NASA/TM—2019–220551

The Effect of Impact Damage Next to Holes on the Bearing Strength of Carbon Fiber Laminates

A.T. Nettles
Marshall Space Flight Center, Huntsville, Alabama

December 2019

The NASA STI Program…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>

- E-mail your question via the Internet to <help@sti.nasa.gov>

- Phone the NASA STI Help Desk at 757–864–9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681–2199, USA

NASA/TM—2019–220551

The Effect of Impact Damage Next to Holes on the Bearing Strength of Carbon Fiber Laminates

A.T. Nettles
Marshall Space Flight Center, Huntsville, Alabama

National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

December 2019

Available from:

NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681–2199, USA
757–864–9658

This report is also available in electronic form at
<http://www.sti.nasa.gov>

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TECHNICAL MEMORANDUM

THE EFFECT OF IMPACT DAMAGE NEXT TO HOLES ON THE BEARING STRENGTH OF CARBON FIBER LAMINATES

1. INTRODUCTION

This study was undertaken as a follow-on to a previous study that examined the effect of hole quality in the bearing strength of carbon fiber laminates.[1] After the author of that previous study had established that hole quality had little effect on the ultimate bearing strength for carbon fiber laminates, the question was raised as to the effects of impact damage next to a hole on the bearing strength of that hole. While this is an unlikely scenario, it is still possible that this may occur on a launch vehicle structure and thus warranted study. After a literature review, results of a few studies on the hole-impact interaction with respect to resulting damage for carbon fiber laminates were found,[2,3] but none that specifically addressed the resulting bearing strength.

In reference 2, it was found that the holes and impact could interact to develop matrix splits. However, the lay-ups used in this study consisted of clumped plies $[0_4/90_4]_S$, which are much more prone to matrix splitting than a laminate that would actually be used in practice (such as a lay-up of $[0/90]_{4S}$). This study also focused on the analytical aspects of the problem rather than the experimental results.

Reference 3 also used $[0_4/90_4]_S$ laminates (clumped plies) and examined the damage morphology, determining that, as the impact damage neared the hole, the damage zone became more asymmetrical. The effect this would have on bearing strength was not addressed.

The experimental work presented in this study was to develop empirical data relating hole-impact damage effects on the resulting bearing strength of a commonly used (quasi-isotropic) lay-up of carbon fiber laminate. The emphasis was not on the morphology of the resulting damage, as it was in references 2 and 3, but rather on the practical aspects of how this damage affected the bearing strength and how this compared to the companion study[1] on the effect of hole quality on the bearing strength of the laminate.

2. EXPERIMENTAL

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.

2.1 Preparation of Holes

In this study, holes of a ‘good’ quality were used with good being defined in reference 1 and consisting of small amounts of back face break out with no delaminations through the thickness.

The good holes were made with a high quality 6-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 visual appearance of the back side (drill bit exit side) of a typical hole is shown in figure 1.

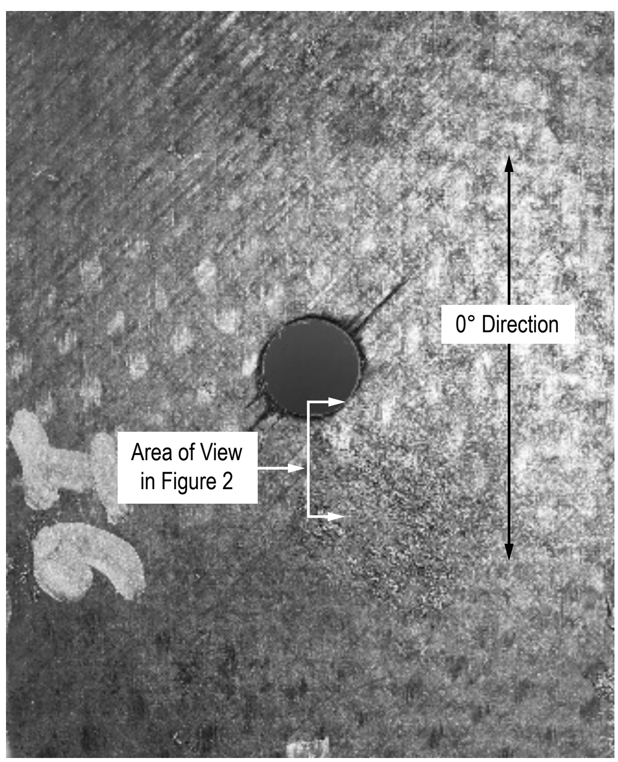

Figure 1. Photograph of hole quality used in this study (view of drill bit exit side).

