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The Effect of Hole Quality on the Bearing Strength of Carbon Fiber Laminates

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TECHNICAL MEMORANDUM

THE EFFECT OF HOLE QUALITY ON THE BEARING STRENGTH OF CARBON FIBER LAMINATES

1. INTRODUCTION

On programs involving flight hardware for launch vehicles that the author has been involved in over the years, the question always arises as to how to best machine and inspect holes drilled for fasteners. While common sense dictates that 'well-drilled' holes are desired over 'poorly drilled' holes for bolt bearing applications, the effect of hole quality on the bearing strength of carbon fiber laminates has not been extensively studied in the open literature. If this effect is not quantitatively known, the question of what hole quality needs to be required for the flight hardware cannot be answered. In addition, the function of the part with respect to the holes needs to be taken into account. There is no such thing as a defect-free hole since some chip-out of fibers within the hole will occur regardless of drill bit and backing plate pressure. For most holes machined in a carbon fiber laminate, some extent of delamination and fiber breakout on the entrance and exit of the hole is going to occur. Much time and money can be spent on trying to perfect the drilling technique and subsequent inspection of holes in carbon fiber laminates, including adding extra plies of cloth to the surfaces to help prevent fiber breakout; but is this effort really justified if little-to-no increase in bearing strength is realized by good-quality holes over those of lesser quality?

In the few studies that are presented in the open literature that have examined the effect of hole quality on the bearing strength of continuous fibrous composites[1–5], it appears that holes with minor damage actually have higher bearing strengths than holes of high quality with little-to-no delamination around the hole. Holes that are intentionally 'bad' gave lower bearing strength values, but only by a small percentage. The term "bearing strength" is actually ambiguous, since there are typically three places along the load-deflection curve of a bearing test that can be used to determine this value. The ultimate bearing load is the simplest of these and is taken at the maximum load that was carried during the bearing test. The offset bearing load is sometimes used, and a more practical strength value can be taken as the first initial load drop (of a certain percentage) along the load-deflection curve.

In reference 1, two levels of holes with damage (mostly delamination) were created by using a dull drill bit and two feed rates (the faster rate giving more damage) with no backing plate used to prevent fiber breakout. The results showed an 11% drop in tensile bearing strength over baseline (holes drilled with high-quality bits, fast rotation speed and slow feed rate with a backing plate to produce high-quality holes) for the worst holes and a 6% drop for holes with medium damage. In reference 2, holes drilled at a slow rotation speed and high feed rate produced delaminations on the exit ply that measured about 3 hole diameters in width. High rotation speed and slow feed rate produced holes that gave no delaminations. No statistical difference in tension or compression-bearing stress was found, with bearing strength taken at the first load drop. A similar result was found for glass/epoxy laminates[3] in which some damage around the hole gave higher bearing strength with the first load drop being defined as bearing strength. However, for grotesquely damaged holes, the bearing strength was reduced. Three different drill bits were used to produce holes of three different qualities in reference 4. Results of static tensile bearing testing showed an 11% decrease in peak bearing stress for the poorest holes and no difference between the best- and second-best-quality holes. In reference 5, carbon epoxy laminates with three different quality of holes where assessed for both the initial load drop and the ultimate load of a bearing load-deflection curve, and it was found that the ultimate load was independent of hole quality, but better holes gave a higher bearing strength value when based on the initial load drop.

For ASTM standards D5961 (bearing strength)[6] and D6484 (open hole compression)[7], it is suggested to machine holes "without damage to the laminate," which can be interpreted many ways since perfection is not possible and some damage always occurs. It is mentioned also that "damage caused by hole preparation will affect strength results. Some types of damage, such as longitudinal splitting and delamination, can blunt the stress concentration caused by the hole, increasing the force-carrying capacity of the specimen and the calculated strength." This seemingly counterintuitive result is explained by Hart-Smith.[8]

With respect to holes drilled in flight hardware, the first question that needs to be answered is "What bearing strength value is needed to meet the loads requirements for the structure under consideration?" not "How good of a hole can be made?". For some highly loaded joints, this bearing strength value may be the design driver, and for some joints, the bearing strength may need to be much less. There is no need to attempt to drill and inspect near-perfect holes, as this will be of no use if large margins to failure exist for bearing strength.

The experimental work presented in this study is to develop more empirical data relating hole quality to bearing strength in an attempt to help better understand what quality of hole is required for bearing strength purposes so as to avoid costly machining and inspection procedures, since available data[1–5] show little benefit of high-quality holes over those of lesser quality.

