

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

**INVESTIGATING THE INFLUENCE OF MATERIAL AND GEOMETRICAL  
FACTORS ON BONDED JOINT STRENGTH: A PARAMETRIC CZM  
ANALYSIS OF SINGLE LAP JOINTS**

**M.Sc. THESIS**

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**Department of Aeronautics and Astronautics Engineering**

**Aeronautics and Astronautics Engineering Programme**

**SEPTEMBER 2025**



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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ**

**MALZEME VE GEOMETRİK FAKTÖRLERİN YAPIŞTIRMALI  
BAĞLANTILARIN DAYANIMINA ETKİSİNİN İNCELENMESİ: TEK  
BİNDİRMELİ BAĞLANTILARDA PARAMETRİK CZM ANALİZİ**

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## FOREWORD

This thesis has been prepared as a partial fulfillment of the requirements for the Master of Science degree in Aeronautical and Astronautical Engineering at Istanbul Technical University. The study focuses on the investigation of adhesively bonded joints using cohesive zone modeling, with particular emphasis on the effects of adhesive thickness, overlap length, and material selection.

I would like to express my deepest gratitude to my thesis advisor, Assoc. Prof. Dr. Seher EKEN, for her solution-oriented approach, invaluable guidance, and continuous support throughout the research process. Her constructive comments and encouragement have been crucial in overcoming challenges and shaping the quality of this work.

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This thesis is also a personal milestone, reflecting the perseverance and effort I have put into both my academic journey and my professional development.

September 2025

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## **ABBREVIATIONS**

|                |                                                      |
|----------------|------------------------------------------------------|
| <b>ASTM</b>    | : American Society for Testing and Materials         |
| <b>ALLSE</b>   | : Strain Energy Dissipation (Abaqus output variable) |
| <b>BK</b>      | : Benzeggagh-Kenane                                  |
| <b>CFRP</b>    | : Carbon Fiber Reinforced Polymer                    |
| <b>CZM</b>     | : Cohesive Zone Model                                |
| <b>DCB</b>     | : Double Cantilever Beam                             |
| <b>DLJ</b>     | : Double Lap Joint                                   |
| <b>ENF</b>     | : End-Notched Flexure                                |
| <b>FEA</b>     | : Finite Element Analysis                            |
| <b>FEM</b>     | : Finite Element Method                              |
| <b>ISO</b>     | : International Organization for Standardization     |
| <b>LEFM</b>    | : Linear Elastic Fracture Mechanics                  |
| <b>MOGA-II</b> | : Multi-Objective Genetic Algorithm                  |
| <b>NASA</b>    | : National Aeronautics and Space Administration      |
| <b>SDEG</b>    | : Damage Variable (Abaqus Output)                    |
| <b>SLJ</b>     | : Single Lap Joint                                   |
| <b>SSY</b>     | : Small-Scale Yielding                               |
| <b>TAST</b>    | : Thick Adherend Shear Test                          |
| <b>TSL</b>     | : Traction-Separation Law                            |
| <b>UV</b>      | : Ultraviolet Radiation                              |
| <b>VCCT</b>    | : Virtual Crack Closure Technique                    |



## SYMBOLS

|            |                                            |
|------------|--------------------------------------------|
| $A_c$      | : Strain energy density                    |
| $D$        | : Damage variable                          |
| $E$        | : Elastic modulus                          |
| $G$        | : Shear modulus                            |
| $G_0$      | : Intrinsic fracture energy                |
| $G_I$      | : Mode I - Fracture energy                 |
| $G_{II}$   | : Mode II - Fracture energy                |
| $G_c$      | : Critical strain energy release rate      |
| $G_p$      | : Plastic-dissipation fracture energy      |
| $F_{ult}$  | : Ultimate load                            |
| $K$        | : Stress intensity factor                  |
| $K_n$      | : Normal Stress intensity factor           |
| $K_s$      | : Shear Stress intensity factor            |
| $L_0$      | : Overlap length                           |
| $r_p$      | : Plastic zone height                      |
| $u$        | : Displacement                             |
| $t_{ad}$   | : Adhesive thickness                       |
| $T_n$      | : Normal tractions                         |
| $T_s$      | : Shear tractions                          |
| $\nu$      | : Poisson's ratio                          |
| $Z$        | : Toughness ratio                          |
| $\sigma$   | : Stress                                   |
| $\sigma_f$ | : Separation strength                      |
| $\sigma_y$ | : Tensile yield stress                     |
| $\tau_y$   | : Shear yield stress                       |
| $\epsilon$ | : Strain                                   |
| $\delta$   | : Separation or Crack Opening Displacement |
| $\eta$     | : Benzeggagh-Kenane                        |



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# **INVESTIGATING THE INFLUENCE OF MATERIAL AND GEOMETRICAL FACTORS ON BONDED JOINT STRENGTH: A PARAMETRIC CZM ANALYSIS OF SINGLE LAP JOINTS**

## **SUMMARY**

Adhesive bonding has become a cornerstone technology in aerospace, automotive, defense, and energy sectors, enabling the integration of lightweight and high-strength assemblies that would be difficult or impossible to realize with traditional mechanical fastening techniques. Beyond weight savings, bonded joints eliminate the need for bolts or rivets that often create stress concentrations, thereby improving fatigue life, ensuring smoother aerodynamic surfaces, and enhancing corrosion resistance. These advantages, however, come with the critical challenge of guaranteeing reliable and predictable structural performance. In aerospace applications in particular, bonded joints must undergo rigorous certification before being deployed in airframe structures, and this requirement necessitates either extensive experimental campaigns or high-fidelity numerical models that can reduce reliance on physical testing.

Traditional fracture and fatigue testing approaches are limited by cost, time, and scalability. Each new adhesive, thickness, or joint geometry typically requires dedicated specimen production, fixturing, and long-term test programs. This motivates the increasing reliance on numerical simulation methods that can replicate crack initiation, progressive damage, and failure. Among such approaches, cohesive zone model has emerged as one of the most robust and widely accepted frameworks, bridging the gap between continuum mechanics and fracture mechanics. By embedding cohesive elements along bond interfaces, the model allows traction–separation laws to govern the entire fracture process from elastic loading, through damage initiation at peak traction, to progressive degradation and eventual failure controlled by critical fracture energies. This capacity to replicate mixed-mode fracture, involving both Mode I opening and Mode II shear, makes cohesive zone modeling particularly suited to bonded joint analyses, where real loading scenarios rarely involve pure modes.

The main objective of this M.Sc. thesis is to establish a fully automated, parametric cohesive zone model based framework for investigating the interplay of three critical parameters: adhesive thickness, overlap length, and adhesive material type. Unlike many prior studies that focused on one parameter at a time, this work explicitly considers their coupled effects, allowing for a more realistic and comprehensive understanding of structural performance. Four commercially relevant adhesives, namely AV138/HV998, Hysol EA 9361, Sikaforce 7888, and Araldite 2015, were chosen to represent a range from brittle to ductile systems. Their traction–separation properties were derived from literature-based tensile and shear test data, including double cantilever beam and end-notched flexure fracture energies. Importantly, the parameters were not taken as fixed constants but formulated as explicit functions of

thickness, capturing both intrinsic fracture toughness and additional plastic dissipation effects in thicker layers.

A robust Python scripting infrastructure was developed in Abaqus to automate every stage of the simulation workflow, including geometry construction, mesh generation, cohesive property assignment, job submission, and result post-processing. This automation ensured repeatability and allowed the exploration of large design matrices that would be impractical to evaluate manually. The outputs, including load–displacement curves, ultimate load, dissipated fracture energy and damage variables, were systematically extracted and synthesized into design maps. These maps serve as quick-reference engineering guidelines that identify optimal regions of adhesive thickness and overlap length for each adhesive system. For instance, the ductile Hysol EA 9361 demonstrated a non-monotonic response with optimum performance in the 0.20–0.30 millimeter thickness range, while the brittle Araldite 2015 performed best with thin bond-lines and shorter overlaps.

While the parametric study itself yields valuable insights, the thesis advances one step further by integrating multi-objective optimization into the framework. Using ModeFRONTIER as the optimization environment, adhesive thickness, overlap length, and adhesive type were treated as decision variables, while the objectives were defined as maximizing both ultimate load and energy dissipation. A constraint was imposed on minimum damage progression to ensure structural integrity and avoid solutions that rely on premature cohesive failure. The MOGA-II evolutionary algorithm was employed, chosen for its ability to handle nonlinear and discontinuous responses typical of cohesive zone based simulations

The optimization campaign generated approximately 997 unique design points, of which only 273, representing about 27 percent, converged successfully due to the intrinsic numerical challenges of modeling progressive damage in brittle adhesives. Among these, 98 solutions, representing about 10 percent of the total runs, satisfied all objectives and constraints, forming the final Pareto-optimal set. The results confirmed several important trends. Adhesive thickness does not exhibit a simple monotonic relationship with performance, since depending on the adhesive type, increasing thickness can enhance ductile energy absorption but diminish peak load capacity. Overlap length consistently plays a dominant role in determining strength, though beyond a critical threshold additional length contributes little to further performance gains. Adhesive selection emerges as the most influential parameter, dictating whether trade-offs between energy and load are favorable or limiting.

Visualization of the Pareto fronts highlighted how engineers can navigate between conflicting objectives. When prioritizing maximum load, brittle adhesives such as AV138 or Araldite 2015 may appear attractive. However, when energy absorption and damage tolerance are equally valued, ductile systems such as Hysol EA 9361 or Sikaforce 7888 provide superior balance. These trade-offs underscore the necessity of multi-objective approaches rather than single-metric optimization in bonded joint design.

The combined parametric and optimization framework represents the innovative contribution of this thesis. The parametric design maps offer immediate, interpretable guidelines for specific adhesives, while the optimization study delivers Pareto-based

strategies that help designers tailor joints to competing performance requirements. Together, they provide a dual-level tool: on one hand, a practical engineering reference, and on the other, a rigorous decision-making foundation for multi-objective structural design.

Equally important is the methodological flexibility of the framework. The automation scripts can be readily extended to new adhesives, alternative adherend materials such as composites, or other joint geometries such as double-lap or scarf joints. The incorporation of thickness-dependent cohesive functions ensures transferability to a broad range of industrial scenarios, where bond-line thickness often varies due to manufacturing tolerances. Moreover, the optimization setup can easily accommodate additional objectives, such as minimizing weight or maximizing fatigue life, further aligning with aerospace industry certification needs.

In conclusion, this thesis demonstrates that adhesive joint performance cannot be fully understood by varying a single parameter in isolation. Instead, meaningful design insights arise only when material type, geometry, and damage evolution are examined in concert and optimized under realistic constraints. By delivering both parametric guidelines and optimization-based Pareto strategies, this work provides a comprehensive framework that reduces reliance on experimental trial-and-error and accelerates the adoption of adhesive bonding in critical structural applications. The outcomes make a significant contribution to cohesive zone modeling, adhesive joint design, and computational optimization, positioning this framework as a reference methodology for future industrial and academic studies alike.



# TEK TESIRLI YAPISTIRMA BAGLANTILARI UZERINDE MALZEME VE GEOMETRIK FAKTORLERIN ETKISININ INCELENMESI: PARAMETRIK CZM ANALIZI

## ÖZET

Yapıştırma teknolojileri son yıllarda hem endüstriyel uygulamalarda hem de akademik çalışmalarda hızla gelişim göstermiş ve geleneksel bağlantı yöntemlerine güçlü bir alternatif haline gelmiştir. Özellikle havacılık sektöründe kullanılan metal ve kompozit yapısal elemanların birleştirilmesinde, perçinleme, cıvatalama ve kaynak gibi yöntemlerin yerini giderek daha fazla yapıştırıcı temelli yöntemler almaktadır. Bunun temel nedeni, yapıştırmalı bağlantıların sunduğu çok yönlü avantajlardır. Mekanik bağlantı elemanlarının ortadan kaldırılmasıyla yapılar daha hafif hale gelmekte, aerodinamik yüzey sürekliliği bozulmadan korunmakta, gerilme yığılmaları önlenerek yorulma ömrü artmakta ve ek olarak korozyon direnci, titreşim sönümleme ve elektriksel yalıtım gibi faydalar elde edilmektedir. Bu avantajlar yapıştırıcıların kullanımını cazip kılmakta, ancak sertifikasyon süreçleri ve güvenilirlik konusundaki zorluklar nedeniyle özellikle birincil uçak yapılarında kullanımlarını sınırlamaktadır.

Bununla birlikte, yapıştırıcıların kritik yük taşıyan birincil yapılarda kullanılabilmesi için sertifikasyon süreçlerinde yüksek düzeyde güvenilirlik sağlanması gerekmektedir. Deneysel kırılma ve yorulma testleri bu doğrulamanın önemli bir parçasıdır. Ancak her yeni yapıştırıcı türü, kalınlık veya bindirme uzunluğu için özel numuneler üretmek, bunları uzun süren testlere tabi tutmak ve elde edilen sonuçları analiz etmek büyük maliyetlere ve ciddi zaman kayıplarına yol açmaktadır. Ayrıca deneysel yöntemler parametrik çeşitliliği kapsamakta yetersiz kalabilmektedir. Bu nedenle son yıllarda yapıştırıcı bağlantıların davranışlarını öngörmek için yüksek doğruluklu ve tekrar edilebilir sonuçlar üretebilen sayısal simülasyon yöntemlerine yönelim artmıştır.

CZM, yapıştırıcı bağlantıların kırılma davranışlarını, malzeme ayrışması ve çatlak ilerlemesini traction–separation yasaları çerçevesinde modelleyerek temsil etmektedir. Yapıştırma yüzeyine yerleştirilen cohesive elemanlar, elastik bölgede rijit bir tepki vermekte, kritik gerilme seviyesine ulaşıldığında hasar başlamaktadır. Hasarın ilerlemesiyle birlikte rijitlik kademeli olarak azalarak yumuşama davranışı ortaya çıkmakta ve belirli bir kırılma enerjisi tüketildikten sonra tam ayrılma gerçekleşmektedir. Böylelikle, Mod I (çekme açılma) ve Mod II (kayma) davranışları gerçeğe yakın şekilde yakalanabilmekte, ayrıca karma yükleme durumları için de karışık mod kırılmaları doğru biçimde simüle edilebilmektedir. Bu yöntem, lineer elastik kırılma mekaniğinin uç noktalardaki sonsuz gerilme sorunlarını aşarak yapıştırıcı tabakasının gerçekçi mekanik yanıtını temsil edebilmektedir. Özellikle triangular, bilinear ve trapezoidal gibi farklı traction–separation şekilleri literatürde farklı yapıştırıcı türleri için önerilmiştir. Bu tez kapsamında kalınlığa bağlı parametreler tanımlanarak cohesive özelliklerin geometrik değişkenlere göre gerçekçi biçimde güncellenmesi sağlanmıştır. Böylece yapıştırıcı kalınlığı değiştikçe rijitlik,

dayanım ve kırılma enerjisi de fonksiyonel olarak yeniden hesaplanmış, ince tabakaların gevrek davranışı ile kalın tabakalarda görülen plastik enerji tüketimi aynı model içinde temsil edilmiştir.

Bu yüksek lisans tezinde, yapıştırıcı kalınlığı, bindirme uzunluğu ve yapıştırıcı malzemesi parametrelerinin birlikte incelendiği kapsamlı bir sayısal analiz gerçekleştirilmiştir. Çalışmada AV138/HV998, Hysol EA 9361, Sikaforce 7888 ve Araldite 2015 olmak üzere dört farklı yapıştırıcı ele alınmıştır. Bu yapıştırıcılar literatürde sıkça kullanılan ve gevrekten süneğe geniş bir mekanik yelpazeyi temsil eden ticari sistemlerdir. Her biri için çekme ve kayma mukavemeti değerleri, kırılma toklukları ve rijitlik parametreleri literatürden toplanmış; cohesive zone model parametreleri kalınlığa bağlı fonksiyonlar halinde tanımlanmıştır.

Sayısal çalışmalar Abaqus sonlu elemanlar yazılımında yürütülmüş, Python tabanlı bir otomasyon kodu ile desteklenmiştir. Kod altyapısı geometri oluşturma, ağ yapısı tanımlama, cohesive özelliklerin atanması, yükleme ve sınır koşullarının uygulanması, job tanımlama ve çalıştırma, sonuçların toplanması gibi tüm adımları otomatik olarak yürütmüştür. Böylece çok sayıda farklı kalınlık, bindirme uzunluğu ve malzeme kombinasyonu hızlı ve güvenilir biçimde simüle edilmiştir. Analizlerden elde edilen temel çıktı değişkenleri yük–yer değiştirme eğrileri, nihai yük kapasitesi, yapıştırıcı tabakasında harcanan enerji (ALLSE) ve hasar değişkeni (SDEG) olmuştur.

Parametrik analizlerin sonucunda tasarım haritaları elde edilmiştir. Bu haritalar, farklı yapıştırıcılar için optimum kalınlık ve bindirme uzunluğu aralıklarını göstermektedir. Örneğin, Hysol EA 9361 yapıştırıcısında 0,20–0,30 mm kalınlık ve 20–25 mm bindirme uzunluğu optimum performans sağlamış, Araldite 2015 ise daha ince tabakalarda yüksek yük taşıma kapasitesi göstermiştir. Bu sonuçlar literatürle uyumlu bulunmuş ve sünek–gevrek ayrımının tasarım kararlarında kritik rol oynadığı bir kez daha ortaya konmuştur.

Çalışmanın ikinci aşamasında, yalnızca parametrik analiz ile sınırlı kalınmamış, aynı zamanda çok amaçlı optimizasyon da gerçekleştirilmiştir. ModeFRONTIER yazılımı kullanılarak kurulan optimizasyon modelinde karar değişkenleri yapıştırıcı kalınlığı, bindirme uzunluğu ve yapıştırıcı türü olarak belirlenmiştir. Amaç fonksiyonları ise hem nihai yük kapasitesinin hem de enerji sönmeme kapasitesinin artırılmasıdır. Optimizasyonun fiziksel anlamlılığını korumak üzere, yapıştırıcı tabakada tam hasar evriminin gerçekleşmesini şart koşan bir kısıt uygulanmış; SDEG'nin 1.0 değerine ulaşmadığı koşullar elenerek yapıştırıcı dışı (adherend) hasar modları veya sayısal olarak yarım kalan koşullar Pareto değerlendirmesine dahil edilmemiştir. Optimizasyonda MOGA-II algoritması tercih edilmiş, çünkü evrimsel yapısı sayesinde doğrusal olmayan ve yüksek oranda başarısızlık riski taşıyan CZM analizlerini yönetebilme kapasitesi bulunmaktadır.

Optimizasyon sürecinde yaklaşık 997 farklı tasarım noktası üretilmiştir. Bunların 273 tanesi başarıyla tamamlanabilmiş, geri kalan kısmında ise özellikle gevrek yapıştırıcılarda ani rijitlik kaybı nedeniyle çözüm alınamamıştır. Başarıyla sonuçlanan analizlerden 98 tanesi tüm amaç ve kısıtları karşılamış ve Pareto-optimum kümesini oluşturmuştur. Bu çözümler incelendiğinde yapıştırıcı kalınlığının performansa doğrusal bir etkisi olmadığı, sünek yapıştırıcılarda kalınlık artışının enerji yutma kapasitesini artırırken nihai yükü azalttığı, gevrek yapıştırıcılarda ise tersine daha ince kalınlıkların yüksek yük kapasitesi sunduğu görülmüştür. Bindirme uzunluğu performansı en güçlü şekilde etkileyen geometrik parametrelerden biri olarak belirlenmiş, ancak belirli bir eşik değerinin ardından daha fazla artış sağlamamıştır. Yapıştırıcı seçiminin ise tüm senaryolarda en belirleyici faktör olduğu ortaya konmuştur.

Pareto-optimum sonuçların değerlendirilmesi mühendislik açısından önemli ipuçları sunmaktadır. Yük taşıma kapasitesinin öncelikli olduğu senaryolarda gevrek yapıştırıcılar öne çıkmakta, enerji sönümleme ve hasar toleransının da önemsendiği durumlarda ise sünek yapıştırıcılar daha uygun çözümler vermektedir. Böylelikle farklı uygulama ihtiyaçlarına göre hangi yapıştırıcı ve hangi geometrik parametrelerin seçilmesi gerektiği sayısal olarak gösterilmiştir.

Tezin yenilikçi katkısı, parametrik analiz ve çok amaçlı optimizasyonun bir arada yürütülerek hem doğrudan kullanılabilir tasarım haritaları hem de Pareto-optimum çözümler üzerinden performansa dayalı stratejiler sunmasıdır. Geliştirilen otomasyon altyapısı yalnızca dört yapıştırıcı ve tek bindirmeli bağlantılarla sınırlı olmayıp farklı malzemelere, örneğin kompozit esaslı yapılar, veya farklı bağlantı tiplerine de kolaylıkla uyarlanabilir. Kalınlığa bağlı fonksiyonların dahil edilmesi üretim toleranslarının etkilerini dikkate alabilmekte ve endüstriyel koşullara daha gerçekçi bir yaklaşım sunmaktadır. Ayrıca optimizasyon yapısına yeni amaçlar eklemek, örneğin ağırlık minimizasyonu veya yorulma ömrü maksimize edilmesi, mümkündür.

Sonuç olarak, bu tez çalışması yapıştırırmalı bağlantıların performansının yalnızca tek bir parametre üzerinden değerlendirilemeyeceğini, ancak malzeme türü, geometrik özellikler ve hasar ilerlemesinin birlikte incelenmesiyle gerçekçi ve kullanılabilir tasarım ilkelerinin elde edilebileceğini göstermektedir. Parametrik haritalar pratik mühendislik uygulamaları için hızlı bir referans sağlarken, çok amaçlı optimizasyon sonuçları tasarımcıların farklı performans kriterleri arasında bilinçli seçim yapmasına olanak vermektedir. Böylece deneysel deneme-yanılmaya olan bağımlılık azaltılmakta, maliyetler düşürülmekte ve havacılık gibi kritik sektörlerde yapıştırıcı kullanımının yaygınlaşmasına doğrudan katkı sunulmaktadır. Çalışma, CZM tabanlı sayısal tasarım ve optimizasyon süreçlerine hem akademik hem de endüstriyel açıdan önemli bir katkı niteliği taşımaktadır.

Bu tez kapsamında elde edilen sonuçlar önemli bir çerçeve sunmakla birlikte, ileride yapılacak çalışmalar için çeşitli araştırma alanları da mevcuttur. Mevcut modelleme yalnızca yapıştırıcı tabakadaki hasara odaklanmıştır; gelecekte metalik ve kompozit aderendlerin matris çatlaması, tabaka ayrılması veya ilerleyici hasar mekanizmalarının da modele dahil edilmesiyle daha kapsamlı sonuçlar elde edilebilir. Tek bindirmeli bağlantılar dışında çift bindirmeli, scarf ya da kademeli bindirmeli tasarımların incelenmesi, gerilme dağılımını iyileştirerek daha verimli çözümler ortaya koyabilir. Ayrıca, bu çalışma statik yükler altında yürütülmüştür; gerçek servis koşullarını temsil eden yorulma ve darbe yüklemelerinin de analize dahil edilmesi, yapıştırırmalı bağlantıların ömür performansını daha gerçekçi şekilde değerlendirmeye imkân tanıyacaktır. Son olarak, optimizasyonla seçilen tasarımların deneysel yöntemlerle doğrulanması, sayısal modelin güvenilirliğini pekiştirecek ve endüstriyel uygulamalara geçişte kritik rol oynayacaktır. Bu öneriler, mevcut bulguların daha da genişletilmesine ve yapıştırıcı bağlantıların mühendislikteki kullanımının güçlendirilmesine katkı sağlayacaktır.



# **1. INTRODUCTION**

## **1.1 Motivation of Thesis Study**

In recent decades, adhesive bonding has emerged as a critical joining method across industries such as aerospace, automotive, defense, and energy due to its capability to create lightweight and high-strength structures. Unlike traditional fastening methods, bonded joints eliminate stress concentrations caused by mechanical connectors and enable more uniform load transfer, improved fatigue life, and smoother aerodynamic profiles. Despite these advantages, their wider adoption in primary structural components, particularly in aerospace, is hindered by certification challenges, difficulty in inspection, and limited confidence in failure predictability.

As a result, engineers increasingly rely on numerical methods that can accurately replicate the mechanical behavior of bonded joints under realistic loading conditions. Among these, the Cohesive Zone Model (CZM) has gained prominence for its ability to capture progressive damage and crack propagation via traction–separation laws. CZM effectively bridges the gap between continuum and fracture mechanics, enabling high-fidelity simulation of interface failures. However, while many studies have explored the effect of individual parameters on joint performance, a comprehensive framework that evaluates multiple interacting design variables such as adhesive thickness, overlap length, and adhesive type within a single cohesive modeling setup remains limited.

Consequently, the present work is motivated by the need for a practical, automated simulation platform that not only evaluates these variables within a unified CZM framework but also optimizes them against competing performance objectives. Embedding multi-objective optimization on top of the parametric pipeline allows the study to move from trend identification to decision-quality design guidance, aligning early-stage material and geometry choices with strength toughness trade-offs.

## 1.2 Objective and Scope of Study

The first objective of this thesis is to develop a parametric and automated CZM-based finite element framework for systematically investigating the influence of key design variables adhesive thickness, overlap length, and adhesive material on the mechanical performance of single-lap bonded joints. By analyzing their combined effects within a unified simulation environment, the study aims to uncover critical trends and design guidelines that can be directly applied in aerospace structural joint optimization.

To achieve this, four industrial-grade adhesives (AV138/HV998, Hysol EA 9361, Sikaforce® 7888, and Araldite® 2015) are modelled based on their literature-based mechanical properties and fracture toughness values. The simulation framework, implemented in Abaqus using Python scripting, enables automated geometry generation, meshing, material assignment, job submission, and result extraction across a defined design matrix.

The scope of the study is limited to 2D plane-strain models of single-lap joints with steel adherends. The parametric analysis spans adhesive thicknesses from 0.1 mm to 1.0 mm and overlap lengths from 10 mm to 30 mm. CZM parameters, such as stiffness, critical strengths, and fracture energies, are formulated as functions of thickness to capture both intrinsic and thickness-dependent fracture behavior. The mechanical performance is assessed using response metrics including ultimate load, cohesive energy dissipation, and damage evolution patterns.

The second objective is to augment this framework with a multi-objective optimization study that searches the joint design space for configurations balancing toughness and strength. Specifically, the optimization simultaneously maximizes dissipated energy (ALLSE) and ultimate load ( $F_{ult}$ ) while enforcing a full cohesive-failure condition by requiring the damage variable to reach  $SDEG = 1.0$ ; this constraint guarantees physically relevant, adhesive-dominated failure and filters out runs that terminate prematurely or fail in the adherends. The design space spans adhesive thickness, overlap length and adhesive ID within practically relevant bounds, and results are synthesized into Pareto fronts to provide actionable design guidance.

