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JOINTS SUBJECTED TO HIGH LOADING RATES

M. Sc. Thesis by

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled "**JOINTS SUBJECTED TO HIGH LOADING RATES**" completed by **Orkun YAVUZ** under supervision of **PROF. DR. Ferhat KADIOĞLU** and we certifythat in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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JOINTS SUBJECTED TO HIGH LOADING RATES

ABSTRACT

In joining techniques, various types of joints, such as adhesive-bonded, bolted, hybrid, and pinned joints, are utilized. These joints can be employed mechanically and/or adhesively, depending on their designated applications. Adhesive bonding, a joining technique increasingly employed in recent years across diverse fields including automotive, aerospace, space, and defense industries, offers advantages such as enhancing mechanical performance at joints and improving predictability in damage mechanics. Given the critical importance of this area, our study was conducted to investigate adhesive bonding in comparison to other joint types intended for use in these fields. Our aim is to examine the effects of repeated loadings on the performance of adhesively-bonded single lap joints. Using both experimental and numerical approaches, a projectile with a mass of 1.25 grams and a density of 11.3 grams/cm3 was fired at a specially designed experimental setup at a velocity of 279.97 m/s, and the entire experiment was recorded with a high-speed camera. The single lap joints (SLJs) were manufactured from 6061 aluminum adherend (AA6061) material and were bonded with a thermosetting modified epoxy adhesive film (AF163-2K) produced by 3M Scotch-Weld™. The joints, with a thickness of 4 mm and an overlap length of 15 mm, were subjected to ballistic testing with 2 shots and 3 shots, followed by quasi-static tensile testing. When comparing the joints subjected to 2 shots and 3 shots with the non-impacted and 1 shot impacted ones, it was found that while the joints subjected to 2 shots with a 15 mm overlap length mechanically deteriorated, joints subjected to 3 shots experienced rupture at the end of the experiment. Theoretical information has been confirmed by experimental data. The inputs were analyzed in the ABAQUS program using the Johnson-Cook deformation parameters, and the experimental results were numerically validated within the program.

Keywords: Joining techniques, adhesive joints, ballistic test.

YÜKSEK YÜKLEME ORANLARINA MARUZ KALAN BİRLEŞİMLER

ÖZ

Birleştirme tekniklerinde, yapıştırma-birleştirme, cıvatalı, hibrit ve çivili gibi çeşitli eklem türleri kullanılır. Bu eklem türleri, belirlenmiş uygulamalara bağlı olarak mekanik ve/veya yapıştırıcı bir şekilde kullanılabilir. Son yıllarda otomotiv, havacılık, uzay ve savunma endüstrileri gibi çeşitli alanlarda artan bir şekilde kullanılan yapıştırma birleştirme, eklem yerlerinde mekanik performansı artırma ve hasar mekaniğinde tahmin edilebilirliği iyileştirme gibi avantajlar sunar. Bu alandaki kritik öneme göre, çalışmamız bu alanlarda kullanılacak diğer eklem türleriyle karşılaştırılarak yapıştırma birleştirmeyi incelemek üzere gerçekleştirilmiştir. Amacımız, yapıştırıcıyla birleştirilmiş tek kollu eklem yerlerinin tekrarlı yüklemelerin performansındaki etkilerini incelemektir. Deneysel ve sayısal yaklaşımları kullanarak, 1.25 gr kütle ve 11.3 gr/cm3 yoğunluğa sahip bir cisim, özel olarak tasarlanmış bir deney düzeneği kullanılarak 279.97 m/s hızla ateşlenmiştir ve tüm deney yüksek hızlı bir kamera ile kaydedilmiştir. Tek lap eklem (SLJ'ler), 6061 alüminyum yapıştırıcı (AA6061) malzemesinden imal edilmiş ve 3M Scotch-Weld™ tarafından üretilen termo-ayarlamlı modifiye epoksi yapıştırıcı film (AF163-2K) ile birleştirilmiştir. Eklem kalınlığı 4 mm ve üst üste binme uzunluğu 15 mm olan eklem, balistik test için 2 atış ve 3 atışa tabi tutulmuş ve ardından kısmi-statik çekme testine tabi tutulmuştur. 2 atış ve 3 atışa tabi tutulan eklemle, etkilenmemiş ve 1 atış yapılan eklem karşılaştırıldığında, 15 mm üst üste binme uzunluğuyla 2 atış yapılan eklemde mekanik bozulma meydana geldiği, 3 atış yapılan eklemde ise deneyin sonunda kopma meydana geldiği bulunmuştur. Teorik bilgiler, deneysel veriler tarafından onaylanmıştır. Girişler, Johnson-Cook deformasyon parametreleri kullanılarak ABAQUS programında analiz edilmiş ve deneysel sonuçlar program içinde sayısal olarak doğrulanmıştır.

Anahtar kelimeler: Birleştirme teknikleri, yapıştırıcılı birleşimler, balistik test

CONTENTS

NOMENCLATURE

Roman Letter Symbols

$\dot{\epsilon_p}$	Effective Plastic Strain Rate, mm/mm
ϵ_p	Effective Plastic Strain, mm/mm
A	Initial Yield Strength, MPa
B	Strain Hardening, MPa
N	Dimensionless Strain Hardening Exponent
T	Current Temperature, K
T_r	Reference Temperature, K
T_m	Melting Temperature, K
T_t	Top Adherend Thickness, mm
T_b	Bottom Adherend Thickness, mm
E	Modulus of Elasticity, MPa
G_a	Adhesive Shear Modulus, MPa
T_a	Adhesive Thickness, mm
M	Bending Moment, N-m
V	Transverse Force at The End of The Overlap Area, N/m^2
K	Bending Moment Factor
C	Half of The Overlap Length, mm
M_0	Edge Moment, N-m
T_0	Adhesive Shear Stress, N/m^2
Σ_0	Transverse Normal Stresses, N/m^2
SHPB	Split Hopkinson Pressure Bar
SLJ	Single Lap Joints
J-C	Johnson-Cook
CFRP	Carbon Fiber-Reinforced Polymers

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CHAPTER 1

INTRODUCTION

With the latest developments in technology, various techniques of joining, both similar and dissimilar materials, are being applied in many fields, particularly aviation, space, and defense. These applications are of critical importance depending on the specific use case.

Bolted connections are employed to link materials, creating mechanical structures. In contrast to adhesive bonding and welding techniques, bolted joints have gained extensive usage owing to their substantial load-bearing capability, straightforward assembly, and cost-effectiveness. Additionally, they enable easy part replacement, repair, and maintenance, and offer adjustability or mobility. Nonetheless, a primary drawback of bolted joints arises from the development of concentrated stress zones at the bolt hole locations. This phenomenon could potentially result in premature joint failure, attributed to net-section, shear-out, or bearing failures, or their combinations.

Adhesive bonding is a joining technique that has been used in various fields in recent years, including automotive, aerospace, space, and defense industries, due to its advantages such as enhancing the mechanical performance in joints and improving predictability in damage mechanics. In addition to having a uniform stress distribution, Adhesively Bonded Joints' (ADJ) main advantages include the improvement of aerodynamics and smoothness, sealing and corrosion resistance, fatigue durability, superior damping characteristics, and reduced machining requirements.

The hybrid joint (HJ) merges the benefits of two or more joining methods. It is known that they have higher static and fatigue strength compared to simple joints, as well as higher stiffness and improved durability.

Although there are various types of joints and joining techniques, there has been limited research on Single Lap Joints under high loading rates. Therefore, it is important to investigate Single Lap Joints under high loading rates, especially when considering critical areas. Such investigations can provide insights into various fields such as defense, aviation, and space.

1.1 Aims and Objectives

This study aims to investigate the joint strengths of adhesively bonded Single Lap Joints (SLJ) exposed to repeated high loading rates by employing both experimental and numerical approaches. When considering the critical applications and working conditions of Single Lap Joints, it is known that they are subjected to various types and rates of loads. Various scientific studies have already demonstrated how their strengths are affected under high loading rates.

In this study, evaluations have been made on the joint strengths of adhesively bonded joints exposed to repeated high loading rates, considering the results obtained from previous studies. The joints, which have an adherend thickness of 4 mm and overlap length of 15 mm, were subjected to up to 3 shots for the ballistic test, followed by quasi-static tensile testing. The impacted joints, then, were compared to the non-impacted and one shot impacted ones, which was a subject of investigation carried out before. The experiment allowed for reaching a conclusion about the effect of repeated high loadings on the performance of adhesively bonded single lap joints by interpreting and comparing previous studies. A numerical study was also conducted using an ABAQUS package program to validate the experimental results.

1.2 Literature Review

Many works deal with adhesively bonded joints under static, dynamic, and impact loadings. When we consider joints, especially adhesively bonded joints, there are studies on this subject in the literature. In these studies, geometric parameters for the performance of joint structures (such as overlap length, adhesive thickness, joint configuration), material properties (adhesive and adherend), environmental factors (humidity, temperature), surface preparation and damage mode are examined.

For example, M. El Zaroug and colleagues [1] explored the mechanical behavior of single lap joints under tensile loading, examining the performance of bolted, bonded, and hybrid joints. The study involved three distinct adherend thicknesses and two different adherend materials, each exhibiting diverse mechanical characteristics, and it was found that the adhesive layer consistently experienced the initial failure. As the thickness of the adherend material increased, there was a corresponding increase in the maximum load capacity, while the displacement to failure decreased.

D. F. S. Saldanha et al. [2] conducted a tensile test and drop weight impact test on an epoxy adhesive named XNR 6852 and reported the results.

Yinhuan Yang [3] subjected single-lap adhesive joints of three types of T700/Exopy unidirectional laminates to tensile loading. The findings revealed an increase in joint failure strength with an increase in adherend thickness.

Do Won Seo et al. [4] tested the single-lap joints with different joint conditions according to ASTM D1002-94 [5] using a tensile-shear test. It was verified that increasing the load by extending the overlap length was not efficient.

F. Kadioglu et al. [6] conducted a study to examine the effects of changing overlap lengths and composite adherend thicknesses on the behavior of single-lap joints bonded with adhesives (specifically, Hexply 8552S/A280-5H produced by Hexcel) under both tensile and bending loads. The study involved testing joints with overlap lengths of 15mm, 25mm, and 40mm, as well as adherends with thicknesses of 2mm and 3mm.

The results revealed that an increase in the overlap length led to a significant enhancement in joint performance. Furthermore, the researchers observed that thicker adherends contributed to an approximate of 100% improvement in performance when compared to thinner ones.

Kadioglu [7] investigated the joints behavior under quasi-static buckling conditions using adherent thicknesses of 2mm, 4mm, and 6mm, a 25mm overlap length, and AA6061 and AA7075 adherends, and an adhesive film (AF163-2K). After an in-depth investigation of the compression (buckling) test results, it became evident that relatively thicker adherends had a pronounced positive effect on enhancing joint strength. The plasticity of adherends emerged as a pivotal parameter influencing joint strength, consequently, adherends with superior mechanical properties (AA7075) yielded greater joint strength.

In addition, studies have been conducted on various factors such as different types of surfaces, temperatures, geometric parameters (such as overlap lengths and adherend thickness), or fiber orientations on composite materials [8-11].

P.N.B. Reis et al. [12] conducted an examination into how moisture affects the tensile and impact strength of single lap joints with different adherends. The adherends for the joints were made of Docol 1000 high elastic limit steel plates, 1.5 mm thick, and composite plates, 2 mm thick. Subsequently, the joints were subjected to the Charpy impact tests. It was observed that the tensile strength decreased in adhesive joints featuring both steel and composite adherends.

J. J. M. Machado et al. [13] conducted experiments on single-lap joints (SLJ) made from three different materials, each with a 25mm overlap length (two aluminum alloys: 5754-H22 and 6060-T6, and CFRP). Tests were conducted under three different conditions: low temperature (-30°C), room temperature (24°C), and high temperature (80°C). After the tests, the specimens were subjected to both quasi-static and falling weight impact tests. The aluminum joints, characterized by similar configurations, demonstrated minimal sensitivity to low temperatures and manifested failure loads considerably inferior to those observed in joints comprised of CFRP materials.

Under quasi-static conditions, the aluminum-aluminum similar joints absorbed the highest amount of energy for all tested temperatures.

C. Galliot et al. [14] conducted experiments including quasi-static and drop weight impact tests on carbon/epoxy laminate joints bonded with adhesives to examine their dynamic characteristics. Their observations revealed that, with an increase in the loading rate, there was a notable enhancement in failure strength, absorbed energy, and stiffness.

J. J. M. Machado and colleagues [15] conducted a study by performing quasi-static and falling weight tests on CFRP single-lap joints with 12.5mm and 25mm overlap lengths under different temperature conditions: low, room temperature, and high temperature (-30°C, 24°C, 80°C). Their findings indicated a direct correlation between temperature and failure load.

Impact tests conducted on but joints using split Hopkinson test bars have been the subject of research by various researchers [16-17].

J.A. Harris and R.D. Adams [18] investigated the strength and energy absorption of SLJs under Izod pendulum tests using four types of epoxy adhesives and three types of adherents. Their findings indicated that the absorption of energy was not derived from the adhesive but rather from the deformation of the adherend material. It can be concluded that a bonded joint can demonstrate favorable energy-absorption traits if the joint or joints can retain enough strength during impact loading to facilitate substantial plastic deformation of the adherends.

A study was carried out by A. Komorek and J. Godzimirski [19] to assess the impact strength of lap joints. They conducted tests using a modified pendulum tester and observed that hybrid connections exhibited superior impact strength when compared to adhesive and rivet joints.

H. Boling and G. Dongyun [20] conducted a numerical investigation into the dynamic analysis of single-lap adhesively bonded composite-titanium joints (Ti-6Al-4V STA) subjected to solid particle impact (2024-T3 aluminum).

They employed Araldite AV138 to bond the titanium and composite adherends and conducted impact tests using a one-stage gas gun. It was determined that the maximum stress within the adhesive layer decreased with an augmentation in the adhesive layer thickness, overlap length, projectile diameter, and projectile impact velocity. Furthermore, they observed that, for high modulus adhesives, the influence of strain rate on stress and elastic strain is nearly negligible under low loading rate conditions.

C. Sato and K. Ikegami [21] conducted a study on the transmission of dynamic stress waves and dynamic stress distribution in adhesive-bonded single lap joints, conical single lap joints, and inclined single lap joints. This comprehensive study employed both analytical and experimental approaches. Utilizing an air gun, the acceleration of a spherical striker was employed, revealing that stress intensity and fluctuations in stress within scarf joints were relatively lower when compared to the levels observed in single lap joints and tapered lap joints. Furthermore, the research yielded valuable ideas into stress concentration phenomena.

Amar Prakash et al. [22] numerically studied the response to high-velocity impact of a composite plate incorporating ceramic material using epoxy, with thicknesses ranging from 0.1 to 1.5 mm. An ogive-nosed projectile traveling at a velocity of 830 m/s was employed in impact testing to explore the influence of adhesive thickness. They found that the adhesive layer thickness influences the impact performance.

L. Goglio et al. [23] conducted a study on the high strain-rate compression and tension behavior of a two-component epoxy adhesive. They discovered that the epoxy adhesive was highly sensitive to strain rate, up to 103 s-1, and observed that the adhesive's yield strength increased by up to three times under compression and up to five times under tension when compared to quasi-static values. The elastic modulus remained unchanged when subjected to both high and quasi-static loading.

F. Kadioglu et al. [24] conducted research focused on the ballistic performance of Single Lap Joints (SLJs) with two different overlap lengths, 15 mm and 25 mm. During the experiments, these joints were subjected to projectile impact at a velocity of approximately 288 m/s, with a mass of 1.25 g, and a density of 11.3 g/cm^3. When comparing the impacted joints to the non-impacted ones under static conditions, it was observed that the SLJs with a 15 mm overlap length exhibited a notable reduction of around 40% in load to failure compared to their non-impacted counterparts. In contrast, the SLJs with a 25 mm overlap length seemed to withstand the projectile impact without significant effects.

When numerous previous studies are considered, it is observed that there is a limited amount of research on Single Lap Joints (SLJs) subjected to repeated high loading, and only a few studies have examined SLJs under high loading rates. It is believed that investigating Single Lap Joints under high loading rates can provide insights into various fields such as defense, aviation, and space, among others.

CHAPTER 2

JOINTS

2.1 General View Of Joints

Adhesive bonding emerges as a prevalent method for joining materials, particularly in critical fields like aerospace structural applications, space, defense, automotive, and other crucial domains. The effectiveness of adhesively bonded single-lap joints in these applications relies on establishing a harmonious balance between mechanical and dynamic properties to ensure their optimal performance.