A cross-sectional photomicrograph of the hole quality is shown in figure 2. The specimen was sectioned through the center of the holes in the 0° direction (as shown in fig. 1). Only one edge of the hole is shown, since the other side had a similar appearance.

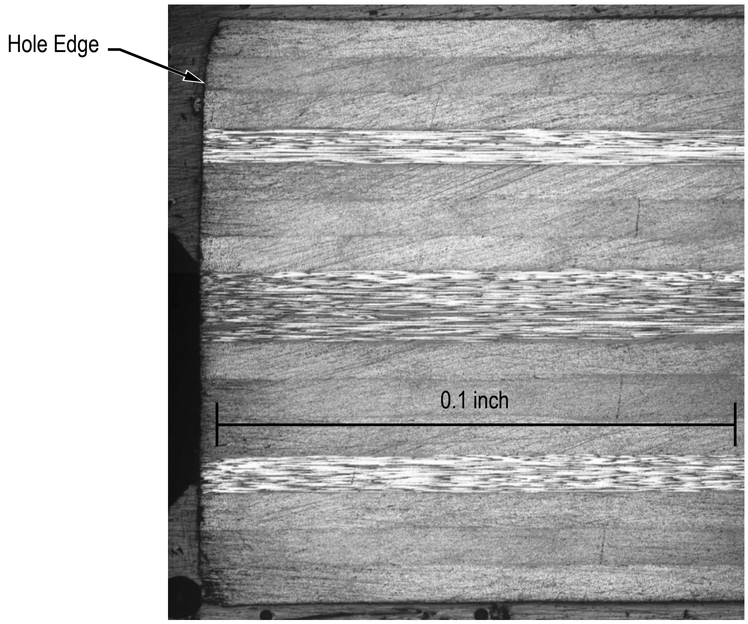

Figure 2. Cross-Sectional micrograph of the hole quality used in this study.

A drop weight instrumented impact tower was used to inflict damage to the specimens. The impactor had a diameter of 0.5 in, and the specimens were sandwiched between two steel plates with holes to allow the tup to pass through (top plate) and to allow some transverse flexing of the laminate (bottom plate), which would produce more damage than if the laminate rested on a rigid surface. A schematic and photograph of the specimen clamping apparatus is shown in figure 3.