The outcome is a set of design maps that highlight optimal parameter combinations for different adhesives, providing a valuable reference for engineering practitioners and researchers involved in bonded joint design and validation.

## 2. LITERATURE REVIEW

### 2.1 Adhesively Bonded Joints

Bonded joints provide a method of joining structural components without using rivets or welds, by employing an adhesive material. Intending to extend the performance and operational lives of aircraft, this joint type is becoming a focal topic in aviation. Besides providing better fatigue life with distributing the load uniformly and decreasing friction wear and stress concentration can be minimized with the absence of mechanical fasteners like bolts.

Fokker has been utilizing adhesive bonding techniques in aircraft manufacturing for more than five decades, making it one of the pioneers in this field. Corresponding to the increase in composite material usage, adhesively bonding joints have also increased since the 1963 studies. Today, these joint types can be seen at both military and commercial aircraft like the F-18, F-22, and AIRBUS A380, where 42% of bonded composite assemblies contribute to economical operations through reduced weight. Figure 2.1 illustrates representative applications of adhesively bonded joints on the Airbus A380 airframe, highlighting how extensive composite bonding contributes to structural efficiency and weight reduction in modern aircraft [1].

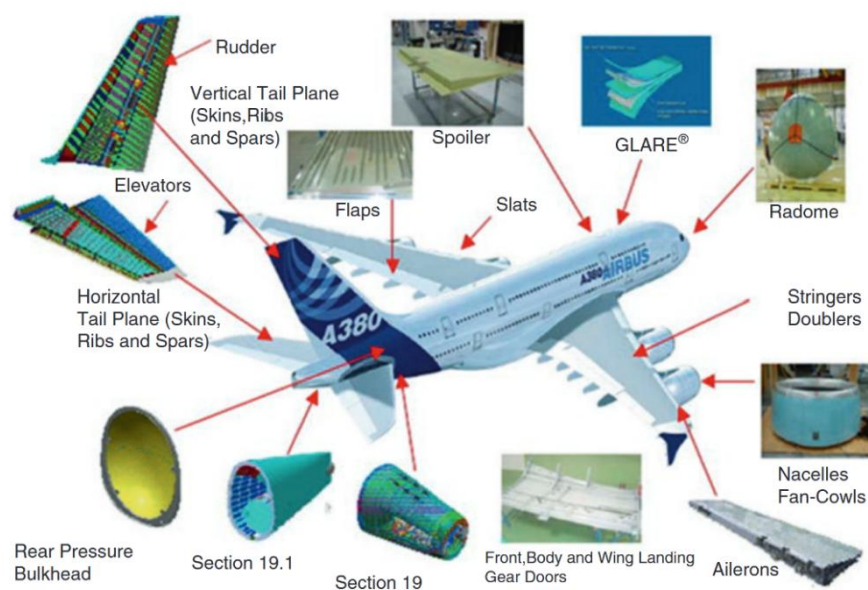


**Figure 2.1:** Adhesively Bonded Joints on Airbus A380 [1]

In addition to the advantages, safety is still the most important issue in adhesively bonded joints. Since the non-destructive testing method cannot be applied to these joints, more destructive tests, high safety factors, and the use of additional fasteners to ensure that the structure still works when the bond has completely failed are actually obstacles to obtaining maximum efficiency from this joint type. Therefore, studies and developments on this joint type are important for the aviation sector [2,3]. Table 2.1 summarizes the principal advantages and limitations of adhesively bonded joints, framing the trade-offs that motivate the subsequent design and modeling choices in this study.

**Table 2.1:** Adhesively Bonded Joints Advantages and Disadvantages

| Adhesively Bonded Joints    |                                                  |
|-----------------------------|--------------------------------------------------|
| Advantages                  | Disadvantages                                    |
| Lighter structures          | Inspection and testing                           |
| Stiffer joints              | Highly sensitive to environmental conditions     |
| Excellent fatigue life      | Disassembly                                      |
| Smooth aerodynamic surfaces | Surface preparation process                      |
| Lower stress concentration  | High-quality control and certification processes |
| Design flexibility          |                                                  |
| Damage tolerant             |                                                  |

## 2.2 Failure Modes

Facilitating the increased use of adhesive bonds is possible by identifying the reasons behind these joints' failure. Adhesive joints can fail in many different ways compared to bolted joints. A frequent type of failure observed in bonded joints is adhesive failure, where the detachment takes place along the boundary between the adhesive and the adherend. Another significant type is cohesive failure, which happens within the adhesive layer itself. In contrast to this, cohesion can be so strong that it leads to damage to substrates, that called “adherend failure”. Each failure mode can be further

categorized into distinct subtypes. Detailed information regarding these classifications is provided in the Figure 2.2 [2].

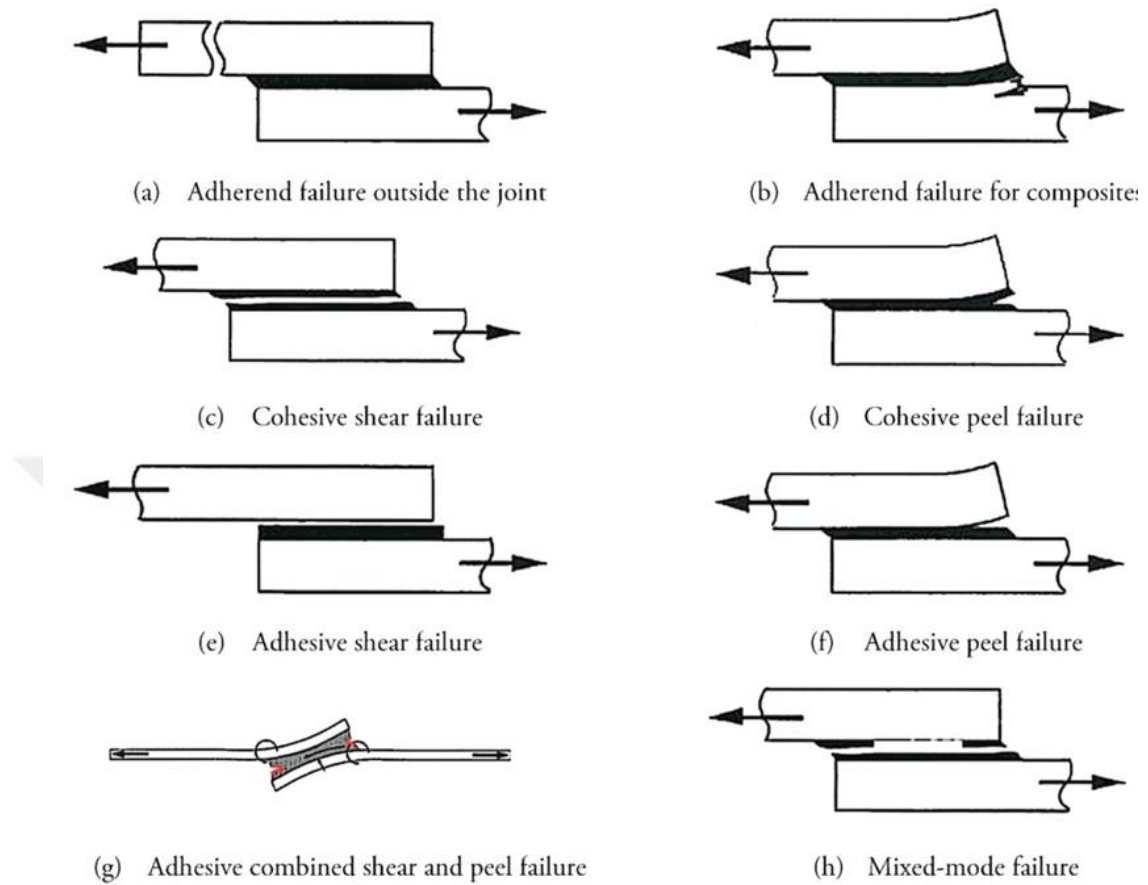


**Figure 2.2:** Adhesively Bonded Joints Failure Modes [2]

Various factors contribute to the occurrence of different failure modes. For instance, adhesive failure typically results from poor surface treatment or incorrect application techniques, whereas cohesive failure is more likely due to unsuitable adhesive selection or design-related issues [4,5]. Environmental factors are a major factor in all of these failure modes. Concurrently, inadequate testing and quality control processes can cause potential failures to be missed. A fishbone diagram illustrating the causal factors for this topic is presented in Figure 2.3. The primary focus of this research will be on the influence of design parameters and material properties, which will be detailed in the next chapter.

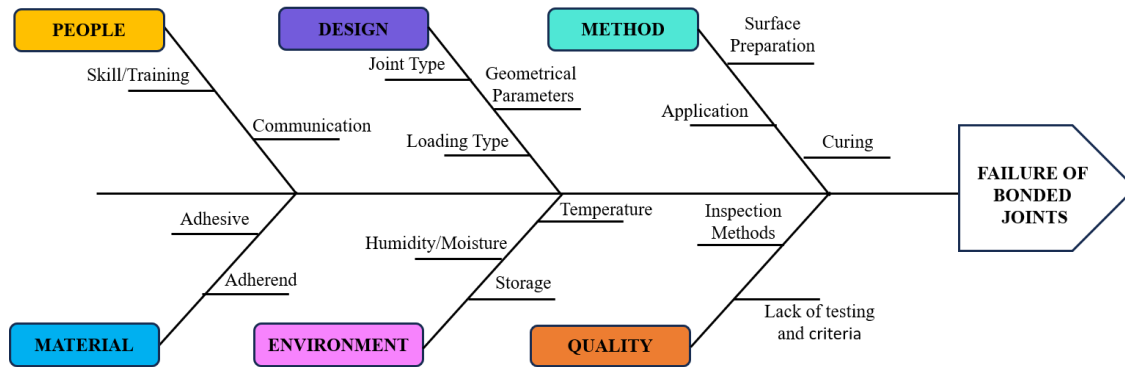


**Figure 2.3: Failure of Bonded Joints Fishbone Diagram**

## 2.3 Parameters that Affect the Performance of the Bonded Joints

The performance of adhesively bonded joints varies significantly depending on various parameters. These parameters directly affect the load-carrying capacity, damage development and long-term strength of the joint. Modeling approaches, such as cohesive zone modeling, highlight the importance of accurately defining adhesive constitutive parameters like critical energy release rates and strengths, which are influenced by geometrical factors such as adhesive and adherend thickness. Therefore, the selection of materials, optimization of geometry, and consideration of processing and environmental conditions are critical steps in ensuring reliable bonded joint performance.

### 2.3.1 Geometrical parameters

#### 2.3.1.1 Adhesive and adherend thickness

Adhesive layer thickness is a primary geometric variable because it governs both the local stress field and the global load-bearing capacity of a bonded joint. Most experimental and numerical studies report an inverse relationship between thickness and ultimate strength: as the bond line becomes thicker, peak shear and peel stresses migrate away from the overlap center and intensify near the ends, reducing effective load transfer.

However, this trend is sensitive to both material and loading conditions. In the study conducted by Silva et al. (2021), the maximum displacement under tensile loading increased linearly with thickness for ductile epoxies, while the same increase produced little or no benefit and sometimes an early strength drop in brittle adhesives. The same study reported that energy absorption increased with thickness in ductile systems but decreased in brittle ones [6].

A study that investigates scarf type bonded joints shows that; while the maximum displacement under tensile load is directly proportional to the adhesive thickness in ductile adhesives. As opposite, this relationship is observed different in brittle adhesives. In addition, while the energy absorption capacity increases as the thickness increases in ductile adhesives, this energy decreases in brittle adhesives [7].

Various studies have identified an optimum adhesive thickness range for each structural system. This range has been reported to vary between 0.05 mm and 0.3 mm in most cases [8]. Single lap joint (SLJ) tests combining CFRP and aluminum adherends confirmed that peak bond strength lies inside this window, with thicker or thinner layers giving lower strength despite the larger bonded area [4].

Adherend thickness exerts a coupled influence. Thin adherends undergo greater deformations under loading, creating high bending and peeling stresses in the adhesive layer. This situation causes local damage to occur at an early stage, especially in brittle adhesive. This effect highlighted by Karachalios et al. (2018) for SLJs with low-thickness aluminum adherends, it was observed that bending effects increased and local damages were more concentrated in the adhesive area in single-lap joints formed with low-thickness aluminum adherends [9]. Finite-element work by Zhou et al. (2017) quantified the benefit of stiffening the substrate: raising plate thickness from 2.5 mm to 4 mm cut peak interfacial shear by roughly 18% and produced a flatter stress map [10].

Yet increasing adherend gauge is not a free gain. Beyond a certain point the added weight and cost outweigh the stress-reduction benefit, so designers must seek an optimum adhesive–adherend thickness pair that meets both strength and mass targets. The selection is further complicated when the adhesive and adherend moduli differ

widely, because modulus mismatch amplifies interface stresses and can trigger premature failure.

### **2.3.1.2 Overlap length**

In general, as the lap length increases, the joint strength also increases, because a longer lap provides a larger bonding surface, improving load transfer. However, this increase is not always linear and tends to reach saturation and stabilize after a certain length [11]. This behavior depends on many factors, such as the thickness parameter. The type of adhesive, the adherent material and the type of loading are the main factors that determine the effect of the overlap length on the strength. For example, when using ductile adhesives, increasing the overlap length significantly increases the load-carrying capacity, while it has been observed that this effect is quite limited in brittle adhesives [6]. Nonetheless, the normalized bond strength which is identified as maximum load/lap area generally tends to decrease as the lap length increases [12]. This situation is due to the inhomogeneity of the stress distribution in long overlap lengths. Since shear and peel stresses are concentrated especially at the overlap ends, the extra overlap area does not contribute enough to the load bearing. In fact, some studies have shown that when the overlap length is increased, the maximum shear stress remains constant at a certain value and further increase does not contribute to the joint strength [2].

The length of the overlap has a direct influence on how the joint fails. In shorter overlaps, particularly when composite adherends are involved, failure may initiate within the adherend itself, such as delamination, under static loading. In contrast, longer overlaps tend to fail either within the adhesive layer or along the adhesive-adherend interface [11].

Therefore, determining an appropriate lap length requires careful optimization, taking into account the adhesive's mechanical behavior, the structural characteristics of the adherends, and the nature of the applied loads. When using ductile adhesives, extending the lap length can enhance both joint strength and energy absorption. However, this improvement tends to be much less pronounced or even negligible when brittle adhesives are used [6, 7].

### **2.3.1.3 Surface preparation and surface morphology**

In adhesive bonding, surface preparation and surface quality are critical parameters that directly affect the mechanical strength and long-term performance of the bond. Surface preparation includes the removal of contaminants, physical roughening and chemical modification of the surface. These processes generally provide more effective adhesion of the adhesive to the surface and enhance both cohesion and adhesion mechanisms. The geometrical characteristics of the surface, in particular, the roughness, the indentation structure, and the complexity of the surface profile, significantly affect the bonding behavior.

In an ideal bonding surface, the adhesive is expected to penetrate into the micro-indentations and physically lock into place. Surface roughness can increase load-carrying capacity by enhancing mechanical interlocking, especially when used with ductile adhesives. For example, it has been reported that bonding strength increases by 20–30% in aluminum adherends where the surface profile is made more complex and indented. In addition, both chemical bonding and adhesion performance can be optimized by increasing the free energy of the surface through processes such as UV irradiation, plasma applications or chromic acid roughening [5]. In addition, a statistical study conducted by Rajkumar et al. (2017) analyzed the effects of parameters such as surface roughness, adhesive thickness, and overlap length on shear strength. The study revealed that increasing the surface roughness significantly improved the bond strength and optimizing these parameters together led to significant increases in the overall joint performance [13].

On the other hand, excessive roughness does not always provide benefits. When the surface becomes too rough, it can be difficult for the adhesive to fully penetrate all the gaps. This can lead to areas of non-contact or air pockets, weakening the bond integrity. High roughness can also lead to local stress concentrations, leading to premature failure of the joint. The viscosity of the adhesive is also decisive in this interaction: adhesives with low viscosity can better adapt to high roughness, while smoother surfaces may be preferred for adhesives with high viscosity.

#### **2.3.1.4 Fillet/Spew**

It is especially observed at single-lap adhesive joints, the highest shear and peel stresses are usually concentrated at the beginning and end regions of the adhesive. The adhesive protrusions, called fillets or spews, that form or are specifically applied at these end regions play a critical role in the strength and failure behavior of the joint. The fillet geometry reduces the stress gradient at the ends, tempered stress concentrations, thus both providing longer adhesive strength and contributing to a delay in the failure point.

Studies have shown that properly designed fillets can increase the joint strength by 10–25%. For example, in a study conducted by da Silva et al. (2006), it was observed that SLJ specimens with epoxy adhesives and a smooth and wide fillet on the edges showed higher fracture strength compared to models without fillets and that the damage shifted from the tip to the center. In addition, this study revealed that fillet geometry not only increased the static strength but also changed the failure mode. In joints without fillets, failure generally started suddenly at the adhesive ends; in fillet-supported joints, this process progressed in a more widespread and ductile manner [14].

Fillet geometry has significant effects not only on statics but also on fatigue behavior. In experimental and numerical studies conducted by Wu et al., it was reported that “arc” and “full triangular” fillet types prolong crack initiation time, reduce maximum stresses and significantly increase fatigue life. In particular, “full triangular” fillet geometry provided the best performance in terms of fatigue strength. In the same study, it was emphasized that unbonded areas accelerate crack propagation and negatively affect fatigue life [15].

However, there are some limiting factors that should be considered in fillet application. Excessive spew material can leak out of the mold, causing aesthetic problems, increased weight, and deviations in assembly tolerances. Therefore, in the application of fillet geometry, a careful balance must be established between increased performance and production and design requirements.

#### **2.3.1.5 Joint type**

Bond-line architecture dictates how loads are channeled through the adhesive and, by extension, where failure is likely to start. The most common types of joints include

single lap, double lap, step lap, scarf, butt, and T-joints as illustrated in Figure 2.4 [2]. Each has its own advantages and limitations for specific applications.

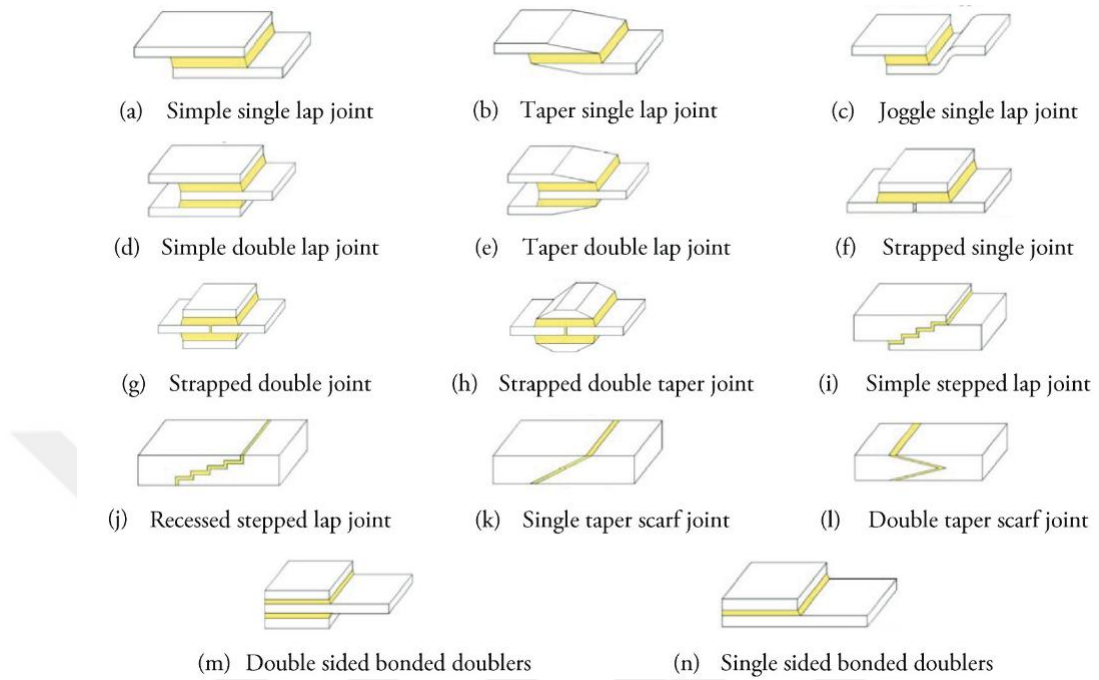


**Figure 2.4:** Type of joints [2]

Single lap joints are widely favored for their straightforward design and ease of manufacturing. Nonetheless, because the load path is not perfectly axial, bending moments develop within the joint. These moments can generate significant peel stresses at the edges of the adhesive layer, potentially triggering early failure. Double lap joints (DLJ) are preferred to reduce this problem. DLJ configurations transfer the load symmetrically, improving stress distribution and providing higher bond strength.

Geometrically advanced joints such as scarf and step lap are preferred especially in composite materials. These joint types reduce stress concentrations on the bonding surface and ensure a smoother transfer of load. In this way, they offer higher strength and longer life under both static and fatigue loading. It has been shown in the literature that scarf joints offer higher strength/weight ratio and fatigue resistance than SLJ structures when production tolerances are controlled correctly [3, 7]. In addition, the same studies have determined that different joint configurations affect not only the bearing capacity but also the failure mode. In scarf joints, failure usually occurs within the adhesive, while in SLJ joints, failures at the adhesive are more common due to

local stress concentrations. A comparison of various adhesively bonded joint configurations reveals how joint design influences the strength and stress distribution in dissimilar material combinations. The layout of the joint plays a key role in determining load transfer efficiency and failure behavior. In particular, the damage tolerance of scarf and stepped-lap composite joints under quasi-static loading shows notable differences, highlighting the importance of joint geometry in enhancing structural performance.

Butt joints are considered structurally weak and are generally used in low load-bearing applications or in systems supported by mechanical connections. Such joints are sensitive to cleavage and peel stresses. Therefore, they are generally not preferred in applications requiring high strength. Experimental studies have shown that the residual strength of butt joints decreases significantly under the effect of systematic discontinuous damage [16].

T-joints are widely used in structural frameworks where rigid connections must be provided. Such joints require the structure to operate under mixed loading conditions (peel, bending, shear). However, T-joints can also cause stress concentrations in the adhesive, especially under bending loads. Numerical analysis studies show that the bond strength in such configurations is sensitively dependent on the material and geometry parameters [17].

### **2.3.2 Mechanical parameters**

The overall behavior of adhesively bonded joints is strongly influenced by the mechanical characteristics of the materials involved, with the adhesive and adherend properties playing a particularly critical role in determining joint strength and reliability. These parameters directly determine the load-carrying capacity, deformation behavior, energy dissipation ability and failure mode of the joint.

#### **2.3.2.1 Adhesive material**

The mechanical and physical characteristics of the adhesive are among the key factors influencing the overall performance of a bonded joint. Choosing the right adhesive involves considering multiple aspects, including the type of adherend material, required curing conditions, environmental exposure, loading conditions, and cost

constraints. Therefore, the industry is constantly developing new types of adhesives with improved properties to meet different application requirements.

Adhesives can generally be brittle or ductile in character according to their mechanical behavior. This distinction is an important factor, especially determining the deformation behavior under load, energy absorption capacity and failure mode. Ductile adhesives are typically based on polyurethane, acrylic or modified epoxy. Although these adhesives have a relatively low elastic modulus, they exhibit high deformation capacity and offer longer life under impact and fatigue loads thanks to their energy absorption capabilities. Ductile adhesives do not lose their full load-carrying capacity at the moment of rupture but can maintain partial load-carrying capacity [18]. In addition, in these types of adhesives, the maximum displacement amount is directly proportional to the adhesive thickness; this feature allows more energy to be dissipated by increasing the adhesive thickness, unlike brittle adhesives [7].

Brittle adhesives are generally epoxy based and provide advantages in applications requiring stiffness due to their high elastic modulus. However, due to their low ductility and limited energy absorption capacity, they exhibit brittle behavior under impact and fatigue loading. Although they can be preferred in applications requiring short-term and high rigidity, they are quite sensitive to peel and separation type stresses. In brittle adhesives, rupture usually occurs suddenly and the load carrying capacity is almost completely lost [18]. As we discussed in previous sections, different responses are observed for each geometric parameter depending on the adhesive material.

The compatibility of adhesive and adherend is also of great importance. A mismatch in elastic modulus between the adhesive and adherends can lead to uneven stress distribution along the bond line, creating localized stress concentrations that may result in early failure of the joint. Therefore, not only the strength of the adhesive but also its mechanical and chemical compatibility with the adherend must be carefully evaluated.

#### **2.3.2.2 Adherend material**

Adherend materials used in adhesive joints are one of the basic parameters that directly affect the overall strength, stress distribution, fracture behavior, and failure mode of

the joint. Adhesively bonded joints are employed to connect a broad spectrum of materials, ranging from metals like aluminum, steel, and titanium to advanced composites. They are also commonly used in hybrid configurations, including composite-to-composite, metal-to-metal, and composite-to-metal assemblies. Specific examples include unidirectional carbon-epoxy pre-preg, high-strength steel, aluminum alloy 5083, titanium, CFRP-aluminum alloy, and jute, glass, and hybrid jute/glass fiber-reinforced polymer composites [19,20]

The adherend material influences the strength of the joint. Studies have investigated the strength of joints with different adherends [21,22]. Rigid adherends with high elastic modulus transmit stress more rigidly, while low modulus adherends are more flexible and can distribute the load on the adhesive more evenly. However, when the elastic modulus difference is large, intense stress concentrations can occur at the adhesive-adherent interface, which can cause premature failure in the bonding zone [23].

### **2.3.3 Environmental parameters**

The environmental conditions that adhesive joints are subjected to during their service life play a critical role in determining the long-term durability of both the adhesive and the bonded interface. Factors such as temperature fluctuations, humidity, water exposure, UV radiation, contact with chemicals (e.g., fuel, oil, or cleaning agents), and freeze-thaw cycles can degrade the adhesive's physical structure and chemical stability. Such degradation may result in reduced adhesion, cracking, embrittlement, or softening of the adhesive layer, ultimately compromising the joint's strength and reliability.

High temperatures can cause serious reductions in mechanical strength, especially in thermoset adhesives, when the glass transition temperature is approached or exceeded. At low temperatures, ductile adhesives can become brittle and their impact strength can decrease. In addition, temperature-humidity combinations can cause chemical degradation such as hydrolysis and plasticization, especially in hygroscopic epoxy-based adhesives. For example, Peng et al. (2024) demonstrated that epoxy-CFRP/titanium single lap joints conditioned at 95% RH and 60°C for 1000h suffered a 20–40% decrease in tensile strength [10].

