Cutting of adherends from alloy by the manual sheet cutting tool

Finally, after cutting with proper dimensions measuring wih the verniar caliper we get each specimen.

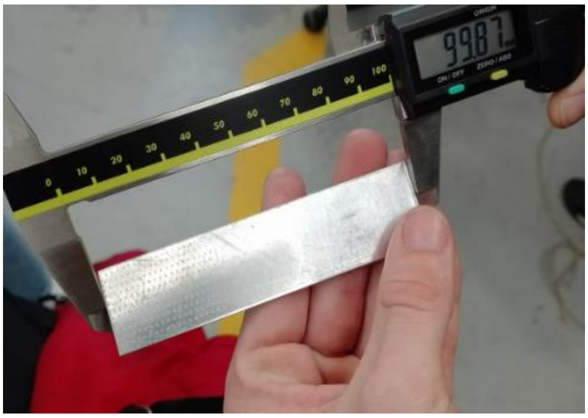

Figure 29:Prepared Specimen with required dimensions

4.1.3 Surface Preparation

After preparation of adherends, these kind of areas should not be handled directly at all. Since grease or other contaminants are present, this cannot be avoided. The reason of cleaning the surface to create a stronger and better bond is illustrated in the picture below.

Figure 30:Unclean surface of the adherends after cutting

We have to prepare the adherend surfaces according to the surface treatment guidelines provided by the adhesive standard (e.g. EN 13887) that has been mentioned is ISO-4587 standards. [32]

Cleaning:

To obtain optimum bond, From the instructions provided in standards like EN 13887, I tried to ensure that surfaces were clean and free from contaminants. Thus, I cleaned those surfaces with a piece of sandpaper to remove surface irregularities like dust and LOCTITE SF 7063 cleaner to remove contaminants such as grease and oil. This is how I could promote the adhesion between them. [33]

Figure 31:LOCTITE SF 7063, parts cleaner before joining. [28]

Priming:

Figure 32:Loctite SF 770 primer[28]

To improve the adhesion, LOCTITE SF 770 primer was applied after cleaning the substrates to the bond area by brushing. Then, we finally got our prepared specimen for the adhesive application that is shown in Fig. 33. [28]

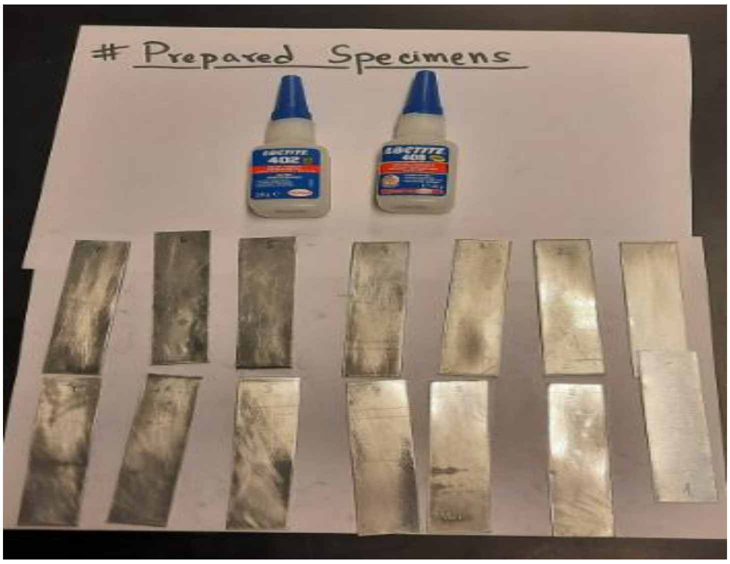

Figure 33: Specimen after surface cleaning

4.1.4 Application of Adhesives

The adherend surfaces that have been prepared are now covered with Loctite 402 and 408 after applying them on the surfaces based on the bonding requirements. For achieving the proper result for our Tensile strength experiment, 12 pieces of adherend surfaces are made into 6 pairs of specimens, 3 pairs of which are used for Loctite 402 and the remaining 3 pairs for Loctite 408. [33]

Air bubbles and other contaminants were carefully avoided as they could weaken the bond in the adhesive layer.

