Bonded-Bolted Composite Joints

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Various aspects of the combination of adhesive bonding and mechanical fastening for fibrous composite structures are considered. The factors accounted for in the theories are explained and the source of the complete derivations is given. Analyses of undamaged structures show that, because the adhesive bond load path is so much stiffer than the load path through bolts or rivets, the combination is no stronger than a well-designed bonded joint alone. However, the combination of bonding and bolting is shown to be particularly useful for repair and to prevent damage from spreading. The issues raised are illustrated by specific analyses of large stepped-lap composite to metal joints.

Introduction

THE subject of this paper is the design and analysis of high-load-transfer joints in advanced composite structures. Analysis methods have been developed and coded as the Fortran IV computer programs A4EI, A4EJ, and A4EK for adhesively bonded joints, mechanically fastened joints, and combined bonded-bolted joints, respectively.[1] These programs are an outgrowth of an earlier investigation that led to the A4EG program for the nonlinear (elastic-plastic) analysis of stepped-lap adhesively bonded joints.[2] The A4EG program has been used extensively throughout the U.S. aerospace industry, with a notable application being the wing-root splice on the F-18.

The newer program for adhesively bonded joints, A4EI, permitted variable adhesive properties to be included throughout the bond area. Effects such as flaws, porosity, variable layer thickness, and nonuniform moisture content could then be covered.[3,4] In addition, the opportunity was taken to improve the logic in the code in order to increase the speed of the iterations substantially.

The multirow bolted joint program, A4EJ, was the key to attaining composite joints that developed load intensities as high as 50,000 lb/in. at a gross section strain level of 0.005 in the unreinforced basic laminates. Those highly loaded, very efficient joints are a measure of the success of the extensive testing conducted to develop splices suitable for fibrous composite wings on large transport aircraft.[5]

The use of these programs to optimize the detailed dimensions of adhesively bonded or mechanically fastened joints is illustrated by worked examples.[1,3,5] The ability to improve upon initial designs by analysis rather than by extensive testing is a prime benefit of these programs.

The combined program, A4EK, confirmed what is already well known—bonding and bolting do not work well together when both load paths are intact. On the other hand, worked examples show that the combination can be particularly useful for repairs or to confine any spread of initial damage in thick composite or laminated structures.[1]

Further examples of the use of these programs to analyze various bonded and bolted joints can be found in the contract report on which this paper is based.[1] That report expands the coverage beyond the illustrative solutions given herein.

The analyses presented here are based on static strength. Good joint design practice requires some conservatism with respect to ultimate strength or some other allowance for possible fatigue damage in service.

Features of the Analyses

The solutions to these problems have been obtained by continuum mechanics formulations. The actual differential equations are straightforward, none being more difficult than a standard fourth-order linear differential equation with coefficients that are constant between any two adjacent stations in the analytical model of the joints. The only real difficulties encountered were associated with the movement of the transitions between linear and nonlinear behavior, as a function of load level, and with numerical convergence of a problem that requires greater accuracy than can be achieved on IBM computers in single precision. The computer programs are coded for IBM double precision or CDC precision.

Figure 1 shows the effects that are included in the analysis of adhesively bonded joints. These same effects apply to the simpler joints with one or more uniform adherends, as well as the stepped-lap joint shown. The adherend properties E, ν, and α are prescribed to be linear, but can vary from step to step. The adhesive shear stress is distributed uniformly across its thickness and induced peel stresses are ignored because they are shown to be negligible, in comparison with the shear stresses, in properly proportioned joints.

The adhesive has been modeled as both elastic-plastic and bilinear materials (see Fig. 2) in the derivations.[1] However, only the elastic-plastic model is included in the computer program. Both representations are equally accurate, but the elastic-plastic model should be reproportioned for fractional load levels. Only a single input is needed for any load level with the bilinear model.

The models are established by matching the strain energy (area under the stress-strain curve) and the stress and strain at failure or at some reduced load level, as appropriate. The complete derviations of the equations for the equilibrium and for compatibility of deformations are already documented[1-3]; therefore, they will not be repeated here.

The analysis of the load transfer through mechanical fasteners includes the effects shown in Fig. 3. A single-shear installation is shown, but the analysis and computer code are equally applicable to a double-shear joint. Dissimilar thermal coefficients of the members being joined are accounted for, just as with the adhesively bonded joint analysis.

Most filamentary composite members could be treated as linearly elastic to failure. However, the nonlinear behavior of ±45 deg laminates can be approximated by the Ramberg-

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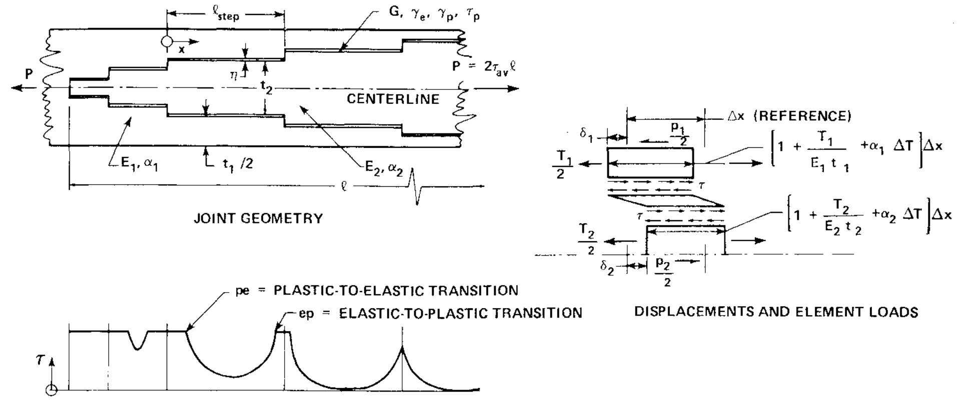


Fig. 1 Notation and geometry for adhesive-bonded stepped-lap joint analysis.

