AD-786 520

STRESS ANALYSIS OF STRUCTURAL JOINTS AND INTERFACES

A SELECTIVE ANNOTATED BIBLIOGRAPHY

ARMY MATERIALS AND MECHANICS RESEARCH CENTER

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AMMRC MS 74-10
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER: AD-786 520
4. TITLE (and Subtitle): STRESS ANALYSIS OF STRUCTURAL JOINTS AND INTERFACES - A SELECTIVE ANNOTATED BIBLIOGRAPHY
5. TYPE OF REPORT & PERIOD COVERED:
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): Margaret M. Murphy and Edward M. Lenoe
8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, AMXMR-PL
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
11. CONTROLLING OFFICE NAME AND ADDRESS: U. S. Army Materiel Command, Alexandria, Virginia 22333
12. REPORT DATE: September 1974
13. NUMBER OF PAGES: 65
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Bibliographies	Bonded joints	Structural joints
Stress analysis	Welded joints	Laminates
Joints	Fasteners	Interfaces

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An annotated bibliography is presented of the work reported in the literature (1968-1974) on the stress analysis of structural joints and interfaces. In addition to work on structural joints, bonded joints, welded joints, and fasteners, work on the stress analysis of flawed and unflawed layered media of dissimilar isotropic and anisotropic materials is also included. (Authors)

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PREFACE

PURPOSE - This bibliography was prepared in support of the 1974 Army Symposium on Solid Mechanics, "The Role of Mechanics in Design - Structural Joints." The literature of joining technology is widely distributed in many books, journals, reports, etc. While there are numerous general bibliographies relating to joints, the authors are not aware of any recent endeavors. Thus this bibliography aims to summarize the current literature in a compact form with special emphasis on solid mechanics.

SCOPE - Review of the literature revealed a tremendous number of publications relating to mechanical behavior, design and analysis, structural testing, manufacturing and process controls, materials development, and nondestructive evaluation and quality control. Restricting concern to design and analysis, mechanical behavior, and structural testing reduced the volume of literature to 850 references. Nonetheless the required effort for a detailed and well annotated bibliography exceeded available manpower and could not have been accomplished within the desired time frame.

In an effort to reduce the volume of material it was decided to select pertinent references related to the "solid mechanics" theme by emphasizing stress analysis of joints. The bibliography is not comprehensive in the respect that many articles which included and emphasized experimental results were not surveyed. By this somewhat arbitrary restriction, the body of literature was reduced to manageable proportions. Papers dealing with elastostatic, elastodynamic, and thermal stress analysis of flawed and unflawed layered media were included with the idea that such analysis would provide further insight into response of interfaces and joints. These articles were limited to treatment of several layers of dissimilar isotropic and anisotropic materials. So-called micromechanics solutions, related to idealized fiber reinforced composites, were however excluded from this category.

ARRANGEMENT - The bibliography is arranged in broad subject areas. References that could have been included in more than one subject area are entered only in the main subject area. Entries are in alphabetical order by author.

LIMITATIONS - Because of the vast body of literature available in many languages only material published between 1968 and 1974 in the English language has been included. In instances where the results of a specific research study have been published in more than one format, an attempt has been made to annotate the most comprehensive publication and reference the others.

ACKNOWLEDGMENTS - The assistance of Mrs. M. Gould and the typing of the manuscript provided by Mrs. E. Dugan, Miss H. Johnson, and Miss C. Josey are gratefully acknowledged. The technical assistance of Mr. W. Matthews and the persevering efforts of Miss R. Markus to provide many of the references and her diligent proofreading of the manuscript are also greatly appreciated.

The basic sources of information were standard bibliographic reference tools including:

APPLIED MECHANICS REVIEWS
APPLIED SCIENCE AND TECHNOLOGY INDEX
CHEMICAL ABSTRACTS
DEFENSE DOCUMENTATION CENTER. TECHNICAL ABSTRACT BULLETIN (TAB)
DISSERTATION ABSTRACTS INTERNATIONAL
ENGINEERING INDEX
INTERNATIONAL AEROSPACE ABSTRACTS
METALS ABSTRACTS
NASA SCIENTIFIC AND TECHNICAL AEROSPACE REPORTS (STAR)
U.S. ATOMIC ENERGY COMMISSION. NUCLEAR SCIENCE ABSTRACTS
U.S. GOVERNMENT REPORTS ANNOUNCEMENTS (GRA)

Further references were found in texts, especially those publications covering proceedings in the field.

CONTENTS

4. Masubuchi, K., Simmons, F. B., and Munroe, R. E., "Analysis of Thermal Stresses and Metal Movement During Welding." Battelle Memorial Institute, Columbus, Ohio. U. S. Army Missile Command Contract Report No. RSIC-820, July 1968. (AD 676 830)

A literature survey on thermal stresses during welding and buckling after welding is described. From the analyses, a computer program was developed to calculate thermal stresses and resulting residual stresses due to a moving heat source and is included in the Appendix. Studies on three-dimensional movement during welding of flat plate specimens are summarized and interpreted. Results indicate that local metal movement during welding is caused by bending moment and general metal movement is caused by buckling.

5. Niranjan, V., "Bonded Joints: A Photoelastic Study." Toronto University, Institute for Aerospace Studies, Ontario. Research Report No. UTIAS-TN-138, July 1970.

The existing literature on bonded metal-to-metal joints on the stress distributions in the adhesive layer is reviewed. The stress distribution is of significance for bonded joints designed to fail in the adhesive, either under static or fatigue loads. The stress distributions in the metal due to stress concentrations around the bonded joint are studied. These high stresses can be reduced in both the adhesive and the metal by chamfering the metal edges.

6. Pollard, B. and Cover, R. I., "Fatigue of Steel Weldments," Weld. J., 51 (1972), 544s-554s.

A critical review of the literature published from 1938-1971 on the subject of fatigue of steel weldments was made to determine the major variables which influence the fatigue behavior. The study showed that: (1) weld geometry is the most important factor in determining the fatigue properties of a weld, (2) welding processes influence the fatigue strength by producing welds of varying surface roughness and weld metal soundness, (3) residual stress only affects fatigue strength for alternating loads, (4) post weld treatments which produce compressive residual stresses may increase fatigue strength, (5) microstructure of the weld metal and the heat affected zone have a minor effect on fatigue strength. An extensive bibliography is included.

7. Sanders, W. W., Jr., "Fatigue Behavior of Aluminum Alloy Weldments," Weld. Res. Counc. Bull., No. 171 (1972), 1-30.

A summary of an extensive literature search of both published and unpublished papers and reports on the fatigue behavior of Al alloy weldments is presented. The fatigue behavior of butt-welded and fillet-welded joints is discussed and a "Summary of Fatigue Strength Data" for both configurations are included in tabular form in the Appendix. The study shows that the most critical factor affecting fatigue strength is the weld reinforcement, with the notch acuity at the toe of reinforcement being the single most important consideration. It is also shown that fatigue strength is reduced by loss of cross section due to internal defects and that in a good quality weld, the type of butt-weld joint does not seem to affect strength. A detailed bibliography is included.

8. Schlothauer, J., "Bibliographic Data of German and Foreign Literature in the Field of Adhesive-Bonded Metal Joints (1966-1968)." Deutsche Forschungs und Versuchsanstait fur Luftund Raumfahrt, Institut fur Flugzeugbau, Braunschweig, West Germany. Report No. DLR-MITT-69-10, July 1969. (N70-11083)

A bibliography containing available German and English references on the subject of adhesive-bonded metal joints during the period 1966-1968.

9. Whitehurst, C. A. and Durkin, W. T., "A Study of the Thermal Conductance of Bolted Joints." Final Report. Louisiana State University, Division of Engineering Research, Baton Rouge. National Aeronautics and Space Administration Contract Report No. NASA-CR-102639, 1970. (N70-25816)

A review, evaluation, comparison, and utilization of current literature regarding the phenomena of heat transfer across the interface of discontinuous materials indicated the need for a simplified experimental design oriented approach for predicting the thermal resistance of a bolted lap joint. Experimental work is compared with the current literature and a qualitative analysis is made of the present theories to demonstrate the inherent difficulties in combining the variables related to a theoretically approximate solvable set of equations.

BONDED JOINTS

10. Adams, R. D. and Peppiatt, N. A., "Effect of Poisson's Ratio Strains in Adherends on Stresses of an Idealized Lap Joint," J. Strain Anal., 8 (1973), 134-39.

Shear stresses in the adhesive layer and direct stresses in the adherends acting at right angles to the direction of the applied load, which are caused by Poisson's ratio strains in the adherends, were investigated. The normal stresses along and across the adherends are described by two simultaneous second-order partial-differential equations which were solved by both an approximate analytical method and a finite difference technique and which agreed closely. The adhesive shear stresses were obtained by differentiating these solutions. The transverse shear which occurs at the corners of the lap making them the most highly stressed parts of the adhesive, had a maximum value for metals ∿ 1/3 of the maximum longitudinal shear stress. Bonding adherends of dissimilar stiffness produced greater stress concentration than similar adherends.

11. Barker, R. M. and Hatt, F., "Analysis of Bonded Joints in Vehicular Structures," AIAA J., 11 (1973), 1650-54.

The behavior of an adhesive joint bonding an advanced composite to a metallic substrate was evaluated by a linear elastic finite-element analysis. The adhesive layer is treated as a separate elastic medium of finite thickness to remove the stress singularity that exists when dissimilar materials are joined. Results for both a single lap joint and a smoothly tapered joint for two thickness of the adhesive layer are presented. In a lap joint the load transfer mechanism is basically shear and high stresses occur in the adhesive near the ends and the stresses increase as the thickness of the adhesive layer decreases. In a smoothly tapered joint, the load mechanism is a combination of shear and tension, peak shear stresses in the adhesive are reduced and occur at only one end of the joint, thus it is a more efficient joint. Recommendations for reducing stress concentrations and for improved joint design are given.

See also: Barker, R. M. and Hatt, F., "Analysis of Bonded Joints in Vehicular Structures," AIAA Paper 73-371, 1973.

12. Brock, L. M. and Achenbach, J. D., "Extension of an Interface Flaw under the Influence of Transient Waves," Int. J. Solids Structures, 9 (1973), 53-68.

The initiation of debonding which is caused by stress concentrations that are generated when a system of transient horizontally polarized shear waves strikes the tip of an interface flaw, at an interface of two elastic solids of different elastic constants and mass densities was examined. It is shown that for a system of step-stress waves the zone of the interface yielding initially extends linearly with time. The speed of the leading edge of the zone of interface yielding is computed for various values of the parameters defining the materials and the system of waves. The time of rupture and the interface stress ahead of the yield zone are presented by analytical expressions.

13. Chang, D. J., "Stress Distribution in an Adhesive Joint." Unpublished Ph.D. dissertation, University of California, Los Angeles, 1972.

Stress distribution in lap joints under cleavage and tension-shear loading was investigated on the basis of classical two dimensional theory of elasticity. The thickness of the adhesive layer is assumed to be zero. The cleavage problem is reduced to a Fredholm integral equation of the second kind and the tension-shear problem to a pair of Fredholm integral equations of the second kind. Numerical results are presented for the distribution of bond forces and for stress intensity factors at the edge of the bond covering practical material combinations and geometrical patterns.

14. Cherry, B. W. and Harrison, N. L., "The Optimum Profile for a Lap Joint," J. Adhes., 2 (1970), 125-28.

Study was undertaken to attempt to show that with the correct choice of the profiles of the adherends, lap joints with uniform shear stress throughout the joint can be manufactured. There are no shear stress concentrations in the adhesive and maximum load carrying capacity of the adhesive is developed. The calculation method is presented and practical applications are briefly discussed. The computations are based on elastic modulus and strain and are accordingly subject to limitations imposed by small-strain linear elasticity theory.

15. DeLollis, N. J., "Theory of Adhesion-Mechanism of Bond Failure and Mechanism of Bond Improvement. Part 1 - Evolution and Present Status of the Theories of Adhesion," Adhes. Age, 11, No. 12 (1968), 21-25.

A mechanism of bond failure intended to correct practical and theoretical knowledge of bond strengths and to supply reasons for failure and a practical guide for developing optimum bond strength are proposed for structural-metal-adhesive designs. Results indicate that surface modifications improve bonds and weak boundary layers need not be significant factors in adhesion. Polymers studied include polyethylene, silicone and polyurethane. The paper also briefly comments on the development and current status of theories of adhesion.

16. DeVries, K. L., Williams, M. L., and Chang, M. D., "Adhesive Fracture of a Lap Shear Joint," Exper. Mech., 14 (1974), 89-97.

