OPTIMIZATION OF JOINTS IN LIGHT WEIGHT COMPOSITE STRUCTURES

Prof. W. Steven Johnson

Georgia Tech, School of Materials Science and Engineering, Atlanta, GA, USA, 30332-0295
steve.johnson@mse.gatech.edu

Keywords: bonded joints, bolted joints, fatigue, failure

Abstract

This paper presents a review of good practices that can be used to make reliable joints in light weight composite structures. First a rationale will be presented as to the importance of composite joints. Then key considerations will be presented for mechanically fastened joints. Issues such as lay-up dependent stress concentrations, damage modes, influence of torque, bolt bearing and by-pass, and novel new non-traditional lay-ups. Next bonded joints will be discussed. Issues such as the minimization of peel stresses, fracture mechanics applications, ply stacking, and environmental effects are addressed.

1 Introduction

Practitioners of composite structures realize that most the concerns about strength and fatigue issues are primarily directed toward the joints. This is simply because that is where the continuous fibers that give composites their superior strength and stiffness are cut and the load must be reintroduced into the adjacent structural component. There are two primary ways to do this: mechanical fastening and/or adhesive bonding. The purpose of this paper is to review some of the key papers that have been written to help understand each of these potential joining processes. Only a key figure or two from each paper is given below. The readers are encouraged to obtain the papers for much more information. The mechanical fastened joints will be reviewed first followed by the adhesively bonded joints.

2 Mechanically Fastened Joints

The advantages of mechanical fastened joints are many: disassembly possible, little surface preparation required, relatively easy to inspect, well accepted process, and fast. The main disadvantages are: machining required, stress concentrations, lower strength to weight ratios, corrosion and potential increase in drag.

The stress concentrations can be significant and are very much a function of lay-up as shown in Figure 1 by Hong and Crews [1]. The harder the lay-up (the larger percentage of zero degree plies) the higher is the stress concentration.

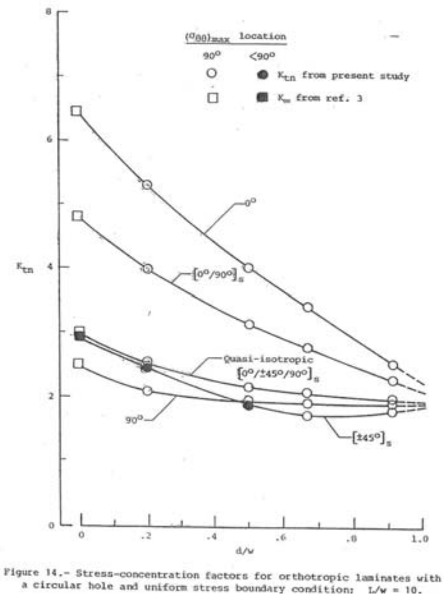
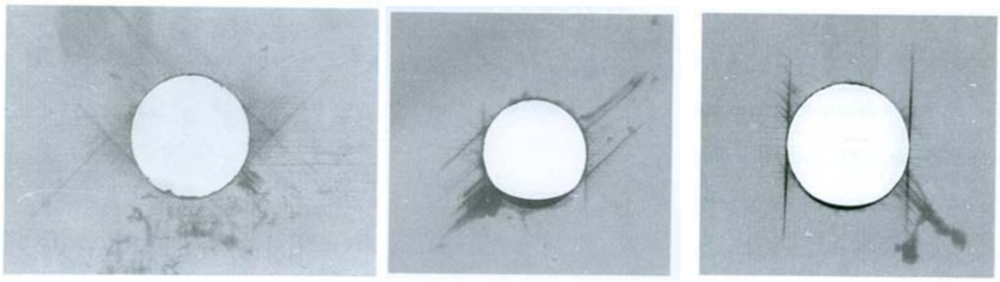


Figure 1. Stress-concentration factors for orthotropic laminates with a circular hole and uniform boundary conditions: L/w=10 [1].

The damage modes around fastener holes also vary significantly with the lay-up as shown in Figure 2 by Etheridge, Johnson and Reeves [2]. Dye enhanced radiography was used to capture the damage. This paper also gives the rate of damage progression with applied loading.



Soft lay-up Quasi-isotropic Hard lay-up

Figure 2. Radiographs of the damage at approximately 90% of failure load. Much more “splitting” in the hard lay-up [2].

