NAVORD REPORT 2372

ADHESIVES HANDBOOK PART I

ENGINEERING PRINCIPLES

1 February 1952

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

ADHESIVES HANDBOOK PART I
ENGINEERING PRINCIPLES

Prepared by:
H. A. Perry, Jr., L. Hardis, H. E. Mathews, Jr.,
L. Briggs, E. W. Eagleson and R. S. Fey

ABSTRACT: This preliminary report presents some aspects of the physical and engineering principles as presently understood, for the design, assembly and inspection of adhesives bonds and for the testing of adhesives.

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NAVORD Report 2272 1 February 1952

This is a Preliminary Report in which an effort has been made to compile available information on the physical and engineering principles involved in the design, bonding, inspection and testing of adhesive bonds, especially of those types most frequently used in ordnance devices. The literature in this field is fragmentary and inadequate and it is hoped that valuable experience obtained by the users of this report will be made available to the authors for incorporation in subsequent revisions. NAVORD Report 2273 (Restricted) is a companion to this Report and contains engineering data on adhesives and adherends in loose leaf form for use in specific adhesive bond design problems, as well as abstracts of government and commercial specifications on adhesives. These Reports were prepared at the request of the Bureau of Ordnance under NOL Task Relb-450, entitled "Adhesives for Ordnance Use". Large segments of the field of adhesives technology remain controversial to date. The opinions expressed in this Report are those of the authors and are published for information only. The Laboratory wishes to express its appreciation to Dr. G. M. Kline and Mr. F. W. Reinhart of the National Bureau of Standards for granting permission to reproduce their valuable paper on "The Fundamentals of Adhesion" which had been published earlier in "Mechanical Engineering" and in the "Paper Trade Journal".

W. G. SCHINDLER
Rear Admiral, USN
Commander

S W Booth
S. W. BOOTH
By direction

CONTENTS

Section Page

I Introduction 1

II Theoretical Background 4

The Fundamentals of Adhesion.............. 4

The Distribution of Stresses in Adhesive Bonds 17

The Rheology of Polymers 47

The Statistics of Fracture 58

III Design Principles for Structural Adhesive Bonds................................... 70

General Discussion 70

Advantages and Disadvantages of Adhesive Bonds 70

Selection of Joint Geometry 72

Selection of Adhesive..................... 80

Selection of Dimensions................... 82

Test Data Showing the Influence of Some Design Parameters........................ 86

IV Bonding Processes.......................... 92

General Considerations.................... 92

Surface Preparation of Adherends......... 92

Application of the Adhesive............... 94

Application of Pressure................... 101

Application of Heat....................... 103

V Test and Inspection Methods................ 110

General Discussion........................ 110

ASTM Test Methods........................ 111

Model Testing............................. 117

Inspection of Adhesive Bonds.............. 117

VI Glossary.................................. 120

which is a first order approximation assuming small strains and which is useful with some metals, is not appropriate for use in the design of an adhesive bond in view of the viscoelastic properties and non-linear stress-strain relationships which are characteristic of all but the most brittle and highly crosslinked polymeric substances from which adhesives are compounded. From a statistical viewpoint adhesive bonds exhibit distributions of mechanical strengths which are scattered more widely than those observed in metals for reasons which are not well understood. Lastly, a material may be tested as an adhesive only by testing a structure containing a bonded layer of the material, the stress distributions in which are not yet defined. In fact, the actual mechanical strengths of materials in a bond cannot be characterized except in terms of the net strength of the particular assembly tested, and adhesives can be compared only by comparing the performance of given bonded assemblies.

In view of the difficulties associated with the chemical, mechanical and statistical aspects of the technology of adhesives, together with the limited market for adhesives, no great effort has been applied by industrial interests toward the development of this field very far beyond the status of an art, and the development of improved adhesives has been to great extent a "cut and try" process, with great reliance being placed on consumer acceptance for further direction of chemical formulation.

In turn, the engineer is forced to approach his design problems in a similar fashion, using his best judgment as to the materials, processes and geometries to employ and evaluating his decisions by studying the performance and reliability of the finished structure. From the ordnance engineer's point of view the main drawbacks to the use of an adhesive bond include the reputation of adhesives for low reliability, the relative backwardness of the technology of adhesives and the scarcity of useful information on the thousands of adhesives which are available commercially. However, the advantages of adhesive bonds over mechanical and other means of attachment, particularly the ability of an adhesive to spread stresses in a weak structural material and to bear heavy loads, together with dielectric characteristics, sealant properties and ease of fabrication without vibration or shock and sometimes without heat, make an adhesive bond attractive to the engineer and impel him to muddle through a bond design despite the attendant uncertainties.

practical importance using the theory developed by Goland and Reissner, the results of which are included in the Section. In addition, the various theories of strength fracture and creep are discussed briefly in relation to the behavior of adhesive bond.

In Section III the authors have set forth a framework for a systematic approach to the design of an adhesive bond, which framework is now in the process of development at this laboratory. The system is inoperable in its present form due to the lack of accurate descriptions of stress concentrations in adhesive bonds and due to a lack of definitive data on the statistical distribution of strength after exposure to service environments. However it is presented to show the trends in thinking which may lead to an tolerable systematic approach as further research and development is carried out. For the immediate assistance of the design engineer practical advice is given regarding the many factors which are involved in a design problem.

In treating the topic of bonding processes in Section IV the subject has been approached in a general way, covering the available forms of adhesives, spreading techniques, the assembly of the bond, the application of force and the heating of the bond. Specific directions for the use of proprietary adhesives are set forth in the companion report along with the properties of the adhesives.

Test methods and inspection procedures are described and discussed in Section V, the aim being to acquaint the engineer with those methods which are available and with current opinions relating to their theory and validity as well as to discuss the usefulness of the data obtainable by this use. The inspection of completed bonds is discussed and the various methods which have been proposed for this purpose are described.

A glossary of terms is given in Section VI. This glossary was developed by the ASTM Committee D-14 on Adhesives and has been modified by the authors to a minor extent as dictated by circumstances.

Section II. THEORETICAL BACKGROUND

The Fundamentals of Adhesion (1) - G. M. Kline (2) and F. W. Reinhart (2)

The most significant factor in adhesion is the molecular attraction operative between the adherend and the adhesive.

---

(1) This paper was published in "The Paper Trade Journal" in 1950 and is reporduced with the permission of the authors.

(2) National Bureau of Standards, Washington, D. C.

There are many physical factors which affect the strength of a bond by determining the closeness of contact of the adherend and adhesive, by altering the surface area involved, or by influencing the stress conditions in the joint either as initially formed or under external loading. Although some of the strength of a bond between an adhesive and a porous surface can be attributed to tendrils of adhesive which enter the pores, this mechanical interpenetration can not account for more than a small fraction of the joint strength. Evidence has accumulated from many pertinent fields which indicates that molecular attractive forces are primarily responsible for the bond between any two surfaces.

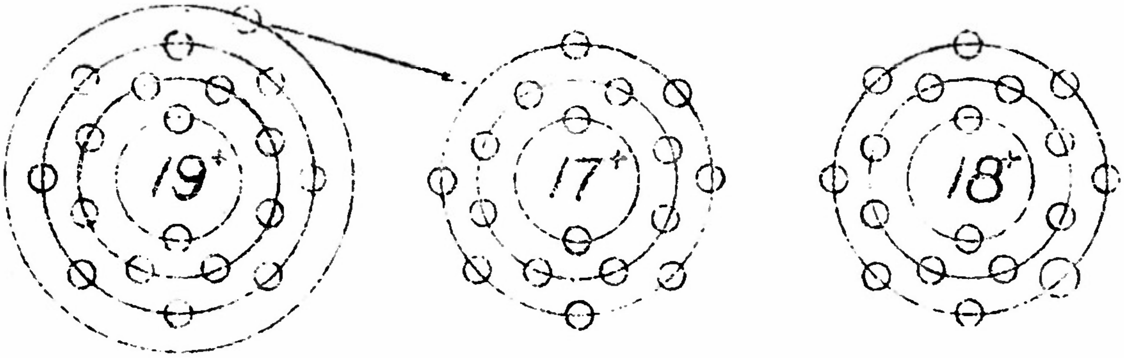
The types of chemical bonds involved in specific adhesion will be reviewed first in this paper, followed by a discussion of various physical factors which affect bond strengths.

CHEMICAL FACTORS IN ADHESION

In considering the chemical and physical phenomena involved in adhesion and cohesion, four general types of chemical bonds must be recognized: electrostatic, covalent, and metallic, which are referred to as primary valence bonds, and residual bonding attraction forces, commonly known as van der Waal forces, which are referred to as secondady valence bonds.

PRIMARY BONDS

Electrostatic bonds. Electrostatic or polar bonds are the type which act to hold together the atoms in common salts. An element immediately preceding a rare gas in the periodic table is strongly electronegative, whereas one immediately following it is strongly electropositive. There is a tendency on the part of the reactive elements to change their configurations to conform with those of the rare gases, which are remarkably inert. Thus, an atom of potassium combines with one of chlorine by means of an electron transfer which results in the configuration of argon for each.



By means of this mutual claim on the transferred electron the two ions will remain closely associated with one another as potassium chloride. This association can be interfered with, however, as by solution in water, in which case the potassium chloride will dissociate into chlorine as a negative ion and potassium as a positive ion. If the water is removed by evaporation, these ions will align themselves to form a crystal lattice. In such a solid the attractive forces between the oppositely charged ions, except those on the surface, will be satisfied. However, in an amorphous solid some of the attractive polar forces will not be satisfied because of the random distribution of the ions.

Co-valent bonds. These are the type which act to hold together the atoms of carbon, hydrogen, and other elements in organic compounds. It is also this type of bond which holds the atoms together in diatomic gases, such as chlorine. A co-valent bond is one formed by two atoms sharing electrons in such a way as to account for the stability of each in attaining the rare gas configuration. Thus, in the chlorine molecule each atom requires an electron to complete its outer shell.

In this molecule the positive attraction of the nucleus of each atom is equally great on each of the two negative charges of the shared pair. Substances formed by such bonds do not ionize in solution. In the case of carbon, it has an outer shell of four electrons which it will share in covalent bonds with other atoms to obtain a stable outer shell structure of eight electrons. In stable gas methane it shares an electron with each of four hydrogen atoms

$$\cdot\overset{\cdot}{\underset{\cdot}{C}}\cdot \qquad 4H\cdot \longrightarrow H\overset{\cdot\cdot}{\underset{\cdot\cdot}{:C:}}H$$

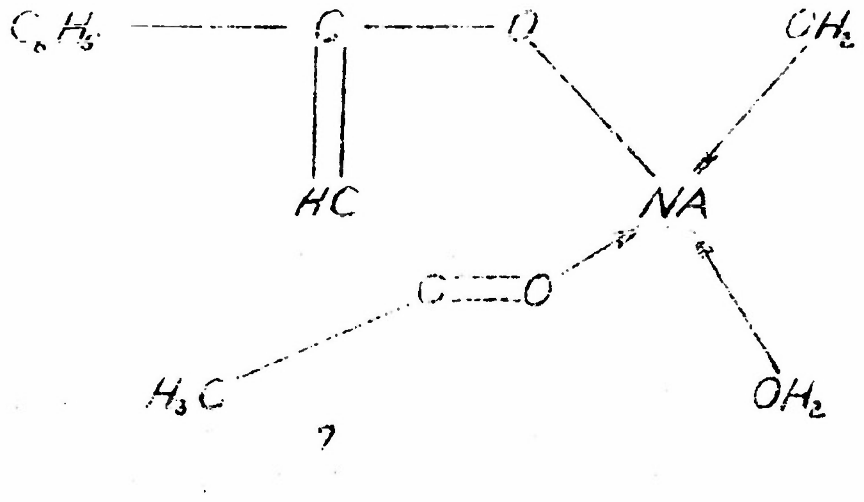
In the crystalline form of carbon (diamond) it shares an electron with each of four other carbon atoms.

There is a special type of co-valent bond which involves sharing of electrons by an atom in a normally stable compound with other atoms. For example, the sulfur atom in dimethyl sulfide has formed two normal co-valent bonds with two carbon atoms to bring about the completion of its full complement of eight electrons in its outer shell.

$$H_3C:\overset{\cdot\cdot}{\underset{\cdot\cdot}{S}}:CH_3 \longrightarrow H_3C-\overset{O}{\underset{O}{S}}-CH_3$$

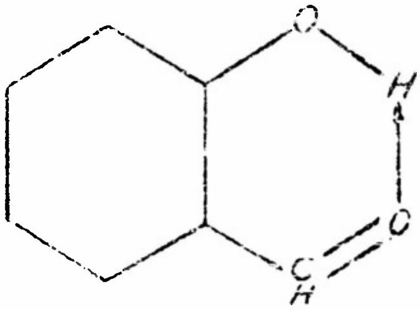
However, this compound can take on two oxygen atoms to form dimethyl sulfone; in this compound the sulfur atom is sharing four of its electrons with two oxygen atoms in addition to sharing its other two electrons in normal co-valent bonds with carbon. Such bonds formed in normally saturated compounds are called coordinate co-valent bonds.

This same mechanism is used to explain another phenomenon occurring in organic molecules; namely, the chelate compounds. The peculiar properties of the hydrate of the sodium derivative of benzoyl acetone indicate that this substance may be represented by the formula



in which the arrow indicates that two electrons are contributed by each such oxygen atom. It will be noted that in effect seven electrons are being shared with the sodium atom to give it an outer shell structure of eight electrons. If the two molecules of water were present as water of crystallization, the compound should have the same chemical properties as the anhydrous salt is insoluble in toluene, whereas the hydrate is soluble, indicating that a different compound has been formed by coordinate co-valent bonding with the water molecules.

Similarly, evidence indicates that the phenolic hydrogen in salicylaldehyde is itself linked to the oxygen of the aldehyde group by a coordinate co-valent bond.



This leads to a very important case of this type of bonding -- namely, the formation of hydrogen bridges between molecules. Many substances containing hydroxyl groups exhibit this structure and even water has been shown to have a trimeric structure in ice. Thus, coordinate co-valent bonding may be an important factor in adhesion between substances containing hydroxyl or related groups

Metallic bonds. As the name indicates, these are the type which hold the atoms of metals together. A pure metal consists of a crystalline arrangement of metallic cations with free electrons moving in the interstices in a continuous set of energy levels. Thus, a metal structure is relatively homogeneous and nonpolar. However, because of its freely flowing electrons a metal has mirror image forces induced at its surfaces which are equal and opposite to the polar forces of an adhesive used on it. Therefore, insofar as polar properties are concerned, an adhesive would have as great an affinity for a metal as it would have for a material of polarity comparable to its own

SECONDARY BONDS

Van der Waals forces are responsible for the so-called secondary bonds between substances as contrasted with the primary bonds -- electrostatic, co-valent and metallic -- which are based on the potent forces of attraction between atomic nuclei and orbital electrons. When such primary bonds are formed, the positive and negative charges of the participating atoms are not completely neutralized. There remain in many molecules residual energies which are very nearly of stable bond forming magnitudes. Van der Waals provided equations for calculating the magnitudes of these residual attractive forces for all substances. These forces are greater for the molecules of compounds than for molecules of elements or inert atoms, thus indicating that unequal distribution of charges accounts for the larger residual force field. The more asymmetric the molecule, the greater the Van der Waals forces will be. These secondary bonding forces are of considerable significance in the adhesive behavior of complex substances.

Van der Waals forces can be attributed to three different effects: (1) the orientation effect of permanent electric dipoles; (2) the induction effect of permanent dipoles on polarizable molecules; and (3) the dispersion effect of internal electron motions independent of dipole moments. These effects can be better understood by considering the geometry of molecules and their behavior in an electric field.

Orientation forces. Molecules in which the centers of mass of the positive and negative charges are not coincident because of asymmetric internal structure possess an electric moment, i.e., they have an electric dipole. In the organic field, molecules containing oxygen, nitrogen, sulfur, and halogen atoms possess permanent electric dipoles. Such molecules tend to orient themselves in a uniform electric field, attempting to align themselves with the dipole axis parallel to the direction of the field. Even without an applied electric field, dipole molecules can exert an orienting influence on similar molecules by attraction between the unlike poles of each.

Induction forces. Molecules which do not possess a permanent dipole moment, with the exception of the inert gases, may be polarized by placing them in a uniform electric field. Since these two poles are produced only by the external field, the molecules are said to possess induced dipole moments. The permanent dipole of another molecule can serve to induce the field. The dipole molecules are, of course, also polarized additionally by the external electric field. These induced forces are small compared with the orientation and dispersion forces involved in secondary bonds.

Dispersion forces. Forces of attraction exist even between atoms of the inert gases in which there is spherical symmetry of the charge shells and hence no orientation or induction effects. The London dispersion forces are attributable to the interactions always occurring between electron systems because of constantly shifting electron positions. They are present in all molecules as residual valence forces. These dispersion forces are never as powerful as the orientation forces.

De Bruyne (1) has pointed out that the orientation and dispersion forces correspond, respectively, to those operative in the hydrophilic or polar liquids such as water, and the hydrophobic or nonpolar liquids, such as benzene. The fact that these two liquids do not mix is attributable to the strength of the orientation forces between the permanent dipoles of the water molecules, squeezing out the adjacent benzene molecules. Similar considerations may be expected to apply to the interaction between an adhesive and an adherend. In general, strong joints to polar adherends are not obtained with nonpolar adhesives, and vice versa. Thus, wood calls for hydrophilic or polar adhesives while rubber requires hydrophobic or nonpolar adhesives. Furthermore, nonpolar adhesives, which must rely mainly on dispersion forces, should not be expected to produce bonds as strong as those of polar adhesives which can possess orientation attractions many times greater than can be produced by dispersion forces. De Bruyne cites this as a possible explanation for the fact that the most effective method of rubber bonding appears to depend upon producing primary bonds, e.g., by the reaction of sulfur with both the rubber molecule and the adherend.

CHEMICAL NATURE OF SURFACES

A knowledge of the chemical nature of surfaces is necessary in order to understand the mechanism of bond formation between adhesives and adherends.

The surfaces of solids are entirely different from their internal structures. The simple treatments of grinding and polishing differ very greatly in their effects on surface nature. In metals, especially, X-ray diffraction patterns show that grinding removes sections of the surface without appreciable distortion of the remaining crystal structure, whereas polishing removes the promontories and deposits materials from them in the crevasses, leaving a smooth transparent amorphous film known as the Beilby layer. This layer has more of the characteristics of a liquid than a solid and is much more reactive. If, for example, a metal vapor is condensed upon a polished metal surface, a crystal pattern is first obtained, but on standing this changes to that of a completely amorphous structure. If a nail is hammered into a crystalline surface, the amourphous strengths because 1) the adhesive does not flow sufficiently to make good contact with the adherend or 2) if drastic bonding conditions are used to make the adhesive flow to make contact, the adhesive becomes too rigid to relieve stresses developed on returning to room conditions, thus lowering the bond strength.

McLaren and Seiler (2) showed that provided the molecular weight is high enough so that cohesive failures do not occur the adhesion is independent of the molecular weight. However, it seems reasonable to expect that in a case where adhesion depends on end groups, an increase in molecular weight would result in a decrease in adhesion.

Molecular weight distribution. A low molecular weight fraction in a polymer tends to act as a plasticizer. The flow characteristics are increased, making the relief of stresses more likely. This effect, however, can be carried too far and result in a polymeric adhesive with low cohesive strength.

Plasticizers. The addition of plasticizers to a polymeric material results usually in a decrease in cohesive strength and an increase in flow characteristics. By choosing the proper amount and kind of plasticizer, it is often possible to convert too rigid a polymer with many other desirable characteristics into a good adhesive. The addition of a plasticizer of a different chemical type may affect the molecular forces responsible for the adhesion. By addition of the proper plasticizer, it is often possible to increase or decrease the adhesion of a specific adhesive-adherend system.

Tack temperature. The tack temperature is related to the flow characteristics and to the molecular weight of the polymer in question. The tack temperature is indicative of the region in which the material flows more or less readily. It is apparent that a material which a low tack temperature will have low cohesive strength and one with a high tack temperature will not have the requisite flow characteristics. Hence, an apparent relation between tack temperature and adhesion would be expected.

Absorbed materials. An adhesive will sometimes bond to only certain random areas of an apparently clean adherend or good bonds will be obtained with one lot of adherend and not with another similar lot. These inconsistent results can often be explained by the presence of absorbed gases, water, oil, or other materials on the surface of the adherend which are difficult to remove and are not visible to the eye. Special cleaning, storing, and handling techniques are often needed to obtain reproducible results.

BIBLIOGRAPHY

1. Anonymous, "Some Recent Advances in Synthetic Adhesives," Plastics (London) 9, 228 (May 1945).
2. Anonymous, "Acetate Adhesives. Welding with Solvents," Modern Packaging 19, 120 (July 1946).
3. Anonymous, "Packaging Institute Standard Test Method for Heat-Sealing Strength," Modern Packaging 20, 150 (Sept. 1946).
4. Anonymous, "Resin Adhesives in Car Bodies," Modern Plastics 24, 174 (June 1947).
5. Anonymous, "Edge Glued by Machine," Modern Plastics 25, 138 (Oct. 1947).
6. Anonymous, "Wall Tile Adhesive," Modern Plastics 25, 214 (Dec. 1947).
7. Anonymous, "Adhesives, Too, are Fasteners," Electrical Manufacturing 42, 94 (July 1948).
8. Armitage, F.D., "Preparation and Storage of Adhesives," Printing and Allied Trades Research Association Bulletin No. 3, p. 24 (1945).
9. Biddle, A. "Laminating Adhesives and Their Applications," Paper Trade Journal 122, 34 (June 6, 1946).
10. Bikerman, J.J., "Fundamentals of Tackiness and Adhesion," Journal of Colloid Science 2, 163 (Feb. 1947).
11. Bruce, H.D., Olson, W.Z., Black, J.M., and Rauch, A.H., "Development of Joint Strength in Birch Plywood Glued with Phenol-, Resorcinol-, and Melamine-Resin Glues Cured at Several Temperatures," U. S. Department of Agriculture, Forest Products Laboratory Report No. 1531, 4 pp. (1946).
12. Burnett, R.S., and Parker, E.D., "Peanut-Meal Plywood Glue", Transactions of the American Society of Mechanical Engineers 68, 751 (Oct. 1946).
13. Coles, H.W., Deuberry, H.B., Curry, F.P., and Schulz, W.F., "Plastics as Optical Cements", Modern Plastics 24, 141 (June 1947).
14. De Bruyne, N.A., "Synthetic Adhesives", Plastics (London 9, 228 (1945).
15. De Lollis, N.J., "Industrial Adhesives," Product Engineering 18, 117 (Nov.); 137 (Dec. 1947).
16. De Lollis, N.J., Rucker, N., and Wier, J.E., "Comparative Strengths of Some Adhesive-Adherend Systems," N.A.C.A. Technical Note No. 1863 (Mar. 1949).
17. Dietz, A.G.H., and Grinsfelder, H., "Fatigue Studies on Urea Assembly Adhesives," Transactions of the American Society of Mechanical Engineers 66, 442 (July 1944); Modern Plastics 21, 119 (Apr. 1944).
18. Dosker, C.D., and Knauss, A.C., "Laminating Lumber for Extreme Service Conditions," Mechanical Engineering 66, 763 (Dec. 1944).
19. Dowling, A.P., "Wood Aircraft Assembly Glues," Modern Plastics 23, 156 (Sept. 1945).
20. Dubin, E.A., "Glued-Laminated Arches with Sawed Laminations," Mechanical Engineering 67, 813 (Dec. 1945).

42. Malden, T.W., "Rubber Bonding and the Plastics Industry," Plastics (London) 10, 625 (Dec. 1946).
43. Maxwell, J.W., "Shear Strength of Glue Joints as Affected by Wood Surfaces and Pressures," Transactions of the American Society of Mechanical Engineers 67, 104 (Feb. 1945).
44. Meissner, H.P., and Merrill, E.W., "Some Factors Affecting Adhesive Bond Formation" ASTM Bulletin No. 151, 80 (Mar. 1948).
45. Meissner, H.P., and Merrill, E.W., "Coalescence Behavior of Some High Polymers," Modern Plastics 26, 104 (Apr. 1949).
46. Merrill, J.A., "Adhesives for Rubber," Rubber Age 59, 313 (June 1946).
47. Moser, F., "Some Fundamentsls of Glass Adhesion," ASTM Bulletin No. 150, 51 (Jan. 1948).
48. Murty, N.N., "Adhesives Based on Shellac and Its Derivatives", Plastics (London) 9, 585 (Dec. 1945).
49. Perry, T.D., "Wood to Metal Adhesives," Mechanical Engineering 68, 1035 (Dec. 1946).
50. Perry, T.D., "Metal to Metal Adhesives," Plastics (Chicago) 6, 26 (Feb. 1947).
51. Perry, T.D., "Durability of Urea-Formaldehyde Adhesives," Modern Plastics 25, 86 (Mar. 1948).
52. Persoz, B., "Adhesivity and its Measurement," Peintures, pigments, vernis 21, 162 (1945).
53. Platow, R.C., and Dietz, A.G.H., "Strength Properties," "Symposium on Adhesives," 1946. Philadelphia: American Society for Testing Materials.
54. Preiswerk, E., and von Zeerleder, A., "Plastic Bonding of Light Metals," Plastics (London) 10, 357 (July 1946).
55. Reinsmith, G., "Preparation and Use of Specifications for Adhesives," "Symposium on Adhesives," 1946. Philadelphia: American Society for Testing Materials.
56. Repsher, L., "Analytical Procedures Used on Adhesives." "Symposium on Adhesives," 1946. Philadelphia: American Society for Testing Materials.
57. Rice, H.L., "Influence of Polarity on Adhesion of Surface Coatings and Organic Finishes," Organic Finishing 9, No. 5, 24 (1948).
58. Rinker, R.C., and Kline, G.M., "Survey of Adhesives and Adhesion," National Advisory Committee for Aeronautics Technical Note No. 989 (Aug. 1945); Modern Plastics 23, 153 (Oct. 1945); 164 (Nov. 1945).
59. Rinker, R.C., and Kline, G.M., "A General Theory of Adhesion." "Symposium on Adhesives," 1946. Philadelphia: American Society for Testing Materials.
60. Rose, K., "Adhesives for Metald and Nonmetals," Metals and Alloys 20, 959 (1944).
61. Rose, K., "Industrial Adhesives," Materials and Methods 27, 94 (Feb. 1948).
62. Sawyer, F.G., Hodgins, T.S., and Zeller, J.H., "Phenolic

Resin Glues for Plywood." Industrial and Engineering Chemistry 40, 1011 (June 1948).
63. Seiler, C.J., and McLaren, A.D., "Theories of Adhesion as Applied to the Adhesive Properties of High Polymers," ASTM Bulletin No. 155, 50 (Dec. 1948).
64. Silver, I., "Shear Impact and Shear Tensile Properties of Adhesives," Modern Plastics, 26, 95 (May 1949).
65. Smith, L.T., and Hamilton, R.M., "Starch Adhesives," Chemical Engineering News 22, 1482 (Sept. 10, 1944).
66. Swayze, D.L., "Adhesives--Modern Tool of Fabrication," S.A.E. Journal 54, 412 (Aug. 1946).
67. Truax, T. R., and Blomquist, F.R., "Types and Uses of Adhesives." "symposium on Adhesives," 1946. Philadelphia: American Society for Testing Materials.
68. Wehmer, F., "Use and Evaluation of Some Specialty Adhesives," Mechanical Engineering 67, 380 (June 1945).
69. Wehmer, F., "Permanence Tests of Adhesive Bonds." "Symposium on Adhesives." 1946. Philadelphia: American Society for Testing Materials.

Distribution of Stresses in Adhesive Bonds

The problem of stress distribution in a bonded joint is very important. From preliminary work, both experimental and analytical, there is sufficient evidence to indicate that there are high stress concentrations at the boundaries of the bonded joint. Very little work has been done on the problem of stress distributions in bonded joints with the exception of shear lap joints. The impetus for work in this direction has been provided by the aircraft industry in which the adhesive bonding of thin sheet metal, principally aluminum, offers great promise of better joint efficiency as compared with riveting or spot welding.

There are two main factors causing high stress concentrations at the ends of a shear lap joint (1) differential strains on the adhesive set up by the varying rigidities of the adhesive and adherends in an adhesively bonded joint system and (2) bending moments imparted to the joint by the geometry and the bending rigidity of the system. To get a physical concept of strains and consequently stresses in the joint, note Figure 1 which illustrates a section of a shear lap joint before the load is applied. The adhesive thickness and joint geometry are exaggerated for purposes of visual clarity. The joint (overlap) length is notated 2c, the two joined sheets are considered to be of equal thickness t and are presumed to extend a distance l to either side of the joint. The joint width, in a direction normal to the plane of the section shown, is assumed to be large compared with the sheet thickness.

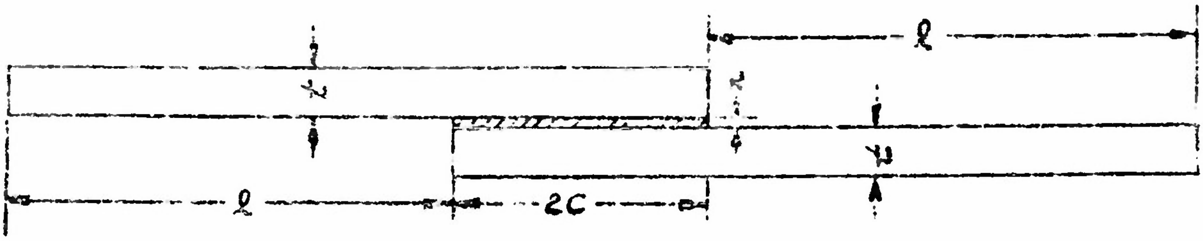


Figure 1
Typical section of an unstressed shear lap joint

In Figure 2 loading is applied to the adherends as a uniformly distributed loading per unit length p. This may be replaced by a single concentrated load per unit length T which is equal to pt. The concentrated loading T forms a couple and the ensuing deformation of the joint system tends to reduce the moment arm of the couple. Figure 2 shows the shape assumed by a shear lap joint when tensile loading is applied to the adherends.

Figure 2
Shape assumed by a shear lap joint when tensile loading is applied

From the deformation of the joint system, it is possible to note the loading on the joint after tensile loading T is applied. In Figure 3, the loading on the adhesive layer is shown:

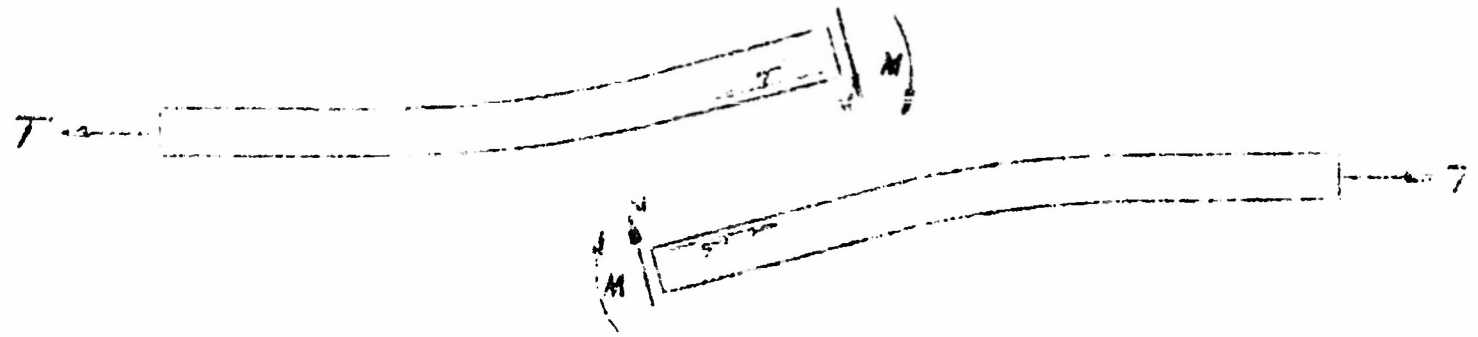


Figure 3
Loading on a Shear lap joint when tensile loading
is applied

In this sketch, we can see that the unit tensile loading on the adherend sheet produces a bending moment M, a transverse shear load V and a shear load T' on the adhesive joint. If the deformation of the joint is small, then the shear load T' will be approximately equal to the applied tensile loading T. Thus, it is possible to note that the magnitude of M and V will be a function of the bending rigidity of the adherend system and of the rigidity of the adhesive layer. It is also possible to note that both M and V will cause unequal stress distribution in the shear lap joint. Strain distribution is the second major factor in unequal stress distribution. To illustrate, consider Figure 4 which shows an unstrained section of a shear lap joint. The nine arrows represent equidistant planes in the adhesive layer perpendicular to the plane of the joint. When loading is applied in this case neglecting the bending moment M and the transverse shear load V, the deformation of the adhesive layer takes the shape as shown in Figure 5. This illustration, again, is highly exaggerated but serves to illustrate the mechanism of adhesive deformation in a shear lap joint. We see that the loading is not equally carried by the entire overlap of the joint but that the portion of the adherend in the over lap area nearest to the applied loading tends to carry the major part of the load. This would produce the greatest stresses at the ends of the joint and relatively low stresses in the middle of the joint. Examining adhesive planes "a" and "i",

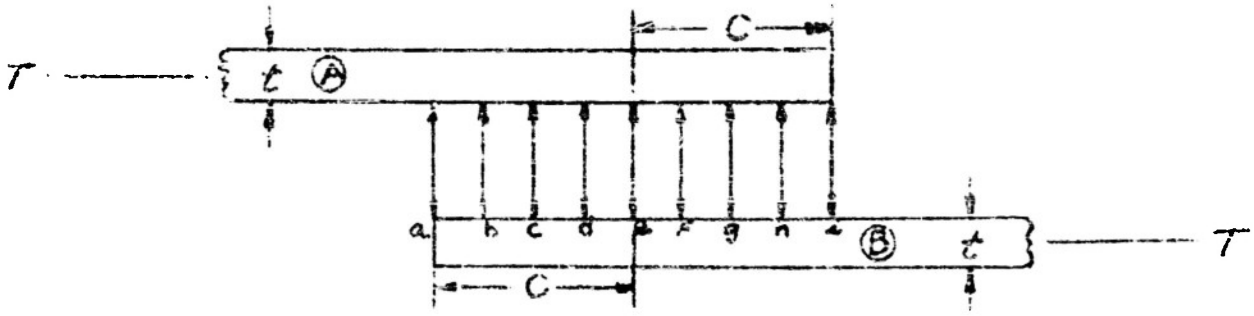


Figure 4
Shear Lap Joint before load is applied. Adhesive thickness exaggerated

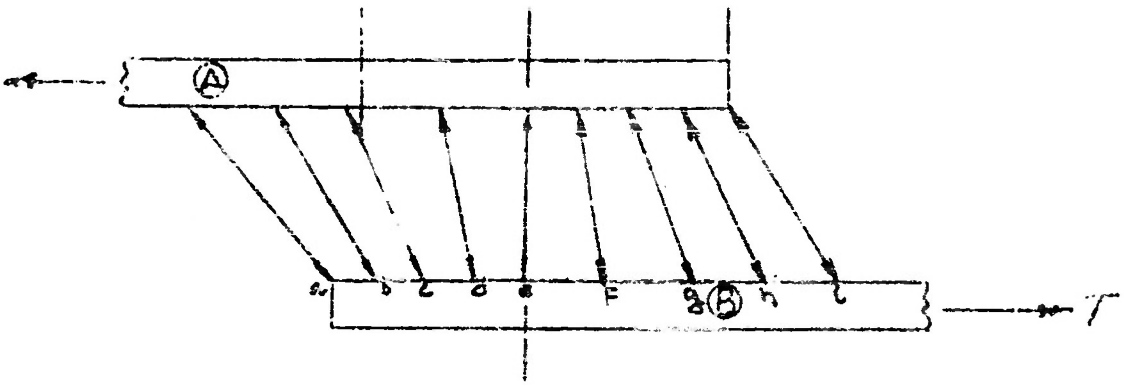


Figure 5
Shear Lap Joint after load is applied (after De Bruyne)

we note that these planes not only undergo the greatest shear deformation but the greatest strain elongation (See Figure 6). We can thus predict that the ends not only carry the greatest shear stress but the greatest tensile stress and that the tensile stress of the adhesive may be the governing criterion of the strength of a shear lap joint instead of the shear strength as would be normally expected for the predominant shear loading. Again, we can conclude that the deformation of the adhesive layer is a function of the geometry of the joint and the relative rigidities of the adherends and the adhesive.

