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BIBLIOGRAPHY

Finite element analysis and simulation of adhesive bonding, soldering and brazing: A bibliography (1976–1996)

Jaroslav Mackerle

Linköping Institute of Technology, Department of Mechanical Engineering, S-581 83 Linköping, Sweden

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Abstract. This paper gives a bibliographical review of the finite element methods (FEMs) applied to the analysis and simulation of adhesive bonding, soldering and brazing processes. The bibliography at the end of the paper contains references to papers, conference proceedings and theses/dissertations on the subjects that were published in 1976–1996. The following topics are included: *adhesive bonding*—stress analysis of adhesive bonding in general, stress analysis and design of specific bonded joints, fracture mechanics and fatigue analysis, destructive and nondestructive evaluation of bonds, other topics; *soldering*—thermal stresses and deformation analysis of solder joints, fracture mechanics aspects and fatigue analysis of solder joints, solder joint reliability; and *brazing*—finite element analysis and simulation.

1. Introduction

Adhesive bonding is a material joining process in which an adhesive, placed between the faying surfaces, solidifies to produce an adhesive bond. Adhesively bonded joints are an increasing alternative to mechanical joints in engineering applications.

Soldering is a group of welding processes which produce coalescence of materials by heating them to a suitable temperature and by using a filler metal having a liquidus not exceeding 425 °C and below the solidus of the base metals. The filler is distributed between the fitted surfaces by capillary action. Filler metals usually melt between 175–370 °C, and are generally lead and tin alloys. Brazing is distinguished from soldering in that that brazing employs a filler metal melting above 425 °C.

Soldering offers the following advantages over the brazing process: a low-energy input, precise control over the amount of solder, solders with various melting temperature can be selected, the process is economic and has a possibility of process automation, joint reliability is high, joints can be easily repaired. Definitions of processes handled in this paper can be found in many books, e.g. [1].

To design joints in engineering structures, it is necessary to be able to analyse them. This means to determine stresses and strains under the given loading, and to predict the probable points of failure. During the last two decades many of the existing adhesive bonding processes, as well as soldering and brazing have been simulated by numerical methods, especially by finite element methods. The finite element method, these days a commonly used method, is well suited to the estimation of stresses in joints of almost any geometrical shape. A numerical simulation of adhesive bonding, soldering or brazing is not easy, it is a complex process involving the interaction of thermal, mechanical and metallurgical

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phenomena; the mechanics of material interfaces is still a challenge to researchers working in the field of mechanics of solids.

This paper gives a review of published papers dealing with finite element methods applied in the areas of adhesion bonding, soldering and brazing, respectively. For a more efficient information retrieval, the lists of references of papers published between 1976–1996 are divided into the following topics:

- adhesive bonding
- soldering
- brazing.

The paper is organized into two parts. In the first one each topic is reviewed and current trends in the application of finite element techniques are mentioned. The second part contains appendices A and B. Appendix A lists papers published in the open literature for the period 1976–1996 on the subjects presented above. References have been retrieved from the author's database, MAKEBASE [2, 3]. Appendix B explains abbreviations used in the reference listings. Readers interested in the finite element literature in general are referred to [4] or to the author's Internet Finite Element Books Bibliography (http://ohio.ikp.liu.se/fe/index.html).

The range of applications of finite element methods in the areas of adhesive bonding, soldering and brazing is wide and cannot be presented in a single paper; therefore the aim of this review is to give the reader an encyclopaedic view on these subjects. For a literature review on finite element analysis and simulation of welding the reader is referred to the author's earlier review paper [5].

2. Finite elements and adhesive bonding

Adhesive bonding of components made up of metallic, composite and ceramic materials has received an increased interest in structural applications in the standard industries as well as in advanced technology ones, including mechanical, civil and electrical engineering, automotive and aircraft industry, aeronautics, electronics, biomechanics, etc. Adhesive bonding allows a more homogeneous stress distribution in joints than the other joining techniques. It offers weight savings and the stability of the physical and mechanical properties of the adherends. Adhesive bonding does not modify the materials assembled and improves the fatigue durability.

Structural adhesives are generally thermosets such as epoxy, acrylic, polyurethane and phenolic adhesives. They exhibit time-dependent properties. Adhesive joints can fail after prolonged periods of time at loads below quasi-static fracture loads (creep rupture, static fatigue).