Bolted fasteners in thick composite structure are, of course, torqued. Depending on the size of the bolt head, washer and nut, the amount of torque can greatly influence bearing strength as shown in Figure 3 by Crews [3]. However, as shown by Shivakumar and Crews [4] in Figure 4 the torque can relax over time. Therefore some of the torque benefits will be lost over time and needs to be accounted for in design for long life. Notice that the torque usually relaxes to about half the initial value.

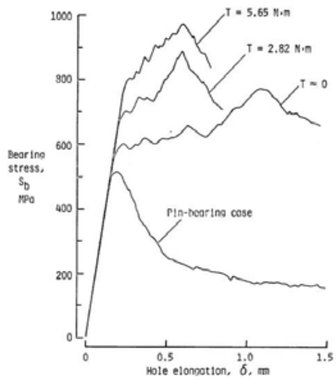


Figure 3. The higher the torque the higher is the bearing stress at failure [3].

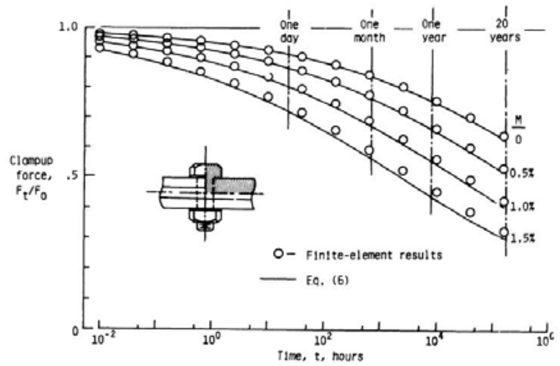


Figure 4. Torque relaxation as a function of time. Higher temperatures can accelerate the relaxation. [4].

Of course most mechanically fastened joints consist of multiple rows of fastener, therefore bolt bearing AND by-pass loads must be considered. Crews and Naik [5] conducted a series of unique experiments that clearly showed that failure is a function of both bearing and by-pass loads as depicted in Figure 5.

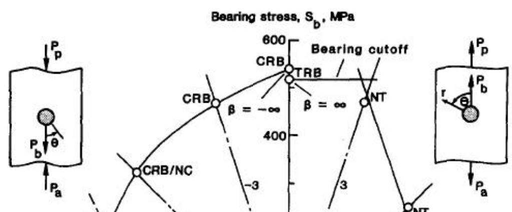


Figure 5. The failure envelop is a function of both bearing and by-pass loadings [5].

Figure 2 showed that hard lay-ups tend to “shear out” from splitting next to the hole. This greatly limits the use of harder, stiffer lay-ups. However, Tompson and Johnson [6] recently showed that by using a non-traditional lay-up with ±5° instead of all 0° fibers and greatly suppress splitting and increase strength with little loss of stiffness. These laminates will be referred to by the percentage of certain plies. $[0_4/45/0_3/90/0]_s$ will be known as 80/10/10, respectively– the percentage of 0°/45°/90° plies. Similarly, $[\pm5/65/(\pm5)_2/-65/\pm5]_s$ becomes

80/20 (80% of ±5° plies, 20% of ±65° plies) Both these laminates are all considered to be "hard" laminates, because the longitudinal stiffness is significantly higher than the transverse stiffness. Figure 6 shows the split length growth on the sides of the pin loaded holes as a function of maximum cyclic applied load. The traditional 80/10/10 lay-up is the upper curve and clearly demonstrates much earlier split initiation and much longer split growth than the non-traditional 80/20 lay-up. Figure 7 shows radiographs of the final damage state for each lay-up.

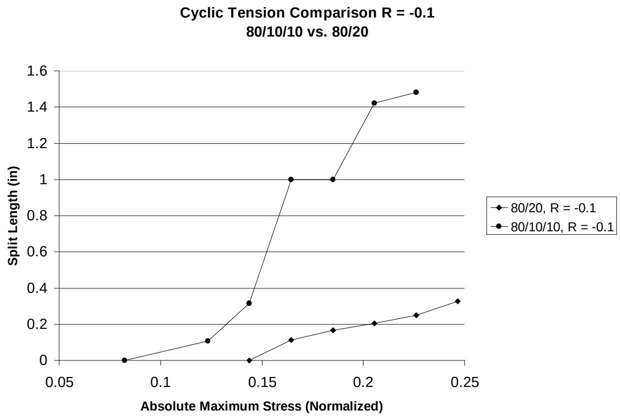


Figure 6. Measured split lengths under load using radiographic measurements. The top data curve is for the traditional [80/10/10] lay-up. [6].