Figure 34:Application of Loctite 402 and 408 for bonding.

Bonding of Substrate Materials:

The adhesive application procedure was performed in a proper manner according to ISO 4587 guidelines to obtain optimum bonding strength. This allowed us to ensure proper alignment and uniform bond thickness, thus minimizing variability between specimens. Our effort was maximum to ensure this. Still, some variations were observed.

We tried to join the adherends together to form lap joint configuration with a specified overlap length (12.5 mm ± 0.25 mm).

Then, we tried to use glass spheres to control bond thickness (typical thickness: 0.2 mm). Variation was observed in the distribution of adhesives. [32]

Now, we had to wait for the bond to get its optimal strength and be prepared for the tensile test.

4.1.5 Conditioning

The specimens had to be tested and conditioned in one of the ISO 291 standard conditioning environments. These conditions are often specified by the adhesive manufacturer or may be based on industry standards.

Temperature and Humidity: The specimens needed to be conditioned at specific temperature and humidity conditions to simulate real-world environmental exposure. According to one of the standars, we tried our conditioning at 23°C ± 2°C and 50% ± 5% based on our room temperature and humidity. [34]

Curing:

After adhesive application, the adherends were brought together to form the bond. The curing process begins immediately after the adhesive comes into contact with the adherend surfaces. We let the curing occur at room temperature (ambient curing) based on the instructions provided in Standards ISO 291. [34]

Typically, specimens are cured for a specific duration to allow the adhesive to fully set and develop its strength through chemical reactions or physical changes to form a strong bond between the adherends. According to the standards, our sample were cured for a full day at room temperature. [34]

4.1.6 Performance of Tensile Test

Procedure:

The specimen was placed in each grip symmetrically, 50 mm ± 1 mm from the nearest overlap edge. To ensure that the applied force is in the plane of the adhesive bond, a shim can be used in the grips. The testing apparatus, INSTRON 68TM-10 was used to conduct the tensile test. Every type of specimen was held between the upper and lower clamps, with the difference in distance between them depending on the gauge length of the specimen.

Figure 35:measurement for tensile test

Performance of Tensile Test

The machine was set to run at a constant test speed, allowing 65 seconds ± 20 seconds to break the average joint.
When using a machine that operates at a constant rate, the shear load must be applied between 8,3 and 9,8 MPa per minute.

Initial Parameters

Displacement Rate	5 mm min
Force	10 N
Displacement	0.01 mm

Figure 36:performance of the tensile test

As soon as the test starts, the upper and lower clamps continue to separate at the specified, constant speed. The gauge length variations and material test parameters will be displayed by the machine's internal data collection program. And the force applied by the machine to the adhesive specimen will be monitored by this until the failure happens.Within a period of time, the breaking of the bond between the material will be observed.

4.2 Results of Test

After the tensile test was successfully completed with the assistance of the instron machine, the data collected from the machine was exported to an Excel file for each specimen which contained all the required parameters to evaluate the results. Three different tensile force-displacement graphs for each type of specimen for both Loctite 402 and 408 glues were generated via Excel as shown in the figures below. The result of the test is shown below:

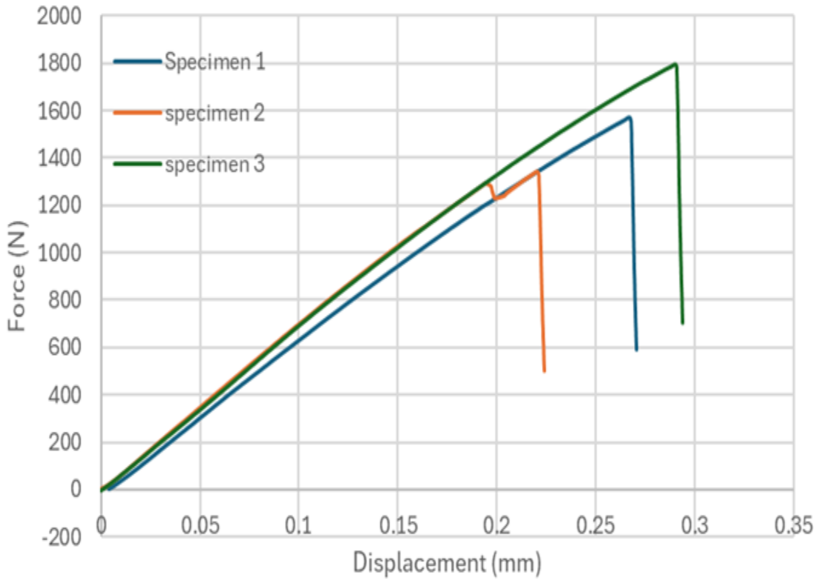

Figure 37:Breaking force vs Displacement diagram for Loctite 402

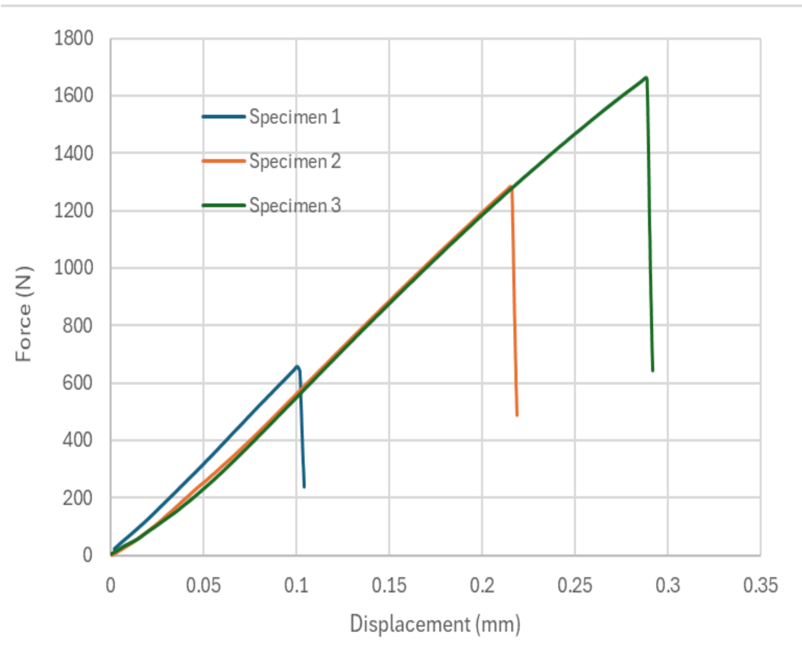

Figure 38:Breaking force vs Displacement diagram for Loctite 408

The maximum force (Breaking force) that was responsible to break the bond of each specimen at some particular time period can be observed from the curves.

4.3 Evaluation of the strength results

1. The arithmetic mean of the breaking force is calculated for all 3 valid specimens tested for each adhesives using the formula:

Mean Breaking Force = Σ Breaking Force / n

∑BreakingForce represents the sum of breaking forces measured for all valid specimens.

n is the number of valid specimens tested.

Here n=3 for my experiment as 3 specimens have been selected for each Loctite adhesives.

2. The mean breaking force divided by the cross-sectional area of adhesive bond yields the breaking stress (in megapascals). The Formula is:
Breaking Stress = Mean Breaking Force / A

The cross-sectional area of the adhesive bond is expressed as A, commonly measured in square millimeters.

Cross-Sectional Area of Specimen: A=Width×Thickness (including the adhesive layer)

3. The lap shear strength was calculated as the ratio of the mean breaking force to the shear area of the adhesive bond. The formula used is:

Lap Shear Strength = Mean Breaking Force / A_s

Lap Shear Area of Bond: A_s = Length of overlap×width of the lap joint

For the aim of design,

Shear Strength= ½ Tensile Strength [calc tensile] According to traditional engineering practice. The dimensions are given in Table 6. Using the formulas, Table 6 and data from excel we get our desired results. For the specimen,

we got **Cross Sectional Area= 45 mm^2 and (Lap) Shear Area= 312.5 mm^2**

4.3.1 Result after Calculation

After we performed the test using the Instron Machine, I collected the data regarding the breaking force (in newtons) for each specimen tested by Loctite 402 and 408.