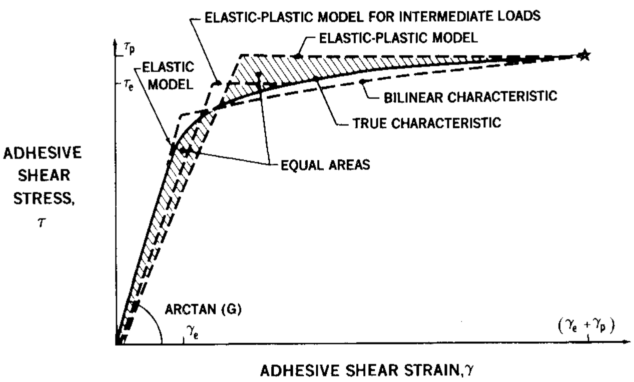


Fig. 2 Representations of adhesive nonlinear shear behavior.

Osgood formulation (see Fig. 4) incorporated to account for the ductile behavior of typical metal alloys used for aircraft construction. Such nonlinearity tends to increase the load transferred on the most critical outermost fasteners, with respect to the predictions of a perfectly linear analysis.

This feature is omitted from the adhesively bonded joint analysis for two reasons. First, the adhesive layer is known, by testing with aluminum alloy adherends, to fail progressively once the metal yields, even if the adhesive could have withstood a larger, more rapidly applied load. Second, the mathematics become intractable if nonlinear adherend behavior is combined with continuous load transfer.

The fastener load-deflection characteristic shown in Fig. 5 covers both tensile and compressive shear loads because the associated stress trajectories are so different, as shown in Fig. 6. Consequently, the respective nonlinear behaviors also differ. Figure 5 includes provision for any initial clearances, or preloads, at each bolt hole. These load-deflection characteristics still must be measured experimentally in most cases, although an expression has been shown to predict the elastic stiffness of double-shear joints to sufficient accuracy.[3]

Single-shear installations are less well characterized because the fraction of the eccentricity in the load path that is reacted by bearing on the fastener head and nut varies so much with the different fastener designs. This leaves the degree of nonuniformity in the bearing stresses on the shank of the fastener undefined.

This fastener load-deflection curve customarily includes the local distortion around the bolt hole, as shown in Fig. 7. That is how the basic measurements are taken in the first place, and it greatly simplifies the mathematical expressions for stretching or compressing the member in between the fastener stations.

In multirow bolted joints, the stress concentration due to the bolt "bearing" load at a particular hole interacts with the stress concentration associated with the "bypass" load that is reacted at other bolts. The effects of this interaction are characterized in Fig. 8 for tensile shear loading. This interaction is the reason why it is so important to make accurate estimates of the distribution of load transfer within composite joints having more than one row of fasteners. Similar interactions for compressive shear loading have been presented in Ref. 1.

These two analyses have been combined for bonded and bolted joints with all of the same characterizations retained except for nonlinear behavior of the adherends. Therefore, the combined program, A4EK, does not supersede the individual programs, A4EI and A4EJ. In any case, the input to and storage requirements for A4EK are roughly twice as great as for the others. Thus, there is a need for each of these programs.

Bonded and Bolted Joints

Various worked examples have revealed some characteristics of the behavior of structures that contain parallel bonded and bolted load paths. Some of these findings are explained here, using the large titanium to carbon-epoxy joint shown in Fig. 9 as a reference. The joint transfers load between a laminate 0.81 in. thick and a titanium plate 0.51 in. thick, 5 in., long, contains seven rows of 5/16-in.-diam bolts, and has seven steps in the bonded area. The discussions here are based on theoretical assessments of this joint, which has not been built and tested. However, the same theories have been shown to capable of predicting the failures of other large joints to within 5%.[5]

Figure 10 characterizes the load transfer through this joint when there are no defects at all. The remarkable finding is that the bolts transmit barely 1% of the total load transferred because they represent a far less stiff load path than is provided by the adhesive. Consequently, as long as the adhesive layer is intact, the fasteners cannot be subject to sufficient relative motion between the adherends to develop any significant load themselves. It should also be noted that the adhesive is stronger than the adherends, and the most critical location is at the first bolt hole in the composite laminate.

Figure 11 shows the predicted strength of the corresponding all-bonded joint. Surprising, the strength of 34,322 lb/in. is slightly greater than the 33,096 lb/in. for the bonded and bolted joint. The reason for this is that the elimination of the hole moved the critical location in the composite laminate. Again, the adhesive is not critical, although it is strained beyond the desirable minimum with regard to creep resistance. The peak adhesive strain is not far beyond the knee in the stress-strain curve; there is considerable margin for load redistribution around flaws or damage. The most significant change with respect to the analysis shown in Fig. 10 is the change in critical location in the adherends. The tip of the stepped titanium plate is now predicted to be critical at the