## 2.4 Analytical methods

Volkersan and Goland and Reissner are considered pioneers of adhesive-bonded joints stress analysis. Early approaches are generally based on single lap joints due to simplicity. Volkersen worked on a concept that differential shear demonstrates non-uniform shear stress distribution in the cohesive zone, with the assumption that deformation occurred only in shear. Potentially, applying the method to the double lap joint could have given more accurate results since this approach neglects bending effects in single lap joints. On the contrary, Goland and Reissner (1944) address this critical bending moment and transverse force that occurs due to joint end rotation by adding the bending moment factor ( $k$ ) and transverse force factor ( $k'$ ). They estimate the adhesive shear and peel stresses. Large deflections were ignored in Goland and Reissner's theory. Even though Hart-Smith (1973) takes this factor into account and expanded the approach, the deformation of the adhesive is still ignored [24,25,26].

As analytical models became more advanced, the developed equations became too sophisticated that surpassed to be solved with simple closed forms and necessitated the use of data processors. Consequently, gradual evolution driven by the increasing complexity needed to model real-world joint behaviors like material and geometric nonlinearity, anisotropic adherends, or various joint geometries and loadings pushes models towards numerical solutions [27]. Pirvics' work (1974) is an early numerical solution needed example that applies to many different joint types with emphasis minimization of the internal energy. The years 1975-1977, through-thickness adherend deformations were the main point for research, recognizing the importance of composite structures. Names such as Renton and Vinson, and Srinivas and Allman have contributed to this field of study. Allman's analysis allowed for through-thickness variation of adhesive peel stress, but did not explicitly model laminated composite construction details like Renton and Vinson. The simple design methodology proposed by Adams et al features with proposed minimal computational method by predicting joint strength for multiple combinations, non-yielding adherends with ductile adhesives, and yielding adherends/any adhesive, semi-ductile/brittle adhesives/ with non-yielding adherends [28].

## 2.5 Numerical methods

### 2.5.1 Continuum mechanics

As explained in the failure mode section, failure can occur in different sections within the joint. Continuum mechanics assumes that materials are continuous masses without considering their microscopic atomic or molecular structure, and deals with the assumption that the adherend does not fail. It assumes that the material deforms reversibly and proportionally to the applied stress, akin to Hooke's Law. The behavior of the adhesive is often modeled using linear elasticity theory, which provides a continuum mechanics framework for describing its response under load. This approach enables the stress distribution to vary across the thickness of the bond line, capturing the internal variations that develop due to loading conditions and material interactions. Adhesive edges are subject to maximum peel and shear stresses, which in theory go on indefinitely as the adhesive layer gets reduced to an infinitesimally thin thickness. This edge-dominated stress state normally leads to the initiation of adhesive joint failure at these locations [29].

### 2.5.2 Fracture mechanics

Fracture mechanics interprets deboned growth in terms of energy release rate ( $G$ ), a concept introduced by Griffith to quantify the energy liberated per unit crack extension. This term fundamentally quantifies the energy released as a crack, or deboned, grows. The relationship between the released energy ( $G$ ), the total potential energy ( $U$ ), and the crack length ( $a$ ) is expressed in Eq. (2.1). A critical value of the energy release rate, often termed fracture toughness and sometimes associated with the stress intensity factor ( $K$ ), signifies that sufficient crack driving force exists to initiate crack propagation, leading to an increase in released energy.

$$G = \frac{dU}{da} \quad (2.1)$$

- $G$ : Energy release rate — the amount of energy released per unit increase in crack length.
- $U$ : Total potential energy of the system (elastic energy + external work).
- $a$ : Crack length.

While continuum mechanics can predict crack initiation, fracture mechanics specifically addresses the propagation of pre-existing cracks, a fundamental prerequisite for its application. The behavior of stresses right at a crack tip is intensely complex, with dependencies on applied loads, the specific crack geometry, and the material's properties. This complexity is further compounded by environmental factors such as temperature and moisture. To chasten, 3 modes describe how the crack faces move relative to one another and what kind of stress causes that movement. Grasping each of these modes is essential for studies to predict how a crack will grow and, ultimately, how a material will fail.

Mode I, also known as the opening mode, takes place when the dominant force is applied normal to the crack plane, causing the crack faces to separate directly apart. This is perhaps the most commonly observed and analyzed fracture mode in engineering applications. Mode II, referred to as the in-plane shear mode, occurs when forces act parallel to the crack plane but perpendicular to the crack front, causing the crack faces to slide against each other, similar to a tearing motion. Mode III, known as the out-of-plane shear mode, involves shear forces acting parallel to both the crack plane and the crack front, resulting in a twisting or scissoring movement between the crack surfaces. This motion is distinct from Mode II as it doesn't occur within the plane of the crack opening as illustrated in Fig 2.5 [30].

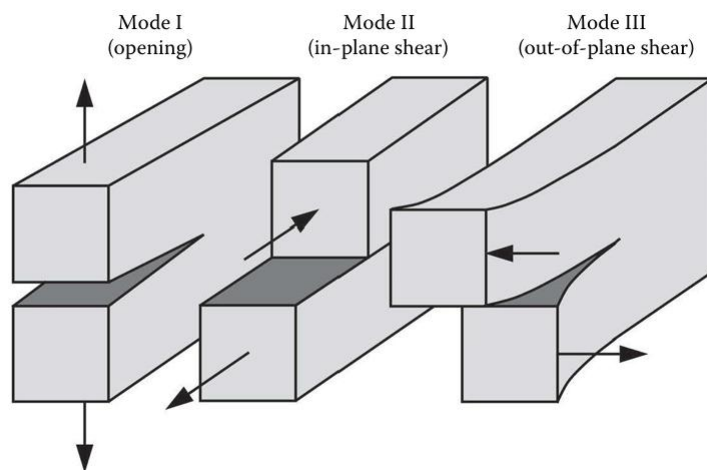


**Figure 2.5:** Representations of fracture modes I, II, and III [30]

In practical engineering scenarios, a crack will be subjected to a concurrent combination of these fundamental deformation modes, a state referred to as mixed-mode fracture. In mixed-mode loading, the stresses at the crack tip are a superposition

of the stress fields corresponding to two or more of the pure modes. Failure criteria for this mode are assumed as Eq. (2.2), where  $\alpha$ ,  $\beta$ , and  $\gamma$  exponents are taken 1 for linear criterion and 2 for quadratic criterion.

$$\left(\frac{G_I}{G_{IC}}\right)^\alpha + \left(\frac{G_{II}}{G_{IIC}}\right)^\beta + \left(\frac{G_{III}}{G_{IIIC}}\right)^\gamma = 1 \quad (2.2)$$

### 2.5.3 Damage mechanics

Unlike fracture mechanics, which typically deals with the existing, well-defined macro-cracks and their propagation, damage mechanics differs by focusing on the gradual accumulation of micro-defects throughout a material volume. It models material degradation by introducing internal variables often called damage parameters that reduce properties like stiffness or strength in the constitutive equations. These models are particularly effective in capturing the response of both ductile and brittle materials under multiaxial and cyclic loading conditions. By simulating the evolution of distributed micro-damage within a process zone, damage mechanics enables the prediction of stiffness degradation and delayed failure prior to macroscopic crack formation [31].

A most up-to-date modeling approach, cohesive zone model, emerges as a crucial link between these two approaches. CZM adeptly translates the underlying principles of material degradation into a numerically tractable framework. Conceptually, it bridges the gap between classical continuum mechanics and traditional fracture mechanics. A key benefit of the cohesive zone model is its capacity to overcome the common stress singularity at a crack tip, which is problematic in linear elastic fracture mechanics. Instead, CZM models the region ahead of the crack as a zone where stress remains finite and damage is distributed. This feature is especially useful for accurately simulating thin adhesive layers, which often experience complex stress patterns. Considering these advantages and its effectiveness in simulating progressive interface failure, cohesive zone model has been selected as the main methodology for this thesis. Its specific implementation is explained in detail in next chapter.

### **3. METHODOLOGY AND MODELING**

#### **3.1 Cohesive Zone Method**

##### **3.1.1 Fundamentals and evolution of the CZM**

The cohesive zone model is a way of looking at fracture mechanics that tries to model how material interfaces break down and separate over time, especially in bonded joints. CZM is different from traditional fracture theories because it sees crack propagation as a process zone ahead of the crack tip, where finite tractions can still be transferred across surfaces that are only partially separated. The idea came about to get around the main problems with older analytical and numerical methods, especially when it came to predicting fractures in composite materials and adhesive joints.

Adhesively bonded joints inherently contain discontinuities at their interfaces, which typically represent the most critical and vulnerable regions along the load transfer path. These discontinuities give rise to stress singularities which are extremely high and unrealistic stress values in particular at the edges of the interface. Because of this, numerical stress predictions in these areas become very sensitive to how finely the mesh is refined and how close it is to geometric boundaries. To deal with this, some researchers have tried to find stress or strain values at random distances from single points. But these kinds of methods are usually only useful for certain cases and don't work in general or have a physical meaning, which makes them less reliable for making predictions [32].

The origin of CZM dates to the 1960s: Dugdale (1960) modeled a plastic “strip” at a crack tip with a constant yield stress, while Barenblatt (1962) introduced a stress distribution ahead of a crack to represent atomic-bond cohesion. These early models envisioned finite cohesive tractions that drop to zero at a critical opening. Hillerborg et al. (1976) later implemented a fictitious crack (CZM) in a finite-element context for concrete, introducing the traction-opening formulation now common in CZM. Thus, modern CZM combines linear elasticity with a traction-separation law (TSL) that governs damage. In 1960, the Dugdale model described constant cohesive stress equal

to the yield strength distributed along a finite length at the crack tip in ductile materials. In 1962, Barenblatt proposed a model for brittle fracture, introducing a variable cohesive stress distribution ahead of a crack tip to mimic interatomic forces. Finally, in 1976, Hillerborg and co-workers developed the “fictitious crack” model for concrete within the finite-element framework, where traction was expressed directly as a function of crack opening, a formulation that constitutes the basis of the modern traction-separation law [33,34,35].

Maximum stress, strain, or strain energy were examples of local continuum-based failure criteria that were frequently used in traditional FEA techniques. However, without manual user intervention, they were unable to track the growth of non-self-similar cracks and the spread of damage across the joint. The Virtual Crack Closure Technique (VCCT) and other methods of Linear Elastic Fracture Mechanics (LEFM) are restricted to small-scale yielding close to the crack tip and necessitate a predefined crack. They are therefore inappropriate for toughened adhesives, where there may be a sizable plastic zone prior to the crack. On the other hand, CZM provides a more thorough and accurate fracture modeling method by enabling the simultaneous simulation of damage initiation and evolution.

The area close to the crack tip becomes crucial when a material fractures. Although no actual material can tolerate such stress, LEFM suggests that stress at this point becomes infinite. To address this contradiction, cohesive zone model was developed. It imagines a region that has not yet completely opened, directly in front of the crack tip. Despite their partial separation, the two faces in this zone are still able to transmit forces. Consequently, there are limited, physically significant stresses in this area. A more realistic depiction of fracture behavior and energy dissipation is made possible by CZM, which records the slow separation of material surfaces rather than letting cracks spread instantly.

The fundamental constitutive relationship in cohesive zone model is the Traction-Separation Law (TSL), sometimes referred to as a cohesive or separation law. It describes the relationship between the relative displacement or separation of potential crack surfaces and the stress across those surfaces. This law captures the material's resistance to fracture and controls the mechanical response within the cohesive zone by acting tangentially along the possible crack path. A typical TSL rises from zero to

a peak traction and then decays to zero at complete separation. The area under this curve is the fracture energy.

Various shapes of TSL are used to model different materials which represent in Figure 3.1 [36].

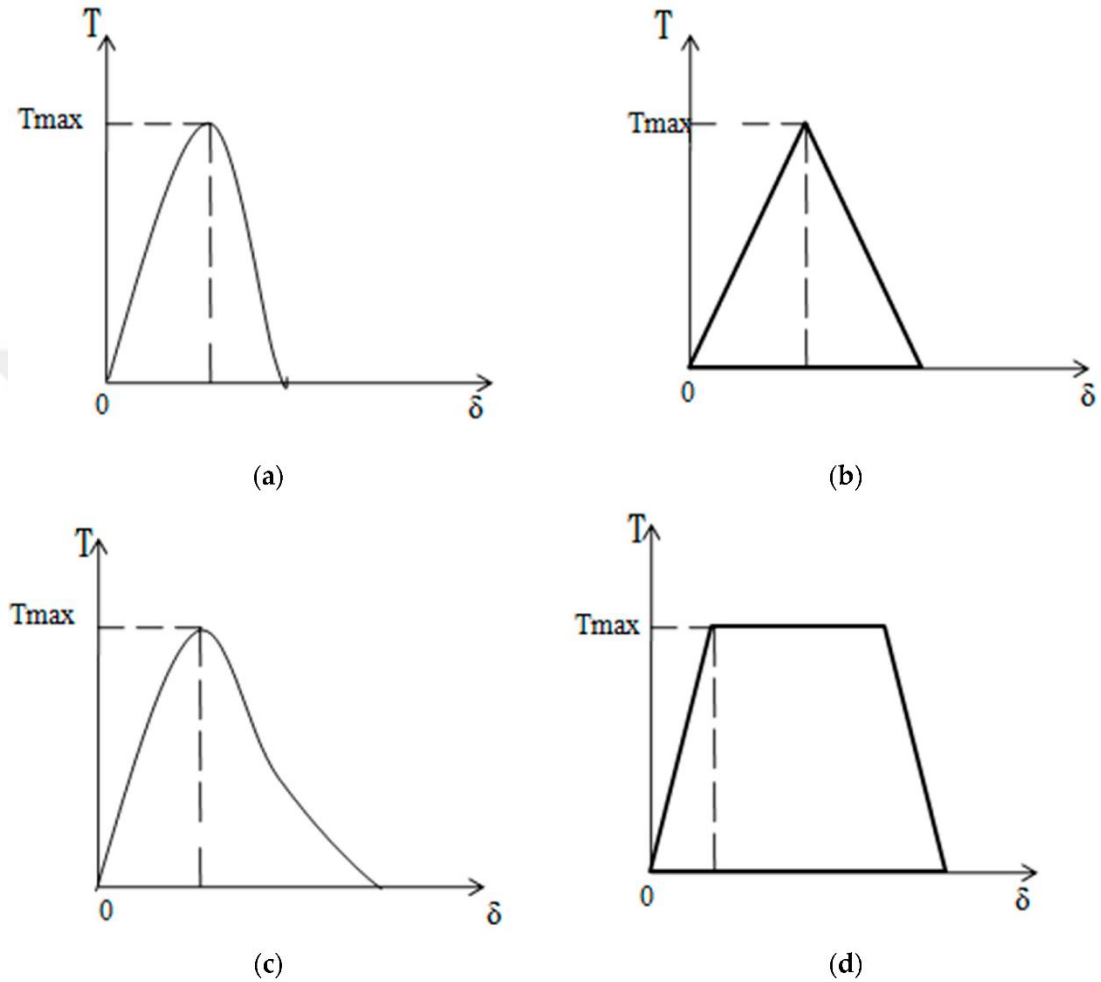


**Figure 3.1:** a) exponential traction–separation law (b) bilinear traction–separation law (c) polynomial traction–separation law (d) trapezoid traction–separation law [36]

The choice of traction–separation law shape is essentially a choice about how the post-peak softening behavior is represented. Different shapes emphasize different aspects of the fracture process, and the right one is the shape that best matches the measured load–displacement response of your adhesive and the failure morphology you expect.

A triangular law is the most economical description: stiffness up to a single peak, then a straight decline to complete separation. It works well for brittle to moderately ductile adhesives whose post-peak response is roughly linear, and it is robust and easy to calibrate when you have limited data. A bilinear law introduces a visible change of

slope after the peak. It is useful when your experiments show a rapid initial drop followed by a gentler tail. This shape lets you represent an early localization phase and a subsequent stable-growth phase without adding too much complexity.

A trapezoidal law adds a plateau at approximately constant traction before softening to zero. That plateau captures plastic-like flow and distributed damage, so it suits ductile adhesives and thicker bond lines where energy absorption is spread over a longer separation range. It also lets you increase dissipated energy without artificially inflating peak traction. An exponential law replaces sharp slope changes with a rounded decay. It can be chosen when test curves show a gradual, curved post-peak or when numerical smoothness and convergence are priorities. It often helps in simulations prone to snap-back or mesh sensitivity around the peak.

Since fracture behavior varies depending on the material type and joint configuration, the form of the traction–separation law (TSL) must be tailored accordingly. As noted in the study by Alfano and Crisfield (2006), both triangular and bilinear TSL shapes are commonly employed, each characterized by an initial linear increase in traction followed by a linear softening phase [37]. Bilinear shape is the most recommended due to its simplicity and applicability exceptionally composite and brittle materials. As an alternative for ductile materials, trapezoidal law that includes an elastic rise plateau and softening is preferred. Tvergaard and Hutchinson have initial studies for this shape. Exponential traction law which is proposed by Xu and Needleman [38].

### **3.1.2 The property identification methods**

The material properties used as input for Finite Element Analysis (FEM) simulations of adhesive joints are primarily obtained through experimental testing. These tests characterize the behavior of the adhesive and serve as an identification card, indicating its flexibility, durability, and damage response.

One of the most fundamental methods for evaluating the tensile behavior of an adhesive is the uniaxial tensile test, which is used to determine key properties such as Young's modulus ( $E$ ), yield strength ( $\sigma_y$ ), tensile failure strength ( $\sigma_r$ ), and tensile failure strain ( $\epsilon_r$ ). Adhesive samples prepared in the standard "dog bone" shape are pulled in accordance with international standards such as EN ISO 527-2 or ASTM

D638. Adhesive responds when stretched, when it permanently changes shape, and when it breaks are revealed as result of this test [39,40].

The Thick Adherend Shear Test (TAST) is a common method for shear characterization, conducted in accordance with standards such as ISO 11003-2:1999. This test uses a specimen designed to create a pure shear loading in a central section when compressed. These tests provide data to determine properties like shear modulus ( $G$ ), shear yield strength ( $\tau_y$ ), shear failure strength ( $\tau_r$ ), and shear failure strain ( $\gamma_r$ ) [41].

Most required parameter is the critical strain energy release rate ( $G_c$ ) for CZM implementation. This parameter indicates the adhesive's damage tolerance and resistance to fracture. In Mode I, also called tensile or cleavage fracture toughness ( $G_{Ic}$ ), the crack in the adhesive tends to open under tensile forces. This parameter is typically measured using tests such as double cantilever beam or Compact Tension tests. The DCB test, standardized in procedures such as ASTM D3433-99, is performed by introducing a controlled crack in the specimen, and the collected data are converted to  $G_{Ic}$  through reduction methods such as the Compliance Calibration Method (Irwin-Kies equation), Direct Beam Theory, Corrected Beam Theory, and the J-integral approach [42]. In Mode II, referred to as shear fracture toughness ( $G_{IIc}$ ), the crack propagates under shear forces rather than tensile opening. The most common experimental technique for determining this property is the End Notch Bend (ENB) test, which provides a reliable measure of the adhesive's shear fracture resistance [43].

For the Finite Element Analysis (FEA) presented in this study, the essential material parameters for the adhesives were directly obtained from experimental characterizations performed in the referenced works by Campilho et al. (2012), da Silva et al. (2008), and Fernandes & Campilho (2017). These studies include tensile and shear tests such as the Double Cantilever Beam (DCB), End-Notched Flexure (ENF), and Thick Adherend Shear Test (TAST), ensuring that both Mode I and Mode II fracture properties were appropriately captured for use in cohesive zone modeling [44, 45, 19].

## 3.2 Finite Element Modeling

### 3.2.1 Implementation and applications of CZM on FEM

In Finite Element Analysis (FEA), TSLs are typically implemented using special cohesive elements or interface elements placed along potential fracture paths. These elements are conceptually similar to springs placed between adjacent surfaces that are expected to separate. In FEM, they connect paired nodes of solid elements on either side of the potential fracture plane. In Abaqus, where this study is performed, cohesive behavior is defined by a traction–separation law in the material or section properties. This involves specifying an elastic response, a damage initiation criterion, and a damage evolution law. The damage variables are based on nominal stresses and strains per original interface area and thickness.

Since this study is based on a two-dimensional model, only the normal and shear directions are considered, while the out-of-plane direction is omitted.

The user defines initial stiffness coefficients  $K_n$  and  $K_s$  (normal and shear) to govern the linear portion of the TSL up to damage initiation. In the intact regime, nominal tractions relate to separations as defined in Eq. (3.1). Here,  $\delta_n$  and  $\delta_s$  denote the normal and shear separations, respectively, which represent the relative displacements between opposing cohesive surfaces prior to damage.

$$T_n = K_n \delta_n \quad \text{and} \quad T_s = K_s \delta_s \quad (3.1)$$

After damage, the effective secant stiffness is reduced. In general, the cohesive traction vector ( $T$ ) is given by Eq. (3.2):

$$T = (1 - D)K\delta \quad (3.2)$$

The scalar variable  $D$  represents the progression of damage within a material, capturing the cumulative effects of all active degradation mechanisms. Initially set to zero,  $D$  increases as damage develops, ultimately influencing the stiffness and load-carrying capacity of the material. In Abaqus, similar formulations are employed, where unloading behavior follows the current secant stiffness, reflecting the material's degraded state.

From fracture mechanics, it is well understood that multiple damage mechanisms can act simultaneously within the same material. The point at which degradation begins is

defined by a damage initiation criterion, marking the onset of stiffness reduction in the cohesive zone.

Abaqus provides various options to define this initiation. One common approach is the quadratic stress criterion, which assumes that damage begins when the stresses, either normal to the interface or in the first or second shear direction, reach critical levels. This criterion captures both pure and mixed-mode loading conditions effectively.

$$\left(\frac{T_n}{T_n^0}\right)^2 + \left(\frac{T_s}{T_s^0}\right)^2 = 1 \quad (3.3)$$

In 2D planar problems either the maximum nominal stress or the quadratic stress criterion, are typically used. In this study, the quadratic nominal stress criterion is adopted due to it accounts for the coupled effect of both normal and shear stresses, unlike the maximum stress criteria that treats each traction component independently and may not accurately reflect the interaction between modes.

After damage initiation, the cohesive traction reduces progressively following a defined softening law until complete separation occurs. In Abaqus, this damage evolution can be characterized either by specifying the fracture energy or by defining the critical separation displacement. Given the presence of mixed-mode loading in the current study, the Benzeggagh–Kenane (BK) criterion is employed, as it provides an effective means of capturing the variation in fracture energy with respect to the mix mode, particularly when Mode I and Mode II fracture energies differ. The BK criterion defines the mixed-mode fracture energy ( $G$ ) as Eq (3.4) where  $\eta$  is B-K parameter normally obtained from experiment.

$$G_n^c + (G_s^c - G_n^c) \left(\frac{G_s}{G_T}\right)^\eta = G^c \quad (3.4)$$

When damage evolution is included in the analysis, the scalar damage variable  $D$  increases monotonically from undamaged state to fully failed state as loading progresses beyond the point of damage initiation. In cases where linear softening behavior is assumed, Abaqus applies a damage evolution formulation that simplifies to the expression proposed by Camanho and Davila (2002) shown in Eq. (3.5). Here,

$\Delta_c$  denotes the critical separation at damage onset,  $\Delta_{\max}$  is the maximum separation attained during loading, and  $\Delta_f$  represents the final separation at complete failure. This approach provides a consistent and physically meaningful description of how stiffness degrades in the adhesive as a function of separation [46].

$$D = \frac{\Delta_f(\Delta_{\max} - \Delta_c)}{\Delta_{\max}(\Delta_f - \Delta_c)} \quad (3.5)$$

Models with strain-softening like CZM are inherently nonlinear and can have convergence difficulties. As damage accumulates, the global stiffness matrix degrades, which can cause loss of positive definiteness or snap-back behavior. In particular, brittle adhesives which have sharp drop in TSL lead to very rapid stiffness loss. A cohesive element may lose nearly all load-carrying capacity over a tiny displacement increment. When such issues arise, the use of viscous regularization and carefully controlled load stepping is recommended, particularly when modeling brittle adhesives. However, it is crucial that these techniques are applied correctly and in a controlled manner, as improper implementation may lead to misleading or non-physical results, thereby compromising the accuracy of the simulation.

### 3.2.2 FEM validation

To validate the finite element methodology adopted in this thesis, a benchmark study from the literature was reproduced. The reference case was the work of Liao et al. (2013) [7]. In their study, scarf joints bonded with brittle (AV138/HV998) and ductile (EA9361) epoxy adhesives were analyzed under uniaxial tensile loading using a bilinear cohesive zone model. The control parameters were the adhesive thickness, scarf angle and adhesive type.

The same geometrical and material conditions were implemented in Abaqus for validation. The adherends were modeled as high-strength steel with a width of 27.7 mm and a long edge of 92.0 mm. The geometrical configuration of the scarf joint used for validation is illustrated in Figure 3.2, where the overlap geometry and boundary conditions are represented in accordance with the reference study [23]. The adhesive layer was represented with 4-node cohesive elements (COH2D4), while the adherends

were meshed using CPE4R plane-strain elements. The adhesive shared nodes with the adherends. The lower adherend was fully constrained, and a displacement-controlled tensile load was applied to the upper adherend, identical to the reference setup.

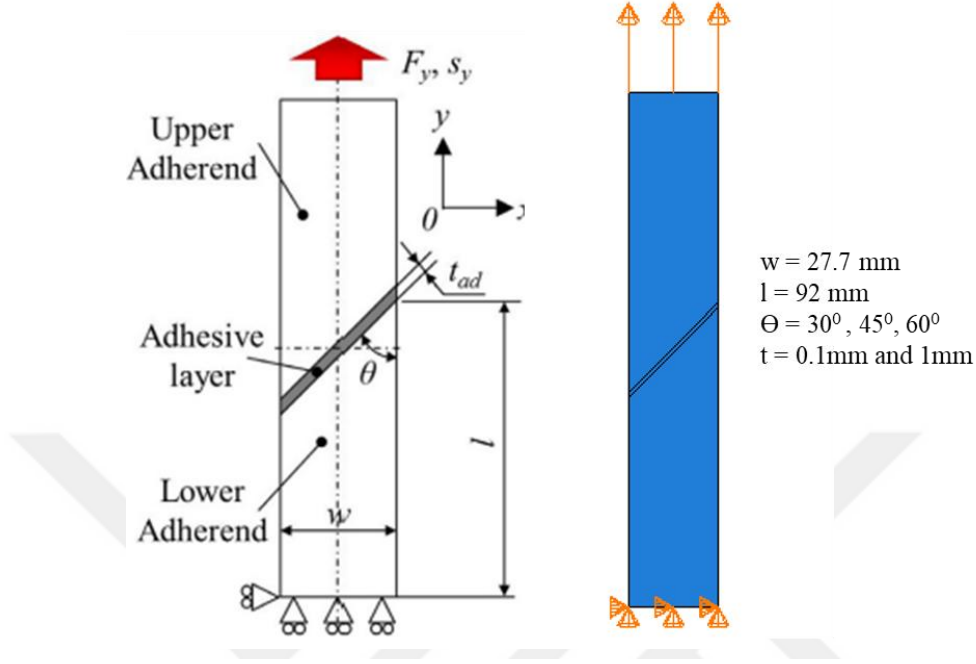


**Figure 3.2:** Geometrical configuration of scarf joint for validation: schematic representation from literature [7] and finite element model developed in Abaqus

Simulations were carried out for scarf angles of 30°, 45°, and 60° and adhesive thicknesses of 0.1 mm and 1.0 mm. The ductile adhesive (EA9361) primarily exhibited a gradual post-peak softening with failure displacement directly proportional to the adhesive thickness, whereas the brittle adhesive (AV138/HV998) showed an abrupt post-peak drop in load-carrying capacity. These trends matched closely with those reported by Liao et al. (2013) [7]. Furthermore, the ultimate load decreased with increasing adhesive thickness and scarf angle, as illustrated in Figure 3.3, confirming the consistency of the present CZM implementation with both numerical and experimental results in the literature. To illustrate the similarity of the overall response between the present model and the reference, one representative case with  $\theta = 45^\circ$  and  $t = 0.1$  mm was selected. As shown in Figure 3.4, the load–displacement responses exhibit comparable trends, confirming that the implemented CZM approach can reliably reproduce the reference behavior.