There are many types of adhesive joints: lapped, scarf, bevel, peel, butt, butt-strap joints, etc. Linear and nonlinear finite element analyses have been carried out on different types of adhesive joints, and the adhesive effective stresses and strains have been evaluated. To make a correct analysis it is important to account for: differences in the basic mechanical properties, hygrothermal behaviour, the occurrence of high stress gradients in certain regions of the joint. The adhesive layer is thin compared with the thickness of the adherends. A fine mesh in these areas is required so the number of degrees of freedom in a joint is rather high. A full finite element analysis should include, first of all, the effects of bending, adherend shear, end effects and nonlinear behaviour of the adhesive. The supposed best results of the analysis will be achieved by nonlinear finite element analyses where both material and geometrical nonlinearities are considered.

Durability of joints is a major concern when components are designed utilizing classical or newly developed materials. A strong emphasis is placed on quantification of the structural loads and stresses. Here the finite element techniques take their important role. Predictions have also to be made of the likely points of failure. Adhesive bonded joints contain inherent defects from their manufacture. From these defects the crack initiation starts and leads later to failure of the assembly. The fracture strength of adhesive joints depends on a number of factors and their combinations—e.g. adhesive type, cure cycle, adherend type, bondline thickness, etc. The energy release rate at the onset of cracking has been found to uniquely characterize the fracture resistance of adhesive joints.

Failure of an adhesive bonded joint can be interfacial (adhesive) and cohesive. Adhesive failure occurs at the interface between an adhesive and an adherend, and fracture surfaces are comparatively smooth. The cohesive fractured surfaces are complex where the crack propagates within the adhesive layer.

A growing number of applications of bonded joints require improved methods for their testing and control to evaluate their behaviours. Destructive tests are performed to appraise the mechanical performance of adhesive bonded joints. These joints are constrained by a specific type of loading. A great variety of test geometries and specimens are used to obtain adhesive properties and strength of adhesive joints. The measured parameters are the load and strain needed to create failure. The finite element method is used to model and evaluate the experimental work. Several experimental test methods are known for testing adhesive joints under various loading conditions: lap shear joints (single or double), tensile butt joints, floating roller peel, T-peel, wedge tests, etc. The most widely used test is the single lap joint configuration. Another experimental method based on Moire interferometry can give detailed *in situ* information on the strain field in the adhesive joint. Development of laser measurement techniques provides an accurate point-by-point measurement of displacements in the adherend and adhesive bonded joint.

Over the last decade considerable effort has been spent in order to develop adhesively bonded repairs (i.e. fibre composite patches, bonded steel sleeves) to increase the fatigue life of structures/components. A significant reduction in the stress intensity factors can be achieved. Also interleaving techniques have been used. Interleaving means adding a tough adhesive interlayer between plies by which the delamination resistance of composite laminates may be enhanced.

Presented references on adhesive bonding joints listed in appendix A are divided into the following topics:

- stress analysis of adhesive bonding in general
- stress analysis and design of specific bonded joints
- fracture mechanics and fatigue analysis
- destructive and nondestructive evaluation of bonds
- other topics.

Stress analysis of adhesive bonding in general

Topics included: fundamentals and review of adhesion bonding; relationship between adhesion and mechanical properties; the mechanics of bonded joints; 2D and 3D linear and nonlinear finite element analyses; material and geometrical nonlinear analysis; viscoelastic and viscoplastic analysis; creep analysis; dynamic response of bonded joints; bonded joints under bending; influence of moisture diffusion and thermal loads; adhesive contact problems with debonding; stress distribution in an adhesive layer; design of bonded joints.

Stress analysis and design of specific bonded joints

Listed references in appendix A are each concerned with a specific type of adhesive bonded joint. The topics of the studies are: linear and nonlinear stress analysis; studies of mechanical behaviours; time-dependent mechanical behaviours; edge effect analysis; influence of mechanical and geometry variations on the behaviour of bonded joints; thermal performance in joints; shear stresses; interfacial stresses and deformations; extensional damping in joints; joints under impact loads; design of adhesively bonded joints.

Types of analysed joints: lap joints (single, double); tubular lap joints; lap shear joints; stepped lap joints; corner joints; containment corner joints; strap joints; butt joints; scarf joints; stepped scarf joints; T-shaped joints; L-shaped joints; double–doubler joints; adhesive shrink-fits.

Types of material: metal–metal; composite–composite; composite–metal; plastics–metal; aluminum structures; elastomers.