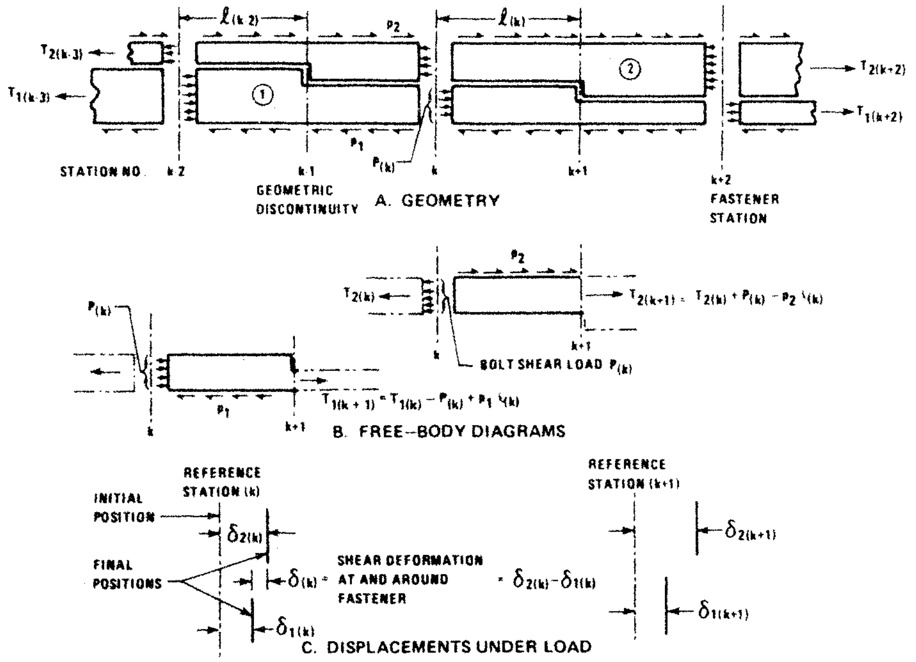


Fig. 3 Loads and deformations on the elements of a bolted joint.

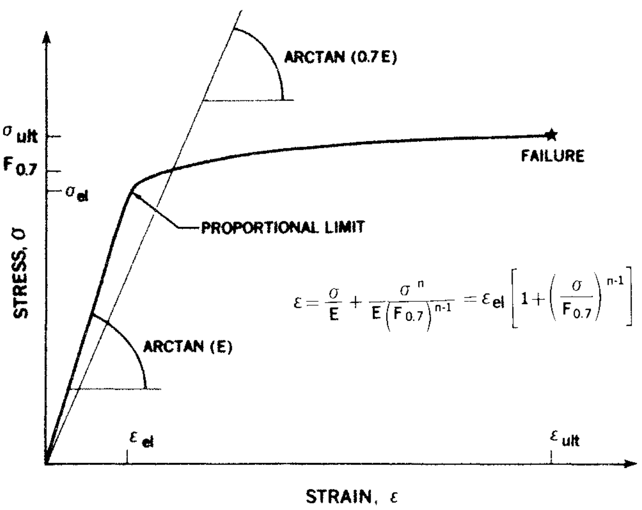


Fig. 4 Ramberg-Osgood nonlinear characterization of stress-strain behavior.

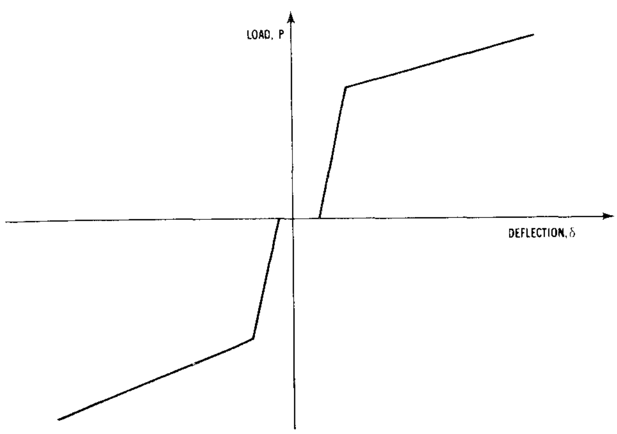


Fig. 5 Idealized fastener load-deflection characteristics.

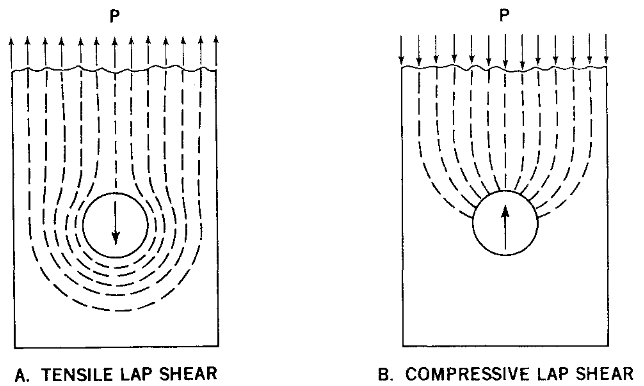


Fig. 6 Stress trajectories around bolts for tensile and compressive lap shear.

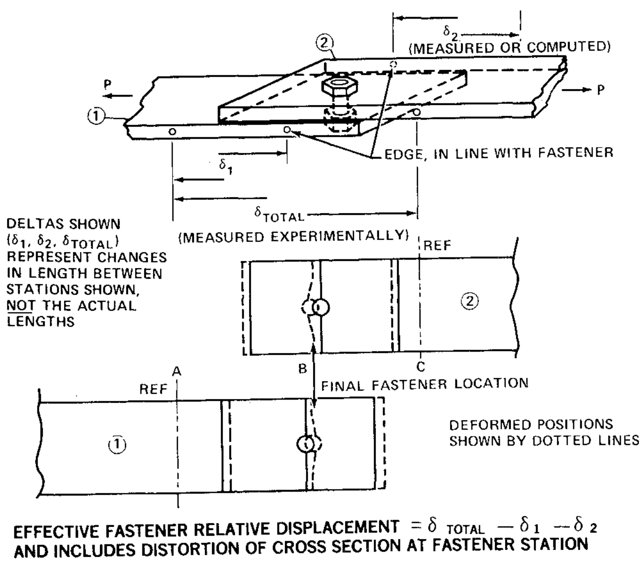


Fig. 7 Deformations in a mechanically fastened joint.

root of the end step. This location is frequently critical in titanium-to-composite bonded stepped-lap joints. The criticality is normally relieved by shortening the end step, as explained in Figs. 5-9 of Ref. 1. However, that cannot be done here because the optimum end step is barely longer than the bolt diameter.

