Magd Abdel Wahab

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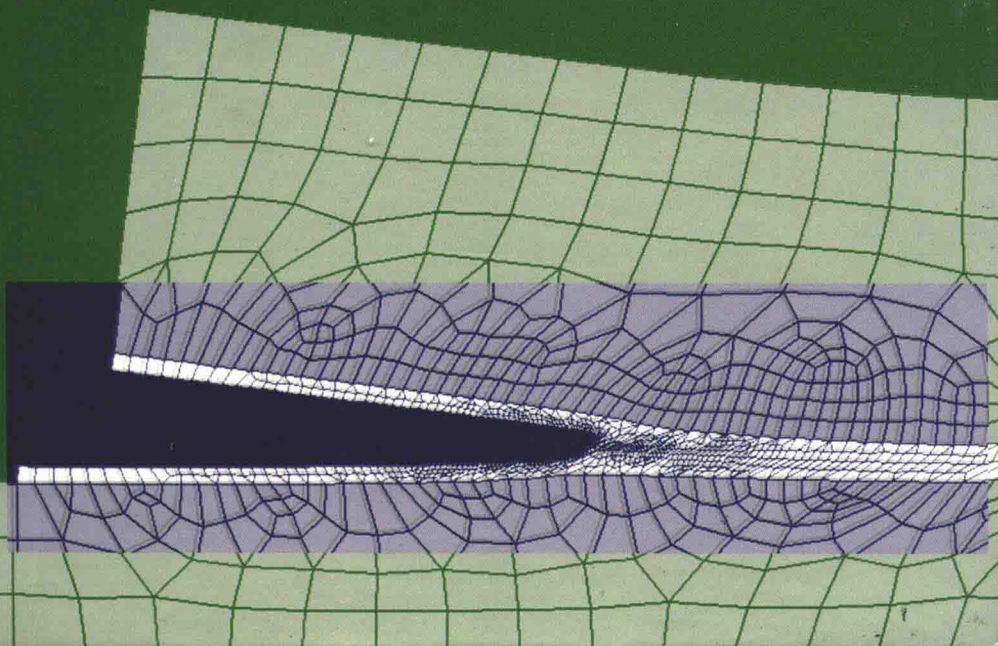
Finite Element Analysis with ANSYS



The Mechanics of Adhesives in Composite and Metal Joints

Finite Element Analysis with ANSYS

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The Mechanics of Adhesives in Composite and Metal Joints

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Downloadable files for ANSYS

This book discusses macrofiles for creating models of different types of adhered joints using ANSYS. A full list of the joint types and file names can be found in **Appendix A–Summary of ANSYS files** (p. 211).

These macrofiles, in text-editable format, are available for download from the publisher's website (www.destechpub.com).

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Files may be opened using a text editor, e.g., Notepad. Files can be run in ANSYS, version 12.0 or higher. A brief discussion of using ANSYS, including techniques for creating input files, can be found in **Chapter 3**, sections 3.3 (p. 59) and 3.6 (p. 93). ANSYS requires a user license, which is not included with this book.

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To my Lord
The Lord of Earth and Heaven
Allah Almighty
Without your mercy, knowledge would not exist

Preface

ADHESIVE BONDING TECHNOLOGY is a powerful joining technique, especially for thin sheets of metal or composites. The superiority of adhesive bonding is manifest in its high fatigue resistance and high strength-to-weight ratio. Since an adhesively bonded joint consists of different materials, its structural analysis is complicated and requires many special considerations and assumptions. For instance, when adhesives are used to join thin sheets, large deformation behavior is expected under thermal and mechanical loads. In addition, modern adhesives display significant degrees of plasticity, which further complicates analysis. For an analysis of this kind that includes diverse materials and geometric non-linearities, a reliable analytical solution is almost impossible.