A single-lap shear joint is analyzed by adhesive fracture which is compared on the basis of both maximum stress criteria and energy. Experimental data indicate the energy criteria yield more accurate results. In the analysis stresses were introduced into an energy balance to determine the initiation of adhesive fracture. From knowledge of the applied loads at the ends of the test pieces, resulting internal loads upon the ends of the center part of the specimen near the tip were determined and from this the stresses within the central part of the lap area were calculated. The problem was formulated as one of plane strain consisting of two rectangular sheets of equal thickness, unit width, tab-end length, and central length.

17. DeVries, K. L., Williams, M. L., and Chang, M. D., "A Fracture Mechanics Analysis of Adhesive Failure in a Single Lap Shear Joint." SESA Paper 1990A, 1972.

The Goland-Reissner analysis was used to determine the stress distribution in a single lap shear joint and the initiation of adhesive fracture was determined from an energy balance equation. Taking the deformation of joint sheets into account, the stress in the joint due to applied loads was determined by the finite deflection theory of critically bent plates. The problem was formulated as one in plane strain consisting of two rectangular sheets of equal thickness and unit width. Contributions to the energy change with crack length were calculated. The analysis is compared with a maximum stress criteria for a lap joint.

18. Dickson, J. N., Hsu, T., and McKenney, J. M., "Development of an Understanding of the Fatigue Phenomena of Bonded and Bolted Joints in Advanced Filamentary Composite Materials. Volume 1. Analysis Methods." Final Report August 1970-April 1972. Lockheed-Georgia Company, Lockheed Aircraft Corporation, Marietta. Air Force Flight Dynamics Laboratory Contract Report No. AFFDL-TR-72-64-Vol. I, June 1972. (AD 750 132)

This report of the study is divided into three chapters: (1) Closed Form Analysis Method, (2) Finite Element Analysis, (3) Photoelastic Stress Analysis. Emphasis was placed on the development of closed form analysis procedures for bonded joints in laminated composites. A comprehensive linear analysis method and associated computer program (BONJO 1) was developed and the numerical results obtained were compared with finite element analyses, strain gage data, and photoelastic results. The program was extended to include joints with ideally elastic-plastic adhesive stress-strain behavior. Finite element analyses used to evaluate the step lap bonded and bolted joints are presented and discussed. Photoelastic stress analysis procedures are also described and discussed.

19. Erdogan, F. and Ratwani, M., "Stress Distribution in Bonded Joints," J. Composite Mater., 5 (1971), 378-93.

The problem of stress distribution in plates, one orthotropic and the other isotropic, bonded through stepped joints was analyzed. The adhesive layer is regarded as a shear spring between the plates and load is applied in the plane of the plates perpendicular to the joint line. Numerical examples of resulting closed-form solution are given for: (1) a single-lap Al-epoxy-steel joint, (2) a multiply stepped Al-B epoxy joint, (3) a smoothly tapered Al-B epoxy joint. Bonding shear stress was greatest at the end of a step. Results were relatively insensitive to boundary conditions when perpendicular to the joint line.

20. Hamel, D. R., Korbacher, G. K., and Smith, D. M., "Fatigue Strength Optimization of Bonded Joints," Trans. ASME, Ser. D: J. Basic Eng., 93 (1971), 649-56.

Bonded double strap joint specimens both with the conventional square (90°) strap edge and with a 10° bevel on the strap edge were fatigue tested. The test data were plotted as S-N curves and compared with those of plain metal specimens. Results indicated that the stress concentrations on the square strap edges were essentially lower than predicted theoretically and the gain in fatigue strength due to bevelling of the edges is limited.

21. Harrison, N. L. and Harrison, W. J., "The Stresses in an Adhesive Layer," J. Adhes., 3 (1972), 195-212.

The finite element method is used for calculating the stresses near the ends of a parallel-sided adhesive layer having aspect ratios of 10 or greater and a Poisson's ratio of 0.49 or less. The material is treated as linearly elastic and isotropic. The stress fields at distances > 5 thicknesses from the free surface are uniform when the layer is subject to uniform conditions of displacement at the adhering surfaces. The stresses in the uniform stress region determine the stress field throughout the layer. When the stress field is expressed by functions of reduced coordinates of position obtained by normalizing the Cartesian coordinates by the layer thickness, these functions are independent of the aspect ratio or the thickness for uniform boundary displacements. Shrinkage stresses and stresses in joints under both tension perpendicular to the plane of the adhesive layer and shear may be calculated by this method. Features of these stress fields are described and presented in graphical contour plot form.

22. Hart-Smith, L. J., "Adhesive-Bonded Double-Lap Joints." Douglas Aircraft Company, Inc., McDonnell-Douglas Corporation, Long Beach, California. National Aeronautics and Space Administration Contract Report No. NASA-CR-112235, January 1973. (N74-13195)

Analytical solutions that extend the elastic Volkersen solution and account for adhesive plasticity, for the static load carrying capacity of double-lap adhesive-bonded joints were derived. Results indicated that the influence of the adhesive on the maximum potential bond strength is dependent on the strain energy in shear per unit area of bond. Failures induced by peel stresses at the joint ends were examined and this mode of failure was found to be particularly important for composite adherends. The solutions may be used for design purposes.

23. Hart-Smith, L. J., "Adhesive-Bonded Single-Lap Joints." Douglas Aircraft Company, Inc., McDonnell-Douglas Corporation, Long Beach, California. National Aeronautics and Space Administration Contract Report No. NASA-CR-112236, January 1973. (N74-13196)

Analytical solutions for the static loading carrying capacity of single-lap bonded joints were derived. For procedures and results see the previous entry in this bibliography.

24. Hart-Smith, L. J., "Adhesive Bonded Scarf and Stepped-Lap Joints." Douglas Aircraft Company, Inc., McDonnell-Douglas Corporation, Long Beach, California. National Aeronautics and Space Administration Contract Report No. NASA-CR-112237, January 1973. (N74-13197)

Continuum mechanics solutions for the static load-carrying capacity of scarf and stepped-lap adhesive-bonded joints were derived. Adhesive plasticity and adherend stiffness imbalance and thermal mismatch were accounted for. A simple algebraic formula which can be used as a close lower bound for scarf joint solutions is presented. The critical adherend and adhesive stresses for each step in stepped-lap joints were computed using the programs developed. Comparison of the scarf joint solutions and the double-lap joint solutions showed marked differences in behavior. The potential bond shear strength of long overlaps continues to increase with infinitely long overlaps on the scarf joints. The stepped-lap solutions exhibit some characteristics of both scarf and double-lap joints. The program may be used to optimize the joint proportions.

25. Hart-Smith, L. J., "Non-Classical Adhesive-Bonded Joints in Practical Aerospace Construction." Douglas Aircraft Company, Inc., McDonnell-Douglas Corporation, Long Beach, California. National Aeronautics and Space Administration Contract Report No. NASA-CR-112238, January 1973. (N74-12555)

Solutions were derived for adhesive joints with non-classical geometries with particular attention given to bonded doublers and to selective reinforcement by unidirectional composites. Non-dimensional charts are presented for the efficiency limit imposed on the skin as a result of the eccentricity in the load path through the doubler. Relatively larger doublers were used to minimize the effective eccentricity. Transfer stresses associated with selective reinforcement of metal structures by advanced composites are analyzed. The adhesive joint analysis for shear flow in a multi-cell torque box, adhesive plasticity, adherend stiffness and thermal imbalances are also included. A simple analysis/design technique of solution in terms of upper and lower bounds on an all-plastic adhesive analysis is introduced.

26. Hart-Smith, L. J., "Analysis and Design of Advanced Composite Bonded Joints." Final Report. Douglas Aircraft Company, Inc., McDonnell-Douglas Corporation, Long Beach, California. National Aeronautics and Space Administration Contract Report No. NASA-CR-2218, April 1974. (N74-20564)

A summary of the work reported in the four previous entries in this bibliography, on the analysis of various types of adhesive-bonded joints is presented. Emphasis is placed on the non-dimensionalized solutions in terms of the governing parameters to illustrate the overall joint behavioral phenomena in terms of the three characteristic failure modes - laminated induced, adhesive shear, and adhesive peel. Three detailed Appendixes are included, "Practical Design Configuration," "Scaling Effects in Bonded Joints," and "Surface Preparation for Adhesive Bonding."

27. Jemian, W. A. and Wilcox, R. C., "Study of the Onset of Permanent Deformation in Structurally Bonded Joints." Final Report 19 November 1971-19 April 1973. Auburn University, Department of Mechanical Engineering, Auburn, Alabama. U.S. Army Missile Command Contract Report, 1973. (AD 768 689)

The elastic sample compliance vs. crack length curve for lap-shear adhesive bonded samples was found to have a positive curvature and an increasing slope as the crack length increased. The effects of various parameters on this curve were determined. Results of finite element computation showed that sample compliance is a linear function of adhesive thickness and sample stiffness depends directly upon overlap length, adherend thickness, adhesive and adherend moduli, and adhesive width. A standard fracture toughness testing procedure for lap-shear samples was outlined.

See also: Jemian, W. A. and Ventrice, M. B., "The Fracture Toughness of Adhesive-Bonded Joints," J. Adhes., 1 (1969), 190-207.

28. Knauss, W. G., "Fracture Mechanics and the Time Dependent Strength of Adhesive Joints," J. Compos. Mater., 5 (1971), 176-92.

Fracture mechanics including the various modes by which fracture can progress in joints formed with polymeric adhesives was investigated. In the analysis the geometric and loading factors were separated from the strength characteristics. Using the creep or relaxation behavior of the polymer and the fracture energy of the bond interface or of the adhesive the time-dependence of the process in the absence of a corrosive atmosphere is discussed. Analytical reasons and a criterion for the possible rate dependence of the failure path location along different interfaces of adherends and the adhesive are given.

See also: Knauss, W. G., "Fracture Mechanics and the Time Dependent Strength of Adhesive Joints." California Institute of Technology, Pasadena, California. National Aeronautics and Space Administration Contract Report No. NASA-CR-111761, September 1970. (N71-14080)

29. Lubkin, J. L. and Lewis, L. C., "Adhesive Shear Flow for an Axially-Loaded, Finite Stringer Bonded to an Infinite Sheet," Quart. J. Mech. Appl. Math. 23 (1970), 521-33.

A mixed Volterra-Fredholm integral equation governing the adhesive shear flow is solved for a range of two dimensionless parameters. These parameters describe the relative stiffness of the adhesive and sheet as well as that of the adhesive and stringer. Results indicated uniform shear flow or little stress concentration when the adhesive is very flexible but very large stress concentrations are possible at one or both of the stringer ends if the adhesive layer is relatively thick.

30. Pahoja, M. H., "Elastic Stress Analysis of an Adhesive Lap Joint Subjected to Tension, Shear Force and Bending Moments." Unpublished Ph.D. dissertation. University of Illinois, Department of Theoretical and Applied Mechanics, Urbana, 1972.

Stress analysis, treated as plane strain of a lap joint subjected to general loading - tension, shear force, and bending moments - is presented. Variation in the material properties and thickness of the two adherends is considered. The displacement field in the adhesive layer is expressed in series form and the compatibility condition at the interface is used to express the displacement field in the adherends. The potential energy of the joint is calculated and minimized to obtain linear ordinary differential equations and boundary conditions. Two specimens of a lap joint with 0.25" layer of a photoelastic plastic simulating adhesive were tested photoelastically with good agreement between theoretical and experimental results.
See also: Pahoja, M. H., "Stress Analysis of an Adhesive Lap Joint Subjected to Tension, Shear Force and Bending Moments." University of Illinois, Department of Theoretical and Applied Mechanics, Urbana. Naval Air Systems Command Contract Report No. UILU-ENG-72-6009, August 1972. (AD 753 469)

31. Peterson, J., "Toward Rational Design of Adhesive Joints," SAMPE Quart. 2, No. 3 (1971), 16-19.

An analysis to evaluate ordinary lapped adhesive joints without an extensive testing program is presented. The complex behavior of adhesive joints can be reduced to elementary terms by consideration of member stresses and strains. The analysis and comparison techniques for a joint testing program can be used as a design tool to compare proposed joint configurations. The ideas are based on elementary strength of materials concepts.

52. Renton, W. J. and Vinson, J. R., "The Analysis and Design of Composite Material Bonded Joints under Static and Fatigue Loading." University of Delaware, Department of Mechanical and Aerospace Engineering, Newark. Air Force Office of Scientific Research Contract Report No. AFOSR-TR-73-1627, August 1973. (AD 766 932)

Extensive research was conducted to provide analytical methods and design methodology for bonded joints in structures of laminated composite materials under static and fatigue loads. An analytical closed solution including transverse shear deformations and normal strain, adherend anisotropy, and adhesive properties for adhesive joints and adherends was developed. A digital computer program provides rapid design and analysis and an inclusive parameter study provides trends and methodology. Shear and extensional stiffness and ultimate stresses of the adhesive in the joint configurations are provided by the static tests developed. Fatigue tests were conducted for various geometries, loadings, and adherend materials. An extensive bibliography is included.