It has the potential to outperform mechanical fastening in the assembly of composite components, attributed to a comparatively even stress distribution as opposed to the highly concentrated stress observed in mechanically fastened joints. It finds application across diverse sectors, including construction, aviation, and automotive industries. In aviation, it is utilized for the assembly of thin-walled structural materials, while in the construction domain, it is applied to strengthen concrete structures through the bonding of composite materials. [25]

In joint techniques, such as bonded, bolted, hybrid, pinned, etc., various types of joints are used, and these joints can be employed either mechanically or adhesively, depending on their designated applications. The main types of joints, as shown in Figure 2.1 below. [26]

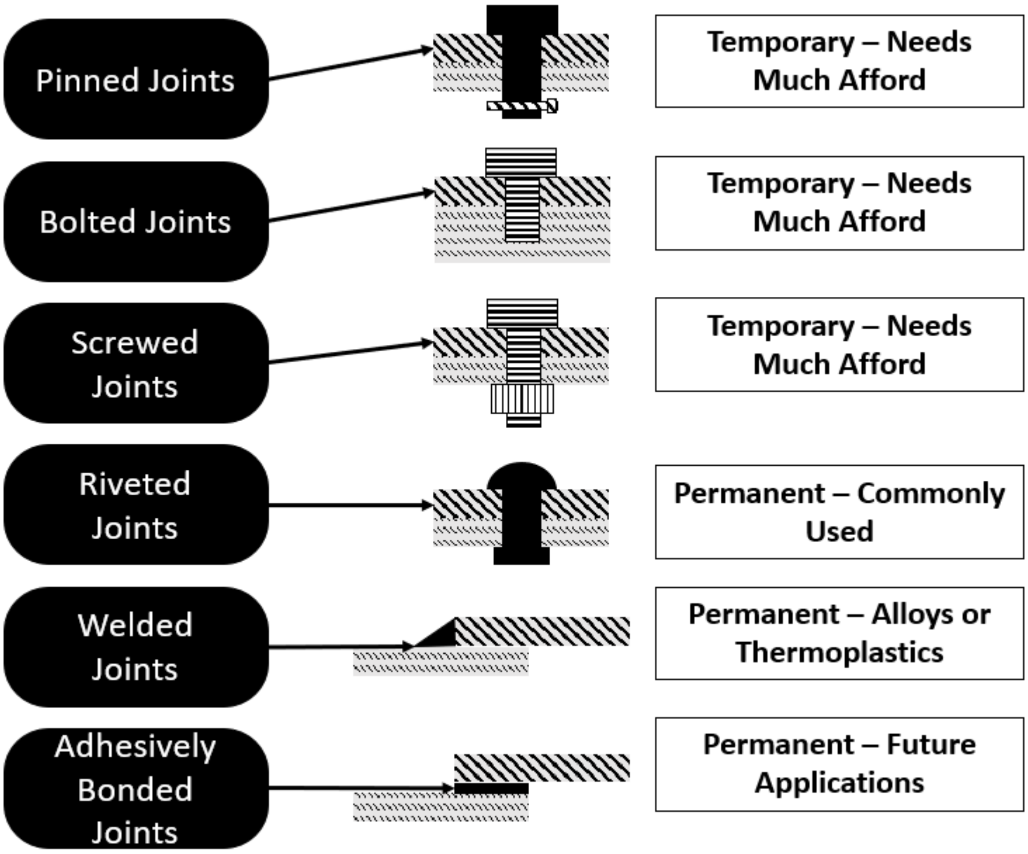

Figure 2.1: Main types of joints [26]

When we examine Figure 2.1, it is observed that these joints are achieved through three techniques. These techniques are listed below.

1- Mechanical Joining

2- Welding

3- Adhesive Bonding

2.2 Mechanical Joining

Mechanical joining is the most commonly used method for joining objects. It involves using a device (a mechanical fastener) to connect two or more objects together mechanically. These joints are chosen for their ability to enhance the load-carrying capacities of structures and enable easy replacement and repair. The examination of mechanical joints can be divided into two parts:

1- Mechanical fastening

2- Mechanical attachment

Both methods join the parts to each other by physical interference or interlocking.

In the context of mechanical fastening, an extra instrument is utilized to generate interference between components. Well-recognized examples consist of fastening elements such as rivets, bolts, screws, nails, and staples, while less conspicuous but equally familiar instances involve stitches, laces, lashings, wire-wraps, alongside buttons and zippers. [27]

In mechanical attachment, there is no need for supplementary devices or fasteners; the joining process relies on the interference or interlocking of geometric features intentionally designed or integrated into the components being joined. Various instances may be provided, including T-slots and wedge connections. Additional examples comprise elastic thermal shrink fits, as well as elastic or plastic mechanical interference fits in thermoplastic components. [27]

Mechanical joints utilize compressive residual stresses within the joint to maintain contact between components and require the distribution of tensile stress away from the system. While the stress concentration within the structure stands out as a major drawback of using mechanical joints, the increase in weight in the created joint due to the use of mechanical joints is also taken into consideration.

2.3 Welding

Welding is a joining process that joins materials, typically metals, polymers, or ceramics, by causing coalescence. This process involves melting the materials to be joined, typically adding a filler material to form a pool of molten material, which upon cooling, solidifies and creates a strong bond between the components. The result is a permanent, homogeneous joint that often retains the strength and characteristics of the base materials.

Unlike adhesive bonding, welding typically doesn't entail or necessitate any chemical reaction. It relies on the tendency of elemental particles to attract each other and form bonds. The bonds formed within the joint reflect the bond types inherent in the materials undergoing connection. Welding offers a significant advantage through the development of joints known for their superior structural integrity, efficiency, and lasting nature. However, drawbacks associated with the process include alterations in material composition and microstructure (in the majority of methods) and, paradoxically, the inability to dismantle the joint without causing considerable damage to the components. [27]

2.4 Adhesive bonding

Adhesive bonding is a joining technique that has been used in various fields in recent years, including automotive, aerospace, space, and defense industries, due to its advantages such as enhancing the mechanical performance in joints and improving predictability in damage mechanics. Adhesive bonding constitutes a method of joining materials, wherein an adhesive substance is applied between the surfaces of adherends and undergoes a solidification process, resulting in the formation of an adhesive bond. In addition to having a uniform stress distribution, its main advantages include the improvement of aerodynamics and smoothness, sealing and corrosion resistance, fatigue durability, superior damping characteristics, and reduced machining requirements. [28]

In contrast, adhesive joints exhibit greater continuity and hold the potential advantages of an efficient strength-to-weight relationship, versatile design possibilities, and simplified fabrication processes. [29]

Adhesive bonding has several disadvantages, such as surface preparation, cure time, temperature and pressure application, and storage conditions. The comparison made with mechanical joints is shown in Table 2.1.

Table 2.1 Comparison between Adhesive Joining and Mechanical Joining

	Advantages	**Disadvantages**
Adhesive Joining	Uniform stress distribution	Special surface preparation is needed
	Smooth surface	It can be affected by environmental factors such as temperature and humidity.
	Higher damage tolerance	Weak to peel loading
	Reduces costs	Inspect difficulty
	Provides design flexibility	Cure time is required
Mechanical Joining	Easier to disassemble	Stress concentration around fasteners
	Easy to inspect	Low resistance to fatigue
	There is no need for surface preparation	Increases the structure weight
	No weak against peel loading	It becomes difficult to achieve smoothness on aerodynamic surfaces.
	It is less affected by environmental factors	Extensive shimming is often required for composites

The joint configurations for adhesive joints vary based on their applications or purposes. For instance, as illustrated in Figure 2.2, joining configurations can be utilized in structural panel components, while configurations as shown in Figure 2.3 can be employed for purposes like repairing or strengthening structural defects.

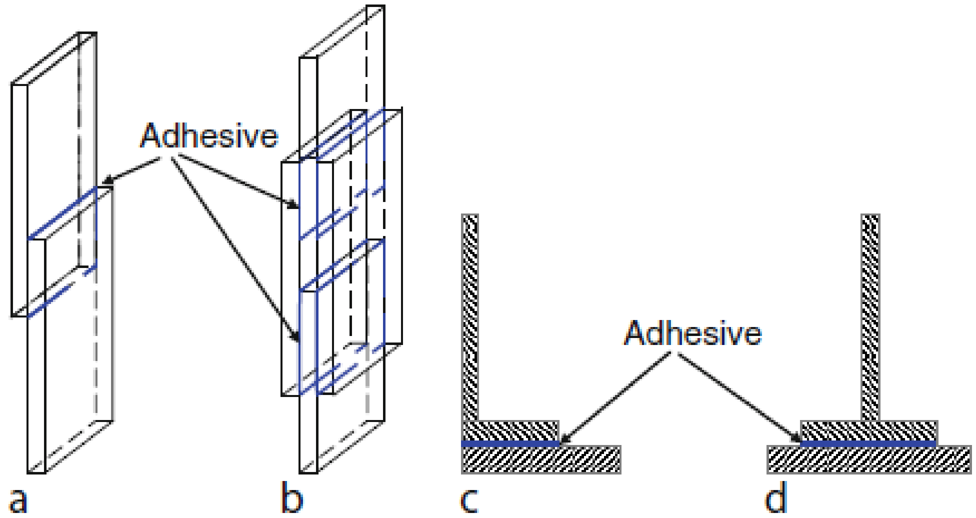

Figure 2.2: Some types of joints: (a) single lap joint; (b) double lap joint; (c) L-joint; (d) T- joint [25]

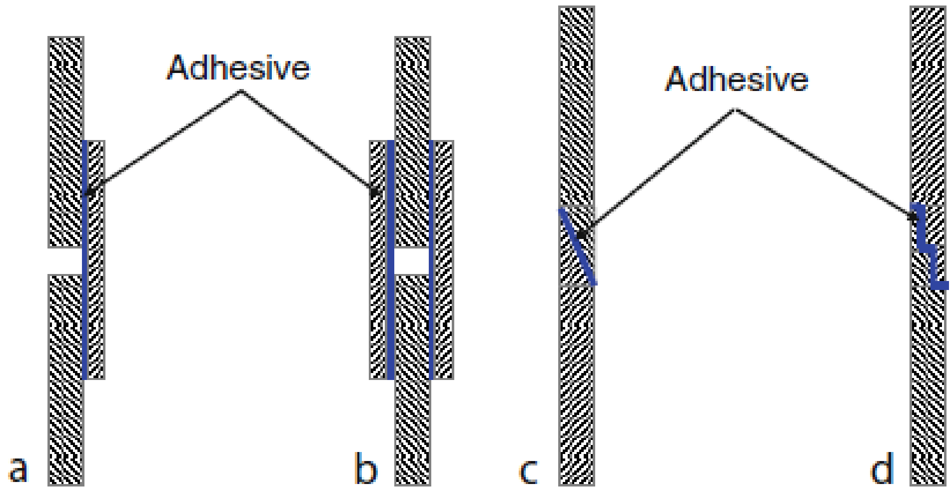

Figure 2.3: (a) and (b) are single and double strap joint respectively, (c) and (d) are scarf joint and step joint respectively. [25]

2.5 Adhesively Bonded Joints

2.5.1 Adhesion Mechanisms

Due to the complex structures of adhesive mechanisms, it is not possible to define them with a single mechanism. The scope of each mechanism can vary depending on the adhesive bonding method chosen. In adhesive connections, the connection is completed through an interface contact between the adhered material and the adhesive. There are many theories explaining the phenomenon of adhesion. Some of the main ones are as follows.

-Adsorption Theory

-Mechanical Theory

-Electrostatic Theory

-Diffusion Theory

-Weak Boundary-Layer Theory

2.5.1.1 Adsorption Theory

The theory of adsorption underscores the idea that upon contact between adhesive and substrate, cohesive forces are initiated between them. If the wetting extent is favorable, these forces, whether primary (e.g., covalent) or secondary (such as van der Waals forces), are typically deemed adequate to establish a strong bond. In challenging conditions, primary bonding may be essential to ensure the durability of the bond. [30]

2.5.1.2 Mechanical Theory

The mechanical theory centers on the interlocking phenomenon between the adhesive and a textured substrate surface. Effective wetting is imperative, as inadequate wetting or surface roughening is prone to result in diminished bond strength. This theory has demonstrated applicability to surfaces exhibiting macroscopic roughness, as well as to microfibrous and microporous surfaces like anodized aluminum.

The heightened adhesion is correlated with an augmented capacity for plastic energy dissipation during fracture within the bulk adhesive material. [30]

2.5.1.3 Electrostatic Theory

The theory highlights electrical occurrences, such as sparking, that may manifest during the disruption of an adhesive bond. This theory explores the transfer of electrostatic charge between the adhesive and substrate, conceptualizing the adhesive-substrate system akin to a parallel plate capacitor. However, contemporary assessments indicate that the energy involved in this process is typically modest in comparison to adhesion fracture energies. Consequently, the electrostatic theory receives notably less robust support than it did around half a century ago. [30]

2.5.1.4 Diffusion Theory

The diffusion theory has garnered growing attention, particularly in light of the advancement of the reptation theory in polymer chain dynamics. This theory offers a framework for understanding polymer-to-polymer adhesion, providing insights into the temporal and molecular weight dependencies inherent in adhesion to polymers exhibiting diverse compatibilities. [30]

2.5.1.5 Weak Boundary-Layer Theory

The significance of meticulous examination of the failure site in an adhesive bond is underscored, with a focus on discussing the involvement of less robust boundary layers. [30]

2.5.2 Adhesives

Adhesive bonding offers numerous advantages, such as achieving more consistent stress distributions when contrasted with the utilization of mechanical fasteners. Adhesives ensure complete contact with mating surfaces, creating a barrier against fluids and gases that could potentially lead to degradation in the assembled structure. Additionally, adhesives can serve as effective electrical and/or thermal insulators or conductors within joints.

Adhesives can be categorized according to both their chemical composition and physical structure, as well as their respective reaction and processing conditions. This categorization aids in defining the application method, curing process, assembly, and fixturing of the adhesive, tailored to the characteristics and intended use of the objects to be bonded. Consequently, a thorough consideration of this classification streamlines the adhesive selection process. [31]

Adhesives are classified according to many parameters. These are basically classified as follows;

- Polymer based ones, for example; natural or synthetic
- Functionality within the polymer; for example; thermoset, thermoplastic or elastomer
- Physical forms
- Chemical family, for example; silicone, epoxy
- Application methods
- Functional type, for example; pressure sensitive, water based, structural

2.5.3 General Properties of Aluminum Alloys

Aluminum alloys are frequently employed in mechanical and structural designs, electrical applications, and similar fields, particularly in aviation, automotive, and defense. Another notable application of aluminum alloys is in chemical containers, as well as in energy and electronic applications, owing to their non-ferromagnetic properties.

The 6061 aluminum alloy stands out as the most commonly used aluminum alloy, primarily composed of magnesium and silicon. It exhibits excellent mechanical properties, good workability, weldability, machinability, a high strength-to-weight ratio, electrical conductivity, thermal conductivity, and corrosion resistance.

Although high-performance composites, such as carbon fiber-reinforced polymers (CFRP), are commonly utilized in the primary structures of modern aircraft, materials like aluminum or steel are also frequently employed in aviation. Figure 2.4 provides an example illustrating the materials used in a sample aircraft.

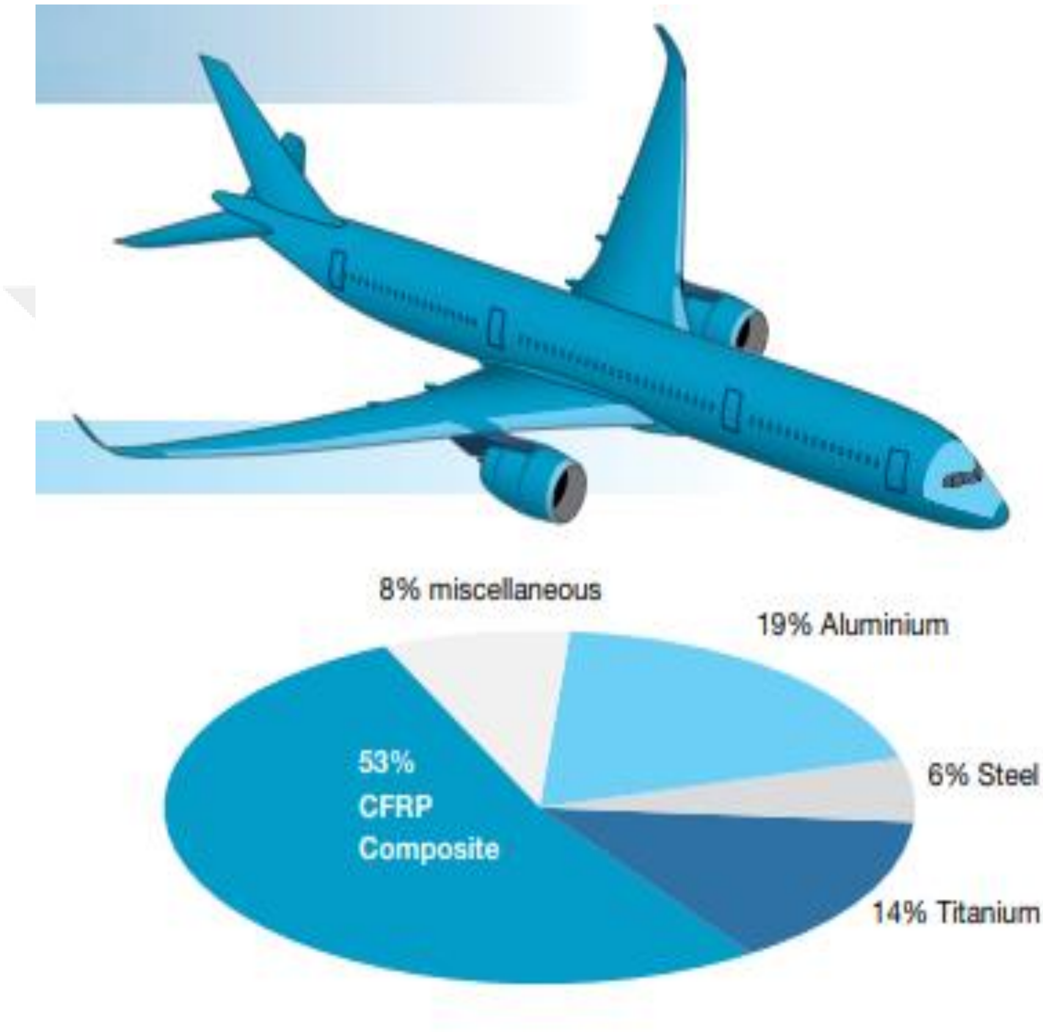

Figure 2.4: Materials used in the Airbus A350 XWB [32]

2.5.4 Failure Analysis

In material deformation analysis, ABAQUS, ANSYS and similar numerical analysis programs are used in many complex geometries and various loading and conditions are tested through these programs. These programs play a role in establishing the structure in a reliable and inexpensive way.