This validation confirms that the adopted finite element approach and cohesive zone modeling framework are capable of accurately representing the failure mechanisms of

adhesively bonded joints. Consequently, the same modeling strategy is confidently extended to the parametric analysis of single-lap joints presented in Section 3.3.

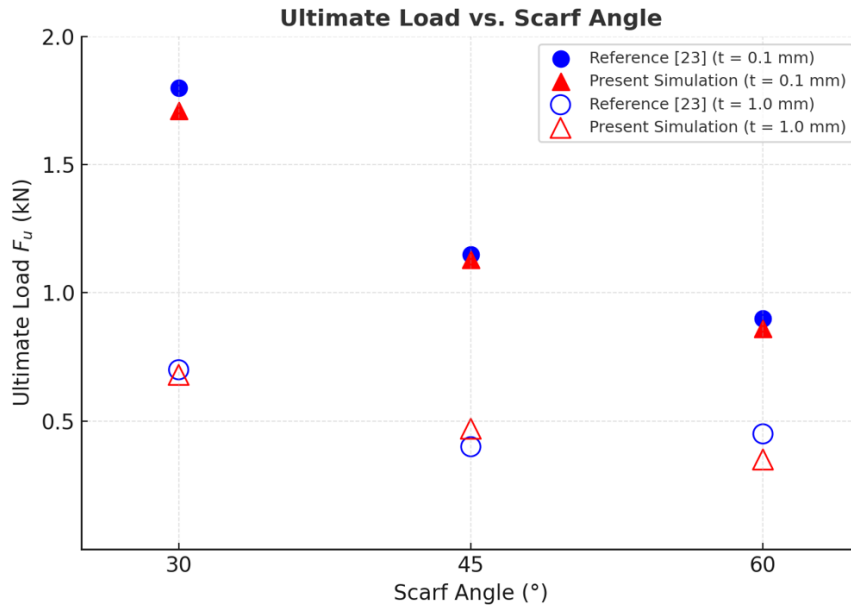


**Figure 3.4:** Ultimate load for each scarf angle: comparison between the present model prediction with the reference study [7]

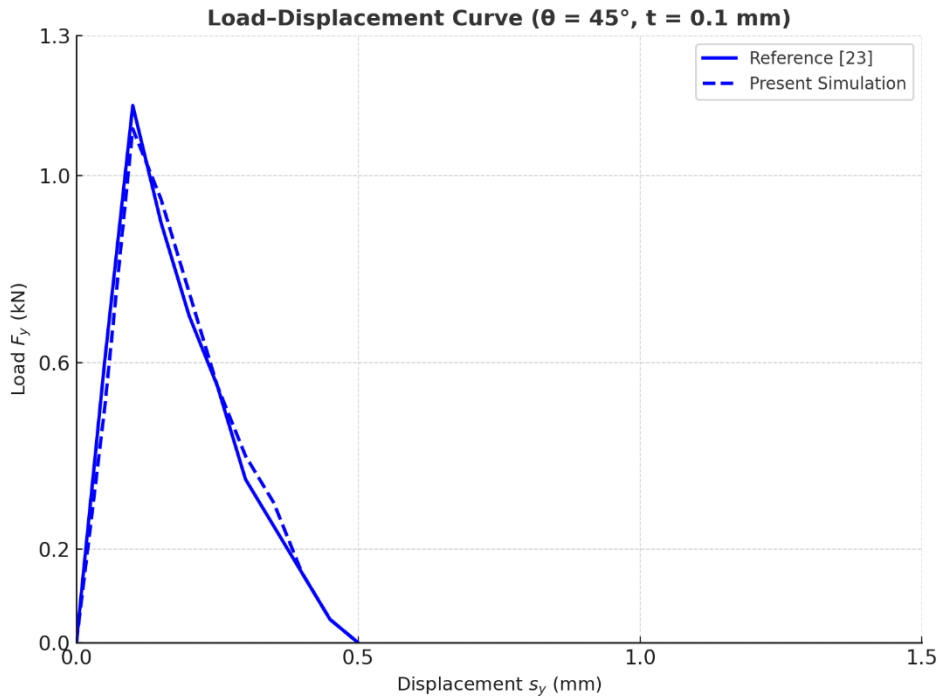


**Figure 3.3:** Comparison of load–displacement responses at  $\theta = 45^\circ$  and  $t = 0.1$  mm: Reference [7] vs. present simulation

### 3.3 Parametric Design Study

Following the validation study, the finite element model was adapted to analyze single-lap joints (SLJs), which constitute the primary focus of this thesis. The parametric study considered variations in all major design variables identified in the literature, detailed in Chapter 2.3, as influencing single-lap joint behavior. Unlike the scarf-joint validation, where a more uniform stress distribution was present, the SLJ configuration emphasizes peel–shear interactions. Moreover, in contrast to the benchmark, the present study incorporates multiple adhesives with thickness-dependent CZM parameters, systematically varies overlap length, and employs an optimization framework with outputs such as ALLSE and SDEG, supported by automated Abaqus–Python workflows.

#### 3.3.1 Model description

The finite-element framework adopted for this thesis is a two-dimensional plane-strain representation of a single-lap joint (SLJ), whose overall geometry mirrors widely used experimental set-ups reported for bonded-joint characterization tests. Each adherend is modelled as 2D with a 120 mm long and 3 mm thick steel plate, while the adhesive occupies a rectangular bond-line centered on the mid-span. Overlap length, adhesive thickness and adhesive material are treated as input variables and are automatically reassigned by a Python script written for Abaqus/Standard. The script parametrically builds the part topology, partitions the bond-line, seeds a structured mesh and populates material properties; it then submits a batch of analyses covering the entire design matrix and archive’s reaction forces, displacements and dissipated fracture energy for subsequent statistical processing.

Cohesive behavior is represented by a single row of four-node quadrilateral cohesive elements (COH2D4) positioned between the two adherend halves. The overlap region was discretized using a uniform element length of 1 mm along the bond line and a single element through the adhesive thickness, corresponding to the nominal adhesive thickness. The adopted discretization ensured mesh-independent results because, in cohesive zone modeling, the response is governed by the traction–separation law and the fracture energy, rather than by the absolute element size. As long as the cohesive law is properly defined to capture the correct energy release rate, the global load–

displacement response remains mesh-independent. Therefore, no separate mesh refinement study was deemed necessary. Each element follows a linear-elastic traction–separation law until the quadratic nominal-stress criterion is met, after which damage grows according to a linear softening relationship. Employing the quadratic formulation is particularly important for single-lap joints, where eccentric loading induces significant and concurrent peel and shear stresses; the coupled criterion therefore provides a more realistic description of damage onset and improves both physical fidelity and numerical stability in cohesive-zone simulations.

Moreover, cohesive law shapes were selected in accordance with the adhesive’s ductility, informed by prior evaluations that demonstrated the importance of matching TSL shape to fracture behavior. For instance, brittle adhesives were best modeled using triangular laws, while trapezoidal or bilinear forms captured the progressive damage in more ductile systems [45]. Consequently, the selected cohesive properties used in this study not only represent realistic mechanical behavior but also ensure robust and mesh-independent numerical performance across a range of adhesive thicknesses and overlap geometries.

Mixed-mode fracture energy is evaluated with the Benzeggagh–Kenane power law, and consistent with values commonly reported for structural epoxies subjected to appreciable shear contributions this study adopts  $\eta = 2.285$ . Although the literature quotes a typical range of 1.5–2.5, the chosen value offers a balanced transition between Mode I and Mode II fracture energies, ensuring numerical robustness and physical consistency while maintaining comparability with previous cohesive-zone studies that lack specimen-specific mixed-mode calibration [46].

Critical strengths and fracture energies are not constant but scale with using empirically derived thickness functions embedded in the script; the calibration coefficients are taken from Mode I DCB, Mode II ENF and shear TAST tests published for the same commercial adhesives. Adherends are discretized with reduced-integration continuum elements (CPE4R) so that bending-induced peel stresses that an intrinsic feature of SLJs are accurately captured.

The left-hand adherend is clamped, the right-hand adherend is driven by a prescribed axial displacement and lateral motion is suppressed to replicate pin-aligned grips in

quasi-static tensile tests. The applied displacement was selected to drive the joint to failure in simulation without causing undue bulk deformation. Automatic time incrementation, geometric non-linearity, viscous regularization damping factor and energy balance tracking are activated to secure convergence during rapid post-peak softening.

Figure 3.5 outlines the single-lap joint (SLJ) configuration together with the finite-element mesh, clarifying the geometric layout and discretization used later to generate load–displacement and damage metrics.

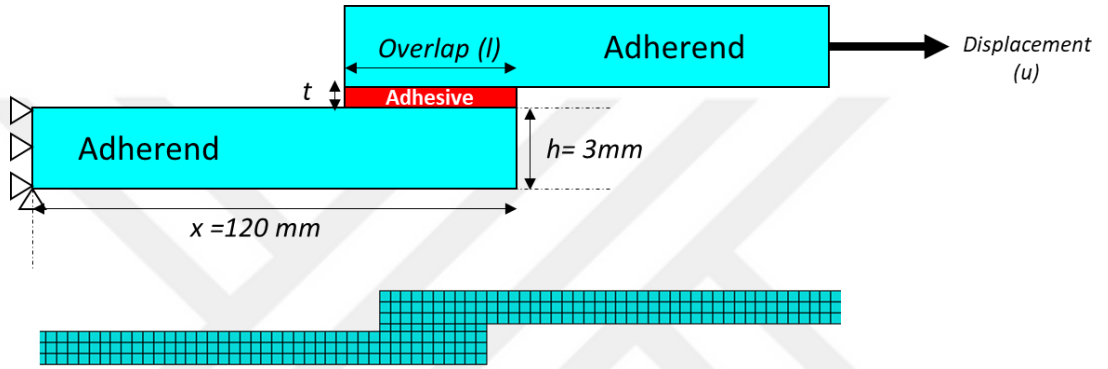


**Figure 3.5:** Single Lap Joint Configuration and FEA Mesh

The single-lap joint (SLJ) configuration was chosen instead of scarf, double-lap, or butt geometries because it naturally imposes a pronounced combination of peel and shear stresses, creating an ideal scenario for assessing cohesive-zone formulations. Moreover, a substantial body of benchmark data is available for SLJs, which facilitates validation of predicted failure loads and process-zone lengths. The structural response of an SLJ is also highly sensitive to variations in overlap length and adhesive thickness, characteristics that align directly with the objectives of this parametric investigation into geometric optimization. All remaining specimen dimensions like overall length, width, and tab length follow the consensus values recommended in the referenced experimental programs, ensuring that the numerical results can later be cross-checked against independent laboratory measurements.

### 3.3.2 Selected parameter & ranges

The parametric matrix was deliberately limited to adhesive thickness, overlap length, and constituent materials because these three variables exert the most direct and independent influence on the global performance of a single-lap joint, while other geometric or surface-related factors can be held constant without compromising the validity of the comparative study. Table 3.1 lists the study variables that define the parametric space, establishing how geometry and material choices are systematically varied in subsequent analyses.

**Table 3.1:** Study Variables

| Parameter          | Value(s)                               |
|--------------------|----------------------------------------|
| Overlap length     | 10, 20, 30 mm                          |
| Adhesive thickness | 0.10, 0.25, 0.50, 0.75, 1.00 mm        |
| Adhesive type      | AV138, Araldite 2015, EA 9321, EA 9361 |

Overlap length and adhesive thickness dominate the stress transfer mechanism in an SLJ since short overlaps suffer premature peel-dominated failure, whereas very long overlaps hit a plateau in strength once the interface stresses saturate. The study therefore spans 10–30 mm, capturing the transition from inefficient to quasi-optimum load transfer observed experimentally.

Adhesive thickness is varied from 0.10 mm comparable with aerospace shim layers to 1 mm, a level at which the confinement effect is largely relieved and plastic energy absorption becomes significant. Steel is chosen as adherend materials to represent typical structural metals, with steel's high elastic modulus reflecting rigid substrates as commonly assumed in the literature. Table 3.2 compiles the mechanical properties of the adherends, providing the elastic inputs required to couple adherend response with interface damage in the CZM simulations.

**Table 3.2:** Adherend Mechanical Properties

| Inputs                      | STEEL |
|-----------------------------|-------|
| Young's Modulus, E<br>(MPa) | 4890  |
| Poisson's ratio, $\nu$      | 0.35  |

Multiple adhesive types covering a range of stiffness and toughness were included. Selected adhesives represent brittle, moderately ductile and highly ductile classes, allowing assessment of how cohesive-law shape and fracture energy influence optimization trends. In addition, factors such as high temperature resistance, mechanical strength and environmental resistance are very important for main structural components in the aerospace industry. Therefore, high-performance adhesives such as AV138/HV998, Hysol EA 9361 and Sikaforce® 7888 are widely used materials in the industry and selected for this study. Table 3.3 reports baseline mechanical properties of the four adhesives considered, forming the basis for traction–separation parameterization prior to thickness-dependent adjustments.

**Table 3.3:** Adhesive Material Mechanical Properties [1, 7, 19, 21]

| Inputs                                  | AV138/<br>HV998 | Hysol EA<br>9361 | Sikaforce®<br>7888 | Araldite®<br>2015 |
|-----------------------------------------|-----------------|------------------|--------------------|-------------------|
| Young Modulus's, E<br>(MPa)             | 4890            | 670              | 1890               | 1850              |
| Shear Modulus, G<br>(MPa)               | 1560            | 239.3            | 710                | 560               |
| Poisson's ratio, $\nu$                  | 0.35            | 0.4              | 0.33               | 0.33              |
| Tensile Yield Strength<br>(MPa)         | 36.49           | 4.23             | 13.2               | 12.63             |
| Tensile Yield Strain                    | -               | 0.00631          | 0.00698            | 0.00683           |
| Tensile Failure Strength<br>(MPa)       | 39.45           | 7.99             | 28.6               | 21.63             |
| Tensile Failure Strain                  | -               | 0.043            | 0.043              | 0.0477            |
| Shear Yield Strength<br>(MPa)           | 25.1            | 2.44             | 15.3               | 14.6              |
| Shear Yield Strain                      | -               | 0.0102           | 0.0215             | 0.0261            |
| Shear Failure Strength<br>(MPa)         | 30.2            | 5.54             | 20                 | 17.9              |
| Shear Failure Strain                    | -               | -                | 1                  | 0.439             |
| Toughness Mode I, $A_{c, I}$<br>(MPa)   | -               | 2.69             | 0.75               | 0.70              |
| Toughness Mode II, $A_{c, II}$<br>(MPa) | -               | 2.69             | 17.27              | 6.71              |

Alternative factors such as fillet geometry, adherend thickness, or surface preparation were deliberately fixed. Fillets and spew chamfers indisputably mitigate peel stresses, yet their principal effect is most pronounced in highly brittle adhesives; because the present study already spans a brittleness-to-ductility spectrum, adding fillet angle as another dimension would confound interpretation and would demand a much larger

design matrix to avoid aliasing. Surface roughness and surface-treatment variables are controlled experimentally by specifying identical grit-blasting and priming procedures; in numerical models they enter only via fracture-energy values, which are already embedded in the cohesive law. By focusing on these three orthogonal drivers of joint behavior, the study achieves a tractable factorial plan that still exposes the dominant interactions most relevant to structural design and optimization.

### 3.3.3 Thickness-dependent material functions

In the current study, the cohesive-zone parameters, the initial stiffness, the fracture energies (Mode I and II), and the separation strengths are depended by material thickness. Therefore, relationship between them is formulated as explicit functions of the adhesive layer thickness. This approach ensures that each simulation intrinsically accounts for the transition between thin-layer and thick-layer fracture regimes, reflecting small-scale yielding and damage-saturation phenomena within a unified framework.

#### 3.3.3.1 Cohesive stiffness

The penalty stiffness assigned to the cohesive elements in tension and shear), denoted  $K_n(t)$  and  $K_s(t)$  respectively, is expressed in Eq. (3.6) and is chosen so that the elastic compliance of the interface matches that of a bulk adhesive layer of thickness  $t_{ad}$ :

$$K_{n(t)} = \frac{E}{t_{ad}} \quad \text{and} \quad K_{s(t)} = \frac{G}{t_{ad}} \quad (3.6)$$

where  $E$  and  $G$  are the bulk Young's and shear moduli of the adhesive. By construction, thinner layers yield higher stiffness values, whereas thicker layers become more compliant, in direct correspondence with continuum elasticity.

#### 3.3.3.2 Total fracture energy

In many adhesive-joint studies, the total fracture energy of the bond layer is simply taken from standard DCB or ENF tests and applied unchanged, regardless of bond-line thickness. This expedient approach may be adequate for brittle adhesives or within a

narrow thickness range, but it cannot capture the well-documented increase of toughness as the layer transitions from small-scale yielding to fully developed plastic flow.

Since objective of this study is understanding geometrical properties effect on joint, each cohesive-zone parameter calculated as an explicit function of the adhesive thickness taken reference of Xu and Wei study [12]. Thereby embedding both the intrinsic fracture properties and the plastic-dissipation effects into a unified, thickness-sensitive description.

Total fracture energy is captured by two segments: an intrinsic component,  $G_0$  and a plastic-dissipation component,  $G_p$ , as expressed in Eq. (3.7). The intrinsic term reflects the energy required to cleave molecular bonds at the crack faces and is effectively independent of thickness and measured by test [47].

The plastic-dissipation term  $G_p$  accounts for the work done in yielding the adhesive bulk as defined in Eqs. (3.8) and (3.9) and is known to grow with thickness until the plastic zone becomes self-limited.

$$G_T(t) = G_0 + G_p(t) \quad (3.7)$$

$$G_p = 2 \int_0^{t_{ad}/2} A_c \, dy \quad (3.8)$$

$$A_c = \int_0^{\varepsilon_{ij}} \sigma_{ij} \, d\varepsilon_{ij} \quad (3.9)$$

At the vicinity of the crack tip, two distinct regions can be identified. The surrounding elastic zone continues to respond linearly, whereas the localized plastic zone at the crack tip experiences stresses exceeding the yield surface, leading to permanent deformation of the material. The height of this plastic zone, measured normal to the crack plane along the  $90^\circ$  radial direction, is defined as  $r_p(90)$  can be evaluated using the expressions provided in Eq. (3.10). It is a length-scale that tells how far plasticity spreads into the adhesive thickness before stresses fall back below yield. Pardoen et al. plots this height versus bond thickness and shows that it can be hundreds of microns for a soft, ductile adhesive and only tens of microns for a stiff, brittle one [48].

Small-scale yielding (SSY) assumes that the plastic zone around the crack tip remains much smaller than the key geometric features of the joint, such as the adhesive thickness, crack length, and the thickness of the adherends. This allows the use of linear elastic fracture mechanics without significant loss of accuracy. Under SSY the outer field around the crack is still governed by linear-elastic fracture mechanics.

$$r_p^I = \frac{1}{3\pi} \frac{E}{1-\nu^2} \frac{G_{0I}}{\sigma_y^2} \quad r_p^{II} = \frac{1}{2\pi} \frac{E}{1-\nu^2} \frac{G_{0II}}{\tau_y^2} \quad (3.10)$$

where  $\sigma_y$  and  $\tau_y$  are the tensile and shear yield stresses, respectively, and  $\nu$  is Poisson's ratio. The critical bond-line thickness at which plastic dissipation saturates is defined as Eq. (3.11).

$$t_c = 2r_p^{max}(90) \quad (3.11)$$

The plastic dissipation term, is formulated in Eq. (3.12), accounts for the work done in yielding the adhesive bulk and is known to grow with thickness until the plastic zone becomes self-limited.

$$G_p(t) = A_c \min(t, 2r_p) \quad (3.12)$$

For brittle materials,  $r_p$  value becomes extremely small because  $\tau_y$  or  $\sigma_y$  is high and there is almost no plastic work. In most practical joints even a 0.2 – 0.5 mm bond line is already  $t_c \gg 2r_p$ , so the joint is always in the “plateau” regime. Published experiments confirm that brittle adhesives have plastic zones that are small compared with the layer thickness and therefore intrinsic fracture energy  $G_0$ , representing the molecular cleavage energy at the crack faces as expressed in Eq. (3.13) [7,34].

$$G \approx G_0 + 2U r_p^{II} \quad \text{with } U \rightarrow 0 \Rightarrow G \approx G_0 \text{ (constant)} \quad (3.13)$$

### 3.3.3.3 Separation strength

To account for how plastic dissipation in the adhesive layer influences its peak traction as the thickness varies, a toughness ratio  $Z$  is introduced. This ratio is associated with the size of the plastic zone that forms ahead of the crack tip, providing a link between adhesive thickness and the material's effective separation strength. Physically,  $Z$  measures the relative importance of plastic dissipation versus purely cohesive fracture. A larger  $Z$  implies that plastic deformation contributes more energy during crack advance, making the interface response tougher and less sensitive to variations in layer thickness.

Eq. (3.13) is expressed the toughness ratio:

$$Z = \frac{A_c t_c}{G_0} \quad (3.13)$$

and using  $t_c$  formulation, the dimensionless separation strength is as Eq. (3.14).

$$\hat{\sigma}/\sigma_f = \begin{cases} \sqrt{\frac{1 + Z \frac{t}{t_c}}{(1 + Z) \frac{t}{t_c}}} & t < t_c \\ 1 & t \geq t_c \end{cases} \quad (3.14)$$

For very brittle adhesives, plastic dissipation is negligible  $U \approx 0$ , hence  $Z \rightarrow 0$ . However, in practice most brittle joints are tested at  $t \geq t_c$ , so one directly uses the measured bulk separation strength  $\sigma_f$  as the cohesive-law peak traction, without invoking the  $Z$ -based thickness correction.

The thickness varies from 0.1mm to 1mm in this parametric study, however the CZM parameters obtained for 0.5mm thickness are listed in the table below for representativeness. Table 3.4 summarizes thickness-dependent cohesive parameters used in the model, highlighting how stiffness, strengths and fracture energies scale with bond line thickness to capture ductile–brittle contrasts.

**Table 3.4:** Adhesive Material Thickness-Dependence Mechanical Properties

| Inputs                                     | AV138/HV9<br>98 | Hysol EA<br>9361 | Sikaforce®<br>7888 | Araldite®<br>2015 |
|--------------------------------------------|-----------------|------------------|--------------------|-------------------|
| $t_{ad}$ (mm)                              | 0.5             | 0.5              | 0.5                | 0.5               |
| Stiffness, $K_n$<br>(MPa/mm)               | 9780            | 1340             | 3780               | 3700              |
| Stiffness, $K_s$<br>(MPa/mm)               | 3120            | 478.6            | 1420               | 1120              |
| $t_c$ , Mode I<br>(mm)                     | N/A             | 30.86            | 3.33               | 1.00              |
| $t_c$ , Mode II<br>(mm)                    | N/A             | 185.17           | 12.67              | 8.68              |
| Separation<br>strength, ModeI<br>(MPa)     | 39.45           | 13.49            | 46.53              | 24.60             |
| Separation<br>strength, ModeII<br>(MPa)    | 30.2            | 12.17            | 25.08              | 24.62             |
| Total fracture<br>energy, ModeI<br>(N/mm)  | 0.2             | 3.955            | 1.41               | 0.64              |
| Total fracture<br>energy, ModeII<br>(N/mm) | 0.38            | 6.57             | 13.90              | 6.72              |

### 3.3.4 Response metrics

To evaluate the mechanical performance of the single-lap joints under varying geometric and material conditions, a set of cohesive zone model-based response metrics was defined. these metrics are selected to provide comprehensive insight into both the global joint behavior and the local failure mechanisms that emerge from the adhesive layer. Each output variable plays a distinct role in understanding how the joint initiates, progresses, and completes failure, thereby supporting both validation and parametric comparison efforts.

The first and most fundamental output is the load–displacement curve, which plots the total reaction force at the fixed end of the joint against the applied displacement at the loaded end. This curve captures the global stiffness of the joint, the ultimate load capacity and the post-peak softening behavior that reflects progressive damage in the adhesive. The shape and slope of the curve are directly linked to the mechanical performance of the joint, particularly its strength and energy absorption potential.

Furthermore, the point of maximum displacement also serves as an indicator of the deformation capacity of the adhesive and the onset of catastrophic failure.

A second metric is the damage variable output (D), which is a scalar value ranging from 0 (intact) to 1 (fully failed) that quantifies the progressive degradation of cohesive elements. This variable enables visualization of the damage front as it propagates across the bond line and provides a direct indicator of failure mode. Mapping the distribution of D over time clarifies whether failure initiates at the edges of the overlap, progresses uniformly, or localizes in specific regions information that is vital for validating the physical plausibility of the simulation.

Another crucial output is cohesive energy dissipation, which represents the total energy consumed by the cohesive elements as they undergo damage and failure. In Abaqus, this is typically accessed via energy-related outputs such as ALLCD or ALLDMD. This value reflects the toughness of the joint, corresponding to the area under the traction–separation curve multiplied by the effective failure area. Comparing energy dissipation across different joint configurations provides insight into the ductility or brittleness of the adhesive response and serves as a complement to peak load data in cases where failure is driven by energy rather than strength.

Table 3.5 defines the response metrics extracted from simulations, load–displacement, ultimate load, damage variable and cohesive energy dissipation, which together provide a multi-mechanism view of joint performance.

**Table 3.5:** Response Metrics of Study

| Response Metric             | Description                                         |
|-----------------------------|-----------------------------------------------------|
| Load–Displacement Curve     | Global stiffness, failure point, softening behavior |
| Ultimate Load               | Peak force before failure; strength indicator       |
| Damage Variable (D)         | Scalar field showing damage progression (0–1)       |
| Cohesive Energy Dissipation | Energy absorbed by cohesive elements during failure |

Together, these response metrics provide a multi-scale and multi-mechanism perspective on joint performance. They form the basis for evaluating the effects of parameter variation, validating the cohesive zone formulation, and identifying design strategies to enhance bonded joint reliability.