The results of omitting the adhesive and of relying on the fasteners alone to transfer the load are shown in Fig. 12. Despite their ineffectiveness in Fig. 10, the bolts here are predicted to transfer 28,380 lb/in. with no assistance from the adhesive. This load transfer is not substantially less than when the adhesive acts alone. The adherends undergo greater relative motion without the adhesive and that permits the bolts to develop higher shear loads. The greater flexibility permits these bolts to transfer nearly 70 times as much load as in the combined case. The critical location is in the composite laminate at the second row of bolts; the bearing load on the first row is greatly reduced by the thinness of the titanium there.

A comparison of Figs. 10-12 indicates that bonding and bolting do not work together in that joint. While there may be valid reasons for combining bonding and bolting, it should not be done with the expectation that the joint strength will increase. In particular, the combined joint strength is most definitely not the sum of the individual bonded and bolted strengths.

Use of Bonding and Bolting in Repairs

When bolts are substituted for locally defective or damaged bonds, the combination of bonding and bolting can be effective. This is shown by a comparison of Figs. 13 and 14, which present the analysis of essentially the same joint as shown in Fig. 9, but with no effective adhesive for the central three steps. (The outermost steps in Fig. 13 are slightly longer than in Fig. 14, but this has no bearing on the joint strengths or assessment.) Figures 15, 17, 42, and 44 of Ref. 1 present similar assessments of bolted repairs of flaws at each end of the overlap rather than at the middle.

In Fig. 13, the bond flaw or damage appears to be sufficient to move the most highly strained adhesive from the ends of the overlap in Fig. 11 to new locations adjacent to the flaw. This is significant since a lesser flaw would not have changed the critical location[4] and the bolts would then have had only a slightly greater effect in Fig. 14 than they had in Fig. 10. There is no universal size of bond flaw to cause this shift in critical location. The size varies with the overall joint geometry.

Figure 14 shows significant, but far from critical, bolt loads in the flawed area of the bond and trivial loads in areas in which the bond remains intact. Such a prediction is to be expected on the basis of the results shown in Figs. 10 and 12. Nevertheless, the bolts would still transfer only 14% of the total load, even though the bond was defective over nearly one-half of the total area.

This paradox can be explained by a closer look at Figs. 13 and 14. The minimum adhesive shear strains in the outermost steps are raised dramatically in Fig. 14 from their values in Fig. 13. The fasteners serve primarily to reduce the criticality of the peak strain in the adhesive adjacent to the flaw. Consequently, *all* of the remaining adhesive can then be stressed more highly than before, and the load level can be raised until the adhesive again becomes critical. In the presence of the fasteners, the adhesive alone was able to transfer 20,618 lb/in. compared with only 18,705 lb/in. without the fasteners. The repaired strength is predicted to be 24,027 lb/in., which is significantly less than the 33,096 lb/in. of the unflawed joint, but represents a greater fraction of load than the normal ratio of limit to ultimate.

From these analyses, it is concluded that bolts through damaged or defective areas in adhesively bonded joints not only transfer significant load themselves, but also alleviate any adjacent critical locations in the adhesive bond, enabling the remaining adhesive to be stressed more highly before failure. This is important because bonded-only repairs of most thick composite structures are rendered impractical by the need to thoroughly dry out the laminate to be repaired—and that may take days at even 250°F—and by the need to remove any absorbed hydrocarbons such as from fuel or ultrasonic inspection couplants. Also the bonded-only repair of even a 1 in.

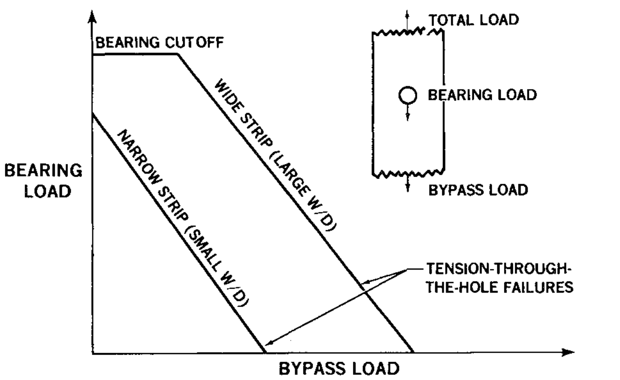


Fig. 8 Bearing/bypass load interaction for loaded bolts in advanced composites.