According to, ISO 4587 I have to express the results of the tests as the arithmetic mean of the breaking force, in newtons, or the breaking stress, in megapascals, of the valid specimens. The lap shear strength, in megapascals is to be calculated too. The result is illustrated in the following tables.

Parameters	Result
Mean Breaking Force	1570.248 N
Breaking stress	34.894 Mpa
(Lap) Shear Strength	5.025 Mpa
Tensile Strength	10.05 MPa [tensile ref]

Table 8:Result for the specimens with Loctite 402

Parameters	Result
Mean Breaking Force	1201.688 N
Breaking stress	26.70418 Mpa
Lap Shear Strength	3.845 Mpa
Tensile Strength	7.69 Mpa

Table 9:Result for the specimens with Loctite 408

A comparative analysis can be carried out between Loctite 402 and Loctite 408 adhesives with the assistance of the results provided in the tables 8 and 9. This will assist us to figure out how to obtain findings that are superior to these so that we can match the outcomes observed in the industry.

5 Analysis of Results and Conclusion

5.1 Comparison of strength results

Loctite 402 vs 408:

Mean Breaking Force: From the calculation presented in table 7 and 8, we have found that the mean breaking force for Loctite specimens prepared with Loctite 402 glue shows a greater mean breaking force of 1570.248 N compared to 1201.6881 N for Loctite 408.

This shows that the adhesive bond made with Loctite 402 can bear a greater applied force before the failure compared to that of Loctite 408.

Breaking Stress: The breaking stress for the materials bonded with Loctite 408 has been calculated at 26.704 MPa, whereas the specimens bonded with Loctite 402 showed a breaking stress of 34.894 Mpa. It's visible that along with having a larger mean breaking force, Loctite 402 exhibited a greater breaking stress, expressing that it can withstand higher stress levels per unit area before the failure occurs compared to that with Loctite 408.

Lap Shear Strength:

The lap shear strength for the materials joined with Loctite 408 is 3.845 MPa, while it is slightly higher for Loctite 402 with a value of 5.025 Mpa.

This explains that the adhesive bond formed with Loctite 402 also shows bigger resistance to the shear forces compared to Loctite 402.

As a result, it is observed specimen with Loctite 402 have bigger Tensile strength too that can withstand higher stress while being streched before breaking it with the force than that with Loctite 408.

To conclude, both Loctite 402 and 408 adhesives show their bonding properties, with each formulas showing their strengths in different forms. However, Loctite 402 constantly performs better than Loctite 408 in terms of the strenth.

Loctite 402 shows greater mean breaking force, suggesting better overall load-bearing capacity, as well as greater strength in resisting forces that leads to the failure, compared to Loctite 408. Moreover, Loctite 402 shows greater breaking stress, suggesting better resistance to stress while the load is applied.

In addition, Lap shear strength is considered as an important measure of adhesive bond strength. Loctite 402 shows a higher value for this too than Loctite 408. It indicates that the bond formed by Loctite 402 between two adherends is more resistant to shearing forces compared to the bond created by Loctite 408. As a result, the tensile strength of Loctite 402 outperforms that of Loctite 408. This implies a greater level of durability and reliability in applications where tensile stresses are significant.

In summary, the data shows the superior performance of Loctite 402 over Loctite 408 over multiple properties, indicating that it can be a better an reliable choice for bonding applications in terms of durabilty and higher strength for the manaufacturing industry.