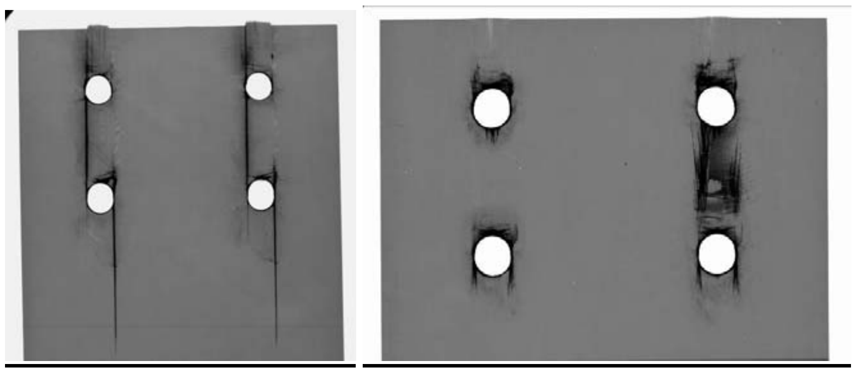


Figure 7. Left radiograph is the final damage state of the 80/10/10 and the right photo is the final damage state of the 80/20 lay-up [6]

3. Bonded Joints

Adhesively bonded joints offer several advantages over mechanically fastened joints: high strength to weight ratios, aerodynamic, good fatigue resistance, sealing capability and corrosion resistance. However they also, of course, have some draw-backs: cure time required, directional strength issues, surface preparation required, and inspection can be difficult. Proper design of a bonded joint is critical if good strength and fatigue resistance is to be achieved.

John Hart-Smith has made numerous contributions to the advancement of bonded joint design. Figure 7 is an example of his work. This figure basically shows that an adequately long over-lap and significant taper is required to greatly lower the harmful peel stresses at the joint tip. This Hart-Smith approach is based upon stress analysis and assuming that no defect or debond is present.

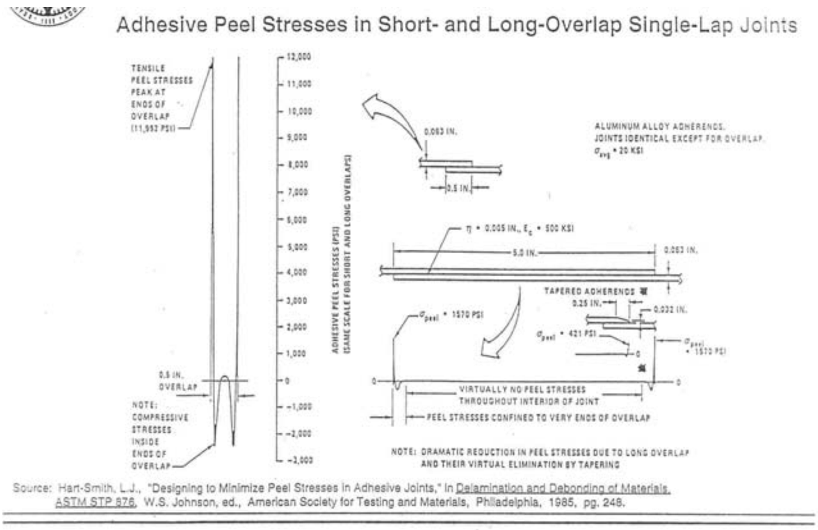


Figure 8. A summary of the Hart-Smith approach to bonded joint design based upon minimizing the peel stresses [7].

In the early 1980's Johnson and colleagues at NASA Langley Research Center pioneered a fracture mechanics approach to designing bonded composite joints [8-11]. Figure 9 is a simple schematic of their approach [9].