2. EXPERIMENTAL

2.1 Preparation of Holes

In this study, holes of four different qualities were evaluated. For convenience, these four levels of hole quality from worst to best will be referred to as: (1) bad, (2) medium, (3) good, and (4) best. The bad holes were made with a twist drill rotating at a relatively slow speed and forced through the laminate at a fast rate. No backing plate was used for these. The medium holes were made with a four-flute, square-end mill rotating at a slow speed and fed at a fast rate with a backing plate. The good holes were made with a high-quality, six-flute, square, diamond-coated end mill rotating at a fast speed and fed very slowly through the laminate. No backing plate was used. This quality hole was intended to mimic field drilling conditions where sometimes a backing plate cannot be used due to inaccessibility. The best holes were made using the aforementioned high-quality end mill and a special jig made to prevent delamination pull-up and backface breakout.
A photograph of this fixture is shown in figure 1, and a schematic side view is shown in figure 2. The top PLEXIGLAS® plate was tightened down onto the specimen to sandwich the specimen between the upper Plexiglas and lower aluminum base. A sacrificial piece of carbon/epoxy was placed directly under the specimen to help prevent fiber breakout. Photographs of the bits used are shown in figure 3. The visual appearance of these four hole qualities, along with a thermography image of each, is shown in figure 4.

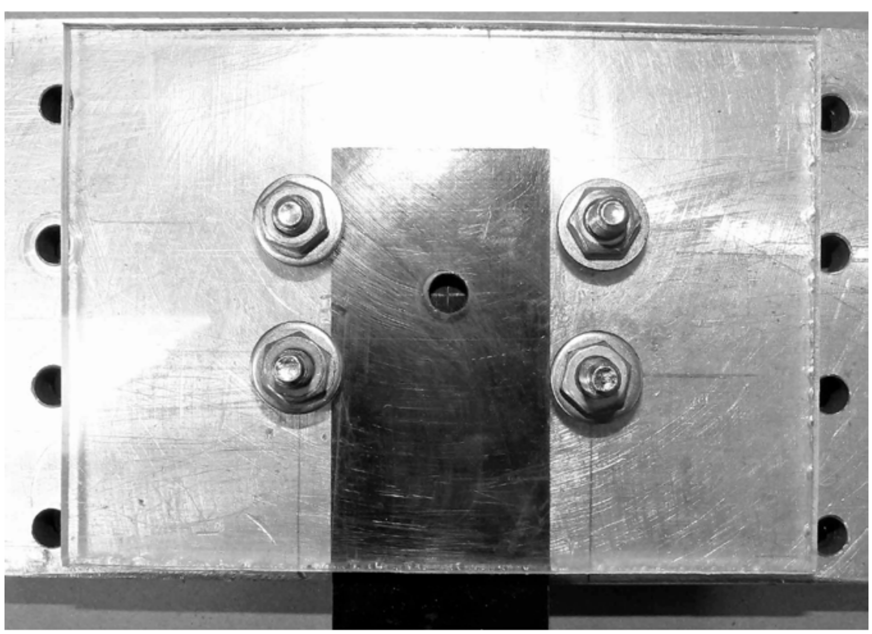

Figure 1. Jig used to drill best holes.

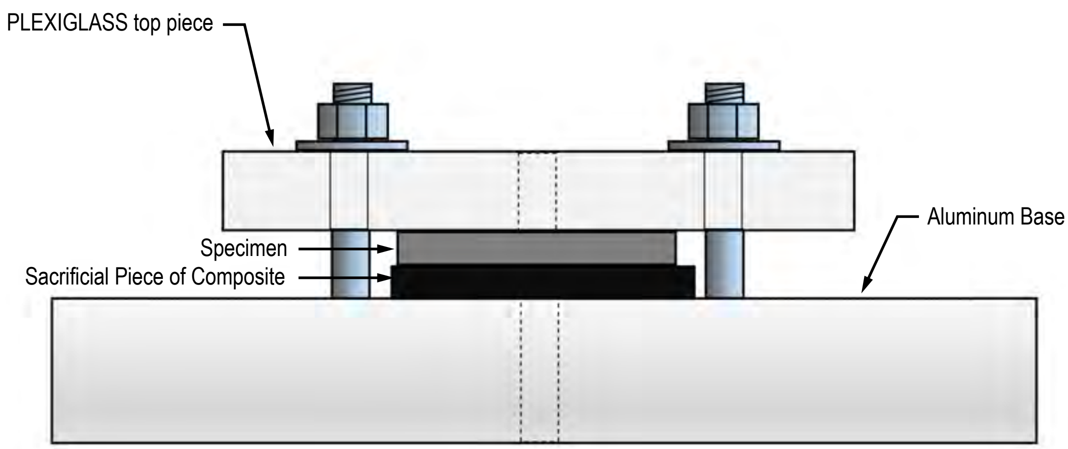

Figure 2. Side view schematic of jig used to drill best holes.