Nonetheless, these codes currently lack inclusive failure models crucial in the design of engineering components. This limitation stems from the inherently complex nature of the physical failure process. Ductile and brittle fracture mechanisms exhibit notable distinctions, influenced by diverse factors like strain rate, temperature, and more. Moreover, the failure characteristics of certain materials can transition from ductile fracture under quasi-static loading to a brittle mode at elevated strain rates. [33]

Many researchers have studied material damage models, and among these models, those dealing with ductile materials are divided into two. Microscopic models based on continuum mechanics, macroscopic models based on experimental knowledge.

2.5.4.1 Continuum Mechanics

In the traditional framework, Continuum Mechanics enables the characterization of heterogeneous microprocesses occurring during the deformation of materials. Structures at the macroscale, including elastic and plastic strains along with their associated hardening effects, are commonly modeled using global continuum variables within the framework of Continuum Mechanics. This is the case despite the non-homogeneous nature of micro defects such as grains, sub-grains, dislocations, and cells. The damaging processes correspond to localizations and accumulations of the strains and are considerably more irreversible. [34] The core principle of this approach revolves around assessing the material's permissible limits by comparing them to the maximum stress and/or strain values derived from the analyses.

2.5.4.2 Johnson-Cook Failure Model

The Johnson-Cook (Johnson & Cook, 1983) constitutive model was presented by Johnson and Cook in the early 1980s and is frequently used in impact and structure analysis today. The Johnson-Cook model is formulated based on Von Mises tensile flow stress, incorporating aspects of strain hardening, strain rate hardening, and thermal softening. Johnson-Cook deformation model is represented in Equation (2.1), which is shown below.

$$\sigma_y = [\ A+B\epsilon_p^{-n}]\ [C.\ln(\frac{\dot{\epsilon_p}}{\dot{\epsilon}_0}]\ [1-(\frac{T-T_r}{T_m-T_r})^m] \quad (2.1)$$

The parameter ϵ_p is the effective plastic strain, $\dot{\epsilon_p}$ is the effective plastic strain rate, $\dot{\epsilon}_0$ is a reference plastic strain rate, A is the initial yield strength of the material at quasi-static strain rate, B represents strain hardening, n is a dimensionless strain hardening exponent. The value of n determines the material's plastic flow direction and material model: (1) when n=1, the material is an ideal linear elastic material; (2) when n=0, the material is nonlinear elastic; (3) when 0 < n < 1, the material is elastoplastic. C is the dimensionless model parameter which determines strain rate effect, m is dimensionless model parameter which determines thermal softening effect. T represents current temperature, T_r and T_m are the reference temperature and melting temperature, respectively.

2.6 Analytical Models For Lap Joints

2.6.1 Volkersen Model

In 1938, Volkersen [35] introduced the shear lug method, also known as his shear lag model. This analytical approach was initially proposed for mechanical joints featuring multiple fasteners. Subsequently, the model was applied to adhesively bonded lap joints, assuming that the adherends experience tension, and the adhesive undergoes shear deformation, with both stresses remaining constant across the thickness.

The adhesive shear stress distribution (τ) is shown in Equation (2.2):

$$\tau = \frac{P}{bl}\frac{w}{2}\frac{\cosh(wX)}{\sinh(w/2)} + \left(\frac{\psi-1}{\psi+1}\right)\frac{w}{2}\frac{\sinh(wX)}{\cosh(w/2)} \quad (2.2)$$

where P is the applied load, b the joint width, and l the overlap,

$$w^2 = (1+\psi)\phi \tag{2.3}$$

$$\psi = t_t / t_b \tag{2.4}$$

$$\phi = \frac{G_a l^2}{E t_t t_a} \tag{2.5}$$

$$X = \frac{x}{l}, \qquad -\frac{1}{2} \leq X \leq \frac{1}{2} \tag{2.6}$$

In the Equations (2.3), (2.4), (2.5) (2.6) above, t_t represents the thickness of the top adherend, t_b denotes the bottom adherend, E signifies the modulus of the adherend, G_a represents the shear modulus of the adhesive, and t_a corresponds to the thickness of the adhesive. The longitudinal coordinate x is referenced from the midpoint of the overlap. [36]

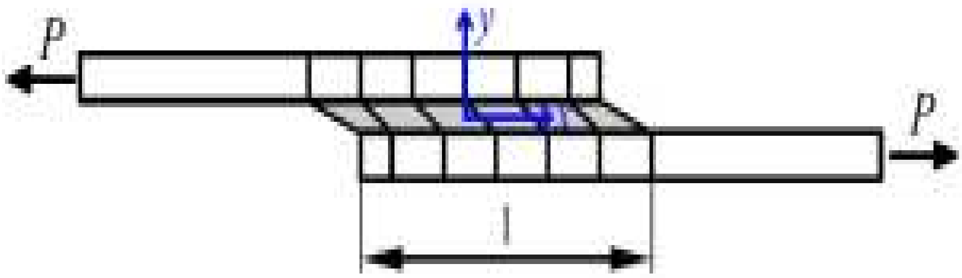

Figure 2.5: Volkersen Model [37]

2.6.2 Goland and Reissner Model

Goland and Reissner were pioneers in addressing the influences stemming from the rotation of adherends, as shown in Figure 2.6. Their approach involved a two-part division of the problem: (a) determining the loads at the edges of the joints through the application of the finite deflection theory of cylindrically bent plates, and (b) establishing the stresses within the joints resulting from the applied loads. [37] Goland and Reissner concur in their methodologies, acknowledging that the flexural forces induce peel stress within the adhesive layer. Both approaches incorporate consideration of the edge moment on the overlap factor.

Furthermore, they share the perspective that both the adhesive and adherend demonstrate elastic characteristics in their analyses.

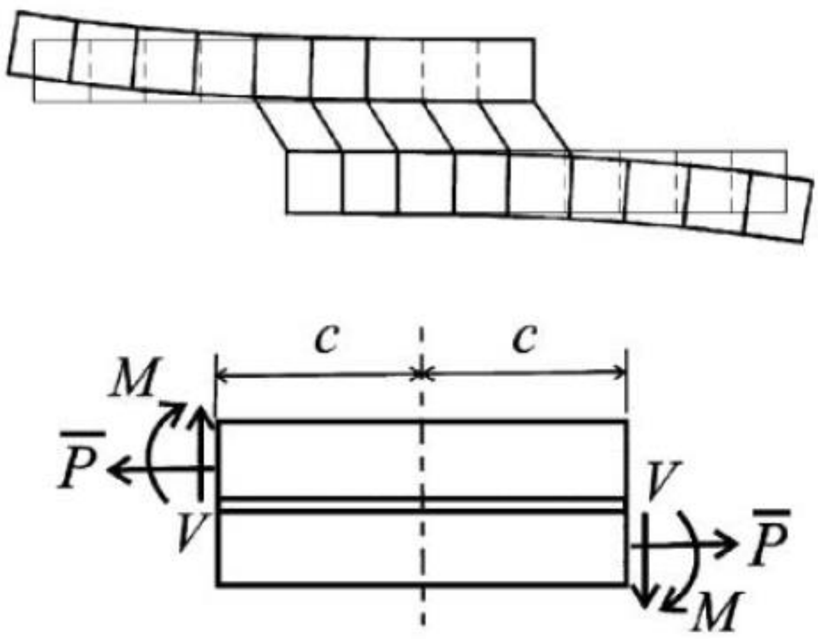

Figure 2.6: Deformation model of Goland and Reissner [37]

"M" represents the bending moment, "V" denotes the transverse force at the end of the overlap area, "t" signifies the adherend thickness, "k" is the bending moment factor, "P" stands for the tensile load, and "c" represents half of the overlap length in the equations. The tensile stress and shear stress of the adhesive layer in the calculations for the overlapped area are illustrated in Equations (2.7) and (2.8).

$$M=k\frac{Pt}{2} \tag{2.7}$$

$$V= k'\frac{Pt}{c} \tag{2.8}$$

2.6.3 Hart-Smith Model

In the year 1973, Hart-Smith presented an improved model that removes the constraint of a lumped overlap, which was assumed in the Goland and Reissner analysis. This advancement includes the treatment of adherends as beams resting on an elastic foundation. Additionally, the model introduced stress solutions for adhesives exhibiting both linear elastic and elastic-plastic behaviors.

Hart-Smith offered an intricate analysis that essentially integrates parts I and III of Goland and Reissner's work. It considers the distinct deformations of both the upper and lower adherends within the overlap, a more realistic approach compared to the simplified lumped overlap assumption.

The Hart-Smith analysis involves the determination of the edge moment, M_0, and adhesive shear and transverse normal stresses (τ_0, and (σ_0), simultaneously.

The M_0, obtained from this approach is a function of E, c, t, I, T, E_C and η (recall that EC and v are not included in the Goland and Reissner's MC, formulation) [38]

However, while the significant deformation effect in the outer adherend is considered in the application of this model, the deflection effect in the overlap region is disregarded.

$$M_0 \cong T\left(\frac{t+\eta}{2}\right)\left(\frac{1}{1+\xi c+\frac{\xi^2 c^2}{6}}\right) or \tag{2.9}$$

$$k \cong \left(1+\frac{\eta}{t}\right)\left(\frac{1}{1+\xi c+\frac{\xi^2 c^2}{6}}\right) \tag{2.10}$$

CHAPTER 3

IMPACT

3.1 Fundementals

Impact mechanics is one of the most complex and detailed disciplines from an engineering perspective. It sheds light on numerous outcomes in terms of applications and scientific studies, and is examined in various fields such as defense, aviation, and construction.

A ballistic-grade dynamics problem requires a detailed consideration of its experimental observations and, if any, the underlying theory. Impact mechanics encompasses a broad subject where research has been undertaken to understand transient loads, industrial accidents and explosions that produce high strain rates. Impact-induced stress waves occur, which propagate through high-speed deformation under the effect of impact. The motion of waves is felt everywhere, as in the case of earthquakes, tsunamis, and explosions. [39]

A prominent historical pattern involves grouping impact parameters, defined by prevalent and challenging engineering scenarios where impact poses a threat. Five illustrative categories frequently encountered in the literature include crashworthiness, dropped tools, runway debris, bird strike, and ballistic events. Ballistics encompasses the study of the trajectory and impact of various projectiles. This scientific and artistic discipline is dedicated to the design and launch of projectiles, aiming to achieve specific performance outcomes and target precision. In the realm of ballistics, projectiles utilize impact forces to penetrate surfaces that might endure substantial pressure. For instance, at standard bullet velocities, a rubber sheet exhibits characteristics similar to glass—breaking rather than stretching or vibrating. [39]

When all these aspects are combined, the examination of the impact mechanics of specific materials requires comprehensive investigation of topics such as action-response, damage assessment, external factors (temperature), and strain rate etc., necessitating detailed material modeling.

3.2 Methods Used in Testing

When investigating adhesively bonded single lap joints under impact conditions, specialized methods are employed to assess the joint's performance and integrity in dynamic loading scenarios. The main reason for using these methods is to achieve the desired performance under operating conditions. Various methods dependent on strain rate are employed, and these methods are tested based on loading rates and deformation ratios. The main investigation methods used are outlined in this section.

3.2.1 Quasi Static Material Test

Quasi-static material testing encompasses the assessment of a material's mechanical properties under deliberate and controlled loading conditions, often at a consistent and low strain rate. This approach permits researchers to examine how the material behaves and responds to externally applied forces, offering valuable insights into its stiffness, strength, and deformation attributes. In contrast to dynamic testing, quasi-static testing is centered around conditions where the loading rate is sufficiently gradual to uphold equilibrium throughout the test, facilitating precise measurements and analysis of material properties.

3.2.2 Drop Weight Test

The procedure generally involves a mass dropping process, where a weight collides with a clamp typically bolted to the lower substrate of the specimen. In Figure 3.1, the arrangement employed to secure the sample in place is observable.

Controlling the weight of the impacting mass allows for the management of the energy applied to the impact, while the chosen falling distance determines the impact velocity.

Figure 3.1: Rosand Instrumented Falling Weight Test Machine [15]

3.2.3 Charpy Impact Test

The Charpy impact test is a method designed to quantify the energy absorbed by a material during fracture when subjected to high-velocity impact conditions. This test evaluates the material's capacity to endure abrupt loads and assists in defining its notch sensitivity, ductility, and overall toughness. Specimens with either rectangular or V-notch configurations are crafted from the material under examination, with the notch creating a stress concentration to mimic a potential weak point.

Following specimen preparation, it is securely affixed in a testing apparatus, positioned such that the notch faces outward. A pendulum or striking device is then released from a predetermined height to impact the opposite side of the notched specimen, causing it to fracture. The energy absorbed during this fracture is gauged by observing the pendulum's swing after impact. The difference in potential energy before and after impact serves as a metric for the absorbed energy.

Typically, the results are expressed in terms of the absorbed energy measured in joules or foot-pounds. A lower absorbed energy value indicates a higher degree of brittleness in the material.

The Charpy impact test plays a pivotal role in evaluating the impact resistance of materials utilized across diverse engineering applications, including construction, manufacturing, and structural design. It aids in predicting the behavior of a material under sudden loading conditions, supplying valuable insights for material selection and ensuring the safety and reliability of structures and components. In various applications, there are variations of Charpy impact test apparatus, such as modified impact test apparatus, to obtain results with desired specifications. The Charpy impact test apparatus and modified test apparatus are shown in Figures 3.2 and 3.3.

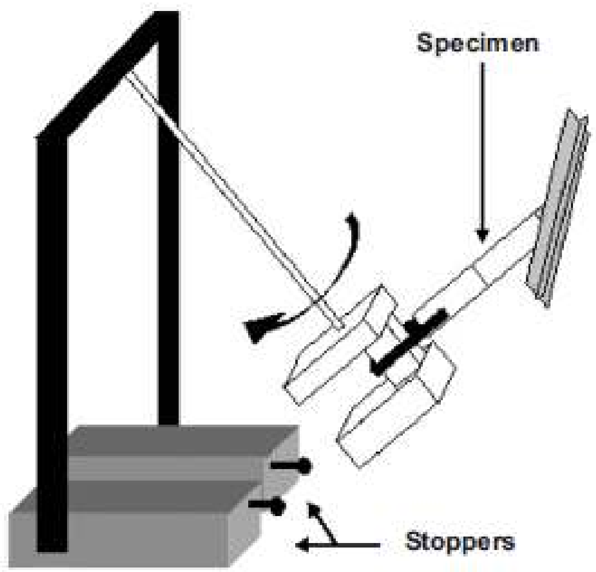

Figure 3.2: A schematized modified pendulum impact test apparatus. [40]

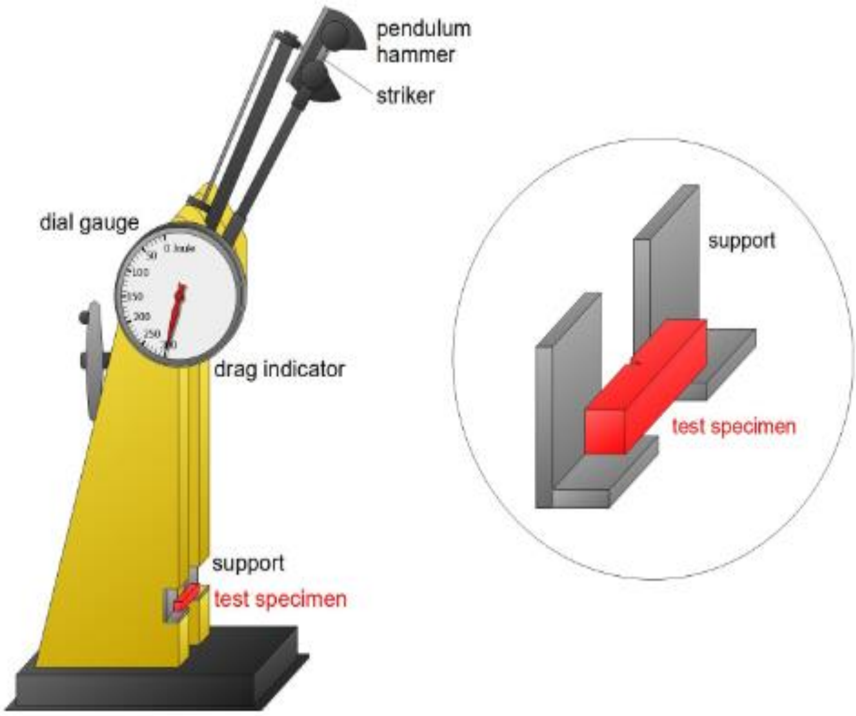

Figure 3.3: A schematized Charpy impact test apparatus. [41]

3.2.4 Izod Impact Test

The Izod impact test is a standardized procedure employed to assess the toughness or impact resistance of materials, with a particular focus on polymers and metals. Named after the British engineer Edwin Gilbert Izod, who pioneered the method, this test involves the machining of a notched sample, often in the form of a rectangular bar, from the material under investigation. The V-shaped notch is deliberately introduced to generate a stress concentration, simulating a potential weak point in the material. The specimen is securely clamped in a vertical position, with the notched side facing outward. Subsequently, a pendulum or striker is released from a predetermined height to impact the notched side of the specimen, resulting in its fracture.