53. Rice, J. S., "Crack Stability of an Adhesive Layer," <u>J. Franklin Inst.</u>, <u>294</u> (1972), 1-11.

The stability of crack which is present in an adhesive layer that bonds an elastic plate to a rigid layer was investigated. The Wieghardt foundation was assumed as the model for the adhesive layer. The crack was loaded by internal pressure. Results are given for a relatively rigid and a relatively flexible plate. For brittle fracture crack theory in an elastic continuum there is an equivalence between the energy and stress intensity criteria for fracture. This equivalence is not evident in the models proposed for the adhesive layer. For instance the energy criteria does not contain the modulus of the adhesive layer unless higher order terms are included in the approximate model. Thus further analytical effort is required to arrive at an adequate model.

54. Schijve, J., "Some Elementary Calculations on Secondary Bending in Simple Lap Joints." National Aerospace Laboratory, Amsterdam, Netherlands. Research Report No. NLR-TR-72036-U, March 1972. (N72-31911)

Formulas for calculating the permanent bending deformations of lap joints resulting from tension loads are presented. Calculations indicate that the effect of clamping conditions on secondary bending will generally be small but a small amount of permanent bending deformation at the overlap will have a significant effect on the secondary bending.

35. Terekhova, L. P. and Skoryi, I. A., "Stresses in Bonded Joints of Thin Cylindrical Shells," Strength Mater., 4 (1973), 1271-74. Translation of Probl. Prochn., No. 10 (1972), 108-10.

Stresses in both the adhesive layer and the jointed shells were determined as a function of external loads and the elasticity parameters of the adhesive and the shells. Calculations showed that the normal stresses in the shells remain constant regardless of the modulus of elasticity for the adhesive and the length of the joints and also that variation in the length of the joint has no effect on the extent of the edge zones but the maximum tangential stress in the adhesive layer changes slightly as the joint length changes. Reducing the thickness of the shell by a factor of two increases the stress by 50%.

36. Trantina, G. G., "Fracture Mechanics Approach to Adhesive Joints," J. Composite Mater., 6 (1972), 192-207.

A finite element stress analysis for a slant edge-cracked plate furnished the opening and shear mode stress intensity factors over a wide range of slant angles and crack lengths in a study of crack extension in an adhesive system under combined mode loading. By varying the angle between the adhesive layer and the load line in a single-edge-notched specimen, combined mode crack extension was observed and combined mode fracture toughness values were then determined. The effect of the location of the crack tip-bond (center or interface) is also discussed.

See also: Trantina, G. G., "Fracture Mechanics Approach to Adhesive Joints." University of Illinois, Department of Theoretical and Applied Mechanics, Urbana. Naval Air Systems Command Contract Report No. UILU-ENG-71-60014, August 1971. (AD 731 992)

37. Wah, T., "Stress Distribution in a Bonded Anisotropic Lap Joint," Trans. ASME, Ser. H: J. Eng. Mater. Tech., 95 (1973), 174-81.

A theoretical analysis of a bonded lap joint in the elastic range is presented. It is assumed that: the adhesive is isotropic, the joint is sufficiently wide to be in a plane strain state, and bending is symmetrical. To simplify the problem it is supposed that the laminated adherends are symmetrical so that the bending and stretching terms are uncoupled. Numerical results are given and based on these a simplification of the analysis is suggested.

38. Westmann, R. A., "An Elementary Model for Yielding Slip in Adhesive Joints." Institut fuer Festkoerpermechanik, Freiburg, West Germany. Research Report No. WB-1/73, January 1973.

Stress and displacement analyses for an adhesive joint modeled by two elastic half planes connected by an infinitely thin bond line of finite length, were conducted and results are presented. It was assumed that the connection transfers a normal and shear force as well as a resultant moment. Yielding and slip along the bond line accounted for inelasticity in the adhesive. The Barenblatt-Dugdale approach and singular integral equations were used to obtain the pertinent stress and displacement components along the bond line. Failure of the joint was analytically predicted by employing the concept of a critical COD or a critical plastic zone size. Results are compared with predictions made by the brittle fracture theory.

39. Westmann, R. A., "A Structural Model in Adhesive Mechanics." Institut fuer Festkoerpermechanik, Freiburg, West Germany. Research Report No. WB-6/73, May 1973.

A preliminary structural model for the approximate stress analysis of adhesive joints is presented. A reinforced plate theory which accounts for both shearing and plate thickness deformations was used for the model. A double cantilever beam test specimen was considered to assess the accuracy of the model. Expressions for the bond line tractions and crack tip stress intensity factors are presented and show good agreement with values obtained by other methods for a range of geometric parameters.

40. Williams, M. L., "Cohesive-Adhesive Fracture in a Pressurized Double Blister," J. Adhes., 5 (1973), 81-87.

This is an approximate analysis of a three-layer medium which estimates the critical applied pressure and preferred locus of fracture initiation as a function of geometrical and mechanical properties.

41. Williams, M. L., "The Fracture Threshold for an Adhesive Interlayer," J. Appl. Polym. Sci., 14 (1970), 1121-26.

An energy balance criterion for a continuum mechanics model of adhesive failure in a pressurized blister at the interface of an elastic material and a rigid substrate was extended to include an additional elastic interlayer between them. The energy calculations were simplified by using linear elastic beam theory, a Winkler-type elastic foundation (neglecting shear deformation and shear strain energy) was used, and most important separation along the line between the plate and adhesive layer was assumed. Results showed that the tensile modulus-to-thickness ratio of the adhesive layer and the adhesive fracture energy of separation of the respective materials were the most critical design parameters.

42. Wooley, G. R. and Carver, D. R., "Stress Concentration Factors for Bonded Lap Joints," J. Aircraft, 8 (1971), 817-20.

Stress analysis of a bonded, single lap joint by finite element method was completed and a modified version of the Wilson stress analysis program was used for the case of plane stress. Stresses occurring in the adhesive layer, and stress concentrations as a function of geometric and material parameters are presented. Poisson's ratio was taken as 0.3 for each layer and a ratio of adherend and adhesive elastic modulus was varied from 0.1 to 1000. Lap length and joint geometry were treated as independent variables and overall length-to-thickness ratio was arbitrarily taken as 100. The analysis is based on linear displacement function within each element.

FASTENERS

43. Birger, I. A., et al., "The Limiting Plastic Condition and Shear of Threads," Russ. Eng. J., 48, No. 3 (1968), 35-40. Translation of Vestn. Mashinostr., 48, No. 3 (1968), 32.

Fine threads are preferred in some machine designs because the large thread diameter to pitch ratio in which the cross-sectional area of the bolt is greater results in a stronger bolt. The shear strength with a high pitch ratio can be increased when the engagement length, as the nut height, is increased. The maximum number of threads carrying the load characterize the limiting engagement strength when the threads are beginning to yield plastically. A mathematical theory on the subject is presented and an integral equation which is solvable with the aid of successive approximations was developed. The limiting engagement strength is dependent on the ratio between the mechanical properties of the bolt and nut materials and the pitch and diameter of the thread. Joint strength can also be increased by using a coarse thread and a buttress-type thread with a 0° angle to reduce lateral deformation.

44. Bradley, T. L., Lardner, T. J., and Mikic, B. B., "Bolted Joint Interface Pressure for Thermal Contact Resistance," Trans. ASME, Ser. E: J. Appl. Mech, 38 (1971), 542-45.

As part of a study on thermal joint conductance, a three-dimensional photoelastic analysis using the stress freezing technique was used to predict the interface pressure - a factor needed to calculate the thermal contact resistance across a bolted joint. Nine bolted joints were investigated using smooth flat plates of photoelastic material and equal thickness. The integration of the interface pressure distribution over the area of contact was within 10% of the applied load for all experimental results and usually was within 5%.

45. Bragin, D. Ya., Shkanov, I. N., and Vasil'yev, G. V., "Problem of Calculating Bolted Joints under Stress Relaxation and Creep Conditions During Vibrations." Foreign Technology Division, Wright-Patterson Air Force Base, Ohio. Report No. FTD-HT-23-0276-73, May 1973. (AD 761 455)

Existing methods for calculating tight bolted joints for stress relaxation are based on equations corresponding to a particular theory of creep which gives the most accurate quantitative description of creep and stress relaxation of fastening materials in the specific conditions investigated. The equations are described and evaluated.

46. Brombolich, L. J., "Elastic-Plastic Analysis of Stresses Near Fastener Holes." AIAA Paper 73-252, 1973.

A finite element analysis method of determining the stresses near fastener holes is presented. Plasticity, load sequence effects, fastener interference, and the contact problem created by the inability to develop tensile radial stresses across the fastener plate boundary are considered. Several applications are presented and stress distributions in plates containing fasteners which are subject to cyclic, uniaxial, in-plane loading conditions are discussed.

47. Chan, S. K. and Tuba, I. S., "A Finite Element Method for Contact Problems of Solid Bodies - Part I. Theory and Validation," Int. J. Mech Sci., 13 (1971), 615-25.

A modified finite element method for solving problems of elastic bodies in contact is described. The method is general and could be extended to solve problems in other classes of structures. The sample results showed good agreement with corresponding exact solutions.

48. Chan, S. K. and Tuba, I. S., "A Finite Element Method for Contact Problems of Solid Bodies - Part II. Application to Turbine Blade Fastenings," Int. J. Mech. Sci., 13 (1971), 627-39.

The effects of clearances and frictional forces on blade root fastening stress distributions were investigated by the finite element method and the computations were compared with the available photoelastic results.

49. Cruse, T. A., Konish, H. J., Jr., and Waszczak, J. P., "Strength Analyses for Design with Composite Materials Using Metals Technology." Proceedings of the Colloquium on Structural Reliability, The Impact of Advanced Materials on Engineering Design, Pittsburgh, Pa., 9-12 October 1972. Edited by J. L. Swedlow, T. A. Cruse, and J. C. Halpin. Pittsburgh: Carnegie-Mellon University (1972), 222-36.

Using a simple model obtained from lamination theory and restricted to midplane symmetric laminates subject to in-plane loading, the effects of sharp cracks and loaded holes on the strength of composite structures were investigated. The strengths in bolted joints in boron and graphite epoxy plates were evaluated and the fracture of advanced fiber composites was predicted. Results indicate that in order to use linear elastic fracture mechanics to characterize composites factors such as the lower bound on crack length and the material dependence on finite dimension correction factors must be taken into account.

50. Erisman, R. J., "How Dimensionless-Parameter Technique Aids in Theoretical Analysis of Bolted Joint Problems," Fasteners, 23, No. 4 (1968), 9-11.

Two equations are presented graphically in a form which gives most parameters necessary for theoretical solutions to bolting problems. Design parameters include torque distribution, torque-tension ratios, friction-size/torque-tension relationships, and simplifications obtained in stress relationships through dimensionless parameters.

51. Fontenot, J. E., Jr., "The Thermal Conductance of Bolted Joints." Unpublished Ph.D. dissertation, Louisiana State University and Agricultural and Mechanical College, 1968.

Subsequent to a literature review, a comprehensive experimental and analytical program was conducted to attempt to eliminate technological gaps. The survey indicated, for instance, development of a completely analytical method was hampered by each of: (1) experimental data for stress distributions under boltheads, (2) an adequate method for interface stresses in regions of apparent contact at bolted layers, (3) a theoretical method for predicting interface gaps under prescribed stresses. Accordingly these deficiencies were treated and a practical method of determining the interface thermal conductance of a bolted joint, using a minimum of design information, was formulated. Computed values of thermal conductance were used in a finite-difference heat transfer analysis of steady-state temperature gradients across aluminum and stainless steel joints in air and vacuum. Analysis was confirmed via experiments.

52. Fried, E., "A Joint Heat Transfer Data Critical Study and Design Guidelines." General Electric Corporation, Space Systems Organization, Philadelphia, Pa. National Aeronautics and Space Administration Contract Report No. NASA-CR-119933, June 1971. (N71-38345)

Information on the prediction of bolted joint heat transfer was reviewed and guidelines and procedures for design engineers to predict within reasonable limits this joint heat transfer for spacecraft applications are recommended. Tables and graphs on bolted joints and related data are presented and a glossary of terms is provided. Since analytical methods are not completely developed to provide reliable predictions, empirical approaches were used exclusively.