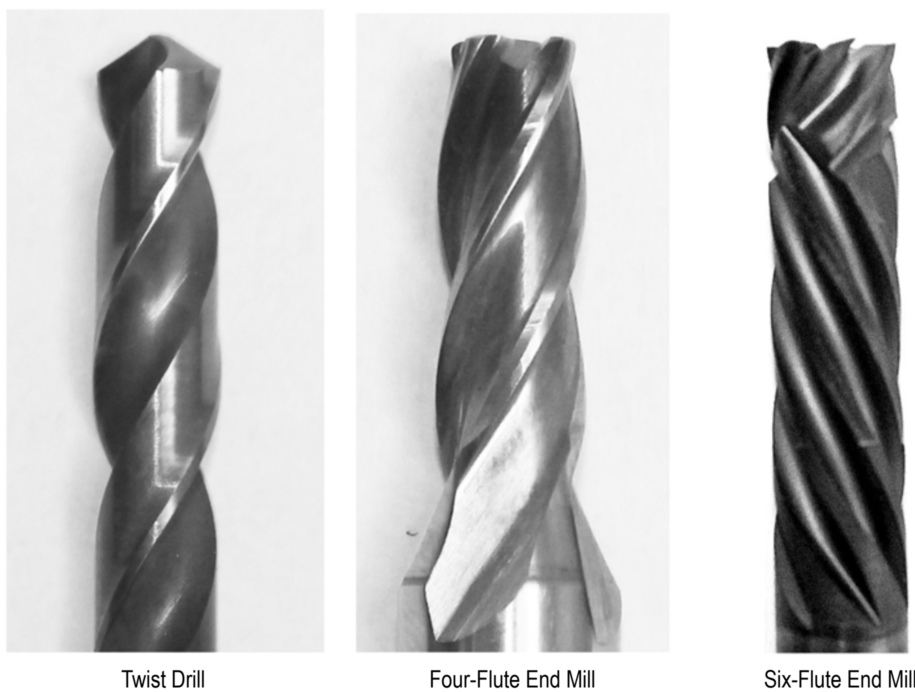

Figure 3. Bits used to drill holes.

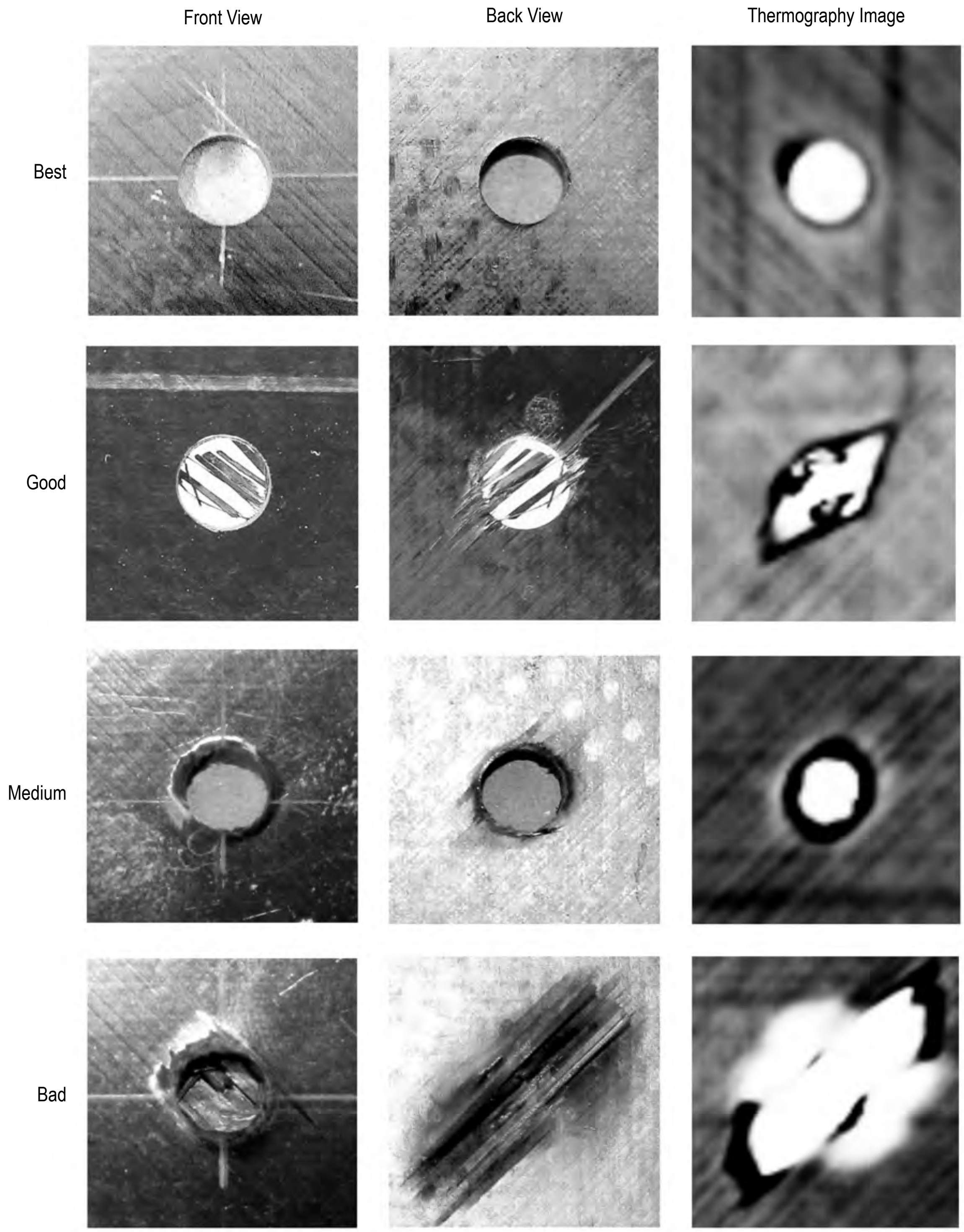

Figure 4. Photographs and thermography images of the four hole qualities used.