Measurement of the energy absorbed during fracture is achieved by observing the pendulum's swing after impact. The difference in potential energy before and after impact serves as a metric for the absorbed energy. Reporting of the results typically involves the energy absorbed, expressed in joules or foot-pounds. A lower absorbed energy value indicates increased material brittleness.

The Izod impact test holds significant importance in evaluating a material's capability to withstand sudden impacts, providing crucial insights into its toughness, notch sensitivity, and overall resistance to impact. These test results find widespread application in material selection processes, quality control procedures, and engineering design considerations, particularly in situations where materials may be subjected to dynamic or impact loading conditions. The Izod impact test apparatus is shown in Figures 3.4.

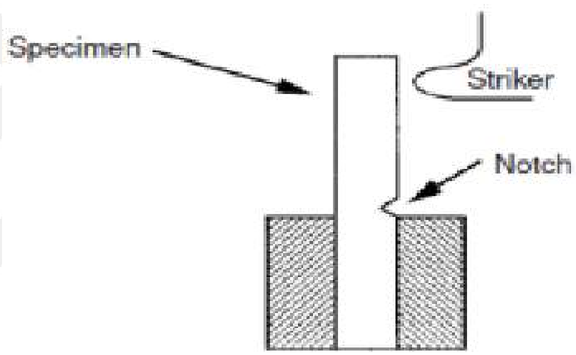

Figure 3.4: A schematized Izod impact test apparatus. [42]

3.2.5 Split Hopkinson Pressure Bar Impact Test (SHPB)

The Split Hopkinson Impact Test is an experimental method employed to analyze the dynamic characteristics of materials under conditions of high strain rates, especially during impact or collision occurrences. The main aim of the SHPB test is to expose a specimen to dynamic loading situations, such as high-velocity impact, and assess the resulting stress and strain reactions. This technique finds widespread application in the fields of materials science, mechanical engineering, and impact physics research.

The test configuration typically consists of three primary elements: the incident bar, specimen, and transmission bar. The incident bar transmits a compressive stress pulse to the specimen, generating a longitudinal stress wave.

This transmitted stress wave travels through the specimen, inducing deformation. Ultimately, the transmission bar captures the stress and strain responses exhibited by the specimen.

In conclusion, the Split Hopkinson Impact Test stands as a robust experimental approach for characterizing the dynamic properties of materials. It provides valuable insights for the design of materials capable of withstanding high-speed impact or collision scenarios, and its applications extend to various fields, including materials science, mechanical engineering, and impact physics research.

A sample Split Hopkinson Pressure Test bar used in the studies of T. Yokoyama and K. Nakai [43] is illustrated in the following Figure 3.5.

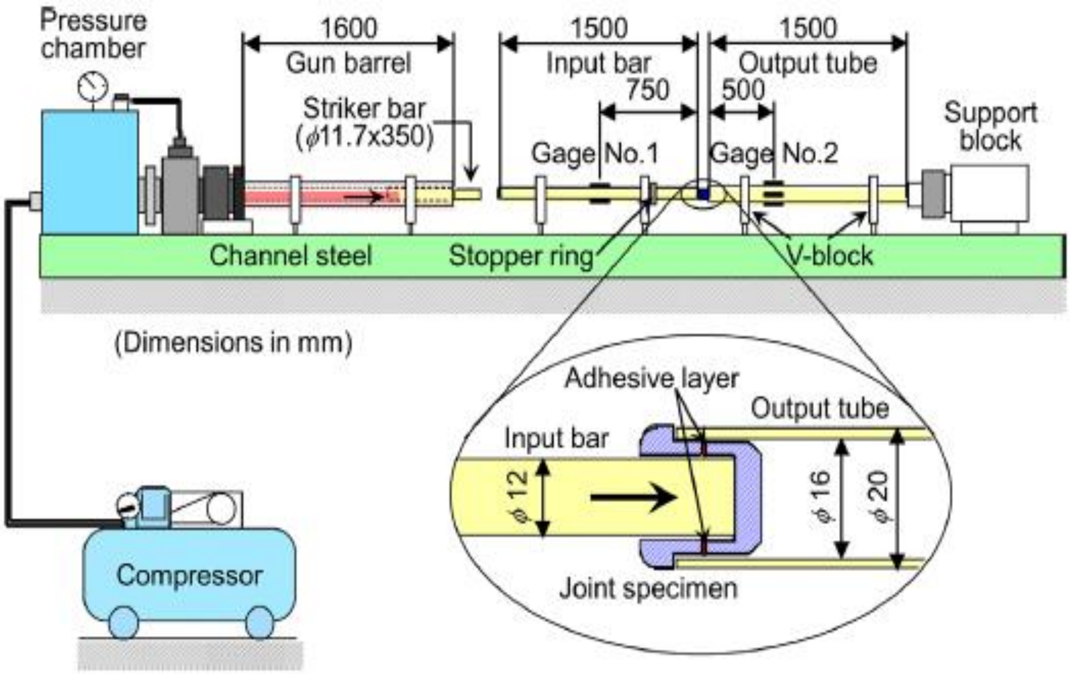

Figure 3.5: Schematic diagram of modified SHPB apparatus using joint specimen [43]

3.2.6 High Velocity Gas Gun Test

The high-velocity gas gun impact test is an experimental methodology employed to examine how materials or structures respond to impacts from high-velocity projectiles. In this approach, a gas gun is utilized to propel a projectile towards a target material, creating conditions that mimic dynamic impacts. This testing method is commonly applied in research fields such as ballistics, materials science, and structural engineering.

Fundamentally, the key principle revolves around propelling a projectile to high velocities through the controlled and repeatable release of compressed gas, typically air or nitrogen. Subsequently, the accelerated projectile is directed towards a target material or structure, replicating impact scenarios akin to real-world situations, such as ballistic impacts or collisions.

The essential components of a high-velocity gas gun impact test generally include the gas gun itself, a projectile, and the target material or structure. The gas gun is comprised of a barrel, a gas chamber, and a mechanism for the rapid release of gas. The projectile is loaded into the barrel, and upon initiating the gas release mechanism, the compressed gas propels the projectile down the barrel toward the target.

These impact tests play a critical role in comprehending how materials and structures behave and perform under extreme impact conditions. The insights gained from such tests are invaluable in the design of materials intended for applications like armor, aerospace components, and protective structures, where resilience against high-speed impacts is a crucial consideration.

The example experimental system below has been schematically illustrated in Figure 3.6.

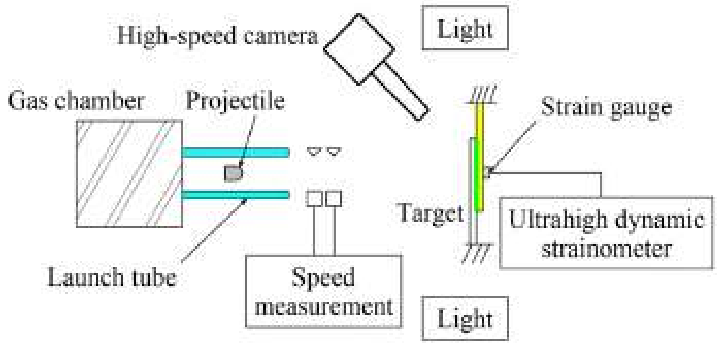

Figure 3.6: Schematic of the High Velocity Gas Gun [44]

CHAPTER 4

THE EXPERIMENTAL AND NUMERICAL STUDY OF THE EFFECTS OF REPEATED HIGH LOADINGS ON THE PERFORMANCE OF ADHESIVELY-BONDED SINGLE LAP JOINTS

4.1 Aim of the Study

This study aims to investigate the effects of repeated high loadings on the performance of adhesively-bonded Single Lap Joints (SLJs) by employing both experimental and numerical approaches.

4.2 Experimental Works

4.2.1 Sample Preparation

The Single Lap Joints (SLJs) were manufactured using AA6061 aluminum adherends, and they were bonded using a thermosetting modified epoxy adhesive film (AF163-2K), a knitted film produced by 3M Scotch-Weld™. The surface preparation of the adherend to be bonded was thoroughly cleaned with acetone. Subsequently, the adhesive film was meticulously applied to the substrate, with special attention to minimizing the entrapment of air during the application process. All the Single Lap Joints (SLJs) were fabricated using a specially-designed jig that allowed for the production of specimens with varying adherend thicknesses and overlap lengths. Subsequently, we placed the jig in a digitally controlled oven, by curing the joints for 60 minutes at a temperature of 125°C while maintaining a pressure of approximately 2 bar, following the supplier's recommendations. The manufactured joints had an overlap length of 15 mm, an adherend thickness of 4 mm, and an adhesive layer thickness of 0.2mm. 15 mm joints are shown in Figure 4.1 and Figure 4.2 prepared before the ballistic test.

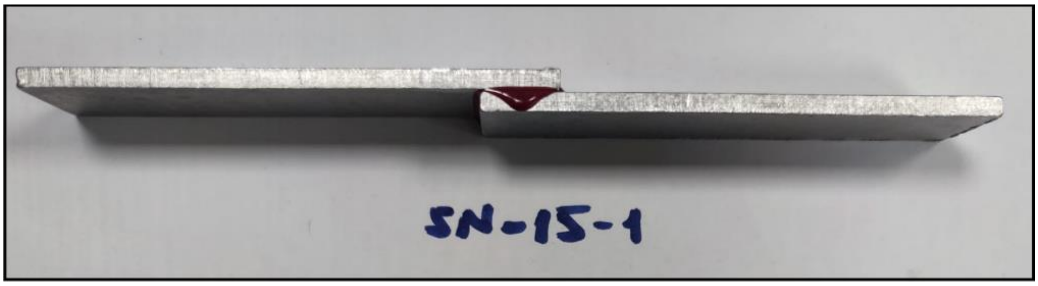

Figure 4.1: Specimen to be subjected to 3 shots - before the ballistic test

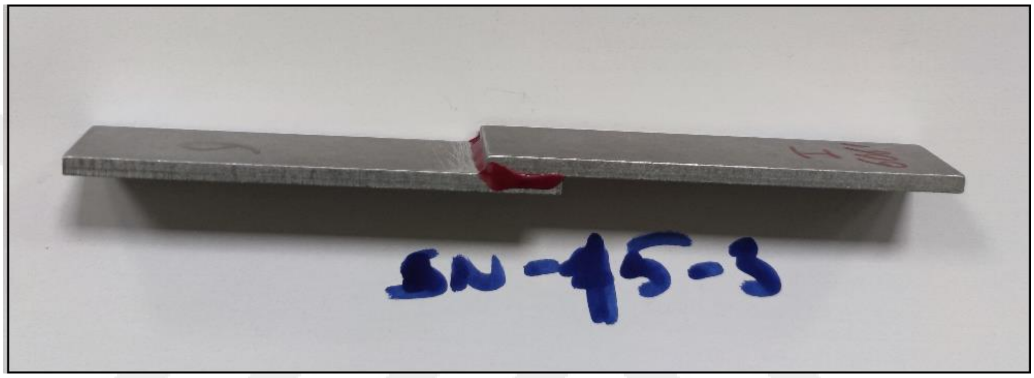

Figure 4.2: Specimen to be subjected to 2 shots - before the ballistic test

4.2.2 Experimental Setup

The ballistic tests were conducted using an air-pressurized gun, as shown in Figure 4.3, which illustrates the experimental setup. The setup includes a high-speed camera, an air-pressurized gun, a data collection system, a clamped-clamped fixation for the specimens, and a test cabin.

Figure 4.3: The experimental set-up for the ballistic test

The specimens fixed in a clamped-clamped configuration according to ASTM-D1002-5 with specially designed apparatus which is shown in Figure 4.4. Air gun has a pressure setting and able to push the projectile up to 300 m/s. The images of the fired bullet were recorded with respect to time using a high-speed camera and a ruler situated in the projected area. Figure 4.5 shows the image taken at 30.000 FPS of the projectile fired at a speed of 280 m/s towards the clamped-clamped fixed specimen, while measuring it with the help of a ruler.

The shot made in a specially designed cabin was recorded with the help of a special fast-motion camera, and then the video recordings were examined and the frames of the projectile just before it hit were captured. Depending on the frame rate of the camera, its speed in consecutive frame rates was calculated based on the distance it traveled on the ruler, and its speed in one second was calculated.

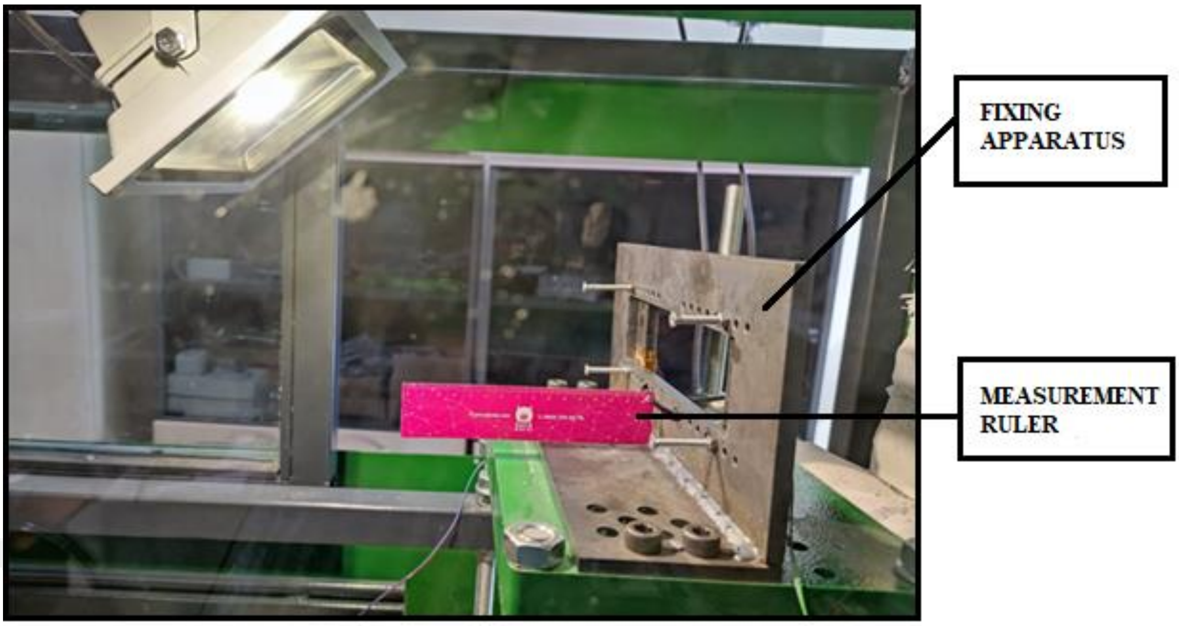

Figure 4.4: The apparatus in which the specimens are fixed in a clamp-clamp configuration and the measurement ruler fixed before the test.