53. Gould, H. H. and Mikic, B. B., "Areas of Contact and Pressure Distribution in Bolted Joints." Massachusetts Institute of Technology, Engineering Projects Laboratory, Cambridge, Mass. National Aeronautics and Space Administration Contract Report No. NASA-CR-102866, June 1970. (N70-41982)

Finite element method was used to compute the pressure distributions in the contact zones and the radii at which flat and smooth asymmetric linear elastic plates of several thicknesses will separate. The radii of separation was also measured by two methods; one employed autoradiographic techniques and the other measured the polished area around the bolt hole of the plate caused by sliding under load in the contact zone. The results obtained are in agreement with experimental data and yield smaller zones of contact than indicated in the literature. The analysis method and the computer programs and instructions for their use are included.

54. Hamada, K., Ukaji, H., and Hayashi, T., "Stress Analysis of Bolted Flanges for Pressure Vessels." Proceedings of the First International Conference on Pressure Vessel Technology, Delft, Netherlands, 29 September-2 October 1969. New York: American Society of Mechanical Engineers (1970), 513-27.

A design method, in accordance with the ASME code, of flanged joints for pressure vessels under bolting and internal pressure loads was investigated. A new digital computer program for the analysis of stresses and distortion in flanges that can provide accurate evaluation of a tapered hub section, interaction with mating flange connected by bolts, and bending stress and stiffness of bolts due to flange rotation is described.

55. Harris, H. G., Ojalvo, I. U., and Hooson, R. E., "Stress and Deflection Analysis of Mechanically Fastened Joints." Grumman Aerospace Corporation, Bethpage, N. Y. Air Force Flight Dynamics Laboratory Contract Report No. AFFDL-TR-70-49, May 1970. (AD 709 221)

A set of stacked parallel plates which transfer planar loads among themselves by means of transverse fasteners were used in an analytical model for predicting both linear and nonlinear stresses and deformation in mechanically fastened joints. The plates were treated by finite element methods of matrix structural analysis in which each element was assumed to be in plane stress for both elastic and plastic states. The techniques were applied to several problems: (1) load-deflection behavior of single-fastener joints, (2) combined elastic-plastic behavior of plates with unloaded holes, (3) residual stress distribution in plates with squeeze rivets, (4) effect of fastener bending and shear deformation on the bearing stress distribution between the fastener and plate, (5) prediction of fatigue life of typical mechanically fastened joints.

56. Markovets, M. P., "Graphic-Analytic Method of Calculating the Time to Failure of Bolts under Stress Relaxation Conditions," Therm. Eng., 17, No. 6 (1970), 77-79. Translation of Teploenergetika, 17, No. 6 (1970), 52-54.

A method based on a comparison of stress relaxation and long-time strength diagrams. With stepwise long-term loading conditions, the reduction of effective cross section can be calculated by determining the times to failure for corresponding loading from the long-time diagram. Time to failure is calculated as the time when the reduction of the effective cross section reaches a critical value - an example is given.

57. Menken, C. M., "Influence of Bolt Loading on Deformation of Pressure Vessel Flanges." Proceedings of the First International Conference on Pressure Vessel Technology, Delft, Netherlands, 29 September-2 October 1969. New York: American Society of Mechanical Engineers (1970), 143-53.

The question of whether rotationally symmetric deformations will occur in flanges of pressure vessels with both rotationally symmetric loading and geometry was investigated. The effect of periodic loading - equal bolt loads - on the deformation of a rotationally symmetric integral flange was studied. Results show that the periodic deformation of the flange can be neglected when compared with rotationally symmetric deformation.

58. Milov, A. B., "Calculation of the Contact Stiffness of Cylindrical Joints." Strength Mater., 5, No. 1 (1973), 74-77. Translation of Probl. Proch., No. 1 (1973), 70-72.

Plane contact problems where the contact zone has considerable dimensions are treated. Pressure distributions in the contact region are approximated with a cosine form. Comparison of the resulting expression for relative deflection and contact angles is made for the two- and three-dimensional elasticity solutions. These are problems of axisymmetrical loading of a thin disc (plane problem) and compression of a solid cylinder by a "band load" (three-dimensional problem). On the basis of the comparison a correction coefficient accounting for the width of the loaded portion and the effect of three dimensions, is presented.

59. Oplinger, D. W. and Gandhi, K. R., "Stresses in Mechanically Fastened Orthotropic Laminates." Paper presented at the 2d Conference on Fibrous Composites in Flight Vehicle Design, Dayton, Ohio, 21-24 May 1974. (Proceedings to be published as an Air Force Flight Dynamics Laboratory Report)

Analytical results for elastic response and failure of mechanically fastened orthotropic plates containing both single and multiple fastener configurations are presented. The least squares collocation method in conjunction with a complex variables formulation for the two-dimensional elastic response was used. An interactive approach was used to determine the contact length, a nonlinear aspect of the problem. The effects of orthotropy and plate geometry as well as those of certain fastener interactions which may be present in rows of fasteners were considered. The joint configurations investigated were single pin, periodic array in finite rectangular plates, and an isolated pin in an infinite plate which corresponds to the case of pins widely spaced and well removed from neighboring boundaries. Results showed the occurrence of an optimum value of s/D of $\sim$ 2.0, which corresponds to a minimum in the ratio peak net section tension to applied stress.

60. Popper, J. B., "A New Method of Screw Strength Calculation," Trans. ASME, Ser. B: J. Eng. Ind., 93 (1971), 1233-38.

Method for calculating the strength of screw fastenings, considering thread geometry, combined tensile and shear stresses and uncertainty of the exact values of friction coefficient, is presented. The calculated strength is smaller but more realistic. Safety factors as low as 1.2 can be used. Equations derived indicate screw strength can be increased and even doubled by the use of preloading washers and by turning the screw back after initial tightening.

61. Potelezhko, V. P. and Solonets, B. P., "Investigation of Tightness of Riveted Joints with Cover Plates," Strength. Mater., 3 (1971), 111-15. Translation of Probl. Proch., No. 1 (1971), 114-17.

The nature of the distribution of the unit pressure between the main elements and the cover plates of a multiple riveted joint was investigated using elastic theory. Graphs are provided which permit determination of rivet distance as a function of rivet-head diameter, and cover and main plate thickness in order to maintain a given relative unit pressure ratio at the midpoint of the rivet spacing. Knowledge of this stress level is important since joint tightness is essentially controlled by the magnitude of this pressure.

62. Potelezhko, V. P. and Solonets, B. P., "Tightness of Riveted Joints," Russ. Eng. J., 51 No. 8 (1971), 36-38. Translation of Vestn. Mashinostr., 51, No. 8 (1971), 30-32.

The tightness of riveted joints was determined by the minimal pressure, "q_{min}" at the mid-point in the shortest distance between rivets. The value of "q_{min}" is dependent on the diameter of the rivet head, "D", the thickness of the joint components "h" and the rivet pitch, "t". The pressure and its distribution are not dependent on the materials that make the joint components.

63. Puppo, A. H. and Haener, J. A., "Application of Micromechanics to Joints and Cutouts." Whittaker Corporation, San Diego, Calif. U.S. Army Aviation Laboratories Contract Report No. USAAVLABS-TR-69-25, April 1969. (AD 688 168)

Analytical and experimental methods were used to study the stress distribution in loop and bolt joints in composite materials. The numerical technique to evaluate the stresses and displacements is described and simple formulas for computing the stresses at critical regions were developed. Photoelastic technique was used for stress distribution tests. Failure location and ultimate loads for several composite joints are shown.

64. Roca, R. T. and Mikic, B. B., "Thermal Cónductance in a Bolted Joint." AIAA Paper 72-282, 1972.

The effect of roughness at the contact region of a bolted joint on both the large scale constriction, and the small scale constriction, which is influenced by the magnitude of the local pressure is shown analytically. The sum of the two constriction effects, the total resistance, may increase or decrease with changing resistance. Examples are given where an optimum roughness minimizes total joint resistance.

65. Wade, L. V. and Stahl, P. A., "Effects of Specimen Radius on the Stress State Near a Roof Bolt Anchor: A Finite Element Determination." Bureau of Mines, Washington, D. C. Research Report No. BuMines-RI-7748, June 1973. (PB 221 863)

The effects of the rock specimen size used in testing anchor performance were determined. Results showed that the stress state at the anchorage horizon varied significantly between 6"d. cores and cores of larger d. but not when the specimen d. was $\geq$ 12". The anchor horizon stress field was not significantly altered by the noninclusion of bearing-plate stress field. The stress state was not significantly changed by the inclusion and subsequent exclusion of the effects of gravity. More realistic mathematical modeling is possible through the use of three-dimensional finite elements.

66. Waszczak, J. P. and Cruse, T. A., "Failure Mode and Strength Predictions of Anisotropic Bolt Bearing Specimens," J. Composite Mater., 5 (1971), 421-25.

The problem of a single bolt in an orthotropic laminate of crossplied configuration was treated by a finite element computer code. A cosine distribution of normal stress acting on half of the hole surface was used to simulate the bolt loading and friction effects were neglected. Three anisotropic failure criterion: maximum stress, maximum strain and distortional energy were evaluated. The distortional energy criterion was found to be reliable and conservative in predicting bolt failure loads in simple bolt bearing tests.

67. Waszczak, J. P. and Cruse, T. A., "A Synthesis Procedure for Mechanically Fastened Joints in Advanced Composite Materials." Final Report November 1971-August 1973. Carnegie-Mellon University, Mechanical Engineering Department, Pittsburgh, Pa. Air Force Materials Laboratory Contract Report No. AFML-TR-73-145, Vol. II, September 1973. (AD 771 795)

A general optimization procedure using simplified results of the author's earlier studies reported in the previous entry of this bibliography. Based on laminate failure modes and minimum weight constraint, an optimization methodology as well as resulting joint configurations are described.

68. White, D. J. and Enderby, L. R., "Finite Element Stress Analysis of a Non-Linear Problem: A Connecting-Rod Eye Loaded by Means of a Pin," J. Strain Anal., 5 (1970), 41-48.

A stress analysis method using existing linear elastic finite element computer programs is given for a non-linear problem - a connecting rod under a tensile load. The connecting rod eye was idealized as a plane stress problem and special overlapping elements were introduced to connect the eye and the pin at radially adjacent nodes. These elements were assigned stiffnesses which were changed in a prescribed manner after each run until compatability of forces and displacements, allowing for initial clearances, was obtained at each connecting point. Eight runs were required to achieve correct displacements but results indicated that the circumferential stresses did not change appreciably after the first few runs. There was good agreement between the calculated results and laboratory test measurements made with electrical-resistance strain gauges.

69. Wilkinson, T. L., "Analysis of Nailed Joints with Dissimilar Members," Proc. ASCE, J. Struct. Div., 98, No. ST9 (1972), 2005-13.

A theoretical model of analysis, based on the theory of beams on elastic foundations, was derived in order to predict the slope of the load-slip curve of two-member nailed wood joints under lateral load. The method allows analysis of joints in which the properties and thickness of the members are dissimilar. The different sizes and materials of the nails as well as the different species of wood are accounted for by incorporating a foundation modulus determined from an elastic bearing constant proportional to the wood density. Elastic bearing constant values for various types of joints and experimental verification of the theoretical expressions are presented.

70. Wilkinson, T. L., "Theoretical Lateral Resistance of Nailed Joints," Proc. ASCE, J. Struct. Div., 97, No. ST5 (1971), 1381-98.

The behavior of beams on elastic foundations was studied by a theoretical analysis and results compared with test data for deflection and proportional limit stresses of nailed joints under lateral load. A simple theoretical equation was derived which relates single shear load with joint slip for a laterally loaded smooth round nail in a two-member wood joint. The elastic bearing constant, experimentally determined, was found to be linearly related to average specific gravity of the wood species.

71. Yip, F. C., "Theory of Thermal Contact Resistance in Vacuum with an Application to Bolted Joints." AIAA Paper 72-281, 1972.

A new expression for thermal contact resistance in vacuum for rough surfaces of normal height distribution was derived and is applicable for both uniform and nonuniform stress distributions which may occur at the interface. The effect of two nonuniform stress distributions on the microcontact resistance of a bolted joint was examined. Analytical results show little difference between uniform and nonuniform stress distributions. A simplified solution which governs the thermal and mechanical properties and the metrology of surfaces is proposed.

WELDED JOINTS

72. Andrews, J. B., Arita, M., and Masubuchi, K., "Analysis of Thermal Stress and Metal Movement During Welding." Massachusetts Institute of Technology, Department of Naval Architecture and Marine Engineering, Cambridge, Mass. National Aeronautics and Space Administration Contract Report No. NASA-CR-61351, December 1970. (N71-26143)

An analytical system for calculating thermal stresses during welding and the associated residual stresses is outlined. Longitudinal stresses, those parallel to the weld line were analyzed. Using the computer program developed, the effect of material properties and welding parameters on the thermal stresses and metal movement were evaluated. Steel, Al, Nb, and Ta materials were studied and a detailed analysis was made of the effects of welding parameters on thermal stresses during bead-on-plate welding of 2219-O Al. Temperature and strain changes were recorded and compared with those calculated with the computer program.