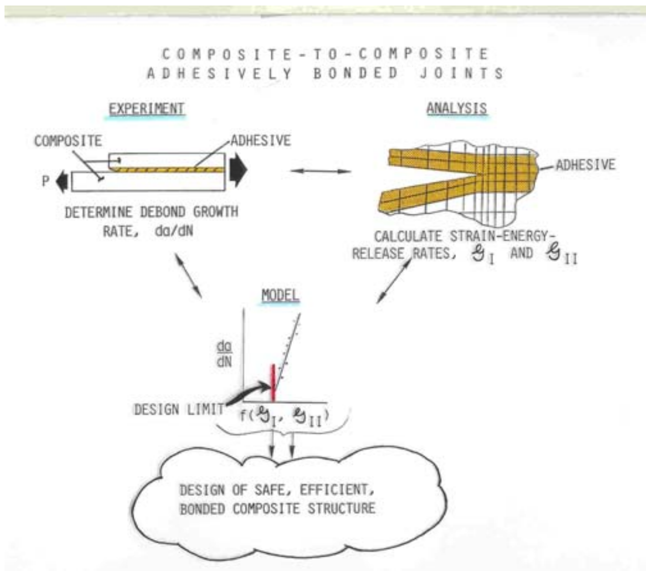


Figure 9. A schematic of using experiment and analysis to develop an approach to relate strain energy release rates to the debond growth rates [9].

Figure 10 shows an example of the predictive capability of long life without significant debond growth for two different adhesives and several different taper angles. This clearly shows that the smaller the taper angle the better the fatigue life (one can go to higher stresses).

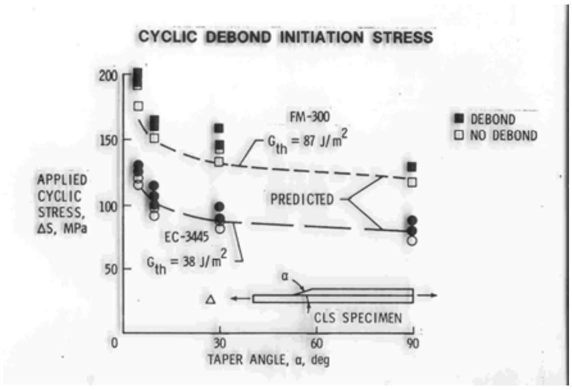


Figure 10. The filled symbols are those that had some debond growth after 2x10^6 cycles. The open symbols had no debond growth [9].

Damage development in adhesively bonded joints is also very dependent on the adherend lay-up. In particular the ply orientation next to the adhesive bondline. Johnson and Mall [10] conducted a study on the debond initiation and subsequent growth path for a number of different lay-ups. Figure 11 is an example of the damage observed. It is the current practice in aerospace to put a 90 or 45 degree ply on the outside in case of scratch damage a weaker ply would be sacrificed. However, that does not bode well for debonding. The debond will quickly leave the stronger adhesive and wander into the laminate through the 45 or 90 degree ply. Having 0 degree fibers on the surface next to the adhesive "traps" the debond in the adhesive layer.

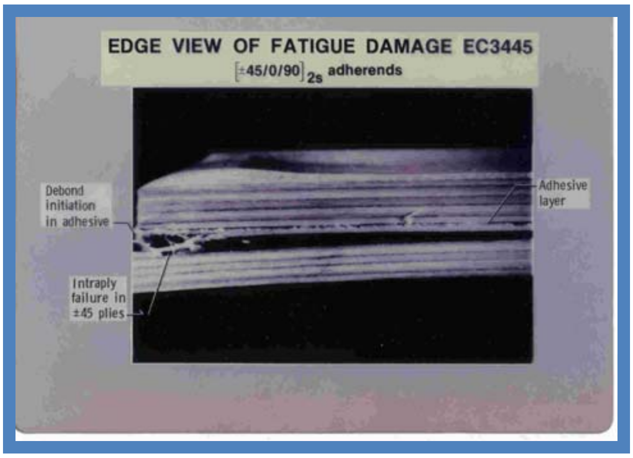


Figure 11. Debond started in adhesive but then rapidly grew through the ±45 layers causing significant delamination in the composite [10].

One also has to be very aware that temperature and moisture conditions can greatly affect the strength of bonded composite joints. An example of this is shown by the work of Lubke, Butkus and Johnson [12] shown in Figure 12. Notice how the mixed-mode fracture toughness is a function of test temperature, and prior cycling. Reference 10 also contains many other results for different conditions. Certainly cold temperature can prove to be very detrimental.