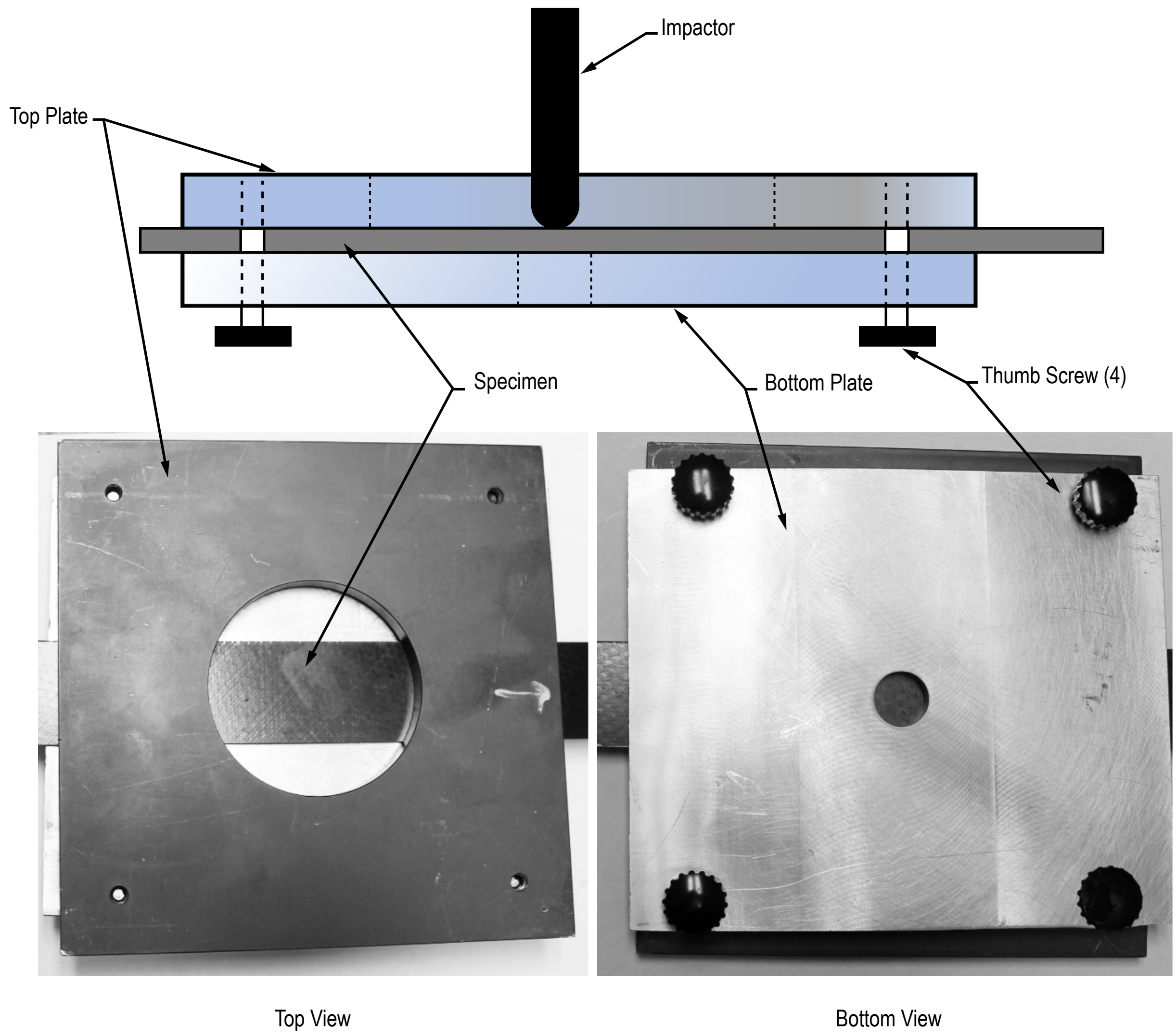

Figure 3. Schematic and photographs of impact test set-up.

A series of impact tests with increasing impact energies were performed on laminates to assess the “Barely Visible Impact Detectability” (BVID) level. Table 1 lists the impacts, and figure 4 shows a close-up of the visual results.

Table 1. List of impacts performed to determine BVID.

Neptune	Label	Units	Value
Gravitational Parameter	GM	km^3/s^2	6835099.5
Mean Equatorial Radius	R_e	km	24764.0
Mean Polar Radius	R_p	km	24341.0
J2 harmonic	J_2		3411e-6
Period		s	57996.0