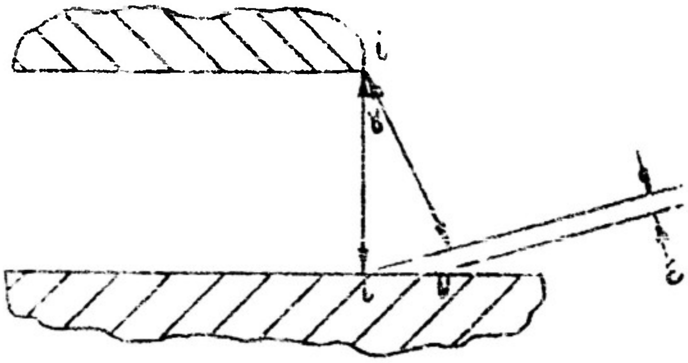


Figure 6
Strain Deformation at free boundary edge after
load is applied

There is ample evidence to support the theory explained in the preceding paragraphs. Shear lap joints fail at the more highly stressed ends; the ends spring apart indicating great tensile or "tearing" stresses. In addition, the strength of a shear lap joint is not proportional to the overlap distance or the shear lap area. We can conclude that if failure were predominantly shear, than the strength of the joint would be proportional to the shear area. Two important papers on this subject have been published and it is proposed to go into each paper in detail. The first is the rigorous theoretical solution of the stress distribution in the adhesive layer of a shear lap joint presented by Goland and Reissner in the March 1944 issue of the Journal of Applied Mechanics. The second is "The Strength of Glued Joints" presented by N. A. De Bruyne in the April 1944 issue of Aircraft Engineering. The second paper is based on experimental data and is of great practical value in the design of shear lap joints.

Goland and Reissner, in their solution of the problem of stress distribution in the adhesive layer of a shear lap joint, used the following notations.

Let p = mean tensile stress per unit length of sheet in psi
t = thickness of sheet in inches
$2c$ = length of overlap in inches
ℓ = length of sheet beyond the overlap assumed to be several times the joint overlap in inches
E = Young's modulus of sheet material in psi

σ_x = Sheet tensile stress parallel to the plane of the joint psi
G = Shear modulus of sheet material in psi
ν = poisson's ratio of sheet material
E = Young's modulus of adhesive in psi
G^c = Shear modulus of adhesive in psi
τ_o^c = Shear stress in the plane of the adhesive layer in psi
σ_o = Adhesive tensile stress perpendicular to the plane of the adhesive layer in psi
σ_c = Adhesive tensile stress in the plane of the adhesive layer in psi
n = Adhesive thickness
τ_{xy} = Sheet shear stress acting in planes parallel to the direction of σ_x and σ_y
σ_y = Sheet tensile stress perpendicular to the plane of the joint psi
M_o = bending moment at the end of the joint in in. lbs.
V_o = Transverse shear at the end of the joint in lbs.
T = Total loading per unit length on the sheet in lbs.

For a diagram of the shear lap joint, see Figure 1.

In order to simplify the problem, the suthors decided to explicitly solve for the two limiting conditions; Case I where the cement layer is so thin that its effect on the flexibility of the joint could be neglected; Case II where the joint flexibility is mainly due to the adhesive layer. To give quantitative relations where these assumptions remain valid, the strain energy of the joint, expressed in terms of the stresses, is given by

$$W = \int_{-c}^{c}\int_{0}^{t}\left\{\frac{1-\nu^2}{E}\left[\sigma_x^2 + \sigma_y^2 - \frac{2\nu}{1-\nu}\sigma_x\,\sigma_y\right] + \frac{1}{G}\tau_{xy}^2\right\}dx\,dy$$

$$+ \frac{1}{E}n\int_{-c}^{c}\left\{\frac{1}{E}\sigma_o^2 + \frac{1}{G_c}\tau_o^2\right\}dx \qquad (1)$$

For Case I, the work of the stress σ_o and τ_o may be neglected when the following order of magnitude relationship is satisfied:

$$\frac{n}{E_c} \ll \frac{t}{E} \quad ; \quad \frac{n}{G_c} \ll \frac{t}{G}$$

and acceptable results should be obtained when:

$$\frac{n}{E_c} \lesssim \frac{1}{10}\frac{t}{E} \quad ; \quad \frac{n}{G_c} \lesssim \frac{1}{10}\frac{t}{G} \qquad (2)$$

This range holds for cementing relatively thick wood and

and plastic sheets. For Case II, the treatment neglects the work of σ_y and τ_{xy} in the sheet as compared to the stresses σ_0 and τ_0 in the cement and the orders of magnitude describing the range in validity of this approximate theory becomes:

$$\frac{t}{E} << \frac{\eta}{E_c} \quad , \quad \frac{t}{G} << \frac{\eta}{G_c}$$

and acceptable results should be obtained when:

$$\frac{t}{E} \lesssim \frac{1}{10}\frac{\eta}{E_c} \quad , \quad \frac{t}{G} \lesssim \frac{1}{10}\frac{\eta}{G_c} \qquad ③$$

these order-of-magnitude considerations apply for the bonding of thin sheet metal. To repeat, these values only establish the regions of validity of the subsequent analysis of the two limiting cases.

Before attempting to solve the stress distribution in the cement joint for the two limiting cases, it is necessary to establish the loading on the joint (See Figure 3) in terms of the mean unit tensile stress on the sheet, in terms of the joint geometry, and in terms of the physical characteristics of the materials.

The precise nature of this relationship is expressed in the following equations:

$$M_0 = \frac{K T t}{2} = \frac{K p t^2}{2} \qquad ④$$

$$V_0 = K T \sqrt{3(1-\nu^2)\frac{p}{E}} \qquad ⑤$$

WHERE

$$K = \frac{\cosh\left[\sqrt{\frac{3(1-\nu^2)}{2}} \cdot \frac{c}{t}\sqrt{\frac{p}{E}}\right]}{\cosh\left[\sqrt{\frac{3(1-\nu^2)}{2}} \cdot \frac{c}{t}\sqrt{\frac{p}{E}}\right] + 2\sqrt{2}\,\sinh\left[\sqrt{\frac{3(1-\nu^2)}{2}} \cdot \frac{c}{t}\sqrt{\frac{p}{E}}\right]}$$

It can be seen that the factor K is non-dimensional and is dependent upon the sheet stress, the joint dimensions and the physical properties of the sheet. K is described by the authors as the joint moment factor. For any particular joint, all values of the joint parameter $\frac{c}{t}\sqrt{\frac{p}{E}}$ are fixed with the exception of p. A graphical plot of the relationship between K and $\frac{c}{t}\sqrt{\frac{p}{E}}$ is shown in Figure 7.

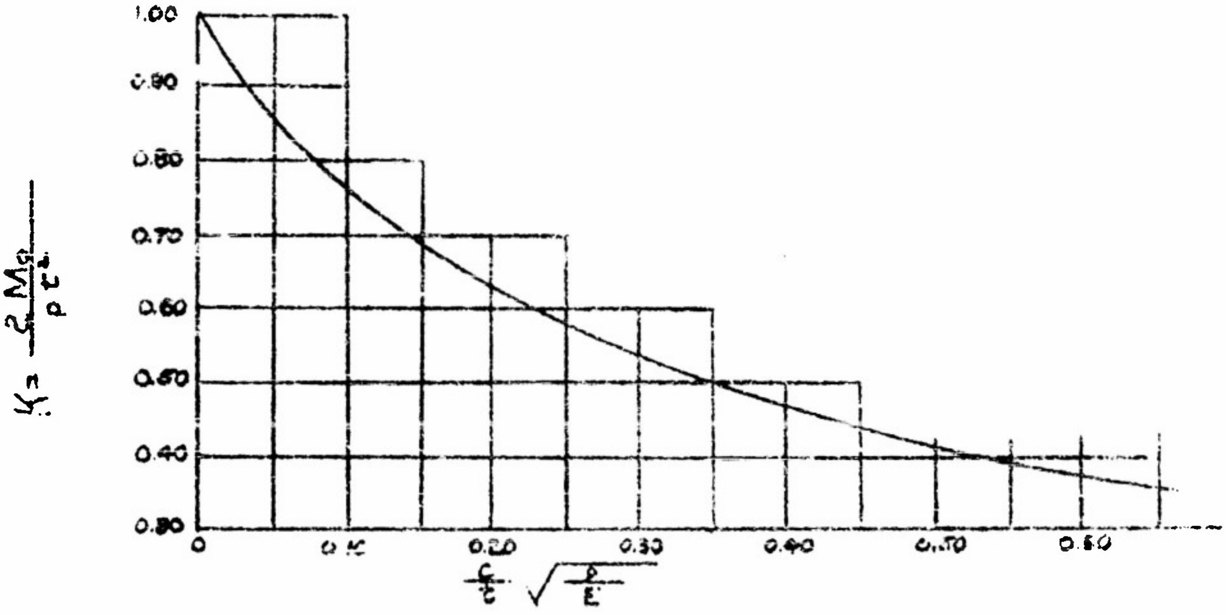


Figure 7
Plot of moment factor K versus $\frac{c}{t}\sqrt{\frac{p}{E}}$

The physical meaning of this relationship is quite clear. As the sheet stress p is increased, the value of K decreases indicating that the bending moment imparted to the joint decreases; in other words, the deformation of the joint is such that the moment arm of the applied couple decreases. From the curve, it is seen that a practical lower limit for K is 0.35. The transverse shear load was found to be quite small for the joint systems with reasonable overlap. The transverse shearing forces are never in excess of 0.02T in actual joints.

Case Y <u>Stress distribution in an Adhesively Bonded Joint for Relatively Inflexible Cement Layers</u>. For this analysis, if the thickness of the adhesive layer in the joint is exceedingly small compared to that of the sheet, the presence of the adhesive can be ignored in the calculation of the stress distribution. For the purpose of the analysis, therefore, the joint can be assumed to consist of a homogeneous slab of thickness 2t, length 2c, large width and of the same physical properties throughout. It is to be noted that this treatment is valid even for cement layers of appreciable thickness, providing the physical properties of the adhesive are at least the same order of magnitude as those of the sheet material.

The loads transmitted by the sheet to the edges of the joint have been determined in the preceding paragraph. They consist of a unit loading p evenly distributed over the sheet cross section, a bending moment M_o (per unit of joint width) and a small transverse shear load V_o. This transverse load V_o will be neglected. It is also assumed that the moment Mo will impart linear stress distribution. This latter assumption implies that the joint remains plane near the edges of the joint. Tests on spot welded joints confirm the validity of this assumption.

The problem therefore resolves itself to the solution of the strain in the mid plane of a wide rectangular slab of length 2c and thickness 2t with loading as shown in Figure 8.

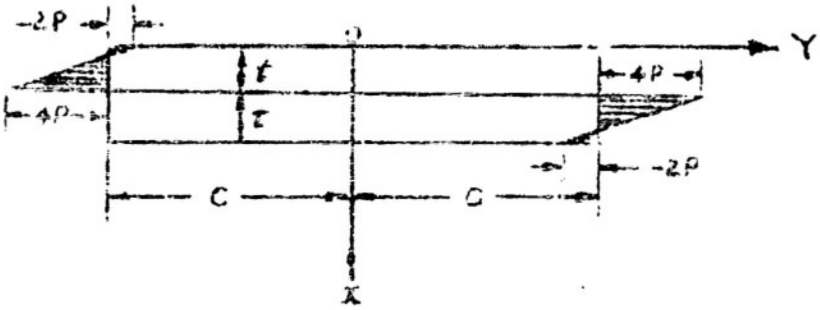


Figure 8
Diagram of joint with relatively inflexible cement layer K = 1.0

This problem cannot be solved directly; resort is made to a method of approximations which appears quite laborious and must be solved for each particular value of K. The solution for the case where K = 1 is shown graphically in Figure 16. It should be noted that for purposes of generality, the stresses are presented as a ratio of the shear and tensile stresses in the adhesive layer to the applied unit stress on the sheet and that absissa is presented as a ratio of the distance from joint edge to the sheet thickness.

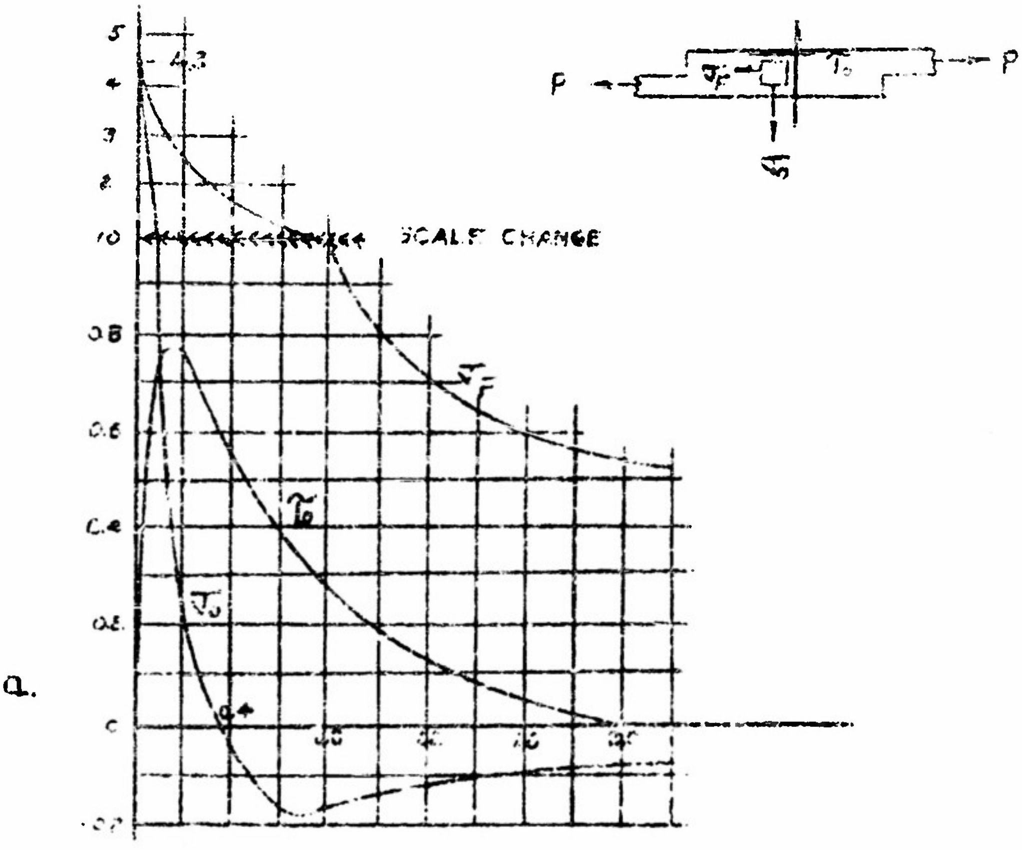


Figure 9
Stress distribution along shear plane in joints with relatively inflexible adhesive for K = 1

The curves shown in Figure 9 confirm the fact that very large stress concentrations are present in the edges of the adhesively bonded joint. It is very interesting to note that the tensile stresses are approximately five times greater than that of the shear stress. This explains why shear lap joint specimens bonded with relatively stiff adhesives snap apart in tension at the edges under a tensile load. It is also interesting to note that a small change in joint geometry might greatly reduce the magnitude of the stress concentration such as filleting or beveling the edges of the sheet on the shear lap joint. This is common practice in machine design for a solid homogeneous material.

It is recognized that the peak values of the stresses at the adhesive layer shear plane will change with the factor K. Figure 10 shows this variation by plotting the maximum values of the cement stress as a function of K.

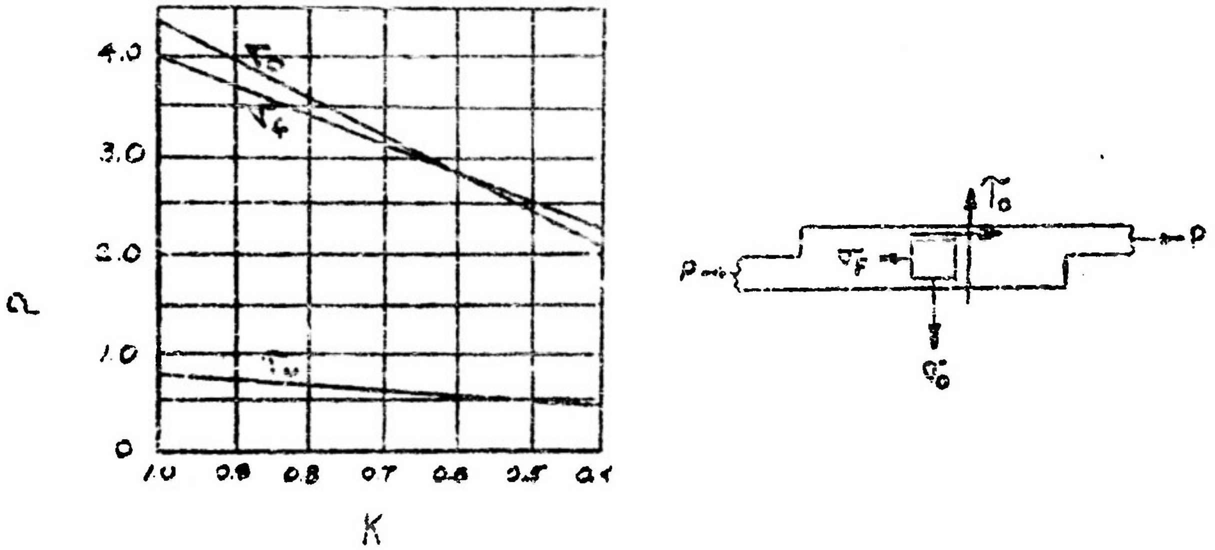


Figure 10
Maximum stresses in shear plane for joints with relatively inflexible cement layers plotted versus moment factor K

It can be seen that for a change in K, the tensile stresses reduce much more rapidly than the shear stress which remains relatively constant.

Case II <u>Stress Distribution in Joints for Relatively Flexible Cement Layers</u>. For this analysis, the following assumptions are made. The transverse normal strain and the shear strain in the jointed sheets are negligibly small compared to the corresponding strains in the cement layer. Assuming that the deformation of the adherends are due solely to the longitudinal normal stress σ_x, it is apparent that the sheets may be treated as cylindrical bent plates, where as the role played by the adhesive layer is analogous to that of a system of infinitesimal coil springs positioned between the two plates. Figure 11 represents the profile of the cemented joint showing the load application in terms of longitudinal stress distributions on the edges.

and

$$\frac{\sigma_o}{p}\left(\frac{c}{t}\right)^2 = \frac{1}{\Delta}\left\{\left(R_2\lambda^2\frac{K}{2} + \lambda K'\,\text{COSH}\,\lambda\,\text{COS}\,\lambda\right)\text{COSH}\,\lambda\frac{x}{c}\,\text{COS}\,\lambda\frac{x}{c}\right. \quad ⑦$$

$$\left. + \left(R_1\lambda^2\frac{K}{2} + \lambda K'\,\text{SINH}\,\lambda\,\text{SIN}\,\lambda\right)\text{SINH}\,\lambda\frac{x}{c}\,\text{SIN}\,\lambda\frac{x}{c}\right\}$$

where

$$\lambda = \gamma\frac{c}{t}$$

$$\gamma^4 = 6\,\frac{E_c}{E}\cdot\frac{t}{n}$$

$$R_1 = \text{COSH}\,\lambda\,\text{SIN}\,\lambda + \text{SINH}\,\lambda\,\text{COS}\,\lambda$$

$$R_2 = \text{SINH}\,\lambda\,\text{COS}\,\lambda - \text{COSH}\,\lambda\,\text{SIN}\,\lambda$$

$$\Delta = \frac{1}{2}\left(\text{SINH}\,2\lambda + \text{SIN}\,2\lambda\right)$$

$$\delta^2 = 8\,\frac{G_c}{E}\cdot\frac{t}{n}$$

$$K = \frac{\text{COSH}\,\mu_2 c}{\text{COSH}\,\mu_2 c + 2\sqrt{2}\,\text{SINH}\,\mu_2 c}$$

$$K' = K\sqrt{3(1-V^2\,\frac{E_c}{E}}\cdot\frac{c}{t}$$

$$\mu_2 c = \sqrt{\frac{3(1-V^2)}{2}}\cdot\frac{c}{t}\sqrt{\frac{E_c}{E}}$$

Equation (6) defines the variation of the shear stress as a function to the applied loading "p" and the distance "x" from the center of the joint for given joint parameters. Equation (7) defines the variation of the normal stress "σ_o" (sometimes referred to as the tearing stress) as a function of the applied loading "p" and the distance "x" from the center of the joint. The graphical representation of these relationships are shown in Figure 13 for given conditions

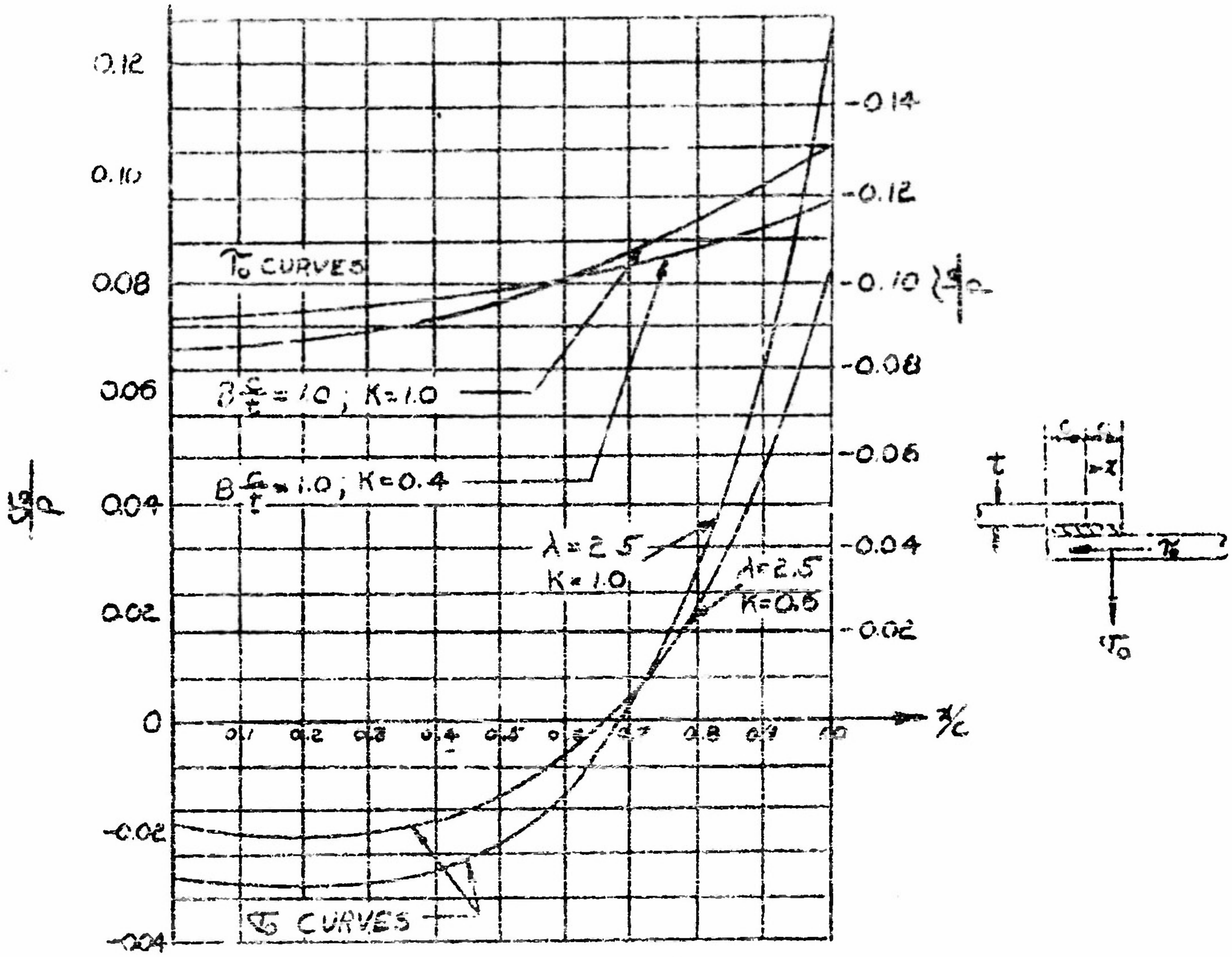


Figure 13
Stress distribution in adhesives in joints with relatively flexible adhesives layers

The maximum value for both the shear and the normal stresses are found at the edge of the joint. The maximum stress can therefore be given for the value x = c.

for shear

$$\frac{\tau_0(\max)}{p} \cdot \frac{c}{t} = -\frac{1}{8}\left[\beta \frac{c}{t}(1+3K)\coth \beta \frac{c}{t} + 3(1-K)\right]$$

for normal tensile

$$\frac{\sigma_0(\max)}{p} \cdot \frac{c}{t} = \lambda^2 \frac{K}{2} \frac{\sinh 2\lambda - \sin 2\lambda}{\sinh 2\lambda + \sin 2\lambda} + \lambda K' \frac{\cosh 2\lambda + \cos 2\lambda}{\sinh 2\lambda + \sin 2\lambda}$$

Both equations (8) and (9) can be represented graphically as functions of the parameters of the system. Figure 14 is a graphical plot of the maximum shear stress.

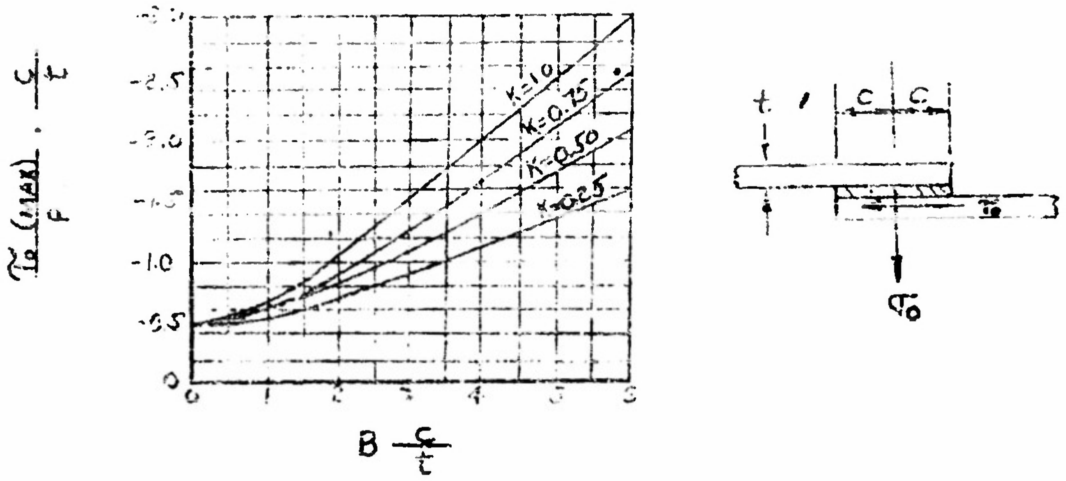


Figure 14
Maximum shear stress in adhesives with relatively flexible adhesive layers

Figure 15 is a graphical plot of the maximum normal stress.

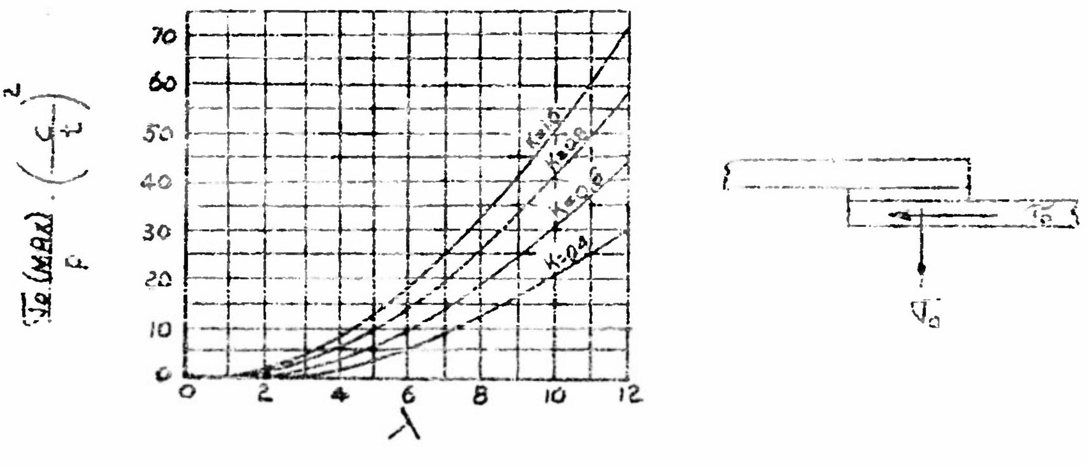


Figure 15
Maximum tearing stresses in adhesives in joints with relatively flexible adhesive layers

This theoretical analysis, in its present form, is far too complex for practical usage. It does serve to point out several interesting conclusions:

a. Very great stress concentrations exist at the edges of a shear lap joint.

b. Although the shear lap joint is in shear load, the predominant stress is a normal (tearing) stress . This is corroborated in actual test.

c. One of the most important parameters of the shear lap joint is the ratio c/t which is the ratio of the joint overlap to the thickness of the sheet adherend.

To demonstrate the use of these formulas, the following hypothetical example of an aircraft type joint is analyzed. With the adhesive area indicated, this joint would be expected to fail at approximately 1250# total load and the average adhesive stress at the failure would be 2000 psi.