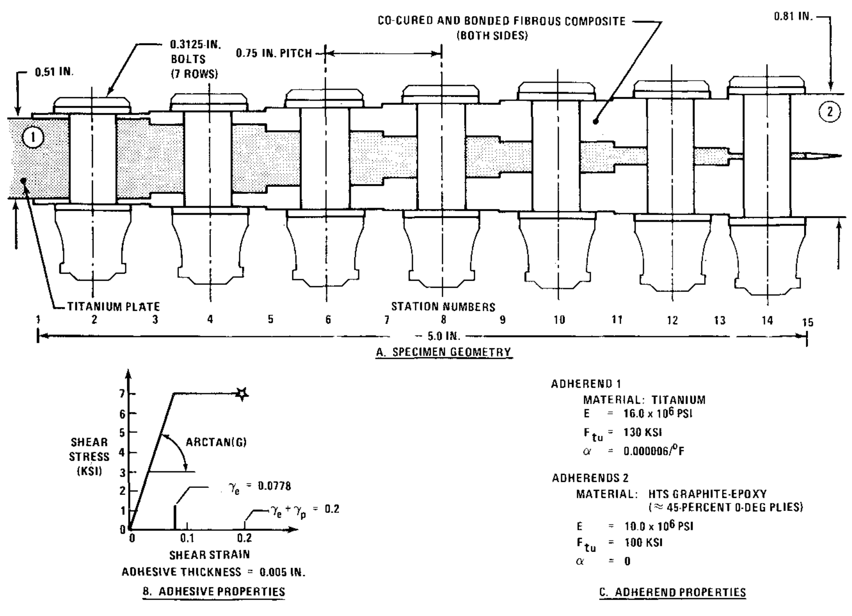


Fig. 9 Stepped-lap bonded-bolted joint.

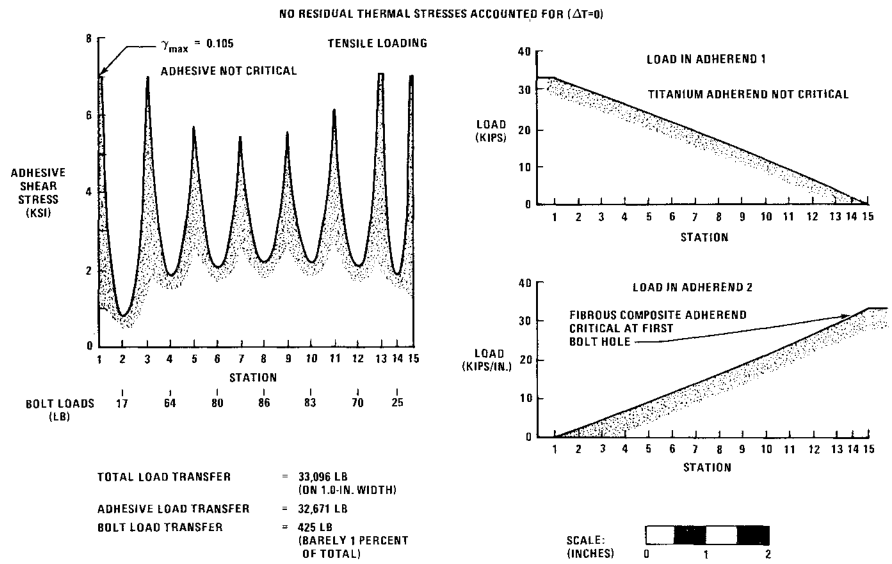


Fig. 10 Load transfer through bonded-bolted stepped-lap joint with no flaws.

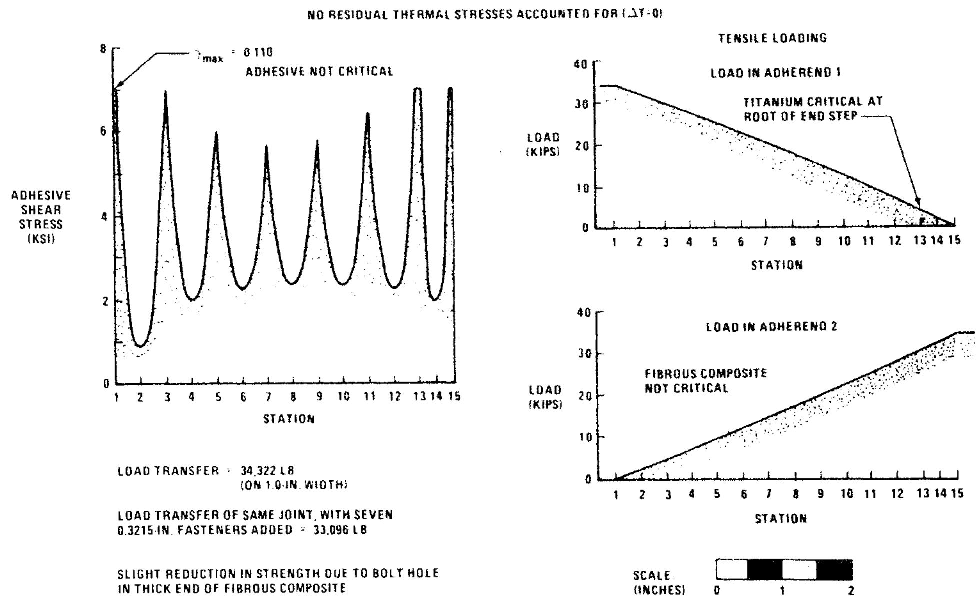


Fig. 11 Load transfer through adhesive-bonded stepped-lap joint with no fasteners.

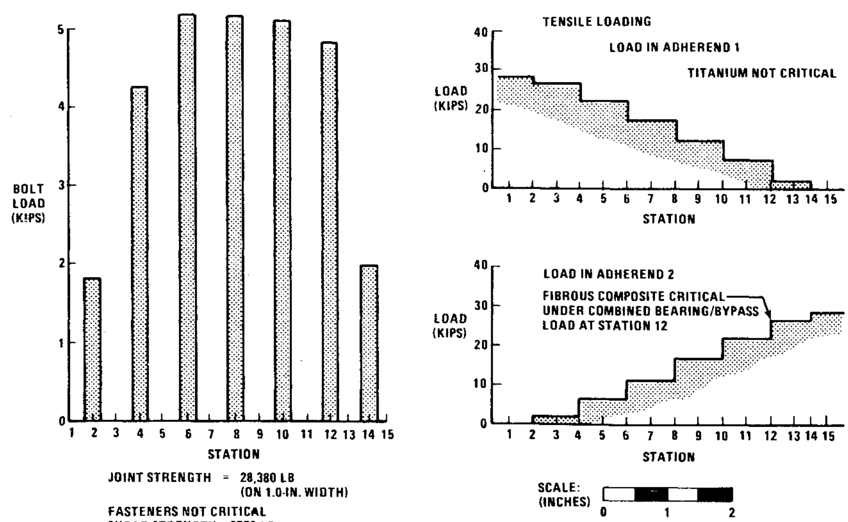


Fig. 12 Load transfer through bolted joint without any adhesive bond.