73. Burmistrov, V. P., "Assessing the Effects of the Design and Technological Parameters on the Reliability of Joints in Components Made of Plate Metal," Automat. Weld., 24, No. 8 (1971), 39-41. Translation of Avt. Svarka, No. 8 (1971), 39-40.

The effects of batch-to-batch variations in mean weld strengths and geometry of weld joints was assessed by simple reliability equations in conjunction with an experimental program. The mathematical model was based on normal probability distributions and a first order linear expansion of a Lagrange function of joint loads and spot weld strengths.

74. Butler, L. J., Pal, S., and Kulak, G. L., "Eccentrically Loaded Welded Connections," Proc. Amer. Soc. Civil Eng., J. Struct. Div., 98, No. ST5 (1972), 989-1005.

An analytical method, using the true load-deformation response of the welds rather than some idealized one, to predict the ultimate load of eccentrically loaded weld groups was developed. Thirteen full-size specimens were tested to verify the validity of the method. By using the more accurate predictions presented, the safety factor can be brought into line with that of other structural components and can be established at a constant value for all connections of this type.

75. Byers, N. R. and Schultz, R. F., "Analysis of a Stub End by the Finite Element Method," Weld. J., 51 (1972), 31s-35s.

Finite element method was used to analyze the axi-symmetric stress problems in the stub end portion of a bolted flange pipe connection. Three different stub end configurations with various material properties of the individual elements as required to represent the weld material or the parent metal were tested. The stresses and coordinates of the centroid for each element comprised the output of the computer program used. The resulting stresses were plotted as contours on the stub end with convergence of stress values observed as the element size was decreased. Results indicated there were no significant differences (< 5%). A typical contour stress plot is shown.

76. Chihoski, R. A., "The Character of Stress Fields Around a Weld Arc Moving on Aluminum Sheet," Weld. J., 51 (1972), 9s-18s.

Using the solutions for temperature rise at points around a moving heat source, isotherms were taken for representative configurations around a moving gas tungsten welding arc. Neglecting shear stresses, the isothermal stress distributions in approximating strips were calculated. The shape and intensity of the tension and compression stresses which are approximate for conditions around the heat source are described for two weld speeds. The elementary analysis provides a systematic explanation of common welding experiences such as cracks, shrinkage, part distortion, sudden changes in current demands and unexpected responses to welding gaps. Several experiments demonstrate qualitative correctness of the model.

77. Finnie, L. and Vaidyanathan, S., "Stress Analysis of Welded Joints with Particular Reference to Circumferential Welds in Cylinders." University of California, College of Engineering, Berkeley. Research Report No. UCRL-13569, 1972.

The differences in the residual stress distribution produced by a circumferential weld between axisymmetrical shells and a butt weld between two flat plates are pointed out. The state of stress in the shells may be estimated from that in the plates. Experimental results on electron beam welded Al parts obtained for a full penetration, single pass weld with no variation of alloy content across the weld showed good agreement with the predictions. It is also shown that multipass welds, partial penetration welds, and welds with a filler metal different from the base metal can all be taken into account using this approach. Two types of simple fracture tests - a small specimen constrained by a rigid fixture and a larger specimen completely unconstrained during arc discharge - were used to show that the extent of crack propagation depends on the fracture properties of the material. Experimental data are given to illustrate both types of tests.

78. Grigor'ev, L. Ia., "Thermal Stresses in a Cylinder in the Case of an Arbitrary Temperature Distribution Along Its Axis," Sov. Appl. Mech., 8, No. 3 (1972), to be published. Translation of Prikl. Mekh., 8, No. 3 (1972), 42-46.

Assuming a constant temperature across the cylinder, the thermoelastic problem of the stresses in a cylinder was solved for an arbitrary linear expansion coefficient. The problem of stress distribution in a welded butt joint between two cylinders having different linear expansion coefficients is solved as an example.

79. Huber, R. A., Bradway, D., Wiedemann, C. M., and Turner, P. W., "Computer Programs for Calculating Peak Temperature Distribution in Welding." Union Carbide Corporation, Oak Ridge, Tenn. Atomic Energy Commission Contract Report No. Y-1627, October 1968.

Computer programs for solving the heat-transfer equations relating to moving heat sources encountered in welding operations were developed. The types of problems solved for the engineer and designer are: (1) thermal mapping to determine the "temperature hill" enveloping the welding heat source on a semi-infinite plate, (2) determining peak temperatures at some distance from the centerline or from the bond line, (3) determining the surface peak temperature at the edge of a plate parallel to the weld, (4) determining the peak temperature on the bottom side of plates having partial-penetration welds.

80. Kozlov, V. S. and Savitskii, A. A., "Determining the Depth of Penetration Welding by Radiation Methods," Weld. Prod., 18, No. 11 (1971), 10-12. Translation of Svar. Proizvod., No. 11 (1971), 7-8.

An infrared pyrometer was used to continuously determine weld depths. The procedure relies on the fact that the penetration depth during welding is related to the vertical temperature distribution in the material. Under the assumption of temperature independent thermophysical constants, and using the three-dimensional Fourier heat conduction equation, the relation between penetration depth and general temperature distribution can be derived.

81. Makhnenko, V. I., Velikoivanenko, E. A., and Shekera, V. M., "Kinetics of the Stressed and Strained State in Sheet Metal When Cracks are Welded Up," Automat. Weld., No. 2 (1970), 36-40. Translation of Avt. Svarka, No. 2 (1970), 36-40.

Kinetic changes in the stress, strain, and temperature distributions around cracks in metal plates during welding-up operations are discussed in terms of theoretical calculations and experimental tests. The development of elastic-plastic deformations and stress states in the heat affected zone when cracks in sheet metal are welded were traced by calculation for both a rigid system and a system with free edges. Compressive strains tend to develop in the region immediately surrounding the weld. In the cooling stage transverse welds change less rapidly with time than longitudinal strains.

82. Masubuchi, K. and Ich, N. T., "Computer Analysis of Degree of Constraint of Practical Butt Joints," Weld. J., 49 (1970), 166s-76s.

Various finite element models were employed to determine appropriate methods to represent constraints typical of joints. The degree of constraint was simulated by various plate configurations containing straight slits, slits with circular ends, H-type and other slits. A constant strain element with relatively coarse gridding (105 nodes) was successful as demonstrated by some confirming experiments.

83. Mehrotra, B. L., "Matrix Analysis of Welded Tubular Joints." Unpublished Ph.D. dissertation, McGill University, 1970.

A numerical procedure based on the finite element in the form of a general purpose computer program to analyze stresses, strains, and deformations of any arbitrarily thin-walled three-dimensional structure having random static loadings, boundary conditions, and variable wall thicknesses, including stiffening was developed and used to analyze joints between rectangular tubular members. Semi-empirical formulas were developed for predicting joint modulus as well as stresses and deflections in the connected branches for symmetrically welded full-width connections between rectangular tubes and a computer program is presented. A two-dimensional plane-stress substitute model is suggested to show the joint behavior of its counterpart three-dimensional full-width connection in the elastic range and then extended to the inelastic range. Full scale experiments were conducted under different loading and boundary conditions to verify the results.

84. Mehrotra, B. L. and Govil, A. K., "Shear Lag Analysis of Rectangular Full-Width Tube Junctions," Proc. ASCE, J. Struct. Div., 98, No. ST1 (1972), 287-305.

A shear lag analysis is suggested for analytically determining the joint stiffness of welded junctions between rectangular hollow tubes. A complete stress analysis of typical connections is given along with numerical values of joint stiffness for most full width connections of sizes included in the 1967 AISC Manual. Results were verified both experimentally and by a three-dimensional finite element solution. Semi-empirical equations for evaluating the joint stiffness are given. Curves showing the special behavior of these joints in load transfer to main member are presented.

85. Nagarajarao, N. R., Marek, P., and Tall, L., "Welded Hybrid Steel Columns," Weld. J., 51 (1972), 462s-72s.

The analysis and results of an investigation to determine the strength of hybrid steel columns composed of low strength webs welded to high strength flanges are presented. Included in theoretical analysis were the tangent modulus and ultimate load, the mechanical properties of the materials, the actual residual stress distribution, and local buckling. Five hybrid shapes fabricated from flame-cut or universal mill plates were tested. Tension specimen coupon, residual stress measurements, stub column tests, and pinned-end column tests with a slenderness ratio of 65 were conducted. Results showed that column strength of hybrid shapes can be predicted from the actual stress distribution by theoretical analysis.

86. Nickell, R. E. and Hibbitt, H. D., "Thermal and Mechanical Analysis of Welded Structures." Brown University, Department of Engineering, Providence, R. I. Office of Naval Research Contract Report No. TR-4, August 1973. (AD 771 946)

Stress analysis of welded structures is discussed in terms of: (1) the legitimacy of plasticity theories for treating the residual stress problem, (2) criteria for choosing plane stress, plane strain, generalized plane strain, or fully three-dimensional models, (3) methods for coping with possible floating regions during cooling, (4) use of linear constraints to treat weld metal deposition and intermittent contact. Because of their importance to the stress analysis of the cooling rate and the welding torch efficiency, the heat transfer problem was examined critically. Finite element analysis is applicable if the solution accuracy can be adequately estimated.

87. Peacock, H. B., Jr., "An Investigation of Residual Stresses and Post-Weld Heat Treatment Cracking in Welded Nickel-Base Alloys." Unpublished Ph.D. dissertation, University of Tennessee, 1970.

As-welded and stress-relieved discs of Inconel 600, Inconel X-750 and René 41 were studied using the Sachs boring technique to evaluate residual stress distributions. The Inconel 600 was also studied by two other experimental methods. The residual stresses were shown to exceed the yield strength of the alloys. Subsequently biaxial stress relaxation characteristics were obtained for the three metals. Heat treatments as well as relaxation phenomena were shown to substantially reduce the residual stresses. Post weld heat-treatment cracking phenomena was also investigated on Waspalloy specimens and scanning electron fractographs revealed intergranular fracture characteristics.

88. Podstrigach, Ya. S. and Osadchuk, V. A., "Investigation of the Stress State of Cylindrical Shells Associated with a Given Tensor of Incompatible Strains, and Application to the Determination of Welding Stresses," Sov. Mater. Sci., 4 (1968), 292-98. Translation of Fiz. Chem. Mekl. Mater., 4 (1968), 400-07.

Residual stresses caused by strain incompatibility at the weld zone were analytically predicted. Using the known strain components, the basic relations used for determining residual stress produced during welding as a result of the contraction of the metal in the weld and because of structural changes in the weld zone were derived. A cylindrical shell geometry was used for the study. Results showed that nonuniform distribution of residual strains along the shell wall thickness has a substantial effect on the residual stress distribution.

89. Prokhorov, N. N., Magerramov, A. G., and Filimonova, N. M., "Effects of the Thermal and Physical Properties of Metals on the Development of Stresses and Strains During Welding," Weld. Prod., 19, No. 1 (1972), 2-6. Translation of Svar. Proizvad., No. 1 (1972), 2-4.

Computer-aided analysis of stress distribution in the weld, effect of heating the metal, and development of stresses along the joint on cooling was completed for several alloys. Stress and distortion were markedly affected by the thermal properties of the metal.

90. Prokhorov, N. N., Prokhorov, N. Nikol, and Asatiani, D. M., "Calculating the Processes of Development of Internal Stresses and Strains When Components Being Welded are Subjected to Thermal and Mechanical Properties," Automat. Weld., 24, No. 11 (1971), 23-27. Translation of Avt. Svarka, No. 11 (1971), 24-28.

The factors affecting the development of internal stresses and strains in metal parts as a result of the thermal effects of welding are discussed. These stresses and strains may be minimized or eliminated by suitable bending of the parts involved during the welding operation. The optimum amount of bending may be calculated from geometrical dimensions of the parts being welded and the physical constants of the materials.

91. Sharapov, Yu. V., "Calculation of the Depth of Penetration for Welding with a Stationary Arc," Weld. Prod., 18, No. 6 (1971), 72-75. Translation of Svar. Proizvod., No. 6 (1971), 46-47.

The depth of penetration and the time of arc burning were calculated for welding with a stationary arc. The effective efficiency of heating of the metal was found to be 0.8-0.9, the overall efficiency of penetration, 15-20%, and the depth of penetration was calculated on the basis of a long-acting point source applied to the non-heat-transmitting boundary surface of a semi-infinite body.