Cross-sectional photomicrographs of the four hole qualities are shown in figure 5. The specimens were sectioned through the center of the holes in the direction of the outermost fibers (+45°). To save space, the actual holes are cropped out of the picture, and only the material on either side is shown.

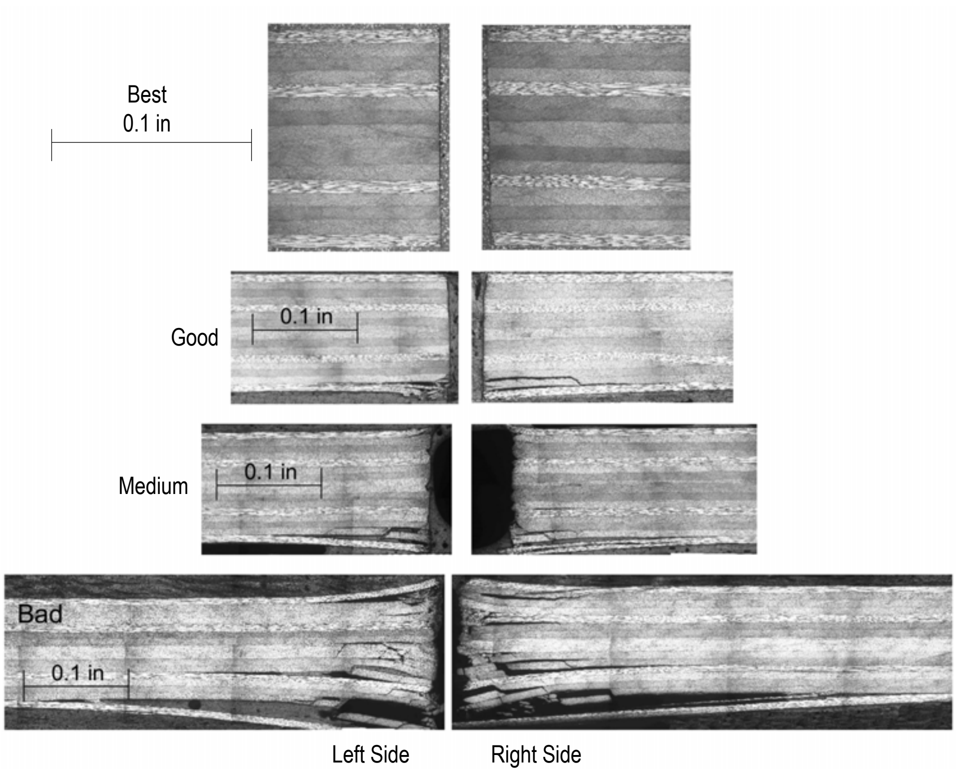

Figure 5. Cross-sectional micrographs of the four hole qualities used in this study.

If fiber breakout on the exit side of the hole is present, it can be seen from the front view of the hole (the good and bad specimens in fig. 4), which had no backing plate. In addition, the thermography images will be elongated as seen in figure 4. The medium and bad holes showed clear visual indications of fiber pull-up as is evidenced by the cross-sectional photomicrographs seen in figure 5. It is apparent that a simple visual examination can ascertain the quality of a hole, and a simple nondestructive evaluation technique, such as thermography, can give quite detailed information about the hole quality.

2.2 Bearing Tests

All specimens used in this test program consisted of 16-ply quasi-isotropic IM7/8552 carbon/epoxy laminates with a layup of $[+45/90/–45/0]_{2S}$. The specimens were machined from a large panel manufactured via automatic tape placement at NASA Marshall Space Flight Center. The nominal thickness of the laminate was 0.111 in. The bearing test used was patterned after

ASTM D5961 Procedure A, double shear in tension. The holes in the specimen measured 0.245 +0.001/–0.000, and the bolt diameter measured 0.245 +0.000/–0.001, giving a light interference fit. The bolts were torqued at 25 in•lb as suggested in reference 6. A photograph of a specimen undergoing a bearing test, along with a typical load-displacement plot, are shown in figure 6. It should be noted that the displacement values presented in this study are simply crosshead displacement and do not represent the true elongation of the hole due to compliance within the system. The displacement values presented are not used in this study in any calculations, thus a more precise measurement of hole elongation was not attempted. This study focused on two areas of the load-displacement curve: (1) the initial load drop (denoted as P_i), which may be of interest to applications in which small displacements of the bolted part may be critical, and (2) the ultimate load (denoted as P_u), which is of interest if the goal of the bolted joint is to simply have the part not fall off the vehicle. In this study, the initial load drop was defined to be at least 1% of the load at which the drop began. The two values used for bearing strength are shown on the load-displacement plot in figure 6. Both of these values will be reported throughout this Technical Memorandum for completeness.