Fracture mechanics and fatigue analysis

The studies of strength and fracture toughness as well as fatigue life estimation of adhesive bonded joints are the subjects of this section. Specific topics included: linear and nonlinear 2D and 3D fracture mechanics; failure mode prediction; progressive failure; critical failure parameters; calculation of adhesive joint fracture parameters; crack initiation and propagation studies; moisture-assisted crack growth; crack–tip stress field; toughness of ductile adhesive joints; mode I, mode II and mixed mode fracture behaviour of adhesive joints; fracture energy release rates; effects of adhesive and adherend thickness; effects of tapering on the strength; effects of debonding; tensile strength; bending strength; torsional strength; impact strength; evaluation of the strength of a specific adhesive joint; thermal fatigue strength; local effects on the strength; fracture load prediction; J-integral computation; stress intensity factors for various types of bonding joints; fatigue crack propagation; fatigue life estimation; cohesive fatigue cracks; damage mechanics and models; parametric studies; strength design.

Destructive and nondestructive evaluation of bonds

Mechanical testing and computer modelling of adhesive bonded joints is the subject of this section. Pointers are given to the literature references dealing with evaluation and comparison between theoretical, numerical and experimental methods.

Some topics included: bond strength measurement; *in situ* testing of adhesive joints; effect of test speed on the strength of adhesive joints; impact strength measurement; measurement of peel stresses in adhesive joints; indentation debonding tests; strain measurements; fatigue life estimation; evaluation of test geometries; fibre–matrix adhesion in composites; testing of mechanical properties of adhesives.

Some experimental methods used: mechanical testing machines; cryogenic and thermal cycling; RF heating of adhesive joints; strain gage measurements; piezoelectric sensors; photoelasticity; laser-photoelasticity; Moire interferometry; ultrasonic techniques; neutron diffraction measurements.

Other topics

Topics included: finite element library—special elements, mixed finite elements, bondline elements, adhesive interface elements, adhesive plate elements, shear–spring elements, nonlinear joint elements, bond and singularity elements; adhesively bonded repairs; bonded repairs of timber structures; bonded repairs of composite structures; repair of fastener holes; adhesion techniques in orthopaedic and dental mechanics; software presentations.

3. Finite element analysis and simulation of soldering

Soldering involves metallurgy, physics and chemistry in the interaction of the joint elements, the constitution of fluxes, the thermal chemistry involved in heating both fluxes and metals to the molten state, and the underlying thermodynamics and fluid dynamics in promoting formation of a soldered joint [1]. The different thermal and mechanical properties of the soldered materials develop a complex residual stress state especially in the joining area, where cracks can be initiated. The design of a product involving soldered joints must be evaluated to ensure that the joints are capable of carrying the applied loads for the expected lifetime of the product.

There are many types of soldered joints: lapped, T-joints, corner, flanged, butt, etc. Soldered joints are widely used in electrical engineering and electronics. Joint design has to provide electrical continuity and permanent strength between electronic components and leads. As can be seen in appendix A, most of the listed papers deal with the soldering process in connection with electronic packaging.

References of papers on finite element analysis and simulation of the soldering processes for the convenience of the reader are divided into the three following subcategories:

- thermal stresses and deformation analysis of solder joints
- fracture mechanics aspects and fatigue analysis of solder joints
- solder joint reliability.

Thermal stresses and deformation analysis of solder joints

Some topics included: thermal stress analysis of solder joints; solder joints in a cyclic thermal environment; creep analysis; linear elastic and inelastic stress and deformation process modelling; plasticity models of solder joints; time and temperature-dependent inelastic deformation analysis; thermoviscoplastic deformation modelling; thermal stress ratchetting deformation; reflow soldering; laser soldering; wave soldering; solder-drop-printing process; physical properties of solders; metal–ceramic solder joints; evaluation of critical design parameters for solder joints; soldering device modelling; predicting shapes of solder joints; random vibration response of solder joints; strain sensitivity studies.

Fracture mechanics aspects and fatigue analysis

Some topics included: fatigue life prediction; thermal fatigue analysis; effect of lead parameters on fatigue life of joints; creep-fatigue analysis; thermal fatigue damage; solder joint cracking; strength evaluation of solder joints; crack growth/propagation.

Solder joint reliability

Some topics included: solder joint reliability analysis; reliability optimization; effects of voids on solder joint reliability; effects of solder thickness on solder joint reliability.