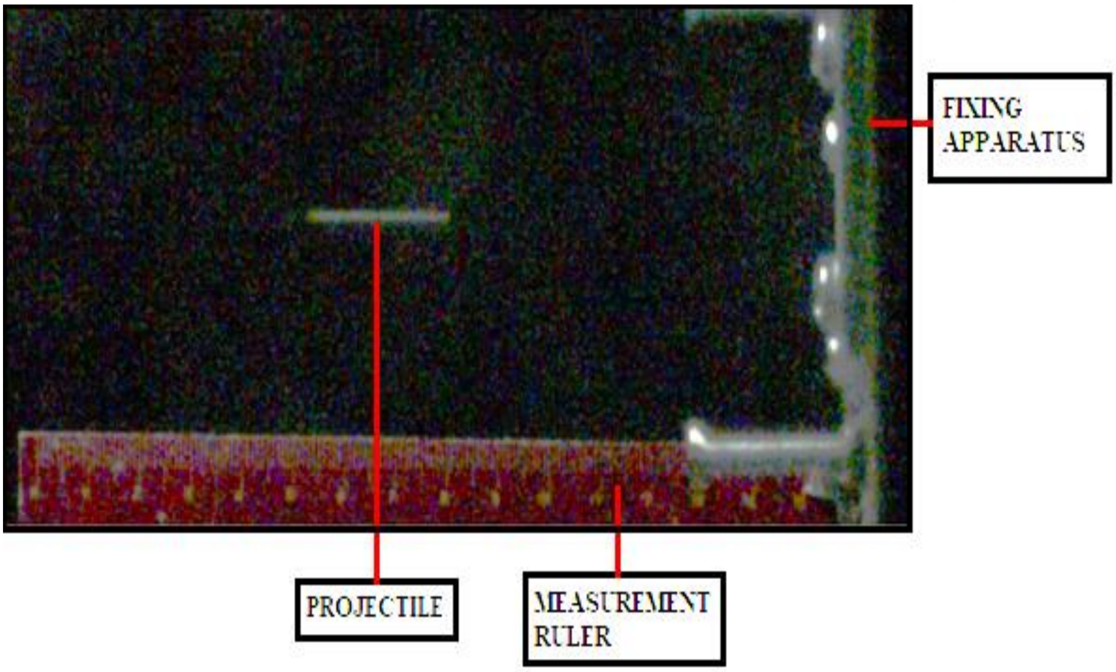

Figure 4.5: The image taken at 30.000 FPS of the projectile fired at a speed of 280 m/s towards the clamped-clamped fixed specimen, while measuring it with the help of a ruler.

4.2.3 Quasi-Static Tensile Test

The impacted samples up to 2 times were subjected to a Besmak BMT-S 100 kN universal testing machine to assess variations in mechanical performance. Because the joints those subjected to 3 times were ruptured at the end of the experiment. The samples were clamped to the testing machine which is shown in Figure 4.6 with a distance of 25 mm from both ends, and then they were tested with a tensile speed of 0.031667 mm/second. The test data of the samples were taken instantly, and force (kN) vs. displacement (mm) graphs are created in Excel. The maximum force of the specimens at break was recorded. The report resulting from the quasi-static test is shown in the Figure 4.7. According to the test results, it was observed that the joint sample reached the maximum load of 4.98 kN and the load to fail is 4.85 kN.

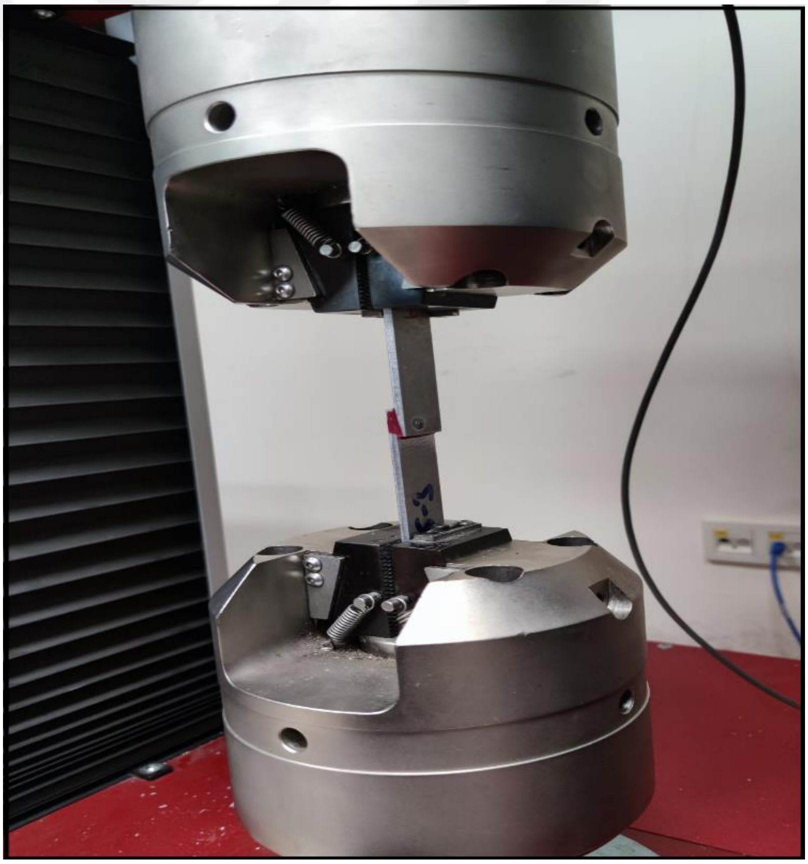

Figure 4.6: Quasi-Static Tensile Test Machine (Besmak-BMTS)

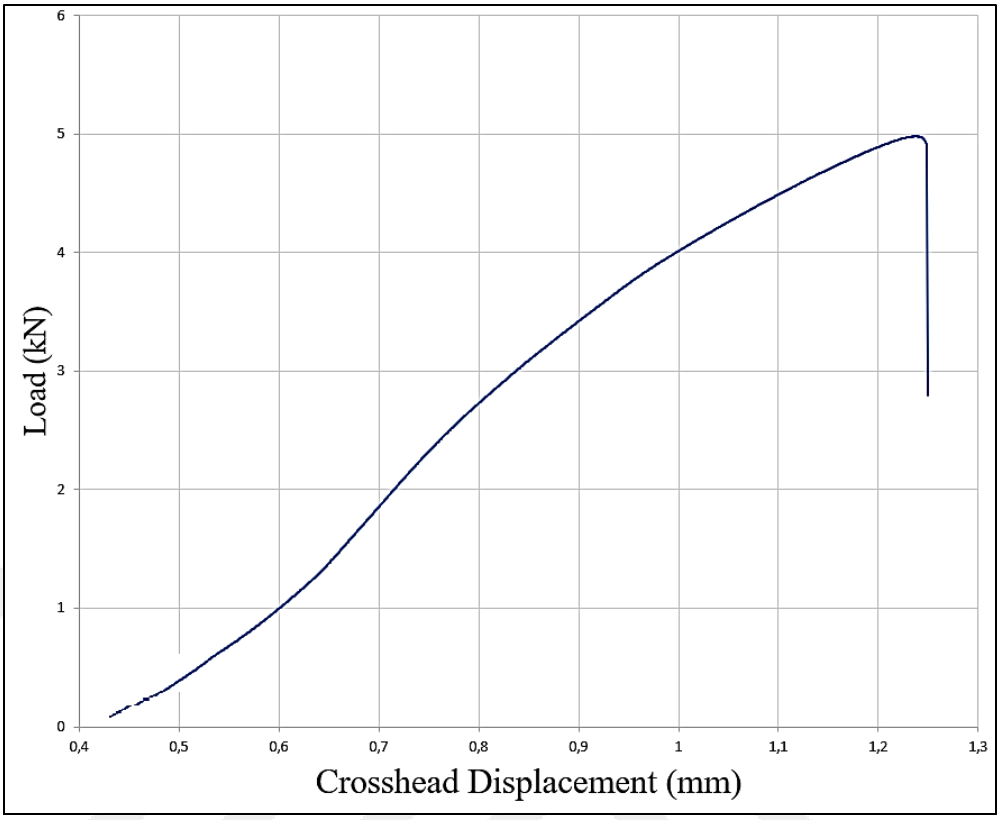

Figure 4.7: Quasi-Static Tensile Test Result

4.2.4 Numerical Modelling

A Finite Element Method was employed using the Abaqus software package to predict the impact performance of Single Lap Joints. The same dimensions as those used in the experiment were employed for the analyses, with clamped-clamped boundary conditions shown in Figure 4.8. The C3D8R element type, a general-purpose linear brick element, was used, and a total of 19898 elements were employed in the model of the adhesively bonded Single Lap Joints with a 15 mm of overlap. The simulation was made according to a single-shot firing condition.

As mentioned earlier, Goglio et al. [23] conducted some experiments observing that the adhesive's yield strength increased by up to three times under compression and up to five times under tension when compared to quasi-static values. The elastic modulus remained unchanged under both high and quasi-static loading conditions.

Therefore, it was assumed that the maximum stress behavior of the adhesive at high impact velocities would be five times higher than that observed in quasi-static tests.

The Von Mises stress criterion was used to evaluate critical stresses in the joint at critical regions, and to predict the failure, which assumes that the failure occurs when the Von Mises stresses reach the ultimate uniaxial stress of the material, which was 239 MPa. With all this information and studies, analysis was made using the Abaqus software package.

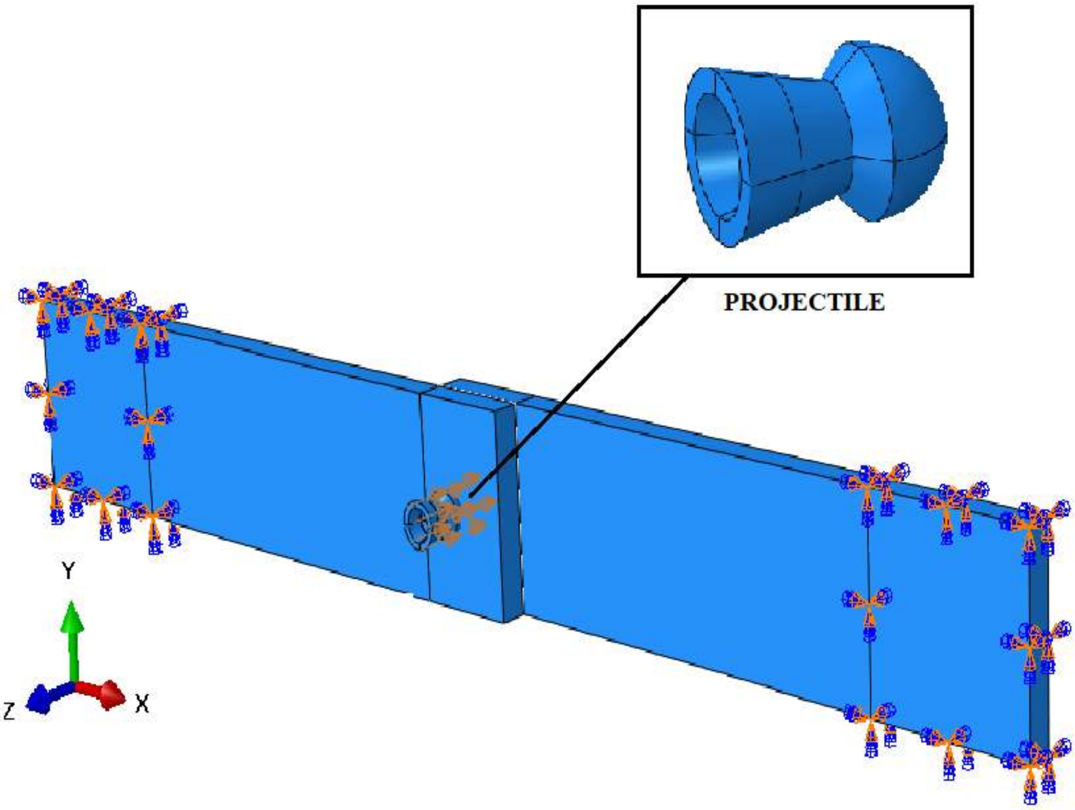

Figure 4.8: The Boundary conditions of adhesively bonded SLJ.

4.2.4.1 Drawing of Joints and Projectile

To analyze adhesive-bonded single lap joints in the Abaqus program, adherends and adhesives must first be designed in the program. Part dimensions designed on the Abaqus part manager module were made in accordance with the technical dimensions specified in Figure 4.9. All dimensions are in millimeters.

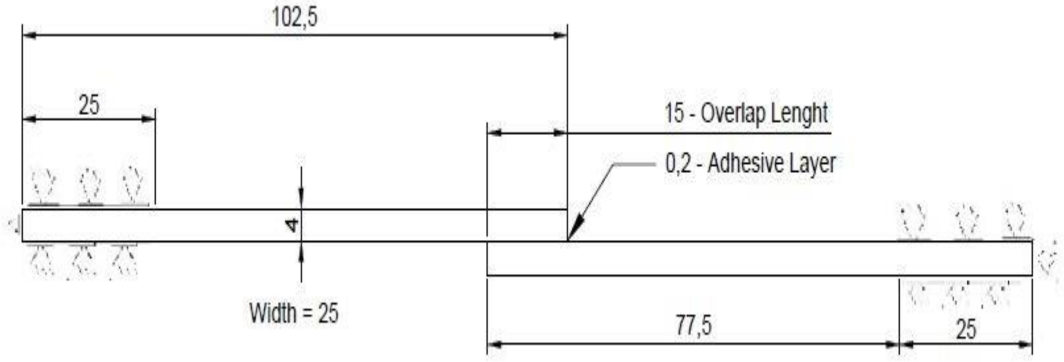

Figure 4.9: The dimensions of adhesively bonded SLJ.

4.2.4.2 Johnson-Cook Material Model Parameters

The Johnson-Cook method for the aluminum adherends and an elasto-plastic curve for the adhesive layer were used as input data for the numerical analysis. The values taken for the numerical analysis of the 6061 Aluminum adherend and lead pellet were based on the values from previous studies. [45][46]

In the Johnson-Cook modeling, A, B, n, and m parameters shown in Table 4.1 which are material constants obtained from tension and compression tests at different strain rates and temperatures. A symbolized by the material's yield stress under reference conditions, B denotes the strain hardening constant, n represents the strain hardening coefficient, m signifies the thermal softening coefficient, and Tr and Tm refer to the reference temperature and the material's melting point, respectively. The maximum stress of the adhesive, 47.8 MPa, was experimentally determined through quasi-static testing. This value was then multiplied by 5 to obtain the maximum stress value (239 MPa) to mimic the actual stress at impact test which was used as input data for the current analysis, as reported in a previous research [24].

The actual tensile stress-strain curve and the corresponding impacted curve of the adhesive, obtained from the quasi-static test and the converted high loading rate, is shown in Figure 4.10. [24]

Table 4.1 Johnson Cook parameters used in numerical analysis for projectile and adherends

Materials	A (MPa)	B (MPa)	N	M	Tr (K)	Tm (K)
Lead	24	300	1.00	1.00	298	925
Aluminium 6061	324	114	0.42	0.34	293	893

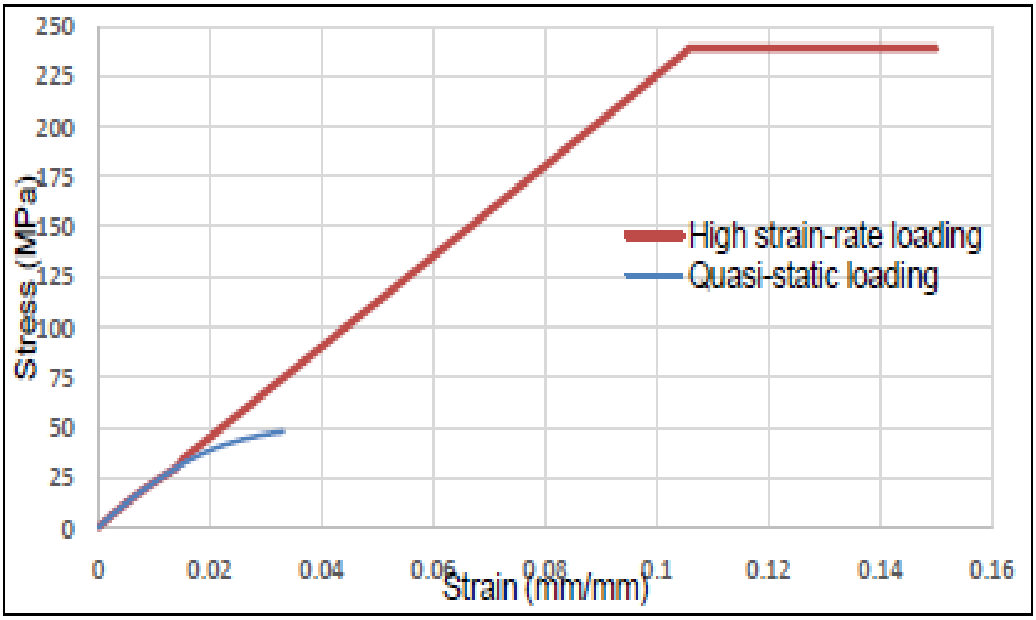

Figure 4.10: Tensile stress-strain curve of the adhesive layer used in the numerical analysis from previous research. [24]

4.2.4.3 Selecting Material Properties

After the drawing of adhesive single lap parts is completed, the material is defined on the part via the Abaqus Property Manager module.