### 3.4 Multi-Objective Optimization

To complement the parametric investigation and derive performance-optimized bonded joint configurations, a multi-objective optimization study was conducted using mode-FRONTIER. The aim was to simultaneously maximize the dissipated fracture energy and the ultimate load of the joint, while ensuring complete cohesive failure. This approach enabled the identification of adhesive type, overlap length, and adhesive thickness combinations that offer the most favorable mechanical performance across a broad design space. This optimization process builds directly upon the same Python-based parametric script utilized earlier, now embedded within an automated workflow that interacts seamlessly with Abaqus and post-processing routines.

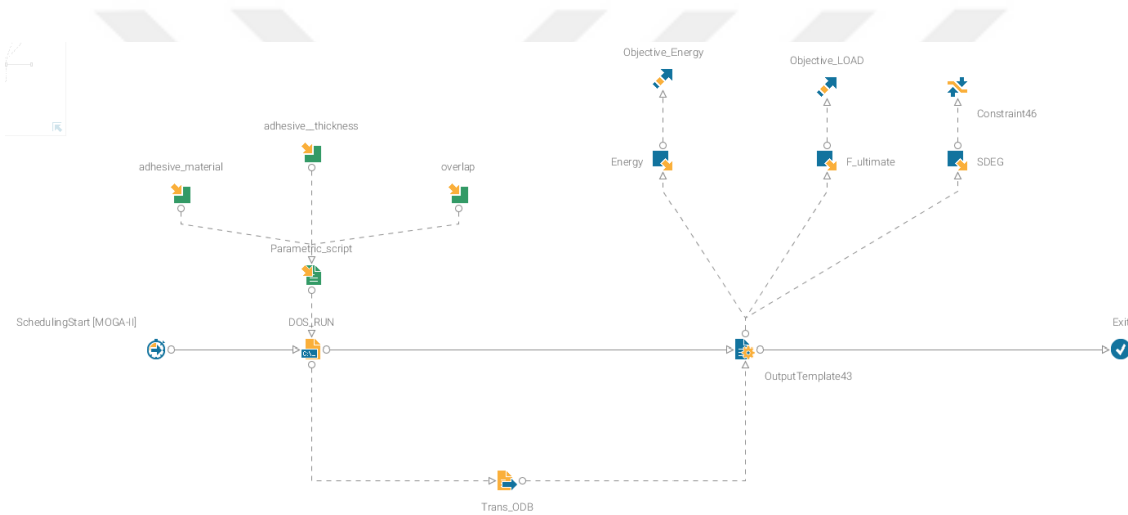


**Figure 3.6: Workflow Architecture**

#### 3.4.1 Workflow architecture

An integrated workflow was constructed to systematically explore the defined design space, evaluate each candidate configuration through simulation, and extract performance metrics for optimization. The workflow, as illustrated in Figure 3.6, includes parameter definition, script execution, simulation run, and output processing components. A DOS\_RUN node launches each simulation using Abaqus/Cae no GUI, while an Output Template reads simulation results exported as text document using a custom parser. Trans\_ODB node to convert binary output into readable format, and all results are fund to the Exit node for analysis and Pareto front generation.

### 3.4.2 Decision variables

The design space was defined by varying the following input parameters within practically relevant ranges. Table 3.6 specifies the admissible ranges and types for adhesive thickness, overlap length and adhesive ID, formalizing the design space searched by the evolutionary algorithm.

**Table 3.6:** Input Parameters within relevant ranges

| Variable             | Symbol    | Type        | Range or Options                        |
|----------------------|-----------|-------------|-----------------------------------------|
| Adhesive thickness   | $t_{adh}$ | Continuous  | 0.1mm - 2.00mm                          |
| Overlap Length       | $L_o$     | Stepwise    | 10mm-50mm                               |
| Adhesive Material ID | L         | Categorical | 1-4<br>(mapped to AV138, EA9361, etc..) |

The script is adapted to interpret the adhesive material parameter as an integer from 1 to 4, each corresponding to a distinct adhesive with thickness-dependent cohesive properties. Table 3.7 maps the categorical adhesive identifiers to their commercial formulations, ensuring unambiguous tracking of material choice across parametric and optimization runs

**Table 3.7:** Adhesive IDs

| Adhesive ID | Adhesive Name  |
|-------------|----------------|
| 1           | AV138/HV998    |
| 2           | HYSOL EA9361   |
| 3           | SIKAFORCE 7888 |
| 4           | ARALDITE 2015  |

### 3.4.3 Objectives and constraint

The optimization problem is defined as a multi-objective maximization in which two performance measures are simultaneously targeted. The first objective is to maximize the dissipated energy (ALLSE), which indicates the joint's toughness and overall energy absorption capacity. A high ALLSE value is particularly desirable in applications requiring enhanced fatigue resistance, better impact tolerance, or improved post-yield performance. The second objective is to maximize the ultimate load ( $F_{ult}$ ), representing the peak load that the joint can sustain before failure. A higher  $F_{ult}$  corresponds to stronger and more load-bearing joints, which are especially critical

in primary structural applications. To ensure realistic and physically relevant results, an additional constraint was imposed on the optimization process by requiring a minimum SDEG value of 1.0. This condition guarantees that the cohesive layer undergoes full damage evolution, thereby filtering out cases where the joint fails in the adherends or terminates prematurely due to convergence difficulties or incomplete fracture progression. Since the focus of this study is adhesive-dominated failure rather than substrate damage, the constraint ensured that only cohesive layer failures with complete damage evolution were included in the final Pareto-optimal set.

Together, these objectives and constraint define a Pareto optimization problem that balances strength and energy performance while maintaining the intended failure mechanism.

#### **3.4.4 Optimization Algorithm and Sampling Strategy**

The optimization was conducted using MOGA-II, a robust evolutionary algorithm known for its ability to maintain diversity across the Pareto front and handle discrete, categorical, and continuous variables simultaneously. MOGA-II employs genetic operators such as mutation and crossover while retaining elite solutions across generations.

Its suitability for nonlinear, multimodal design spaces makes it ideal for the complex interaction space between adhesive chemistry, bond geometry, and mechanical response. The algorithm was configured with a population-based sampling strategy, allowing global exploration in early generations and focused exploitation as convergence progressed.

MOGA-II also supports constraint handling and multi-objective sorting, making it particularly useful in problems like this one, where multiple trade-offs like strength vs. toughness must be balanced.

## **4. RESULTS AND DISCUSSION**

This chapter presents and discusses the results obtained from the numerical analyses and optimization studies carried out in this research. It begins with an examination of the general behavior of the joints, where the characteristic force–displacement responses are compared among the selected adhesives to describe the overall load transfer mechanism and failure progression. The discussion then focuses on the influence of bond-line thickness and overlap length on joint performance, emphasizing their combined effect on ultimate load capacity and dissipated energy. Variations in these geometric parameters are shown to alter the stiffness, peak load, and fracture behavior of the adhesive layer, highlighting the distinct trends between ductile and brittle systems. The final section introduces the optimization results, where a multi-objective framework is applied to identify the most efficient configurations balancing toughness and stiffness. The Pareto-optimal solutions derived from this study provide a quantitative basis for selecting the adhesive material and joint geometry that deliver the best structural performance within the investigated design space.

### **4.1 General Behavior of Joint**

The force–displacement curves generated for all combinations of geometric and material parameters. Bond-line provides a concise illustration of how bond stiffness, cohesive strength and fracture-toughening mechanisms interact in four structurally relevant adhesives. All four curves rise linearly at first, so the opening slope reveals how each joint responds under load: Sikaforce 7888 and Araldite 2015 respond sharply and exhibit a stiff bond-line response, Hysol EA 9361 climbs more gently, and AV138/HV998 shows little capacity to stretch. After reaching the peak, their failure responses begin to diverge. Figure 4.1 compares the force–displacement responses of all four adhesives, showing a shared linear rise followed by clearly different post-peak behaviors that separate progressive failure from abrupt brittle separation.

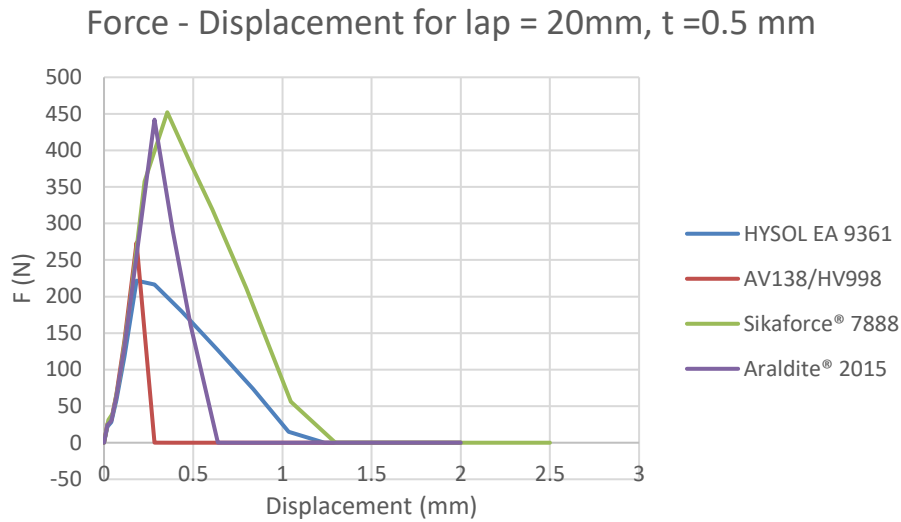


**Figure 4.1:** Force-Displacement Curves for all adhesives

Sikaforce 7888 sustains its peak load for the longest duration and then descends along a broad, gradual slope until the force finally vanishes; crack growth in this adhesive is progressive, allowing the joint to survive through a relatively extended displacement window. Araldite 2015 reaches a comparable summit yet begins to decline sooner; it is strong at initial contact but relinquishes load after only a moderate amount of additional slip. Hysol EA 9361 does not climb to the same high levels, but its softer matrix continues to carry load over much larger displacements, rendering failure as a prolonged process rather than an abrupt collapse. In contrast, AV138/HV998 rises rapidly to its peak and almost immediately drops abruptly to zero load, indicating an essentially elastic response followed by sudden, brittle separation.

Thus, from most gradual to most instantaneous failure: Sikaforce 7888 exhibits the most extended load-bearing phase, Hysol EA 9361 maintains load transfer capacity over a broad stroke despite lower strength, Araldite 2015 loses load capacity once moderate displacement is reached, and AV138/HV998 fails almost as soon as its peak appears.

The SDEG contour plots which represent the damage evolution pattern of the joint confirm the mechanism behind force-displacement shapes. The damage-evolution plots show a consistent initiation pattern: in every adhesive the first non-zero SDEG values appear only in the outermost cohesive elements, while the central region

remains pristine. This observation is consistent with classical single lap joint theory developed by Goland & Reissner that is explained in detail in Chapter 2.3.4. It is shown that eccentric loading creates a bending moment that adds peel to shear, focusing the highest stresses at the lap ends where cracks begin and then propagate inward [44].

Figures 4.2 and 4.3 jointly visualize the initiation and propagation of damage across the overlap, linking field maps to the macroscopic force–displacement response. Figure 4.2 presents the spatial distribution of the damage variable (SDEG) along the lap, confirming edge-initiated cracking and clarifying why peak load and post-peak softening differ among adhesives. Figure 4.3 then focuses on Sikaforce® 7888 to illustrate the evolution of a broad, inward-migrating degradation front that sustains load as damage spreads, in contrast to the sharper localization observed for more brittle systems. These figures connect the morphology of the damage field to energy dissipation capacity and explain the distinct post-peak behaviors identified earlier.

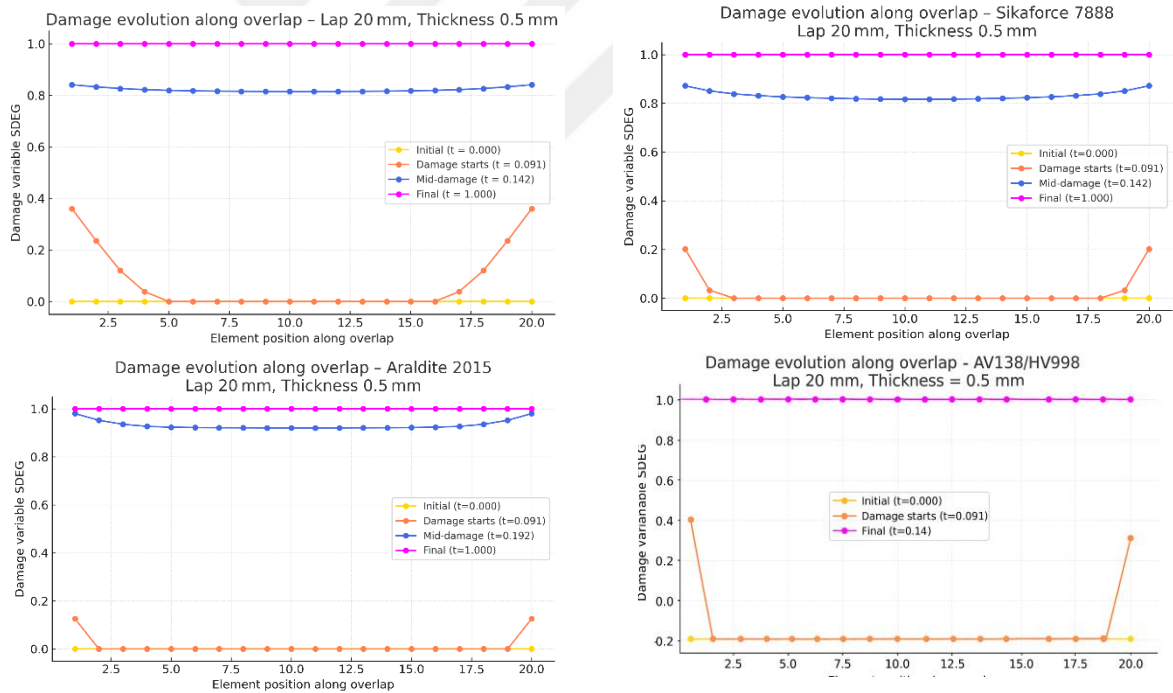


**Figure 4.2: Damage behavior along overlap**

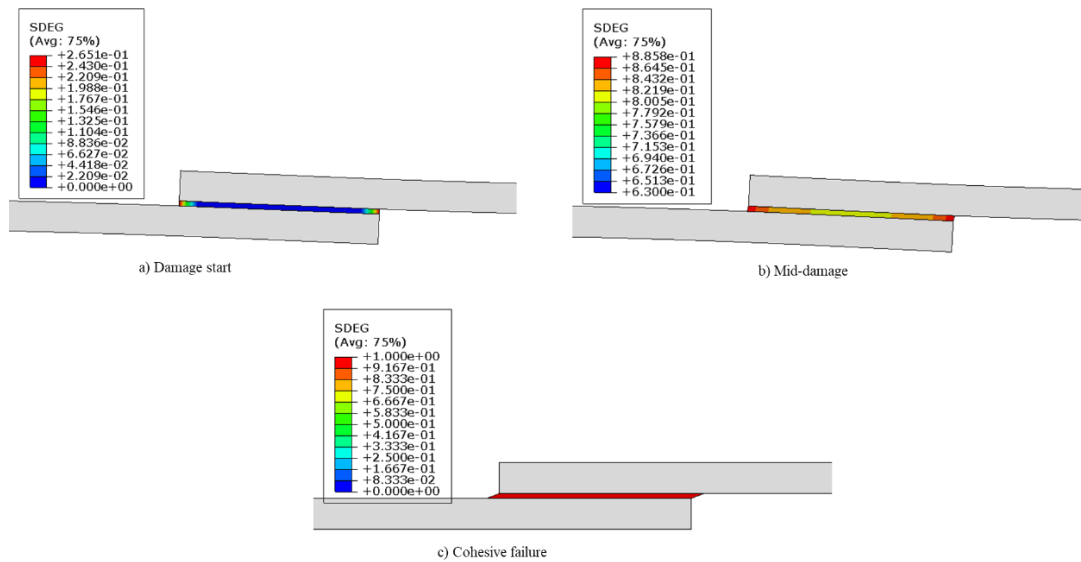


**Figure 4.3:** SIKAFORCE 7888 damage evolution

Sikaforce 7888 develops a broad, gently curved damage front that migrates steadily inwards, so the joint continues to bear load while degradation spreads. Araldite 2015 follows the same pathway but at a faster rate; once damage is triggered, the whole lap approaches a high degradation level within a relatively short displacement. Hysol EA 9361 exhibits a shallow initial gradient and then stabilizes at a moderate SDEG over almost the entire overlap, reflecting its ability to stretch and redistribute load. AV138/HV998 shows no intermediate plateau: edge elements jump to partial damage and the very next state is complete failure across the bond, a hallmark of brittle fracture.

Independent lap-shear and double-cantilever-beam tests reported in the literature [45, 48, 49], exhibit identical edge-initiated crack growth and confirm that the numerical results, and the contrasting behaviors of these four adhesives, faithfully represent real fracture sequences. The simulated SDEG maps replicate the theoretical stress pattern and match the experimental fracture observations, thereby validating the numerical model and confirming the expected damage-propagation rate.

The dissipation-energy curves complete the picture sketched by the force–displacement traces and the SDEG maps. Because the area under each  $F$ – $\delta$  curve is numerically integrated into the “dissipated energy” variable, the ranking seen here is a direct consequence of how long and how smoothly each joint can carry load after the first cracks appear.

Figure 4.4 plots dissipated energy against displacement for each adhesive, confirming that a long, well-controlled degradation path maximizes work absorption.

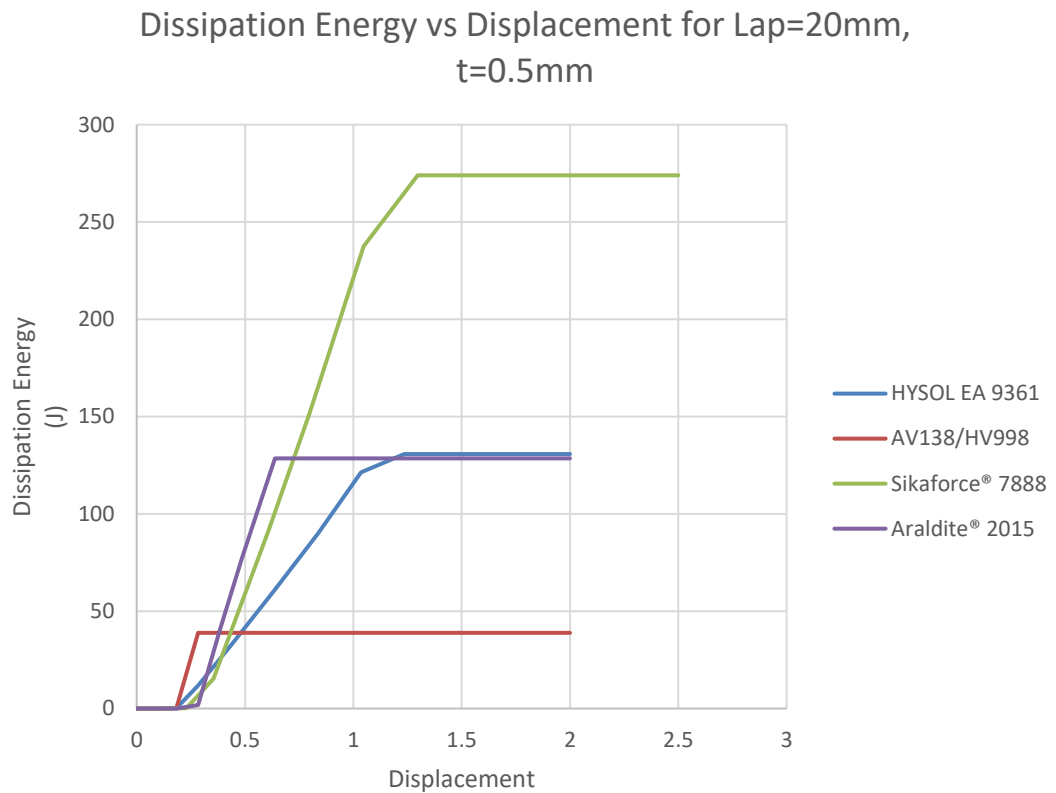


**Figure 4.4:** Dissipation Energy - Displacement curves for all adhesives

The energy plots corroborate the previous interpretations that is a long, controlled degradation path (Sikaforce 7888) maximizes work absorption; moderate ductility (Hysol EA 9361) can rival a stronger but less forgiving system (Araldite 2015); and a brittle adhesive (AV138/HV998) delivers minimal dissipation because damage cannot spread gradually.

## 4.2 Influence of Bond-Line Thickness and Overlap Length on Single-Lap Joint Performance

### 4.2.1 Ultimate Load

When the adhesive layer grows from 0.1 mm to 1 mm every joint, regardless of chemistry, exhibits a reduction in ultimate load. A thicker bond is more compliant; the shear path lengthens and the bending couple at the lap ends amplifies peel stresses; cracks therefore initiate earlier and the peak force falls. Ductile formulations tolerate this penalty better than brittle ones, but the downward slope is universal and has been reported repeatedly in lap-shear testing of both structural epoxies and toughened hybrids [45, 48, 49].

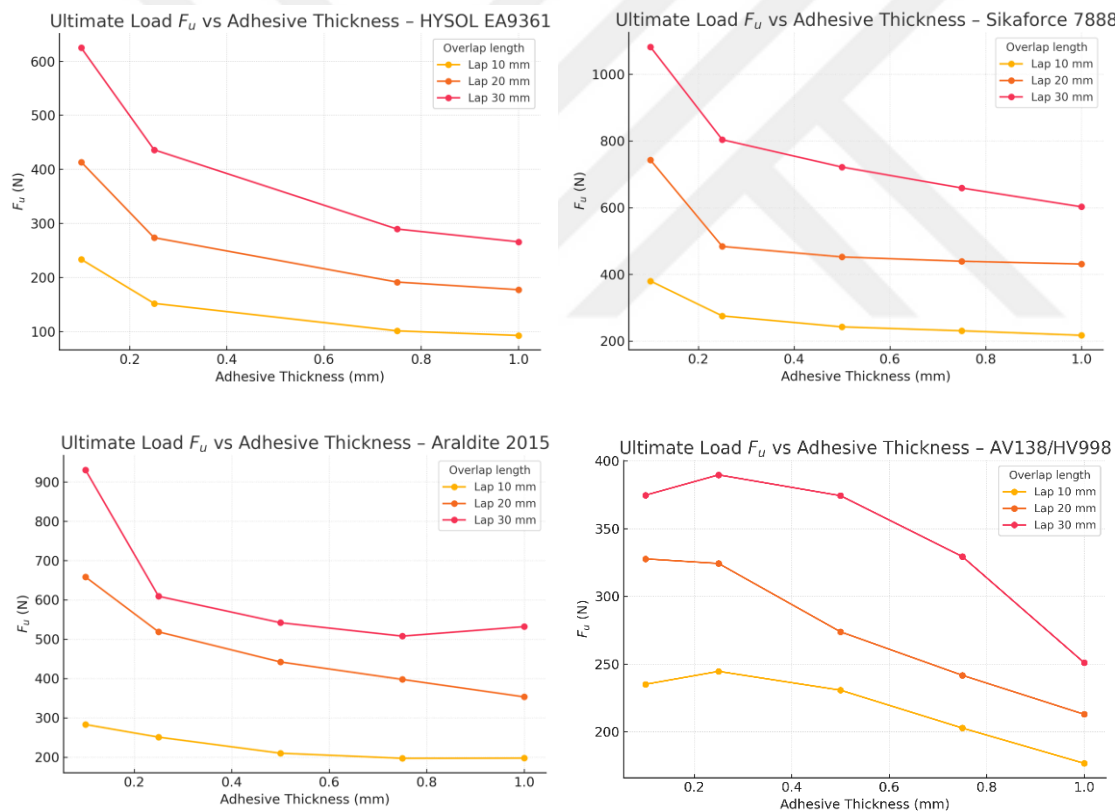


**Figure 4.5:** Failure Load - Adhesive thickness curves for all adhesives

Figure 4.5 reports the universal decline in ultimate load as bond-line thickness increases from 0.1 to 1.0 mm, consistent with added compliance and amplified peel at the lap ends.

In most single-lap joints there is a narrow “optimum-strength” thickness, usually around one-quarter of a millimeter [50]. Below that value the layer is so thin that triaxial constraint is very high; cracks nucleate easily at the ends and the joint fails before the entire shear area can be mobilized. It can be deduced from the results that; moving from 0.10 mm to 0.25 mm releases a large amount of constraint in one step, redistributes the shear more uniformly and at the same time amplifies the peel rotation generated. The net result—in Sikaforce 7888, Araldite 2015 and Hysol EA 9361 alike—is a noticeably steeper drop in across that first increment. Once past the optimum, further thickening simply adds compliance and the strength curve continues to fall, but the slope flattens because the stress distribution is already peel-dominated; each additional tenth of a millimeter has proportionally less influence.

Results behave differently for the brittle AV138/HV998 at 0.25mm thickness. It is known that its high elastic modulus means a 0.10 mm layer is extremely stiff; therefore, any mis-alignment or tiny void might engage peak peel stresses almost instantly, limiting the load. A modest increase to 0.25 mm might ease that stiffness just enough to spread the shear field without yet allowing large rotations, so edge stresses are lower and the joint reaches its maximum capacity at this intermediate thickness. Beyond 0.25 mm the same peel-dominated mechanism that governs the other adhesives takes over and resumes its downward trend.

Increasing lap length from 10 mm to 30 mm raises the peak load for every adhesive because a longer joint distributes shear over a larger area, lowering the average stress needed to trigger cohesive failure. The first step, from 10 mm to 20 mm, delivers the greatest gain; the second step to 30 mm adds only a modest increment, showing that the bond is already approaching the stress-transfer length.

## 4.2.2 Dissipated Energy

The picture reverses for failure energy: added thickness supplies extra volume for elastic storage and plastic dissipation, so the work absorbed to complete fracture rises and for some materials is almost linearly behaved. Tough, ductile systems gain the most, yet even stiff, brittle adhesives show some increase until crack localization curtails further growth.

