

## DESIGN OF BONDED JOINTS IN COMPOSITE MATERIALS

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### Abstract

The primary form of joining high strength advanced composite materials is adhesive bonded joints. The stepped bonded joint is an efficient configuration where the adhesive and composite matrix are co-cured. A design procedure for this type of joint is described along with the analysis technique upon which it is based. A modified elastic analysis accounts for the nonlinear behavior of the adhesive. A computer program with minimum running time and simplified input is utilized for analysis and becomes an efficient link in an iterative design procedure. Comparisons between analytical results and test results are shown. Material properties which are needed for design and methods of measuring these properties are discussed.

### Introduction

In recent years advanced composite materials have been developed to the production level. At Grumman, this capability has been developed through a series of successful composite development programs, supported by both in-house and contract funding. The F14-A boron/epoxy horizontal stabilizer confirms this production capability.

A major problem with these high-strength, high-stiffness materials is that of load introduction. This problem is a result of the highly anisotropic properties of the material. Bonded joints are used quite extensively and efficiently to introduce load into composite materials. Bonded joint technology, including design, analysis and fabrication, is essential for the successful utilization of composite materials. This technology must include design and analysis procedures which are simplified enough to be utilized in successive design iterations and reliable enough to eliminate overly conservative design requirements and minimize element testing. A design and analysis procedure which satisfies these requirements is discussed in this paper.

### Bonded Joint Utilization

The boron/epoxy F14-A horizontal stabilizer, shown in Figure 1, is the first production utilization of advanced composite materials for primary structure. The construction is of full-depth aluminum honeycomb with boron/epoxy skins. All load is introduced into these skins through bonded joints. Each skin is framed by a stepped titanium splice member which is integrally molded into the laminate. The skins are bonded to the honeycomb core and mechanically fastened to the substructures (i. e. the pivot fitting and ribs) through these splice plates. Leading edge, trailing edge and tip structures are also mechanically attached through the splice plates. The loading on these splices vary around the periphery of the stabilizer to a maximum of 17,000 pounds/inch at the pivot fitting.

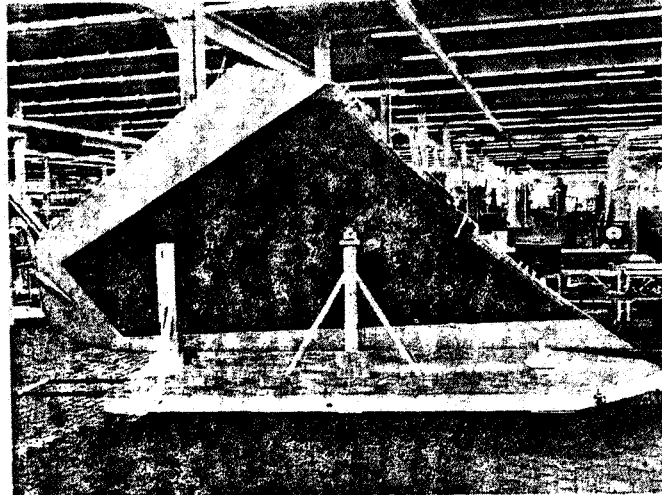


Fig. 1 F-14A Boron/Epoxy Horizontal Stabilizer

The configuration of a typical multi-stepped bonded splice such as those used on the F14-A horizontal stabilizer is shown in Figure 2. The bonded joint effects the transfer of load from the composite laminate to a metal splice plate. Just prior to the stepped region, the composite laminate thickness is increased to further strengthen the joint and to allow for a design with 15% margin of safety (a fitting factor). A fiberglass shim is also included to allow for introduction of a finite thickness of metal at the first step. Each step has a layer of adhesive between the adherends. The composite adherend may vary as to number of plies, ply orientation and step length on every step.