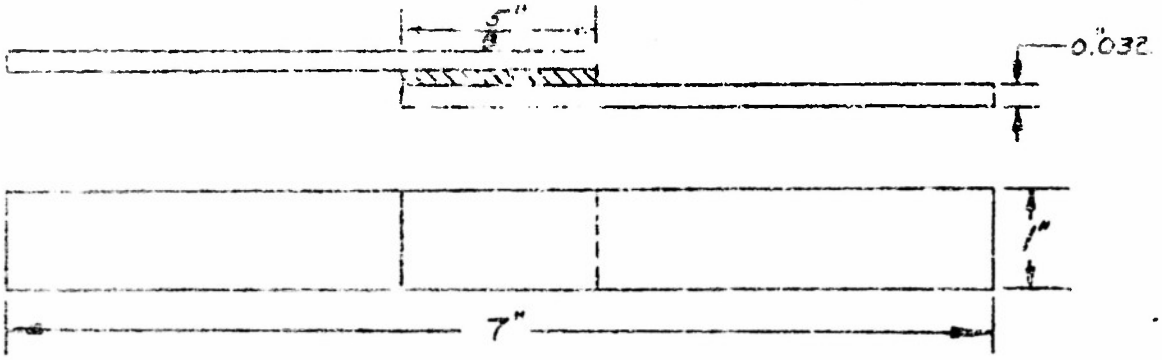


Figure 16
Dimensions of a typical lap joint test specimen

Adherends, Stainless steel
Adhesive, a phenolic polyamide .004 inches thick

Summarizing the adhesive and adherend properties using the symbols defined on page 4, section 3, we have

$$p = 39 \times 10^3$$
$$t = .032$$
$$2c = .625$$

$l = 3.187$
$E = 30 \times 10^6$
$G = 12 \times 10^6$
$\nu = .303$
$E_c = 4 \times 10^5$
$G_c = 148 \times 10^3$
$n = .004$

Evaluating the ratios $\frac{t}{E}$, $\frac{n}{E_c}$, $\frac{t}{G}$ and $\frac{n}{G_c}$ it is apparent that the following relationship holds which classes this joint as one in which the assumptions in Case II hold.

$$\frac{t}{E} \leq \frac{1}{10}\,\frac{n}{E_c} \text{ and } \frac{t}{G} \leq \frac{1}{10}\,\frac{n}{G_c}$$

Tensile and shear equations for Case II are

Shear $$\frac{P_s}{P}\cdot\frac{c}{t} = -\frac{1}{\theta}\left\{\theta\frac{c}{t}\left(1+3K\,\frac{\cosh\theta\frac{c}{t}\cdot\frac{x}{c}}{\sinh\theta\frac{c}{t}}\right)+3(1-K)\right\}$$

Tensile $$\frac{\sigma_c}{P}\left(\frac{c}{t}\right)^2 \quad \frac{1}{\Delta}\left\{\left(R_2\lambda^2\frac{K}{2}+\lambda K'\cosh\lambda\cos\lambda\right)\cosh\lambda\frac{x}{c}\cos\lambda\frac{x}{c} + \left(R_1\lambda^2\frac{K}{2}+\lambda K'\sinh\lambda\sin\lambda\right)\sinh\lambda\frac{x}{c}\sin\lambda\frac{x}{c}\right\}$$

For a particular joint, all factors in the above equations are constant except the terms involving X, therefore the constants common to both equations may be evaluated as defined on page 29.

$$h^4 = 6\,\frac{E_c}{E}\,\frac{t}{n} = 6\,\frac{4\times10^5}{30\times10^5}\cdot\frac{.032}{.004} = .640$$

$$h = .895$$

$$\lambda = h\frac{c}{t} = .895\,\frac{.312}{.032} = 8.726$$

$$R_1 = \cosh\lambda\sin\lambda + \sinh\lambda\cos\lambda = (3077)(.643)+(3077)(-.7657) = -376.75$$

$$R_2 = \sinh\lambda\cos\lambda - \cosh\lambda\sin\lambda = (3077)(-.7657)-(3077)(.643) = 4335.2$$

$$\Delta = \frac{1}{2}(\text{SINH } 2\lambda + \text{SIN } 2\lambda) = 9{,}480{,}750$$

$$B = \sqrt{\frac{3G_c t}{E h}} = \sqrt{\frac{8 \times 148 \times 10^3 \times .032}{30 \times 10^6 \times .004}} = .562$$

$$\mu_2 = \frac{1}{c}\sqrt{\frac{3(1-\nu^2)}{2}} \cdot \frac{c}{t}\sqrt{\frac{P}{E}} = \frac{1}{.312}\sqrt{\frac{3(1-.303^2)}{2}} \cdot \frac{.312}{.032}\sqrt{\frac{39 \times 10^3}{30 \times 10^6}} = 1.317$$

$$K = \frac{\text{COSH } \mu_2 C}{\text{COSH } \mu_2 C + 2\sqrt{2}\ \text{SINH } \mu_2 C} = \frac{\text{COSH } 1.317 \times .312}{\text{COSH } 1.317 \times .312 + 2\sqrt{2}\ \text{SINH } 1.312 \times .312} = .476$$

$$K' = K\sqrt{3(1-\nu^2)\frac{P}{E}} \cdot \frac{c}{t} = .476\sqrt{3(1-.303^2)\frac{33 \times 10^3}{30 \times 10^6}} \cdot \frac{.312}{.032} = .276$$

Substituting these values into the tensile and shear equations and evaluating the remaining constant terms, we have -

For the shear equation

$$\tau_0 = -55.92\ \text{COSH } B\frac{x}{t} - 786.0$$

For the tensile equation

$$\sigma_0 = -3.648\ \text{COSH } \lambda\frac{x}{c}\ \text{COS } \lambda\frac{x}{c} - .0892\ \text{SINH } \lambda\frac{x}{c}\ \text{SIN } \lambda\frac{x}{c}$$

Measuring X from the center of the joint, values of τ_0 and σ_0 are computed and shown in tables 1 and 2 and are plotted graphically in Figure 17.

This joint failed at an apparent shear stress of 2000 psi; therefore, the average shear stress as determined from the shear stress distribution curve should agree closely with the apparent shear stress.

$$\text{ave } \tau_0 = \int_0^c \frac{\tau_0 \, dx}{c} = -\frac{55.9}{c}\int_0^c \cosh \frac{Bx}{t}\, dx - \frac{786}{c}\int_0^c dx$$

$$= -\frac{55.9}{c}\,\frac{t}{B}\left[\sinh \frac{Bx}{t}\right]_0^c - \frac{786}{c}\left[x\right]_0^c = \frac{1.79}{Bc}\sinh \frac{Bc}{t} - 786$$

$$= -10.23 \sinh 5.47 - 786$$

$$\tau_0 = -1214 - 786 = -2000 \text{ psi}$$

The average tensile stress may be determined in like manner.

$$\text{Ave. } \sigma_0 = \int_0^c \frac{\sigma_0 \, dx}{c} = -\frac{3.648}{c}\int_0^c \cosh \lambda\frac{x}{c} \cos \lambda\frac{x}{c}\, dx - \frac{.0892}{c}\int_0^c \sinh \lambda\frac{x}{c} \sin \lambda\frac{x}{c}\, dx$$

$$= -\frac{3.648}{c}\,\frac{c}{2\lambda}\left[\sinh \lambda\frac{x}{c} \cos \lambda\frac{x}{c} + \cosh \lambda\frac{x}{c} \sin \lambda\frac{x}{c}\right]_0^c$$

$$- \frac{.0892}{c}\,\frac{c}{2\lambda}\left[\cosh \lambda\frac{x}{c} \sin \lambda\frac{x}{c} - \sinh \lambda\frac{x}{c} \cos \lambda\frac{x}{c}\right]_0^c$$

$$= -\frac{1.824}{\lambda}\left[\sinh \lambda \cos \lambda + \cosh \lambda \sin \lambda\right] - \frac{.0446}{\lambda}\left[\cosh \lambda \sin \lambda - \sinh \lambda \cos \lambda\right]$$

$$= -.209\left[(3077)(-.7657) + (3077)(.6432)\right] - .00511\left[(3077)(.6432) - (3077)(-.7657)\right]$$

$$= 78.74 - 22.15 = 56.59 \text{ psi} \quad \text{AVERAGE TENSILE STRESS}$$

TABLE 1
TENSILE STRESS DISTRIBUTION IN A TYPICAL LAP JOINT

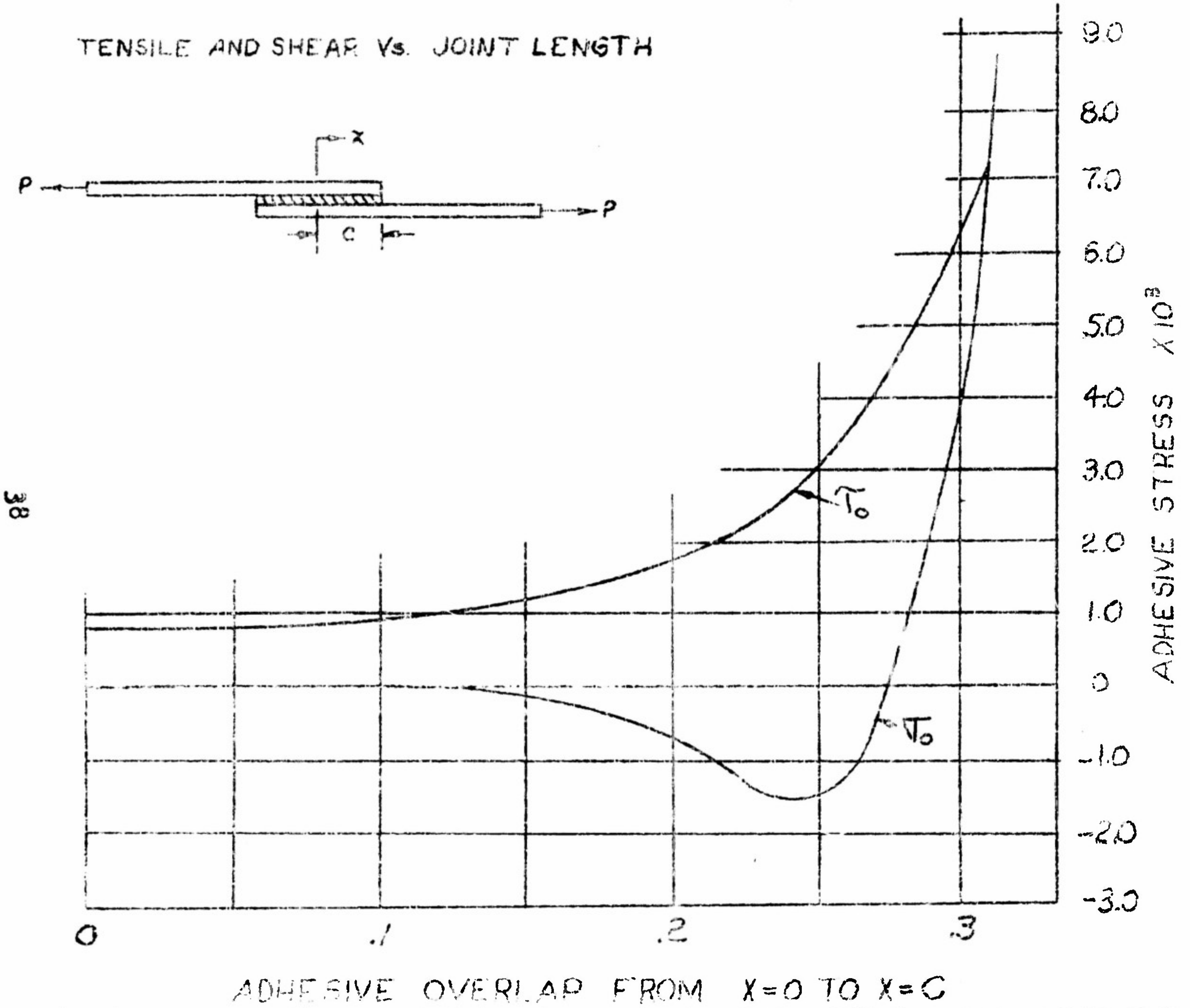
x	$\lambda\frac{x}{c}$	A $\cosh\lambda\frac{x}{c}$	B $\cos\lambda\frac{x}{c}$	C $\sinh\lambda\frac{x}{c}$	D $\sin\lambda\frac{x}{c}$	AB	E 3648AB	CD	F .0682CD	σ_{x}(psi) -E-F
0	0	1	1	0	0	1	3.648	0	0	-3.648
.062	1.734	2.919	-.165	2.748	.987	-.474	-1.730	2.712	.242	1.488
.125	3.496	16.507	-.938	15.477	-.347	-15.481	-56.47	-5.716	-.508	56.98
.250	6.992	544.0	.759	544.0	.651	412.94	1506.4	354.0	31.57	-1537.57
.312	8.726	3077.0	-.766	3077.0	.643	-2356.73	-8597.35	1979.86	176.6	8420.75

TABLE 2
SHEAR STRESS DISTRIBUTION IN A TYPICAL LAP JOINT

x inches	COSH $\frac{\beta x}{t}$	$-55.92 \cosh \frac{\beta x}{t}$	τ_0 (psi) $-55.92 \cosh \frac{\beta x}{t} - 786$
0	1.000	-55.92	-841.92
.062	1.652	-92.38	-878.38
.125	4.546	-254.21	-1040.21
.187	13.36	-747.09	-1533.09
.250	40.37	-2257.49	-3043.49
.312	119.92	-6705.92	-7491.9

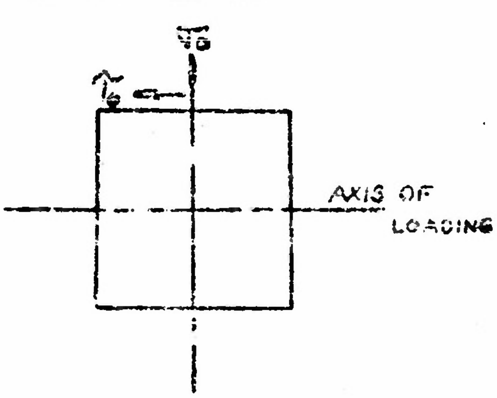
FIGURE 17

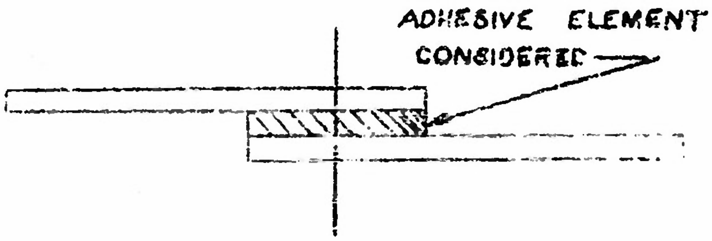
TENSILE AND SHEAR Vs. JOINT LENGTH



From tables 1 and 2, the shear stress at the ends of the joint was found to be 7492 psi and the tensile stress 8420 psi. These stresses occur in the plane of loading and perpendicular to the plane of loading respectively. Even greater tensile and shear stresses exist in the adhesive in planes at some angle from the plane of loading. Maximum (and minimum) values of tensile and shear stresses may be found using combined stress equations.

Consider an element of adhesive at the extreme end of the joint (See sketch). The shear and tensile stresses in the plane of loading and perpendicular to the plane of loading are represented by τ_o and σ_o respectively. In the subsequent analysis, the maximum values of each are represented by τ_o max and σ_o max





Using combined stress equations to determine max. (and min.) tensile and maximum shear stresses

TENSILE

$$\sigma_{o\binom{max.}{min.}} = \frac{\sigma_o}{2} \pm \sqrt{\left(\frac{\sigma_o}{2}\right)^2 + \tau_o^2} = \frac{8420}{2} \pm \sqrt{\left(\frac{-8420}{2}\right)^2 + (7590)^2} = \begin{matrix} 12{,}890 \text{ psi (max.)} \\ -4470 \text{ psi (min)} \end{matrix}$$

SHEAR

$$\tau_{o(max.)} = \sqrt{\left(\frac{\sigma_o}{2}\right)^2 + \tau_o^2} = 8680 \text{ psi}$$

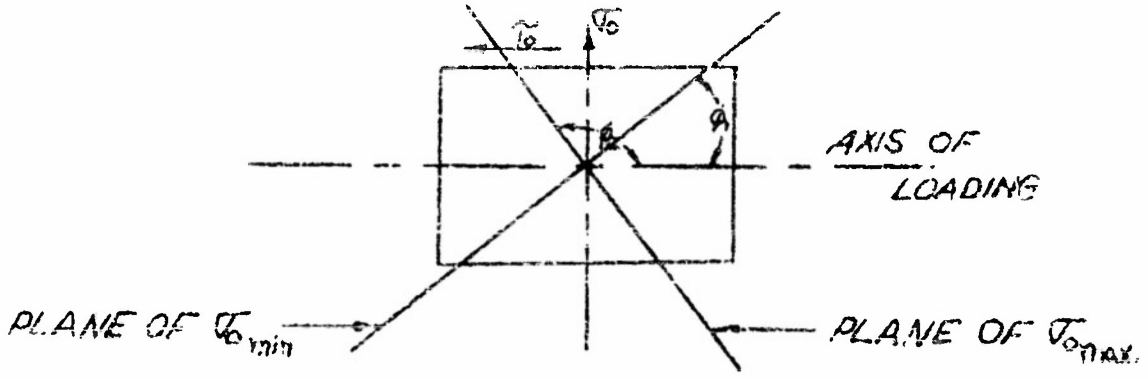
The angle at which the principal tensile stresses are inclined from the axis of loading is defined as

$$\tan 2\phi = \frac{-2\tau_o}{-\sigma_o} = 1.8028$$

Two values of ϕ are possible corresponding to maximum and minimum tensile stresses.

$2\phi = 60° 59'$ $\phi_1 = 30°8'$ ANGLE OF MINIMUM STRESS

$2\phi = 240° 59'$ $\phi_2 = 120°29'$ ANGLE OF MAX. TENSILE STRESS



The planes of maximum shear stress are defined as

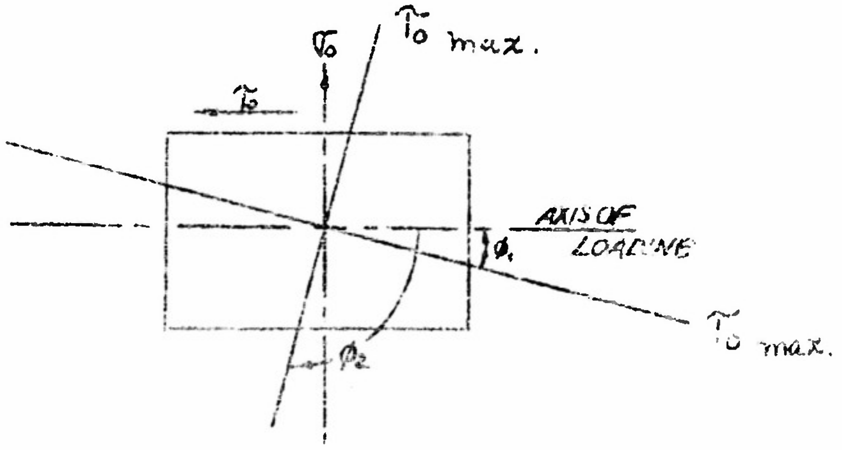
$$\tan 2\phi = -\frac{\sigma_o}{2\tau_o} = \frac{8420}{-15160} = .555$$

Again two values of   are possible

$2\phi = -29°2'$ $\phi_1 = -14°31'$

$2\phi = 209° 2'$ $\phi_2 = -104°31'$

It is apparent that the planes of maximum shear stress make angles of 45° with the planes of maximum and minimum tensile stress.



De Bruyne indicated the existence of high stress concentrations in his experiments on shear lap joints. In pulling apart shear lap test specimens with varying overlap, he noted that increasing the length of overlap does not proportionately increase the strength of the joint. This is shown graphically in Figure 18.

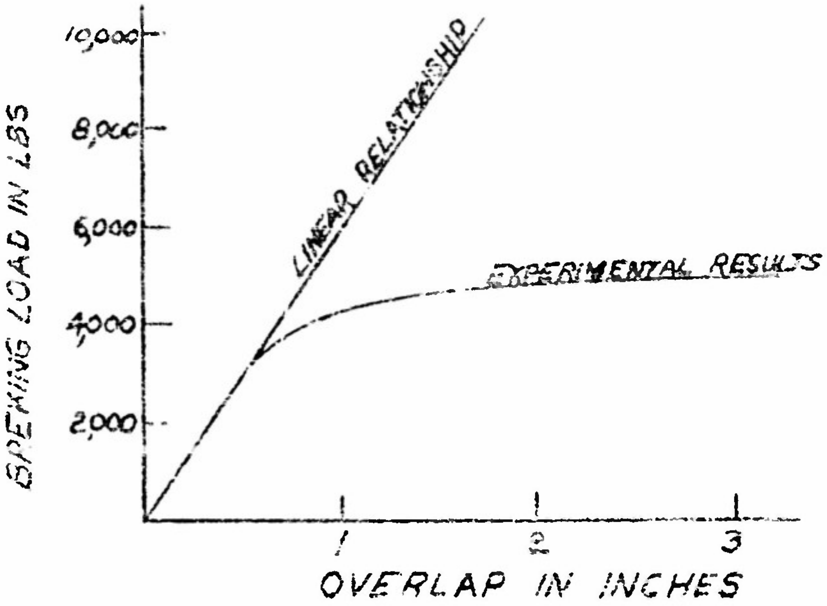


Figure 18
Breaking load as a function of overlap

It was clear from the preceding data that the failing stress, defined as the failing load divided by the joint area, is better described as the apparent failing stress. The real failing stress is much higher than the apparent failing stress and is not uniformly distributed but is concentrated at the ends of the joints. De Bruyne concluded that the important parameter in the strength of a simple shear lap joint for a given material was the ratio of the square root of the thickness of the adherend to the length of overlap which he called the joint factor ($\frac{\sqrt{t}}{2c}$). A condensed table of experimental data for a shear lap joint bonded with redux adhesive is given below.

Description of Joint	Length of overlap 2c	Joint factor	Failing load # *	Apparent failing stress psi
Bright mild steel 1/4" thick x 1".0 wide	0.125	4.0	825	6600
	0.250	2.0	1460	5840
	0.500	1.0	2675	5340
	0.750	0.67	3591	4790
	1.00	0.50	4300	4300
	2.00	0.25	4950	2475
	3.50	0.14	5140	1470
Bright mild steel 1/8" thick x 1".0 wide	0.125	2.82	867	6940
	0.250	1.41	1693	6772
	0.375	0.94	2107	5618
	0.500	0.71	2229	4458
	0.625	6.57	2600	4161
	0.750	0.47	3193	4291
	1.000	0.35	3205	3250
Alclad sheet ".133 thick x 1".0 wide	0.25	1.46	1725	6900
	0.375	0.97	2167	5770
	0.500	0.73	2275	4550
	0.625	0.58	2917	4660
	0.750	0.49	3310	4410
	0.875	0.42	3100	3545
	1.00	0.36	3775	3725
Duraluminum sheet ".0425 x 1".0 wide	0.125	1.65	712	5696
	0.250	0.82	1225	4900
	0.375	0.55	1550	4140
	0.500	0.41	1800	3600
	0.675	0.33	2075	3320
	0.750	0.27	2109	2810
	0.875	0.24	2070	2365
	1.000	0.21	2050	2050
	2.000	0.10	2057	1037
	3.500	0.06	2050	585

*Average of five or more readings.

A plot of the date in Table 1 is shown in Figure 19.

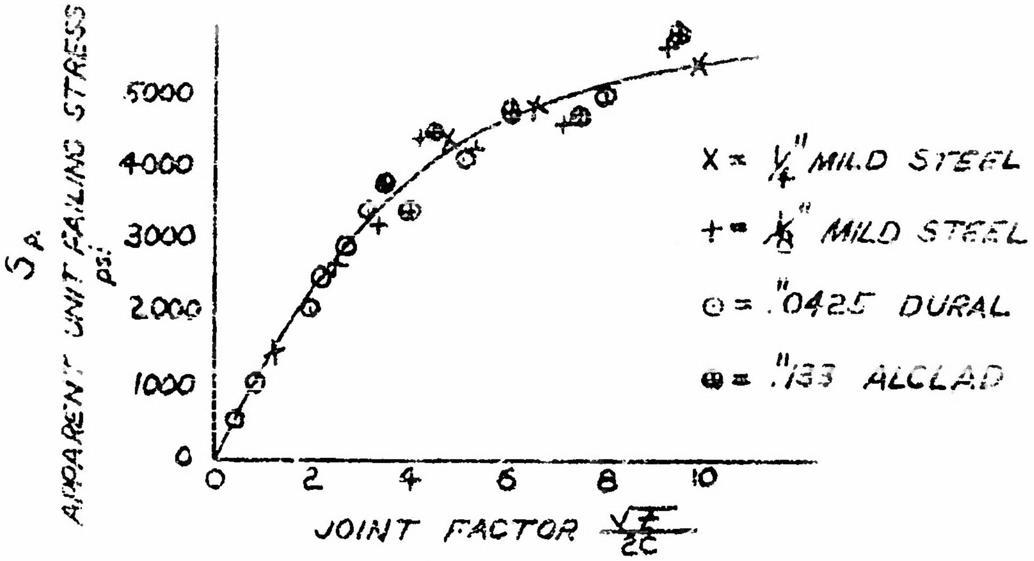


Figure 19
Apparent Unit Failing Stress as a function of
Joint Factor

It will be seen that the data all fall reasonably well on a single curve. This curve has two points of interest:

a. At joint factor between 0 and 0.3, the apparent failing stress is directly proportional to the joint factor and is given by the relation -

$$S_A = 10280 \frac{\sqrt{t}}{2C}$$

b. At high values of the joint factor, S_a asymptotically approaches a value of 5910 psi. Thus with a small overlap, a very high apparent failing stress is obtained because in these circumstances, it approximates the true failing stress.

In order to minimize the effects of differential strains on the adhesively bonded joint, De Bruyne decided to bevel the square ends of the shear lap joint. This was verified by test, and though the increase of strength with overlap is not linear it is a considerable improvement over the curve given by an unmodified shear lap joint. A typical cross-section of a bevelled shear lap joint is shown in Figure 20.

Figure 20
Bevelled shear lap joint

In Table 4, condensed test data on the strength of a bevelled shear lap joint are presented.

TABLE 4
Bevelled Lap Joints - Redux bonded

Description on Joint	Length of Overlap 2c	*Failing load #	Apparent failing stress psi
Steel 1/4" thick	0.50	2966	5932
x 1".0 wide	1.00	4675	4675
	1.50	7283	4850
	2.00	9291	4646
	3.5	13533	3870

*Average of 6 specimens

A plot of the data is shown in Figure 21 and for comparison the equivalent curve for a non-bevelled shear lap joint is also shown.

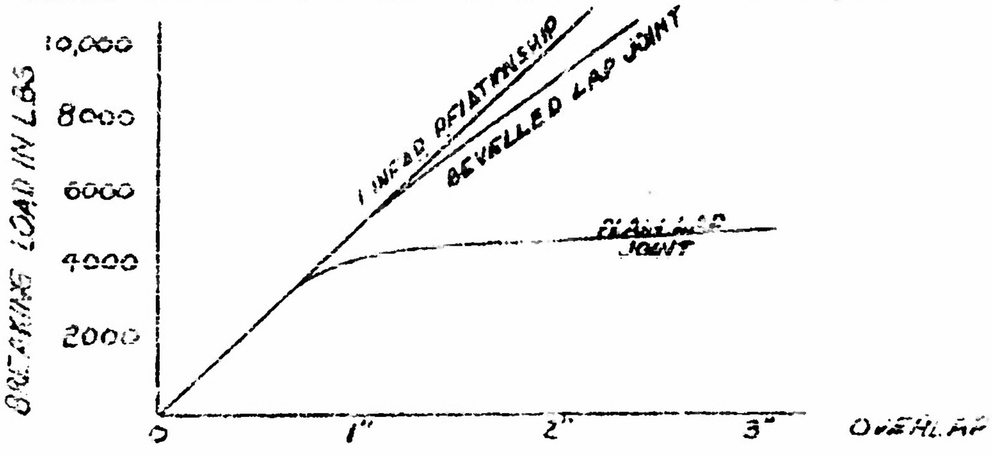


Figure 21
Breaking load, overlap relationship for bevelled & plain lap joint

This lead De Bruyne to the conclusion that the best type of joint is a bevelled or a scarf joint.

To qualitatively illustrate that variation in stress distributions exist in a butt joint under tension, consider the simplest case of adhesivly bonded tensile specimen of circular cross-section acted upon by uniformly distributed axial loading. This is illustrated in Figure 22.

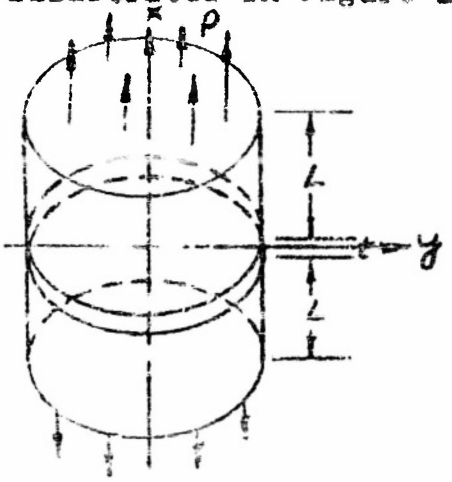


Figure 22
Tensile specimen under uniformly applied load

Let p = uniformly distributed loading psi
d = dia. of tensile specimen inches
t = adhesive larger thickness inches
L = Length of tensile specimen
E = Young's Modulus of the Adherend psi
u = Poisson's ratio for the adherend
E' = Young's Modulus of the Adhesive psi
u' = Poisson's ratio for the adhesive
E_x = Unit Strain (Adherend) in/in
E'_x = Unit Strain (Adhesive) in/in
E_y = Transverse Unit Strain (Adherend) in/in
E'_y = Transverse unit Strain (Adhesive) in/in
δ = Max. lateral contraction of adhesive to adher

Since p is the uniformly distributed loading on the specimen, acting over the entire cross-section, it can be considered as the tensile stress acting on that specimen. The unit strain in the adhesive is

$$E_x = \frac{p}{E} \qquad (1)$$

the unit transverse strain on the adherend is

$$\varepsilon_y = -\mu \frac{P}{E} \qquad (2)$$

the unit strain on the adhesive is

$$\varepsilon'_x = \frac{P}{E'} \qquad (3)$$

the unit transverse strain on the adhesive is

$$\varepsilon'_y = -\mu' \frac{P}{E} \qquad (4)$$

the difference in transverse unit strain between the adherend and the adhesive is

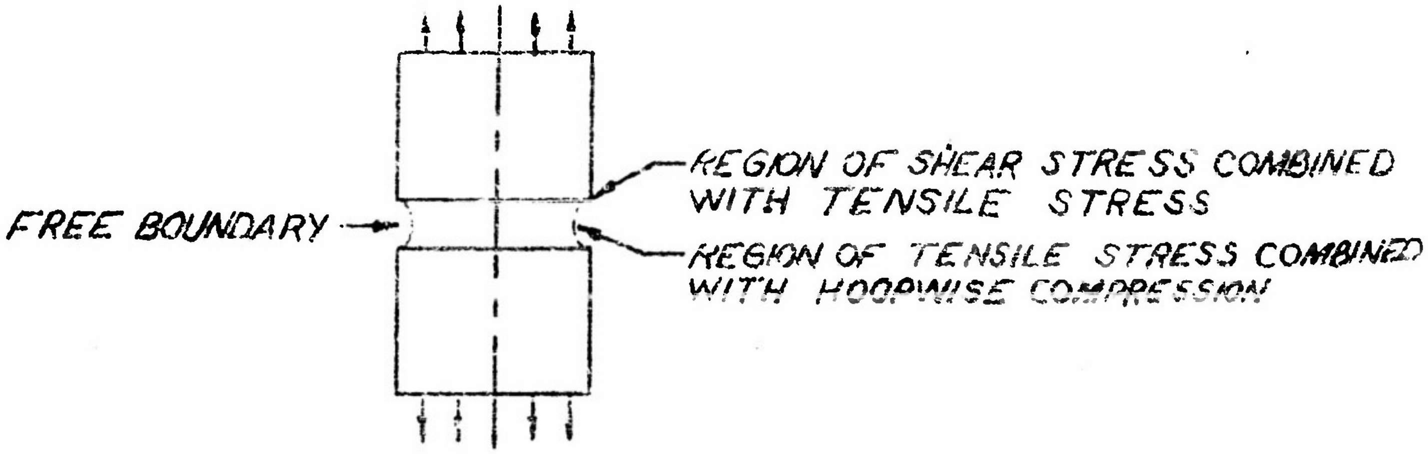
$$\varepsilon = \varepsilon'_y - \varepsilon_y = -\mu' \frac{P}{E} - \left(-\mu \frac{P}{E}\right) = P\left(\frac{\mu}{E} - \frac{\mu'}{E'}\right) \qquad (5)$$

From equations 5, we can note that if wide dissimilarities exist between the υ/E ratios of the adherend to the adhesive, then there would be a substantial difference in the lateral unit strain contractions of the adhesive as compared to the adherend, independent of the length of the specimen or the thickness of the adhesive. Assuming symmetry, the maximum lateral contraction of the adhesive as compared to the adherend would be

$$\delta = \frac{Pd}{2} \left(\frac{\mu}{E} - \frac{{}'}{E'}\right) \qquad (6)$$

Assuming, for the moment, no restraint in shear was offered to the adhesive at the adhesive-adherend interface, then the deformations of the adherends and the adhesive would result in the following exaggerated diagram:

Shear resistance, at the interface, is present and consequently the deformation of the adhesive at the free boundary edge would be expected to be as follows:



We can therefore deduce that, although a uniform loading was imposed on the tensile specimen, a state of combined or bi-axial stress exists at the free boundary edge of the adhesive and that the stress state there is greater in magnitude than the average tensile stress over the cross-sectional area of the specimen.

The analytical solution for the stress distribution in the adhesive of an adhesively bonded tensile specimen with circular cross-section has not been published. It is hoped that this qualitative discussion will serve to acquaint design engineers with the problems attendant upon their use.