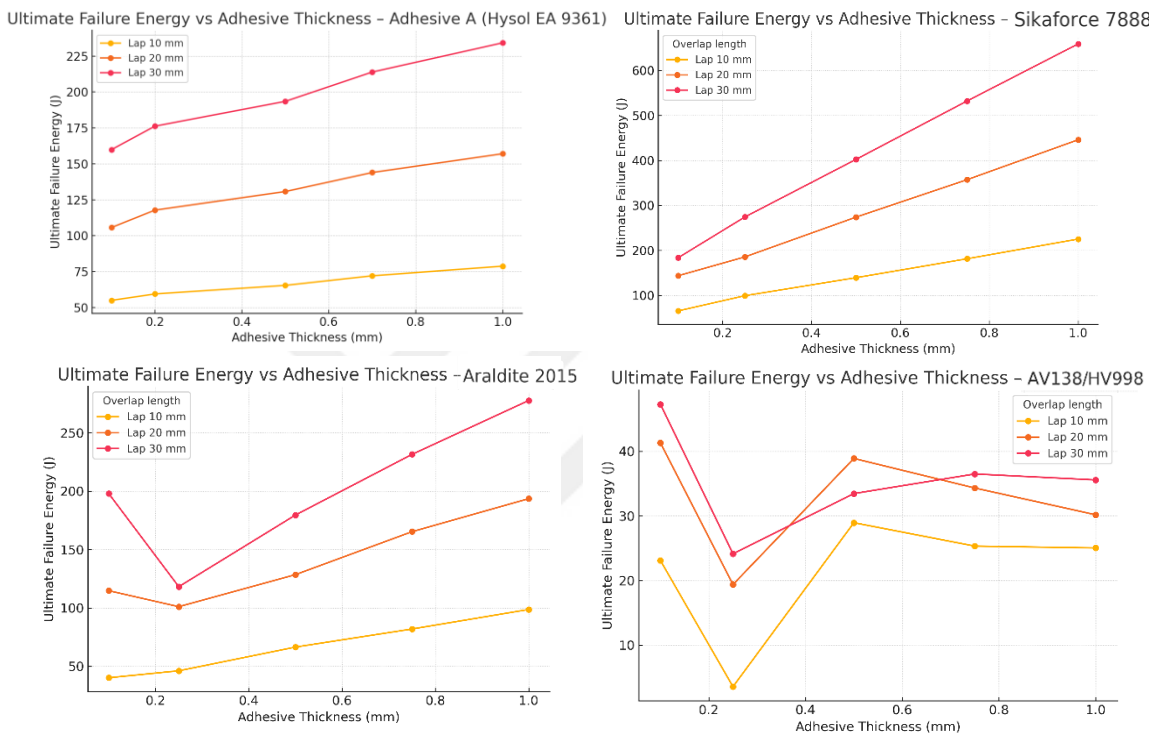


**Figure 4.6:** Dissipation Energy - Adhesive thickness curves for all adhesives

Figure 4.6 consolidates the dissipated-energy response as a function of adhesive thickness for all materials, showing that, unlike the ultimate-load trend, added thickness increases available elastic storage and plastic work so the absorbed energy rises up to the point where crack localization limits further gains.

The curve does not have to track the strength curve: an intermediate thickness can deliver the best compromise when it still carries respectable load yet deforms enough to dissipate considerable work, whereas the very thickest joint may absorb even more energy but only after accepting a much lower peak load. Which scenario dominates depends on the adhesive's ductility: tough hybrids keep gaining, brittle epoxies plateau once localization sets in.

The difference in behavior seen in failure load is also observed in terms of dissipated energy, as they are interrelated. At 0.25 mm AV138/HV998 is strongest but also maximally brittle: once the optimum-strength layer fractures it unloads almost elastically. A thinner 0.10 mm bond breaks at lower force yet sometimes after a slightly longer displacement tail, so its energy is not quite as low. Thickening to 0.50 mm drops the load but allows the joint to deform more before complete separation, so the added displacement more than compensates and the energy jumps. Araldite 2015 shows a milder version of the same pattern: its cavitation toughening reduces brittleness, but at 0.25 mm the layer is still too stiff to yield much, producing the local minimum in seen in the plot.

Extending the overlap from 10 mm to 30 mm enlarges the effective shear area, so ultimate load climbs for all materials, although the incremental benefit diminishes once the overlap exceeds the stress-transfer length. Because energy depends on both load and displacement, its evolution does not have to mirror the ultimate-load curve: a medium overlap might give the highest yet a longer one may still win on absorbed work if the adhesive is capable of stable crack advance.

Brittle adhesives reach this plateau sooner because peeling at the ends overrides the advantage of added area; ductile systems continue to profit from overlap until geometric rotation rather than cohesive strength becomes the governing limit. Failure energy rises almost in direct proportion to overlap for the same reason a crack must traverse a longer path—a trend confirmed by numerous coupon tests on toughened epoxies and hybrid polyurethanes [45, 48, 49].

### **4.3 Optimization Results**

The multi-objective optimization study conducted in the present study aimed to identify the most effective combinations of adhesive thickness, overlap length, and adhesive material to maximize the structural performance of single-lap joints. Unlike the parametric study in Chapter 3.3, where a discrete number of combinations were evaluated manually, this section presents the outcome of a fully automated optimization process that explored the design space systematically using the MOGA-II algorithm within modeFRONTIER.

The multi-objective optimization problem was formulated with two primary goals under the constraint that complete cohesive failure must occur: maximizing the total energy dissipation (ALLSE) and the ultimate load (RF1). These objectives were selected because they jointly characterize the structural performance of a bonded joint: energy dissipation reflects damage tolerance and crack propagation resistance, while ultimate load capacity represents the peak force the joint can withstand before failure. In high-performance aerospace structures, both high energy absorption and load-carrying capacity are desirable for safety and structural efficiency.

In total, the MOGA-II algorithm proposed 997 unique design points during the optimization campaign. However, due to simulation instabilities or output errors, only 273 configurations (~27%) completed successfully and produced valid output data. Among these, 98 solutions (~10% of all attempted points; ~36% of successful runs) satisfied all objectives and constraints, forming the final Pareto-optimal set. Such high attrition rates are not uncommon in computationally intensive, nonlinear, FEA-driven optimization problems, particularly those involving cohesive zone modeling. For instance, simulation-based multi-objective optimization studies frequently report convergence rates in the range of 20% to 50% due to numerous failure modes in complex simulations [51]. It is important to emphasize that the excluded cases do not necessarily correspond to physically unfeasible joints; rather, they predominantly reflect numerical instabilities inherent to nonlinear FEA with cohesive zone modeling. In particular, convergence failures were concentrated in runs with extreme adhesive thicknesses, where sharp stiffness contrasts and rapid softening challenged solver robustness. Therefore, even if additional models had converged, they would likely not have expanded the Pareto front significantly, since the optimum corridor already emerged within the intermediate adhesive thickness regime (0.5–2 mm) combined with moderate-to-high overlaps. Consequently, the Pareto front obtained here can be considered both numerically robust and physically representative of the optimum design space.

The resulting Pareto front contains feasible design alternatives that offer different trade-offs between toughness and strength. These configurations are analyzed in the following subsections to extract practical design trends related to adhesive thickness limits and their non-monotonic influence, overlap length and its dominant role in joint

performance, as well as adhesive material selection and the clear advantage of a specific formulation.

#### 4.3.1 Adhesive Thickness Behavior and Its Non-Monotonic Influence

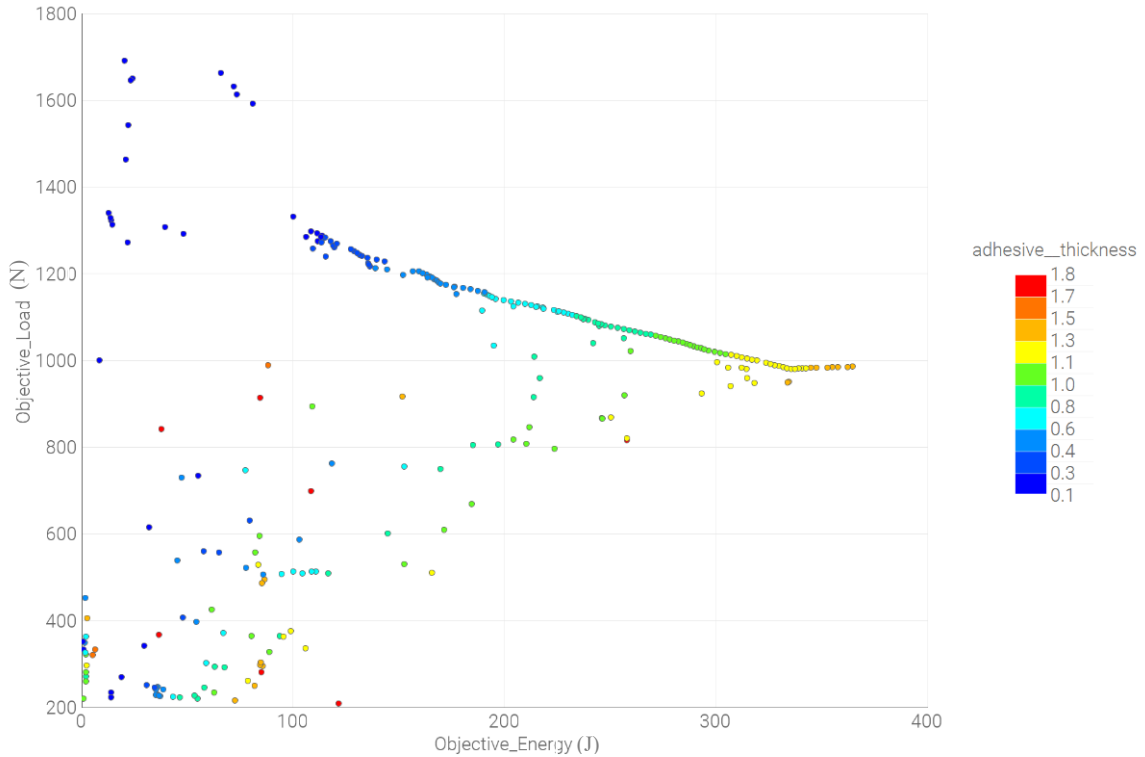


**Figure 4.7:** Energy Dissipation vs. Ultimate Load with Adhesive Thickness Distribution

Figure 4.7 presents the energy–load trade-off annotated by thickness and motivates the subsequent analysis of the non-monotonic thickness influence. Although adhesive thickness was defined as a continuous design variable ranging from 0.10 mm to 2.00 mm, analysis of the Pareto-optimal designs revealed that none of the successful configurations exceeded 1.4 mm.

Pareto-optimal solutions utilized a thickness of 1.4 mm. The rest were predominantly concentrated in the range of 0.5 mm to 1.0 mm, with a median value of approximately 0.745 mm. Figure 4.8 shows the Pareto-optimal thicknesses clustering between 0.5 and 1.0 mm (median  $\approx 0.745$  mm), with only a single design at 1.4 mm.

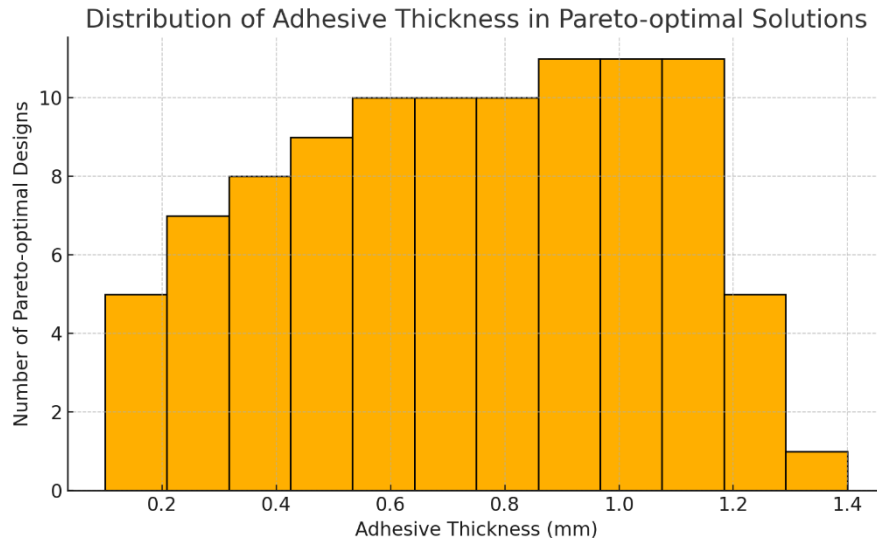


**Figure 4.8:** Pareto-optimal results distribution along adhesive thickness

This indicates a clear non-monotonic relationship between adhesive thickness and joint performance. While the parametric study in Chapter 3.3 showed that increasing thickness often results in greater energy dissipation and higher peak loads, the optimization results demonstrate that this trend is valid only up to a point. Beyond this threshold, the added compliance from thicker adhesive layers may reduce joint stiffness, promote stress concentrations, or lead to premature convergence failures all of which can disqualify a solution based on the imposed SDEG constraint.

Figure 4.9 presents the Pareto front color-coded by adhesive thickness, revealing an intermediate design window that achieves an optimal balance between toughness and stiffness, rather than following a monotonic increase with thickness.

A thicker adhesive layer does not necessarily result in improved joint performance. The optimization instead identified an intermediate thickness range that provides an effective balance between toughness and stiffness. This finding emphasizes the importance of optimization-driven design, as it captures nuanced material-geometry interactions that may be overlooked in conventional parametric studies.

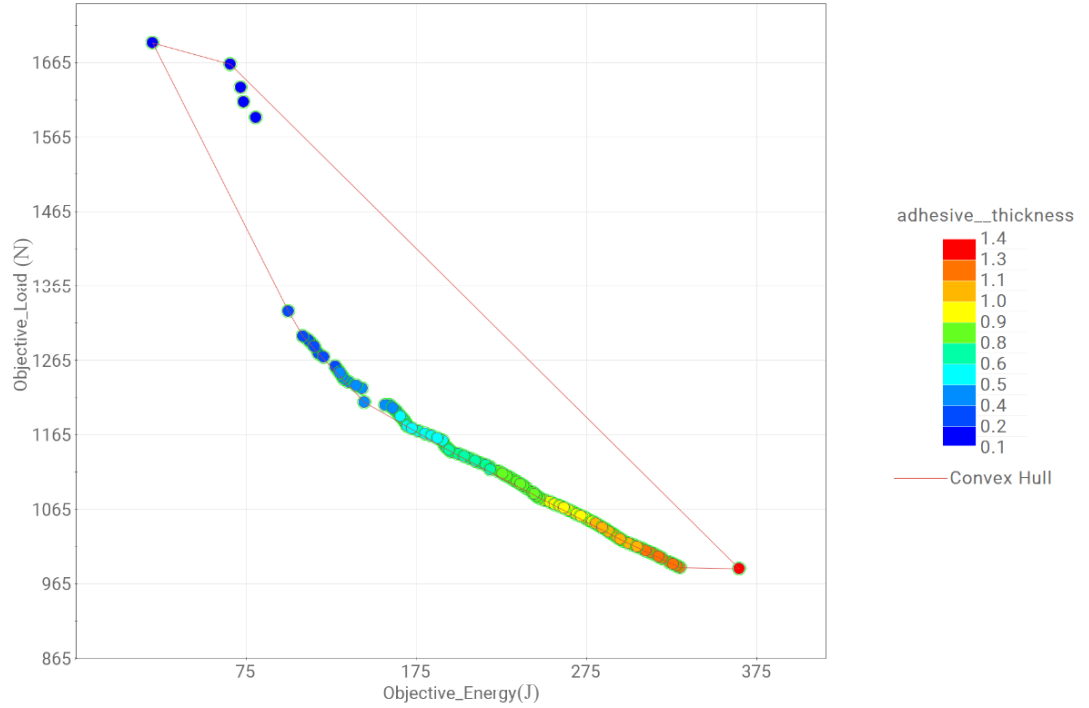


**Figure 4.9:** Pareto Front of Energy Dissipation vs. Ultimate Load with Adhesive Thickness Distribution

#### 4.3.2 Overlap Length and Its Dominant Role in Joint Performance

The overlap length was allowed to vary between 10 mm and 50 mm during the optimization. It was observed that, more than 96% of Pareto-optimal designs featured an overlap length of exactly 50.0 mm, with the remaining few falling slightly below (49.8–49.9 mm). The observed convergence toward the upper bound indicates a direct and monotonic improvement in performance with increasing overlap length, at least within the defined design space.

Figure 4.10 summarizes the overlap effect: within the 10–50 mm design space, > 96% of Pareto-optimal designs sit at 50 mm, reflecting gains from larger bonding area and improved load distribution.

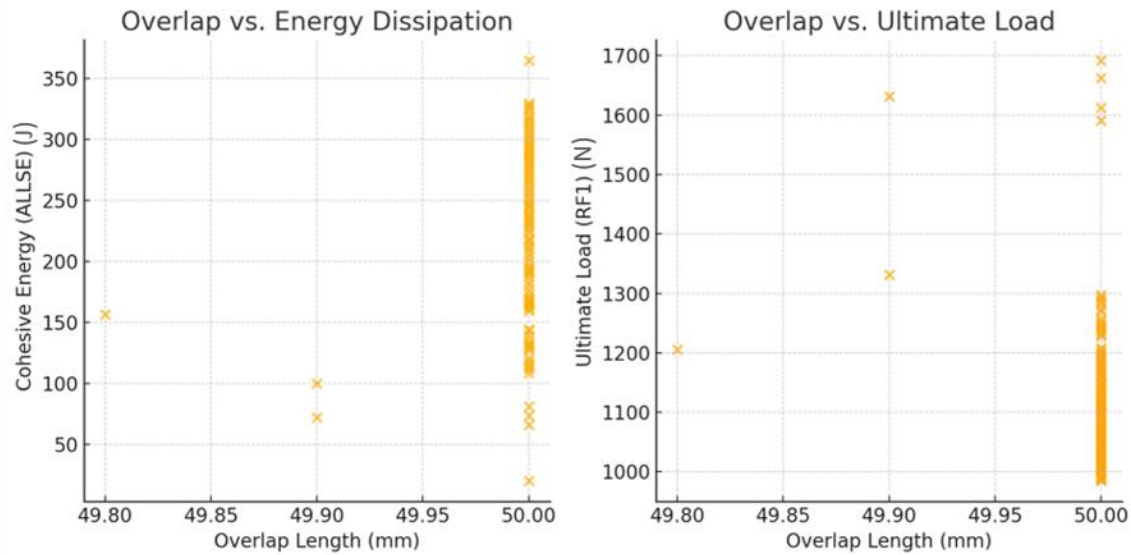


**Figure 4.10: Overlap Effect**

Longer overlaps increase the effective bonding area, reduce average shear stress, and delay failure initiation by distributing loads more evenly across the adhesive layer. In cohesive zone modeling, this directly translates into higher energy absorption and load-bearing capacity, making larger overlaps a structurally favorable design choice.

However, it is important to note that 50 mm was the upper limit imposed in the optimization settings. While the observed trend strongly supports maximizing overlap within this boundary, the possibility of diminishing returns or manufacturing constraints beyond 50 mm was not explored in this study.

### 4.3.3 Adhesive Material Selection

Figure 4.11 differentiates the energy–load trade-off by adhesive material, setting up the finding that a single formulation dominates the optimal set. The optimization study included four different adhesives, each represented by a unique integer (1–4) and modeled with distinct traction–separation laws and thickness-dependent cohesive parameters. It is noteworthy that, the final Pareto front was entirely dominated by Adhesive 3, which corresponds to Sikaforce® 7888 in the material library used.

All 98 optimal solutions were associated with this adhesive, indicating its superior mechanical performance under varying thicknesses and overlaps. The material's cohesive behavior particularly its moderate stiffness, high fracture toughness, and favorable scaling with thickness allowed it to satisfy both the energy and load objectives while meeting the full cohesive failure constraint.

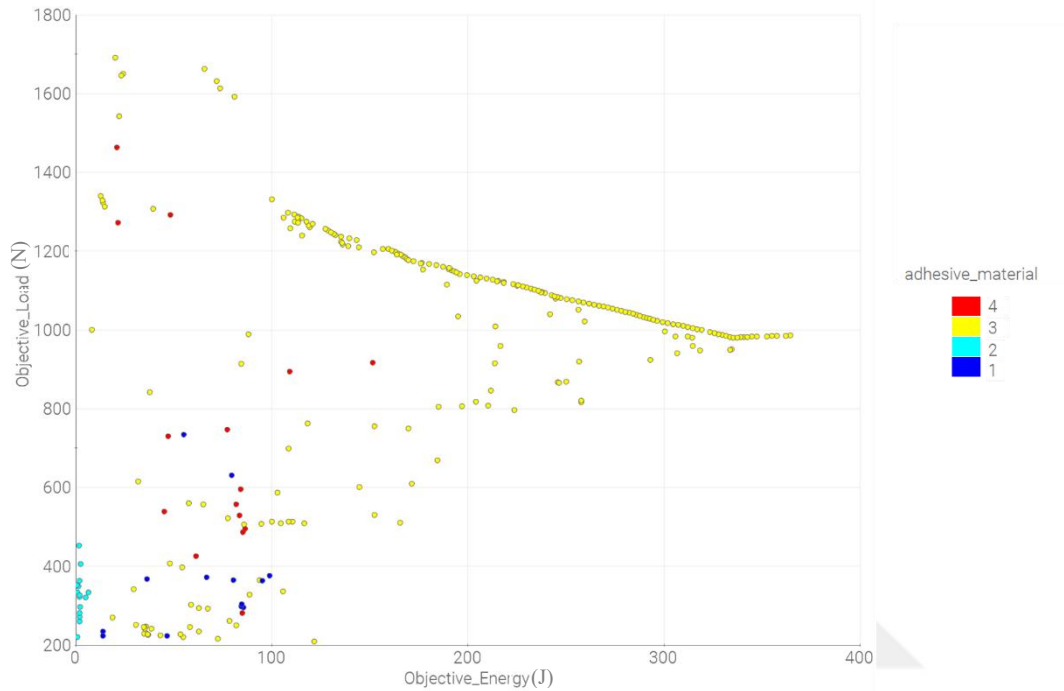


**Figure 4.11:** Energy vs. Load Trade-off with Adhesive Material Differentiation

Figure 4.11 and Figure 4.12 confirms that all 98 Pareto-optimal solutions correspond to Adhesive 3 (Sikaforce® 7888), while other materials likely failed the SDEG criterion due to brittleness, poor thickness adaptability, or early crack localization. Other adhesives may have failed to meet the SDEG requirement due to excessive brittleness, poor adaptability to thickness changes, or early crack localization. This selection result highlights that material choice plays a critical role in bonded joint optimization, and confirms the necessity of incorporating real-world material behavior into simulation workflows.

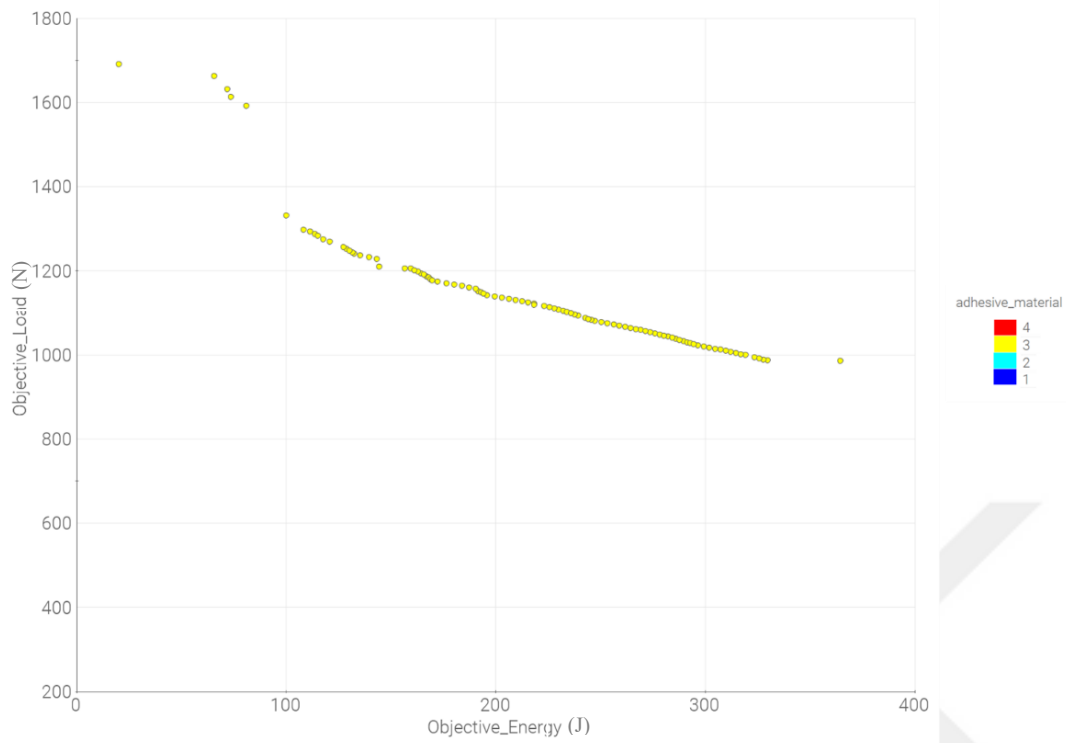


**Figure 4.12:** Pareto results of Energy vs. Load Trade-off with Adhesive Material Differentiation

## 5. CONCLUSION

In this thesis, a comprehensive investigation into the structural behavior of adhesively bonded single-lap joints was conducted through both parametric studies and a multi-objective optimization approach. The work focused on understanding the influence of key design parameters, adhesive thickness, overlap length, and adhesive material properties, on the joint's performance in terms of energy dissipation and load-carrying capacity.

The initial parametric analyses revealed predictable trends: increasing adhesive thickness and overlap length generally enhanced energy absorption and strength, particularly for adhesives with ductile traction–separation behavior. However, the subsequent optimization results challenged and refined these assumptions. Using the MOGA-II algorithm within the modeFRONTIER platform, a total of 997 design points were proposed, of which 273 completed successfully in Abaqus simulations, and only 98 satisfied all constraints to form the final Pareto-optimal set.

Key insights derived from the optimization reveal that adhesive thickness exhibited a non-monotonic relationship with performance. While an increase in thickness initially enhanced energy dissipation, excessively thick layers introduced compliance and stress concentrations that ultimately reduced joint efficiency. The optimal solutions concentrated between 0.5 mm and 1.0 mm, suggesting the existence of a clearly bounded optimum region rather than a monotonic improvement with thickness.

Overlap length, on the other hand, displayed a strongly monotonic trend. Within the investigated design space of 10 mm to 50 mm, nearly all optimal solutions converged at the upper bound, confirming that larger bonding areas improve both cohesive energy absorption and peak load capacity, thereby validating classical joint design heuristics with computational evidence.

Finally, among the four adhesive materials evaluated, only Adhesive 3 (Sikaforce® 7888) appeared in the Pareto front. This adhesive demonstrated a superior balance between stiffness, toughness, and adaptability across varying bond line thicknesses, reinforcing the importance of employing physically accurate, thickness-dependent cohesive zone models in design studies.