Numerical techniques, such as Finite Element Analysis (FEA), offer an efficient and powerful solution for analyzing complicated structures under varying loading conditions, such as those in adhesively bonded joints. FEA can also be used for other types of analyses, e.g., stress, thermal, and diffusion, which are often required to study the behavior and responses of bonded joints during their service life. In the last few decades, rapid advances in FEA technology have led to the development of commercial FEA packages. One of the packages most widely used by engineers is ANSYS.

This book concentrates on studying the mechanics of adhesively bonded composite and metallic joints using FEA, and more specifically, the ANSYS package. The main objective of the book is to provide engineers and scientists working in adhesive bonding technology with the technical know-how to model adhesively bonded joints using ANSYS.

The text can also be used for post-graduate courses in adhesive bonding technology. It also provides fundamental scientific information regarding the theory required to understand FEA simulations and results. The types of problems considered herein are: stress, fracture, cohesive zone modeling (CZM), fatigue crack propagation, thermal, diffusion and coupled field analysis.

Chapter 1 presents a brief history of adhesive bonding, as well as its applications and classifications. The second chapter is devoted to reviewing basic mechanics theories used in the following chapters, including stress and strain, plasticity, fracture mechanics, heat transfer, and diffusion. Chapter 3 covers the fundamentals of FEA and introduces the ANSYS package. The theoretical background of structural mechanics, heat transfer and diffusion problems is explained. Element types, as well as FEA formulations, are considered. Chapter 4 concentrates on defining element types, material models and constructing the FE mesh for several types of un-cracked and cracked adhesive joints. Modeling damage in bonded joints using CZM is also considered, and the models developed in Chapter 4 are then used to perform different types of analyses in Chapters 5 through 9. In Chapter 5, stress analysis for four different joints is presented, while fracture and CZM analyses are explained in Chapter 6. The seventh chapter focuses on fatigue crack propagation analysis and lifetime prediction of two adhesively bonded joints. Thermal and diffusion analyses of three different joints are explained in Chapter 8, Finally, in Chapter 9, coupled thermal-stress and diffusion-stress analyses are carried out. All ANSYS input files described in the chapters of the book are also available in electronic files provided with the book.

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CHAPTER 1

An Introduction to Adhesive Joints

1.1. INTRODUCTION

ADHESIVE is defined as a substance that is capable of strongly and permanently holding two surfaces together. Bonding is the joining of the two materials, known as substrates or adherends, using an adhesive material. The terms substrate and adherend are synonymously used in the literature, although sometimes the term substrate refers to the material before bonding and the term adherend after bonding. For convenience and to avoid confusion, we shall use the term substrate throughout the book. The adhesive material adheres to the substrates and transfers the forces between them. In general, the bonding will not be broken unless the bond is destroyed. An example of a typical adhesively bonded joint is shown in Figure 1.1, from which different regions can be identified. The interphase is a thin region near the contact between adhesive and substrate and has different physical and chemical properties from adhesive and substrate materials. The term interphase is to be distinguished from the term interface, which is the plane of contact between the surfaces of two materials. A second region that can be seen in Figure 1.1 is the primer, which is applied to the surface prior to the application of an adhesive. Although not always used, a primer improves the performance of bond and protects the surface until the adhesive is applied.

Nowadays, adhesive bonding becomes the most universal joining technique as it can be used to join any type of materials. Consequently, adhesive bonding joining technique gains lots of popularity because it offers flexible design and can have a wide range of industrial applica-

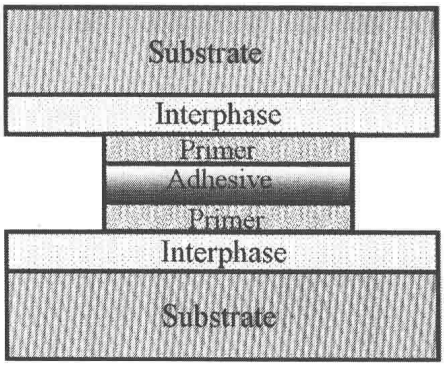

FIGURE 1.1. A typical adhesively bonded joint.