The Rheology of Polymers

The strain under stress of an imperfectly elastic solid is governed not only by the magnitude and direction of the stress and the temperature of the material, but also upon the duration of the stress and the previous history of the material. Thus, for example, a candle on a warm day will bend and sag at a steady but imperceptible rate under the steady influence of gravity. If one attempts to straighten the candle in a short time it will break in brittle fracture. However, if hung by the wick in a warm place the candle will straighten in due time without fracture. Again, if a flat strip of polymethyl methacrylate plastic is warmed in hot water it may be twisted and bent into intricate shapes. If held in an odd shape and allowed to cool to room temperature, the strip will become rigid and retian the deformation for an indefinite period. If the deformed strip is thrown back into the hot water it will "remember" its original flat shape and straighten out through the relief of its internal stresses without the application of external stress. Lastly, if a piece of methacrylate is clamped under a known deformation for a period of time it is found that the stress is reduced progressively with time and when released, requires time to recover substantially all of its original dimensions.

The strength of a material or, more exactly, the critical value of the stress at which fracture occurs is not only by the direction of stress and the temperature of the material but also by the duration of the stress and the previous history of the material. Thus for example the strength observed when a strip of polymethylmethacrylate is loaded to its critical value in less than a second is twice that of observed when the strip is loaded in an hour. Again, a strip of the same material which has a history of stress and/or environmental degradation is weaker at any given strain rate than a similar strip of new material.

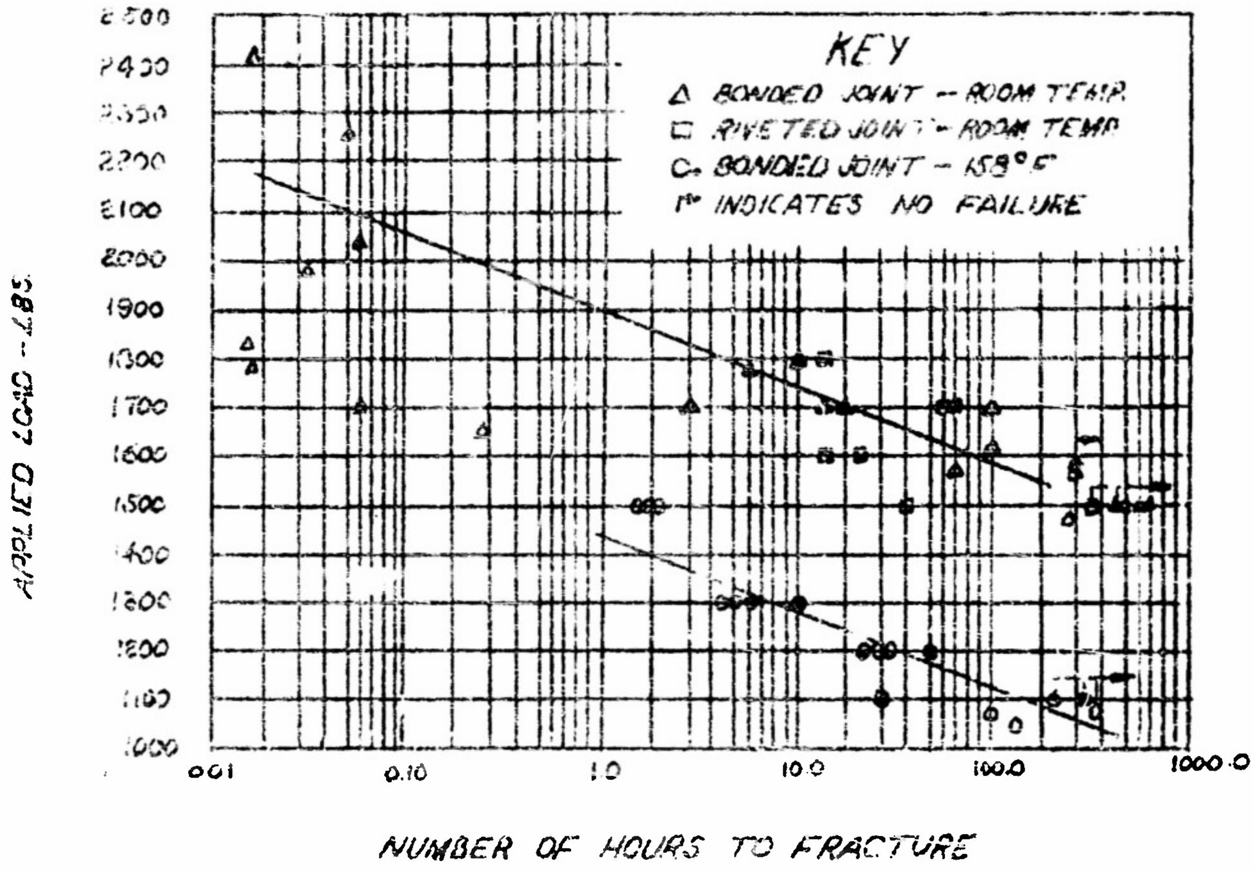
Adhesive bonds exhibit these effects. The dimensional changes resulting from protracted loading are not of great significance in ordinary engineering applications, but may be important if the adhesive is to be relied upon to position an instrument within precise tolerances. The reduction of strength of an adhesive due to previous history of protracted loading may not be important in the instrument but may be important in a structural application in which great reliance is to be placed on the structure after a history of storage, transportation and protracted loading. Figure 23 shows the critical value of the load as affected by time in adhesive bonds and riveted joints in thin gauge aluminum sheet.

As a background for the engineer, some elementary aspects of rheology, the study of the deformation or flow of matter under load is presented here. The fundamental goal of rheology is to describe the behavior of materials in terms of four variables: stress, strain, time and temperature. The two extremes in rheological behavior are the ideal or Newtonian liquid, which extremes can be handled by the engineer using well known equations. However, the mathematical description of the behavior of intermediate substances is more complex and increasing attention is being focused on the problem. (1), (2).

(1) A. Nadai -"Theory of Flow and Fracture of Solids" McGraw-Hill

(2) W. Prager -"Theory of Perfectly Plastic Solids" John Wiley

LONG TERM STATIC SHEAR STRENGTH OF RIVETED AND CYCLEWELDED JOINTS



SHORT TERM STATIC STRENGTH OF RIVETED SINGLE LAP SHEAR JOINTS --- 1370 TO 1890 PSI

SHORT TERM STATIC STRENGTH OF BONDED SINGLE LAP CYCLE-WELDED JOINTS --- 2020 TO 3470 PSI AT 78°F

1520 TO 2640 PSI AT 158°F

RATE OF LOADING FOR SHORT TERM SPECIMENS 30 TO 60 SEC.

Figure 23

(1) Army Air Forces Material Center, "Time-Fracture Tests of Cycle-Weld Bonded Metal Joints", Serial No. EXP-M-51/Str290, Add. 3, 28 Sept. 1942.

An important phenomenon associated with time and temperature of plastic or visco-elastic materials are creep and relaxation effects. Creep is the continued deformation of a material under a constant stress. Relaxation is the process of stress readjustment in a plastic material under a condition of constant strain differentials. Both of these properties are functions of time.

MATHEMATICAL DESCRIPTION OF RELAXATION AND CREEP

If a body is ideally elastic, the stress strain relation is a constant and it may be expressed in the form

$$\frac{d\epsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt}$$

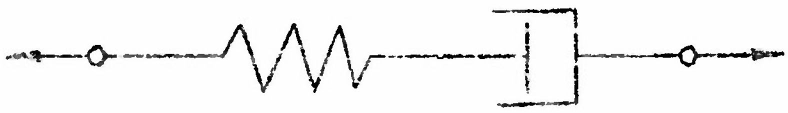
ϵ = unit Strain
σ = unit tensile Stress
E = young's Modulus
t = time

where if a body possesses viscosity, the rate of flow or constant stress is given by

$$\frac{d\epsilon}{dt} = \frac{\sigma}{\eta}$$

where n = viscosity.

We may, at this time, introduce a mechanical analogy for viscosity and elasticity by assuming a steel spring as the elastic element and a dashpot as the viscous element. If the system is placed in series, the combination is frequently called a Maxwell unit. Such an arrangement is as follows:



In this case, the rate of flow is

$$\frac{d\epsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt} + \frac{\sigma}{\eta}$$

or

$$\frac{d\sigma}{dt} = E\frac{d\epsilon}{dt} - \frac{\sigma}{\lambda}$$

where

$$\lambda = \frac{\eta}{E}$$

(ratio of elastic modulus in tension or compression to coefficient of viscosity). The analagous equation for shear stress is

$$\frac{d\tau}{dt} = G\frac{d\gamma}{dt} - \frac{\tau}{\lambda'}$$

where

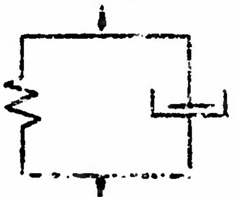
$\lambda' = \frac{\eta}{G}$

γ = unit shear stress

τ = unit shear strain

G = shear modulus

When the pair of elements are placed in parallel, the arrangement will be as follows:



Any deformation takes place equally and simultaneously in the spring and the dashpot. Mechanically, this system behaves like a retarded steel spring. This combination is called a Vogt Unit and accounts for the stress-strain relationship being a function of rate of loading.

RELAXATION AND CREEP (SERIES OR MAXWELL UNIT)

If a Maxwell unit is given a certain strain that is initially rapidly applied but then held constant, the deformation will originally occur almost entirely in the spring but, in time, flow will take place in the viscous element (the piston moves) and the load on the spring (stress) will be gradually dissipated. Since in this case ϵ is held constant $\frac{d\epsilon}{dt} = 0$ and

$$\frac{d\sigma}{dt} = -\frac{\sigma}{\lambda}$$

Integrating and assuming an initial stress σ_0, the equation becomes

$$\sigma = \sigma_0 \; e^{-t/\lambda}$$

This is the equation of "relaxation" and the relaxation time λ is the time necessary to reduce the initial stress to $\frac{1}{e}$ of its original value where e = 2.718. At infinite time, none of the original stress will remain.

Consider the series combination at constant stress. In this case, we let $\frac{d\sigma}{dt} = 0$ and therefore

$$\frac{d\varepsilon}{dt} = \frac{\sigma}{n}$$

Integrate and for initial conditions, when $t = 0$, assume an initial strain. The flow (creep) curve becomes

$$\varepsilon = \varepsilon_0 + \frac{\sigma}{n} t$$

Let $V_0 = \frac{\sigma}{n}$ (constant called creep rate) therefore

$$\varepsilon = \varepsilon_0 + V_0 t$$

RELAXATION, CREEP, ELASTIC MEMORY
(PARALLEL COMBINATION OR VOGT UNIT)

If a Vogt unit is given a stress with the aim of achieving a particular strain, the stress required to achieve that strain will depend upon the rate of deformation. In any case, once the desired strain is achieved, the stress is constant at the value . It is evident that this system does not provide for any relaxation mechanism under constant strain. For when the elastic and viscous elements are in parallel, each element takes its share of the load. However, the load carrying capacity of the viscous element is a function of the rate of change of the strain. As the strain rate stops (after the stress becomes constant) the load is gradually transferred from the viscous element to the elastic element thus storing energy in the elastic element. The load carrying ability of the parallel combination is given as

$$\sigma = E\varepsilon + n\frac{d\varepsilon}{dt}$$

Integrating, we get

$$\ln(\sigma - E\varepsilon) = -\frac{E}{n}t + c$$

For the evaluation of the constant c, we must visualize the physical picture of the stressed Vogt Unit. After the load is applied (and remains constant for a constant stress), the loading is gradually shifted from the viscous element to the elastic element. The time $t = 0$ is referred to the point when the load starts shifting.

when $t = 0$, $\varepsilon = \varepsilon_0$ $\qquad c = \ln(\sigma - E\varepsilon_0)$

the complete equation becomes

$$\sigma - E\varepsilon = (\sigma - E\varepsilon_o)e^{-\frac{E}{\eta}t}$$

recalling that for an elastic deformation

$$\varepsilon_o = \frac{\sigma}{E} \text{ and } \lambda = \frac{E}{\eta}$$

Substitute

$$\varepsilon_o - \varepsilon = \frac{\sigma}{E}\left(1 - e^{-\frac{t}{\lambda}}\right)$$

We must note that ε is the strain after a time referred to the strained condition ε_o. To refer the strain to the original unstrained condition, let

$$\varepsilon_R = \varepsilon_o - \varepsilon$$

where ε_R = residual strain present

$$\varepsilon_R = \varepsilon_o\left(1 - e^{-\frac{t}{\lambda}}\right)$$

The physical significance of this is quite clear. After a stress is applied to a Vogt Unit, the shifting of load from the viscous to elastic element which stores energy and thus tries to restore the element back to the original position when the load is removed. The degree to which this can be accomplished is a function of t and of the constant λ. This phenomenon of partial elastic recovery is known as elastic memory and is involved in the mechanical behavior of most high polymers. Equation points out that at an infinite time, there should be complete recovery.

The Maxwell and the Vogt Unit may be set up in any series parallel arrangement to describe and explain the behavior of many visco-elastic materials. These combinations may become increasingly complex. It should be noted that the term $\frac{t}{\lambda}$ is an important parameter in all the eugations. This essentially is the ratio of the action time to the relaxation time for the material. The larger this ratio, the less the relaxation and the more elastic the behavior. Conversely, the smaller this ratio, the less elastic and the more viscous the behavior.

MECHANICAL BEHAVIOR OF HIGH POLYMERS

To illustrate the preceding discussion, consider a curve typical of those obtained experimentally for the initial flow and relaxation of many plastics. This curve, as shown in Figure 24, is obtained by applying a load to a specimen maintaining the load at a constant level for a definite period, and then removing the load.

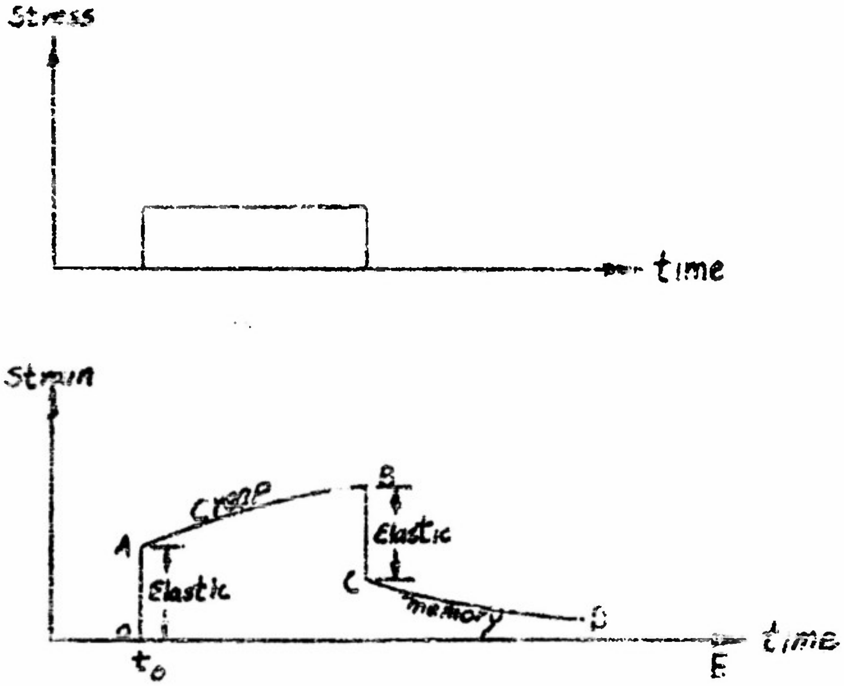


Figure 24
Initial cycle of Creep and Elastic Memory
typical of many plastics

On application of the stress there is an instantaneous deformation OA. This is followed by creep from A to B. On removal of stress at time t, an instantaneous partial recovery takes place BC, followed by a creep recovery (elastic memory) from C_1 to D at time t_2. Further recovery after time t_2 is so slight as to be negligible. DE representing a permanent deformation left at the end of the loading cycle. It is profitable to attempt to use a mechanical model to explain this behavior. A suitable model may be composed of elastic and viscous elements acting in series and parallel.

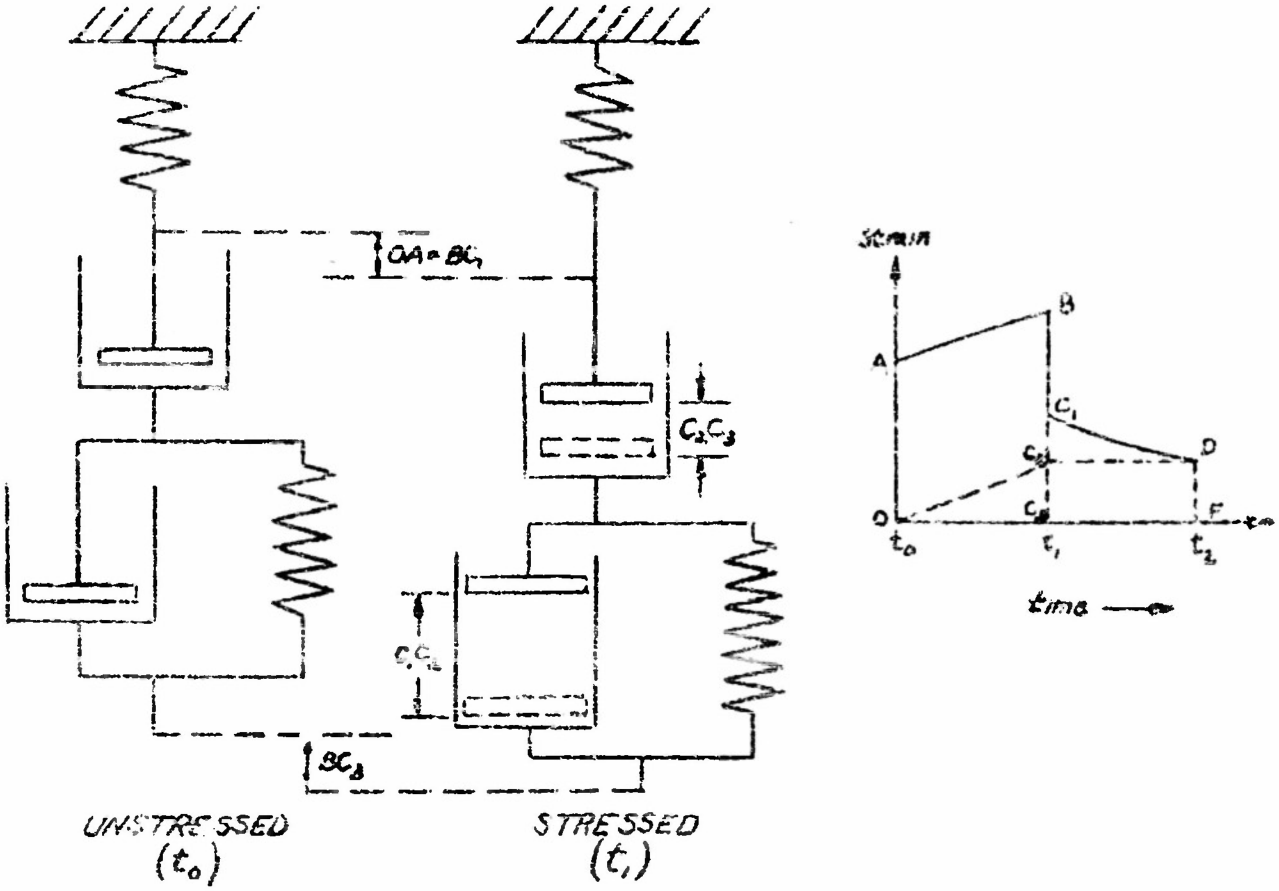


Figure 25
Elastic and viscous elements acting in series and in parallel

Obviously, the creep AB is composed of two components, which become distinguishable only during creep recovery. The elastic component of the creep C_1C_2 (in the parallel circuit) is termed primary creep and is recoverable. Primary creep is retarded. The non-recoverable component (C_2C_3, DE) is termed secondary creep.

Let us consider the case of a constant strain applied to the specimen and then suddenly forced back to its former position. The strain diagram would be as shown in Figure 26.

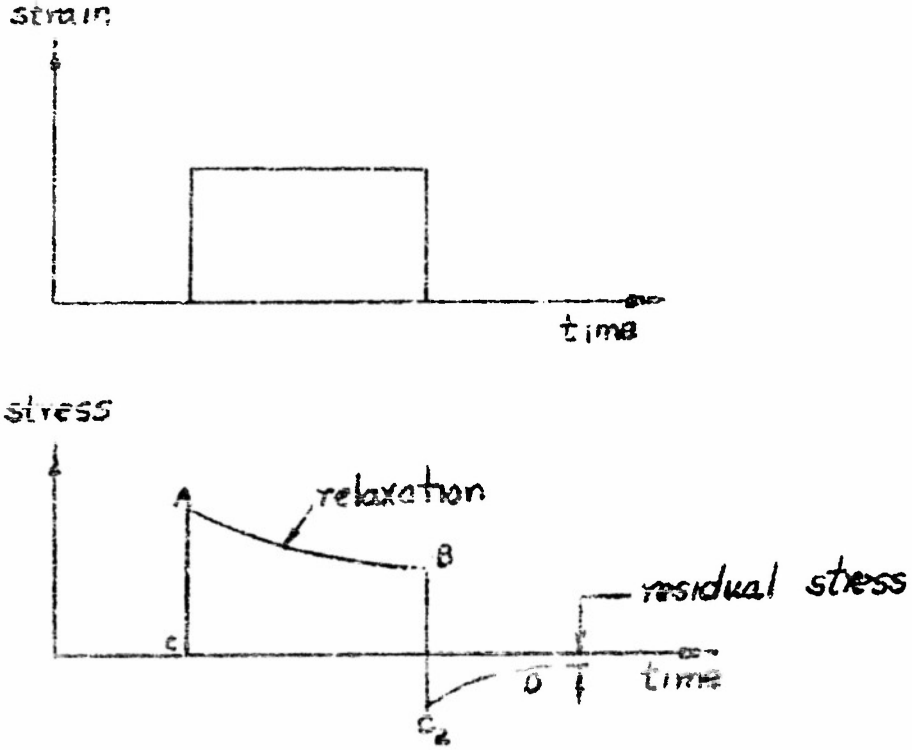


Figure 26
Strain-time relationship typical of many plastics

In this case, a given strain is applied to the specimen at t_0 and held constant until t_1. During this period, the stress in the model has reduced from A to B. To return the specimen to its original position, a negative load must be applie to the specimen C_1C_2. However, this load also relaxes as a function of time and at t_2, a small residual stress may exist. To illustrate by the mechanical model, examine Figure 27.

The foregoing has dealt with the behavior of visco-elastic substances with regard to their deformation under constant stress, or their relaxation of stress under constant deformation. The picture is even more complicated if neither the stress nor the deformation is constant but is a function of time.

Rheology is not sufficiently advanced to be of much help quantitatively in these complex situations, however, an understanding of the advances to date in this field will no

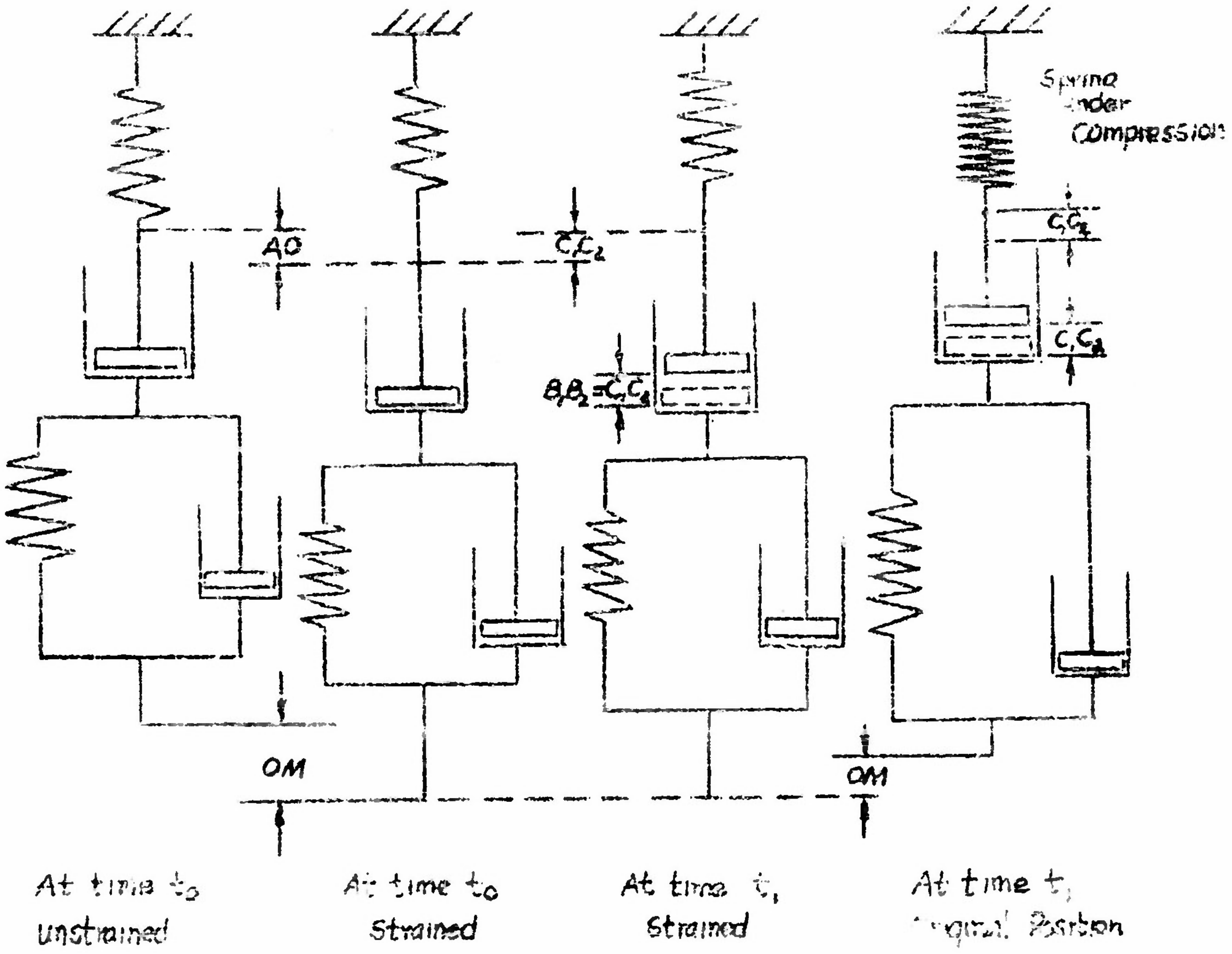


Figure 27
Elastic and viscous elements acting in series and in parallel-constant strain

doubt be of assistance to the engineer in visualizing the possibilities which he may encounter in employing viscoelastic substances in engineering applications.

An uncured adhesive during the bonding process takes the form of a liquid, either by fusion or solution, and proceeds through stages of increasing viscosity, gelation and solidification, approaching but never attaining the properties of a Hookian solid to a degree depending on its composition, temperature and the completeness of any chemical reactions involved, thus exhibiting in various stages of the development of the bond rheological properties. It is certainly not valid to treat a thermoplastic adhesive, and probably not valid to treat some of the most cross-linked types of thermosetting adhesive, as a Hookian solid. Rather, it is necessary to keep in mind the viscoelastic properties of these substances and to apply the principles of rheology wherever possible

Statistics of Fracture

Strength is a measure of the resistance of a material to fracture. In a loose usage strength denotes the stress at which the material "fails" either by fracture or by plastic deformation. However, the stress at which plastic deformation takes place should be called the yield stress. Here we are concerned with the critical value of stress at which fracture occurs.

Fracture is not one single physical phenomenon; there are several essentially different processes that may lead to the failure of a body by the action of mechanical forces. The same material may fail with different mechanisms of fracture according to the stress and strain conditions, strain rate and to the temperature; thus a polystyrene may show brittle fracture at low temperatures and rupture by molecular sliding at higher temperatures. "Bouncing putty", a silicone polymer, appears to fail by fibrous fracture at high strain rates and to rupture by molecular sliding or viscous flow at low strain rates.

Attempts to characterize fracture mechanisms in neat categories appear not to have been very profitable from the engineers' point of view, the mechanisms apparently overlapping each other in degrees depending upon subtle differences in the condition of the materials and of the tests. With plastic materials the fracture condition involves the entire strain history in addition to the principal stresses. Under triaxial stress the fracture condition will, in general, involve all principal stresses and (if the material is orthotropic) the orientation of the principal axes. Nothing is known about the mechanisms of fracture of adhesives in thin layers. It is therefore, best without further ado to go on to the statistical aspects of the subject.

It is a truism, of which the mathematical implications are of no little interest, that the strength of a chain is that of its weakest link. It might also be, a truism that the strength of a bundle of chains is that of the strongest chain. In the first case the formulation of the problem becomes that of the statistical distribution of smallest values in samples of size n where n is the number of links.(1) In the second case the problem becomes that of the statistical distribution of extreme values in samples of size n' where n is the number of chains.(2)

Griffith(3) assumed that the discrepancy between theoretically estimated values of tensile strength of glass was due to the presence of very small cracks or other flaws around which a strong stress concentration arose when the glass was stretched. He showed that the observed tensile stress may be increased by removing or making ineffective the most dangerous cracks, having tested freshly drawn glass rods which showed tensile strengths up to 10^6 psi whereas after a few hours the rods showed strengths in the order of 10^5 psi. Joffe(4) tried to eliminate surface cracks on sodium chloride crystals by dissolving the surface in warm water during the test, and claimed strengths in the wet crystal 300 times greater than that of the dry crystal. Orowan(5) tested sheets of mica, making the edge stress free by using grips narrower than the width of the lamella, so that only the central part of the lamella was under stress, thus avoiding stressing any edge cracks, and obtained values ten times that normally reported for mica.

According to the theory of the statistical distribution of the smallest values in samples of size n where n is the number of flaws, and assuming a Gaussian distribution(6)

$$\frac{1}{\sigma\sqrt{2\pi}}\exp-\frac{(X-u)^2}{2\sigma^2}$$

the most probable value of the smallest value is equal to

$$X_n = u-\sigma\left(\sqrt{2\log n}+\frac{\log\log n+\log 4\pi}{2\sqrt{2\log n}}\right)$$

and the distribution of smallest values, where n is large, is

$$X = u-\sigma\left(\sqrt{2\log n}+\frac{\log\log n+\log 4\pi}{2\sqrt{2\log n}}+\frac{\log\xi}{\sqrt{2\log n}}\right)$$

where u = arithmetic mean strength
σ = standard deviation
n = number of flaws
ξ = $nF(x)$ = probability density function

It may be seen that the most probable value decreases as a multiple of $(\log n)^{\frac{1}{2}}$ and the variance decreases as n increases and is equal to $\pi^2\sigma^2/2\log n$. A typical set of curves according to this distribution for u = 20,000, σ = 1000, and n = 10, 100, 1000 is shown in Figure 26. It is to be noted that these curves, particularly those in which n is relatively small, are skewed to the left. Compare the shape of these curves with the histogram for ninety-six tensile adhesion tests on a polyester resin acting as an adhesive between aluminum surfaces in Figure 27. It may be observed that the adhesive tensile strength histogram is skewed slightly, if at all, to the left, indicating, according to the above, that we are dealing with a fairly large number of flaws in a tensile bond. A more strongly skewed histogram for twenty-six single lap adhesive joints containing a thermoplastic adhesive is shown in Figure 28. We mayspeculate that the lesser number of flaws exhibited by this set of lap joints as compared to the number of flaws in the set of tensilejoints may be explained on the statement of Goland and Reissner that fracture of a lap specimen may be expected to start at the edges of overlap. Thus, if flaws are distributed at random throughout the volume and surface of the adhesive the number which may contribute to low values in a tensile specimen should exceed the number at the edges of a lap specimen.

Time has not permitted the authors to investigate the theory of flaws beyond these elementary and uncertain speculations, nor does the theory explain the nature of the flaws. However, the skewness of histograms is a common observation in the strength of a variety of materials and should be studied further.