Furthermore, the application of a full cohesive failure constraint ( $SDEG \geq 1.0$ ) ensured that the optimization favored designs where damage was confined to the adhesive layer, avoiding undesirable failure in the adherends. This filtering not only improved the physical relevance of the solutions but also exposed how certain geometric or material choices can shift failure mechanisms outside the target region.

In conclusion, this work demonstrates that optimization-driven studies can uncover deeper insights than conventional parametric approaches by accounting for the complex, nonlinear interactions between geometry, material, and failure mechanisms. The findings provide actionable guidance for engineers seeking to maximize joint performance in weight-sensitive and high-integrity structural applications, such as those found in aerospace systems.

## **5.1 Future Works and Recommendations**

This thesis has primarily focused on adhesive failure behavior in single-lap joints under static loading, using cohesive zone modeling with varying thickness and material properties. However, to expand the applicability and fidelity of the findings, several future research directions are recommended.

One important extension would be to incorporate adherend failure mechanisms into the modeling framework. In the current study, only adhesive failure was allowed, with full damage evolution enforced in the cohesive layer. In real bonded structures, however, failure may initiate or propagate within the adherends, especially when high-stiffness or thin adhesives are used. To capture this, future studies could integrate material failure criteria for metallic and composite adherends, such as progressive failure in laminated composites, matrix cracking, or delamination. This would also enable the optimization to consider not just the adhesive configuration, but the adherend material system and lay-up sequence, allowing joint performance to be maximized holistically across both components

Another recommendation is to expand the scope beyond the single-lap joint geometry. Although widely studied, SLJs are prone to severe peel and shear concentrations at the overlap ends, which limits their structural efficiency. Exploring alternative geometries—such as double-lap joints, scarf joints, or stepped-lap configurations—could reveal designs that better distribute stresses and delay failure initiation. A comparative optimization across these joint types could guide selection based on loading, weight, or manufacturability constraints in real applications.

Moreover, the mechanical behavior of bonded joints under cyclic or impact loading conditions remains a critical topic for future work. Most real-world applications, especially in aerospace and automotive structures, involve fatigue loading or transient events. Extending the current cohesive zone models to include fatigue damage evolution laws would provide insight into lifetime performance, crack initiation thresholds, and energy dissipation capacity under realistic service conditions. The incorporation of fatigue resistance into the optimization objectives would also enable the discovery of damage-tolerant joint designs.

Finally, to bridge the gap between simulation and application, experimental validation of selected optimal designs is strongly recommended. Physical testing under controlled loading can verify the accuracy of the cohesive zone formulations, highlight effects such as manufacturing defects or surface preparation quality, and provide critical feedback for refining the models. Such experimental benchmarking is essential for translating optimization findings into practical engineering recommendations.



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## **APPENDICES**

**APPENDIX A:** Script for Parametric Study

**APPENDIX B:** Script for Optimization Study



## APPENDIX A

```
from abaqus import *
from abaqusConstants import *
import part
import sketch
import material
import section
import assembly
import step
import interaction
import mesh
import regionToolset
import connectorBehavior
import odbAccess
import visualization
import xyPlot
import displayGroupOdbToolset as dgo
import math

# -----
# PARAMETERS
# -----

# Define lists of different parameters
lap_lengths = [10.0, 20.0, 30.0]
adhesive_thicknesses = [0.1, 0.25, 0.5, 0.75, 1.0]
plate_length = 120.0
plate_thickness = 3.0
adhesive_mesh_size = 1.0
adherend_mesh_size = 1.0
initial_displacement = 2.0

# Define different material properties for plates and adhesives
plate_materials = {
    'Steel': {
        'elastic': (209000.0, 0.29)
    },
    'Aluminum': {
        'elastic': (70000.0, 0.33)
    }
}

# List of different materials combinations
material_combinations = [
    ('Steel', 'AdhesiveA'), ('Steel', 'AdhesiveB'), ('Steel',
'AdhesiveC'), ('Steel', 'AdhesiveD')
]

# Retry Parameters
MAX_RETRIES = 10
RETRY_DISPLACEMENT_INCREMENT = 0.75

# -----
# JOB CREATION AND SUBMISSION WITH RETRY MECHANISM
# -----
def submit_with_retry(job_name, model_name, initial_displacement):
    retry_count = 0
```

```

        current_displacement = initial_displacement # Start with the
initial displacement
        while retry_count < MAX_RETRIES:
            print "Retry #{}: Submitting job '{}' with displacement
{}".format(retry_count, job_name, current_displacement)
            # Check if the displacement boundary condition exists
            model = mdb.models[model_name]
            if 'Displacement' not in model.boundaryConditions.keys():
                print "Error: Boundary condition 'Displacement' not
found in model '{}'.format(model_name)
                return
            # Update the displacement boundary condition
            print "Updating displacement boundary condition to ul =
{}".format(current_displacement)

model.boundaryConditions['Displacement'].setValues(ul=current_displa
cement)
            # Check if the job already exists; if so, delete it
            if job_name in mdb.jobs.keys():
                del mdb.jobs[job_name]
            # Create and submit the job
            mdb.Job(name=job_name, model=model_name)
            mdb.jobs[job_name].submit()
            mdb.jobs[job_name].waitForCompletion()
            # Check the job status
            job_status = mdb.jobs[job_name].status # Use the status
property
            if job_status == COMPLETED:
                print "Job '{}' completed
successfully.".format(job_name)
                return
            elif job_status == ABORTED:
                print "Job '{}' aborted. Retrying...".format(job_name)
                retry_count += 1
                current_displacement *= RETRY_DISPLACEMENT_INCREMENT
            else:
                print "Job '{}' ended with unexpected status: {}.
Exiting retry loop.".format(job_name, job_status)
                return
            print "Job '{}' failed after {} retries.".format(job_name,
MAX_RETRIES)

# -----
# MODEL SETUP LOOP FOR PARAMETER COMBINATIONS
# -----

for plate_material, adhesive_type in material_combinations:
    for lap_length in lap_lengths:
        for adhesive_thickness in adhesive_thicknesses:
            model_name =
'SingleLapJoint2D_{}_{}_Lap{}_Thick{}'.format(
                plate_material, adhesive_type, int(lap_length),
int(adhesive_thickness*10) # Using int() for cleaner name
            )
            print "Creating model: {}".format(model_name)
            # Check if the model already exists in the model
database
            if model_name not in mdb.models.keys():
                # Create the model only if it doesn't exist already
                model = mdb.Model(name=model_name)
            else:

```

```

        model = mdb.models[model_name]
        print "Model {} already exists.".format(model_name)
        continue # Skip the rest of the model definition if
it exists
# -----
-
# PART CREATION
# -----
-
# Plate 1
s1 = model.ConstrainedSketch(name='plate1_profile',
sheetSize=200.0)
s1.rectangle(point1=(0.0, 0.0), point2=(plate_length,
plate_thickness))
p1 = model.Part(name='Plate1',
dimensionality=TWO_D_PLANAR, type=DEFORMABLE_BODY)
p1.BaseShell(sketch=s1)
del model.sketches['plate1_profile']
# Plate 2
s2 = model.ConstrainedSketch(name='plate2_profile',
sheetSize=200.0)
s2.rectangle(point1=(plate_length-lap_length,
plate_thickness + adhesive_thickness),
point2=(2*plate_length-lap_length,
2*plate_thickness + adhesive_thickness))
p2 = model.Part(name='Plate2',
dimensionality=TWO_D_PLANAR, type=DEFORMABLE_BODY)
p2.BaseShell(sketch=s2)
del model.sketches['plate2_profile']
# Adhesive
s3 = model.ConstrainedSketch(name='adhesive_profile',
sheetSize=200.0)
s3.rectangle(point1=(plate_length-lap_length,
plate_thickness),
point2=(plate_length, plate_thickness +
adhesive_thickness))
p3 = model.Part(name='Adhesive',
dimensionality=TWO_D_PLANAR, type=DEFORMABLE_BODY)
p3.BaseShell(sketch=s3)
del model.sketches['adhesive_profile']
# -----
-
# MATERIALS
# -----
-
# Plate Material
print("Assigning plate material:
{}".format(plate_material))
model.Material(name=plate_material)

model.materials[plate_material].Elastic(table=(plate_materials[plate
_material]['elastic'], ))
# Adhesive material properties as a function of
thickness
# Define formulas for AdhesiveA - HYSOL EA 9361
alfa=1.25
E_A = 670
v_A=0.4
G_A = E_A/(2*(v_A+1))
Cohesive_Energy_A_modeI = 2.61
Cohesive_Energy_A_modeII = 5.22

```

```

Yield_strength_I_A = 4.23
Yield_strength_II_A = 2.44
Tensile_strength_I_A = 7.99
Tensile_strength_II_A = 5.54
r_p_A_max_modeI= alfa*(1/(3*math.pi))*(E_A/(1-
v_A**2))*(Cohesive_Energy_A_modeI/Yield_strength_I_A**2)
r_p_A_max_modeII= alfa*(1/(3*math.pi))*(E_A/(1-
v_A**2))*(Cohesive_Energy_A_modeII/Yield_strength_II_A**2)
t_c_A_modeI = 2*r_p_A_max_modeI
t_c_A_modeII = 2*r_p_A_max_modeII
Area_A = 2.69
nu_A_modeI = Area_A*t_c_A_modeI/Cohesive_Energy_A_modeI
nu_A_modeII =
Area_A*t_c_A_modeII/Cohesive_Energy_A_modeII
if adhesive_thickness<t_c_A_modeI:
    Sep_strength_A_modeI =
((1+nu_A_modeI*(adhesive_thickness/t_c_A_modeI))/((1+nu_A_modeI)*(ad
hesive_thickness/t_c_A_modeI)))*0.5*Tensile_strength_I_A
    Fracture_E_A_modeI =
Cohesive_Energy_A_modeI+Area_A*adhesive_thickness
else:
    Sep_strength_A_modeI = Tensile_strength_I_A

Fracture_E_A_modeI=Cohesive_Energy_A_modeI+Area_A*t_c_A_modeI
if adhesive_thickness<t_c_A_modeII:
    Sep_strength_A_modeII =
((1+nu_A_modeII*(adhesive_thickness/t_c_A_modeII))/((1+nu_A_modeII)*
(adhesive_thickness/t_c_A_modeII)))*0.5*Tensile_strength_II_A

Fracture_E_A_modeII=Cohesive_Energy_A_modeII+Area_A*adhesive_thickne
ss
else:
    Sep_strength_A_modeII = Tensile_strength_II_A

Fracture_E_A_modeII=Cohesive_Energy_A_modeII+Area_A*t_c_A_modeII

def adhesive_a_elastic(adhesive_thickness):
    return (E_A / adhesive_thickness, G_A /
adhesive_thickness, G_A /adhesive_thickness)
def adhesive_a_damage_initiation(adhesive_thickness):
    return (Sep_strength_A_modeI, Sep_strength_A_modeII,
Sep_strength_A_modeII)
def adhesive_a_damage_evolution(adhesive_thickness):
    return (Fracture_E_A_modeI, Fracture_E_A_modeII,
Fracture_E_A_modeII)
# Define formulas for AdhesiveB - AV138/HV998
alfa=1.25
E_B = 4890
v_B=0.35
G_B = 1560
Cohesive_Energy_B_modeI = 0.2
Cohesive_Energy_B_modeII = 0.38
Tensile_strength_I_B = 39.45
Tensile_strength_II_B = 30.2
Sep_strength_B_modeI = Tensile_strength_I_B
Fracture_E_B_modeI=Cohesive_Energy_B_modeI
Sep_strength_B_modeII = Tensile_strength_II_B
Fracture_E_B_modeII=Cohesive_Energy_B_modeII

def adhesive_b_elastic(adhesive_thickness):

```

```

        return ( E_B / adhesive_thickness, G_B /
adhesive_thickness, G_B /adhesive_thickness)
    def adhesive_b_damage_initiation(adhesive_thickness):
        return (Sep_strength_B_modeI, Sep_strength_B_modeII,
Sep_strength_B_modeII)
    def adhesive_b_damage_evolution(adhesive_thickness):
        return (Fracture_E_B_modeI, Fracture_E_B_modeII,
Fracture_E_B_modeII)
    # Define formulas for AdhesiveC - SikaForce 788
    alfa=1.25
    E_C = 1890
    v_C=0.33
    G_C = 710
    Cohesive_Energy_C_modeI = 1.03
    Cohesive_Energy_C_modeII = 5.27
    Yield_strength_I_C = 13.2
    Yield_strength_II_C = 15.3
    Tensile_strength_I_C = 28.6
    Tensile_strength_II_C = 20
    r_p_C_max_modeI= alfa*(1/(3*math.pi))*(E_C/(1-
v_C**2))*(Cohesive_Energy_C_modeI/Yield_strength_I_C**2)
    r_p_C_max_modeII= alfa*(1/(3*math.pi))*(E_C/(1-
v_C**2))*(Cohesive_Energy_C_modeII/Yield_strength_II_C**2)
    t_c_C_modeI = 2*r_p_C_max_modeI
    t_c_C_modeII = 2*r_p_C_max_modeII
    Area_I_C = 0.75
    Area_II_C = 17.27
    nu_C_modeI =
Area_I_C*t_c_C_modeI/Cohesive_Energy_C_modeI
    nu_C_modeII =
Area_II_C*t_c_C_modeII/Cohesive_Energy_C_modeII
    if adhesive_thickness<t_c_C_modeI:
        Sep_strength_C_modeI =
((1+nu_C_modeI*(adhesive_thickness/t_c_C_modeI))/((1+nu_C_modeI)*(ad
hesive_thickness/t_c_C_modeI)))*0.5*Tensile_strength_I_C

Fracture_E_C_modeI=Cohesive_Energy_C_modeI+Area_I_C*adhesive_thickne
ss
    else:
        Sep_strength_C_modeI = Tensile_strength_I_C

Fracture_E_C_modeI=Cohesive_Energy_C_modeI+Area_I_C*t_c_C_modeI
    if adhesive_thickness<t_c_C_modeII:
        Sep_strength_C_modeII =
((1+nu_C_modeII*(adhesive_thickness/t_c_C_modeII))/((1+nu_C_modeII)*
(adhesive_thickness/t_c_C_modeII)))*0.5*Tensile_strength_II_C

Fracture_E_C_modeII=Cohesive_Energy_C_modeII+Area_II_C*adhesive_thic
kness
    else:
        Sep_strength_C_modeII = Tensile_strength_II_C

Fracture_E_C_modeII=Cohesive_Energy_C_modeII+Area_II_C*t_c_C_modeII
    def adhesive_c_elastic(adhesive_thickness):
        return ( E_C / adhesive_thickness, G_C /
adhesive_thickness, G_C /adhesive_thickness)
    def adhesive_c_damage_initiation(adhesive_thickness):
        return (Sep_strength_C_modeI, Sep_strength_C_modeII,
Sep_strength_C_modeII)
    def adhesive_c_damage_evolution(adhesive_thickness):

```

```

        return (Fracture_E_C_modeI, Fracture_E_C_modeII,
Fracture_E_C_modeII)
        # Define formulas for AdhesiveD - Araldite 2015
        alfa=1.25
        E_D = 1850
        v_D=0.33
        G_D = 560
        Cohesive_Energy_D_modeI = 0.29
        Cohesive_Energy_D_modeII = 3.36
        Yield_strength_I_D = 12.63
        Yield_strength_II_D = 14.6
        Tensile_strength_I_D = 21.63
        Tensile_strength_II_D = 17.9
        r_p_D_max_modeI= alfa*(1/(3*math.pi))*(E_D/(1-
v_D**2))*(Cohesive_Energy_D_modeI/Yield_strength_I_D**2)
        r_p_D_max_modeII= alfa*(1/(3*math.pi))*(E_D/(1-
v_D**2))*(Cohesive_Energy_D_modeII/Yield_strength_II_D**2)
        t_c_D_modeI = 2*r_p_D_max_modeI
        t_c_D_modeII = 2*r_p_D_max_modeII
        Area_I_D = 0.70
        Area_II_D = 6.71
        nu_D_modeI =
Area_I_D*t_c_D_modeI/Cohesive_Energy_D_modeI
        nu_D_modeII =
Area_II_D*t_c_D_modeII/Cohesive_Energy_D_modeII
        if adhesive_thickness<t_c_D_modeI:
            Sep_strength_D_modeI =
((1+nu_D_modeI*(adhesive_thickness/t_c_D_modeI))/((1+nu_D_modeI)*(ad
hesive_thickness/t_c_D_modeI)))*0.5*Tensile_strength_I_D

Fracture_E_D_modeI=Cohesive_Energy_D_modeI+Area_I_D*adhesive_thickne
ss
        else:
            Sep_strength_D_modeI = Tensile_strength_I_D

Fracture_E_D_modeI=Cohesive_Energy_D_modeI+Area_I_D*t_c_D_modeI
        if adhesive_thickness<t_c_D_modeII:
            Sep_strength_D_modeII =
((1+nu_D_modeII*(adhesive_thickness/t_c_D_modeII))/((1+nu_D_modeII)*
(adhesive_thickness/t_c_D_modeII)))*0.5*Tensile_strength_II_D

Fracture_E_D_modeII=Cohesive_Energy_D_modeII+Area_II_D*adhesive_thic
kness
        else:
            Sep_strength_D_modeII = Tensile_strength_II_D

Fracture_E_D_modeII=Cohesive_Energy_D_modeII+Area_II_D*t_c_D_modeII
        def adhesive_d_elastic(adhesive_thickness):
            return ( E_D / adhesive_thickness, G_D /
adhesive_thickness, G_D /adhesive_thickness)
        def adhesive_d_damage_initiation(adhesive_thickness):
            return (Sep_strength_D_modeI, Sep_strength_D_modeII,
Sep_strength_D_modeII)
        def adhesive_d_damage_evolution(adhesive_thickness):
            return (Fracture_E_D_modeI, Fracture_E_D_modeII,
Fracture_E_D_modeII)
        # Adhesive Material
        print("Assigning adhesive material: {} with thickness
{}".format(adhesive_type, adhesive_thickness))
        if adhesive_type == 'AdhesiveA':

```

```

        elastic_values =
adhesive_a_elastic(adhesive_thickness)
        damage_initiation_values =
adhesive_a_damage_initiation(adhesive_thickness)
        damage_evolution_values =
adhesive_a_damage_evolution(adhesive_thickness)
        elif adhesive_type == 'AdhesiveB':
            elastic_values =
adhesive_b_elastic(adhesive_thickness)
            damage_initiation_values =
adhesive_b_damage_initiation(adhesive_thickness)
            damage_evolution_values =
adhesive_b_damage_evolution(adhesive_thickness)
            elif adhesive_type == 'AdhesiveC':
                elastic_values =
adhesive_c_elastic(adhesive_thickness)
                damage_initiation_values =
adhesive_c_damage_initiation(adhesive_thickness)
                damage_evolution_values =
adhesive_c_damage_evolution(adhesive_thickness)
                elif adhesive_type == 'AdhesiveD':
                    elastic_values =
adhesive_d_elastic(adhesive_thickness)
                    damage_initiation_values =
adhesive_d_damage_initiation(adhesive_thickness)
                    damage_evolution_values =
adhesive_d_damage_evolution(adhesive_thickness)
                else:
                    print("Unknown adhesive type '{}'. Skipping material
assignment.".format(adhesive_type))
                    continue
            adhesive_material_name = adhesive_type + '_Thick' +
str(int(adhesive_thickness * 10))
            model.Material(name=adhesive_material_name)
            model.materials[adhesive_material_name].Elastic(
                type=TRACTION, table=(elastic_values,)
            )

model.materials[adhesive_material_name].QuadsDamageInitiation(
    table=(damage_initiation_values,)
)

model.materials[adhesive_material_name].quadsDamageInitiation.Damage
Evolution(
    type=ENERGY, mixedModeBehavior=BK, power=2.284,
table=(damage_evolution_values,)
)
# -----
-
# SECTIONS AND ASSIGNMENT
# -----
-

    model.HomogeneousSolidSection(name='PlateSection',
material=plate_material)
    model.CohesiveSection(name='AdhesiveSection',
material=adhesive_type + '_Thick' + str(int(adhesive_thickness*10)),
                                response=TRACTION_SEPARATION,
outOfPlaneThickness=None)

p1.SectionAssignment(region=regionToolset.Region(faces=p1.faces),
sectionName='PlateSection')

```

```

p2.SectionAssignment(region=regionToolset.Region(faces=p2.faces),
sectionName='PlateSection')

p3.SectionAssignment(region=regionToolset.Region(faces=p3.faces),
sectionName='AdhesiveSection')
# -----
-----
# MESHING
# -----
-
    for part_obj, mesh_size, elem_type in [(p1,
adherend_mesh_size, CPE4R), (p2, adherend_mesh_size, CPE4R)]:
        faces =
part_obj.faces.getSequenceFromMask(mask=('[#1 ]', ), )
        part_obj.setMeshControls(regions=faces,
technique=STRUCTURED)
        face_region = part_obj.Set(faces=faces,
name='%s_MeshSet' % part_obj.name)
        part_obj.setElementType(regions=face_region,

elemTypes=(mesh.ElemType(elemCode=elem_type,
elemLibrary=STANDARD),))
        part_obj.seedPart(size=mesh_size,
deviationFactor=0.1)
        part_obj.generateMesh()
# Adhesive mesh
        faces = p3.faces.getSequenceFromMask(mask=('[#1 ]', ), )
        p3.setMeshControls(regions=faces, elemShape=QUAD,
technique=SWEEP)
        face_region = p3.Set(faces=faces,
name='Adhesive_MeshSet')
        p3.setElementType(regions=face_region,

elemTypes=(mesh.ElemType(elemCode=COH2D4, elemLibrary=STANDARD),))
        p3.seedPart(size=adhesive_mesh_size,
deviationFactor=0.1)
        p3.generateMesh()
# -----
-----
# ASSEMBLY
# -----
-
    a = model.rootAssembly
    a.DatumCsysByDefault(CARTESIAN)
    a.Instance(name='Plate1-1', part=p1, dependent=ON)
    a.Instance(name='Plate2-1', part=p2, dependent=ON)
    a.Instance(name='Adhesive-1', part=p3, dependent=ON)
    cohesive_element_labels = [e.label for e in p3.elements]
    a.SetFromElementLabels(
        name='COHESIVE',
        elementLabels=(['Adhesive-1',
cohesive_element_labels])
    )
# -----
-
# INTERACTIONS
# -----
-
    def create_tie(master_inst, master_mask, slave_inst,
slave_mask, name):

```

```

        master_edges =
a.instances[master_inst].edges.getSequenceFromMask(mask=(master_mask
,))
        slave_edges =
a.instances[slave_inst].edges.getSequenceFromMask(mask=(slave_mask,)
)
        mdb.models[model_name].Tie(name=name,

master=regionToolset.Region(edges=master_edges),

slave=regionToolset.Region(edges=slave_edges),

positionToleranceMethod=COMPUTED, adjust=ON, tieRotations=ON,
thickness=ON)
        create_tie('Plate1-1', '[#4 ]', 'Adhesive-1', '[#1 ]',
'Constraint-1')
        create_tie('Plate2-1', '[#1 ]', 'Adhesive-1', '[#4 ]',
'Constraint-2')
        # -----
-
        # STEP AND OUTPUT
        # -----
-
        model.StaticStep(name='Step-1', previous='Initial',
maxNumInc=1000,
                                initialInc=0.01, minInc=1e-15,
maxInc=0.1, stabilizationMethod=DISSIPATED_ENERGY_FRACTION,
                                continueDampingFactors=True,
adaptiveDampingRatio=0.001, nlgeom=ON)
        model.FieldOutputRequest(name='F-Output-1',
createStepName='Step-1',
                                variables=('CF', 'LE', 'PE',
'PEEQ', 'PEMAG', 'RF', 'S', 'U', 'SDEG', 'DMICRT'))
        edges = a.instances['Plate2-1'].edges
        edges_load = edges.getSequenceFromMask(mask=('[#2 ]', ),
)
        a.Set(edges=edges_load, name='Free_edge')
        model.HistoryOutputRequest(name='H-Output-2',
createStepName='Step-1',
                                variables=('RF1', 'U1'),
region=a.sets['Free_edge'])
        model.steps['Step-1'].control.setValues(
            allowPropagation=OFF, resetDefaultValues=OFF,
            displacementField=(0.005, 0.1, 0.0, 0.0, 0.02, 1e-
05, 0.001, 1e-08, 1.0, 1e-05),
            electricalPotentialField=(0.005, 0.1, 0.0, 0.0,
0.02, 1e-05, 0.001, 1e-08, 1.0, 1e-05),
            hydrostaticFluidPressureField=(0.005, 0.1, 0.0, 0.0,
0.02, 1e-05, 0.001, 1e-08, 1.0, 1e-05),
            rotationField=(0.005, 0.1, 0.0, 0.0, 0.02, 1e-05,
0.001, 1e-08, 1.0, 1e-05),
            timeIncrementation=(8.0, 10.0, 9.0, 16.0, 10.0, 4.0,
12.0, 10.0, 6.0, 3.0, 50.0),
            lineSearch=(4.0, 4.0, 0.25, 0.25, 0.15)
        )
        # -----
-
        # BOUNDARY CONDITIONS
        # -----
-

```

```

        fixed_edges = a.instances['Platel-
1'].edges.getSequenceFromMask(mask=('[#8 ]', ), )
        a.Set(edges=fixed_edges, name='Fixed_Edge')
        model.DisplacementBC(name='Fixed', createStepName='Step-
1',
                                region=a.sets['Fixed_Edge'],
u1=0.0)
        fixed_corner = a.instances['Platel-
1'].vertices.getSequenceFromMask(mask=('[#1 ]', ), )
        a.Set(vertices=fixed_corner, name='Corner')
        model.DisplacementBC(name='Fixed_corner',
createStepName='Step-1',
                                region=a.sets['Corner'], u2=0.0)
        a.Set(edges=edges_load, name='Load')
        model.DisplacementBC(name='Displacement',
createStepName='Step-1',
                                region=a.sets['Load'],
u1=initial_displacement)
        # -----
-----
# JOB CREATION AND SUBMISSION
# -----
-
        job_name = model_name + '_Job'
        print("Creating job for model: {}".format(model_name))
        # Ensure the job does not already exist
        if job_name in mdb.jobs.keys():
            print("Job '{}' already exists. Removing and
recreating.".format(job_name))
            del mdb.jobs[job_name]
        # Create the job
        mdb.Job(name=job_name, model=model_name)
        print("Job '{}' created successfully.".format(job_name))
        # Submit the job with retry mechanism
        submit_with_retry(job_name, model_name,
initial_displacement)