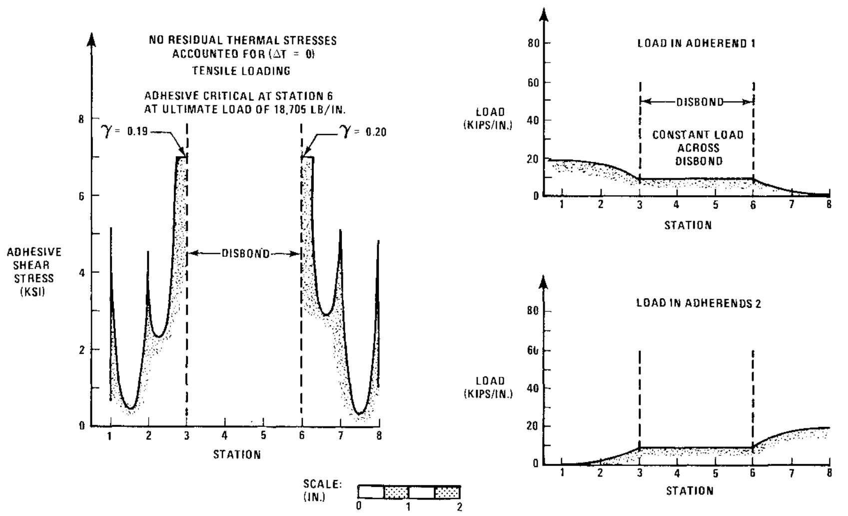


Fig. 13 Strength loss and load redistribution due to disbonds in stepped-lap joints.

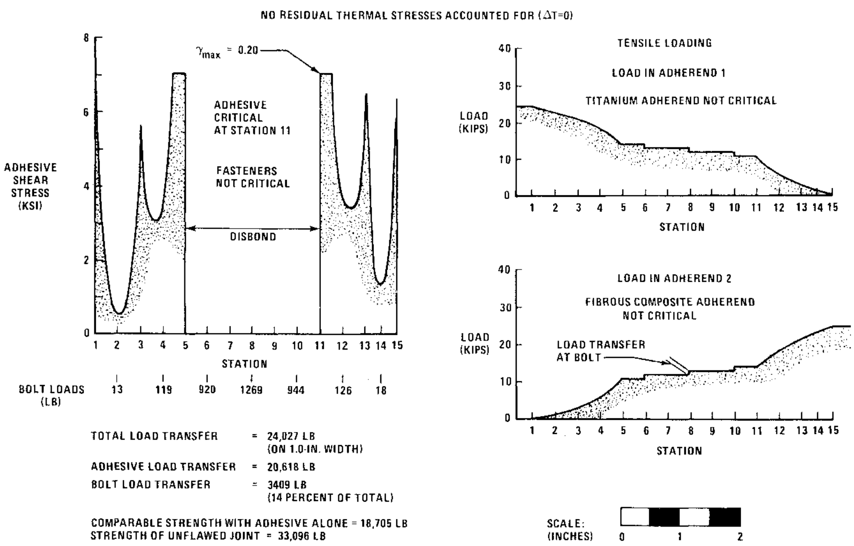


Fig. 14 Load transfer through flawed bonded joint reinforced by bolts.

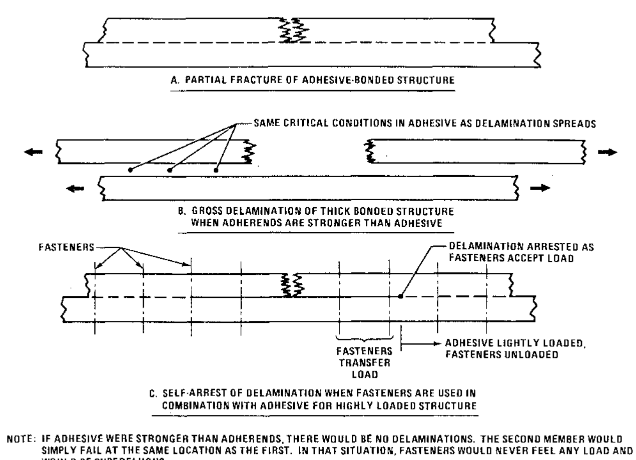


Fig. 15 Need for fail-safe fasteners in thick bonded structures.

hole in a 1-in. thick laminate would require careful scarfing of a tapered surface more than 40 in. in diameter. Such a repair might require the removal of virtually all of the structure not previously damaged!