Assuming a normal (not skewed) distribution of values the theory of statistics provides a measure of the reliability of a structure which is of immediate value in the design process. If we assume that an accidental error is the algebraic sum of an infinite number of elemental errors, each of which is likely to be positive as well as negative, it can be shown that for a very large number of measurements, which contain only accidental errors, the error will follow the normal distribution on Gaussian distribution law

$$y_x = \frac{1}{\sigma\sqrt{2\pi}} \exp - \frac{\sigma^2 x^2}{2}$$

where

x = value of an error (the difference between the observed and the true value of the quantity)

y_x = the probability of occurrence of an error of magnitude x

σ = constant associated with the particular set of observations in question - known as the standard deviation

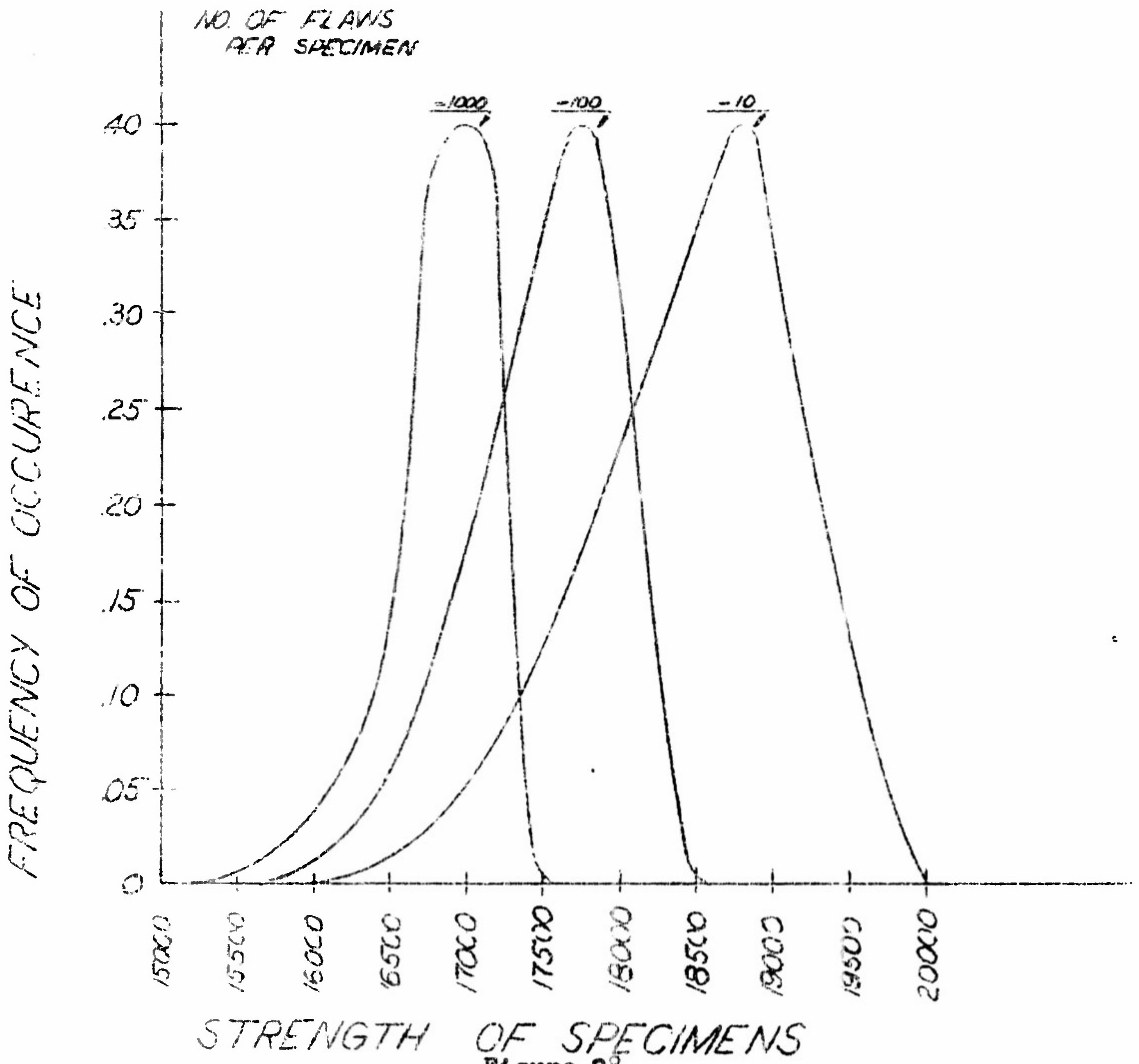

NO. OF FLAWS PER SPECIMEN
-1000
-100
-10
FREQUENCY OF OCCURENCE
.40
.35
.30
.25
.20
.15
.10
.05
0
15000
15500
16000
16500
17000
17500
18000
18500
19000
19500
20000
STRENGTH OF SPECIMENS

Figure 28

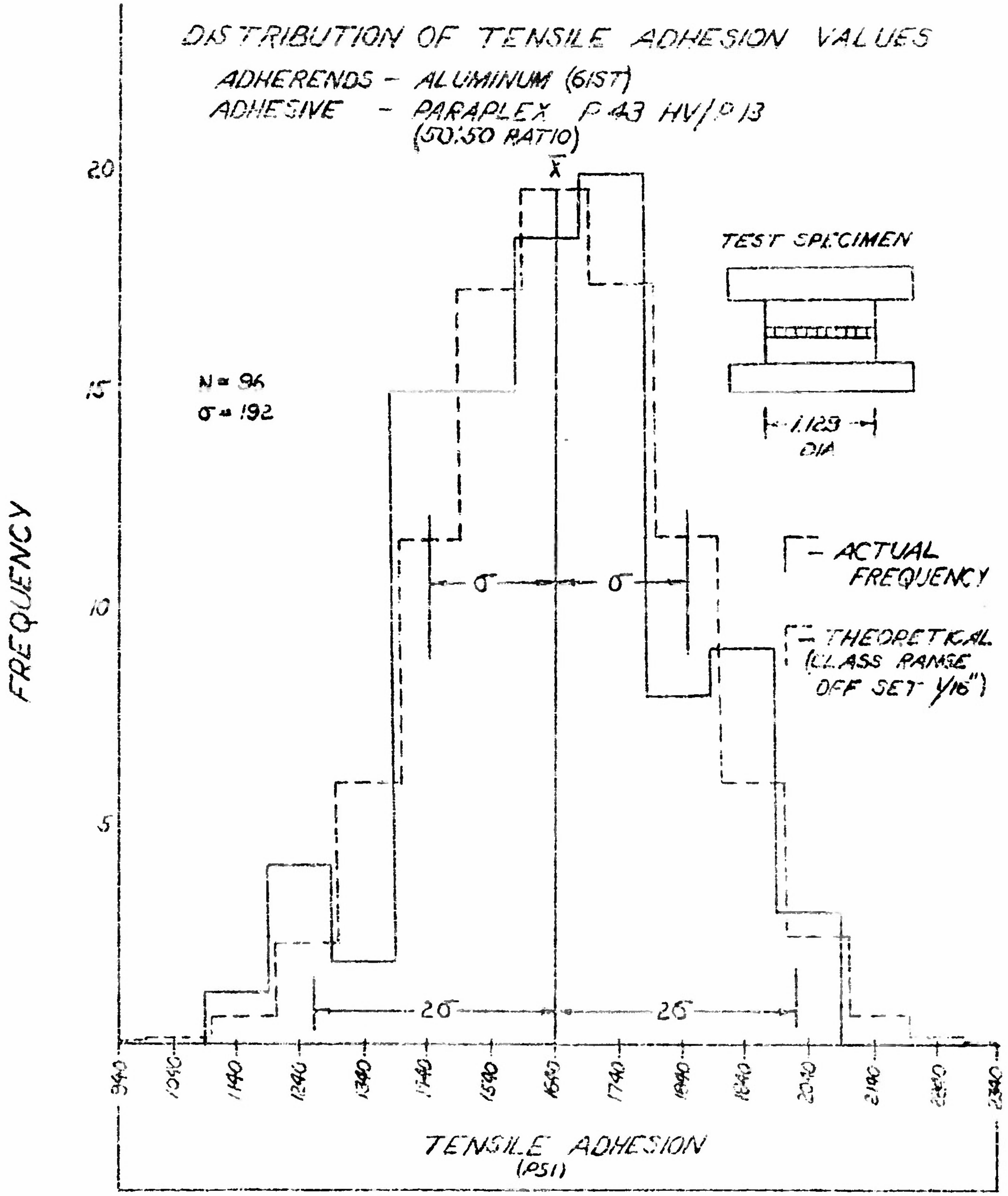
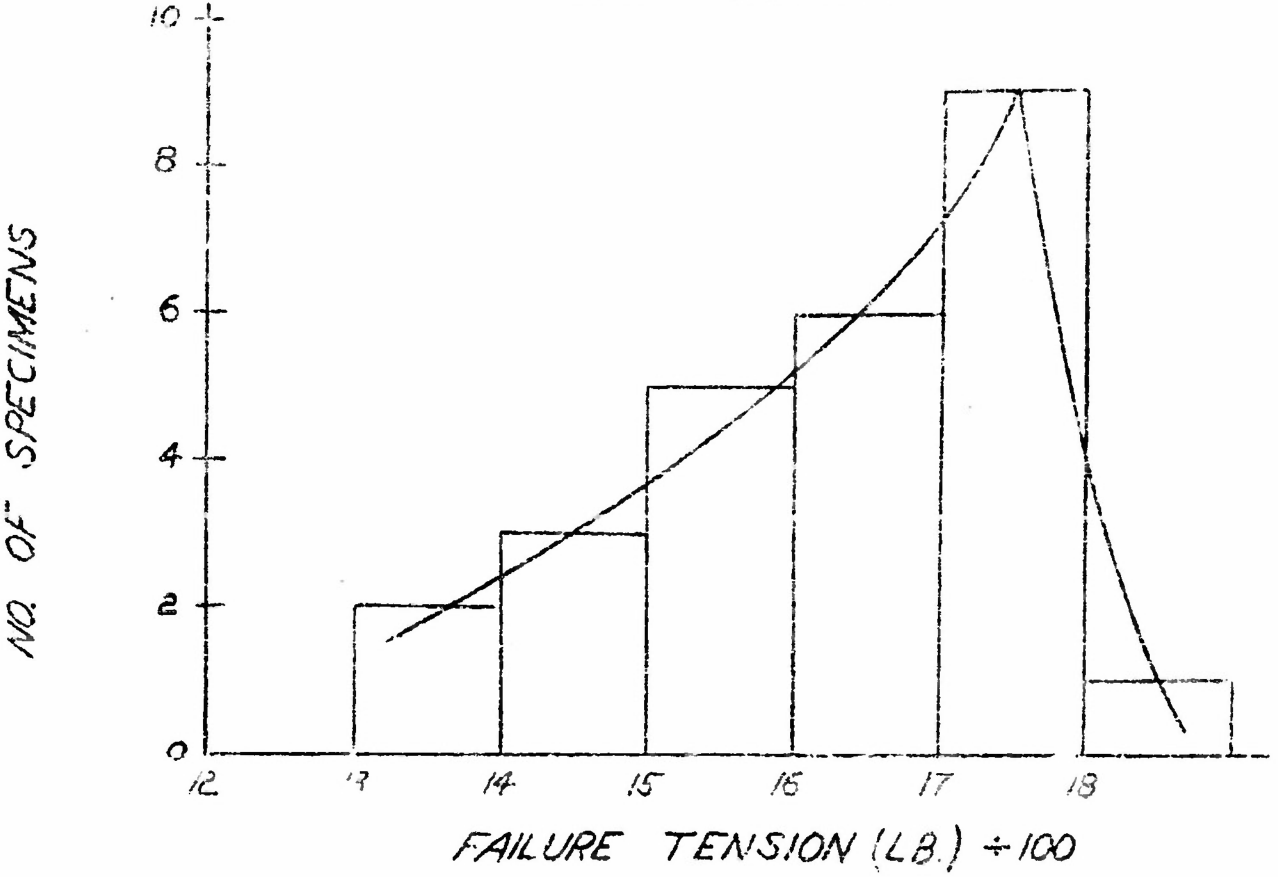

DISTRIBUTION OF TENSILE ADHESION VALUES
ADHERENDS - ALUMINUM (61ST)
ADHESIVE - PARAPLEX P-43 HV/P-13
(50:50 RATIO)
X̄
N = 96
σ = 192
TEST SPECIMEN
1.129
DIA
σ
σ
2σ
2σ
- ACTUAL FREQUENCY
- THEORETICAL (CLASS RANGE OFF SET 1/16")
FREQUENCY
20
15
10
5
940
1040
1140
1240
1340
1440
1540
1640
1740
1840
1940
2040
2140
2240
2340
TENSILE ADHESION
(PSI)

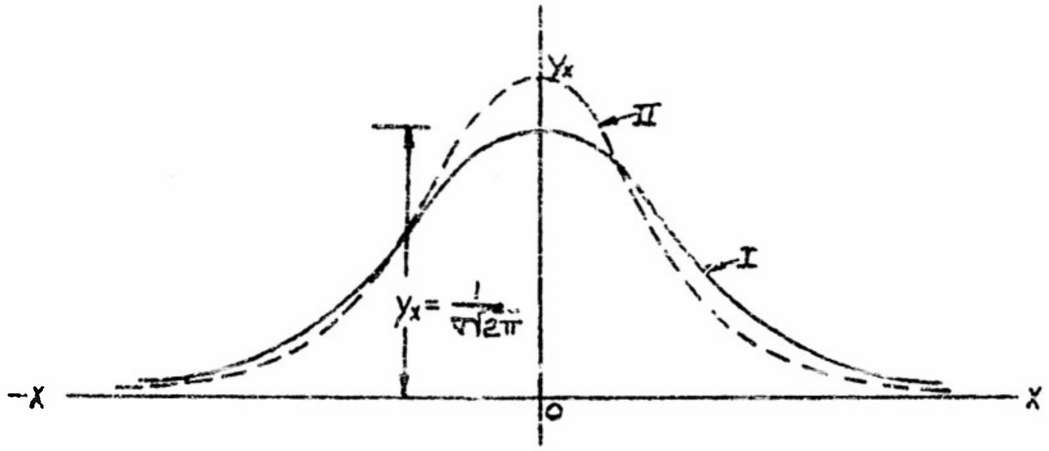
Figure 29



Mechanical Spreader Used at 50% R. H. and 77° F.
Dried with 40 psi at 77° F.
Aged 14 days at 140° F.

Figure 30
Distribution of strengths of single lap joints

The graphical representation of this equation is the familiar normal frequency distribution curve:



From the frequency distribution curve, we may deduce the following information:

a. The area under the curve is unity, expressing the condition that all errors or deviations lie between $-\infty$ and $\neq \infty$ and that the total sum of all the probabilities is equal to 100%.

b. When $x = 0$, $y_x = \frac{1}{\sigma\sqrt{2\pi}}$ where σ is a characteristic of the particular set of measurements. If another set of measurements are taken and results in curve II, it becomes evident that this curve has a higher probability for accuracy. Therefore, the constant of the set of measurements σ may be looked upon as an index of precision or the scatter of the measurements. The smaller the value of the standard deviation σ, the smaller the scatter in the observed values.

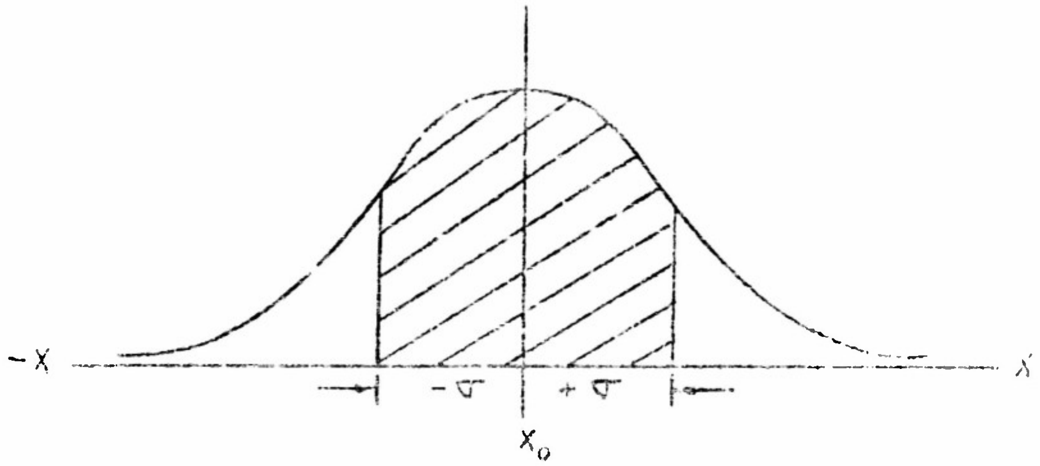
On the basis of the normal frequency law, if a large number of n measurements $\bar{X}$, $\bar{X}_2$, $\bar{X}_3$, $+ \cdots \bar{X}_n$ are taken, all with equal skill and care of a quantity X, the most probable value of the quantity is X_o, the arithmetic mean of all measurements. Expressed mathematically

$$X_o = \frac{X_1 + X_2 + X_3 + \cdots X_n}{n}$$

Expressed graphically, the mean or average value is the symmetrical axis of the normal frequency distribution curve. The mean value is useful in establishing the average value of a set of measurements but it gives no indication of the relative distribution of the measurements with respect to the mean value. This is the function of the standard deviation. The Standard Deviation is given by

$$\sigma = \sqrt{\frac{(x_0-x_1)^2+(x_0-x_2)^2+\cdots(x_0-x_n)^2}{n-1}}$$

The standard deviation has a useful property in that any proportion of the standard deviation used as the upper and lower limits of the probability curve defines a definite area of that curve between the limits. Since the area under curve between limits is the measure of the probability of a measurement occurring between those limits, the standard deviation therefore, is a measure of the reliability that can be expected for a measurement to fall between certain values. To illustrate, assume a statistically accurate probability curve with one standard deviation as the upper and lower limit. This is as follows:



The area in question has been cross-hatched. Geometrically, the points of inflection of the curve occur at distances σ from the axis.

Since the total area under the curve (from +∞ to -∞) is equal to unity (sum of all the probabilities), the area under the curve bounded by the standard deviation will always be 68.3% of the total area. This holds true for any proportion of the standard deviation. The probability that a measured quantity will fall between limits about a mean value; the limits being defined by the standard deviation σ times a constant n is as follows:

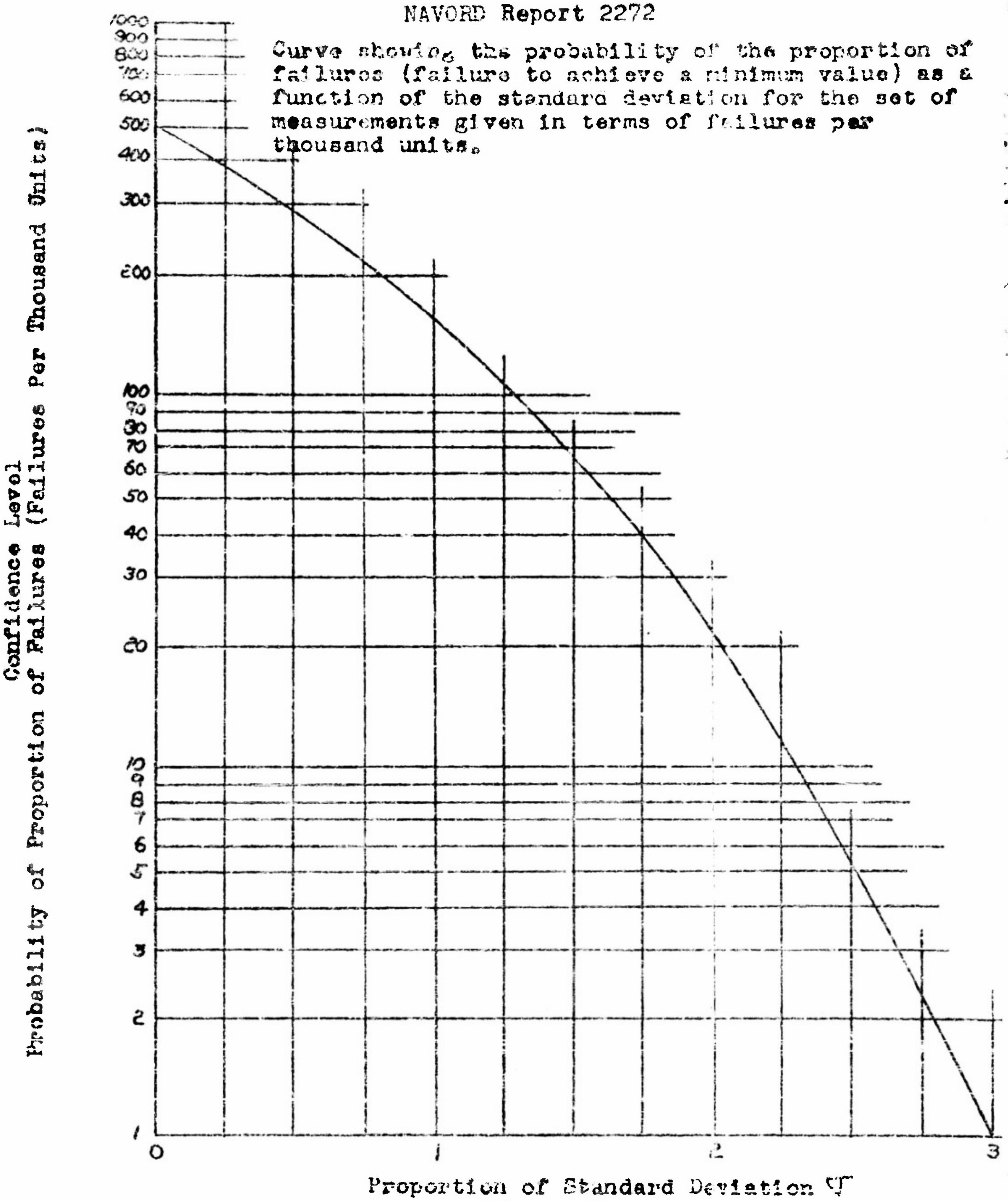
Multiples of the Standard Deviation n	Probability (area under curve) P(%)
0.5	38.30
1.0	68.26
1.5	86.64
2.0	95.54
2.5	98.76
3.0	99.74

As a rule, a designer is not interested in the upper limits (max. strength values) but only in the lower limits (min. strength values). He is principally concerned with the probability that a strength value will exceed a certain minimum. The probability that a given measurement will exceed a minimum value $(\bar{x}_0 - n\sigma)$, the minimum value being defined below the mean value less the proportion of standard deviation in question, is as follows:

Multiples of the Standard Deviation n	Probability (that a measure will exceed a minimum value)
0.5	69.15
1.0	84.13
1.5	93.32
2.0	97.72
2.5	99.38
3.0	99.87
4.0	99.99

For the graphical representation, see Figure 31.

We can now introduce the concept of confidence level; that is the reliability that the designer can expect of his strength values. This pre-supposes that the designer has available the mean value of a series of tests on a pertinent adhesively bonded joint assembly and the standard deviation of that set of measurements. With this information available, the designer may set the design value of the strength of the adhesive. (See Figure 32)



Curve showing the probability of the proportion of failures (failure to achieve a minimum value) as a function of the standard deviation for the set of measurements given in terms of failures per thousand units.

Figure 31

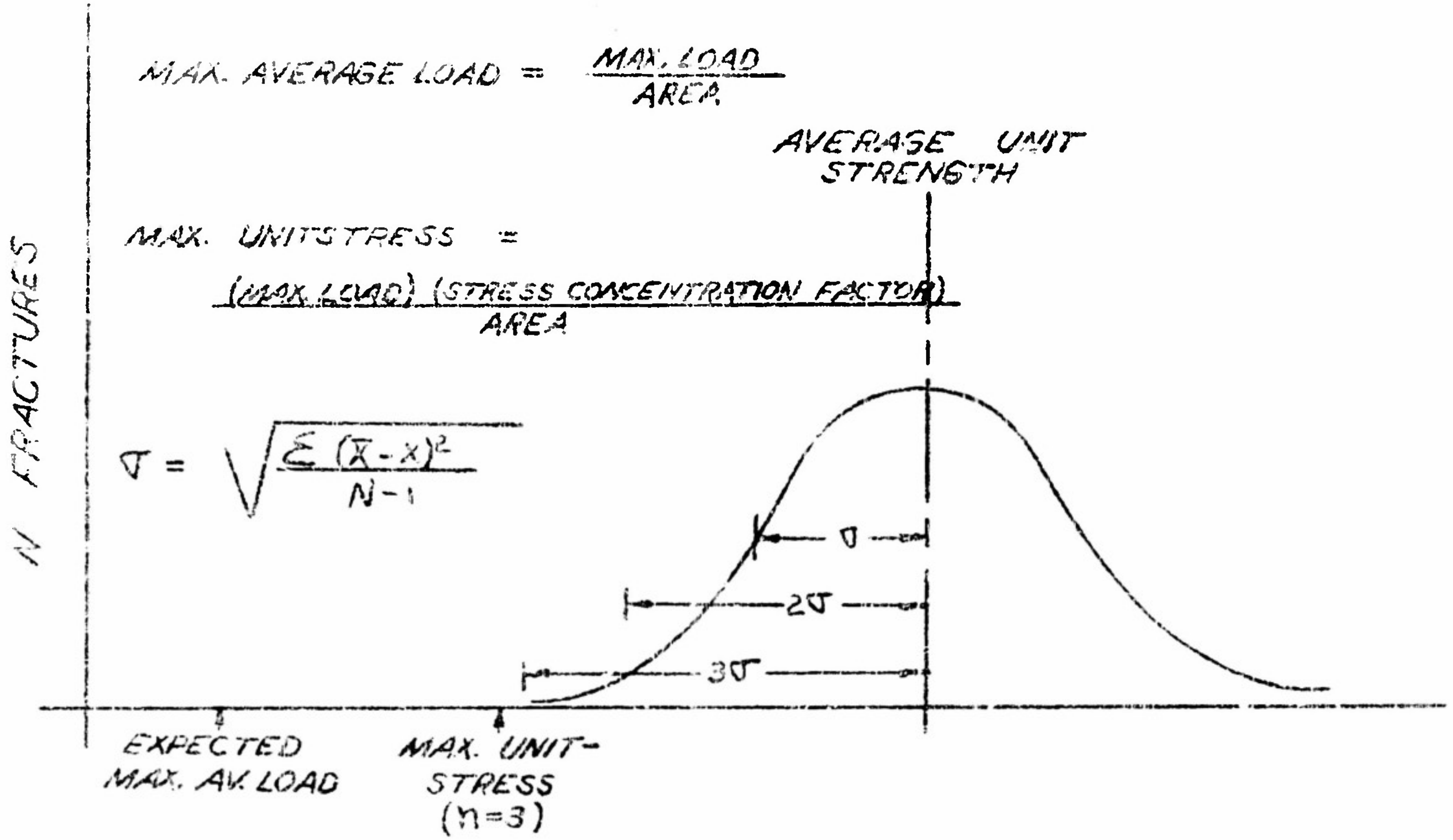


Figure 32
Illustration of use of statistical distributions of strengths in a design problem

REFERENCES

1. F. T. Pierce, "Tensile Tests for Cotton Yarns v. "The Weakest Link-Theorems on the Strength of Long and Composite Specimens", J. Tex. Inst. 17, [illegible] (1926)

2. H. E. Daniels, "The Statistical Theory of the Strength of Bundles of Threads I" Proc. Royal Soc. (London) 183,405 (1945)

3. A. A. Griffith "The Phenomena of Rupture and Flow in Solids", Phil. Trans. Roy. Soc. 221A, 163 (1920)

4. "The Physics of Crystals", A. F. Joffe, 1928 (New York

5. "Fracture and Strength of Solids", E. Orowan, Rep. Phys. Soc. Progr. Phys. 12, 185-232 (1948-49)

6. "Statistical Aspects of Fracture", B. Epstein, J. Apl. Phys. 19, 140-7 (Feb 1948)

7. L. H. C. Tippett, 'On the Extreme Individuals and the Range of Samples Taken from a Normal Population", Biometrica 17, 36A (1925)

8. W. Weifull, "A Statistical Theory of the Strength of Materials", Ing. Vetenskaps Akad. Handl. No. 151 (1939) "The Phenomena of Fupture in Solids" Ibid No. 153 (1939)

SECTION III: DESIGN PRINCIPLES FOR STRUCTURAL ADHESIVE BONDS

General Discussion

In any design problem, involving the joining or fastening of two rigid members for structural or stress carrying purposes and which utilizes adhesives as the joining material, the designer is faced with various problems in making the assembly strong enough to withstand the expected loads imposed on the structure. The design engineer would like to know the pure strength, (average values and statistical distributions) and the plastic and elastic constants of the materials and the distribution of the stresses in the adhesive and the structure under load. From the foregoing, he could determine the proper geometry of the structure to withstand the load. Unfortunately both the pure strength values of adhesive and the stress distributions in adhesively bonded joints are largely unknown for reasons which are discussed in Sections II and V, and very few data are available on the elastic constants of adhesive layers. Further, data on the influence of degrading influences of mechanical and environmental degrading influences on the properties of adhesives are few.

Yet, the application of the simplified design practices used for stress studies on engineering materials to an adhesive joint assembly may lead to serious and gross errors. It is hoped that the following discussions will acquaint the design engineer with the problems to be faced in the design of such a joint, and with such tentative concepts as do exist, so that he may have proper perspective on the problem and thus more intelligently apply his judgment and background to the solution of bonding problems that might be encountered.

Advantages and Disadvantages of Adhesive Bonds

In approaching the design of a structure the engineer often has an opportunity to choose between an adhesive bond, a threaded joint, riveted or bolted joint in a lock ring joint, a soldered joint or a welded joint. At some considerable risk of over-simplification or oversight of special cases, the relative merits of the more important of the possible means of attachment are set forth in the following table to serve at least as a stimulus for thought on the subject by the engineer as he decides on the type of attachment he will employ in the design of his structure.

TABLE 5

Design Factors	Adhesive Bonds	Metal Rivets, Bolts	Threads: Metal Lockrings	Welds Solder In Metals
Short time Strength				
High Bearing Strength Adherends	Good	Good	Good	Good
Low Bearing Strength Adherends	Good	Poor	Poor	Good
Long Time Strength				
High Bearing Strength Adherends	Poor	Good	Good	Good
Low Bearing Strength Adherends	Poor	Poor	Poor	Good
Initial Dimensional Stability Under Load	Good	Poor	Poor	Good
Dimensional Stability Under Long Time Load				
Non-ductile Adherends	Poor	Good	Good	Good
Ductile Adherends	Poor	Poor	Poor	As good as adherend
Strength at Elevated Temperatures	Poor	Good	Good	Good
Peel or Cleavage Strength	Poor	Good	Not applic.	Poor
Additional Sealing Required Against Leaks	No	Yes	Yes	No
Electrical Conductivity	No	Yes	Yes	Yes
Magnetic Susceptibility	1	>1	>1	>1
Requires access to interior of closed or reentrant cavities	No	Sometimes		Sometimes
Pre-assembly adherend tolerances	Loose	Tight	Tight	Loose
Vibration or friction in assembly	No	Yes	Yes	No

TABLE 5 (Continued)

Design Factors	Adhesive Bonds	Metal Rivets, Bolts	Threads; Metal Lockrings	Welds Solder In Metals
Heating during assembly	Some adhesives require no heat	No	No	Yes
Time required before joint may be stressed	Up to a week	Zero	Zero	When cool
Assembly jigs required	Yes	Yes	No	Yes

Let it be assumed that the engineer has decided to employ an adhesive bond in the design of a structure. He is now faced with the choice of bond geometry, the choice of an adhesive, the assignment of dimensions to the bond, the design of any jigs or fixtures required, the description of the steps in the bonding process, the description of the test and inspection procedures to be followed, the classification of defects and the preparation of specifications covering the above.

Selection of Joint Geometry

There is no precision method of selecting a joint geometry for use in a given application because of the large number of joints possible and the many conditions which will affect the selection of joint geometry. There are, however, several factors of primary importance to which careful consideration must be given. These are listed below. Compromises must be made and the ingenuity of the designer must be depended upon to meet the needs of his specific problem.

OPERATIONAL REQUIREMENTS

Load magnitude, direction and duration are the primary considerations in selecting joint geometry. A particular joint may have great strength when loaded in one direction but be very weak when loaded in another. As an example, a butt joint possesses great strength when loaded in compression but is very weak when subjected to tensile loading. A lap joint will withstand fairly high tensile loading but will fail in bending or shear loading. To guide the designer in selecting a satisfactory joint geometry for various directions of loading, Table 6 has been prepared comparing different joint geometries when subjected to various types of loads.

The magnitude and duration of loading will determine what area of adhesive is required and in so doing, indicate one geometry of joint over another since the adhesive area of certain joint designs is limited. Also, the adhesive area of certain joints is more effectively used than in others. This comparative mechanical efficiency is roughly indicated in the Table. The design stress for the adhesive should be determined by destructively testing joints of the geometry to be used and will not necessarily be comparable to the design figure specified by the adhesive manufacturer. If long term loading is required, the adhesive should not be stressed over 2/5 to 3/5 of its static load strength. If space available for the joint is limited and relatively high adhesive stresses are required, it would be well to use scarfed or bevelled joints to minimize stress concentrations.

SPECIAL REQUIREMENTS

Occasionally, special operational requirements will affect joint geometry selection. If a joint is to be water tight or pressure tight, a geometry having a long overlap will be good insurance against leakage. When an adhesive joint is to act as an electrical condenser, the adhesive area (consequently joint geometry) will be determined by the required capacity, the adhesive thickness and dielectric constant. The simplest joint geometry to consider for a condenser is a butt joint with capacity, $C = \frac{kA}{4\ d}$ where

k = adhesive specific inductive capacity

A = adhesive area

d = adhesive thickness

MACHINING AND ASSEMBLING

Machining considerations are of greatest importance when a thickness sensitive low viscosity adhesive is used in a scarf or tubular scarf joint. It is extremely important that the scarf angle be essentially the same on both adherends. Unless the scarf is the landed type, special jigs will be required to maintain the proper clearance between adherends during the cure period. Even with a landed tubular scarf or tubular lap it may be necessary to pass a tight fitting mandrel through the tubes to insure the adherends being coaxial therefore providing equal adhesive thickness around the tube. In general the degree of accuracy in machining depends on the degree of sensitivity of the adhesive to thickness variation.

Attempting to machine a plain scarf joint to a feathered edge often results in frayed edges, especially if the adherends are plastic. Turning a scarf on a large diameter plastic tube is extremely difficult since it is very easy to press the tube out of round when chucking it. Even the pressure of the machine tool will result in a deflection in the tube. When taken from the machine, the scarf becomes oval. When mated with the other adherend, a variable adhesive thickness results.

To a certain extent the choice of geometry will be influenced by limitations arising in the application of heat or pressure in the bonding process.