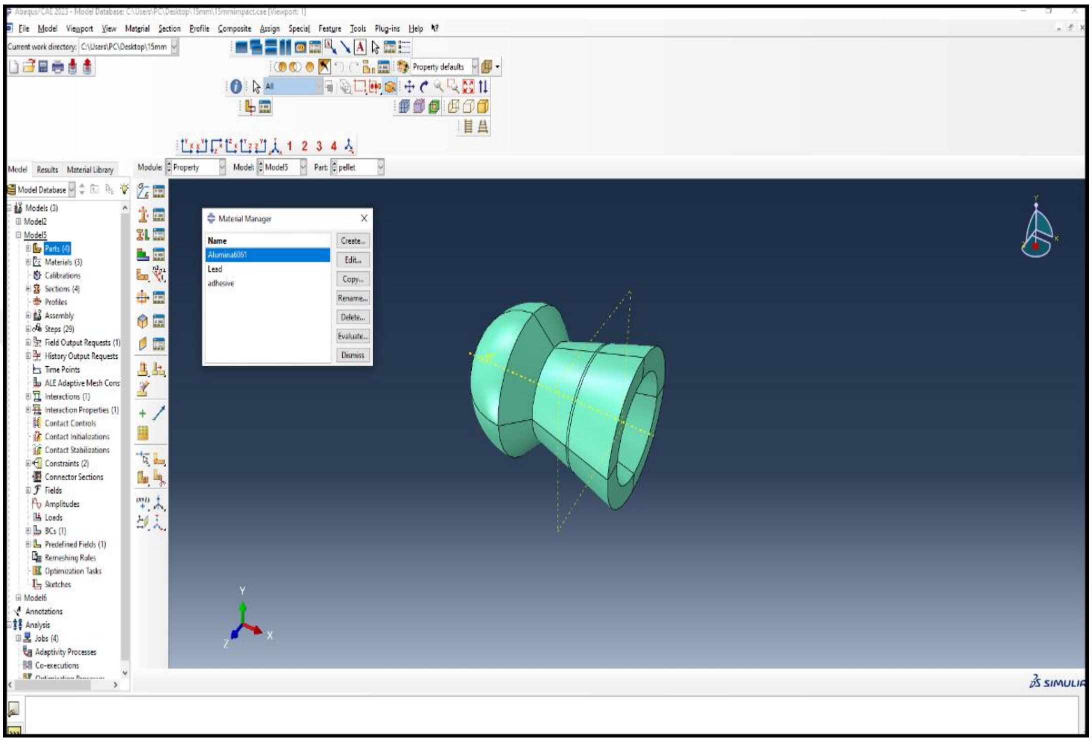

Figure 4.11: Design of Single Lap Joint via properties module

The properties of the materials designed to be used in the analysis and the entered parameters are stated in the Table 4.2.

Table 4.2: Parameters Used in Properties Module

<table>
<tr><th colspan="2">Parameters</th><th>Aluminium 6061</th><th>Lead Pellet (Projectile)</th><th>Adhesive-(AF-163 2K)</th></tr>
<tr><td colspan="2">Density (tonne/mm^3)</td><td>2.8E-09</td><td>1.066E-08</td><td>1.355E-09</td></tr>
<tr><td rowspan="2">Elastic (MPa)</td><td>Young's Modulus</td><td>69000</td><td>1000</td><td>2000</td></tr>
<tr><td>Poisson's Ratio</td><td>0.33</td><td>0.42</td><td>0.3</td></tr>
<tr><td colspan="2">Plastic (Mpa)</td><td>The entered values are stated in the previous section. (Table 4.1)</td><td>The entered values are stated in the previous section. (Table 4.1)</td><td>From stress/strain curve Figure (4.10)</td></tr>
<tr><td rowspan="8">Damage For Ductile Materials-Johnson-Cook Damage (mm, MPa, Kelvin)</td><td>d1</td><td>-0.77</td><td rowspan="8">-</td><td rowspan="8">-</td></tr>
<tr><td>d2</td><td>1.45</td></tr>
<tr><td>d3</td><td>-0.47</td></tr>
<tr><td>d4</td><td>0</td></tr>
<tr><td>d5</td><td>1.6</td></tr>
<tr><td>Melting Temperature</td><td>925</td></tr>
<tr><td>Transition Temperature</td><td>294</td></tr>
<tr><td>Reference Strain Rate</td><td>0</td></tr>
</table>

4.2.4.4 Assembly, Step, Interaction, Loading, Meshing Properties

After the drawing process of the parts and assignment of material properties, the assembly process is carried out for the Adhesively Bonded Single Lap Joint connection. The assembly process is done from the Assembly tab. Parts; It is called from the Assembly > Create Instance section and their locations are determined. Created assembly is shown in Figure 4.12.

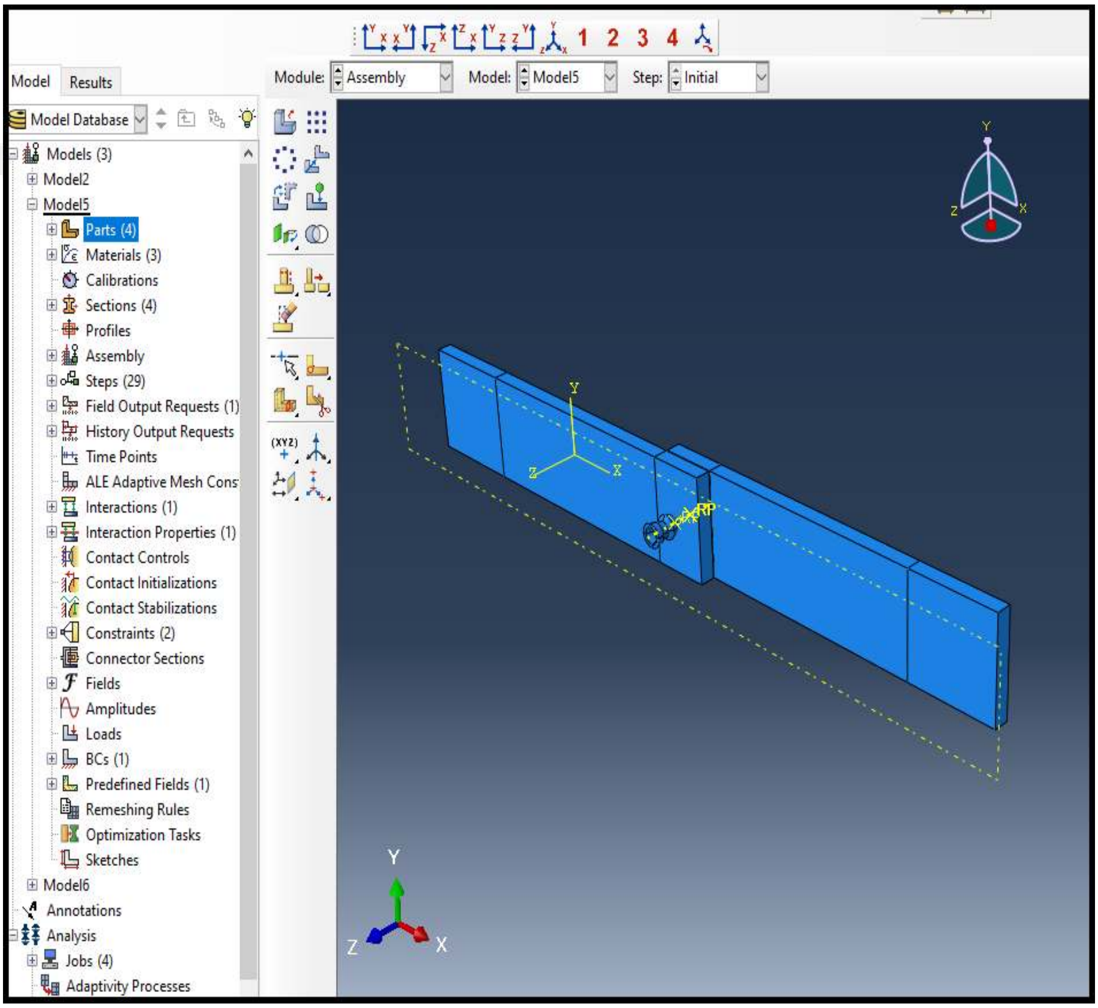

Figure 4.12: Assembled view of Single Lap Joint in Abaqus package programme

The next module on the program is the step module, and our analysis type Dynamic>Explicit is determined in this section. The specified menu is shown in the Figure 4.13.

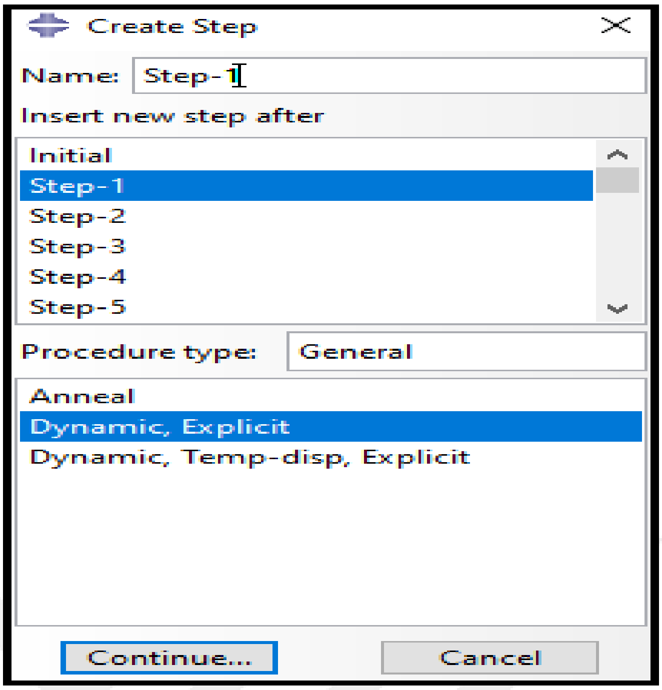

Figure 4.13: Determining the analysis type via the Step menu.

Part relationships are determined with the Abaqus Interaction module tool in Figure 4.14. Contact is selected from the Interaction properties menu, then Tangential Behavior > Penalty > Friction Coeff 0.7 value, then Hard contact is selected from the Normal Behavior option and this step is completed. The specified parameters are defined by selecting them in the General Contact (Explicit) section in the Interaction Manager.

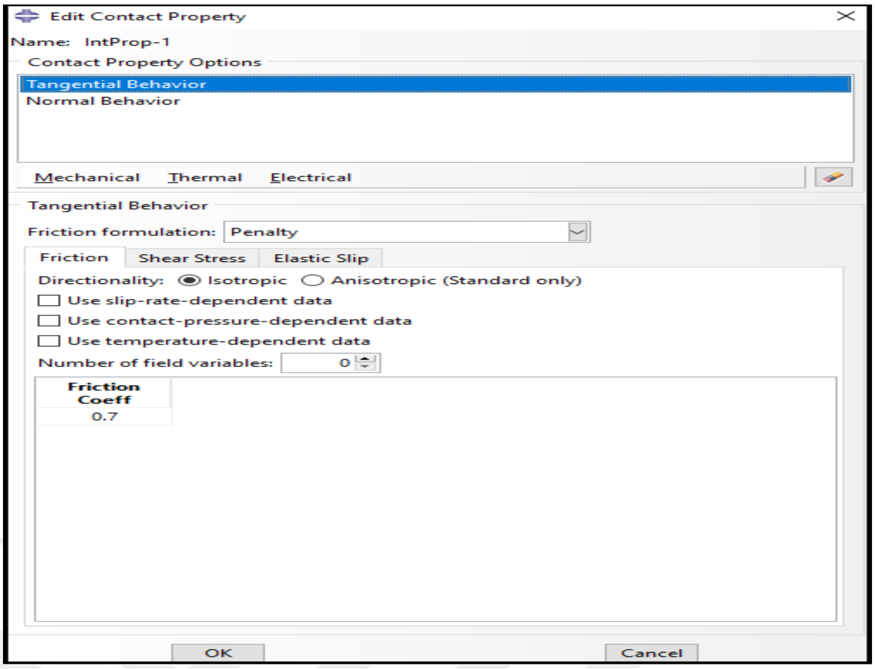

Figure 4.14: Determining contact property via the Interaction Properties menu.

After determining the relationships between the parts, the next definitions are made within the load module. After the relationships between the parts are determined, subsequent definitions are made within the load module shown in Figure 4.15. For initial from the Load> Create Boundary Condition section, it is fixed on two surface area so that the SLJ can be simulated in accordance with the real experiment. Then, the speed of the projectile is selected from the Predefined Field Manager > Type-Speed > Step-Initial and the speed is completed by defining 279970 mm/sec, which is our average speed in the experiment. The specified parameters are shown in Figure 4.16.

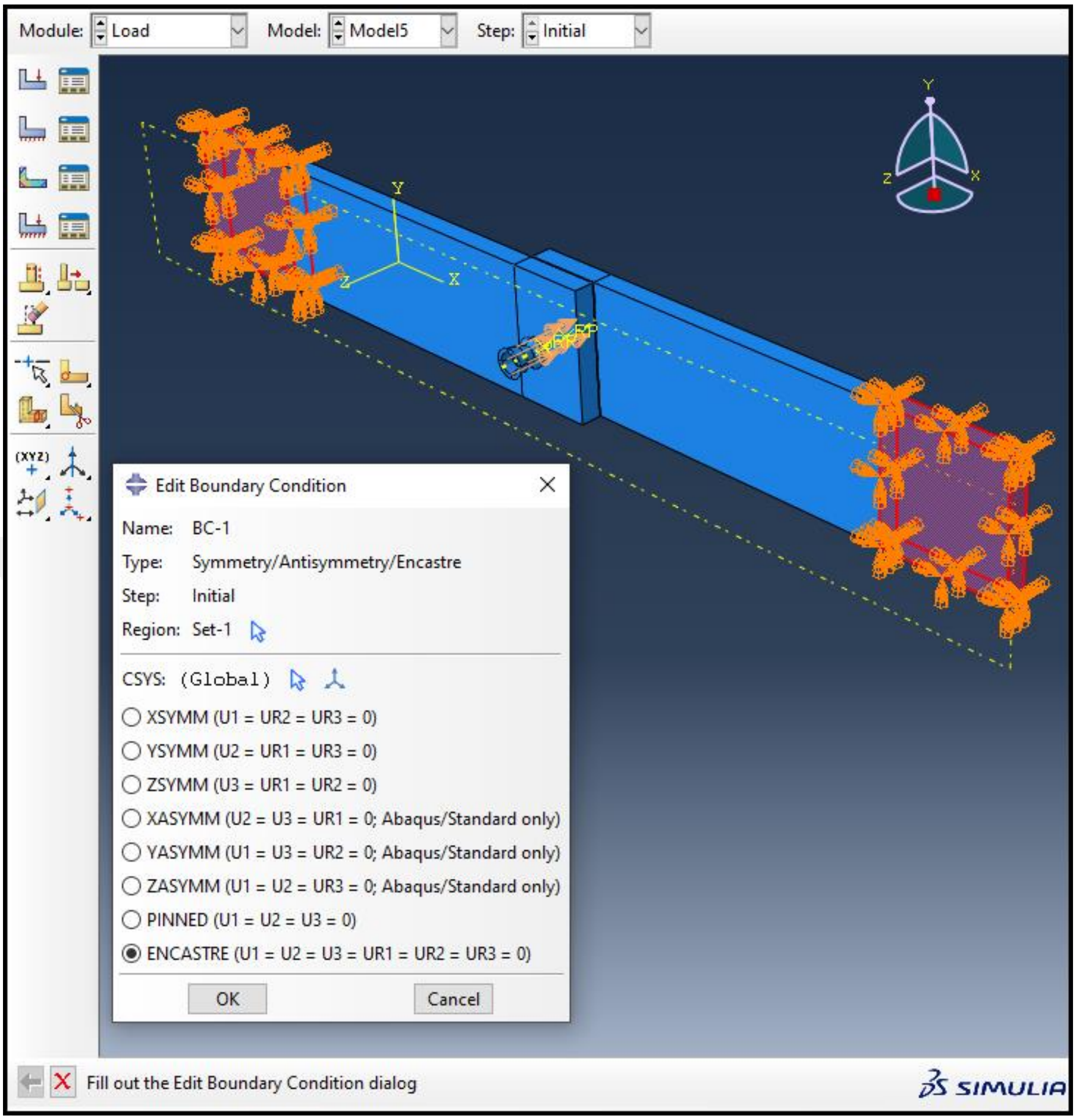

Figure 4.15: Determining the boundary conditions in load module.