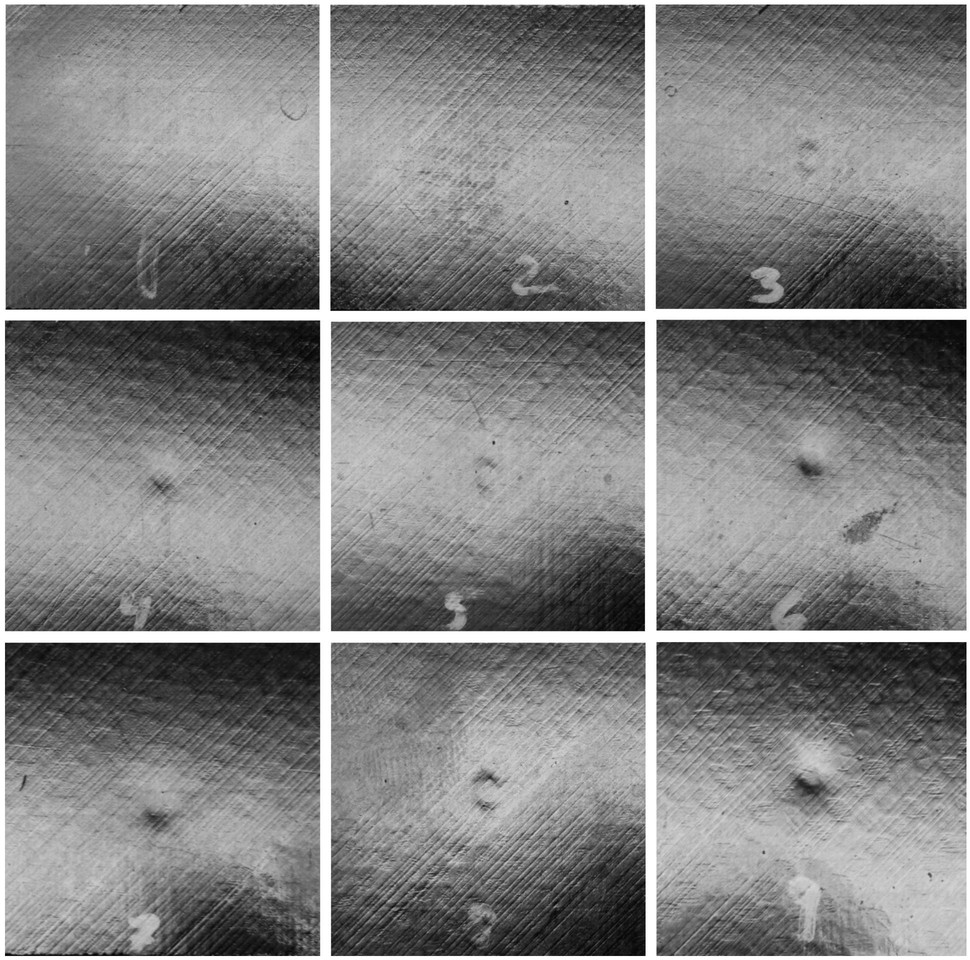

Figure 4. Visual indications of the impacts in table 1.

As a conservative measure, hit number 8 (5.6 ft•lb) was used in the remainder of this study.

A cross-section through the damage zone of a specimen (without a hole) impacted at 5.6 ft•lb is shown in figure 5 to give the reader an indication of the amount of damage formed within the laminate due to an impact of that severity.

Figure 5. Cross-section of damage used in this study (without hole).

2.2 Impact Damage With Holes

The first set of tests consisted of imparting impact damage and then drilling a hole 0.25 in away from the top section of the visible impact dent. The alignment of the hole and impact damage was such that a worst case scenario was represented. This would occur if the impact damage was below the loaded hole, since the material below the hole carries all of the bearing load. This is shown schematically in figure 6. A photograph of a hole near impact damage is shown in figure 7.

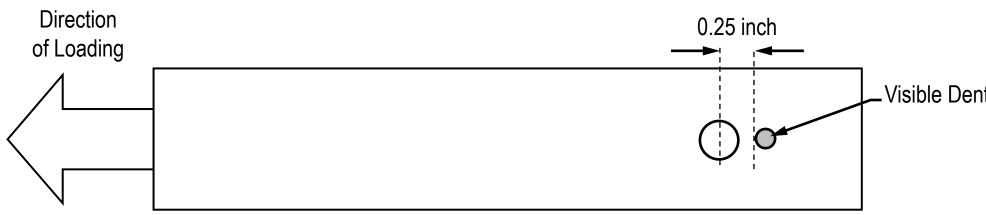

Figure 6. Schematic of hole/impact damage locations on specimens.