tions. It is replacing traditional joining techniques in many applications. With the advances of polymer chemistry, modern adhesives may have high strength and short curing time. Therefore, a very strong adhesively bonded joint can be obtained in a very short time. Adhesive is suitable for joining thin sheets and this is the reason why it becomes very popular in aerospace and automotive industries, where light weight is of primary importance. Adhesive bonding has many advantages, which are summarized as follows:

1. It offers the possibility to join large surfaces, dissimilar materials and thin substrates.
2. It provides good uniform load distribution, except at edges.
3. It does not make any visible surface marking.
4. It has excellent fatigue performance.
5. It has good damping and vibration properties.
6. It requires low heat so that substrates are not affected.
7. It provides high strength to weight ratio.

However, adhesive bonding has several disadvantages, which are summarized as follows:

1. Cleaning and surface pre-treatment is required in order to achieve high quality bonding.
2. Long curing periods may be required.
3. Pressure and fixtures may be required.
4. Inspection of joints after bonding is difficult.
5. It is sensitive to high temperature and moisture concentration.
6. Special training may be required.

A comparison between three different joining techniques, namely riveting, welding and adhesive bonding, is presented in Table 1.1, which summarizes the advantages and disadvantages of each technique and can be used to identify which fastening method is suitable for a particular application. For example, for thin metal structures used in aerospace and automotive industries, the transmission of stresses is more effective by adhesive bonding than by riveting or welding joining methods. Materials such as plastics, Fibre Reinforced Polymer (FRP) composites and elastomers are easier joined by adhesives than by other techniques. Welding is sometimes difficult for light metals such as aluminium, titanium and magnesium due to the high level of heat, and therefore adhesive bonding provides a good alternative for joining them. One of the main advantages of adhesive bonding is its excellent fatigue performance when compared to other joining techniques [1]. In Figure 1.2, a sketch of stress versus number of cycles, S-N curve, for a metal substrate, a riveted joint and an adhesive joint is shown. The fatigue resistance of the adhesive joint is far better than that of the riveted joint and close to that of the metal substrate.

The modes of failure in an adhesively bonded joint can be cohesive, adhesive or a combination of cohesive/adhesive failures as shown in Figure 1.3. Cohesive failure, Figure 1.3(a) can be either in the adhesive layer or in the substrate. In the example given in Figure 1.3(a), cohesive failure is in the adhesive layer, which may take place when the interface is stronger than the adhesive material. Adhesive failure, Figure

TABLE 1.1. Comparison Between Riveting, Welding and Adhesive Bonding Techniques.

Characteristic	Riveting	Welding	Adhesive Bonding
Joining thin materials	Poor	Fair	Excellent
Limits on material combination	Fair	Poor	Excellent
Requirement for surface preparation	Excellent	Good	Poor
Tooling	Excellent	Fair	Fair
Heat requirement	Excellent	Poor	Good/Fair
Stress distribution	Poor	Good/Fair	Excellent
Sealing function	Poor	Fair	Good
Distortion assembly	Fair	Poor	Excellent
Solvent resistance	Excellent	Excellent	Fair
Effect of temperature	Excellent	Excellent	Poor
Ease of repair	Good	Poor	Fair
Level of required skills	Excellent	Good	Excellent