4. Finite element analysis and simulation of brazing

Bonding between ceramics and metals by brazing has become an important technology. Braze-joined components yield high strengths and allow for applications at high temperatures. Ceramics as known have very good mechanical properties at high temperatures and high resistance to wear and corrosion, but they are brittle and make difficulty in machining. For the strength of brazed joints there are several important parameters such as temperature, time, pressure and atmosphere. The thermal mismatch of the components leads to the development of residual stresses during cooling from brazing to room temperature.

Industrial applications of brazing range from structural components in heat engines to metal cutting tools, coatings in electronic devices, etc.

Experimental methods (i.e. neutron diffraction) are used together with finite element methods (temperature-dependent elastic–plastic analysis) first of all to measure/calculate these residual stresses. There are also studies of the effect of processing parameters on the bonding strength.

Acknowledgments

The bibliography presented in appendix A is by no means complete but it gives a comprehensive representation of different finite element applications on the subjects. The author wishes to apologize for the unintentional exclusion of missing references and would appreciate receiving comments and pointers to other relevant literature for a future update.

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Appendix A. A bibliography (1976–1996)

This bibliography provides a list of literature references on finite element applications in adhesive bonding, soldering and brazing. Presented listings contain papers published in scientific journals, conference proceedings, and theses/dissertations retrospectively to 1976. References have been retrieved from the author's database, MAKEBASE. The COMPENDEX database, Metals Abstracts and Applied Mechanics Review have also been checked. Presented references are grouped into the same sections as listed in the first part of this paper.

The emphasis of this bibliography is to list, first of all, papers published in various international journals. There have been numerous national and international conferences and symposia held worldwide but the conference proceedings are a source of neverending bibliographical confusion. No review on conference proceedings can ever be comprehensive but some conferences have been examined and a selection of references thereto is also presented in this paper. The main criticism of conferences is that the material presented is often a repetition of what is published elsewhere in the literature, and the complaint of an uneven quality of papers is also often heard. Surveys have shown low usage of published conference proceedings in practice. Also, many of the important conference papers are published afterwards in an edited version in international journals.

References are not arranged chronologically but are sorted in each category alphabetically according to the first author's name. If a specific paper is relevant for several subject categories, the same reference can be listed under all relevant section headings.

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Appendix B. Abbreviations used in the bibliography sections in appendix A

In this appendix some abbreviations used in the bibliography sections are explained to assist both readers and reference librarians.

AFFDL	Air Force Flight Dynamics Laboratory, USA
AFWAL	Air Force Wright Aeronautical Laboratory, USA
ANTEC	Annual Technical Conference of the Society of Plastics Engineers
ASCE	American Society of Civil Engineers, 345 E 47th St, New York, NY 10017, USA
ASME	American Society of Mechanical Engineers, 345 E 47th St, New York, NY 10017, USA
ASTM	American Society for Testing and Materials, 1916 Race St, Philadelphia, PA 19103, USA
BGA	Ball grid array
CAD	Computer-aided design
CFRP	Carbon fiber reinforced plastics
CGA	Column grid array
CMP	Computational Mechanics Publications, Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK
COD	Crack-opening displacement
CTE	Coefficient of thermal expansion
DCB	Double cantilever beam
EMAS	Engineering Materials Advisory Services Ltd., 339 Halesowen Rd, Cradley Health, Warley, West Midlands, B64 6PH, UK
FEM	Finite element method
FRP	Fiber reinforced plastics
GFRP	Glass fiber reinforced plastics
IC	Integrated circuit
IEEE	The Institute of Electrical and Electronics Engineers, Inc., 345 East 47th St, New York, NY 10017, USA
IEPS	International Electronics Packaging Society, Wheaton, IL, USA
I/O	Input/Output
LCC	Leadless chip carrier
LSI	Large-scale integrated (circuit)
NASA	National Aeronautics and Space Administration
NEPCON	National Electronic Packaging and Production Conference
PCB	Printed circuit board

PGA	Pin grid array
PQFP	Plastic quad flat pack
SAE	Society of Automotive Engineers, 400 Commonwealth Dr, Warrendale, PA 15096, USA
SBC	Solder ball connection
SIF	Stress intensity factor
SM	Surface mount
SMC	Sheet molding compound
SMD	Surface mount device
SMT	Surface mount technology
SOUTHCON	South Conference Record, USA
SPIE	The International Society for Optical Engineering, PO Box 10, Bellingham, WA 98227-0010, USA
TCE	Trichlorethylene
VLSI	Very-large-scale integrated (circuit)
VPI & State University	Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
WPAFB	Wright–Patterson Air Force Base, Dayton, OH 45433, USA
YAG	Yttrium–aluminium–garnet (laser)