92. Shron, R. A., "Tensile Strength in Creep of Welded Joints with a Soft Interlayer," Weld. Prod., 17, No. 5 (1970), 8-13. Translation of Svar. Proizvoid, No. 5 (1970), 6-8.

Both a theoretical solution and a procedure for calculating the high-temperature strength of joints were devised using the known findings of creep theory and ideas on the strength of joints with soft interlayers. In the ductile failure range, the creep strength and life of these joints increase as the relative thickness of the interlayer decreases. The strength and life of the soft interlayer are lower than for the soft material under no restraint in the brittle fracture range.

93. Szelagowski, F., "State of Stress in an Infinite Strip Induced by Shrinkage of the Joint," Bull. Acad. Pol. Sci., Ser. Sci. Tech., 18 (1970), 383-86.

An analytical approach for estimating the stresses associated with transverse shrinkage of weld joints is presented. Boundary conditions are formulated in terms of the conventional complex variable stress functions of elasticity. A conformal mapping transformation is used to represent both the weld joint and the strip's lateral sides on the real axis in the mapped plane. The maximum normal stresses existing in the weld interface region are estimated by an evaluation of the boundary condition equations.

94. Tong, H. and Giedt, W. H., "Depth of Penetration During Electron Beam Welding," Trans. ASME, Ser. C: J. Heat Trans., 93 (1971), 155-63.

A mathematical analysis of the deep welding mechanism is presented. Models previously used represented the deposition of electron beam energy by a steady line force. The calculations presented here show that due to an oscillating flow of the molten material, the electron beam energy is deposited on a surface which varies from close to horizontal to the sides of a cone-shaped cavity. Results showed that the depth of penetration could be predicted with ±20% accuracy from a knowledge of process conditions and base material properties.

95. Turiyanskii, L. I., "Calculating the Strength of Ring Welds under Complex Stress Conditions," Weld. Prod., 18, No. 11 (1971), 8-10. Translation of Svar. Proizvod., No. 11 (1971), 6-7.

Formulas for calculating the resultant stresses at the critical points of circular welds under the simultaneous action of bending and torsion were derived using theories of elasticity and strength. Improved formulae for calculating the tangential stresses in these welds in relation to the geometry of the system and the physical and mechanical properties of the metals involved were derived. Computing equations for the strength of welds made under standard conditions are presented.

96. Vinokurov, V. A. and Grigor'yants, A. G., "The Theoretical Determination of Temporary and Residual Strains and Stresses on Welding Titanium and Aluminum-Alloy Plates," Weld. Prod., 15, No. 5 (1968), 2-6. Translation of Svar. Proizvod., No. 5 (1968), 2-4.

A method, using a digital computer, to provide a theoretical determination of strains and stresses on welding Ti and Al-alloy plates is described. The parameters are determined as the elastic-plastic zones travel in the plate.

INTERFACES AND LAYERED CONFIGURATIONS

97. Ashbaugh, N. E., "Stresses in Laminated Composites Containing a Broken Layer. Part I. Analysis." University of California, La Jolla, Department of the Aerospace and Mechanical Sciences, San Diego. Air Force Office of Scientific Research Contract Report No. AFOSR-TR-72-0032, October, 1971. (AD 736 834)

The stress field around a stress-free crack in a bi-material laminated composite with elastic constituents was determined when external loads open the crack surfaces. The crack was made by a broken layer and had a finite length. In this problem the only nonzero boundary stress is a normal stress on the crack surface but in this investigation the solution presented applies to a more general problem where either the normal displacement or the normal stress can be prescribed. The stresses are given by integral expressions containing the derivative of the normal displacement along the crack surface.

98. Bennett, S. J., DeVries, K. L., and Williams, M. L., "Adhesive Fracture Mechanics," Int. J. Fract., 10 (1974), 33-43.

An axisymmetric finite element numerical analysis was conducted for two layer blister specimens of different thickness and debond radii to establish the energy balance for various arbitrary thicknesses. A continuous curve for arbitrary specimen thickness was produced. The numerical procedures for energy balance analysis are included and may be used for analyzing geometries other than blister test specimens.

99. Bogy, D. B. and Wang, K. C., "Stress Singularities at Interface Corners in Bonded Dissimilar Isotropic Elastic Materials," Int. J. Solids Struct., 7 (1971), 993-1005.

The plane problem of two materially dissimilar isotropic, homogeneous, elastic wedges, bonded together along both their common faces in such a way that the cross section forms a composite full-plane with a single corner in the otherwise straight interface boundary, was investigated. Loading was due to a regular plane body force field with finite resultant applied to a bounded subregion of one of the wedge domains. The effects of the material constants and corner angle on the order of the singularity in the stress field at the corner are emphasized. Numerical results are presented for several angles and all physically relevant composites. It is also shown that stress singularity associated with the traction and displacement problems for the reentrant wedge element is the most severe.

100. Bregman, A. M. and Kassir, M. K., "Thermal Fracture of Bonded Dissimilar Media Containing a Penny-Shaped Crack," Int. J. Fract., 10 (1974), 87-98.

The problem of uniform flow of heat disturbed by an insulated penny-shaped crack along the bonding surface of two semi-infinite elastic media having different thermo-mechanical properties is formulated. The problem of the infinite space is reduced to that of a half-space depending on two functions. It is subsequently reduced to a problem of linear combinations of two analytical functions (Hilbert problem) in a plane solvable by Muskhelishvili's method of complex variables. Stress intensity factors and local stress field equations are derived and used in conjunction with Griffith's energy criteria to obtain the critical temperature gradient which produces initial crack extension along the bond surface. This stress analysis is also applicable to a penny-shaped crack between two dissimilar solids under shear loadings.

101. Brock, L. M. and Achenbach, J. D., "Dynamic and Quasi-Static Extension of an Interface Flaw." Developments in Mechanics, Vol. 7. Proceedings of the 13th Midwestern Mechanics Conference held at the University of Pittsburgh, 13-15 August 1973. Pittsburgh: University of Pittsburgh (1973), 595-607.

An analytical study on the influence of the effects of inertia on the initial stages of debonding at an interface of two elastic solids of different elastic constants and mass densities is presented. The debonding is caused by stress concentrations that are generated when a system of transient horizontally polarized shear waves strikes the tip of an interface flaw. It is assumed that the rupture of the adhesive is preceded by yielding of the adhesive. It is shown that for a system of step-stress waves the zone of interface yielding initially extends linearly with time. Wave motions generated by actual interface failure were excluded from this investigation. The speed of the loading edge of the interface yielding zone are computed and compared with the corresponding values for the fully dynamic problem.

102. Brown, E. J. and Erdogan, F., "Thermal Stresses in Bonded Materials Containing Cuts on the Interface," Int. J. Eng. Sci., 6 (1968), 517-29.

A direct method of obtaining quasi-static thermal stresses in bonded materials containing fully or partially insulated flat cavities on the interface was developed. Steady-state plane thermoelastic problems were considered and the importance of the insulation is discussed. Results showed that the normal stress is the dominant bonding stress in thermal stress problems and therefore potentially more dangerous than residual stress resulting from homogeneous temperature changes.

103. Chen, E. P. and Sih, G. C., "Interfacial Delamination of a Layered Composite under Anti-Plane Strain," J. Compos. Mater., 5 (1971), 12-23.

A model having a number of bonded layers of different materials containing a finite crack along one interface was used to study debonding failure of a laminar composite. The proposed model consisted of two inner layers of finite height and two outer layers of infinite height whose elastic properties are the averages over a large number of layers of a different material under anti-plane shear and solved by the integral transform method. Numerical results using the proposed model in which the elastic properties alternate from layer to layer revealed the variations of the amplitude of the local stress field with ratios of shear module, p_1/p_2 and layer thickness to half crack length, h/a. The case of a cracked layer sandwiched between two elastic half-planes of another material is also discussed.

104. Erdogan, F., "Bonded Dissimilar Materials Containing Cracks Parallel to the Interface," Eng. Fract. Mech., 3 (1971), 231-40.

The plane problem of two bonded semi-infinite elastic media with different thermomechanical properties, in which one of the half planes contained a crack parallel to the interface was considered. Results indicated (1) in a homogeneous medium with a crack parallel to a free surface, the stress intensity factor increases as the distance from the crack to the surface decreases, (2) in bonded dissimilar materials with a crack parallel to the interface in the medium with higher modulus, the stress intensity factor increases as the distance from the crack to the interface decreases, but if the crack lies in the medium of lower modulus, the stress intensity factor decreases as the crack-to-interface distance decreases, (3) in symmetric loading the crack tends to propagate to the side with less stiffness. Cracks were found to curve toward the free surface or the interface if the adjoining medium had lower modulus, and away from the interface if the modulus is higher.

105. Erdogan, F. and Biricikoglu, V., "Two Bonded Half Planes with a Crack Going Through the Interface." Lehigh University, Institute of Fracture and Solid Mechanics, Bethlehem, Pa. National Aeronautics and Space Administration Contract Report No. NASA-CR-2181, February 1973. (N73-16910)

The plane problem of two bonded elastic half planes containing a finite crack perpendicular to and going through the interface was investigated. The problem was formulated as a system of singular integral equations with generalized Cauchy kernels. Crack surface displacements and both normal and shear components of the stress intensity factors are given.

106. Erdogan, F. and Civelek, M. B., "Contact Problem for an Elastic Reinforcement Bonded to an Elastic Plate." Lehigh University, Department of Mechanical Engineering and Mechanics, Bethlehem, Pa. National Aeronautics and Space Administration Contract Report No. NASA-CR-132273, February 1973. (N73-26933)

The boundary between two materials where the stiffening layer is treated as an elastic membrane and the base plate is assumed to be an elastic continuum, was assumed to be either one of direct adhesion or through a thin adhesive layer which is treated as a shear spring. The solution for a case in which both the stiffener and the base plate are treated as membranes is also given. The contact stress was obtained for a series of numerical examples.

107. Erdogan, F. and Gupta, G. D., "Stresses Near a Flat Inclusion in Bonded Dissimilar Materials," Int. J. Solids Struct., 8 (1972), 533-47.

The plane elastic problem for bonded materials containing a flat inclusion located parallel to or on the interface which may be rigid or elastic with negligible bending rigidity was investigated. The integral equations for rigid and elastic inclusions were developed and their solutions described. The stress state around the singular points was investigated and a pair of stress intensity factors similar to that for crack problems are defined. Numerical examples for two bonded half planes and for a half plane are given. Stress intensity factors are presented as functions of the ratio of the distance from the interface to the length of the inclusion.

108. Erdogan, F. and Gupta, G. D., "The Torsion Problem of a Disk Bonded to a Dissimilar Shaft," Int. J. Solids Struct., 8 (1972), 93-109.

The torsion of an infinitely long elastic shaft bonded to an elastic disk of finite width and of different elastic constants was investigated. The general problem with axisymmetric edge cracks on the contact area is shown to reduce to a singular integral equation with a simple Cauchy-type singularity. In the limit, when the contact is along the entire width of the disk, the dominant kernel of the integral equation is of generalized Cauchy-type and the solution has a singularity. A series of numerical examples with or without edge cracks and under symmetric and axisymmetric external loads are given. The results of a series of numerical examples with a variation of the torsion problem, two semi-infinite strips under antiplane shear loading, show the effect of the geometry and the material properties on the stress intensity factor.

109. Fichter, W. B., "Shear Stress Intensity Factors for Elastic Sheets with Cover Plates." National Aeronautics and Space Administration, Langley Research Center, Langley Station, Va. Research Report No. NASA-TN-D-7473, April 1974. (N74-21548)

Shear stress intensity factors for three problems concerning inextensible cover plates either bonded to or embedded in an elastic sheet under uniaxial tension were calculated. These factors are small when the ratio of sheet thickness to cover plate length is small but as the ratio increases these factors rapidly approach their asymptotic values for infinite sheet thickness. In the embedded cover plate, the stress intensity factor is also dependent on Poisson's ratio of the sheet material when the ratio of sheet thickness to cover plate length is small.

110. Hein, V. L. and Erdogan, F., "Stress Singularities in a Two-Material Wedge," Int. J. Fract. Mech., 7 (1971), 317-30.

A solution method for plane-strain and plane stress problems in a two-material wedge-shaped region of arbitrary angle is presented. The results were obtained by use of the Mellin transforms and the theory of residues. The characteristic equation was investigated to determine the stress singularity resulting from certain combinations of geometry and material properties and a formal solution is then presented for the case where loading is in the form of a point dislocation along the interface. The results obtained show that for small values of r the dominant effect is due to geometry and the secondary effect caused by the choice of elastic constants of the materials.