FLAT OR MATCHED SEMI-SPHERICAL SURFACES

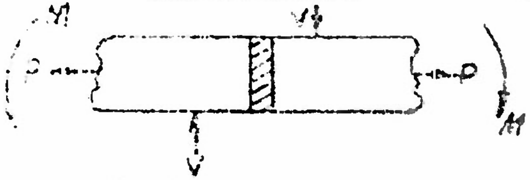
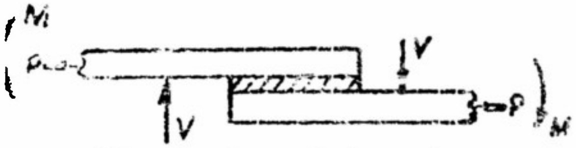
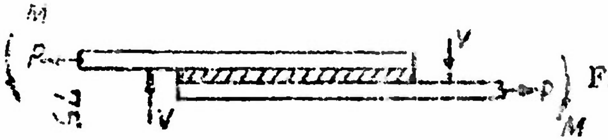
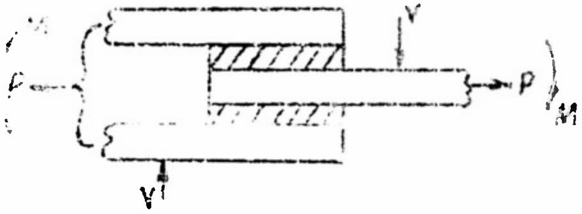
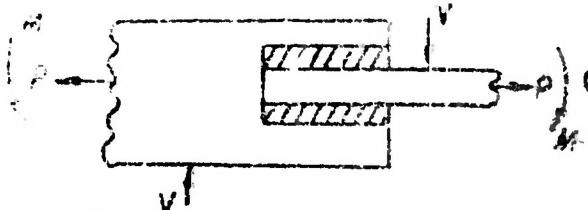
Joints of this general geometry impose no restrictions as regards accessibility of the glue line to heat and pressure. This application is suitable for all types of adhesives. The primary restriction in adhesive selection will result from the porosity and thermal stability of the adherends being utilized.

TUBULAR SURFACES

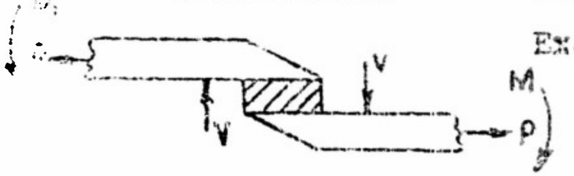
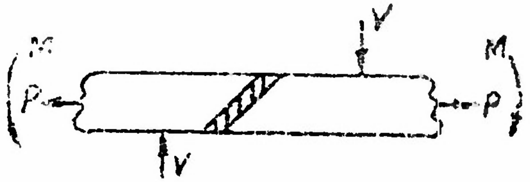
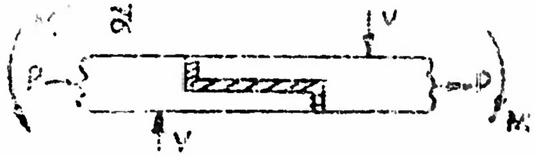
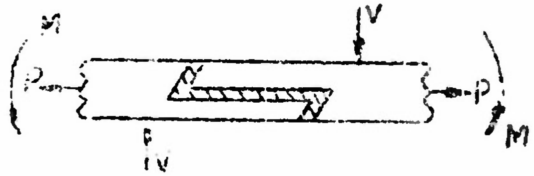
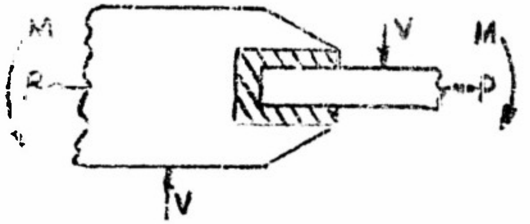
Sleeve Type, Lap Joints. Rigid, tubular lap joints of fixed dimensional clearance represents a geometry where no pressure can be applied to the adhesive during its cure. Fixtures for properly locating and holding the parts in alignment are necessary. Adhesives must be of the 100% reactive type and the shrinkage should be negligible.

TABLE 6

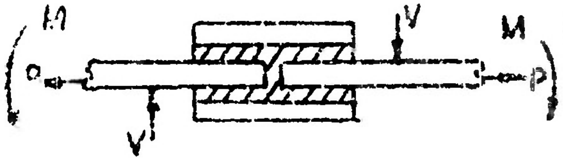
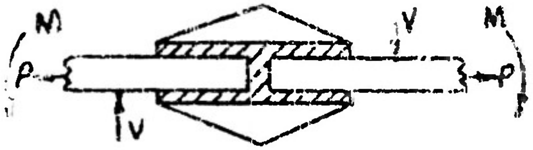
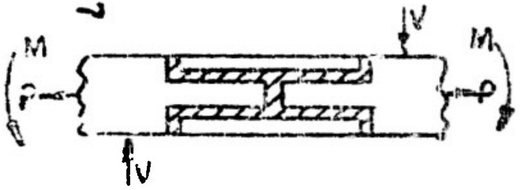
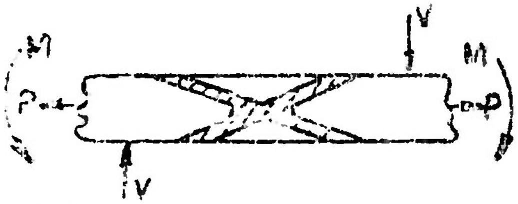
A COMPARISON OF DIFFERENT JOINT GEOMETRIES UNDER VARIOUS LOADS

Flat Joints	Tension (P)	Compression (-P)	Bending (M)	Shear V +V	 -V
 Butt	Poor	Excellent	Poor	Poor	Poor
 Single lap (short)	Good	Good	Poor	Poor	Excellent
 Single lap (long)	Fair	Fair	Fair	Poor	Excellent
 Double lap	Good	Good	Fair	Excellent	Excellent
 Double lap butt	Good	Excellent	Good	Excellent	Excellent

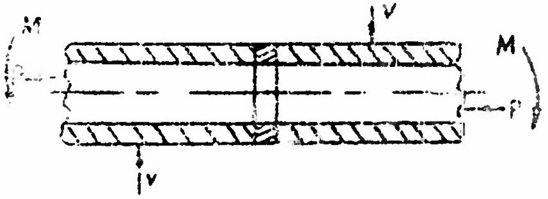
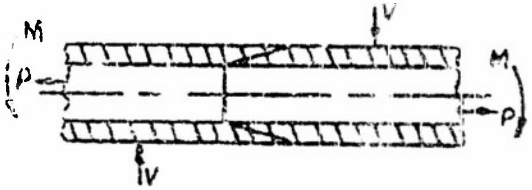
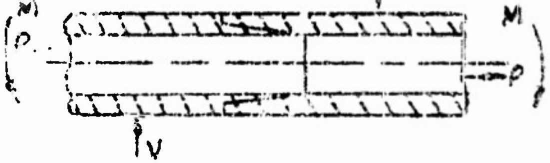
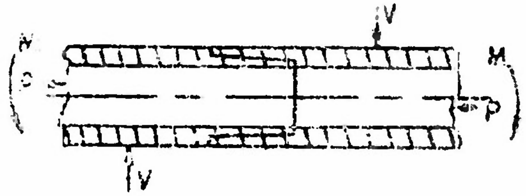
MECHANICAL EFFICIENCY UNDER VARIOUS LOADS

Flat Joints	Tension P	Compression - P	Bending M	Shear V +V	 -V
 Bevelled single lap	Excellent	Fair	Poor	Poor	Excellent
 Scarf	Excellent	Good	Poor	Poor	Excellent
 Double butt lap	Good	Excellent	Fair	Excellent	Poor
	Good	Excellent	Good	Excellent	Fair
 Bevelled double lap butt	Excellent	Excellent	Good	Good	Good

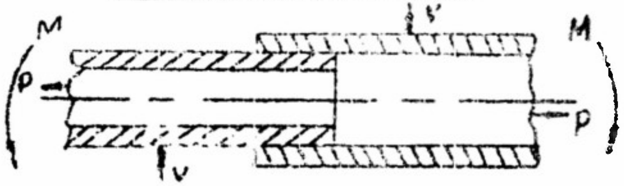
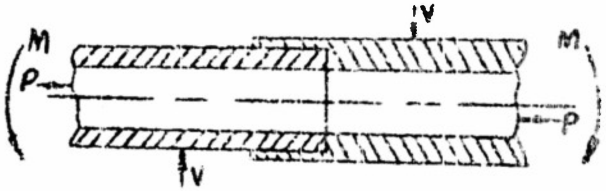
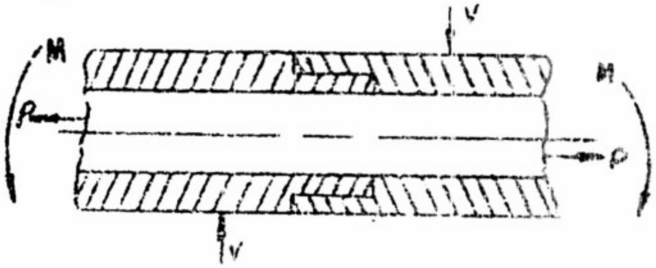
MECHANICAL EFFICIENCY UNDER VARIOUS LOADS

Flat Joints	Tension (P)	Compression (-P)	Bending (M)	Shear V +V	 -V
 Double strap butt	Good	Excellent	Good	Good	Good
 Bevelled double strap butt	Excellent	Excellent	Fair	Good	Good
 Flush double strap butt	Good	Excellent	Good	Good	Good
 Bevelled flush double strap butt	Excellent	Excellent	Fair	Good	Good
 Double landed scarf	Good	Excellent	Fair	Excellent	Poor

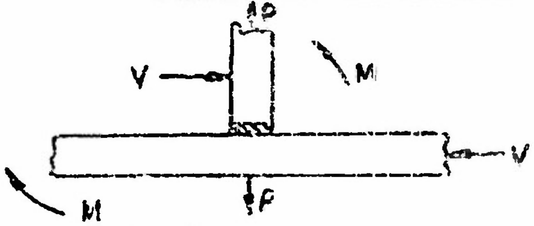
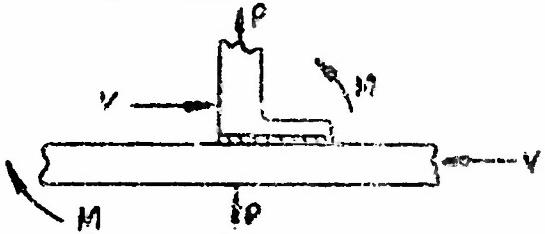
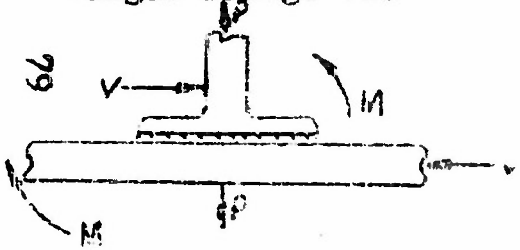
MECHANICAL EFFICIENCY UNDER VARIOUS LOADS

Cylindrical Joints	Tension P	Compression (-P)	Shear V	Bending (M)	Torsion
 Tubular butt	Poor	Excellent	Poor	Poor	Poor
 Tubular scarf	Excellent	Poor near 45° Excellent if Long	Excellent	Excellent	Excellent
 Tubular single land scarf	Good	Excellent	Good	Good	Good
 Tubular double land scarf	Fair	Excellent	Fair	Fair	Fair

MECHANICAL EFFICIENCY UNDER VARIOUS LOADS

Cylindrical Joints	Tension P	Compression (-P)	Shear V	Bending (M)	Torsion
 Sleeve	Good	Fair	Excellent	Good	Good
 Single Land Sleeve	Good	Good	Good	Good	Good
 Dougle Land Sleeve	Good	Excellert	Good	Good	Good

MECHANICAL EFFICIENCY UNDER VARIOUS LOADS

Right Angle Joints	Tension	Compression	Bending	Shear
 Butt tee	Poor	Excellent	Poor	Poor
 Single flange tee	Poor	Excellent	Fair	Fair
 Double flange tee	Fair	Excellent	Good	Good

Equidiameter butt sleeve joints represent a design which is more applicable if compression loading is to be applied to the bond.

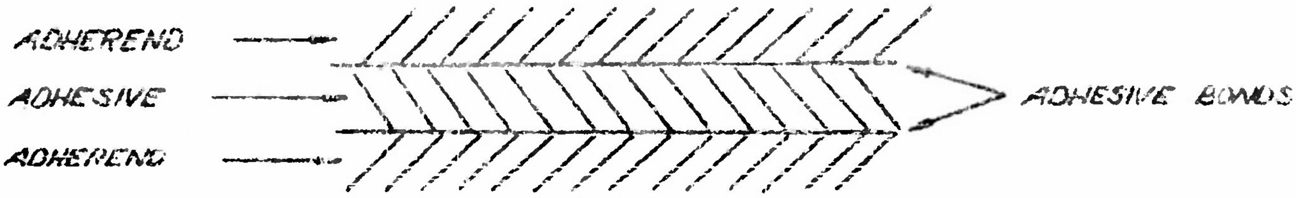
Sleeve type, Lap Joints, Bag Molded. This type of joint is representative of a process in which a phenolic impregnated filler material, such as glass cloth, may be simultaneously laminated and bonded to end fittings. Pressures are usually restricted to 100 psi.

Selection of Adhesive

The selection of an adhesive for a given application is governed by chemical, electrical, mechanical, environmental and processing factors.

The mechanical factors include the critical value of strength of adhesion of the adhesive to the adherends, the critical values of the strength of cohesion of the adhesive or the adherend and the elastic and plastic properties of the adhesive. The environmental factors which may affect the above include exposure to cold, heat, humidity atmospheres, solar radiation, water and chemicals. The processing factors include the handling characteristics of the adhesive, the cleaning of adherends, the spreading of the adhesive, the application of pressure and the application of heat which are covered in Section II of this Report. The designer is referred to NAVORD Report 2273 for specific data on the properties of a large number of adhesives and adherends, which data will be of great usefulness in the choice of an adhesive.

Of primary importance in the selection of an adhesive are the three strengths involved, specific adhesion to the adherend materials to be joined, cohesive strength in the adhesive and cohesive strength in the adherends.



Thus, whichever material possesses the lesser strength at the point of maximum stress will limit the strength of the assembly. As shown in Section II it is possible to compute the principal stresses in certain simple adhesive bonds and to infer magnitudes to these stresses. This process has not been developed fully and is not of great usefulness at present. It is possible, however, to compare the strengths of joints containing the candidate adhesives and to attempt to choose an adhesive which is at least as strong as the adherend materials. Considerable comparative strength data are available in NAVORD Report 2273.

It is to be noted that the designer might consider the possibility in the overall design problem of exchanging an adherend material for another type to which better adhesion may be obtained or which possesses better cohesive strength. In bonding reinforced plastic laminar materials the designer should bear in mind the low bond strength between plies may be the limiting strength of the bond. Or, for example, polyethylene for which no good adhesives have been developed, might be replaced with another thermoplastic material such as polyvinyl chloride.

The elastic properties of an adhesive are important in relation to the flexibility of the bond under external stress or under internal stress such as arise from temperature changes in materials with differential thermal coefficient of expansion.

A bond containing a flexible adhesive will be more resistant to mechanical shock and vibration or thermal shock than a bond containing a brittle adhesive. It is often the case that the cohesive strength of a flexible adhesive is less than that of a brittle adhesive. However, the advantage of toughness of a flexible adhesive may outweigh the advantage of the static strength of a brittle adhesive. It also may be expected that for a given geometry the magnitude of stress concentration in critical spots in a bond may be reduced if a flexible adhesive is used, thus leading to an optimum strength for the bond. See Section II on stress concentrations in adhesive bonds. In bonding such materials as paper, leather, cloth, rubber, etc. choose an adhesive which is at least as flexible as the least flexible of the two bonded surfaces.

The plastic properties of an adhesive may be important in relation to the dimensional stability and strength of the bond under long-time loading. Plasticity may be a drawback if creep under heavy loads cannot be permitted in a bond, or it may be beneficial as a mechanism whereby stress concentrations under minor loads (external or internal due to bonding stresses or differential coefficients of thermal expansion) may be relieved to some extent after a period of time thus increasing the affective strength of the bond. However, very few data are available on the plasticity of adhesives at this time.

In choosing an adhesive, it is well to remember that the materials used in adhesives with the exception of a few materials such as sodium silicate, are made of organic compounds. Thus, they are subject to environmental degradations typical of that class of material. The designer should note all the conditions that the adhesive might be exposed to and operate under and govern the choice of adhesive accordingly. A few of the guidelines in the choice of adhesives based on environmental conditions are presented:

a. In high temperature applications (never above 350°F. for sustained periods) choose an adhesive of the thermo-setting type. These are usually more heat resistant.

b. For low ambient temperatures, choose a flexible adhesive. These are usually of the thermo-plastic type. However, most flexible adhesives become quite rigid at temperatures about -10°F. and care should be taken for adhesive selections in temperatures about this region.

c. Organic solvents and other powerful chemicals, may have deleterious effect on adhesives. Since the range of possibilities are so great in this respect, this factor should be checked carefully.

d. Water soluble adhesives should never be used under hydroscopic conditions.

e. Adhesives will age. Under prolonged exposure to ultra-violet, oxygen, or other agents present in the atmosphere, the physical properties of the adhesive will undergo changes, usually that of degradation. This should be checked if the bonded joint assembly is expected to have a long useful life.

Table 6 presents a broad comparison of adhesive types for use in the first steps in selecting an adhesive. The engineer is referred to NAVORD Report 2273 for detailed data on adhesives and adherends of use in making a final selection of an adhesive for an application.

Selection of Dimensions

The dimensions of a bond are governed by the magnitude, direction and duration of the loads to be placed upon it, by the confidence one desires to place on it, by its history prior to use and by the environment in which it is to operate.

TABLE 7

TYPICAL PROPERTIES OF SOME ADHESIVES

Type of Adhesive	Requires Heat	Suitable for Non-Porous Adherends	Stiffness	Resistance to Creep	Resistance to Heat	Strength in Water or Humid Atmos.	General Chem. Resist.	Dielec. Prop.
Synthetic Adhesives Thermosetting	Some do not	Yes	High	Good	Good	Wide variation (usually good)	Wide variation	Fair
Thermoplastic	Fusion yes Solution no	Yes No	Low to High	Poor	Poor	" " "		Good
Rubber-Base	Yes	Yes	Low	Poor	Fair	" " "		Fair
Rubber-Resin	Yes	Yes	Low	Poor	Fair			
					Good	" " "		Fair
Natural glues								
Casein			Low to High	Good	Poor	Poor	Poor	Poor
Animal				"	Poor	Poor	Poor	Poor
Fish				"	Poor	Poor	Poor	Poor

Thus, if in a given geometry an expected load L will develop a concentration unit stress S at some point in the bond the greatest unit stress must be less than the most probable value of the least value of strength of the adhesive at that point. (See Section II on the stress concentration and the Statistics of Fracture).

From Section II we have seen that stress concentrations may be expected to exist in any type of bond unless the elastic constants of the adhesive are identical with those of the adherends. The unit stresses at the edges of an unbevelled lap joint may be as high as six times the average unit stress in the bond. The stress concentration in other types may be less than six, as may be inferred from the results of DeBruyne's work. As a conservative approach, however, the engineer probably might well use six as a figure for stress concentrations in lap or scarf joints under tension. Means for estimating the stress concentrations in other geometries and types of loading are not available and the engineer will do well to apply a large factor of ignorance to any rough computations he may undertake in this field.

Let us now undertake to compute the bonded area for a single lap joint in thin aluminum sheet to withstand 1000 lbs. load per inch of joint. Let us assume we are convinced that the maximum average unit principal stress our adhesive can with and is 10,000 psi, and that our adhesive exhibits a standard deviation of strengths of 500 psi. Let us also assume that our adhesive after the particular environmental exposure with which we are concerned can withstand only 50% of the load it could withstand initially, and that the ratio of the standard deviation to the average strength is a constant for the adhesive. Let us apply a factor of six for stress concentration factors. Let us require that not more than 1 bond in 1000 fail under the 1000 lb. load or from Figure 31 in Section II the unit stress point not exceed $\bar{X} - 3\sigma$. Figure 32 shows a method for working back from the new strength of the adhesive to the area required in the bond, or in this case the length of overlap.

Although this process is attractive in view of its simplicity it is not operable for use at present because the basic information on stress concentrations and on the effects of environment on the strength of adhesives. It is to be noted that the strength and standard deviation of new adhesives is of no real value in a design problem. What is needed is data on the average strength and deviations of adhesives <u>after</u> various environmental exposures. In lieu of this process the designer would do well to employ a safety factor of 10 in assigning dimensions to an adhesive bond.

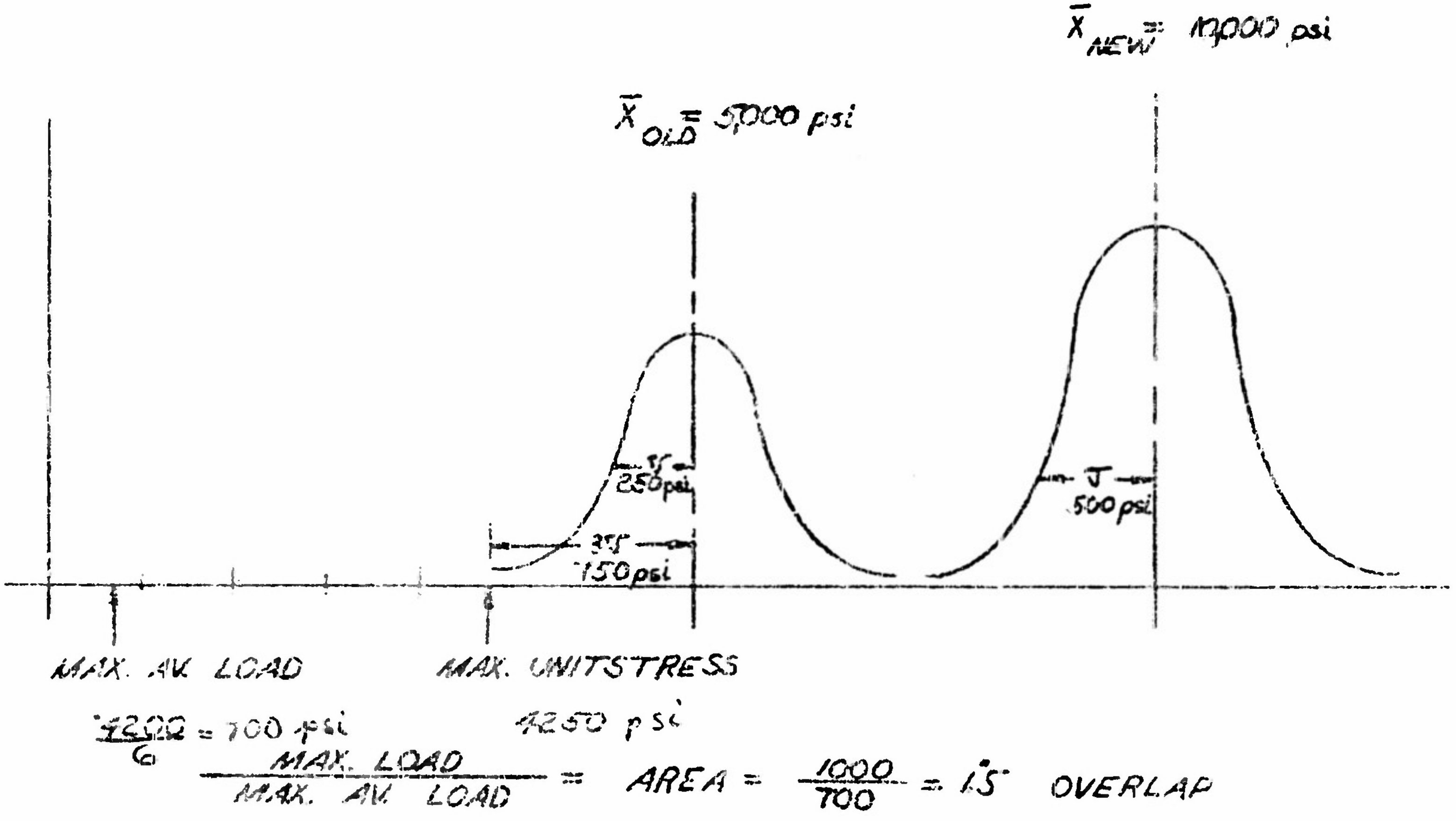


Figure 32
Determination of working stress

Test Data Showing the Influence of Some Design Parameters

A series of correlated tests were conducted by an adhesive manufacturer on the bonding of Alclad Shear Lap specimens using a phenolic-vinyl adhesive. For additional data see NAVORD Report 2273, Comparative Data. These tests illustrate mechanical behavior of joints predicted by the theoretical discussion in Sections II, III, and IV. In addition , the tests are on shear lap joints, which are one of the most important applications of adhesive bonding for stress carrying purposes. These tests, pertinent to the discussion, are now reproduced in full.

STRENGTH OF ADHESIVELY BONDED SHEAR LAP JOINTS

Figures 31 and 32 illustrate the results of tests on shear lap specimens with varying adherend thicknesses and with varying joint overlaps. These relate directly to adherend stiffness and joint geometry. It can be seen, from Figure that varying adherend thickness and overlap length produces marked changes in the average computed unit strength. The larger the overlap, the less the unit strength for a given adherend thickness. The thinner the adherend, the less the unit strength for a given adhesive. For a given adherend thickness, increase in joint overlap does not result in a proportionate increase in joint strength and that a point is reached where any increase in joint overlap does not produce any appreciable increase in joint strength.

EFFECTS OF HIGH TEMPERATURE ON TENSILE SHEAR

Typical plain lap joints were exposed to and tested at temperatures ranging from 70° to 190° F. The results are as follows:

Shear Strength of Joints at Various Temperatures
Plain Lap Joints, 1" Wide: 24ST ALCLAD

Overlap	Thickness of Metal	Temperature	Shear Strength psi	Percentage	Rate of Load Application
½"	.036	70°F	3800	100	3500# 1 min.
"	"	90°F	3780	99	"
"	"	110°F	3700	97	"
"	"	130°F	3480	91	"
"	"	150°F	3080	81	"
"	"	170°F	2400	63	"

Shear Strength of Joints at Various Temperatures
Plain Lap Joints. 1.0 Wide; 24ST ALCLAD (Continued)

Overlap	Thickness of Metal	Temperature	Shear Strength psi	Percentage	Rate of Load Application
⅛"	.036	190°F	1200	32	3500# 1 min.
"	.064	77°F	4350	100	.05 in/min.
"	"	160°F	3200	74	"
1.0	"	77°F	2620	100	"
"	"	160°F	2180	83	"

Hence, it appears that the joints at 160°F. using this class of adhesive may be expected to withstand approximately 75% of their normal load. It was noted that the strength became normal again when temperature was reduced to room conditions.

FATIGUE TESTS

A series of tests were carried out at 60 cycles of load - no load tests until the joint failed, the results are as follows:

Effect of Repeated Loading on Single Lap Joints
1.0 Wide, 3/8" Overlap .064 24ST ALCLAD

Cycles to Failure	Load #/"	Percent of Control
Static Test on Control	3400	100%
31,000	2310	69
60,000	2110	62
76,300	1760	52
106,600	1690	50
389,500	1200	35
780,600	1270	37

Another series of tests was made under conditions of alternating stresses. The machine was operated at 650 or 1300 revolutions per minute, depending on conditions. These data, when reduced to stress-cycle diagrams indicate a fatigue strength of 10 to 20 pounds per square inch. Expressed as a percentage of ultimate flexural strength gives the following.

Cantilever supported	14% of ultimate
End supported	5% of ultimate

Failures in the metal predominated over those of the adhesives in the joint. The results are as follows:

Effect of Alternating Stress on Single Lap Joints 1½" Wide, Cantilever and End Supported Samples
24ST ALCLAD

Support & Construction of End Piece	Metal Thickness Inch	Amplitude Inches	Load Lbs.	Cycles of Reversal
Cantilever				
Support				
1½" overlap	.04	5/16	(1)	70,000
"	"	3/16	"	1,154,000
"	"	1/8	"	3,910,000
"	.064	5/16	2.75	194,000
"	"	3/16	2.75	2,320,000
"	.091	5/16	8.75	174,900
"	"	3/16	6.25	893,000
"	.125	5/16	20.00	31,250
"	"	3/16	13.75	396,600
"	"	1/8	8.75	2,647,000
"	"	1/16	6.25	5,007,700
"	"	1/32	3.75	5,152,600
"	0.188	5/16	56.25	1,040
"	"	1/4	45.00	3,270
"	"	3/16	37.50	18,100
"	"	1/8	27.50	130,000
"	"	1/16	17.50	2,732,000
"	"	1/32	12.50	12,220,000
Cantilever				
Support	.064	5/16	2.75	127,350
½" overlap	"	3/16	2.25	5,080,000
"	"	1/8	1.75	10,300,000
"	"	1/16	1.25	7,580,000 (2)
"	"	1/32	(1)	5,250,000 (2)
"	.091	5/16	8.75	98,800
"	"	3/16	6.25	2,450,000
"	"	1/8	3.75	9,000,000
"	"	1/16	2.50	7,580,000 (2)
"	"	1/32	1.25	5,250,000 (2)
"	.125	5/16	20.00	84,800
"	"	3/16	13.75	436,000

---

(1) Accurate readings unobtainable for such thin metals
(2) Failure wholly in the metal

Effect of Alternating Stress on Single Lap Joints 1.0 Wide, Cantilever and End Supported Samples 24ST ALCLAD (Continued)

Support & Construction of End Piece	Metal Thickness Inches	Amplitude Inches	Load Lbs.	Cycles of Reversal
Cantilever Support				
½" overlap	.125	1/8	8.75	1,150,000
"	"	1/16	6.25	7,580,000 (2)
"	"	1/32	3.75	5,250,000 (2)
"	.188	5/16	56.25	70
"	"	3/16	37.50	2,200
"	"	1/8	27.50	45,000
"	"	1/16	17.50	181,000
"	"	1/32	12.50	1,830,000
End Supports	.091	3/16	85.00	236,000
1.0 overlap	"	1/8	45.00	637,000
"	"	1/16	19.20	5,580,000
"	.125	1/16	28.00	2,080,000
"	.188	1/16	87.50	95,600
End Supports	.064	5/16	171.00	10,800
3/8" overlap	"	1/4	113.00	63,900
"	"	3/16	64.00	710,580
"	"	1/8	33.30	1,895,000
"	"	1/16	15.00	5,742,000

IMPACT STRENGTH IN ADHESIVE AND RIVETED JOINTS

This series of tests were based on single rivet joints of three sizes. Studies were made at three temperatures, -70°F., 74°F., and 180°F. These impact tests were made on a Baldwin-Southwark Plastic Impact Machine, with a special fixture for holding and striking the specimen. The apparatus was enclosed in a special heating box. The results are as follows:

Comparison of Impact Strengths of Alclad Joints Adhesive Bond Alone - Rivets Alone - Adhesive and Rivets Plain Lap Joints ½" wide x ½" overlap .064 24ST ALCLAD (See next page)

---

(1) Accurate readings unobtainable for such thin metals
(2) Failure wholly in the metal

Comparison of Impact Strengths of Alclad Joints Adhesive Bond Alone - Rivets Alone - Adhesive & Rivets Plain Lap Joints ½" wide x ½" overlap .064 24ST ALCLAD

Description	Diameter Rivets	Curing Pressure(1)	Ultimate Impact Strength -70°F	75°F	180°F	Control Sample(2)
Rivets Alone	3/32"	-	-	1.99	-	239
	1/8"	-	-	2.48	2.44	574
	3/16"	-	-	6.72	-	974
Adhesive Alone	-	50	2.40	3.20	2.96	915
	-	300	3.04	3.52	2.24	-
	-	600	2.40	2.16	1.92	671
Adhesive and Rivets	3/32	300	2.15	2.24	1.84	713
	3/16	300	11.12	8.88	9.12	1,220

EFFECT OF HIGH AND LOW TEMPERATURE ON IMPACT

This series of tests were conducted on normally cured bond using a modified Charpy Impact Machine. The samples were exposed to and tested at the temperatures indicated as follows:

Impact Strength of Single Lap Joints ar Various Temperatures 1.0 Wide x ½" Overlap .04 24ST ALCLAD Cleaned by Solvent Degreasing

Temperature	Impact Tensile Shear (ft. lbs)
-40°F	Over 14.4
77°F	Over 16.6
122°F	Over 16.6

It is apparent that the impact strength of this phenolic-vinyl is fairly constant between -40°F and 120°F in the machine used.

EFFECT OF HIGH TEMPERATURE ON CREEP

Creep tests were conducted at the Battelle Memorial Institute under constant comparative test conditions, based on normally cured bonds. Average bond strength was 4,160 psi. Specimens were maintained at the test temperature in an oil bath.

---

(1) In pounds per sq. in.
(2) Control samples were tested in tensile shear to determine that joints were properly prepared. Values are in #/" and tested at 75°F.

Summary of Creep Tests on Single Lap Joints
1" Wide x ½" Overlap .065 24ST
ALCLAD

Description	Average of 3 Tests in Each Series			
Thickness of Joint (inch)	.002	.002	.005	.005
Temperature °F	78	158	158	158
Stress psi	2,650	2,080	2080	2,496
% of Ultimate	50(1)	50	50	70
Creep rate of 400 hrs. per in/hr	.000000082	nil	nil	.0000002
Total Deformation at 400 hr. per in.	.00073	.0046	.0080	.0083
Plastic Deformation at 400 hrs per in.	.00004	.0040	.0065	.0067

SPREAD OF TEST RESULTS

In order to show the spread that can be expected in strength data on adhesively bonded joints, the following were obtained on a limited number of samples of shear lap specimens made of stainless steel.