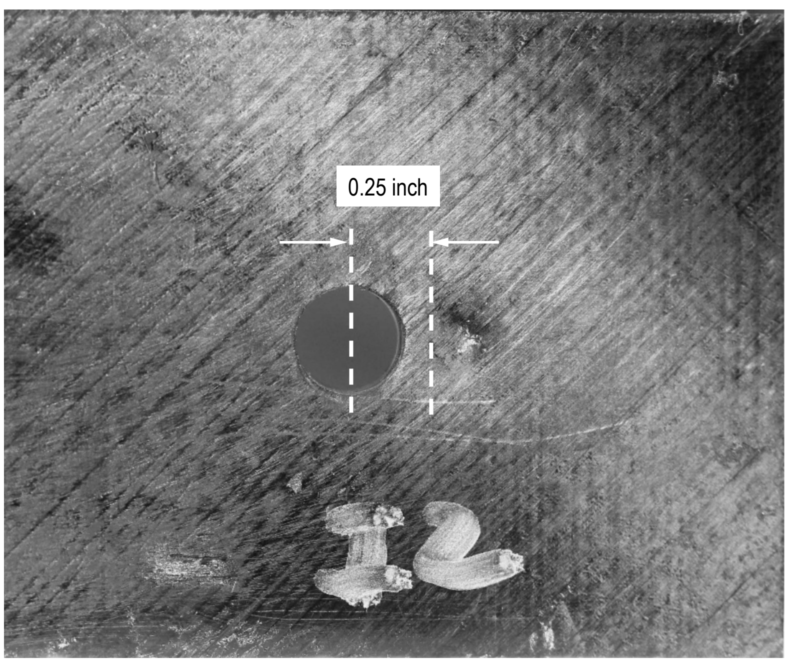

Figure 7. Photograph of hole/impact damage locations on specimens.

A cross-section of a specimen with impact damage near the hole is shown in figure 8 and, as expected, looks like figure 5 only with material removed due to the hole.

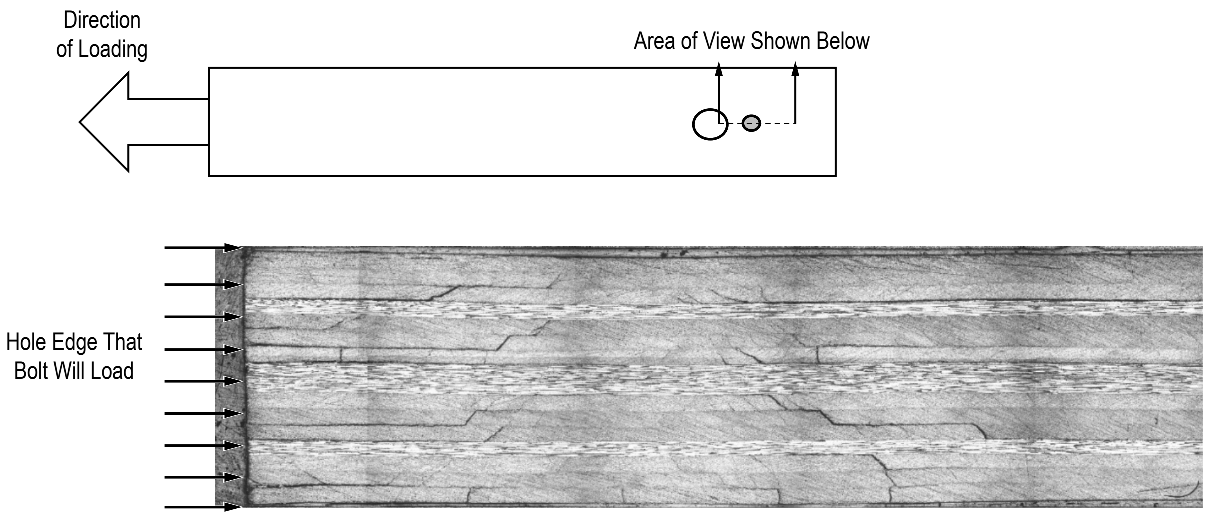

Figure 8. Cross-section of damage (with hole).

As can be seen, there is significant delamination at the hole edge due to the impact damage which looks somewhat like the ‘bad’ quality drilled holes in reference 1, though not quite as severely damaged.

2.3 Bearing Tests

The bearing test used was patterned after ASTM D5961 Procedure A, double shear in tension.[4] 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 by reference 4. A photograph of a specimen undergoing a bearing test and a typical load-displacement plot are shown in figure 9. It should be noted that the displacement values presented in this study are crosshead displacement and do not represent the true elongation of the hole. 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.