111. Hutula, D. N. and Lemke, D. G., "Flexure of Laminated Reissner Plates," J. Spacecr. Rockets, 9 (1972), 84-87.

The flexure of two isotropic Reissner flat plates, bonded by a thin adhesive layer and having both finite transverse normal and shear flexibility was analyzed. Equations governing the stress distribution in the adhesive were developed in general tensor form and allowances were made for different surface shear and normal tractions. Results indicate that the normal stresses are governed by three Helmholtz equations which reduce to Bessel equations in the case of axial symmetry. The stress variation in the adhesive was predicted and results were obtained in terms of the Dinnic function for a clamped circular plate.

112. Jahanshahi, A., "Bond Failure Between Elastic Plates and Rigid Bodies." Cornell University, Department of Theoretical and Applied Mechanics, Ithaca, N. Y. Office of Naval Research Contract Report No. TR-12, April 1972. (AD 741 209)

The problem of continuous failure of bond between a thin elastic plate and a rigid body was studied using the Timoshenko theory of flexural motions of thin plates and the theory of elasticity. The case of bond failure due to line and point forces moving on the plate is investigated.
See also: Jahanshahi, A., "Continuous Bond Failure Due to a Moving Force," Trans. ASME, Ser. E: J. Appl. Mech., 40 (1973), 541-45.

113. Lin, F., "The Elastic Stress Analysis of a Bi-Material Plate with a Crack Normal to the Interfaces." University of Illinois, Department of Theoretical and Applied Mechanics, Urbana. Naval Air Systems Command Contract Report No. T/AM-356, May 1972. (AD 748 299)

The finite element method was used to analyze the elastic stresses of a bi-material plate with a crack normally approaching the interfaces and with crack tips at the interface. Procedures and computer programs for the plate under plane stress conditions were developed and the strength of stress singularity and the stress distribution discussed. The strain energy release rate, G, was calculated by a potential energy method for cracks approaching the interfaces and the strain energy release rate coefficient, G/P^2, of an Al-epoxy system was determined by an experimental compliance calibration procedure. The elastic stress function near the crack tip was determined by a boundary collocation procedure applied to the Zak and Williams stress function.

114. Miller, M. and Cartwright, D. J., "Stress Intensity Factors for a Crack in Two Intersecting Uniformly Stressed Sheets," Int. J. Eng. Sci., 12 (1974), 353-59.

A model for a crack growing simultaneously in the stiffener and the main sheet in which the stiffener is continuously attached is presented. Stress intensity factors were determined for two unequal length cracks bisecting each other at the line of intersection of two uniformly stressed mutually perpendicular infinite sheets. Compatibility of displacements was maintained along the line of intersection of the sheets and the problem was reduced to the solution of a singular integral equation. The effect of different elastic moduli in the sheet and stiffener is shown.

115. Pu, S. L., Scanlon, R. D., and Hussain, M. A., "Stress Singularities Associated with a Crack Inclined to a Bi-Material Interface." Developments in Mechanics, Vol. 7. Proceedings of the 13th Midwestern Mechanics Conference held at the University of Pittsburgh, 13-15 August 1973. Pittsburgh: University of Pittsburgh (1973), 349-64.

The nature of stress singularities associated with a crack inclined to a bimaterial interface under general loading conditions was investigated. The stress singularities were obtained from eigenvalues of a characteristic equation. Because study of these results indicated a physical paradox, the problem was reformulated incorporating boundary layer effects using couple stress theory. It was shown that there are only two possible angles of inclination of a crack to an interface for which the singular stress field of a crack in a homogeneous material could be preserved. This suggests that there are only two possible paths of propagation of a crack as it approaches an interface.

116. Sih, G. C. and Chen, E. P., "Torsion of a Laminar Composite Debonded over a Penny-Shaped Area," J. Franklin Inst., 293 (1972), 251-61.

The effect of an imperfectly bonded laminar composite - modeled by four different materials with the two outer layers being infinite in height and debonding occurring at the interface of the two inner layers - was examined in terms of intensification of the torsional stresses operative near the imperfection. The analysis is based on the application of Hankel transforms and the solution of a pair of dual integral equations and is extended to a multi-layer system. Delamination takes place either in a stable or unstable manner depending on the size of the layer thickness relative to the radius of the debonded area. The influence of lamination tends to lower the stress intensity around the interface imperfection as compared to the stress state in a homogeneous solid solution containing the same imperfection. Numerical results were obtained for two special laminate geometries and are discussed with reference to the pertinent parameters used in the current theory of fracture mechanics.

117. Swanson, S. R., "Finite-Element Solutions for a Cracked Two-Layered Elastic Cylinder," Eng. Fract. Mech., 3 (1971), 283-89.

Stress intensity factors of a two-layered plane strain cylinder with a cracked inner bore under internal pressure loading were obtained using the finite element method. Solutions were obtained for two cylinder geometries and a range of crack sizes using the energy release rate with crack extension calculated by the finite element code. Results showed good comparison with check problems and the procedure is insensitive to element mesh size. Stress intensity results showed that a maximum was reached at an intermediate crack size. A simple approximate formula for K_1, that compared well with numerical results and reduces cases available in the literature to a certain limit, is presented.

118. Swenson, D. O. and Rau, C. A., Jr., "The Stress Distribution Around a Crack Perpendicular to an Interface Between Materials," Int. J. Fract. Mech., 6 (1970), 357-65.

The problem of plane strain of a crack terminating perpendicular to a planar interface between two isotropic half spaces with different elastic constants was solved to obtain the stress distribution in the area of the crack tip. The relative magnitudes of the various stress components and their radial drop off with distance from the crack tip are shown to be affected by the relative elastic constants. It was also shown that differences in Poisson's ratio affect the relative intensities of the various stress components and that these changes vary with the modulus ratio.

119. Wang, C. Y., "Fracture Mechanics for an Interfacial Crack Between Adhesively Bonded Dissimilar Materials." Unpublished Ph.D. dissertation, University of Illinois at Urbana, Champaign, 1972.

A plate composed of two dissimilar materials bonded together along a straight line with a center crack, representing an idealization of an adhesive joint with an interfacial crack caused by faulty joining techniques was studied. The strain energy and J integral methods combined with the finite element technique were extended to a bimaterial problem to calculate the strain energy rate value. Three categories of composite materials with moduli ratio, E sub 2/E sub 1 = 1, 20, and 120 were numerically analyzed and results provided a complete crack-tip stress analysis. The compliance method was used to experimentally verify the numerical results.

See also: Wang, C. Y., "Fracture Mechanics for an Interfacial Crack Between Adhesively Bonded Dissimilar Materials." University of Illinois, Department of Theoretical and Applied Mechanics, Urbana. Naval Air Systems Command Contract Report No. T/AM-353, March 1972. (AD 742 124)

STRUCTURAL JOINTS AND TRANSITIONS

120. Amel'yanovitch, K. K., "Stress and Strain Distribution in the Neighborhood of the Join Between the Dished End and the Cylindrical Body of a Pressure Vessel Made of Dissimilar Materials," Strength Mater., 4 (1972), 358-60. Translation of Probl. Proch., No. 3 (1972), 102-04.

The problem of finding the stress and strain distribution in a vessel consisting of a cylindrical shell and a spherical dished end is reduced to finding the bending moment and shearing forces at the transition section. Indeterminacy at the joint is resolved by imposing compatible linear displacements, angular rotations, forces, and moments. It is shown, for instance, that when the dished end and cylinder are joined at an angle, the bending stresses become less important for increasing thicknesses.

121. Fan, H. Y. and Muki, R., "Load Transfer from a Web to Two Parallel Sheets," Appl. Sci. Res., 25 (November 1971), 1-25.

The elastostic transfer of a tensile load from an infinite strip-shaped web of uniform rectangular cross section of two identical parallel sheets of infinite extent is discussed. The two-dimensional theory of generalized plane stress was used to analyze conditions within the sheet. Two alternative models for the web - one where it is regarded as a two-dimensional continuum and the other it is regarded as a one-dimensional elastic continuum - were considered. An integral Cauchy type singular kernel for the density of bond force between the web and the sheets was obtained in each case. The equation was reduced to a Fredholm integral solution of the second kind.

122. Fedenko, G. I., "Calculation of the Stress Concentration Produced by an Internal Pressure in the Region Where a Cylindrical Shell is Connected to a Branched Pipe," Strength Mater., 4 (1972), 567-74. Translation of Probl. Proch., No. 5 (1972), 59-65.

The results of an integration of the differential equations which describe the equilibrium of a cylindrical shell weakened by a large aperture, yielded a closed form solution for the displacements, the forces, and the moments. The boundary conditions to be used in determining the integration constants are presented. Simple formulas for calculating the stress concentration in an arbitrary point of the region where the cell is connected to the branched pipe are given and the calculated results are compared with experimental data.

123. Fousse, E. M., "Elastic Stress Analysis of Brazed Joints." Unpublished Ph.D. dissertation, Stanford University, 1971.

The elastic state of stress of thin butt-brazed joints (t/d ratio $\leq$ .10) was investigated. With cylindrical coordinates and axial symmetry, Love's stress function was used to determine the stresses and displacements when the base metal was rigid. In this formulation, convergence problems at the outer boundary and inconsistencies for large values of t/d did not allow any satisfactory results to be obtained in the general case of an elastic base metal. The elastic base problem was treated using a perturbation technique and non orthogonal radial stress functions in a series expansion of Chebyshev polynomials. While the analysis does not allow prediction of the five to six fold strengthening over strength of unconstrained braze metal observed in butt-brazed joints, it appears satisfactory for elastic stress estimates.

124. Greste, O., "A Computer Program for the Analysis of Tubular Joints." University of California, Structural Engineering Laboratory, Berkeley. Research Report No. SESM-69-19, November 1969. (PB 189 501)

The finite element analysis of tubular K joints, consisting of two pipes intersecting a third, was investigated. Static-linear-elastic analysis was performed. The model is composed of triangular and quadrilateral shell elements. The finite element mesh refinement was four degrees of freedom and with suitable equipment the meshes could be developed. A variety of boundary and loading conditions can be applied. Displacements, moments and membrane forces, and surface stresses of the structure may be measured.

125. Greste, O. and Clough, R. W., "Finite Element Analysis of Tubular Joints: A Report On a Feasibility Study." University of California, Structural Engineering Laboratory, Berkeley. Research Report No. SESM-67-7, April 1967. (PB 189 497)

The accuracy and reliability of a finite element shell analysis program in the evaluation of stresses and deflections in typical tubular joints were investigated. The results of the finite element solutions were compared with those obtained by a cylindrical shell analytical program and a set of available results.

126. Greste, O. and Clough, R. W., "Finite Element Analysis of Tubular K Joints." University of California, Structural Engineering Laboratory, Berkeley. Research Report No. SESM-70-11, June 1970. (PB 193 560)

The finite element analysis of tubular K joints, consisting of two smaller diameter joints welded to a larger diameter tube, was studied along with the automatic generation of data for the analysis. The model is composed of triangular and quadrilateral shell elements having five degrees of displacement and rotation freedom per node. In order to minimize the computations needed, substructuring is used. A description of the joint geometry and the degree of mesh refinement desired are used in the analysis computer program to generate the finite element model for the joint. The analytical results are compared with the experimental data.

127. Holliday, G. H., "A Three-Dimensional Photoelastic Study of Welded Tubular T-Connections." Unpublished Ph.D. dissertation, University of Houston, 1970.

Stress distributions of intersecting tubular connections were obtained by three dimensional photoelasticity. The problems encountered and recommended practices for making tubular connections are discussed. Stress distributions, particularly near the intersection weld where stresses are high, are also investigated. It is shown that the maximum stress is not at the intersection, but slightly out board because of wall bending. Furthermore the localized bending leads to an oval deflection shape. Thus shell theories must be carefully applied to adequately consider bending effects.

128. Jones, R. M., "Buckling of Stiffened Two-Layered Shells of Revolution with a Circumferentially Cracked Unbonded Layer," AIAA J. 7 (1969), 1151-57.

Orthotropic stiffness layer models were derived for buckling of eccentrically stiffened two-layered shells of revolution with an unbonded, circumferentially cracked layer. The models are used to assess the importance of including the ablative layer in design calculations for two-layered (metallic plus ablative) re-entry vehicle shells. Results indicate that the ablative layer, even when circumferentially cracked and not bonded to the metallic layer, dominates the stiffness and provides an available source of stiffness for design calculations. A numerical example illustrating the application of the derived models is presented.

129. Kaplan, S. M., "Flexibility Coefficients for Structural Joint Assemblies," J. Spacecr. Rockets, 8 (1971), 76-77.

Semiempirical formulations for representing the bending, axial, and torsional flexibility coefficients of structural joint assemblies were developed. Joint flexibility is shown to be inversely proportional to the cube of the joint assembly diameter for the bending and torsional cases, and inversely proportional to this diameter for the axial case.