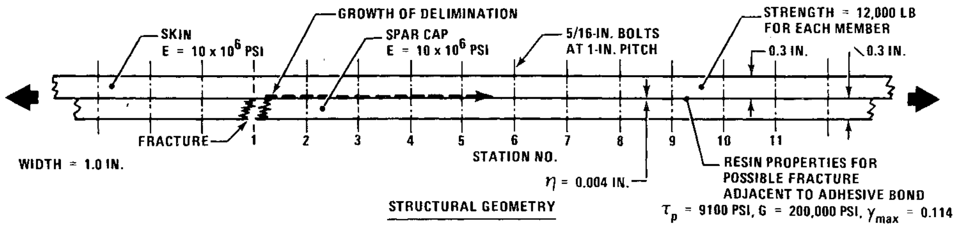
The subject of bonded repairs of composite structures is discussed more fully in Ref. 6; suffice it to say here that there is a real need for mechanical repairs of such structures.

Use of Bonding and Bolting for Damage Tolerance

One other situation in which the combination of adhesive bonding and mechanical fastening of structures can be of benefit occurs in the context of preventing damage from spreading. Such benefits can be attained in many different joint configurations.

One of these configurations is shown in Fig. 15, which simulates the adhesive bonding of two stiff members, one of which is broken or abruptly terminated. This could occur where a skin and spar cap were bonded together and one was broken without initial damage to the other. It could also occur at a stiffener run-out or, in adhesively bonded metallic structures, where one member was broken by a crack that originated at a rivet hole. The sample analysis, using the A4EK program, is presented in Figs. 16 and 17 and shows how the fasteners in the disbonded area pick up significant load and eventually decrease the intensity of the peak in the adhesive shear stress distribution (at the tip of the disbond) so much that further propagation of the disbond would cease.

For the joint shown in Fig. 16, residual strength is limited by the laminate strength through the reduced section at a bolt hole. The figure also indicates that any fracture would be projected to occur in the resin adjacent to the adhesive layer rather than in the adhesive itself. In this case, the bolts are shown to be a very effective means of arresting any damage that otherwise would have spread in an all-bonded structure. The bolts provide fail-safety for the bond in the classical sense.



STATION NUMBER	1	2	3	4	5	6	7	8	9	10	11
1. ZERO DELAMINATION; FAILURE AT 6313 LB											
ADHESIVE SHEAR STRESS (KSI)	9100	74	0	0	0	0	0	0	0	0	0
FASTENER LOAD (LB)	0	1	0	0	0	0	0	0	0	0	0
2. 1.0-IN. DELAMINATION; FAILURE AT 6903 LB											
ADHESIVE SHEAR STRESS (KSI)	0	9100	74	0	0	0	0	0	0	0	0
FASTENER LOAD (LB)	0	295	1	0	0	0	0	0	0	0	0
3. 2.0-IN. DELAMINATION; FAILURE AT 10,468 LB											
ADHESIVE SHEAR STRESS (KSI)	0	0	9100	74	0	0	0	0	0	0	0
FASTENER LOAD (LB)	0	1783	295	1	0	0	0	0	0	0	0
4. 3.0-IN. DELAMINATION; FAILURE AT 12,000 LB*											
ADHESIVE SHEAR STRESS (KSI)	0	0	0	9100	38	0	0	0	0	0	0
FASTENER LOAD (LB)	0	2602	1137	163	0	0	0	0	0	0	0
5. 4.0-IN. DELAMINATION; FAILURE AT 12,000 LB*											
ADHESIVE SHEAR STRESS (KSI)	0	0	0	0	6530	20	0	0	0	0	0
FASTENER LOAD (LB)	0	2782	1394	608	84	0	0	0	0	0	0
6. NO ADHESIVE BOND; FAILURE AT 12,000 LB*											
FASTENER LOAD (LB)	0	2853	1496	785	412	216	113	58	29	12	0

*LIMITED BY ADHEREND STRENGTH

Fig. 16 Use of bolts as fail-safe load paths in bonded structures.

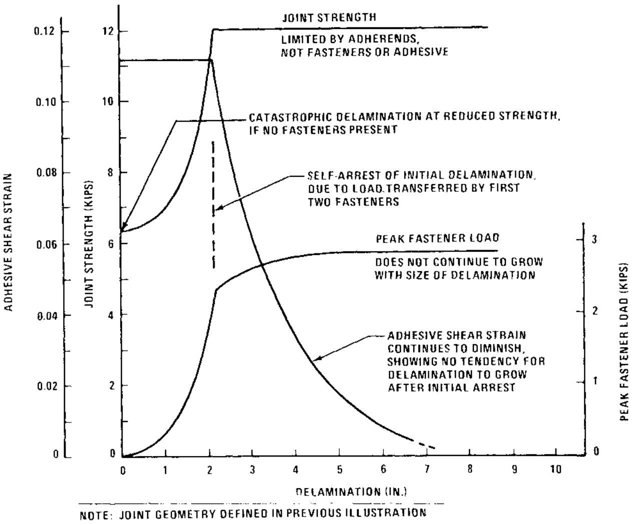


Fig. 17 Damage confinement by combination of bonding and bolting.