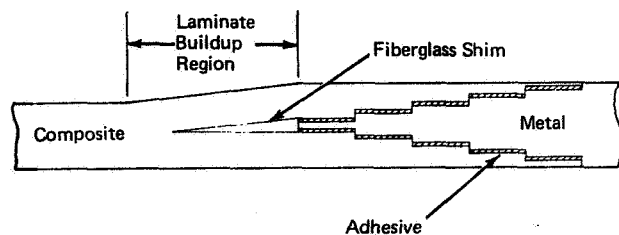


Fig. 2 Stepped Bonded Joint Configuration

Pictures of two typical splices utilizing this concept are shown in Figure 3. These splices are hybrid bonded to titanium with a double splice plate and boron aluminum brazed to titanium. They were tested to 45,000 pounds per inch in tension and 20,000 pounds per inch in compression, respectively, at 350°F. The ease of fabrication and efficient load transfer are the major reasons for the success of this joining method. The joint approximates a scarf and is co-cured to eliminate any

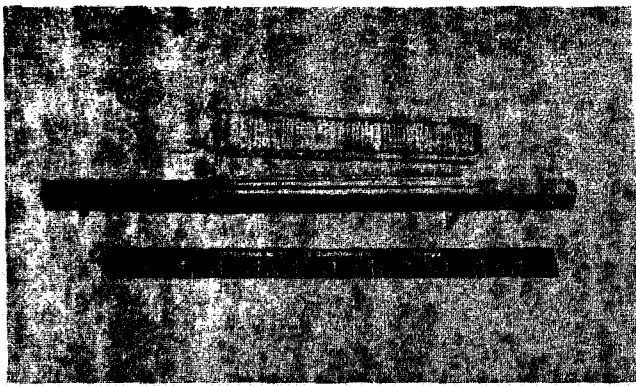


Fig. 3 Typical Stepped Joint Specimens

fit problem. That is, the adhesive layer is cured during the same cycle as the composite matrix and therefore the composite adherend conforms its shape to the metal splice plate.

#### Single Overlap Joint Analysis

Finite Element Analyses (FEA) were originally used to analyse the stepped bonded joints. Because of the extensive input required for a single analysis, use of this analysis in an iterative design procedure was very time consuming. A simplified analysis was thus sought.

Initially, a single overlap joint analysis was developed. The configuration and loading of a typical single overlap joint is shown in Figure 4. Each adherend is loaded at the ends of the overlap with bending moments, axial loads and shear loads. The adhesive exhibits both shear and normal stresses. The assumptions made for this analysis are:

- All materials are linearly elastic
- Adhesive stresses are uniform through its thickness
- Axial stiffness of the adhesive is negligible
- Adherends bend with plane sections remaining plane (shear deflection is neglected)

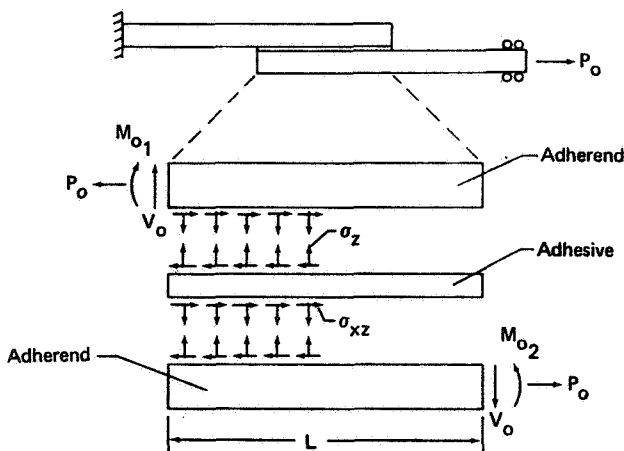


Fig. 4 Configuration And Loading-Single Overlap Bonded Joint

The adhesive stress distributions are then given by the solution of a set of simultaneous differential equations which are presented in Reference 1 along with a closed form solution. The results of this analysis are compared with that of a FEA in Figure 5 for a one-inch overlap of boron/epoxy bonded to titanium. The stresses at each end of the overlap are different due to the unsymmetric configuration of this particular joint. Good correlation is shown and the simplified continuous analysis gives essentially the same solution as the FEA.

Any solution for adhesive stress distributions which is useful for failure analyses must include the nonlinear behavior of the adhesive. Here this effect is included as a modification of the elastic solution. The relation between the elastic and plastic stress concentration factors is assumed to be:

$$K_p = 1 + (K_e - 1) \frac{G_{sec}}{G_{tan}}$$

where:

- $K_e$  = elastic stress concentration factor
- $K_p$  = plastic stress concentration factor
- $G_{sec}$  = second shear modulus at failure
- $G_{tan}$  = initial tangent shear modulus

A similar relation was used by Hardrath and Ohman (Reference 2) for notched plate test data showing good correlation. This relation was based on theoretical analysis of Stowell (Reference 3).