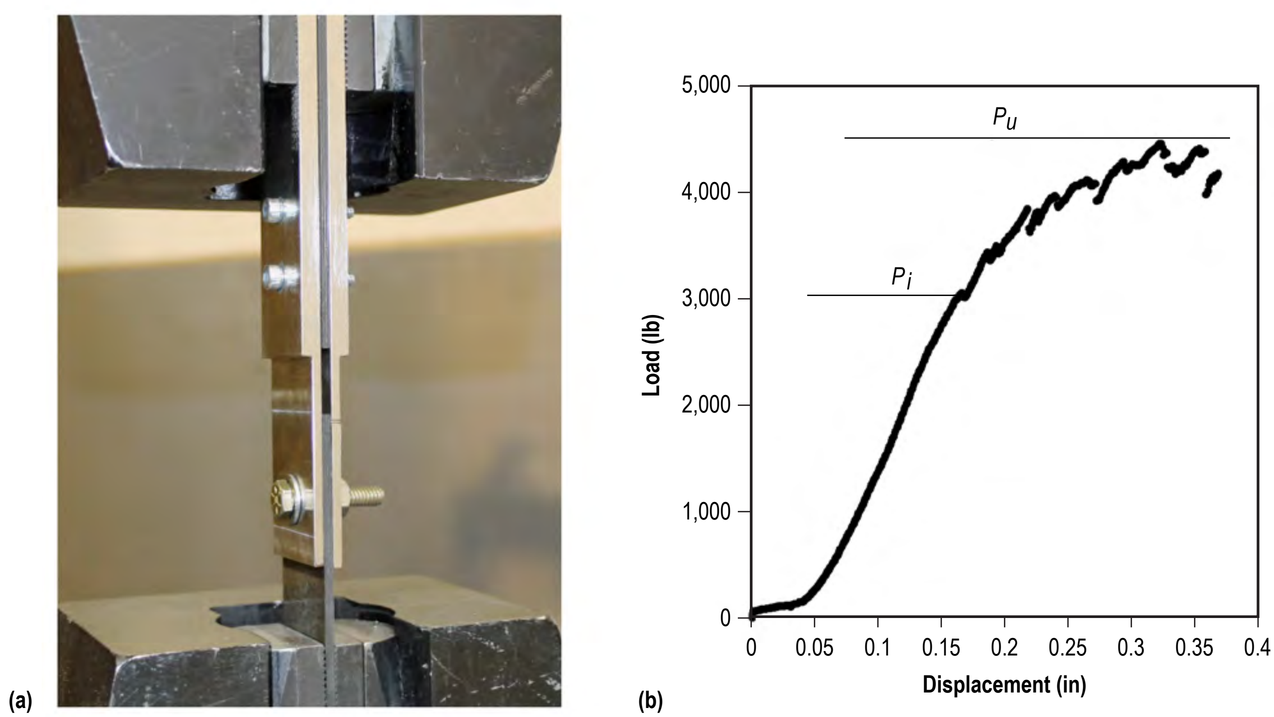

Figure 6. Bearing test used in this study: (a) Photograph and (b) typical load-displacement curve.

3. RESULTS

A typical load-displacement curve for each of the four quality holes is shown in figure 7. The data are shown in table 1 for all of the specimens tested. The average load at which initial load drop occurred and the ultimate bearing load is shown in the bar chart in figure 8 for a visual representation of the results.