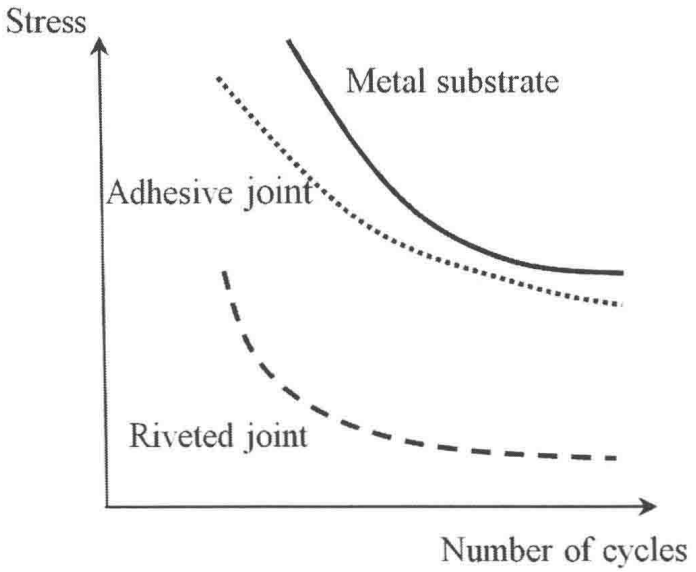

FIGURE 1.2. S-N curves for metal substrate, riveted joint and adhesive joint, adopted from [1].

1.3(b), also known as interfacial failure, takes place when the interface is weaker than the adhesive material and represents a failure of the bond between adhesive and substrate. A combination of cohesive/adhesive failure also is possible as shown in Figure 1.3(c).

Adhesive bonding technology is a multi-disciplinary science that requires the knowledge of a number of scientific disciplines as illustrated in Figure 1.4. Three main academic disciplines, namely mechanics, physics and chemistry are overlapping to produce important research topics, such as adhesion science, polymer science, surface science and

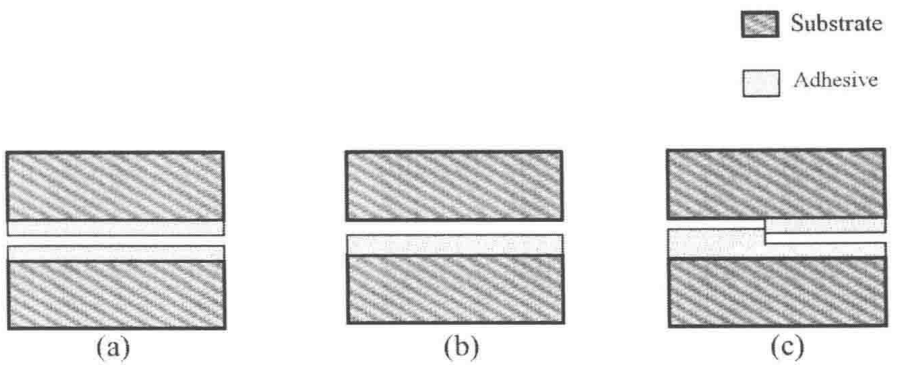

FIGURE 1.3. Typical failures in adhesive; (a) cohesive failure, (b) adhesive failure and (c) cohesive/adhesive failure.