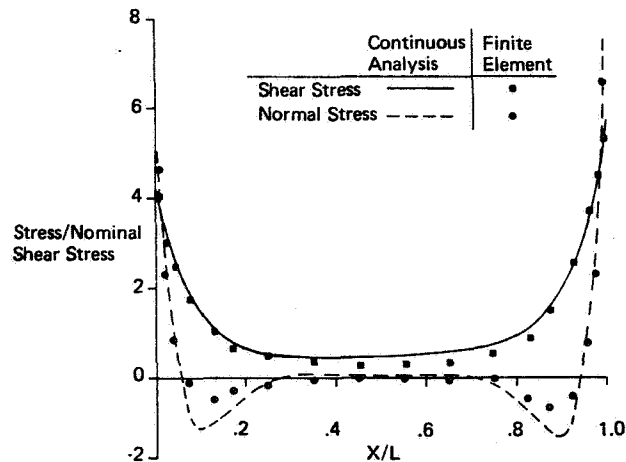


Fig. 5 Adhesive Stress Distributions-Single Overlap Bonded Joint

A nonlinear analysis was performed to test the validity of this modification. A single overlap joint was analyzed neglecting bending. The results of the nonlinear and elastic analyses are shown in Figure 6. For a failure analysis, only the peak stress from the nonlinear analysis is required and this is sought with the modification of the elastic solution. Comparison of the nonlinear and modified elastic solutions is shown in Figure 7. Stress concentration factors are shown for the peak adhesive stress equal to the shear ultimate stress of the adhesive, i.e. at the failure load for the overlap joint. Good correlation is demonstrated over the entire range of the joint length parameter,  $\alpha L$ .

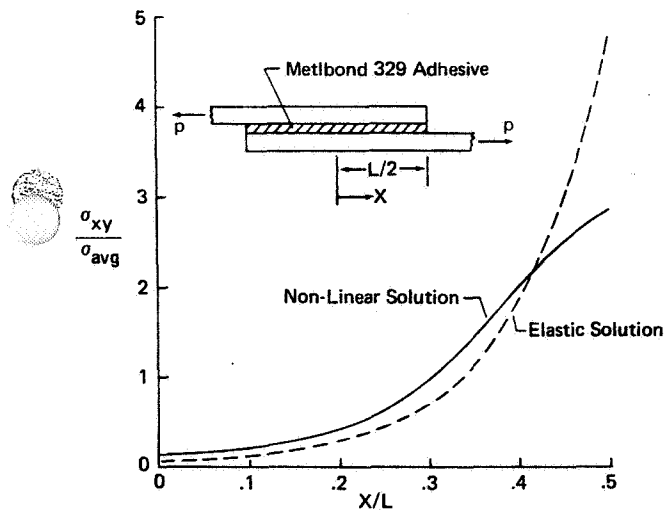


Fig. 6 Non-Linear and Elastic Shear Stress Distributions

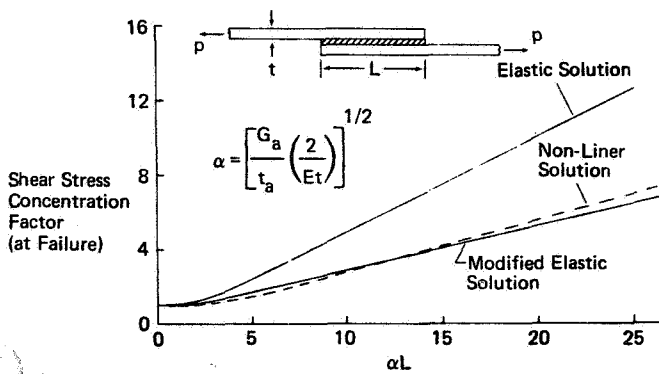


Fig. 7 Comparison of Non-Linear and Modified Elastic Solutions

Using this analysis for predicted strengths a comparison with test results for single overlap joints at room temperature is shown in Figure 8. Separate calculations were required for determination of the loadings at the ends of the overlap (see Figure 4) from an analysis of the entire test specimen and fixture configuration. Stress strain data of the adhesive was required along with the