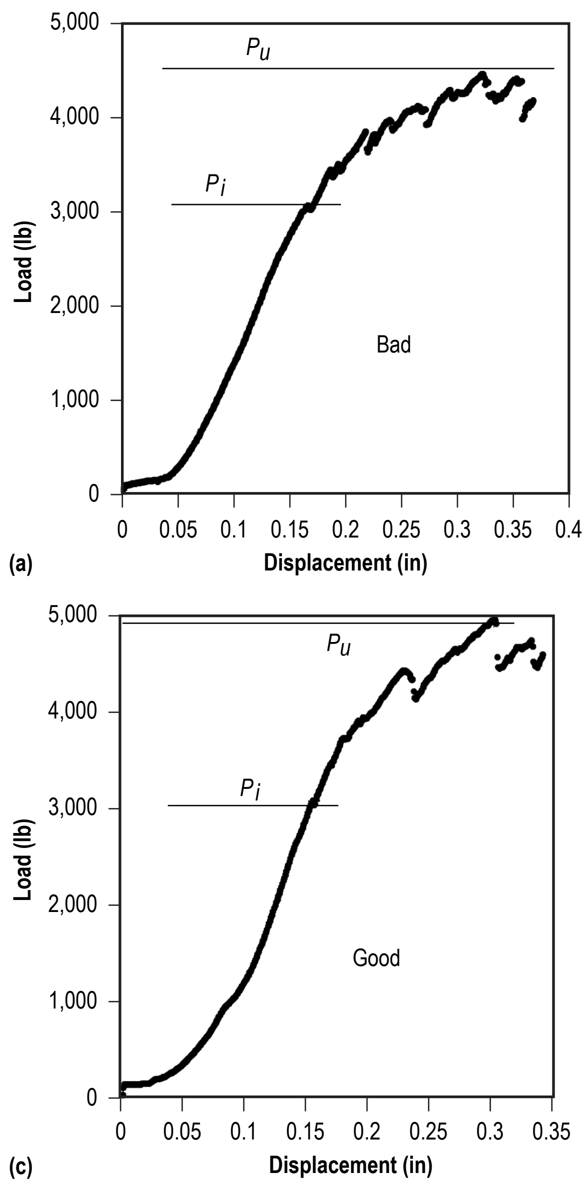

Figure 7. Typical load-displacement curves for the four levels of hole quality examined: (a) Bad, (b) medium, (c) good, and (d) best.

Table 1. Bearing data for all specimens tested.

Specimen	P_i (lb)	P_u (lb)	Specimen	P_i (lb)	P_u (lb)
Best-1	4,023	5,162	Medium-1	3,903	4,970
Best-2	4,227	4,950	Medium-2	4,071	4,649
Best-3	3,456	4,791	Medium-3	4,063	4,763
Best-4	4,117	4,796	Medium-4	4,034	4,623
Best-5	3,731	4,838	Medium-5	4,019	4,937
Best-6	4,110	4,657	Medium-6	3,526	4,168
Best-7	3,834	4,970	Medium-7	3,170	4,387
Best-8	3,529	4,704	Medium-8	3,438	4,563
Best-9	2,972	4,823	Medium-9	3,034	4,684
Best-10	4,144	5,164		3,156	4,558
Average	3,814	4,886	Average	3,641	4,630
S.D.	398	174	S.D.	423	239
Good-1	3,820	4,720	Bad-1	3,624	4,659
Good-2	3,555	4,784	Bad-2	2,800	4,895
Good-3	3,433	5,163	Bad-3	3,204	4,583
Good-4	3,554	4,739	Bad-4	3,808	4,938
Good-5	3,660	4,749	Bad-5	2,997	4,820
Good-6	3,091	4,987	Bad-6	4,055	4,972
Good-7	4,364	4,681	Bad-7	3,997	4,477
Good-8	3,083	4,658	Bad-8	3,280	4,748
Good-9	3,347	5,080	Bad-9	3,175	4,490
Good-10	3,524	4,732	Bad-10	3,549	4,775
Good-11	3,207	4,619	Bad-11	2,644	4,513
Average	3,513	4,810	Bad-12	2,569	4,470
S.D.	365	181	Bad-13	3,373	4,473
			Average	3,313	4,674
			S.D.	484	192