Single Lap Joints in Nickel or Nickel Alloys *
1" Wide x ½" Overlap and .010 Metal Thickness

Nickel or Alloy	Tensile Shear		
	Max.	Min.	Aver.
Monel	1632	418	738
"K" Monel	1070	450	670
Iconel	1270	665	951
Nickel	825	187	742

*Cleaned by scouring with cleansing powder and steel wool. Average shown is of 5 specimens.

---

(1) First column indicates an early series of tests with a higher initial ultimate strength.

SECTION IV. BONDING PROCESSES

General Considerations

The production of high quality joints requires the full recognition of all factors that may affect the quality of the bond such as: surface preparation of the adherends, general handling considerations (preparation of the adhesive for use and application to mating surfaces) fabrication techniques and heat transfer considerations. As adhesives vary with respect to the above factors, it is possible only to generalize on these points. The inherent properties of a particular adhesive formulation such as pot life, optimum spreading rate and storage life are likewise important considerations in any bonding process, and the consumer should follow the manufacturers' instructions closely with respect to all factors involved in the bonding process.

Surface Preparation of Adherends

The importance of properly preparing surfaces to be bonded cannot be minimized. All surfaces should at least be clean of oil, grease or other foreign matter. General methods for cleaning various materials are as follows:

a. Glass

The glass shall be cleaned by heating in a sodium dichromate-sulfuric acid solution followed by a thorough rinse in water.

b. Metals

a. Freshly machined metals or surfaces showing only traces of oxide coatings shall be sanded with No. 400 paper, followed by a solvent rinse or wipe. The pieces shall then be degreased in a trichloroethylene vapor degreasing unit.

b. Large parts shall be sand blasted and the grit removed by air blast. Follow with a solvent rinse or wipe.

c. Plastics, Thermosetting

Remove the glossy surface from molded parts by sanding with No. 220 paper. Freshly machined parts or molded parts which have been sanded shall then be cleaned by a degreasing solvent wash and wipe with toluene and/or methyl ethyl ketone.

d. Plastics, Thermoplastic

Molded parts shall be dipped in a suitable solvent to remove mold lubricants. Caution must be exercised in selection of the solvent so that the surface of the material is not adversely affected.

e. Wood

Sand with No. 00 paper and air blast

f. Rubber

a. The rubber surface shall be sanded or roughened with a scraper and then cleaned with a light naptha.

b. Cyclizing of Cured Rubber: The rubber (natural) shall be cyclized by immersion in concentrated sulphuric acid (Sp.gr.1.84) for a period of 5-10 minutes. Synthetic rubbers (Neoprene, Buna & Hycar) 10-20 minutes. If the acid becomes spent, these times shall be increased to obtain the same degree of cyclization. When it becomes necessary to increase the immersion time beyond 15 minutes, the acid shall be discarded.

Assemblies requiring only one rubber surface or one edge to be bonded to the metal, that surface only shall be cyclized. This can be accomplished by immersion in shallow trays. Use may be made of a sulphuric acid - barytes paste applied on the desired surface by a glass spatula or other implement not attacked by the acid. The paste should be in contact with the rubber for 10 minutes. It is essential, however, that a layer of unspent acid be in contact with the rubber through the entire treatment.

This paste is made up by adding barytes to concentrated sulphuric acid (sp. gr. 1.84) until a paste is formed that will not run, but will stay where placed.

After the acid treatment, whether with the liquid or paste, the rubber should be thoroughly washed clean with water and dried. In the case of the paste application, rubbing during washing is desirable to remove all the barytes.

Cyclizing one surface may also be accomplished by the use of shallow trays with the aid of glass or asbestos cloth acting as a wick between the acid and the rubber to be cyclized, or parts not to be cyclized may be masked off by applying 2 coats of Geon Latex PX8 manufactured by B. F. Goodrich Company, Akron, Ohio.

The coating produced by the acid treatment shall be broken to such an extent by flexing, as to produce a finely cracked surface.

Application of the Adhesive

Practically all commercial adhesives are polymeric materials of natural origin, or synthetic rubbers or resins and their combinations. These materials are supplied in the form of liquids, pastes, films, powders and liquid powder combination. The preparation of the adhesive for use, other than mechanical agitation, may or may not be necessary, depending on the chemical stage and the form in which it is supplied.

For proper spreading, adhesives are generally applied in liquid form, or are liquified at some stage in the bonding process. To achieve strength and a degree of permanence, setting must take place. Liquid adhesives lend themselves to brush coating, dip coating, spray coating and roller coating if they are of low viscosity. High viscosity materials may be applied by knife coating or caulking gun. The film thickness desired, the number of pieces to be coated, and size and shape factors largely determine the application technique to be employed for a given application.

The setting of the adhesive may involve a simple evaporation or absorption of solvent by a porous adherend, sol-gel or liquid-solid transitions, a polymerization process, or a combination of these.(2) Setting of the adhesive may be affected at room or elevated temperatures, depending on type and chemical stage.

A general classification of adhesives according to material type, physical forms available, additives required prior to use, and cure temperature required is presented in Table 7.

Table 7

General Classification of Adhesive Materials and Their Handling

General Type	Adhesive Material Type	Physical Forms Available	Solvents^a	Setting Mechanism^b	Cure^c	Additives Required Prior To Use
Thermosetting Synthetic Resins	Epichlorohydrin-BisPhenol	Powder	None	PP	H	None
		Liquid	None	PP	R	Amines
		Liquid		PP	H	Amines
	Furfuryl Alcohol	Liquid	A	PP	R	Acid
	Phenol-Formaldehyde	Film	None	PP	H	None
		Powder		PP	H	Acid or Alkali
		Liquid	A or A^W	PP	H	None
	Phenol-Acetal	Film	None	PP	H	None
		Liquid	A	PP	H	None
		Liquid	A	PP	H	Powder
	Resorcinol-Formaldehyde	Liquid	A^W	PP	R	Paraformaldehyde
	Urea-Formaldehyde	Powder		PP	R	Water or water-acid
		Liquid	W	PP	R-H	Acids or acid producing salts
	Melamine-Formaldehyde	Film	None	PP	H	None
		Powder		PP	H-I	Water
		Liquid		PP	H	
	Polyester-Styrene	Liquid	None	PP	R-H	Peroxide Catalysts Cobalt Accelerators
Thermoplastic Synthetic Resins	Cellulose Acetate	Liquid	FK	SR	R	None
	Cellulose Acetate Butyrate	Liquid	FK	SR	R	None
	Cellulose Nitrate	Liquid	FK	SR	R	None
	Vinyl Acetal	Liquid	FE	SR	R	None
	Vinyl Acetate	Liquid	FK	SR	R	None
	Vinyl Alcohol	Liquid	W	SR	R	None
	Vinyl Chloride-Acetate	Liquid	FK	SR	R	None
	Styrene	Liquid	H	SR	R	None
	Methyl Methacrylate	Liquid	E, H	SR	R	None

Table 7 (continued)

General Type	Adhesive Material Type	Physical Forms Available	Solvents[a]	Setting Mechanism[b]	Cure[c]	Additives Required Prior To Use
Rubber-Base	Natural	Liquid	H,W H	SR V	R R-H	None *
	Reclaim	Liquid	H,W H	SR V	R R-H	None *
	Neoprene	Liquid	F,H,K F,K	SR V	R R-H	None *
	Butyl	Liquid	H H	SR V	R R-H	None *
	Butadiene-Acrylonitrile	Liquid	H,K H,K,W	SR V	R R-H	None *
	Butadiene-Styrene	Liquid	H,K,W	SR	R	None
	Thiokol	Liquid	H,W H	SR V	R R-H	 Lead Peroxide
Rubber-Resin	Chloroprene/Phenolic	Liquid		V	H	None
	Butadiene-Acrylonitrile/ Phenolic	Liquid	K	SR	R-H	None
	Butadiene-Acrylonitrile/ Vinyl Acetate	Liquid		SR	R	None
Miscellaneous	Casein	Liquid Powder		CR SR	R R	Formaldehyde Water
	Animal	Solids		SR	R	Water
	Fish					
	Soy Bean					

a. Code for Solvents
A=Alcohols
E=Ethers
F=Fatty Acid Esters
H=Aromatic Hydrocarbons
K=Ketones
W=Water

b. Code for Setting Mechanism
PP=Polymerization Process
SR=Solvent Release
CR=Chemical Reaction
V=Vulcanized

c. Cure Temperature
R=68-90°F.
I=87-211°F.
H=212°F. and above.

*The addition of accelerators may or may not be required for vulcanization.

As will be noted in Table 7, the majority of the adhesives materials are supplied in volatile solvents, or as powders which require the addition of liquids prior to their application to mating surfaces. The release of these volatiles is fundamental in obtaining optimum results. Consequently, a critical control must be exercised over the amount of volatiles present when the assembly is closed. In addition due consideration must be given as to whether the assembly is to be processed at room or elevated temperatures.

ROOM TEMPERATURE OPERATIONS

A requisite for room temperature bonding operations is that the adhesive be applied to the mating surfaces and closed while the adhesive is essentially in a semi-liquid state, or that the film of adhesive be capable of reactivation to a tacky state by wiping with solvents.

Porous adherends such as cork, leather, paper and fabrics may readily be bonded to materials of like or unlike composition with solvent release adhesives of the thermoplastic polymer or rubber-base types. Maximum bond strength will be obtained only after the major portion of the solvent has evaporated and only residual traces remain. The rubber-base adhesives may be of the non-vulcanizing or self-vulcanizing type.

Porous adherends such as wood may be bonded with adhesive materials of animal or vegetable origin at room temperatures. However, joints fabricated with these materials are less durable than those made with synthetic resins such as resorcinol or resorcinol-phenol types. As these synthetic resins are in solvents and are set by the addition of hardeners, a rather close control over the open assembly time is necessary.

Thermoplastic adherends may be bonded to each other by either reactivating the mating surfaces with an appropriate solvent or by assembly with a thermoplastic polymer dissolved in a suitable solvent.

Thermosetting plastics may be bonded to each other with suitable thermosetting resins such as resorcinol or phenol-resorcinol types.

The bonding of rigid non-porous adherends such as glass, metals, thermoplastics and hard cured rubber to themselves and in combination must usually be carried out in such a manner that substantially all volatiles are eliminated before closing the assembly if high strength void free joints are to be realized. Consequently, adherend systems composed of these materials are generally processed by precuring the coated parts prior to assembly, and then curing the assembled parts under heat and pressure. However, it is possible to obtain joints of good quality for some applications, by room temperature operations, using non-solvent 100% reactive liquid type polyester or epoxy resins. Polyester type resins will produce high strength bonds with glass, metals and polyester laminates and their combinations. Epoxy resins will produce high strength bonds with metals, phenolic laminates and cyclized hard rubbers and their combinations.

In bonding metals to non-metals a single adhesive is often unsatisfactory for high strength bonding either because it is not possible to satisfy the bonding requirements of both adherends with a one adhesive system or because the non-metal adherend will not withstand the temperature necessary to process the assembly. In addition, the geometry of the joint may not be conducive to the application of substantial pressures. For these reasons it is often necessary to apply and then either pre-dry or pre-cure an elastomeric primer coat on the metallic adherends. Non-metallic adherends such as thermoplasts or thermosets may then be attached at room temperatures by using secondary adhesives such as resorcinol to which hardener has been added.

ELEVATED TEMPERATURE OPERATION

In general, the highest strength adhesive and the most durable under various environmental exposures are of the thermosetting (space polymerizing) class. Although some adhesives of this class may be set at room temperature by the use of addition agents, the majority require cure at elevated temperature. Pressure, temperature, time, rate of heating, and thermal expansion considerations become factors of considerable importance as they have a bearing on the ultimate strength of the bonded joint.

Temperature and time will influence the adhesive strength in that they determine when the film has been completely cured.

Pressure may have a bearing upon the ultimate strength because it directly determines the amount and thickness of the adhesive film, and insures maintenance of the desired contact despite flash or shrinkage of the film.

The rate of heating is important, especially in the case of thermosetting adhesives, when they are in the form of films, powders, or semi-solids. A low heating rate may cause chemical conversion to be cured film before the desired flow characteristics are developed. This tends to prevent adequate wetting of the adherends at moderate pressures, hence points of weakness in the bonded joint. Conversely, too rapid a heating may cause the adhesive to become so fluid that the bond will show an adhesive deficiency.

A requisite for elevated temperature bonding is that substantially all of the volatile solvent be removed from the adherends coated with liquid adhesives prior to closing the assembly. This is of particular importance, especially if the adherends are of a non-porous nature and maximum strengths are to be realized. Both thermoplastic and thermosetting adhesives, whether they be in liquid or solid form, are generally quite adaptable to processing at elevated temperatures depending on the geometry and stability of the adherend system.

To help alleviate residual stresses upon curing at elevated temperatures, two rules may be applied with regard to thermal expansion. First, if possible, all portions of the die or alignment fixture are heated to a uniform and constant temperature. Cold or hot spots are bound to produce non-uniform expansion, resulting in either warpage or undue stress on the bond. Secondly, if possible, the parts should be allowed to reach maximum expansion before pressure is applied. Parts are placed in the curing fixture in their respective relative positions and the adherends are brought just short of closure. A short predetermined time is allowed for the parts to heat, after which time the assembly is closed and pressure applied. Although not eliminating residual stresses, the aforementioned rules will probably reduce such stresses to a minimum.(6)

APPLYING THE ADHESIVE (12)

The following discussion gives a brief description of methods of adhesive application:

Brushing

For comparatively small areas or for assembly gluing operations, the adhesive is sometimes applied by brushing with stiff-bristle brushes or from serrated paddles or hand operated extrusion guns. These methods are seldom applicable, however, to large scale production operating procedures.

Spray-Gun Application

The use of a spray-gun to apply adhesive is usually limited to cases where repeated applications are necessary in order to build up the required adhesive-film thickness or to cases where the handling of the member to which adhesive is to be applied is difficult. The spray-gun method is seldom used in large scale operations, because (1) the amount of solvent for the adhesive which is required to reduce the solution to a suitable spraying viscosity introduces solvent which must subsequently be evaporated; (2) the overspray results in the waste of a considerable portion of adhesive; and (3) suitable spray booths or other ventilating equipments are necessary to provide disposal of the solution vapors.

Doctor Blade

For the continuous application of adhesive to one side of a flexible material, the system of doctor blade and blanket has been widely used. The arrangement of equipment is similar to that used in the coating of paper or cloth. The material to be spread with adhesive is drawn continuously over a supporting blanket, usually rubber, which is an endless belt, moving on a roller system. Against this resilient backing, the web to be coated is drawn across the edge of a doctor blade, and the adhesive is fed to a pool in front of this blade.

Dip Tank and Nip Rolls

The most common system for the impregnation and application of adhesive to both sides of material when the member is flexible, as well as continuous, as in the case of paper, is the dip-tank and nip-roll scheme. In this system, the continuous web is fed over a roller system and completely submerged in a tank containing the adhesive solution. The web leaving the tank is fed through a pair of rollers which are adjusted to remove the excess adhesive and provide a uniform spread. The amount of adhesive applied can be varied in such a system by changing the gap or pressure between the nip-rolls and also, of course, by varying the solids concentration of the dip bath. This sytem is used extensively in the preparation of paper-base and cloth-base laminates, and many minor variations are in common use.

Roller Spreading

The applications of adhesive with roller spreaders is most common when rigid or predimensioned pieces are involved. In a roller spreading system, the adhesive is distributed over a roller from a reservoir by the action of a doctor roller. The adhesive is transferred from the application roller to the bonding surface as the pieces are passed over it.

When relatively heavy spreading rates of adhesive, 60 to 100 lb. of liquid adhesive per 1000 sq. ft. single glue line, are involved, the spreader rolls are usually metal, and the surface is corrugated. For the lighter spreading rates as for synthetic-resin adhesives in the region of 20 to 50 lb. of liquid adhesive per 1000 sq. ft. of single glue line, the spreader rolls are usually rubber-covered and corrugated. The rubber covering permits more even spreading rate by adjustment of the doctor roll pressure.

Although wide viscosity variations are encountered in commercial spreading operations, an absolute adhesive viscosity of 20-30 poises is usually considered optimum. The upper limit for successful spreader operation, particularly with rubber spreaders, is approximately 200-300 poises. Some difficulty may be encountered with such high viscosity adhesives, however.

Application of Pressure(12)

The use of pressure during any bonding operation may vary widely, depending on the particular adhesive under consideration. Pressure during any bonding operation has several functions. The coating of the adhesive in the joint must be reduced to a thin continuous glue line of uniform thickness, and in most cases it must be distributed uniformly over the joint. Most forms of adhesive spreading are likely to be uneven, and in the case of glue-roll spreaders the adhesive is actually applied as a series of ridges of adhesive spread. Pressure also serves to eliminate any imprisoned air and to force the adhesive, during the flow period, into irregularities or pore spaces in the surface of the materials to be bonded. This is particularly importance when only one mating surface is spread with adhesive. Pressure during bonding also serves to hold the two sides of the joint in an uninterruptedly fixed position during the period required for the adhesive to cure or set. For maximum strength, the pressure should be maintained substantially at a fixed level during such bonding operations.

Described briefly here are the most common methods of applying pressure during a bonding operation:

CONTACT OR ROLLER PRESSURE

Laminating under the low specific pressures which can be achieved with rollers or between a web under tension and a roller has until recently been confined to the manufacture of multi-layer paper boards and similar materials with adhesives of very high tack. Such pressure systems are used in the manufacture of corrugated paperboard and solid fiberboard laminates. The development of the so-called contact laminating resins has extended these pressure systems to the continuous manufacture of paper-base and cloth-base laminates in which the supporting web is cellophane or coated paper. The pressures obtained in such a laminating system are of a very low order and are actually only sufficient to bring the flexible adjacent layers into contact.

CLAMPS AND SCREWS

One of the commonest methods of applying pressure, particularly in the wood-working industry, is by the use of screw jacks. The pressure applied by the tightening of a screw or nut, of course, requires distribution over the area to be placed under pressure. In order to obtain uniform pressure when several screws are required for a given assembly, the screws or nuts are usually tightened with torsion wrenches, or at least the pressure is judged during a manual operation. In some cases, motor-driven torsion wrenches are employed.

Retaining clamps are often used as an adjunct to hydraulic presses, particularly in cold-press plywood operation, where the assembly is compressed under hydraulic pressure in a cold press as described below, and the bale or assembly is maintained under pressure by the use of retaining clamps.

PISTON PRESSURE

The pressure exerted by pneumatic or hydraulic pistons has several distinct advantages: It is measurable and, under automatic control, can be continuous. Hydraulic pressure can usually be quickly and easily applied and is particularly suited to repetitive operations on a short time cycle.

Pneumatic piston pressure is frequently encountered where light work is involved but because of compressor limitations is seldom used at piston pressures over approximately 100 psi.

FLUID PRESSURE

The pressure devices outlined above all suffer from the limitation that they are unidirectional and, even with the use of rigid dies, produce complicated pressure systems where areas of curvature through large angles are under consideration. In other words, when unidirectional pressure is applied to curved surfaces, the pressure component exerted at any point on the curve is proportional to the cosine of the angle between the direction of pressure and a perpendicular to the tangent of the curve at the point in question. Where curved sections are under consideration, fluid or omnidirectional pressure is the solution.

The simplest form of fluid pressure is obtained by enclosing the assembly which has been laid up over rigid male dies in a flexible, not necessarily extensible, impervious bag and then exhausting the air from the interior of the assembly. The atmospheric pressure is then exerted over the whole area. In such cases, obviously, the maximum obtainable pressure is atmospheric and therefore limited to approximately 15 psi.

The next step in the development of fluid pressures was the enclosure of such an exhausted assembly in an autoclave and applying steam or air pressure to the outside of the rubber bag and thus increasing the available specific pressure.

Application of Heat

From the previous discussion, it is seen that bonding often requires definite heating cycles to be used in order to obtain the ultimate strength of the adhesive. A deviation from the prescribed cycle may yield a joint deficient in adhesive due to improper flow properties of the material during the preliminary stages of its cure. The importance of this consideration warrants a brief review of the fundamental modes of heat transfer.

It is well understood that heat may flow by three mechanisms:(9,10).

CONDUCTION

Heat is transferred from one part of a body to another part of the same body, or from one body to another in physical contact with it, without appreciable displacement of the particles of the body.

The fundamental law of conduction is that the rate of heat flow, or heat content $dQ/d\theta$, is proportional to the area of cross section A and to the temperature gradient $-dt/dL$, both taken at the point. The proportionality factor k is called the thermal conductivity, defined by the equation:

$$\frac{dQ}{d\theta} = -kA\frac{dt}{dL}$$

In the English system k will be expressed as:

$$(\mathrm{B.t.u.})\,(\mathrm{hr.})^{-1}\,(\mathrm{ft.})^{-1}\,(\mathrm{deg.\ F.})^{-1}$$

It is found experimentally that for a given isotropic substance the thermal conductivity depends essentially on its temperature. Furthermore, except for certain special cases, the conductivity changes relatively slowly with the temperature.

At this point it would be well to define another term of considerable importance in the study of thermal conductivity.(11) This is the thermal diffusivity which is defined by

$$\alpha = \frac{k}{c}$$

where k is the coefficient of thermal conductivity, c the specific heat of unit mass, and ρ the mass per unit volume. It occurs in the Fourier equation of temperature distribution:

$$\frac{\partial\theta}{\partial t} = \frac{k}{\rho c}\left[\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right]$$

where θ is the temperature at any point determined by the coordinates x, y, z, and t is the time. It is therefore seen that the rate of temperature change with change in time at a given point is dependent upon α. The thermal diffusivity is a physical quantity which takes into account the heat storage property of the material, and is the index of the rapidity with which the internal temperature of a slab made of the material increases when heat is suddenly applied at an external surface.

Briefly, for a given material, the thermal conductivity is a measure of the rate of propagation of heat, while the thermal diffusivity is a measure of the rate of change of temperature. It is interesting to note that the dimensions of the thermal diffusivity are L/T^2 (L being the dimension of length and T that of time) where neither a heat or temperature dimensions are present.

The thermal conductivity and thermal diffusivity for various reinforced plastic materials are given in NAVORD Report 2273.

CONVECTION

Heat is transferred from one point to another within a fluid, gas or liquid, by the mixing of one portion of the fluid with another. The motion of the fluid may be entirely the result of difference in the density resulting from the temperature differences, as in natural convection; or the motion may be produced by mechanical means, as in forced convection.

In the flow of fluids, even at high velocities, a residual film persists on the surface of the retaining wall. If heat is passing through the retaining wall to the fluid, the comparatively stagnant film is of great importance in determining the rate of heat transfer. This follows from the facts that all the heat reaching the bulk of the fluid must pass through this film by conduction and that thermal conductivities of fluids are low; so that although the film is thin, the resistance offered by it to the flow of heat is large. On the other hand, beyond the film the turbulence brings about a rapid equalization of temperature. The thermal resistance of the film is quite difficult to measure and an indirect method is used for their calculation. The film coefficient can be defined by the relation:

$$h_1 = \frac{q}{A_1(T_1 - T_2)}$$

T_1 is the temperature at the outer surface of the film and T_2 is the temperature at the solid-film interface.

Much research has been done on the determination of film coefficients and many equations have been developed for their evaluation under specific conditions.

The Dittus-Boelter equation is indicative of the type calculation used for evaluation of film coefficients for fluids in turbulent flow inside clean round pipes:

$$h = 0.0225 \frac{k}{D} \left(\frac{Du\rho}{\mu}\right)^{0.8} \left(\frac{C\mu}{k}\right)^{0.4}$$

h = coefficient of heat transfer

D = diameter

k = thermal conductivity

u = linear velocity

ρ = density

μ = viscosity

C = specific heat

Many variables are encountered in the calculation of film coefficients and the mode of evaluation will depend upon the particular application in question.

RADIATION

Heat is transferred in the form of radiant energy which is emitted in all directions. When this energy strikes another body, part is reflected and part may be transmitted unchanged through the body, depending on its degree of opacity. The remainder is absorbed and quantitatively transformed into heat.

The fundamental law covering the transfer of heat by radiation is Stefan's law: (black body radiation)

$$q = bAT^4$$

A = the area of the radiating surface

T = its absolute temperature in degrees Rankine

All bodies at all temperatures above absolute zero radiate energy according to Stefan's law. Consider a small body of area A and temperature T_2 completely surrounded by a hotter body of temperature T_1. The net amount of heat transferred from the hotter body to the colder body is therefore the algebraic sum of the radiation from the two bodies, so that Stefan's law may be written for the case as

$$q = bA(T_1^4 - T_2^4)$$

where $b = 0.173 \times 10^{-8}$ Btu/(sq.ft.)(hr.)/°Rankine.

This assumes, however, that all of the heat radiated by the cooler body falls on the hotter and is absorbed by it.

No actual substances fulfill this last assumption. Instead of absorbing all of the radiant energy that falls on them, they absorb only a part of it and reflect the rest. An ideal black body is one which reflects none of the energy falling on it. Most objects with a matte black surface approach the theoretical black body closely enough for practical purposes. Polished metal surfaces and white bodies deviate widely from the theoretical black body. It may be shown, however, that inside a closed space where the temperature is uniform throughout, all substances, no matter what their color or surface, behave as black bodies.

Since no bodies actually exhibit black body emission, another term must be included in the Stefan law to give quantitative results:

$$q = \epsilon bAT^4$$

The term ϵ is known as the emissivity of a surface. Emissivity factors for various substances are as follows:(13)

Surface	Temperature (°F)	Emissivity
1. Lampblack	100-700	0.945
2. Aluminum (polished plate)	78	0.055
3. Black Lacquer	100-200	0.80 - 0.95
4. White Lacquer	100-200	0.80 - 0.95
5. Oxidized Iron	390-1110	0.64 - 0.78

DIELECTRIC HEATING

High frequency dielectric heating (14) is used to a considerable extent for electrical non-conducting materials such as wood, plastics and rubber, as a means of producing direct heat throughout a given mass at a uniform rate. The process is carried out by placing the material to be heated between electrodes, which in turn are connected to the source of an alternating electric potential or oscillator. The high frequency field set up between the electrodes is passed through the material and causes the molecules to align themselves to the rapidly alternating reversals of field. This molecular motion results in friction and causes the material to absorb the same amount of energy throughout its cross section, with the result that the temperature rise is uniform regardless of its thermal conductivity.

The power required to heat a non-conducting material is based on the frequency of the field, the square of voltage across the mass, the dielectric constant of the material and its power factor.

$$\text{Power} = 1.41\ E^2 f F_1 \frac{A}{t} \times 10^{-12} \text{ watt}$$

E = voltage

f = frequency, cps

F_1 = loss factor (power factor of material times dielectric constant)

A = Area of material, sq. in.

t = thickness of material, in.

This formula has been suggested by Induction Heating Corporation and is for heating of dielectrics having uniform sections. If the material varies widely in shape, density, and moisture content, corrective allowances will have to be made.

The frequency used should be one that offers the greatest loss factor so that the maximum capacity of the oscillator will be utilized. The voltage used should be as high as possible but slightly below the point where flashover occurs. The usual practice is to raise the voltage until flashover takes place, then reduce it to a safe operating value.

This brief review of heat transfer indicates the methods of heating that can be utilized for the heating of adhesives to their cure temperature. Heating devices which are available include presses, ovens, strip heaters, cartridge heaters, infra red lamps, hot fluids and dielectric heaters. Each application requires special consideration and the selection of the method of heating to be applied will depend upon the peculiarities of the case in question.

REFERENCES

1. Cycleweld Division, Chrysler Corporation, Detroit, Michigan, Brochure entitled "Cleaning of Contact Surfaces for Cyclewelding", 1 March 1946.

2. Schmidt and Marlies, "Principles of High-Polymer Theory and Practice". McGraw-Hill

3. Del Monte, "The Technology of Adhesives". 1947. Reinforced Plastics Series

4. "Symposium on Adhesives". 1946. Philadelphia: American Society for Testing Materials.

5. Forest Products Laboratory Report No. 1336 (Revised) entitled "Synthetic Resin Glues".

6. Swayze, D. L., "Adhesives, Modern Tool of Fabrication" SAE Journal (Transactions) Vol. 54, No. 8.

7. Rose, K., "Industrial Adhesives", Materials and Methods, February 1948.

8. Modern Plastics Encyclopedia and Engineers' Handbook. 1950.

9. Badger, W. L. and McCabe, W. L., "Elements of Chemical Engineering", McGraw-Hill Book Company, New York, 1936.

10. Walker, W. H., Lewis, W. K., McAdams, W. H. and Gilliland, E. R., "Principles of Chemical Engineering", McGraw-Hill Book Company, New York, 1937.

11. Halbmillian, U., "Physical Interpretation of the Thermal Conductivity and Thermal Diffusivity"; Aerodynamics Branch I; Naval Ordnance Laboratory.

12. Dietz, A.G.H., "Engineering Laminates", John Wiley & Sons, Inc. New York, 1949.

13. Perry, J. H., "Chemical Engineers Handbook", McGraw-Hill Book Company, New York, 1941.

14. Curtis, F. W., "Tool Engineers Handbook", American Society of Tool Engineers, McGraw-Hill Book Company, New York, 1949.

SECTION V: TEST AND INSPECTION METHODS

General Discussion

There are two distinct approaches to the problem of designing engineering structures which incorporate adhesive joints. One method is to build the desired structure using some adhesive and then test the entire structure by exposing it to all the forces and environments to which it will be subjected and observing whether or not it performs in a satisfactory manner. The other method consists of choosing an adhesive of known physical properties, and designing a joint in which it is analytically determined that the adhesive strength will not be exceeded during the life of the structure.

The first method must be used where small safety factors are used in structures too complex for accurate analysis such as aircraft. In general, however, this method is only practical where it is economically feasible to build numerous complete assemblies and empirically determine by a comprehensive testing or field evaluation program the suitability of the adhesive application. There is also the disadvantage that each structure configuration must be tested independently.

The second, or analytical, method requires the determination of the stress distribution in the joints to be bonded, and the choice of an adhesive whose physical properties, when used with the adherend materials involved are known or can be determined by tests.

The designer can, with a reasonable degree of accuracy, compute the stress distribution in simple structures made of an engineering material such as steel which can be considered isotropic, homogeneous, and which obeys Hook's law for small deformations. However, the inclusion of an adhesively bonded joint in a structure uniting, as it does, two widely dissimilar materials, vastly increases the difficulty of ascertaining stress distributions. The evaluation of the shear and tensile properties of an adhesive which are pertinent to the analysis of stresses in a bonded joint is also rendered complex by the inherent discontinuous nature of a bonded joint. Goland and Reisner have pointed out that the stress distribution in a simple lap joint varies considerably with the thickness to elastic modulus ratio of the adhesive to the adherend, and that even in this geometrically simple configuration stress analysis was only possible by utilizing simplifying assumptions which represent only two extreme cases of adhesive and adherend elastic moduli.

ASTM Test Methods

The American Society for Testing Materials has investigated a number of tests used to evaluate adhesives. Some of these have been adopted as standards and others accepted only tentatively. The significance and limitations of some of these tests should be understood by the engineer who wishes to use them as a basis for the evaluation of any adhesive-adherend combination.

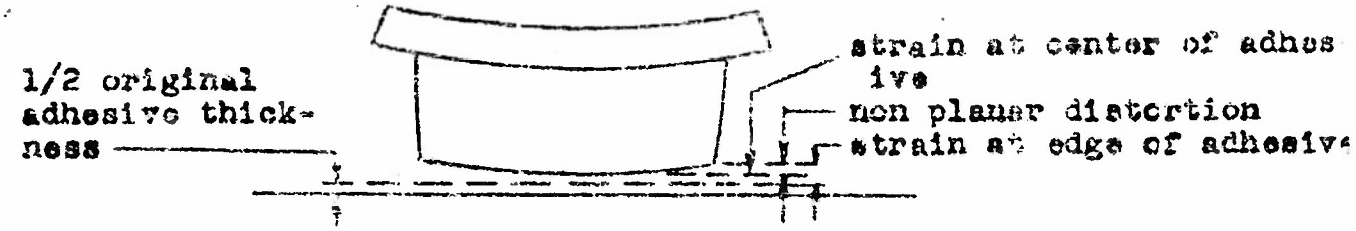
The method which the ASTM has adopted as standard for the measurement of tensile strength appears to have several undesirable features as a method of determining the ultimate tensile strength of an adhesive. It appears that the adhesive film is not strained uniformly due to the proximity of the adhesive bonding area, the load application, and points of high stress concentration caused by specimen geometry.

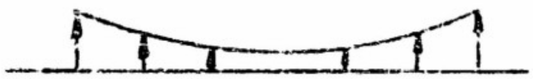
When one wishes to determine the tensile strength of a material the usual procedure is to make a long test specimen of the material having (a) enlarged ends to which a load can be applied, (b) portions which form a gentle transition between the ends and, (c) a center portion of constant cross sectional area. Such a specimen is made long so that there will be little or no irregular distribution of tensile stress in the central portion caused by the grips holding the enlarged ends. The specimens are enlarged so that the maximum stresses developed there due to the test and gripping forces will not cause local failure. The transition sections serve to isolate the test portion from any high local stress concentrations in the gripping portion and allow the stresses to increase steadily, (but not abruptly) to a maximum in the center section. The gradual reduction of area in the transition section also prevents the development of any stress concentrations beyond the gripping portion. This specimen configuration results in the test portion having uniformly distributed stress across any section.

If we compare this typical tensile specimen with the one adopted by ASTM for adhesives, we see that the specimen has no transition between the gripping portion and the test portion, the bonding area is not isolated from the gripping portion, and the test portion is very short with respect to its diameter. Because of these differences there is good reason to suspect that the adhesive bond is not subject to a uniform tensile load, i.e., the bonding surface distorts from a plain surface as the test load is applied resulting in different locations in the adhesive.