5.2 Analysys of Force-Displacement

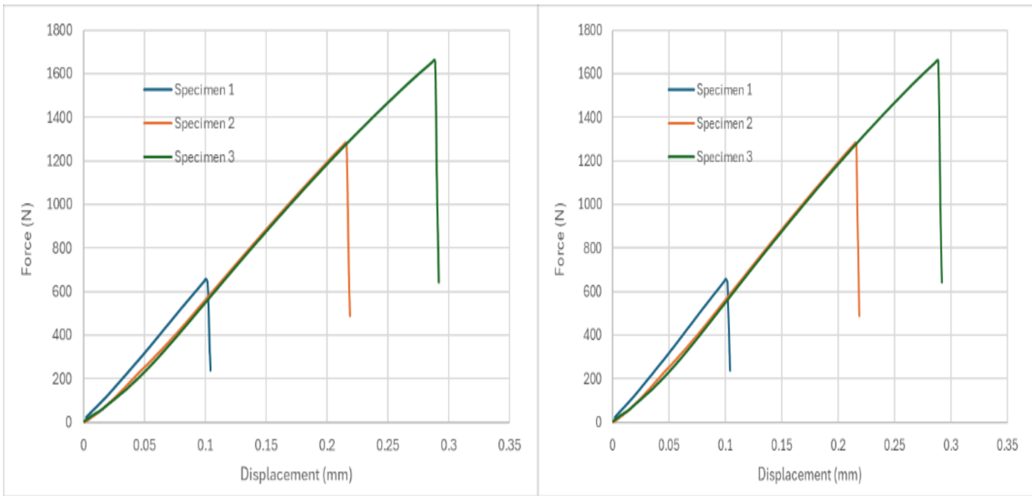

Figure 39:Force result analysis between Loctite 402 and 408

After we received the datas in excel that was imported from the Instron machine used for our tensile test, the tensile force-displacent graph was made for the analysis for both Loctite 402 and 408 adhesives.

In Loctite 402 diagram, we can see the difference between maximum force for each specimen bond breaking is not huge. Specimen 3 has the highest amount of force around 1800 N which is the maximum ultimate tensile strength (UTS) for the adhesive bond that can withstand before failure. The deformation (elongation) experienced by the specimen as the test progresses increased almost at an euqal rate.

However, for Loctite 408 diagram, a huge difference between maximum force for individual specimen is observed. Specimen 3 shows an ultimate tensile strength of almost 1650 N whereas specimen 1 has a value of around 650 N. Their rate of increase of elongation is also higher.

The reason of this difference in breaking force has been observed due to the slight angle formation while joining the samples as you can find in fig 35 and also for the variation in the distribution of adhesives that happened while applying the adhesives. The specimen 2 with Loctite 402 and specimen 1 with Loctite 408 show the least breaking force as they had this slight angle formation that caused the failure in the specimen even with the lowest applied load. Additionally, the unequal distribitution of adhesives had its impact too on the lower breaking force. Moreover, it can be concluded that the specimen joined with Loctite 402 has its properties to withstand a greater breaking force than that with Loctite 408 glues.

5.3 Evaluation of Stress-Strain Curve

Using the simple equations both engineering and true stress-strain graphs were plotted for each specimen in the Stress-Strain graph.

The engineering stress:

$$\sigma_e = \frac{F}{A_0} \quad (1)$$

The true stress:

$$\sigma_t = \frac{F}{A_i} \quad (2)$$

Engineering Strain:

$$\varepsilon_{eng} = \frac{l_f - l_0}{l_0} \quad (3)$$

True Strain:

$$\varepsilon_t = \ln\left(\frac{L_i}{L_0}\right) \quad (4)$$

5.4 Analysis of Stress-Strain Curve

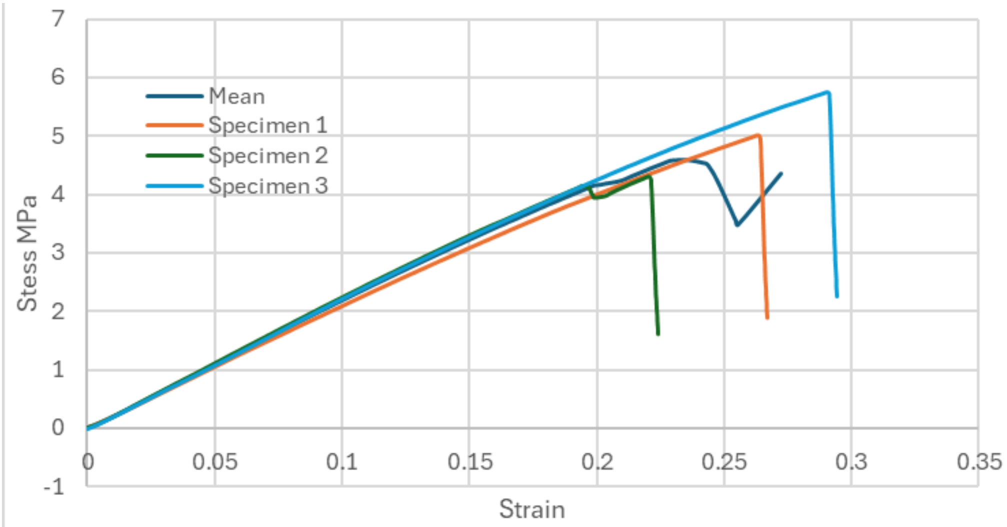

Figure 40:Loctite 402 Stress-Strain diagram

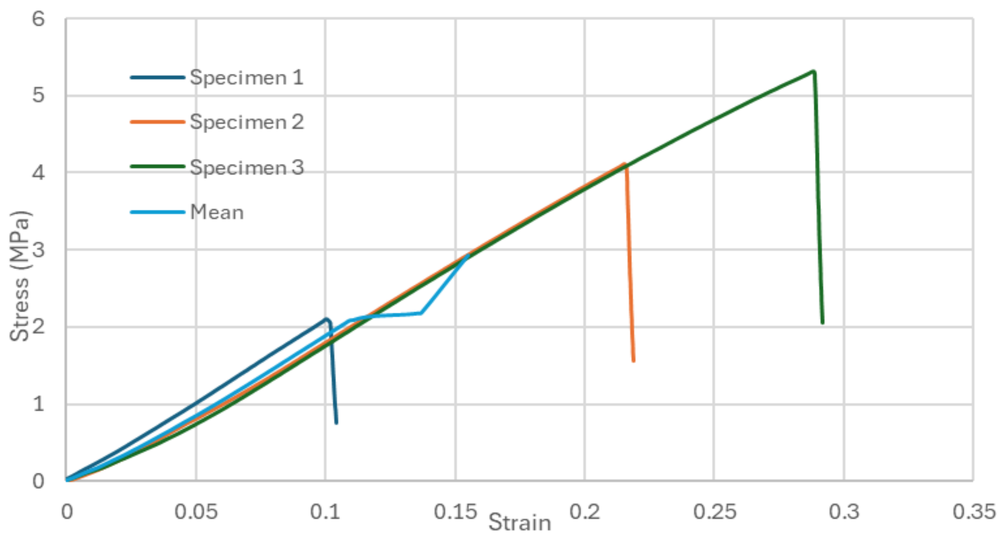

Figure 41:Loctite 408 Stress-Strain diagram

In this step, the stress-strain diagram of the Loctite 402 and Loctite 408 are compared, analyzing the mean stress-strain data sets.

It’s observed that, Ultimate stress of Loctite 402 is relatively larger than 408, with values of around 4.5 and 2.1 respectively.

Loctite 402 had a higher strain deformation compared to 408.

Loctite 402 material experienced a higher amount of stress compared to 408.

However, the elastic deformation (strain) caused by the given stress on Loctite 408 material was comparatively less than that with Loctite 402. As a result, the specimen bonded with Loctite 408 showed an overall higher stress-strain ratio that leads to a higher young modulus of value 21 than that of Loctite 402 which is around 18.26. It indicates the Loctite 408 material is relatively stiff with more rigidity and shows better resistance to deformation under an applied load than Loctite 408 material.

Despite the Loctite 402 material having higher breaking force, stress and lap shear strength, the variation in Young's modulus can be noticed because of the chemical composition, molecular structure, or formation. Loctite 408 may have some additives or modifiers that can improve its stiffness without any significant effect on its breaking force, stress, or lap shear strength.

Moreover, the testing set-up for Loctite 402 and 408 samples, such as variation in temperature, humidity, or specimen preparation can have an impact on the measured values of Young's modulus.