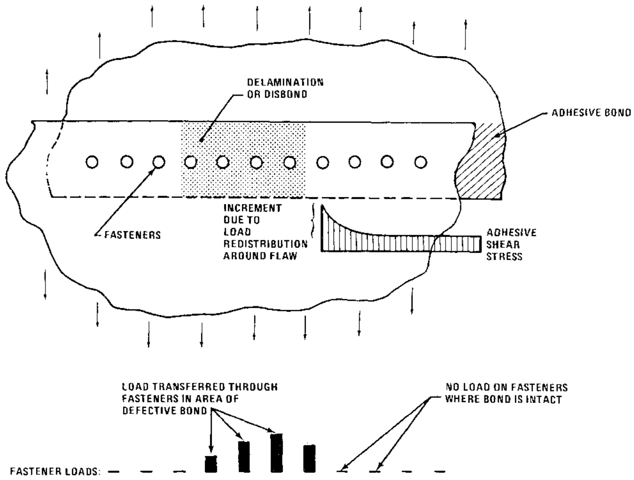
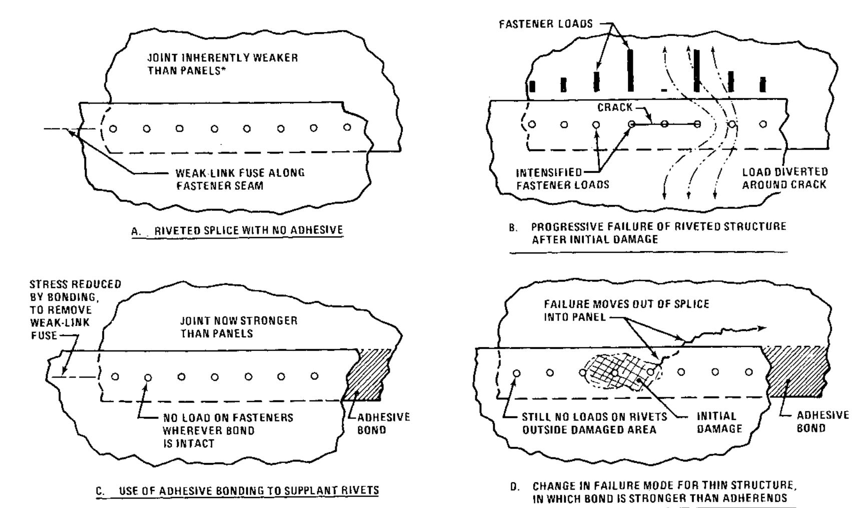


Fig. 18 Independent action of fasteners and adhesive in load redistribution due to bond flaw.



*NOTE: IF SPLICE AREA REINFORCED BY ADHESIVELY BONDED DOUBLERS, WEAK LINK IS MOVED OUT OF SPLICE INTO BASIC PANEL, AS IN D

Fig. 19 Use of adhesive bonds to provide fail-safety for riveted joints in thin structures.

For thinner members, however, the role is reversed and the bond provides fail-safety for bolts or rivets. Although it is beyond the capabilities of the A4EK program, such a joint configuration is described in Fig. 18. The central disbond or delamination shown has some, but not all, of the characteristics of a through-crack in a plate. If the structure adjacent to the flaw is not to be overloaded and failed, the remote stress must be reduced below what the unflawed structure could have withstood. This is indicated by the adhesive shear stress distribution which could have been uniformly high without the flaw. Again, the fasteners accept load only in the area in which there is no stiffer load path through the adhesive bond. Those fastener loads, in turn, decrease the severity of the peak load intensity in the adhesive next to the flaw. However, the adhesive might not be critical at this location. There are three possible critical locations: 1) the laminate at the most heavily loaded fastener; 2) the laminate at the edge of the flaw; and 3) the adhesive at the edge of the flaw. The relative severity of these locations depends most upon the thickness of the laminate, which should be proportional to the load intensity.

The bond is the least likely source of failure for thin laminates, as explained in Fig. 19. In this context, "thin" means that the unflawed bond is stronger than the unflawed adherend. Figure 19 shows how the adhesive bond provides a fail-safe load path to protect the laminate from tearing along the line of fasteners. Actually, a more scientific assessment would conclude that there was no structural justification for these fasteners in the first place. They may be thought of as a tooling aid to hold the members together until the adhesive is cured, but in no sense can they be considered as a fail-safe load path for the adhesive.

Conclusions

The new nonlinear analysis of bonded and bolted joints is particularly useful in the context of damaged or imperfect structures. The method can be used to analyze the residual strength of such structures and the strength after repair. These analyses have confirmed that bonding and bolting together do not achieve any significant advantage over adhesive bonding in well-designed intact structures.

The question of using fail-safe rivets in bonded structures is more complex than is generally recognized. Rivets are usually superfluous in lightly loaded bonded structures because they can never experience any load, even after the structure has been damaged. However, bolts can be very valuable for heavily loaded bonded or composite structures in that they can arrest any initial damage that would spread catastrophically otherwise.

Acknowledgment

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References

[1] Hart-Smith, L.J., "Design Methodology for Bonded-Bolted Composite Joints," Air Force Flight Dynamics Laboratory, Contract Rept. AFWAL-TR-81-3154, Feb. 1982.

[2] Hart-Smith, L.J., "Adhesive-Bonded Scarf and Stepped-Lap Joints," NASA CR-112237, Jan. 1973.

[3] Hart-Smith, L.J., "Further Developments in the Design and Analysis of Adhesive-Bonded Structural Joints," *Joining of Composite Materials,* ASTM STP 749, edited by K.T. Kedward, 1981, pp. 3-31.

[4] Hart-Smith, L.J., "Adhesive Layer Thickness and Porosity Criteria for Bonded Joints," Air Force Materials Laboratory, Contract Rept. AFWAL-TR-82-4172, Dec. 1982.

[5] Nelson, W.D., Bunin, B.L., and Hart-Smith, L.J. "Critical Joints in Large Composite Aircraft Structure," Douglas Aircraft Co. Paper 7266, presented to Sixth Conference on Fibrous Composites in Structural Design, New Orleans, LA, Jan. 1983.

[6] Hart-Smith, L.J., "Design and Analysis of Bonded Repairs of Fibrous Composite Aircraft Structures," Douglas Aircraft Co. Paper 7133, presented to International Workshop on Defense Applications of Advanced Repair Technology for Metal and Composite Structures, Naval Research Laboratory, Washington, DC, July 1981.