130. Kulkarni, S. V., "Mechanics of Delaminations in Layered Cylindrical Shells." Unpublished Ph.D. dissertation, Virginia Polytechnic Institute and State University, 1972.

The dynamic properties of a delaminated shell of revolution were studied in order to construct a model for the use of natural frequency as a parameter in delamination detection. Within the framework of linear thin shell theory and Kirchoff-Love's postulates, the governing equations for a shell revolution were cast into eight differential equations. The classical problem of the free vibrations of a clamped-clamped cylindrical shell was investigated.

The buckling of a partially debonded two layer cylindrical shell subjected to axial compression was investigated. The problem was solved numerically using a "branched integration" technique. Critical loads for different lengths of debonding and inner and outer layer thickness ratios were obtained. Significant differences in the buckling loads were observed and the mode shapes for different layer thicknesses indicated a distinct pattern in each of the debonded layers but the layers tended to buckle with identical mode shapes for certain values of the buckling loads.

See also: Kulkarni, S. V. and Frederick, D., "Frequency as a Parameter in Delamination Problems - A Preliminary Investigation," J. Compos. Mater., 5 (1971), 112-17, and

Kulkarni, S. V. and Frederick, D., "Buckling of Partially Debonded Layered Cylindrical Shells." Virginia Polytechnic Institute and State University, Department of Engineering Science and Mechanics, Blacksburg. Watervliet Arsenal Contract Report No. VPI-E-73-17, April 1973. (AD 760 725)

131. Lionberger, S. R. and Weaver, W., Jr., "Dynamic Response of Frames with Nonrigid Connections," Proc. ASCE, J. Eng. Mech. Div., 95, No. EM1 (1969), 95-114.

The non linear dynamic response of laterally loaded plane rectangular building frames with rotationally flexible connections was approximated by a stiffness method of analysis using a series of incremental linear analyses. Joint rotations and translations at framing levels are the displacements in the analysis - axial strains are excluded. Effects of finite joint sizes are included by assuming that the portions of a frame common to intersections are rigid. Incremental equations of motion are solved using the linear acceleration method coupled with a block tridiagonal elimination scheme. A computer program was developed for the analysis and an example of its application is given.

132. Mandel, J. A., Mathur, R. K., and Chang, Y. C., "Stress Waves at Rigid Right Angle Joint," Proc. ASCE, J. Eng. Mech. Div., 97, No. EM4 (1971), 1173-86.

Analytical and experimental studies of the effect of a rigid right angle joint on the transmission of longitudinal and flexural stress waves were conducted. In order to consider longitudinal and flexural stress simultaneously, a theory combining Timoshenko and Elementary Theories were used in analytical studies. The theory consisted of seven quasi-linear first order potential differential equations that are hyperbolic equations which are solved using the method of characteristics. The analytical results were checked by an experimental program and showed excellent agreement.

133. Mehrotra, B. L. and Govil, A. K., "Shear Lag Analysis of Rectangular Full-Width Tube Junctions," Proc. ASCE, J. Struct. Div., 98, ST1 (1972), 287-305.

Joint moduli as well as longitudinal membrane stresses and deflection of the beam branches subjected to pure couples for square and rectangular tubular beam to square tubular column connections were calculated using Reissner's differential equation for the problem of shear lag in box beams. The deflection curve and two stress distributions obtained are compared with those obtained by other methods. The following assumptions can be made: (1) the shear deformability of the beam flanges results in parabolic displacement profiles across the width, (2) the beam flanges are free at the junction.

134. Pinkney, R. B., "Cyclic Plastic Analysis of Structural Steel Joints." University of California, Earthquake Engineering Research Center, Berkeley. Research Report No. EERC-73-15, August 1973. (PB 226 843)

Cyclic inelastic stress reversal in the joints between beams and columns of an unbraced building frame can be induced by severe lateral loading due to high winds or earthquake. Accurate frame analysis requires a knowledge of joint behavior beyond the elastic range. Accordingly a method of predicting the cyclic inelastic response of a structural steel joint was investigated in this study.

135. Prince, N. and Rashid, Y. R., "Structural Analysis of Shell Intersections." Pressure Vessel Technology, Part I. Design and Analysis. Proceedings of the First International Conference, Delft, Netherlands, 29 September-2 October 1969. New York: American Society of Mechanical Engineers (1969), 245-54.

A finite element analysis, using a triangular plate element whose membrane and bending deformations were approximated by cubic polynomial functions, for general three-dimensional elastic thin shells is presented. The shell surface is approximated by a network of these plate elements having arbitrary orientation, which allows the treatment of shells of arbitrary configurations and loading. The solution of the resulting number of unknowns is discussed briefly and comparisons with a simpler model and a known exact solution are presented.

136. Rodabaugh, E. C., "Phase Report No. 115-1 On Stress Indices for Small Branch Connections with External Loadings." Battelle Memorial Institute, Columbus, Ohio. Oak Ridge National Laboratory Subcontract Report for the U. S. Atomic Energy Commission. Research Report No. ORNL-TM-3014, August 1970.

Stress indexes and simplified design formulas for stress analysis of small branch connections were developed. Equations for reducing the set of nine moments which act on a branch connection are given and numerical values from a piping flexibility analysis of two resultant moments were obtained. Stress indexes to be used with these moments were developed empirically from existing test data and design rules for inclusion in the ANSI standard are proposed. The effects of direct shear force loadings on branch connections are also discussed.

137. Romstad, K. M. and Subramanian, C. V., "Analysis of Frames with Partial Connection Rigidity," Proc. Amer. Soc. Civil Eng., J. Struct. Div., 96, No. ST11 (1970), 2283-2300.

A computer program for the analysis of frames with partially rigid beam-to-column connections is described. A bilinear model was used to approximate the moment-rotation relationships for partially rigid connections. Slopes of the model were graphically determined and used to define connection rigidities. Element stiffness ratios which include the effect of these partial rigidities were derived and then used in a direct stiffness method of solution. Analysis for stability was carried out using the classical method of determining bifurcation states. Examples of problems solved are presented.

138. Rose, J. L., Mortimer, R. W., and Blum, A., "Elastic-Wave Propagation in a Joined Cylindrical-Conical-Cylindrical Shell," Exp. Mech., 13 (1973), 150-56.

Experimental and analytical studies of the problem of longitudinal impact of a thin finite-joined shell, consisting of a cylinder-truncated cone-cylinder were conducted on a model, a 1/100 scale replica of a portion of the Apollo/Saturn V vehicle. Longitudinal and circumferential strain pulses were monitored on each section of the joined shell. Velocity of the impacter ring prior to impact was measured and used as a boundary condition in the solution. A "bending" theory, including tranverse-shear, radial-inertia, and rotary-inertia effects, was used to analyze the finite-joined shell and appropriate transformation relations were developed at each of the joints. By solving the governing equations numerically by the method of characteristics the results were then obtained with good agreement between the analytical and experimental profiles.

139. Schneider, R. W., Jackson, W. M., and Nicolls, W. R., "Photoelastic Study and Fatigue Tests of a Contoured, Integrally Reinforced Branch Connection," Trans. ASME, Ser. B: J. Eng. Ind., 93 (1971), 1021-29.

A contoured, integrally reinforced branch connection in a cylindrical pressure vessel was tested by means of three-dimensional photoelasticity using the stress-freezing and slicing technique on three epoxy models. Internal pressure, a longitudinal moment on the branch, and a transverse bending moment on the branch were modes of load applied, one to each model. Stress concentration factors from the photoelastic tests and stress intensification factors from the bending tests are compared. Stress concentration factors for internal pressure, derived from the photoelastic tests, are presented.

140. Scholes, A. and Strover, E. M., "The Piecewise-Linear Analysis of Two Connecting Structures Including the Effect of Clearance at the Connections," Int. J. Numer. Methods Eng., 3 (1971), 45-51.

A systematic method of force-deflection analysis for structures having connections with clearance is presented. The class of structure may be termed piecewise linear if contact can be assumed to occur only at a number of discrete points. A basic assumption of the linear analysis is that the behavior of the connections is described by the movements of pairs of nodes and that as the load on the structure changes, clearance at these nodes will open or close and each time this occurs the stiffness of the combined structure changes because its configuration has changed.

141. Scordelis, A. C. and Bouwkamp, J. G., "Analytical Study of Tubular Tee-Joints," Proc. ASCE, J. Struct. Div., 96, No. ST1 (1970), 65-87.

The elastic analysis of tubular joints subjected to specific loads or displacements was investigated. The analytical models used simulated a typical tee-type tubular connection consisting of a web tube interwelded and normal to a chord tube which is assumed to be simply supported at its two ends, where end diaphragms exist which are infinitely rigid in their own plane, but perfectly flexible normal to their own plane. In the method of analysis a tubular cylindrical shell under a variety of loadings may be analyzed for any input loading or displacement pattern. The computer programs developed provide automatic solutions for cases with internal stresses or displacements and for the case in which either applied forces or displacements are imposed on the shell at specific points. Results are correlated with data obtained by other investigators.

142. Stevens, J. H. and Layman, W. E., "Development of an Adhesively Bonded Beryllium Propulsion Structure for the Mariner Mars 1971 Spacecraft." Jet Propulsion Laboratory, California Institute of Technology, Pasadena. National Aeronautics and Space Administration Contract Report No. NASA-CR-124742 (JPL-TM-33-517), January 1972. (N72-14871)

The design, testing, and fabrication of the support truss structure, consisting of Be tubes adhesively bonded to Mg end fittings, for the propulsion system of the Mariner 9 spacecraft are described. Adhesive bonding, rather than riveting was used because of the low toughness of Be. The use of Mg in the end fittings resulted in a 50% wt. saving, as compared with Al, because geometric factors in the fitting design resulted in a low stress area and the low density of Mg was beneficial.

143. Toprac, A. A., "Static and Fatigue Behavior of Tubular Connections: A Summary Report." Final Report 1967-1971. University of Texas, Structures Fatigue Research Laboratory, Austin. Naval Facilities Engineering Command Contract Report No. SFRL-TR-P550-12, April 1972. (AD 746 894)

Results of research studies on both static and fatigue strength of tubular joints. A literature review of theoretical and experimental findings is presented. Design considerations for the static strength and fatigue life of these joints are suggested. Design curves indicate the static strength of tubular joints with yield strength and a thickness parameter as influencing factors. S-N curves (stress range vs. cycles to failure) for the fatigue life of T-and K-connections are also presented. Data could be used in design of tubular structures with similar dimensions.

144. VacharajiHiphan, P. and Trahair, N.S., "Warping and Distortion at I-Section Joints," Proc. ASCE, J. Struct. Div., 100, No. ST3 (1974), 547-64.

The warping and distortion at the ends of members of doubly symmetric I-section were studied theoretically and experimentally, and the effect on these properties by the addition of web stiffeners or additional webs was investigated. Analytical expressions for the warping and distortion restraint stiffnesses of single members are given. Study of the behavior of rigid angle joints between I-section members showed that warping and distortion at a joint are interdependent. A finite element model was used to determine the effects of member length, joint angle, and stiffener arrangement on the restraint against end warping. Approximations for estimating the warping restraints were shown to be conservative.

145. Van Campen, D. H., "Stress Distribution in an Arbitrarily Loaded Nozzle-to-Flat Plate Connection," Nucl. Eng. Design, 11 (1970), 495-516.

The mechanical and thermal stresses in arbitrarily loaded nozzle-to-plate connections were determined using a finite element computation method. The general solution for the displacements is taken to be a series solution and because of this a triangular ring element was developed with a nonaxisymmetric strain distribution varying linearly over the cross-section. The proposed method is intended to be used for determining the peak stresses at nozzle-to-cylinder intersections for sufficiently small d/D ratios, $\leq 1/4$.

146. Wei, B. C. F., "Balanced Stresses in Post-Yielded Multi-Material Structural Joints." General Electric Company, Missiles and Space Division, Philadelphia, Pa. National Aeronautics and Space Administration Contract Report No. NASA-CR-109496, November 1969. (N70-26459)

The finite element method was applied to solve the stresses in an axisymmetric post-yielded tongue-and-groove cylindrical post composed of a Ta tongue brazed to a stainless steel groove using a Co base alloy. The stress distribution in the mini-brazed area was also investigated. Bilinear stress-strain relations were established to facilitate a solution to the problem. Stress variations are shown by iso-stress maps in the joint. Results show that the stresses in the post-yielded multilateral joint are balanced, and for example, their peak values from the elasticity solutions are significantly reduced. Bilinear analyses under the thermal loads were found to converge rapidly.

AUTHOR INDEX

Numbers refer to entries in the bibliography

REPORT NUMBER INDEX

Numbers refer to entries in the bibliography

THESIS INDEX

Numbers refer to entries in the bibliography