Therefore, we can conclude that the selection between Loctite 402 and 408 adhesives may depend on certain application requirements beyond the mechanical properties alone. Various factors such as environmental conditions, temperature resistance, humidity, cure time, and compatibility with substrate materials could play a crucial role in the selection process, even if one adhesive shows higher stiffness.

5.5 Comparison with Henkel Loctite 402 and 408 Standards:

The following table shows the value of tensile lap shear strength that is discovered from the technical data sheet of Henkel Loctite 402 and 408. The data is mentioned for Aluminum, the metal that I used as the substrate material with the adhesives for my specimen.

Loctite 402	Loctite 408
Tensile Lap shear strength	Tensile Lap shear strength
20 N/mm²	17.3 N/mm²

Table 10: strength analysis of Henkel Loctite 402 and 408

From the data sheet it is clear too that the strength of Loctite 402 is more than that of Loctite 408 just like in my experiment, which makes it more demanding in the market. However, in my experiment it is seen that the lap shear strength value for Loctite 402 and 408 are 5.025 N/mm² and 3.845 N/mm² respectively which is comparatively lower than the value derived by Henkel experiment.

As mentioned before, various factors could play crucial role in making this difference for the strength values by the same Loctite glues. For example, in Henkel the curing time was 72 hours for the material under different temperature and humidity whereas we performed for 24 hours at room temperature (where the humidity is not constant) according to the instruction provided by ISO 4583.

Moreover, the experimental set-up under controlled laboratory conditions with standardized procedures can have an impact in this difference.

While preparing adhesive specimens, few differences such as surface treatment methods where they may use laser cutting through which proper specimen without any deformed angle can be achieved or adhesive implementation procedure may affect the bonding strength. For example, difference in the amount of adhesive per specimen is observed in my experiment due to some inconsistent controlled procedure.

In addition, throughout experiment, Henkel Loctite might have made adjustments for their batch of adhesives by adding different additives or formulations, that could be a reason for the variations in performance between my samples and the distributed data.

The test performed by the industry may have been conducted by experienced professionals with standard testing arrangement and variations in calibration or maintenance of equipment might show the influence in accuracy of result. In conclusion, even though in a similar manner with Henkel standards, Loctite 402 had a higher strength than that of Loctite 408, however, the environmental variables such as temperature, humidity during curing process and other conditions still could have an impact on the bonding process and as a result variations in (lower) strength result. To improve the strength result, research on more adhesives and the bonding procedures can be carried out further.

5.6 Conclusion

In conclusion, the study on the usage of adhesives in the automotive industry, with a specific focus on Loctite adhesives 402 and 408, has provided valuable insights into the mechanical properties and performance of these adhesive formulations. Through experimental testing conducted on single lap joints using an Instron machine and adhering to ISO 4587 standards, the strength characteristics of the adhesives were evaluated, revealing notable differences between Loctite 402 and 408.

The Findings of the study showed that the strength of Loctite 402 was better than Loctite 408. This was determined among other properties like the mean breaking force, breaking stress, and lap shear strength. Furthermore, it is quite apparent that the strength values acquired during the practical testing were lower compared to the data published in the industry setting. This indicates possible directions for further study and implementation where we can find various approaches to modify the bonding process to achieve a better result and solution for the manufacturing industry.

The comparative analysis of the strength with the industry data ensures that there could be numerous ways to improve adhesive strength testing's precision and dependability in the future. These may include using a wider variety of materials with various qualities, and ensuring that the optimization of testing conditions, such as temperature and humidity control, are reliable and consistent, and refining specimen preparation methods. The precision of specimen preparation may also be increased by using cutting-edge techniques like laser cutting.

As we conclude the thesis, it is apparent that there should be further research on this subject with an analysis of different adhesive formulations for the development and enhancement of adhesive bonding processes. In addition, more studies into how adhesive distribution and surface preparation methods enhance the bonding performance may provide insightful information for advancing adhesive technology in automotive applications. Consequently, it will be far simpler to manufacture lightweight, strong, and reliable products once effective bonding solutions are developed.

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