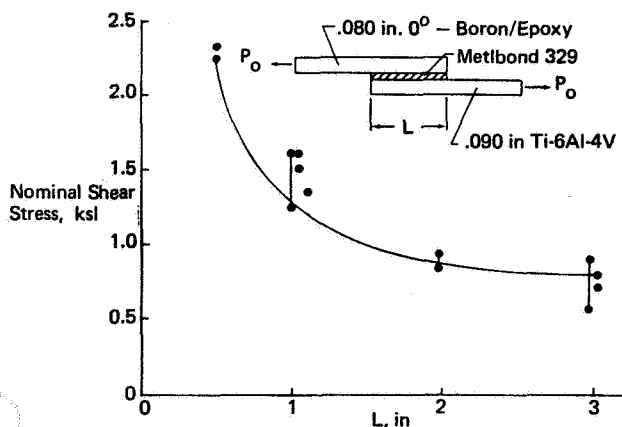


Fig. 8 Correlation With Test Results

properties of the adherends. The best method available for the determination of the adhesive stress strain behavior is the testing of specimens sketched in Figure 9. The tests involve torsion testing of a thin wall cylindrical specimen and tension testing of a round specimen. Both specimens contain a butt joint of the adhesive of interest. These are tests on adhesive bondlines of thicknesses representative of those in an actual joint. Extremely accurate displacement measuring equipment is required to perform these tests and measure the entire stress-strain relation of the adhesive. Accuracy of the order of  $10^{-6}$  inches is required in this equipment. This test

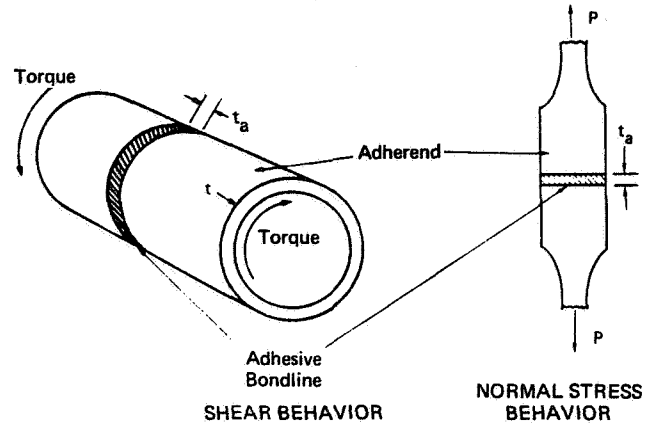


Fig. 9 Adhesive Material Property Tests

technique has been developed at Singer General Precision by Dr. John Rutherford (Reference 4) and successfully used to characterize some adhesives. Tests performed there on Metlbond 329 adhesive were used to determine the adhesive properties, Table 1, which were used for the predicted strengths.

Table 1. Metlbond 329 adhesive properties at room temperature

|                                   |                        |
|-----------------------------------|------------------------|
| Shear Ultimate Stress, $F_{su}$   | 9400 psi               |
| Tension Ultimate Stress, $F_{tu}$ | 7700 psi               |
| Shear Modulus, $G_{tan}$          | $0.34 \times 10^6$ psi |
| Tension Modulus, $E_{tan}$        | $1.43 \times 10^6$ psi |
| $G_{sec}/G_{tan}$                 | 0.29                   |
| $E_{sec}/E_{tan}$                 | 0.64                   |
| Bondline thickness, $t$           | 0.008                  |

#### Stepped Joint Analysis

This modified elastic solution is now used for the analysis of symmetric stepped bonded joints. The single overlap analysis is applied separately to half of each step as shown in Figure 10. Adherend bending is neglected and therefore the adhesive normal stresses assumed to be negligible. This assumption was verified by examination of early FEA results which showed the maximum adhesive normal stress to be less than 10% of the corresponding maximum shear stress. These low normal stresses are due to the symmetry of the joint configuration and the relatively small offset of load lines.