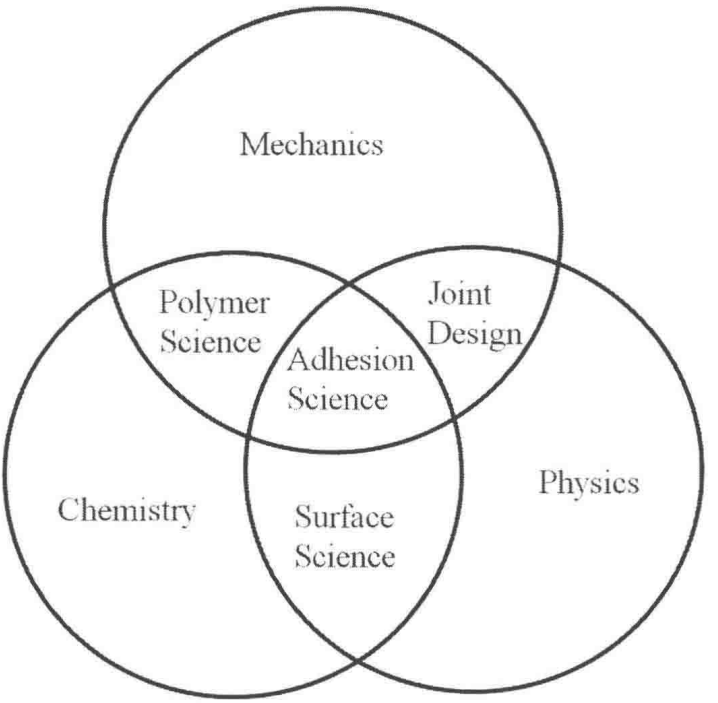

FIGURE 1.4. *Multi-disciplinary aspects of adhesive bonding technology.*

joint design. This book concentrates on the mechanics aspect of adhesive joints and more specifically stress analysis, fracture and damage mechanics, thermal, diffusion and coupled analyses using Finite Element Analysis (FEA) technique.

1.2. A BRIEF HISTORY OF ADHESIVE BONDING

As an Egyptian, I am proud to say that ancient Egyptians were among the early humans in the ancient ages who made use of adhesives. In the tomb of Rekhmara in Tibah, which dates to 1475 B.C., animal glues were used in a wall carving. In the tomb of Tut-an-khamun discovered in 1922 in the Valley of the Kings, a glue tablet was found. Surprisingly, the glue's properties were found to be identical to those at the time of the archaeological investigations indicating that adhesives have not been further developed since the time of ancient Egyptians. Egyptians used glues in many applications including fastening gold leaf to plaster, fastening wood, sealing and repairing alabaster jars, compound bow and as a binder in paints and pigments.

Although I have started with ancient Egyptians, the history of adhe-

sives is much older than that. It is very difficult indeed to trace the exact starting date for the use of adhesives. It might have been started at the same time as the existence of human being. Archaeological evidence suggests that humans have used adhesives for thousands of years, dating back approximately 200,000 B.C. In Koenigsaue in the Harz Mountains in Germany in 1963, residues of adhesives were found on Neanderthal tools dated to approximately 80,000 B.C. Other Neanderthal tools dated to 40,000 B.C. have been found in Umm el Tiel in Syria. Adhesives used by modern humans have been dated to 8,000 B.C. Statues discovered in Babylonian temples contain glues and have been dated to 4,000 B.C. The Sumerians in 3000 B.C. used glue produced from animal skins and the Mesopotamians in 4000 B.C. used asphalt. In 1991, a discovery revealed adhesives were used to bond components of weapons from the Late Neolithic period dated in 3,300 B.C. During the period between 2000 B.C. and 1600 B.C., ancient Greeks used glues in the famous legend of Daedalus and Icarus. The first bonding of structural metal probably was done by the ancient Greek sculptor and architect Theodorus of Samos (from the Greek island of Samos) and is dated to 530 B.C.

In the middle ages, immediately after the decline of Greece and Rome empire, very few records documenting the use of adhesives can be found. It is very likely that adhesives were in use during several centuries. The use of adhesives restarted in the 16th century for inlaying work and further in the 17th century for veneering. In the 18th century, adhesives were used in the production of furniture. In 1690, the production and practical manufacturing of glues started in the Netherlands and moved to England in 1700. The first patent related to glue, titled "a kind of glue called fish glue", was published in Britain in 1754, followed by other patents related to animal glues during the next few hundred years. During this period, animal and vegetable glues were used to bond wood and paper products. By the end of the 19th century and the beginning of the 20th century, many publications appeared to share knowledge of glue use, manufacturing and testing. Advances were noticeable in many issues including glue production on industrial scale, importance of quality control and testing of adhesive products. By around 1920, the use of adhesives in the manufacturing of aircraft and automobile has been started. The adhesives available at that time were of nature origin [2], namely animal glue, fish glue, liquid glue or animal glue in liquid, marine glue made from indiarubber, naphtha and shellac, casein glue, waterproof glue, vegetable glue, flexible glue (modified animal glue) and albumen glues.