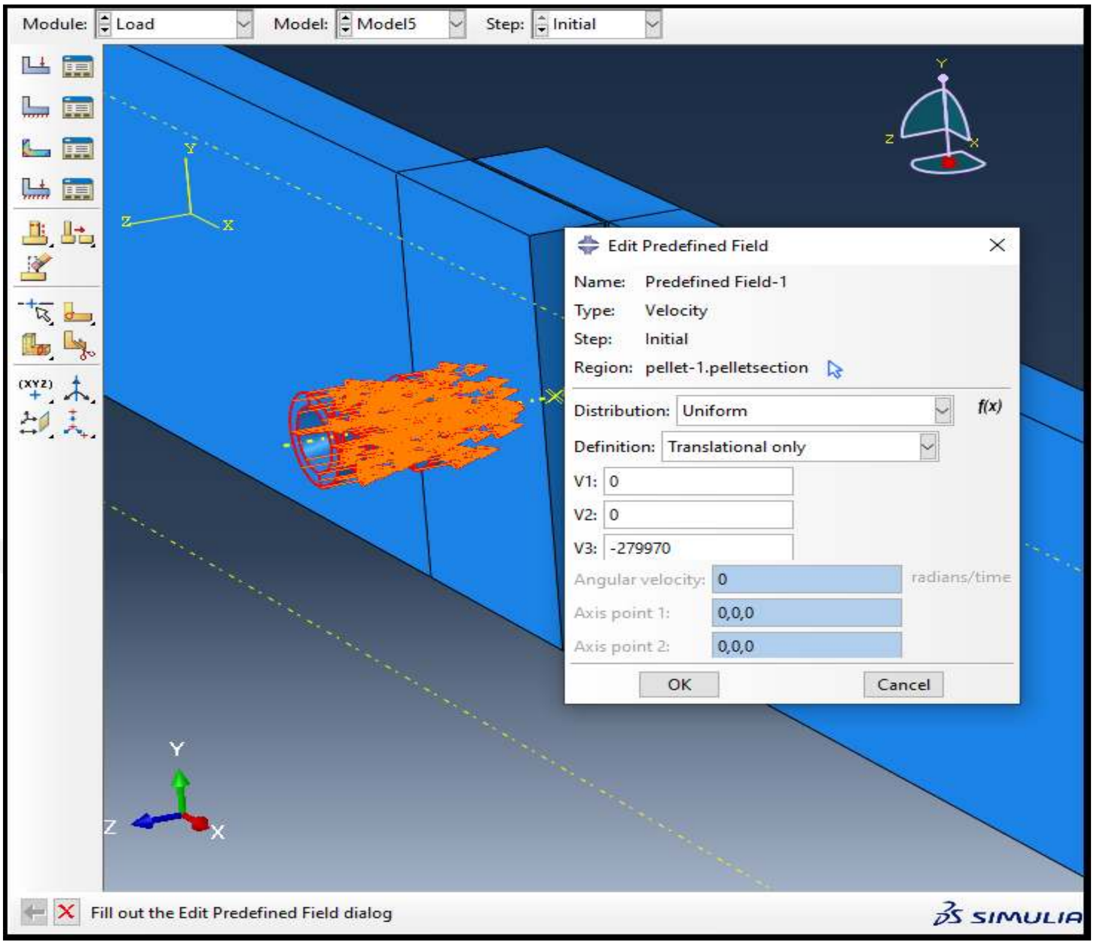

Figure 4.16: Determining the predefined field.

Meshing is an important step in numerical simulations, influencing the accuracy, stability, and efficiency of the results. The element type of adherends, adhesive and projectile (pellet) were C3D8R which is an 8-node a general-purpose linear brick element, reduced integration, hourglass control and a total of 19898 elements were employed in the model of the adhesively bonded Single Lap Joints with a 15 mm of overlap. Fine mesh was applied to obtain a more consistent results in the analysis. As shown in Figure 4.17, pre-analysis procedures are completed after the meshing process of all parts is completed.

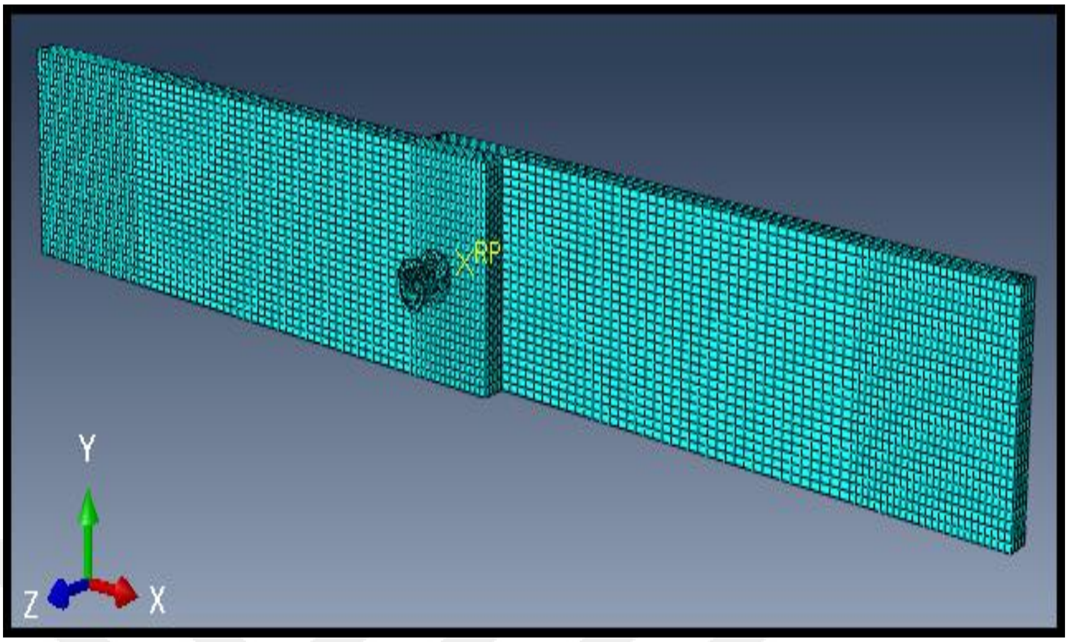

Figure 4.17: Meshed image of assembled Single Lap Joint.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results

Experimental and numerical studies were conducted on adhesively bonded Single Lap Joints subjected to high loading rates.

As a result of the experiment study, 2 shots and 3 shots were made on the single lap joints with 15 mm overlap lenght, the ones with 2 shots were then subjected to the quasi-static tensile test and the values were obtained, and these values will be evaluated in the fallowing sections. Failure occured in the single lap joint with 15 mm overlap lenght, which was exposed to 3 shots, and it could not be subjected to quasi-static tensile testing.

The maps of the numerical analyses have been presented in Figures 5.1-5.3, which account for one shot. The figures have been presented for three different impacting time periods which are: a- initial contact, b- full contact, c- final position of the projectile. During these periods, when the Von Mises stresses are analyzed, it is approximately 313 MPa in the first period, shown in Figure 5.1, while the maximum stress value reaches 601 MPa at the moment of full contact, as shown in Figure 5.2. Subsequently, as can be seen in Figure 5.3, the stress value decreases to approximately 422 MPa.

It is also seen that the projectile contracted and adheres to the upper surface of the adherend, as seen in Figures 5.4-5.5. In Figures 5.6-5.8, Von Mises stresses of the impacted adherends are shown. In Figure 5.7, it is estimated that the stress value of the adherend reaches a value of 392.8 MPa during full contact, and subsequently, this value is seen to decrease to 358 MPa as shown in Figure 5.8. During the initial contact part of the projectile, it is seen to be approximately 313 MPa, and it is indicated in Figure 5.6 that the stress initially concentrates at a point.

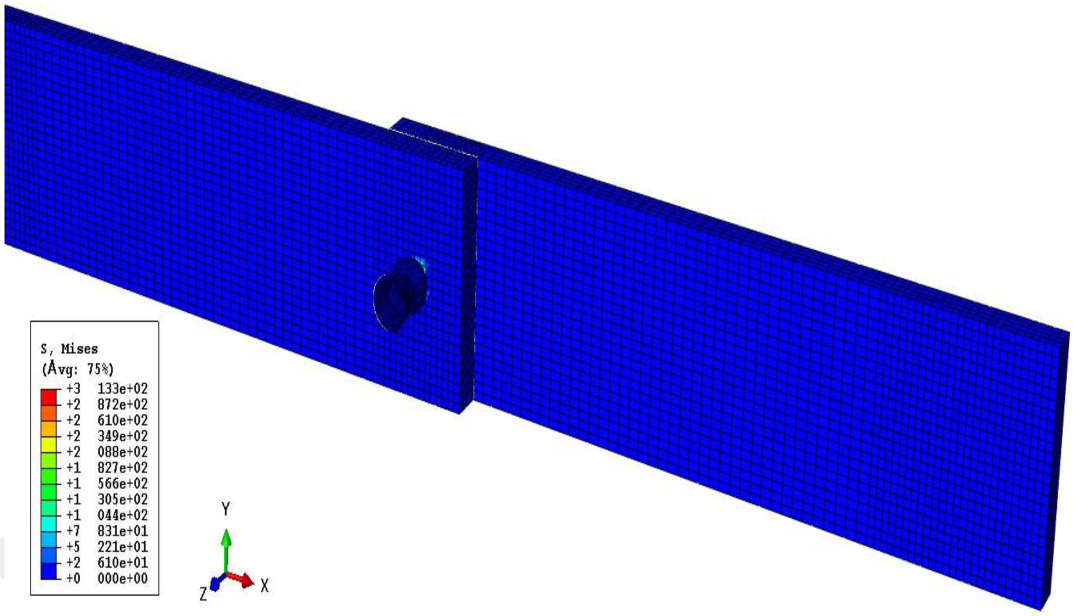

Figure 5.1: A three-dimensional numerical prediction of the von Mises stresses of the joints under impact of the projectile at initial position.

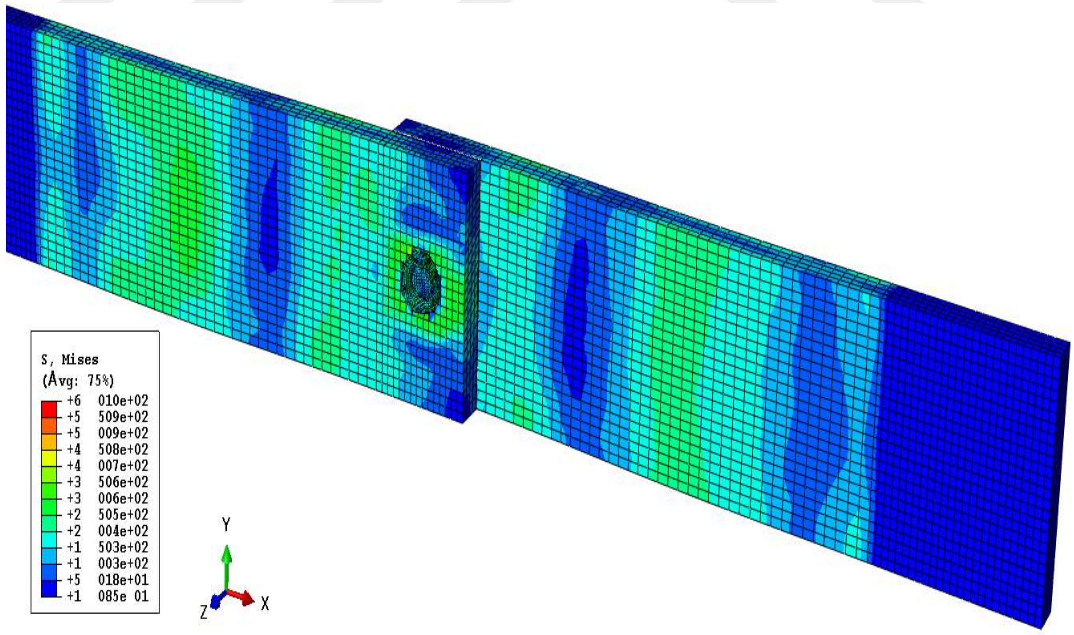

Figure 5.2: A three-dimensional numerical prediction of von Mises stresses in the joints under the impact of a projectile at full contact position.

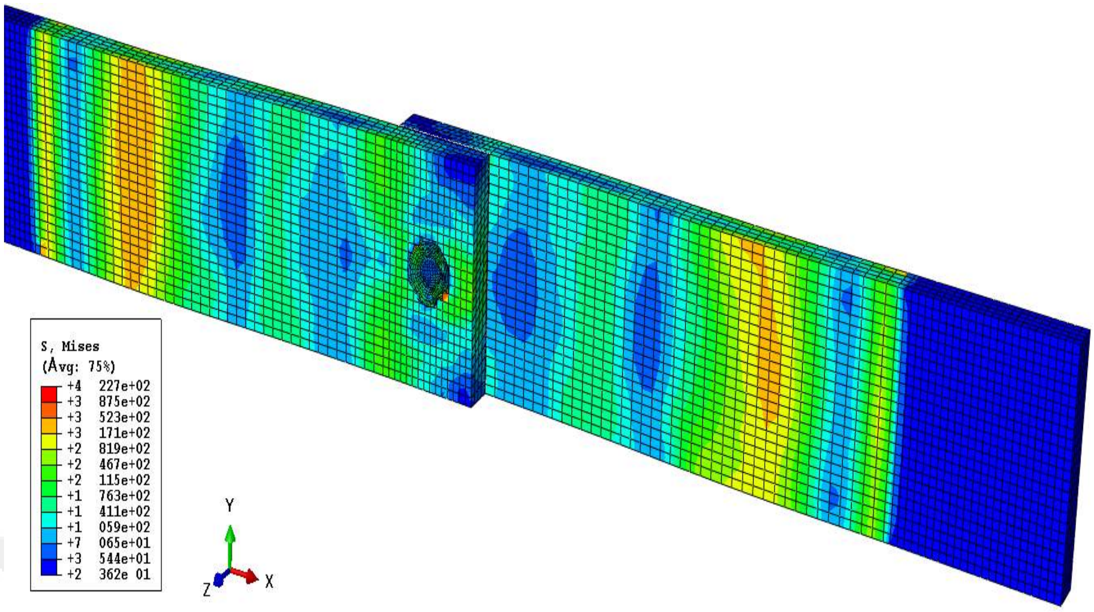

Figure 5.3: A three-dimensional numerical prediction of von Mises stresses in the joints under the impact of a projectile at final position.

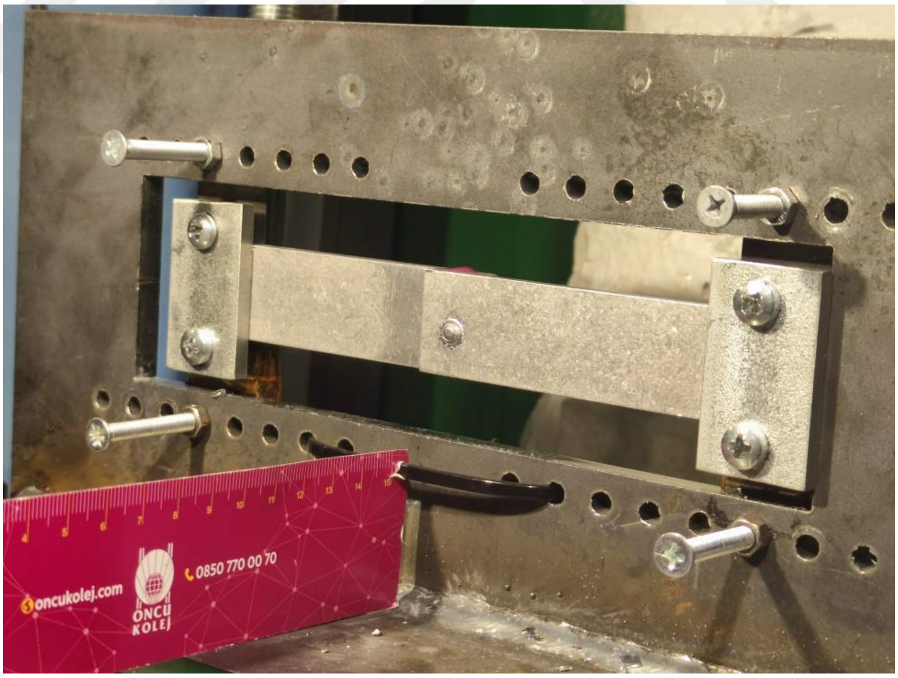

Figure 5.4: The real image of the adhesively bonded SLJ after first shot in the experiment.

Figure 5.5: The real image of the projectile after the 3rd shot in the experiment.

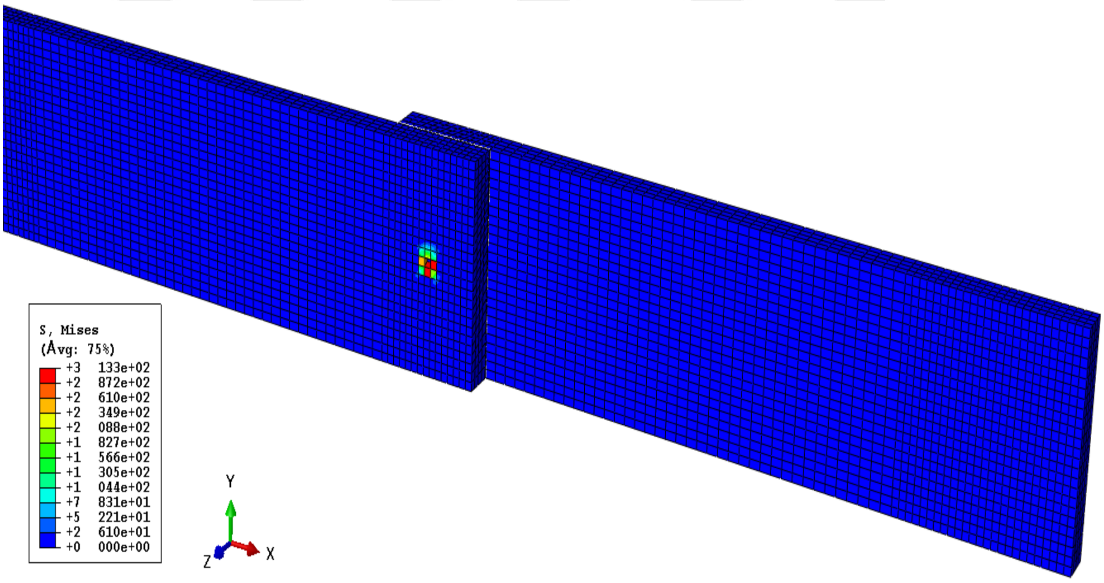

Figure 5.6: A three-dimensional numerical prediction of von Mises stresses in the adherends under the impact of a projectile with a speed of 279.97 m/s at initial position.