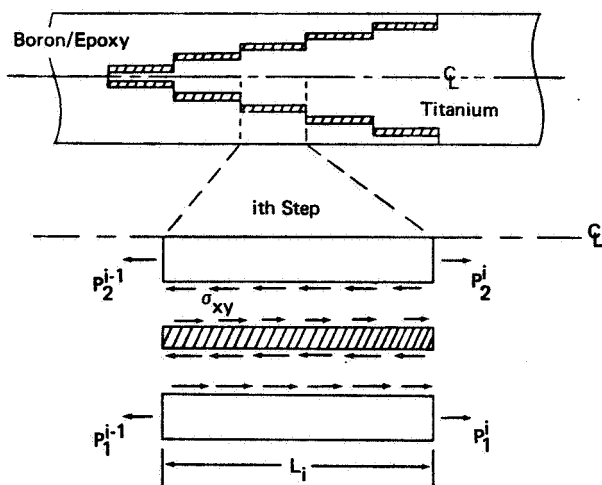


Fig. 10 Symmetric Stepped Bonded Joint

In a typical single overlap joint the normal stresses are greater than the shear stresses. The separate analyses of each step are combined by satisfying compatibility and equilibrium conditions at the internal discontinuities.

The stepped joint analysis is written into a computer program to facilitate the design procedure. The original program, STEP\*, as presented in Reference 1 was used for boron/epoxy to titanium bonded joints. The most recent program, STPS4 (Reference 5), has revisions which include thermal stress calculations and provisions for application to various composite materials. This program was utilized for the prediction of joint strengths in the correlation with test data which is to follow.

The procedure used to design a stepped bonded joint in composite materials is outlined in Figure 11. The closed loop in the cycle is repeated by the designer in an interactive design procedure. The operation is performed quickly at a remote terminal of the computer with complete interaction between the designer and computer. The input data required are the material properties and concise joint configuration parameters (i.e. number of steps, orientation and number of plies on each step, length of each step, and homogeneous adherend thicknesses). The program output includes the overall joint failure loads for many varied failure modes. The designer generally searches for a design with sufficient strength which is relatively balanced in strength.

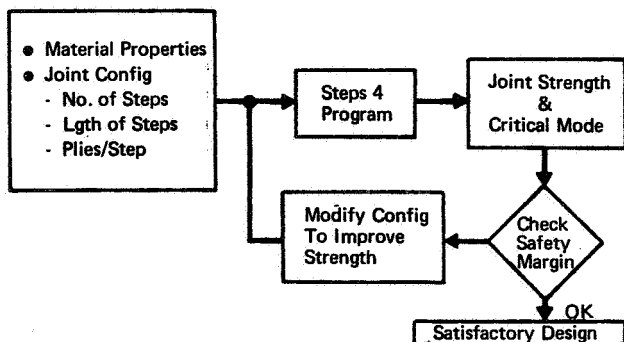


Fig. 11 Stepped Bonded Joints Design Procedure

Correlation with test data for joints designed in this manner is shown in Figure 12. The solid line would represent a one-to-one relation between predicted and test values. The test points shown are averages of test data representing a total of 23 tests. Joints have been tested in both tension and compression for temperatures varying from room temperature to 350°F. Tests have included joint loading as high as 48,000 pounds per inch. The dashed line represents a design value for each joint with the reduction due in part to the use of a 15 percent fitting factor and to the reduction of average material properties for design allowables. Correlation with test data is good with predicted values generally being conservative.

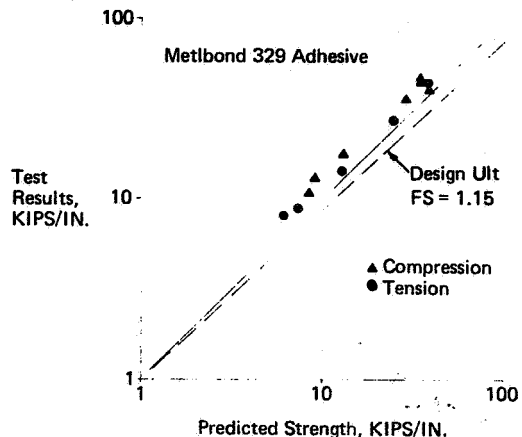


Fig. 12 Comparison of Predicted & Test Strengths of Stepped Bonded Joints

### Conclusions

An analysis and design procedure has been described for stepped bonded joints in composite materials. The analysis utilizing a modified elastic solution is relatively easy to perform with a quick-running computer program. The simplified input required facilitates its use in a iterative design procedure. The predicted strengths are relatively accurate in comparison with test data and consistently conservative.

### References

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