The difference in test loads to cause failure in the specimens of different lengths would seem to corroborate these suspicions.

The type of distortion one might expect from the geometry of the specimen and resulting stress distribution on an elastic adhesive are shown below.





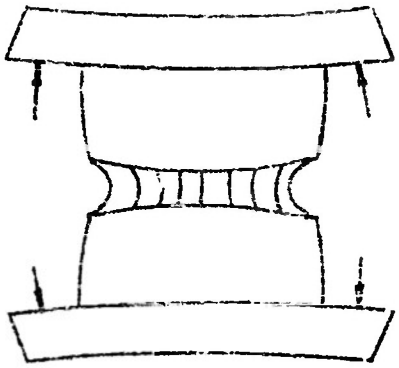
Since the adhesive between the specimen halves is usually only one or two mils thick, it can easily be seen that a very small distortion of the bonding surface will cause large differences in the unit strains values developed in the adhesive. For example, in the above sketch:

Assume: Original film thickness = .002 in.
Non-Planar Distortion = .00001 in.
Unit Strain at Center = 2%
then, strain at center = .00002 in.
strain at edge = ".00002 + ".00001 = ".00003
unit strain at edge = 3%

Since in the elastic range the stress will be proportioned to the strain, the stresses developed at the edge due to the distortion will be 150% of that at the center.

Another, and perhaps unavoidable, source of error in the measurement of the strength of an adhesive subject to pure tension is the development of transverse (or radial) strains which must develop in the adhesive and adherends when they have different Young's Moduli. (See Section II). It is not uncommon for a metallic adherend material to have a modulus 100 times that of the adhesive. If they both have about the same Poisson ratio, the adhesive will try to contract 100 times as much as the adherend which will result in the development of various strains resulting in a non-uniform stress distribution throughout the adhesive.

From the preceding discussions of possible causes of non-uniform stress distribution in a standard adhesive tensile specimen one might expect strains to occur somewhat as exaggerated in the sketch below.



Failure would surely occur just at the boundary of the adhesive where the induced shear and tensile stresses are at a maximum. The measured test load when divided by the bonded area would give values much lower than the inherent or true tensile strength of the adhesive. It can only be said that the standard specimen will give a safe value of tensile strength to use in design computations.

Because most bonded joints in structural applications are usually designed to withstand the applied loads in shear, the evaluation of the shear strength of adhesives is of prime importance. It is unfortunate that, as in tensile testing, it is very difficult, if not impossible, to apply a uniform pure shear loading to an adhesive. The ASTM has proposed several methods for evaluating the shear strength of adhesives by applying tensile or compressive loads to double lap jointed specimens or torsion to solid or tubular butt joints and has adopted a single lap specimen as a compromise between rigor and ease of testing. The results obtained from these tests are not pure shear strength values as the mathematical analysis by Goland and Reisner (See Section II) indicates that the adhesive in lap joints is not subject to pure (or simple) shear.

(b) The analysis of the stresses in an adhesive joint is a problem too complex for accurate solution even in the simplest cases.

Therefore, the application of analytical solutions to the design of structures with bonded joints can only be approximated.

The use of adhesives as dielectrics in electrical assemblies is being given widespread attention. Further, the use of dielectric absorption as a method for the application of heat in bonding processes is now of considerable technological importance particularly in the plywood industry. As a result the development and standardization of electrical test methods for adhesives has become necessary and the ASTM committee D-14 on adhesives has established a sub-committee on Electrical Test Methods for this purpose.

The Sub-committee on Electrical Test Methods has reviewed the methods recommended by the ASTM Committee D-9 on Insulations and feels that with minor adaption the available techniques and equipment will suffice.

A draft of a Tentative Test Method for the Electrical Properties of Adhesives is now being circulated for acceptance. It is reproduced here for information purposes only:

Tentative Methods of Testing Adhesives Used for Electrical Insulation

Scope

1. These methods cover tests for adhesives,

(a) in liquid state which are intended to be cured by dielectric heating, and

(b) in the solid state, which are intended for the purpose of providing electrical insulation. The tests appear in the following order:

Power Factor and Dielectric Constant of Liquid Adhesives

Power Factor and Dielectric Constant of Solid of Highly Viscous Adhesives

Dielectric Strength of Solid Adhesives

Insulation Resistance of Solid of Highly Viscous Adhesives

Arc Resistance of Solid Adhesives

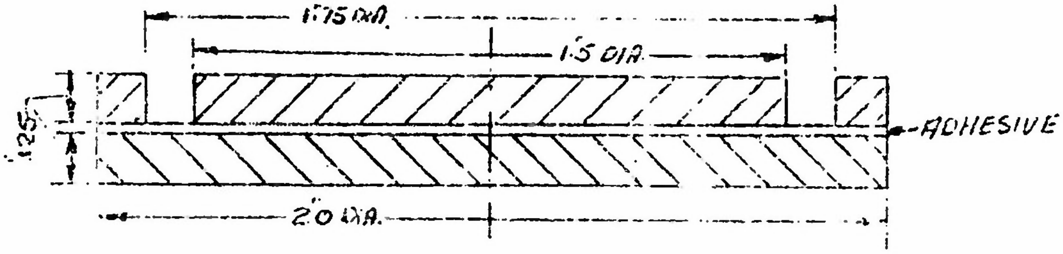
Test Specimens

2. (a) Test specimens for the determination of power factor and dielectric constant of solid or highly viscous adhesives by:

(1) Methods involving a simple capacitor circuit shall be prepared in accordance with the Standard Method of Test for Tensile Properties of Adhesives (D897-49).

(2) Methods involving a capacitor with guard ring shall be prepared as in 2(b).

(b) Test specimens for use in determining the insulation resistance of solid adhesives shall consist of two metal discs, one 1/8" x 2" dia, the other 1/8" x 1.5 dia, and a metal ring 1/8" x 2" OD and 1.75" ID, bonded together by the sample adhesive as shown in Fig. 1. The specimen shall be bonded by the application of pressure or heat if necessary by means of parallel platens in a suitable press. The thickness of glue line shall be not greater than 0".060 nor less than 1".0010.



(c) Test specimens for use in determining the arc resistance of solid adhesives shall consist of panels of silicone resin bonded glass cloth laminate, 4" x 4" x 1/8" coated on one side with one or more layers.

Gluing

3. Gluing and preparation of areas which are to be cemented shall be done in accordance with the procedure as outlined by the manufacturer of the adhesive.

Procedure

POWER FACTOR AND DIELECTRIC CONSTANT OF LIQUID ADHESIVES

4. The power factor and dielectric constant of liquid adhesives shall be determined and reported in accordance with Standard Method of Test for Power Factor and Dielectric Constant of Electrical Insulating Oils of Petroleum Origin (ASTM Designation D924-49).

POWER FACTOR AND DIELECTRIC CONSTANT OF SOLID OR HIGHLY VISCOUS ADHESIVES

5. The power factor and dielectric constant of solid or highly viscous adhesives shall be determined and reported in accordance

with Tentative Methods of Test for Power Factor and Dielectric Constant of Electrical Insulating Materials (D150-47T), except that test specimens shall be prepared in accordance with 2(a).

DIELECTRIC STRENGTH OF SOLID ADHESIVES
6. The dielectric strength of solid adhesives shall be determined and reported in accordance with Tentative Methods of Testing Varnishes Used for Electrical Insulation (D115-48T).

INSULATION RESISTANCE OF SOLID OR HIGHLY VISCOUS ADHESIVES
7. The insulation resistance of solid adhesives shall be determined and reported in accordance with Tentative Methods of Test for Electrical Resistance of Insulating Materials (D257-49T) except that the test specimens shall be prepared in accordance with 2(b).

ARC RESISTANCE OF SOLID ADHESIVES
8. The arc resistance of solid adhesives shall be determined and reported in accordance with Tentative Method of Test for High Voltage, Low Current ACR Resistance of Solid Electrical Insulating Materials (D495-48T) except that the specimens shall be prepared in accordance with 2(c).

9. The report in addition to the items called for in the related methods, shall include the following:
(1) Complete identification of the adhesive applied.
(2) Method of applying the adhesive.

Model Testing

The difficulty of analytical solutions and the cost of full scale testing in any design problem often lead to the use of models as an economical vehicle by which confirmation of design calculations may be made and from which the physical properties of the prototype may be predicted with confidence. Since Goland and Reisner's conclusions for lap joints can be extended to indicate that the stress distribution in a bonded joint varies considerably with the thickness to rigidity ratio of the adhesive to the adherend, the use of scale models to evaluate structures having bonded joints must be made with considerable judgment if serious errors are to be avoided.

Inspection of Adhesive Bonds

The strength and reliability of an adhesive bond is very dependent upon the degree with which the adhesive fills the joint and is attached to the surfaces prepared for it. A full, well bonded joint distributes the stresses uniformly over the adjacent adherend materials. Any flaw in the assembly is likely to lead to fracture at sub-normal loadings due to stress concentrations in the adhesive at the edges of the flaw (See Griffith's theory of flaws - Section II). It is therefore desirable to inspect a bond for flaws after assembly in order that defective bonds may be rejected and the bonding processes revised to eliminate future defective bonds.

Flaws in adhesive bonds include the following: incomplete filling of the joint, inclusion of air, inclusion of solid particles which may act as stress raisers, poor wetting of bonded areas due to insufficient surface cleaning or bonding pressure, insufficient cure of the adhesive, cracks and fissures due to improper design or heat cycle and resultant rapid or excessive shrinkage.

The detection of flaws by visual means throughout the bond is not possible except when transparent adherends are bonded. However, the existence of a good continuous bead of excess adhesive at the edges of the bond gives some assurance that sufficient adhesive was applied and that enough pressure was developed within the joint to extrude some of the adhesive. However, observation of the edges of the bond give no indication of other conditions which may exist within the bond, as a result attention has been directed toward the development of other means for the detection of flaws, x-rays, ultrasonics and electrical measurements have been explored by various investigators in attempts to detect flaws.

X-rays are capable of detecting microscopic flaws such as bubbles or solid inclusion in adhesives in structures the adherends of which are of low atomic number. X-rays give no clue as to the existence of microscopic flaws or of poor adhesion at the adherend surfaces. In structures, the adherends of which are of high atomic number, the amount of x-ray attenuation due to the adhesive is small compared to that due to the adherends and voids in the adhesive are difficult or impossible to detect.

Ultrasonic techniques have been studied as a means for detecting flaws in structures and have been tried on adhesive joints. One technique employs pulsed ultrasonic waves which are transmitted from a transducer pressed against the structure. Echoes from the adhesive bond interfaces from any flaws and from the opposite face, come back to the transducer in the order in which the transmitted wave impinges upon them. The amplitudes of the reflected waves are dependent upon the size and shape of the flaws and upon the differences in acoustic impedences between the adhesive and the adherends. The amplitude of the reflected waves are also dependent upon the damping characteristics of the materials through which the waves must pass. A second technique employs frequency modulated ultrasonic waves which are transmitted into the structure from a transducer pressed against one side. Here, the structure resonates at various frequencies depending upon its dimensions when the frequency sweeps through those frequencies. Having become acquainted with the frequencies and amplitudes at which a flawless structure resonates it is possible to look for additional resonant frequencies in production samples and to interpret these additional frequencies and amplitudes in terms of the quality of the structure. Neither of these techniques have been found to be of particular value in connection with the detection of flaws in adhesive bonds due to attenuation of ultrasonics in most materials and due to the small acoustic differences which are introduced by flaws.

Considerable interest has developed in electrical measurements as a means for the detection of flaws in joints revolving mainly around capacitance measurements in bonds between metallic adherends. It is thought that small differences in the capacitance of a bond may be interpreted in terms of the existence of voids and that loss measurements can be interpreted in terms of the degree of cure of the adhesive. The method does not appear to be of value in connection with the detection of flaws in adhesive layers between non-metallic adherends.

SECTION VI - GLOSSARY

Terms Relating to Adhesives*

Adhere, v. - To cause two surfaces to be held together by adhesion.

Adherend, n. - A body which is held to another body by an adhesive. (See also Substrate.)

Adhesion, n. - The state in which two surfaces are held together by interfacial forces which may consist of valence forces or interlocking action, or both. (See also Adhesion, Mechanical and Adhesion, Specific.)

Adhesion, Mechanical. - Adhesion between surfaces in which the adhesive holds the parts together by interlocking action. (See also Adhesion, Specific.)

Adhesion, Specific. - Adhesion between surfaces which are held together by valence forces of the same type as those which give rise to cohesion. (See also Adhesion, Mechanical).

Adhesive, n. - A substance of holding materials together by surface attachment.

Note: - Adhesive is the general term and includes among others cement, glue, mucilage and paste. All of these terms are loosely used interchangeably. Various descriptive adjectives are applied to the term adhesive to indicate certain characteristics as follows:

Physical form, that is, liquid adhesive, tape adhesive.

Chemical type, that is, silicate adhesive, resin adhesive.

Materials bonded, that is, paper adhesive, metal-plastic adhesive, can label adhesive.

Conditions of use, that is, hot-setting adhesive.

---

* ASTM Designation: D907-49T

Adhesive, Assembly. - An adhesive which can be used for bonding parts together, such as in the manufacture of a boat, airplane, furniture, and the like.

Note: The term assembly adhesive is commonly used in the wood industry to distinguish such adhesives (formerly called "joint glues") from those used in making plywood (sometimes called "veneer glues"). It is applied to adhesives used in fabricating finished structures or goods, or subassemblies thereof, as differentiated from adhesives used in the production of sheet materials for sale as such, for example, plywood or laminates.

Adhesive, Cold-Setting. - An adhesive which sets at temperatures below 20°C. (68°F.). (See also Adhesive, Hot-Setting; Adhesive, Intermediate Temperature Setting; and Adhesive, Room Temperature Setting).

Adhesive, Hot-Setting - An adhesive which requires a temperature at or above 100°C. (212°F.) to set it. (See also Adhesive, Cold-Setting; Adhesive, Intermediate Temperature Setting; and Adhesive, Room Temperature Setting.)

Adhesive, Intermediate Temperature Setting - An adhesive which sets in the temperature range 31 to 99°C. (87 to 211°F.). (See also Adhesive, Cold-Setting, Adhesive, Hot-Setting, and Adhesive, Room Temperature Setting.)

Adhesive, Pressure-Sensitive. - An adhesive made so as to adhere to a surface at room temperature by briefly applied pressure alone.

Adhesive, Room Temperature Setting - An adhesive which sets in the temperature range of 20 to 30°C. (68 to 86°F., in accordance with the limits for Standard Room Temperature specified in the Tentative Methods of Conditioning Plastics and Electrical Insulating Materials for Testing. (ASTM Designation D 618)* (See also Adhesive, Cold-Setting; Adhesive, Hot-Setting; and Adhesive, Intermediate Temperature Setting).

---

* 1949 Book of ASTM Standards, Part 6

__Adhesive, Separate Application__ - A term used to describe an adhesive consisting of two parts, one part being applied to one adherend and the other part to the other adherend and the two brought together to form a joint.

__Adhesive, Warm-Setting__ - A term which is sometimes used as a synonym for Intermediate Temperature Setting Adhesive. (See Adhesive, Intermediate Temperature Setting).

__Aging Time__ - See Time, Joint Conditioning

__Aggressive Tack__ - See Tack, Dry.

__Assembly__, n. - A group of materials or parts, including adhesive, which has been placed together for bonding of which has been bonded together.

__Assembly, Adhesive__ - See Adhesive, Assembly.

__Assembly Glue__ - See Adhesive, Assembly

__Assembly Time__ - See Time, Assembly

__Bag Molding__ - A method of molding or bonding involving the application of fluid pressure, usually by means of air, steam, water, or vacuum, to a flexible cover which, sometimes in conjunction with the rigid die, completely encloses the material to be bonded.

__Binder__, n. - A component of an adhesive composition which is primarily responsible for the adhesive forces which hold two bodies together. (See also Extender and Filler).

__Blister__, n. - An elevation of the surface of an adherend, somewhat resembling in shape a blister on the human skin; its boundaries may be indefinitely outlined and it may have burst and become flattened.

__Note:__ - A blister may be caused by insufficient adhesive; inadequate curing time, temperature or pressure; or trapped air, water, or solvent vapor.

Blocking, n. - An undesired adhesion between touching layers of a material, such as occurs under moderate pressure during storage or use.

Bond, n. - The attachment at an interface between an adhesive and an adherend. (See also Joint.)

Bond, v. - To attach materials together by adhesives.

Catalyst, n. - A substance which markedly speeds up the cure of an adhesive when added in minor quantity as compared to the amounts of the primary reactants. (See also Hardener and Inhibitor.)

Cement, n. - See Adhesive

Cement, v. - See Bond, v., adhere, v.

Closed Assembly Time - See Time, Assembly

Cohesion, n. - The state in which the particles of a single substance are held together by primary or secondary valence forces. As used in the adhesive field, the state in which the particles of the adhesive (or the adherend) are held together.

Cold Flow - See Creep

Cold Pressing - A bonding operation in which an assembly is subjected to pressure without the application of heat.

Cold-Setting Adhesive - See Adhesive, Cold-Setting

Colophony, n. - See Rosin

Condensation, n. - A chemical reaction in which two or more molecules combine with the separation of water or some other simple substance. If a polymer is formed, the process is called polycondensation. (See also Polymerization.)

Conditioning Time - See Time, Joint Conditioning

Copolymer - See Polymer

Copolymerization - See Polymerization

Crazing, n. - Fine cracks which may extend in a network on or under the surface of or through a layer of adhesive.

Creep, n. - The dimensional change with time of a material under load, following the initial instantaneous elastic or rapid deformation. Creep at room temperature is sometimes called Cold Flow.

Cross Laminated - See Laminated, Cross

Cure, v. - To change the physical properties of an adhesive by chemical reaction, which may be condensation, polymerization, or vulcanization; usually accomplished by the action of heat and catalyst, alone or in combination, with or without pressure.

Curing Temperature - See Temperature, Curing

Curing Time - See Time, Curing

Delamination, n. - The separation of layers in a laminate because of failure of the adhesive, either in the adhesive itself or at the interface between the adhesive and the adherend, or because of cohesive failure of the adherend.

Double Spread - See Spread

Dry, v. - To change the physical state of an adhesive on an adherend by the loss of solvent constituents by evaporation or absorption, or both (See also Cure and Set).

Dry Strength - See Strength, Dry

Dry Tack - See Tack, Dry

Drying Temperature - See Temperature, Drying

Drying Time - See Time, Drying

Elastomer, n. - A material which at room temperature can be stretched repeatedly to at least twice its original length and, upon immediate release of the stress, will return with force to its approximate original length.

Extender, n. - A substance, generally having some adhesive action, added to an adhesive to reduce the amount of the primary binder required per unit area. (See also Binder and Filler).

Filler, n. - A relatively non-adhesive substance added to an adhesive to improve its working properties, permanence, strength, or other qualities. (See also Binder and Extender).

Gel, n. - A semisolid system consisting of a network of solid aggregates in which liquid is held.

Gelation, n. - Formation of a gel.

Glue, n. - Originally, a hard gelatin obtained from hides, tendons, cartilage, bones, etc. of animals. Also, an adhesive prepared from this substance by heating with water. Through general use the term is now synonymous with the term "adhesive". (See also Adhesive, Mucilage, Paste, and Sizing).

Glue, v. - See Bond, v.

Gum, n. - Any of a class of colloidal substances, exuded by or prepared from plants, sticky when moist, composed of complex carbohydrates and organic acids, which are soluble or swell in water. (See also Adhesive, Glue, Resin)

Note: - The term gum is sometimes used loosely to denote various materials that exhibit gummy characteristics under certain conditions, for example, gum balata, gum benzoin and gum asphaltum. Gums are included by some in the category of natural resins.

Hardener, n. - A substance or mixture of substances added to an adhesive to promote or control the curing reaction by taking part in it. The term is also used to designate a substance added to control the degree of hardness of the cured film. (See also Catalyst).

Hot-Setting Adhesive - See Adhesive, Hot-Setting.

Inhibitor, n. - A substance which slows down chemical reaction. Inhibitors are sometimes used in certain types of adhesives to prolong storage or working life.

Intermediate Temperature Setting Adhesive - See Adhesive, Intermediate Temperature Setting.

Joint, n. - The location at which two adherends are held together with a layer of adhesive (See also Bond, n.)

Joint Aging Time - See Time, Joint Conditioning.

Joint Conditioning Time - See Time, Joint Conditioning.

Joint, Lap - A joint made by placing one adherend partly over another and bonding together the overlapped portions. (See also Joint, Scarf.)

Joint, Scarf - A joint made by cutting away similar angular segments of two adherends and bonding the adherends with the cut areas fitted together. (See also Joint, Lap)

Joint, Starved - A joint which has an insufficient amount of adhesive to produce a satisfactory bond.

Note: This condition may result from too thin a spread to fill the gap between the adherends, excessive penetration of the adhesive into the adherend, too short an assembly time, or the use of excessive pressure.

Laminate, n. - A product made by bonding together two or more layers of material or materials. (See also Laminated, Cross and Laminated, Parallel.)

Laminate, v. - To unite layers of material with adhesive.

Lamination, n. - The process of preparing a laminate. Also, any layer in a laminate.

Laminated, Cross. - A laminate in which some of the layers of material are oriented at right angles to the remaining layers with respect to the grain or strongest direction in tension. (See also Laminated, Parallel).

Note: Balanced construction of the laminations about the center line of the thickness of the laminate is normally assumed.

Laminated, Parallel - A laminate in which all the layers of material are oriented approximately parallel with respect to the grain or strongest direction in tension. (See also Laminated, Cross.)

Lap Joint - See Joint, Lap.

Mechanical Adhesion - See Adhesion, Mechanical, and Adhesion Specific.

Monomer, n. - A relatively simple compound which can react to form a polymer. (See also Polymer.)

Mucilage, n. - An adhesive prepared from a gum and water. Also in a more general sense, a liquid adhesive which has a low order of bonding strength. (See also Adhesive, Glue, Paste, and Sizing.)

Novolak, n. - A phenolic-aldehydic resin which, unless a source of methylene groups is added, remains permanently thermoplastic. (See also Resinoid and Thermoplastic.)

Open Assembly Time - See Time, Assembly

Parallel Laminated - See Laminated, Parallel.

Paste, n. - An adhesive composition having a characteristic plastic-type consistency, that is, a high order of yield value, such as that of a paste prepared by heating a mixture of starch and water and subsequently cooling the hydrolyzed product. (See also Adhesive, Glue, Mucilage, and Sizing.)

Polycondensation - See Condensation

Polymer, n. - A compound formed by the reaction of simple molecules having functional groups which permit their combination to proceed to high molecular weights under suitable conditions. Polymers may be formed by polymerization (addition polymer) or polycondensation (condensation polymer). When two or more monomers are involved, the product is called a copolymer.

Polymerization, n. - A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When two or more monomers are involved, the process is called copolymerization or heteropolymerization. (See also Condensation.)

Pot Life - See Working Life.

Pressure-Sensitive Adhesive - See Adhesive, Pressure-Sensitive.

Resin, n. - Any of a class of solid or semi-solid organic products of natural or synthetic origin, generally of high molecular weight with no definite melting point. (See also Gum.)

Note: Resins are generally water-insoluble and have little or no tendency to crystallize. However, certain resins, such as some polyvinyl alcohols and polyacrylates, are readily dispersible in water, and others, such as polyamides and polyvinylidene chloride, are readily crystallized.

Resinoid, n. - Any of the class of thermosetting synthetic resins, either in their initial temporarily fusible state or in their final infusible state. (See also Novolak and Thermosetting.)

Retarder - See Inhibitor

Room Temperature Setting Adhesive - See Adhesive, Room Temperature Setting.

Rosin, n. - A resin obtained as a residue in the distillation of crude turpentine from the sap of the pin tree (gum rosin) or from an extract of the stumps and other parts of the tree (wood rosin).

Scarf Joint - See Joint, Scarf

Self-Curing, adj. - See Self-Vulcanizing

Self-Vulcanizing, adj. - Pertaining to an adhesive which undergoes vulcanization without the application of heat.

Separate Application Adhesive - See Adhesive, Separate Application.

Set, n. - To convert an adhesive into a fixed or hardened state by chemical or physical action, such as condensation, polymerization, oxidation, vulcanization, gelation, hydration, or evaporation of volatile constituents. (See also Cure and Dry.)

Setting Temperature - See Temperature, Setting

Setting Time - See Time, Setting

Shelf Life - See Storage Life

Single Spread - See Spread

Size, n. - See Sizing

Sizing, n. - The process of applying a material on a surface in order to fill pores and thus reduce the absorption of the subsequently applied adhesive or coating or to otherwise modify the surface properties of the substrate to improve the adhesion. Also, the material used for this purpose. The latter is sometimes called Size.

Specific Adhesion - See Adhesion, Specific and Adhesion, Mechanical.

Spread, n. - The quantity of adhesive per unit joint area applied to an adherend. It is preferably expressed in pounds of liquid or solid adhesive per thousand square feet of joint area.

1. Single Spread refers to application of adhesive to only one adherend of a joint.
2. Double Spread refers to application of adhesive to both adherends of a joint.

Storage Life - The period of time during which a packaged adhesive can be stored under specified temperature conditions and remain suitable for use. Sometimes called Shelf Life. (See also Working Life.)

Starved Joint - See Joint, Starved.

Strength, Dry - The strength of an adhesive joint determined immediately after drying under specified conditions or after a period of conditioning in the standard laboratory atmosphere. (See also Strength, Wet.)

Strength, Wet - The strength of an adhesive joint determined immediately after removal from a liquid in which it has been immersed under specified conditions of time, temperature and pressure.

Note: The term is commonly used alone to designate strength after immersion in water. In the latex adhesives the term is also used to describe the joint strength when the adherends are brought together with the adhesive still in the wet state.

Substrate, n. - A material upon the surface of which an adhesive-containing substance is spread for any purpose, such as bonding or coating. A broader term than adherend. (See also Adherend).

Tack, n. - Stickiness of an Adhesive.
Note: This property is measured as the pull resistance to effect division without failure or deformation occurring in the adherend surroundings or at the interface while the adhesive still exhibits viscous or plastic flow. The measured value may vary with time temperature, film thickness, etc.

Tack, Dry - The property of certain adhesives, particularly non-vulcanizing rubber adhesives, to adhere on contact to themselves at a stage in the evaporation of volatile constituents, even though they seem dry to the touch. Sometimes called Aggressive Tack.

Tack Range - The period of time in which an adhesive will remain in the tacky-dry condition after application to an adherend, under specified conditions of temperature and humidity.

Tack-Dry, adj. - Pertaining to the condition of an adhesive when the volatile constituents have evaporated or been absorbed sufficiently to leave it in a desired tacky state.

Temperature, Curing - The temperature to which an adhesive or an assembly is subjected to cure the adhesive. (See also Temperature, Drying and Temperature, Setting.)

Note: The temperature attained by the adhesive in the process of curing it (adhesive curing temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly curing temperature).

Temperature-Drying - The temperature to which an adhesive on an adherend or in an assembly or the assembly itself is subjected to dry the adhesive. (See also Temperature, Curing and Temperature, Setting.)

Note: The temperature attained by the adhesive in the process of drying it (adhesive drying temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly drying temperature).

Temperature, Setting - The temperature to which an adhesive or an assembly is subjected to set the adhesive. (See also Temperature, Curing and Temperature, Drying.)

Note: The temperature attained by the adhesive in the process of setting it (adhesive setting temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly setting temperature).

Thermoplastic, adj. - Capable of being repeated softened by heat and hardened by cooling.

Thermoplastic, n. - A material which will repeatedly soften when heated and harden when cooled.

Thermoset, adj. - Pertaining to the state of a resin in which it is relatively infusible.

Thermoset, n. - A material which will undergo or has undergone a chemical reaction by the action of heat, catalysts, ultraviolet light, etc., leading to a relatively infusible state.

Thermosetting, adj. - Having the property of undergoing a chemical reaction by the action of heat, catalysts, ultraviolet light, etc., leading to a relatively infusible state.

Time, Assembly - The time interval between the spreading of the adhesive on the adherend and the application of pressure or heat, or both, to the assembly.

Note: For assemblies involving multiple layers or parts, the assembly time begins with the spreading of the adhesive on the first adherend.

1. Open Assembly Time is the time interval between the spreading of the adhesive on the adherend and the completion of assembly of the parts for bonding.
2. Closed Assembly Time is the time interval between completion of assembly of the parts for bonding and the application of pressure or heat, or both, to the assembly.

Time, Curing - The period of time during which an assembly is subjected to heat or pressure, or both, to cure the adhesive. (See also Time, Drying, Time; Joint Conditioning; and Time, Setting.)

Note: Further cure may take place after removal of the assembly from the conditions of heat or pressure, or both; see Time, Joint Conditioning.

Time, Drying - The period of time during which an adhesive on an adherend or an assembly is allowed to dry with or without the application of heat or pressure, or both. (See also Time, Curing; Time, Joint Conditioning; and Time, Setting.)

Time, Joint Conditioning - The time interval between the removal of the joint from the conditions of heat or pressure, or both, used to accomplish bonding and the attainment of approximately maximum bond strength. Sometimes called Joing Aging Time.

Time, Setting - The period of time during which an assembly is subjected to heat or pressure, or both, to set the adhesive. (See also Time, Curing; Time, Joint Conditioning; and, Time, Drying.)

Vulcanization, n. - A chemical reaction in which the physical properties of a rubber are changed in the direction of decreased plastic flow, less surface tackiness, and increased tensile strength by reacting it with sulfur or other suitable agents. (See also Self-Vulcanizing.)

Vulcanize, v. - To subject to vulcanization.

Warm-Setting Adhesive - See Adhesive, Warm-Setting

Wet Strength - See Strength, Wet.

Wood Failure - The rupturing of wood fibers in strength tests on bonded specimens, usually expressed as the percentage of the total area involved which shows such failure.

Wood Veneer - A thin sheet of wood, generally within the thickness range of 0.01 to 0.25 in., to be used in a laminate.

Working Life - The period of time during which an adhesive, after mixing with catalyst, solvent, or other compounding ingredients, remains suitable for use. (See also Storage Life.)

DISTRIBUTION

	No. of Copies
Bureau of Ordnance	
Re1-2 Attn: Mr. J. F. Case Re2a	10
Re2f	1
Re3b	1
Re3e	1
Re3f	1
Re4c Attn: Mr. Ralph C. Schalla	1
Re5	1
Re6a	1
Re6b	1
Re7a	1
Re8	1
Re9	1
Rec-1 Attn: Mr. W. E. Countryman	1
Qcd	1
Rep	1
Qa	1
PL	1
Mas	1
Ma-1 thru 7	1
Bureau of Aeronautics Attn: Mr. Paul Stone Mr. Jay M. Stevens Rm 1W 58 W Bldg.	1

DISTRIBUTION

	No. of Copies
Naval Ordnance Plant Indianapolis, Indiana	1
Brooklyn Navy Yard Materials Laboratory Attn: Mr. A. W. Cizek, Jr.	1
Office of Naval Research Attn: Dr. Randall Robertson	1
Dr. Louis Larrick	1
Naval Powder Factory Indian Head, Maryland	1
Naval Proving Ground Dahlgren, Virginia	1
Naval Gun Factory Washington, D. C. Attn: Mr. M. M. De Neale	1
Naval Research Laboratory Dr. Peter King	1
Naval Air Development Center Johnsville, Pa. Attn: Mr. Ernest Schleiben	1
National Bureau of Standards	
Attn: Mr. F. W. Reinhart Room 4022, Industrial Building	1
Attn: Dr. P. J. Franklin 332 Ordnance Laboratory	1
Office of the Quartermaster General Attn: Dr. Coutoure, Room 2402 Temporary Building A	1
Engineer Center Engineer Research and Development Laboratory Attn: Mr. Phillip Mitton Materials Branch Fort Belvoir, Virginia	1
Signal Corps Engineering Laboratory Squier Signal Laboratory Materials Section, Attn: Mr. A. W. Rogers	1

DISTRIBUTION

	No. of Copies
Bureau of Ships Code 346 Attn: Mr. J. B. Alfers	1
Bureau of Yards & Docks Attn: Mr. Donohue	1
Office of Chief of Ordnance Room 2C 374 Pentagon Bldg. Attn: Mr. G. Reinsmith Mr. W. S. Mcgillivray (ORDTA) Mr. E. Caponi (ORDTA)	1
Naval Ordnance Test Station Inyokern, California Attn: Mr. W. E. Donaldson	1
Naval Ordnance Test Station Pasadena, California Attn: Mr. Murray	1
Naval Ordnance Test Station Inyokern, California Attn: Mr. C. E. Wineland	1
Forest Products Laboratory Madison 5, Wisconsin	1
Naval Air Experimental Station Naval Air Material Center Naval Base, Philadelphia 12, Pa. Attn: Aero. Matls. Lab.	1
Mare Island Naval Shipyard Rubber Laboratory Vallejo, California Attn: Mr. Ross E. Morris	1
Frankford Arsenal Philadelphia, Pa. Attn: Mr. Marco Petronio	1
Watertown Arsenal Watertown, Mass. Attn: Dr. R. Beeuwkes Mr. E. Hegge	1

DISTRIBUTION

	No. of Copies
Picatinny Arsenal Technical Division Attn: Dr. Gilman Mr. S. J. Lowell	1
Wright Air Development Center Dayton, Ohio Attn: Mr. R. Schwartz	1
Atomic Energy Commission Division of Research Attn: Dr. J. F. White	1
Naval Air Missile Test Center Point Mugu, California Attn: Dr. R. Weller	1