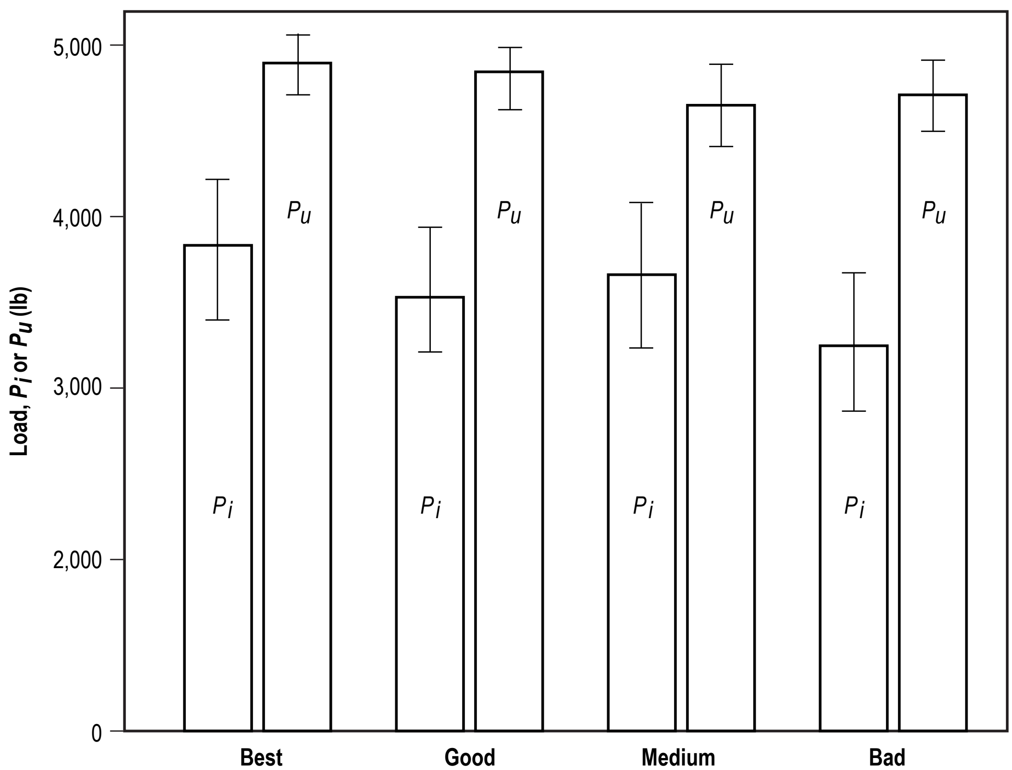

Figure 8. Average value of initial load drop and ultimate bearing load for the four quality holes tested.

3.1 Progression of Damage at a Hole Due to Bearing Stresses

By examining what happens to a hole during a bearing test, one can see why the quality of the hole is of little importance to the ultimate bearing strength of a composite laminate. As a hole is loaded in the bearing by the bolt, the hole elongates in an elastic fashion, during which some form of initial damage occurs. Depending on minor factors, such as clamp-up force, uneven loading in a row of bolted holes, slight angle of bolt, etc., this initial damage can begin at a relatively small load and not even be detectable on a load-displacement plot. Figure 9(a) shows a hole of best quality that has been loaded to the point where audible sounds were heard but before a load drop was noted on the load versus displacement curve, (b) at the time of the first noted load drop, and (c) after the maximum load had been reached. Dashed lines show a view of cross-sections shown in figure 10.

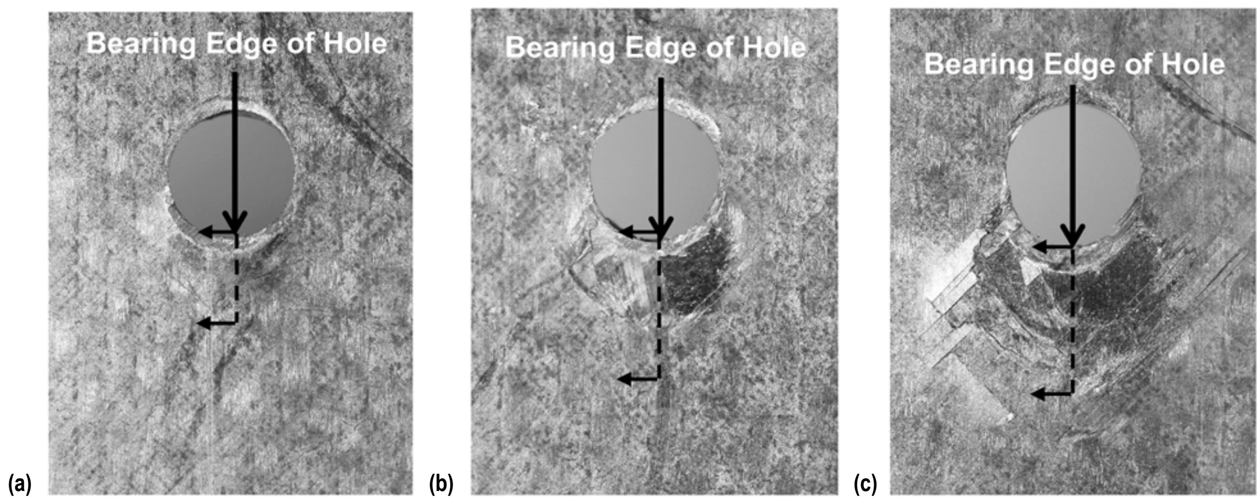

Figure 9. Progression of damage of a best-quality hole from: (a) before initial load drop, (b) after initial load drop, and (c) after maximum load has been reached.