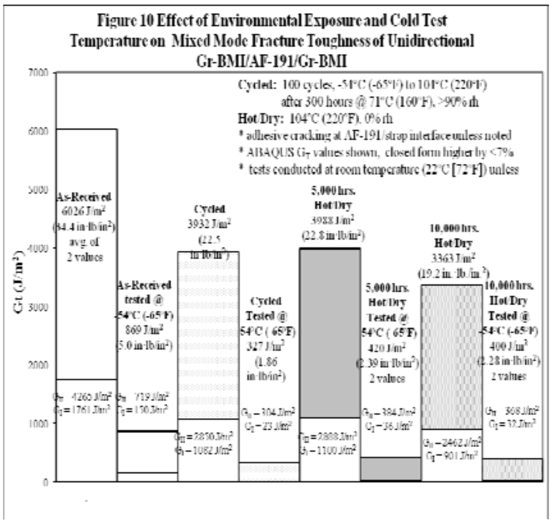


Figure 12. Examples of how temperature and prior cycling can greatly affect the mixed-mode fracture toughness of bonded composite joints [12].

4. Summary

This paper is intended to serve as an overview of relevant work that has been conducted to help design safe efficient structural composite joints. This review is not intended to be all inclusive but rather point designers toward the type of concerns that they need to address. Composite materials are complex, their joints are more complex. The better the designer understands this and understands their options they have in the design process, the better the design will be.

5. References

[1] Hong, C.S., and Crews, jr., J. H., “Stress Concentration Factors for Finite Orthotropic Laminates with a Circular Hole and Uniaxial Loading”, NASA Technical Paper 1469, 1979
[2] Etheridge, G. A., W. S. Johnson, and Scott Reeve. "Effect of lay-up and constraint on tensile notch strength." 13th Annual Technical Conference on Composite Materials. Baltimore. Baltimore: American Society for Composites, 1998. 489-504.
[3] Crews, John H. Bolt-bearing fatigue of a graphite/epoxy laminate. Tech. no. 81851. Hampton, Virginia: NASA, 1980.
[4] Shivakumar, K. N., and John H. Crews. Bolt Clampup relaxation in a graphite/epoxy laminate. Tech. no. 83268. Hampton, Virginia: NASA, 1982.
[5] Crews, John H., and Rajiv A. Naik. "Combined bearing and bypass loading on a graphite/epoxy laminate." Composite Structures 6 (1986): 21-40.
[6] Tompson, C. G. and Johnson, W. S. “Determination of the nontraditional lay-up influence and loading configuration on fatigue damage development under bearing/bypass loading conditions using radiography, J. of Composite Materials, 2011, DOI:10.1177/0021998311401078, Sage
[7] Hart-Smith, L. J., “Designing to Minimize Peel Stresses in Adhesive Joints,” in Delamination and Debonding of Materials, ASTM STP 876, W. S. Johnson, ed, ASTM, Philadelphia, 1985, pg 248.
[8] Dattaguru, B.; Everett, R. A., Jr.; Whitcomb, J. D.; and Johnson, W. S.: "Geometrically-Nonlinear Analysis of Adhesively Bonded Joints". ASME *Journal of Engineering Materials and Technology*, Vol. 106, 1984, pp. 59-65.

[9] Johnson, W.S.; and Mall, S.: “A Fracture Mechanics Approach for Designing Adhesively Bonded Joints.” *Delamination and Debonding of Materials*, W. S. Johnson, Ed., ASTM STP 876, 1985, 189-199.

[10] Johnson, W. S.; and Mall, S.: "Influence of Interface Ply Orientation on Fatigue Damage of Adhesively Bonded Composite Joints". ASTM *Journal of Composites Technology and Research*, Spring 1986, Vol. 8, No. 1, pp. 3-7.

[11] Johnson, W. S.; and Mangalgiri, P. D.: "Investigation of Fiber Bridging in Double Cantilever Beam Specimens", *Journal of Composites Technology and Research*, Vol. 9, No. 1, Spring 1987, pp. 10-13.

[12] Lubke, K. A., Butkus, L. M., and Johnson, W. S., “Environmental Effects on Bonded Graphite/Bismaleimide Structural Joints,” *Composite Structures: Theory and Practice*, ASTM STP 1383, P. Grant and C. Q. Rousseau, Eds., ASTM, West Conshohocken, PA, 2000, pp 491-512.