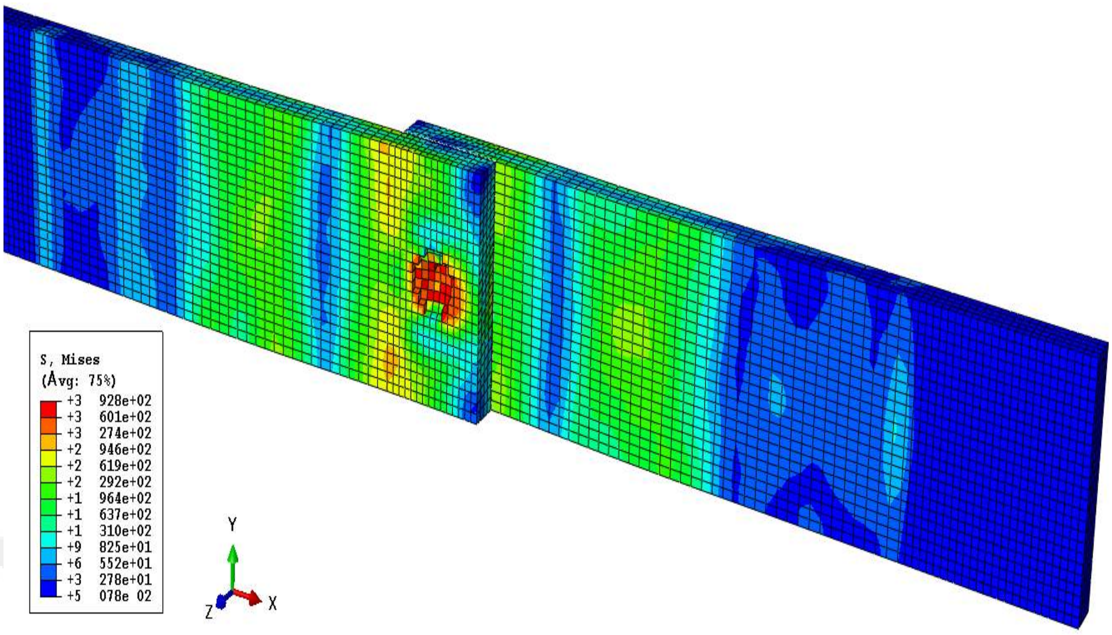

Figure 5.7: A three-dimensional numerical prediction of von Mises stresses in the adherends under the impact of a projectile with a speed of 279.97 m/s at full contact position.

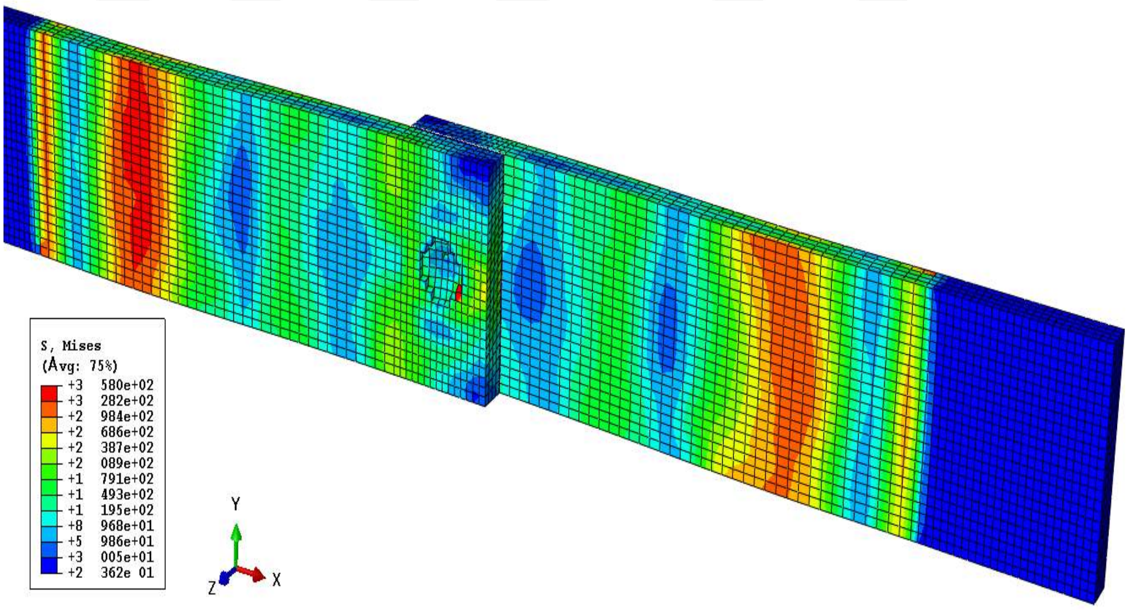

Figure 5.8: A three-dimensional numerical prediction of von Mises stresses in the adherends under the impact of a projectile with a speed of 279.97 m/s at final position.

In Figure 5.9, it can be observed that the von Mises stress level in the adhesive layer of the SLJ specimen is at the maximum failure/damage level, previously mentioned, which is 239 MPa. When examined in more details, it is observed that the stress concentrates at the center but extends towards the middle-right (in the x-direction), reaching the maximum value of uniaxial stress. Additionally, the predicted stress levels have also increased at the two edges of the adhesive and the stress value diminishes to about 212 MPa as seen in Figure 5.10.

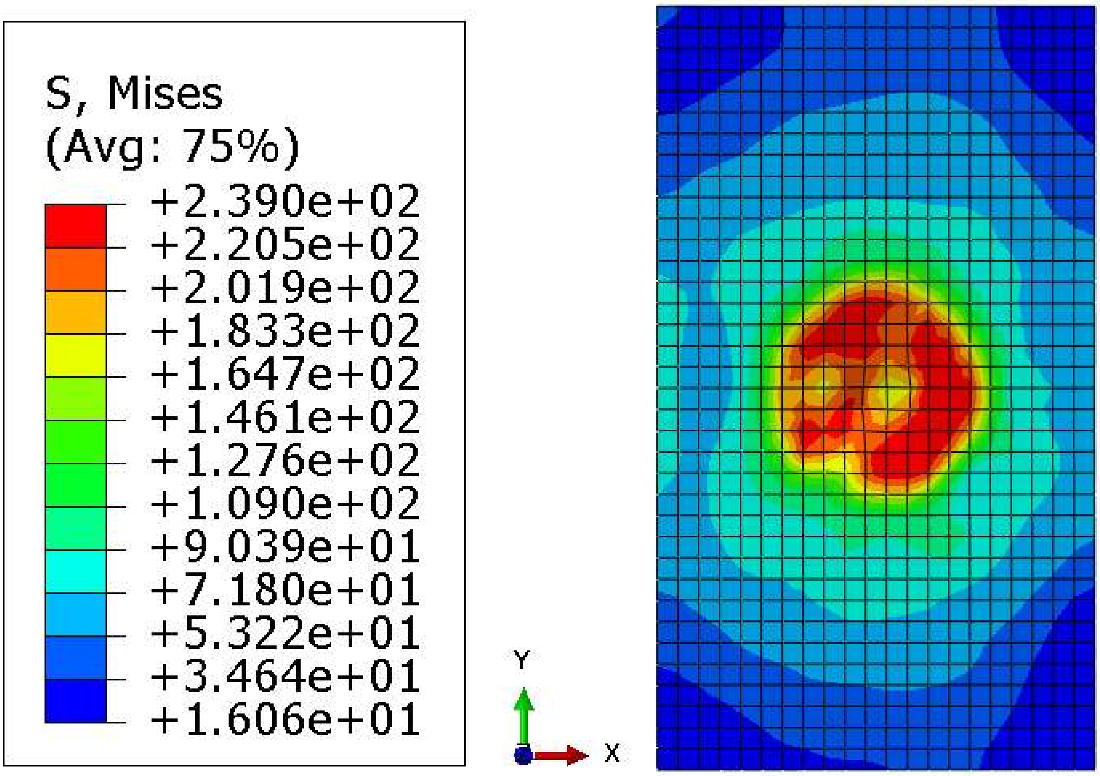

Figure 5.9: A three-dimensional numerical prediction of von Mises stresses of the adhesive layer under the impact of a projectile with a speed of 279.97 m/s at full contact position.

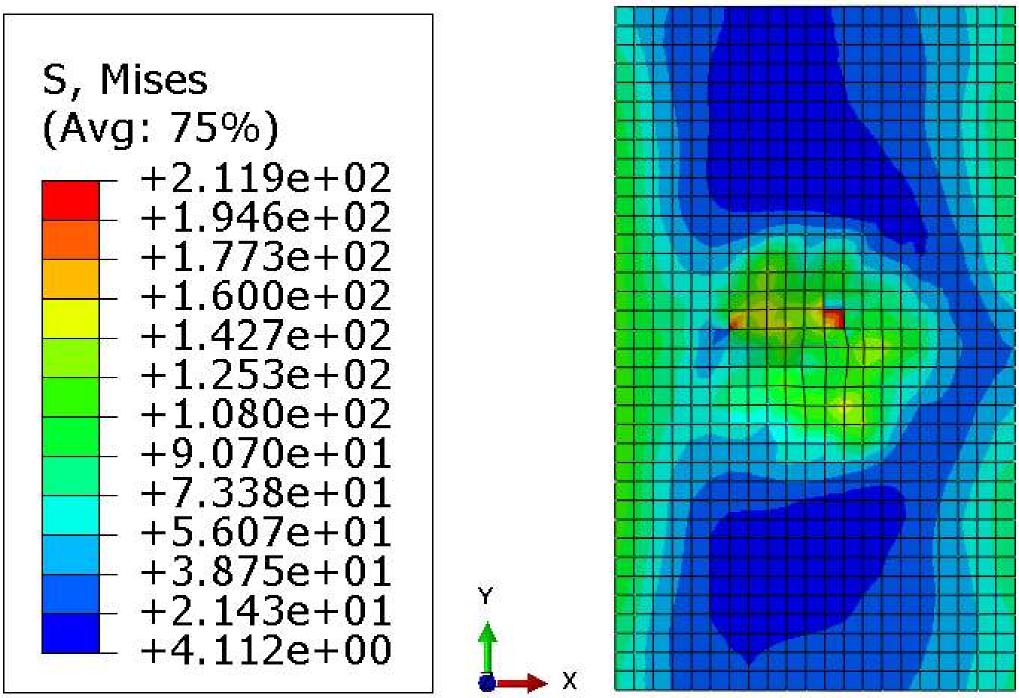

Figure 5.10: A three-dimensional numerical prediction of von Mises stresses of the adhesive layer under the impact of a projectile with a speed of 279.97 m/s at final position.

In parallel with the results of the numerical predictions, the adhesively bonded Single Lap Joint with an overlap length of 15mm did not have a complete separation after the 1st and 2nd shot, but it fully separated after the 3rd shot due to the failure in the adhesive layer, which can be seen in Figure 5.11.

Figure 5.11: The real image of interface of the 15mm overlap Single Lap Joint specimen which were ruptured after 3 shots in the experiment.

Figure 5.12: The real image of front side of the 15mm overlap Single Lap Joint specimen which were ruptured after 3 shots in the experiment.

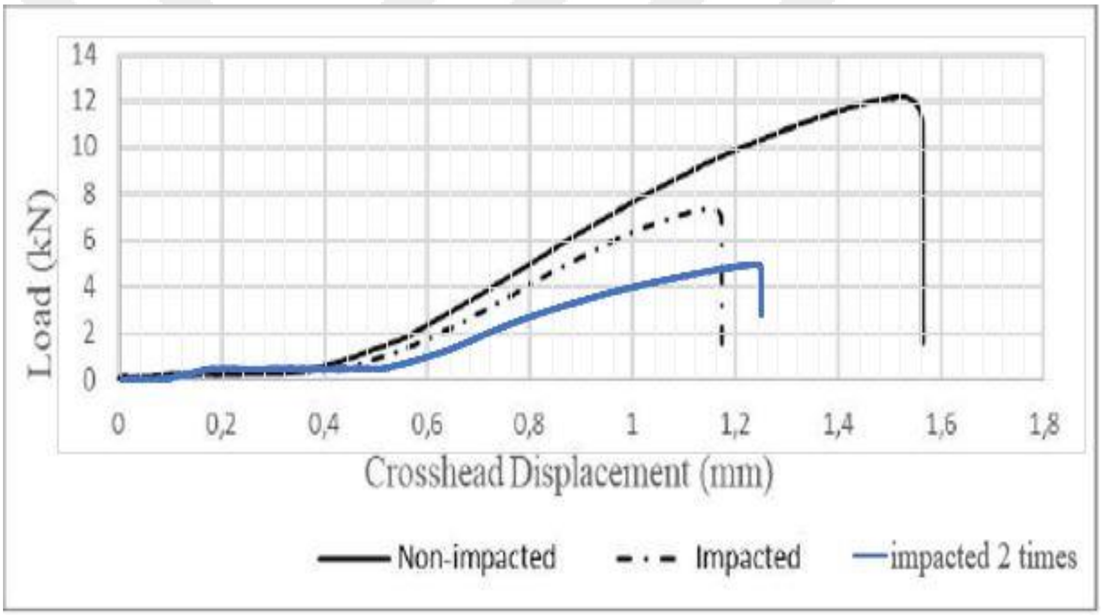

Figure 5.13: Comparison with quasi-static tensile test results from previous study

The results obtained from the numerical analysis were evaluated, and the numerical analysis facilitated our prediction of the potential outcomes when the specimen was impacted at a speed of 280 m/s. However, for more precise results, we subjected the specimen, which had undergone 2 shots, to a quasi-static tensile test using the Besmak BMT-S 100 kN machine.

In a previous study [24], a single shot was fired, and an identical projectile impacted a 15mm overlap length of an adhesively bonded single lap joint at a speed of 288 m/s.

The load-to-failure values of the single lap joint specimens were measured before and after the impact, which was 12.16 kN for non-impacted specimen, 7.32 kN after the-impact, respectively. Comparison with the tensile test results obtained in the previous study [24] is shown in the Figure 5.13.

The load-to-failure value of the specimen subjected to 2 shots was 4.85 kN in the quasi-static test. Compared to the specimen that underwent a single shot in the previous study conducted at a velocity of 288 m/s, the value showed a decrement of about 2.47 kN after 2 shots.

In this case, it can be said that the permanent damage caused by the impact reduced the load-to-failure value by approximately 34%.

Lastly, while the mechanical properties deteriorated in the specimens subjected to 2 shots, the specimens subjected to 3 shots experienced failure in parallel with the numerical analysis results.

CHAPTER 6

CONCLUSION

This study focused on the effects of repeated high loading on adhesively bonded Single Lap Joints (SLJs). SLJs are widely used in various industries, including defense, aerospace, and understanding their behavior under high loading rates is crucial to ensuring their structural integrity. It is also known that in recent years, SLJs have replaced mechanical connections and provide advantages in various aspects.

The effects of repeated high loadings on the performance of adhesively bonded SLJs have been investigated; specifically, the study determines the mechanical behavior and damage mechanisms of the joints when exposed to repeated ballistic shooting.

In the experimental approach, a certain number of bullets were fired into the joints using a specially designed mechanism, the effect was recorded using a high-speed camera, and the joints were subjected to a quasi-static tensile test. The joint adherend material and adhesive material are produced from 6061 aluminum and AF163-2K adhesive film, respectively. In addition, a numerical study was carried out using the ABAQUS package program, in which adhesives and adhesives were modeled using special deformation parameters.

The data for this study were collected through experimental tests using a specially designed setup and high-speed camera. Impacts were recorded and the joints were then subjected to quasi-static tensile testing. Numerical analysis was performed using the ABAQUS package program with specific input data for adhesives and adhesives and these data were determined using the Johnson-Cook deformation model. In the study, it was determined that while mechanical deterioration was observed in the connections exposed to 2 shots, there was a complete failure in the connections exposed to 3 shots. This subject was expanded in the literature by comparing it with the findings of the previous study. The experimental results were consistent with the numerical findings, confirming the validity of the numerical approach. Furthermore, this study contributes to the current knowledge on the behavior of adhesively bonded SLJs under repeated high loads. Previous research has focused primarily on the performance of joints under single-shot impact, and this study expanded the understanding to multiple shots. The findings have practical implications for the design and maintenance of structures using adhesively bonded SLJs. The question of how adhesively bonded SLJs perform under repeated high loadings was addressed by subjecting the joints to multiple ballistic shots and comparing them to non-impact and single-shot percussion joints. The study provided insight into the mechanical behavior of the joints and their failure mechanisms.

In conclusion, the study reveals that adhesively bonded SLJs subjected to repeated high loadings may experience mechanical degradation and eventual failure, and it seems increase in the number of impacts has an important effect on the joint performance. Experimental and numerical results are consistent and confirm the findings. This study contributes to the understanding of the behavior of adhesively bonded SLJs in high loading rate scenario.

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