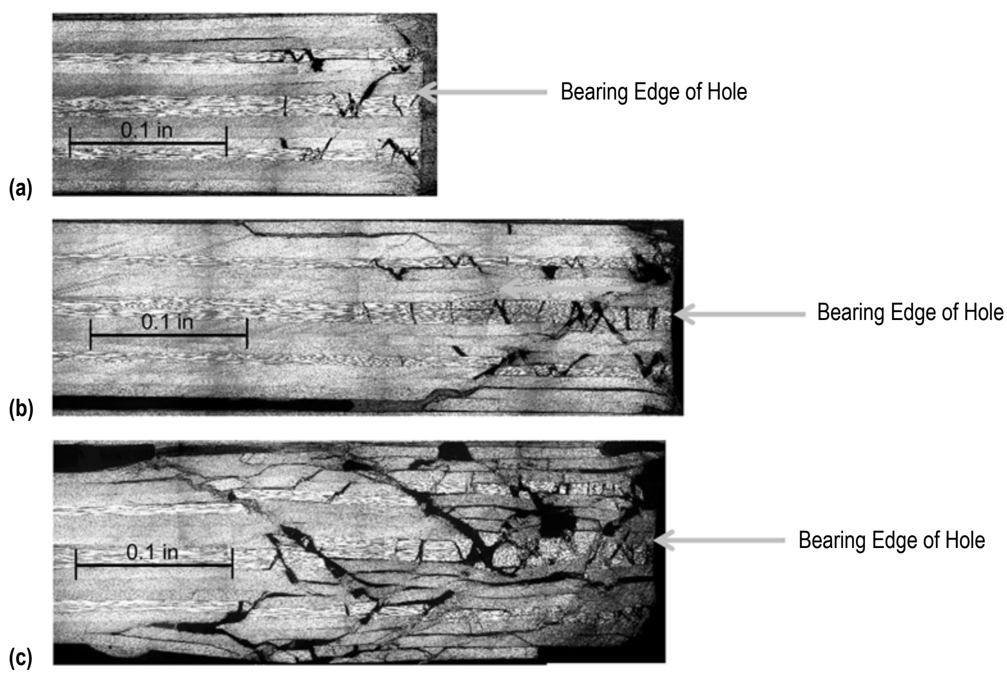

Figure 10. Cross-sectional photomicrographs of progression of damage of a best-quality hole from: (a) before initial load drop, (b) after initial load drop, and (c) after maximum load has been reached.

Figure 10 shows cross-sectional views of the damage in the specimen shown in figure 9. If these are compared to figure 5, before the first load drop occurs, the hole already is as damaged as the worst drilling technique used, thus the best quality of hole quickly becomes one of poor quality, thus the lack of criticality in how well the hold was initially machined into the laminate.

4. CONCLUSION

While the average load at first load drop and ultimate load are slightly higher for the specimens with the best holes, this increase is small and within scatter, even for holes that are grotesquely bad. This is in agreement with previously published data[1–5] with respect to hole quality and bearing strength. Thus, it must be decided early on in a program if attempting to machine and inspect high-quality holes is worth the return on investment.

The data in this study, as well as other studies, suggest a simple visual inspection should suffice for holes drilled in laminates that will experience bearing loads. If a further interrogation is deemed necessary, thermography will give an excellent indication of the quality of the hole, although the quality will have little influence on the bearing strength of the laminate, since the holes quickly become damaged upon bearing stresses that could be below the bearing stress design values.

REFERENCES

1. Garbo, S.P.; Ogonowski, J.M.; and Reiling, H.E.: "Effect of Variances and Manufacturing Tolerances on the Design Strength and Life of Mechanically Fastened Composite Joints," AFWAL-TR-81-3041, Vol. 2, McDonnell Aircraft Company, St. Louis, MO, April 1981.

2. Pengra, J.J.; and Wood, R.E.: "The influence of hole quality on graphite epoxy composite laminates," Paper Presented at the 21st Structures, Structural Dynamics, and Materials Conference, Seattle, WA, May 12–14, 1980 published online August 17, 2012, <https://doi.org/10.2514/6.1980-777>.

3. Tagliaferri, V.; Caprino, G.; and Diterlizzi, A.: "Effect of drilling parameters on the finish and mechanical properties of GFRP composites," *International Journal of Machine Tools and Manufactur*e, Vol. 30, No. 1, pp. 77–84, 1990.

4. Persson, E.; Eriksson, I.; and Zackrisson, L.: "Effects of hole machining defects on the strength and fatigue life of composite laminates," *Composites Part A*, Vol. 28, No. 2, pp. 141–151, <https://doi.org/10.1016/S1359-835X(96)00106-6>, 1997.

5. Abdullah, M.S.; Abdullah, A.B.; Hassan, M.H; and Samad, Z.: "Bearing strength and progressive failure analysis of the punched hole of CFRP under tensile loading," *The International Journal of Advanced Manufacturing Technology*, Vol. 97, pp. 2163–2171, 2018.

6. ASTM D5961-13, "Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates,"ASTM International, West Conshohocken, PA, 2013.

7. ASTM D6484-09, "Standard Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates," ASTM International, West Conshohocken, PA, 2013.

8. Hart-Smith, L.J.: "Design and Analysis of Bolted and Riveted Joints in Fibrous Composite Structures," in *Recent Advances in Structural Joints and Repairs for Composite Materials*, Chapter 7, L. Tong and C. Soutis (eds), Springer, Dordrecht, The Netherlands, pp. 221–254, 2003.

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14. ABSTRACT
In an effort to aid in answering the question "what quality holes need to be drilled and how should they be examined" when dealing with flight hardware made of continuous fiber reinforced plastic, this study examined results of past studies and generated new data to supplement these to come to a general consensus about hole quality and subsequent inspection techniques. The results show that with respect to bearing strength, hole quality has little effect and a visual examination of drilled holes should suffice. Only for intentionally poorly drilled holes were the bearing values significantly affected.

15. SUBJECT TERMS
composite material, bearing strength, impact damage, damage tolerance, bolted joints

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