```

## APPENDIX B

```
# -*- coding: utf-8 -*-
from abaqus import *
from abaqusConstants import *
import part
import sketch
import material
import section
import assembly
import step
import interaction
import mesh
import regionToolset
import connectorBehavior
import odbAccess
import visualization
import xyPlot
import displayGroupOdbToolset as dgo
import math

# -----
# PARAMETERS
# -----

# Define lists of different parameters
lap_lengths = [<VAR name="overlap" format="0.0000E0"
separator="."/>]
adhesive_thicknesses = [<VAR name="adhesive__thickness"
format="0.0000E0" separator="."/>]
adhesive_material_ID = [<VAR name="adhesive_material" format="0"
separator="."/>]
plate_length = 120.0
plate_thickness = 3.0
adhesive_mesh_size = 1.0
adherend_mesh_size = 1.0
initial_displacement = 2.0

# Define different material properties for plates and adhesives
plate_materials = {
    'Steel': {
        'elastic': (209000.0, 0.29)
    }
}

# List of different materials combinations
material_combinations = [
    ('Steel', adhesive_material_ID[0])
]

# Retry Parameters
MAX_RETRIES = 10
RETRY_DISPLACEMENT_INCREMENT = 0.75

# -----
# JOB CREATION AND SUBMISSION WITH RETRY MECHANISM
# -----
def submit_with_retry(job_name, model_name, initial_displacement):
    retry_count = 0
```

```

        current_displacement = initial_displacement # Start with the
initial displacement
        while retry_count < MAX_RETRIES:
            print "Retry #{}: Submitting job '{}' with displacement
{}".format(retry_count, job_name, current_displacement)
            # Check if the displacement boundary condition exists
            model = mdb.models[model_name]
            if 'Displacement' not in model.boundaryConditions.keys():
                print "Error: Boundary condition 'Displacement' not
found in model '{}'.format(model_name)
                return
            # Update the displacement boundary condition
            print "Updating displacement boundary condition to ul =
{}".format(current_displacement)

model.boundaryConditions['Displacement'].setValues(ul=current_displa
cement)
        # Check if the job already exists; if so, delete it
        if job_name in mdb.jobs.keys():
            del mdb.jobs[job_name]
        # Create and submit the job
        mdb.Job(name=job_name, model=model_name)
        mdb.jobs[job_name].submit()
        mdb.jobs[job_name].waitForCompletion()
        # Check the job status
        odb_path = job_name + '.odb'
        if os.path.exists(odb_path):
            print "Job '{}' completed
successfully.".format(job_name)
            # --- MAX ALLSE extraction ---
            try:
                odb_path = job_name + '.odb'
                odb = odbAccess.openOdb(path=odb_path)
                step = odb.steps['Step-1']
                region = step.historyRegions['ElementSet COHESIVE']
                allse_data = region.historyOutputs['ALLSE'].data
                max_allse = max(val for _, val in allse_data)
                print "Max ALLSE (dissipated energy) from COHESIVE
elements: {:.4f}".format(max_allse)
                # Write max_allse to a text file
                output_filename = "max_allse_results.txt"
                with open(output_filename, "a") as f: # Use "a" for
append mode
                    f.write("MAX_ALLSE={:.4f}\n".format(max_allse))
                print "Max ALLSE written to
{}".format(output_filename)
            try:
                total_max_rf1 = 0.0
                for region_name in step.historyRegions.keys():
                    if region_name.startswith('Node PLATE2-1.'):
                        node_rf_region =
step.historyRegions[region_name]
                        for output_key, history_output in
node_rf_region.historyOutputs.items():
                            if output_key.startswith('RF1'):
                                rf1_data = history_output.data
                                if rf1_data:
                                    max_node_rf1 = 0.0
                                    for time_val, rf1_val in
rf1_data:

```

```

abs(max_node_rf1):
rf1_val
max_node_rf1
total_max_rf1 +=
print "Added Max RF1 from
{}: {:.4f}".format(region_name, max_node_rf1)
print "Total MAX RF1 from Free_edge:
{:.4f}".format(total_max_rf1)
with open(output_filename, "a") as f:
    f.write("RF={:.4f}\n".format(total_max_rf1))
print "Total MAX RF1 written to
{}".format(output_filename)
except Exception as e:
    print "Could not extract Total RF1 data:
{}".format(str(e))
    print "Available history regions were:",
step.historyRegions.keys()
# --- Min SDEG extraction for last frame with full-debond
check ---
    try:
        last_frame = step.frames[-1]
        sdeg_field = last_frame.fieldOutputs['SDEG']
        assembly = odb.rootAssembly
        cohesive_element_set =
assembly.elementSets['COHESIVE']
        sdeg_sub =
sdeg_field.getSubset(region=cohesive_element_set, position=CENTROID)
        if sdeg_sub.values:
            min_sdeg = min(val.data for val in
sdeg_sub.values)
            print("Min SDEG from COHESIVE at last frame:
{:.4f}".format(min_sdeg))
            with open(output_filename, "a") as f:
f.write("MIN_SDEG={:.4f}\n".format(min_sdeg))
                print("Min SDEG status written to
{}".format(output_filename))
            else:
                print("No SDEG values found for the COHESIVE
element set in the last frame.")
            except Exception as e:
                print("Could not extract min SDEG data:
{}".format(str(e)))
                odb.close()
            except Exception as e:
                print "Could not extract ALLSE data:
{}".format(str(e))
                return
        elif job_status == ABORTED:
            print "Job '{}' aborted. Retrying...".format(job_name)
            retry_count += 1
            current_displacement *= RETRY_DISPLACEMENT_INCREMENT
        else:
            print "Job '{}' ended with unexpected status: {}".
Exiting retry loop.".format(job_name, job_status)
            return
        print "Job '{}' failed after {} retries.".format(job_name,
MAX_RETRIES)

```

```

# -----
# MODEL SETUP LOOP FOR PARAMETER COMBINATIONS
# -----

for plate_material, adhesive_type in material_combinations:
    for lap_length in lap_lengths:
        for adhesive_thickness in adhesive_thicknesses:
            model_name =
'SingleLapJoint2D_{}_{}_Lap{}_Thick{}'.format(
                plate_material, adhesive_type, int(lap_length),
int(adhesive_thickness*10) # Using int() for cleaner name
            )
            print "Creating model: {}".format(model_name)
            # Check if the model already exists in the model
database
            if model_name not in mdb.models.keys():
                # Create the model only if it doesn't exist already
                model = mdb.Model(name=model_name)
            else:
                model = mdb.models[model_name]
                print "Model {} already exists.".format(model_name)
                continue # Skip the rest of the model definition if
it exists
            # -----
            -
            # PART CREATION
            # -----
            -
            # Plate 1
            s1 = model.ConstrainedSketch(name='plate1_profile',
sheetSize=200.0)
            s1.rectangle(point1=(0.0, 0.0), point2=(plate_length,
plate_thickness))
            p1 = model.Part(name='Plate1',
dimensionality=TWO_D_PLANAR, type=DEFORMABLE_BODY)
            p1.BaseShell(sketch=s1)
            del model.sketches['plate1_profile']
            # Plate 2
            s2 = model.ConstrainedSketch(name='plate2_profile',
sheetSize=200.0)
            s2.rectangle(point1=(plate_length-lap_length,
plate_thickness + adhesive_thickness),
                        point2=(2*plate_length-lap_length,
2*plate_thickness + adhesive_thickness))
            p2 = model.Part(name='Plate2',
dimensionality=TWO_D_PLANAR, type=DEFORMABLE_BODY)
            p2.BaseShell(sketch=s2)
            del model.sketches['plate2_profile']
            # Adhesive
            s3 = model.ConstrainedSketch(name='adhesive_profile',
sheetSize=200.0)
            s3.rectangle(point1=(plate_length-lap_length,
plate_thickness),
                        point2=(plate_length, plate_thickness +
adhesive_thickness))
            p3 = model.Part(name='Adhesive',
dimensionality=TWO_D_PLANAR, type=DEFORMABLE_BODY)
            p3.BaseShell(sketch=s3)
            del model.sketches['adhesive_profile']
            # -----
            -

```

```

# MATERIALS
# -----

-

# Plate Material
print("Assigning plate material:
{}".format(plate_material))
model.Material(name=plate_material)

model.materials[plate_material].Elastic(table=(plate_materials[plate
_material]['elastic'], ))
# Adhesive material properties as a function of
thickness
# Define formulas for AdhesiveA - HYSOL EA 9361
alfa=1.25
E_A = 670
v_A=0.4
G_A = E_A / (2*(v_A+1))
Cohesive_Energy_A_modeI = 2.61
Cohesive_Energy_A_modeII = 5.22
Yield_strength_I_A = 4.23
Yield_strength_II_A = 2.44
Tensile_strength_I_A = 7.99
Tensile_strength_II_A = 5.54
r_p_A_max_modeI= alfa*(1/(3*math.pi))*(E_A/(1-
v_A**2))*(Cohesive_Energy_A_modeI/Yield_strength_I_A**2)
r_p_A_max_modeII= alfa*(1/(3*math.pi))*(E_A/(1-
v_A**2))*(Cohesive_Energy_A_modeII/Yield_strength_II_A**2)
t_c_A_modeI = 2*r_p_A_max_modeI
t_c_A_modeII = 2*r_p_A_max_modeII
Area_A = 2.69
nu_A_modeI = Area_A*t_c_A_modeI/Cohesive_Energy_A_modeI
nu_A_modeII =
Area_A*t_c_A_modeII/Cohesive_Energy_A_modeII
if adhesive_thickness<t_c_A_modeI:
    Sep_strength_A_modeI =
((1+nu_A_modeI*(adhesive_thickness/t_c_A_modeI))/((1+nu_A_modeI)*(ad
hesive_thickness/t_c_A_modeI)))*0.5*Tensile_strength_I_A
    Fracture_E_A_modeI =
Cohesive_Energy_A_modeI+Area_A*adhesive_thickness
else:
    Sep_strength_A_modeI = Tensile_strength_I_A

Fracture_E_A_modeI=Cohesive_Energy_A_modeI+Area_A*t_c_A_modeI
if adhesive_thickness<t_c_A_modeII:
    Sep_strength_A_modeII =
((1+nu_A_modeII*(adhesive_thickness/t_c_A_modeII))/((1+nu_A_modeII)*
(adhesive_thickness/t_c_A_modeII)))*0.5*Tensile_strength_II_A

Fracture_E_A_modeII=Cohesive_Energy_A_modeII+Area_A*adhesive_thickne
ss
else:
    Sep_strength_A_modeII = Tensile_strength_II_A

Fracture_E_A_modeII=Cohesive_Energy_A_modeII+Area_A*t_c_A_modeII

def adhesive_a_elastic(adhesive_thickness):
    return (E_A / adhesive_thickness, G_A /
adhesive_thickness, G_A /adhesive_thickness)
def adhesive_a_damage_initiation(adhesive_thickness):
    return (Sep_strength_A_modeI, Sep_strength_A_modeII,
Sep_strength_A_modeII)

```

```

def adhesive_a_damage_evolution(adhesive_thickness):
    return (Fracture_E_A_modeI, Fracture_E_A_modeII,
Fracture_E_A_modeII)
    # Define formulas for AdhesiveB - AV138/HV998
    alfa=1.25
    E_B = 4890
    v_B=0.35
    G_B = 1560
    Cohesive_Energy_B_modeI = 0.2
    Cohesive_Energy_B_modeII = 0.38
    Tensile_strength_I_B = 39.45
    Tensile_strength_II_B = 30.2
    Sep_strength_B_modeI = Tensile_strength_I_B
    Fracture_E_B_modeI=Cohesive_Energy_B_modeI
    Sep_strength_B_modeII = Tensile_strength_II_B
    Fracture_E_B_modeII=Cohesive_Energy_B_modeII

def adhesive_b_elastic(adhesive_thickness):
    return ( E_B / adhesive_thickness, G_B /
adhesive_thickness, G_B /adhesive_thickness)
def adhesive_b_damage_initiation(adhesive_thickness):
    return (Sep_strength_B_modeI, Sep_strength_B_modeII,
Sep_strength_B_modeII)
def adhesive_b_damage_evolution(adhesive_thickness):
    return (Fracture_E_B_modeI, Fracture_E_B_modeII,
Fracture_E_B_modeII)
    # Define formulas for AdhesiveC - SikaForce 788
    alfa=1.25
    E_C = 1890
    v_C=0.33
    G_C = 710
    Cohesive_Energy_C_modeI = 1.03
    Cohesive_Energy_C_modeII = 5.27
    Yield_strength_I_C = 13.2
    Yield_strength_II_C = 15.3
    Tensile_strength_I_C = 28.6
    Tensile_strength_II_C = 20
    r_p_C_max_modeI= alfa*(1/(3*math.pi))*(E_C/(1-
v_C**2))*(Cohesive_Energy_C_modeI/Yield_strength_I_C**2)
    r_p_C_max_modeII= alfa*(1/(3*math.pi))*(E_C/(1-
v_C**2))*(Cohesive_Energy_C_modeII/Yield_strength_II_C**2)
    t_c_C_modeI = 2*r_p_C_max_modeI
    t_c_C_modeII = 2*r_p_C_max_modeII
    Area_I_C = 0.75
    Area_II_C = 17.27
    nu_C_modeI =
Area_I_C*t_c_C_modeI/Cohesive_Energy_C_modeI
    nu_C_modeII =
Area_II_C*t_c_C_modeII/Cohesive_Energy_C_modeII
    if adhesive_thickness<t_c_C_modeI:
        Sep_strength_C_modeI =
((1+nu_C_modeI*(adhesive_thickness/t_c_C_modeI))/((1+nu_C_modeI)*(ad
hesive_thickness/t_c_C_modeI)))*0.5*Tensile_strength_I_C

Fracture_E_C_modeI=Cohesive_Energy_C_modeI+Area_I_C*adhesive_thickne
ss
    else:
        Sep_strength_C_modeI = Tensile_strength_I_C

Fracture_E_C_modeI=Cohesive_Energy_C_modeI+Area_I_C*t_c_C_modeI
    if adhesive_thickness<t_c_C_modeII:

```

```

        Sep_strength_C_modeII =
((1+nu_C_modeII*(adhesive_thickness/t_c_C_modeII))/((1+nu_C_modeII)*
(adhesive_thickness/t_c_C_modeII)))*0.5*Tensile_strength_II_C

Fracture_E_C_modeII=Cohesive_Energy_C_modeII+Area_II_C*adhesive_thic
kness
    else:
        Sep_strength_C_modeII = Tensile_strength_II_C

Fracture_E_C_modeII=Cohesive_Energy_C_modeII+Area_II_C*t_c_C_modeII
    def adhesive_c_elastic(adhesive_thickness):
        return ( E_C / adhesive_thickness, G_C /
adhesive_thickness, G_C /adhesive_thickness)
    def adhesive_c_damage_initiation(adhesive_thickness):
        return (Sep_strength_C_modeI, Sep_strength_C_modeII,
Sep_strength_C_modeII)
    def adhesive_c_damage_evolution(adhesive_thickness):
        return (Fracture_E_C_modeI, Fracture_E_C_modeII,
Fracture_E_C_modeII)
    # Define formulas for AdhesiveD - Araldite 2015
    alfa=1.25
    E_D = 1850
    v_D=0.33
    G_D = 560
    Cohesive_Energy_D_modeI = 0.29
    Cohesive_Energy_D_modeII = 3.36
    Yield_strength_I_D = 12.63
    Yield_strength_II_D = 14.6
    Tensile_strength_I_D = 21.63
    Tensile_strength_II_D = 17.9
    r_p_D_max_modeI= alfa*(1/(3*math.pi))*(E_D/(1-
v_D**2))*(Cohesive_Energy_D_modeI/Yield_strength_I_D**2)
    r_p_D_max_modeII= alfa*(1/(3*math.pi))*(E_D/(1-
v_D**2))*(Cohesive_Energy_D_modeII/Yield_strength_II_D**2)
    t_c_D_modeI = 2*r_p_D_max_modeI
    t_c_D_modeII = 2*r_p_D_max_modeII
    Area_I_D = 0.70
    Area_II_D = 6.71
    nu_D_modeI =
Area_I_D*t_c_D_modeI/Cohesive_Energy_D_modeI
    nu_D_modeII =
Area_II_D*t_c_D_modeII/Cohesive_Energy_D_modeII
    if adhesive_thickness<t_c_D_modeI:
        Sep_strength_D_modeI =
((1+nu_D_modeI*(adhesive_thickness/t_c_D_modeI))/((1+nu_D_modeI)*(ad
hesive_thickness/t_c_D_modeI)))*0.5*Tensile_strength_I_D

Fracture_E_D_modeI=Cohesive_Energy_D_modeI+Area_I_D*adhesive_thickne
ss
    else:
        Sep_strength_D_modeI = Tensile_strength_I_D

Fracture_E_D_modeI=Cohesive_Energy_D_modeI+Area_I_D*t_c_D_modeI
    if adhesive_thickness<t_c_D_modeII:
        Sep_strength_D_modeII =
((1+nu_D_modeII*(adhesive_thickness/t_c_D_modeII))/((1+nu_D_modeII)*
(adhesive_thickness/t_c_D_modeII)))*0.5*Tensile_strength_II_D

Fracture_E_D_modeII=Cohesive_Energy_D_modeII+Area_II_D*adhesive_thic
kness
    else:

```

```

Sep_strength_D_modeII = Tensile_strength_II_D

Fracture_E_D_modeII=Cohesive_Energy_D_modeII+Area_II_D*t_c_D_modeII
def adhesive_d_elastic(adhesive_thickness):
    return ( E_D / adhesive_thickness, G_D /
adhesive_thickness, G_D /adhesive_thickness)
def adhesive_d_damage_initiation(adhesive_thickness):
    return (Sep_strength_D_modeI, Sep_strength_D_modeII,
Sep_strength_D_modeII)
def adhesive_d_damage_evolution(adhesive_thickness):
    return (Fracture_E_D_modeI, Fracture_E_D_modeII,
Fracture_E_D_modeII)
# Adhesive Material
print("Assigning adhesive material: {} with thickness
{}".format(adhesive_type, adhesive_thickness))
if adhesive_type == 1:
    adhesive_type = 'AdhesiveA'
    elastic_values =
adhesive_a_elastic(adhesive_thickness)
    damage_initiation_values =
adhesive_a_damage_initiation(adhesive_thickness)
    damage_evolution_values =
adhesive_a_damage_evolution(adhesive_thickness)
elif adhesive_type == 2:
    adhesive_type = 'AdhesiveB'
    elastic_values =
adhesive_b_elastic(adhesive_thickness)
    damage_initiation_values =
adhesive_b_damage_initiation(adhesive_thickness)
    damage_evolution_values =
adhesive_b_damage_evolution(adhesive_thickness)
elif adhesive_type == 3:
    adhesive_type = 'AdhesiveC'
    elastic_values =
adhesive_c_elastic(adhesive_thickness)
    damage_initiation_values =
adhesive_c_damage_initiation(adhesive_thickness)
    damage_evolution_values =
adhesive_c_damage_evolution(adhesive_thickness)
elif adhesive_type == 4:
    adhesive_type = 'AdhesiveD'
    elastic_values =
adhesive_d_elastic(adhesive_thickness)
    damage_initiation_values =
adhesive_d_damage_initiation(adhesive_thickness)
    damage_evolution_values =
adhesive_d_damage_evolution(adhesive_thickness)
else:
    print("Unknown adhesive type '{}'. Skipping material
assignment.".format(adhesive_type))
    continue
    adhesive_material_name = adhesive_type + '_Thick' +
str(int(adhesive_thickness * 10))
    model.Material(name=adhesive_material_name)
    model.materials[adhesive_material_name].Elastic(
        type=TRACTION, table=(elastic_values,)
    )

model.materials[adhesive_material_name].QuadsDamageInitiation(
    table=(damage_initiation_values,)
)

```

```

model.materials[adhesive_material_name].quadsDamageInitiation.Damage
Evolution(
    type=ENERGY, mixedModeBehavior=BK, power=2.284,
    table=(damage_evolution_values,)
)
# -----
-
# SECTIONS AND ASSIGNMENT
# -----
-
    model.HomogeneousSolidSection(name='PlateSection',
material=plate_material)
    model.CohesiveSection(name='AdhesiveSection',
material=adhesive_type + '_Thick' + str(int(adhesive_thickness*10)),
                                response=TRACTION_SEPARATION,
outOfPlaneThickness=None)

p1.SectionAssignment(region=regionToolset.Region(faces=p1.faces),
sectionName='PlateSection')

p2.SectionAssignment(region=regionToolset.Region(faces=p2.faces),
sectionName='PlateSection')

p3.SectionAssignment(region=regionToolset.Region(faces=p3.faces),
sectionName='AdhesiveSection')
# -----
-----
# MESHING
# -----
-
    for part_obj, mesh_size, elem_type in [(p1,
adherend_mesh_size, CPE4R), (p2, adherend_mesh_size, CPE4R)]:
        faces =
part_obj.faces.getSequenceFromMask(mask=('[#1 ]', ), )
        part_obj.setMeshControls(regions=faces,
technique=STRUCTURED)
        face_region = part_obj.Set(faces=faces,
name='%s_MeshSet' % part_obj.name)
        part_obj.setElementType(regions=face_region,

elemTypes=(mesh.ElemType(elemCode=elem_type,
elemLibrary=STANDARD),))
        part_obj.seedPart(size=mesh_size,
deviationFactor=0.1)
        part_obj.generateMesh()
        # Adhesive mesh
        faces = p3.faces.getSequenceFromMask(mask=('[#1 ]', ), )
        p3.setMeshControls(regions=faces, elemShape=QUAD,
technique=SWEEP)
        face_region = p3.Set(faces=faces,
name='Adhesive_MeshSet')
        p3.setElementType(regions=face_region,

elemTypes=(mesh.ElemType(elemCode=COH2D4, elemLibrary=STANDARD),))
        p3.seedPart(size=adhesive_mesh_size,
deviationFactor=0.1)
        p3.generateMesh()
# -----
-----
# ASSEMBLY

```

```

# -----
-
a = model.rootAssembly
a.DatumCsysByDefault(CARTESIAN)
a.Instance(name='Plate1-1', part=p1, dependent=ON)
a.Instance(name='Plate2-1', part=p2, dependent=ON)
a.Instance(name='Adhesive-1', part=p3, dependent=ON)
cohesive_element_labels = [e.label for e in p3.elements]
a.SetFromElementLabels(
    name='COHESIVE',
    elementLabels=[('Adhesive-1',
cohesive_element_labels)]
)
# -----
-
# INTERACTIONS
# -----
-
def create_tie(master_inst, master_mask, slave_inst,
slave_mask, name):
    master_edges =
a.instances[master_inst].edges.getSequenceFromMask(mask=(master_mask
,))
    slave_edges =
a.instances[slave_inst].edges.getSequenceFromMask(mask=(slave_mask,)
)
    mdb.models[model_name].Tie(name=name,
master=regionToolset.Region(edges=master_edges),
slave=regionToolset.Region(edges=slave_edges),
positionToleranceMethod=COMPUTED, adjust=ON, tieRotations=ON,
thickness=ON)
    create_tie('Plate1-1', ['#4'], 'Adhesive-1', ['#1'],
'Constraint-1')
    create_tie('Plate2-1', ['#1'], 'Adhesive-1', ['#4'],
'Constraint-2')
# -----
-
# STEP AND OUTPUT
# -----
-
model.StaticStep(name='Step-1', previous='Initial',
maxNumInc=1000,
initialInc=0.01, minInc=1e-15,
maxInc=0.1, stabilizationMethod=DISSIPATED_ENERGY_FRACTION,
continueDampingFactors=True,
adaptiveDampingRatio=0.001, nlgeom=ON)
model.FieldOutputRequest(name='F-Output-1',
createStepName='Step-1',
variables=('CF', 'LE', 'PE',
'PEEQ', 'PEMAG', 'RF', 'S', 'U', 'SDEG', 'DMICRT'))
model.HistoryOutputRequest(name='H-Output-
ALLSE_COHESIVE', createStepName='Step-1',
region=a.sets['COHESIVE'],
variables=('ALLSE',)
)
edges = a.instances['Plate2-1'].edges
edges_load = edges.getSequenceFromMask(mask=('#2'], ),
)

```

```

        a.Set(edges=edges_load, name='Free_edge')
        model.HistoryOutputRequest(name='H-Output-2',
createStepName='Step-1',
                                variables=('RF1', 'U1'),
region=a.sets['Free_edge'])
        model.steps['Step-1'].control.setValues(
            allowPropagation=OFF, resetDefaultValues=OFF,
            displacementField=(0.005, 0.1, 0.0, 0.0, 0.02, 1e-
05, 0.001, 1e-08, 1.0, 1e-05),
            electricalPotentialField=(0.005, 0.1, 0.0, 0.0,
0.02, 1e-05, 0.001, 1e-08, 1.0, 1e-05),
            hydrostaticFluidPressureField=(0.005, 0.1, 0.0, 0.0,
0.02, 1e-05, 0.001, 1e-08, 1.0, 1e-05),
            rotationField=(0.005, 0.1, 0.0, 0.0, 0.02, 1e-05,
0.001, 1e-08, 1.0, 1e-05),
            timeIncrementation=(8.0, 10.0, 9.0, 16.0, 10.0, 4.0,
12.0, 10.0, 6.0, 3.0, 50.0),
            lineSearch=(4.0, 4.0, 0.25, 0.25, 0.15)
        )
        # -----
-
        # BOUNDARY CONDITIONS
        # -----
-
        fixed_edges = a.instances['Platel-
1'].edges.getSequenceFromMask(mask=('[#8 ]', ), )
        a.Set(edges=fixed_edges, name='Fixed_Edge')
        model.DisplacementBC(name='Fixed', createStepName='Step-
1',
                                region=a.sets['Fixed_Edge'],
u1=0.0)
        fixed_corner = a.instances['Platel-
1'].vertices.getSequenceFromMask(mask=('[#1 ]', ), )
        a.Set(vertices=fixed_corner, name='Corner')
        model.DisplacementBC(name='Fixed_corner',
createStepName='Step-1',
                                region=a.sets['Corner'], u2=0.0)
        a.Set(edges=edges_load, name='Load')
        model.DisplacementBC(name='Displacement',
createStepName='Step-1',
                                region=a.sets['Load'],
u1=initial_displacement)
        # -----
-----
        # JOB CREATION AND SUBMISSION
        # -----
-
        job_name = model_name + '_Job'
        print("Creating job for model: {}".format(model_name))
        # Ensure the job does not already exist
        if job_name in mdb.jobs.keys():
            print("Job '{}' already exists. Removing and
recreating.".format(job_name))
            del mdb.jobs[job_name]
        # Create the job
        mdb.Job(name=job_name, model=model_name)
        print("Job '{}' created successfully.".format(job_name))
        # Submit the job with retry mechanism
        submit_with_retry(job_name, model_name,
initial_displacement)

```

## **CURRICULUM VITAE**

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**EDUCATION** :

- **B.Sc.** : 2018, Istanbul Technical University, Faculty of Aeronautics and Astronautics, Astronautical Engineering

### **PROFESSIONAL EXPERIENCE AND REWARDS:**

- 2025-Current GE Aerospace, Lead Design Engineer
- 2018-2025 Turkish Aerospace, Structural Design Engineer