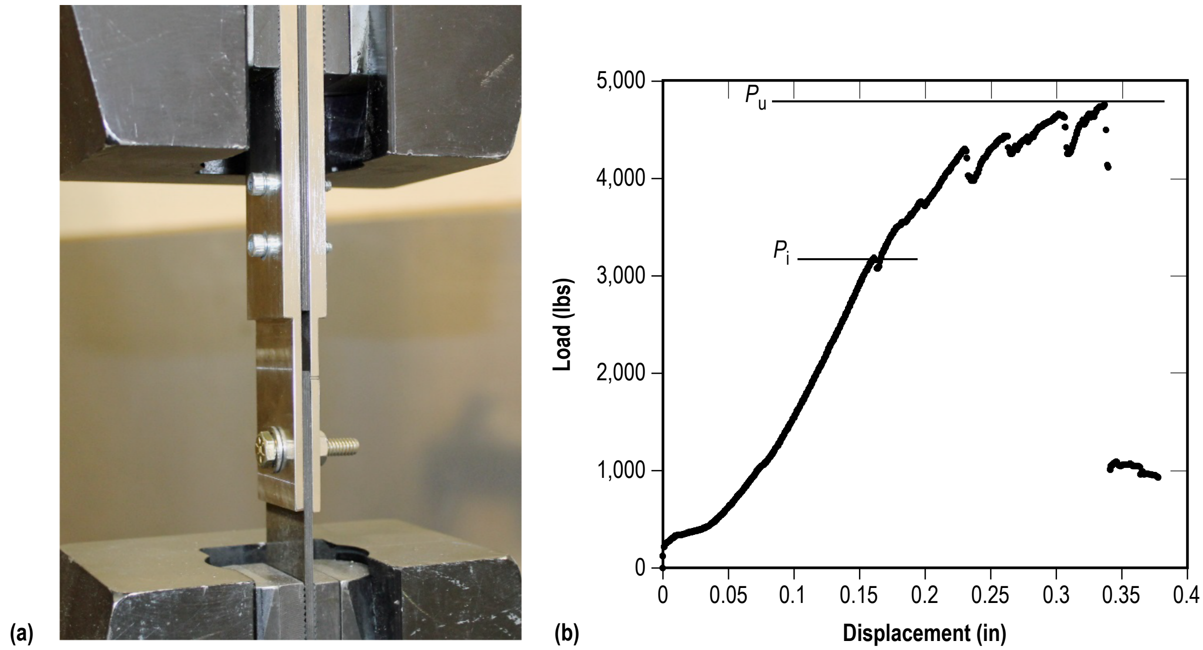

Figure 9. Photograph of (a) bearing test used in this study with (b) typical load-displacement curve

The two values used for bearing strength are shown on the load-displacement plot in figure 9. Both of these values will be reported throughout this manuscript for completeness.

3. RESULTS

3.1 Bearing Strength of Control Samples

As a control, 12 specimens with a hole were tested without impact damage. The results gave an average initial load drop (P_i) as 3552 ± 415 psi and ultimate bearing strength (P_u) as 4580 ± 489 psi. For holes similar in quality to those in reference 1, the values of bearing strength were similar with P_i being measured as 3513 ± 365 psi and P_u being measured as 4810 ± 181 psi.

3.2 Bearing Strength of Specimens With Impact Damage Imparted Near the Hole

Fourteen specimens with impact damage imparted near the hole, as outlined in section 2.3, were tested for bearing strength. The results gave an average initial load drop (P_i) as 3282 ± 235 psi and ultimate strength (P_u) as 4730 ± 183 psi. These values are similar to the "bad" quality holes tested in reference 1, which is not surprising given the amount of damage seen in figure 8, which, as mentioned, looked similar to the damage at the hole edge of the cross-sections of the 'bad' holes (see fig. 5 in reference 1).

3.3 Bearing Strength of Specimens With Hole Drilled Near Impact Damage

As a check to see if there was any difference in bearing strength due to the hole being drilled after an impact versus the hole being drilled before the impact event, 12 specimens had impact damage imparted to them and then a hole drilled near the impact damage such that the distance between the impact and hole was the same as in figure 6. The results gave an average initial load drop (P_i) as 3366 ± 252 psi and ultimate bearing strength (P_u) as 4954 ± 151 psi, which is similar to the values found for the specimens that had the hole drilled after the impact damage.

4. CONCLUSIONS

From the data obtained in this study, it is evident that impact damage near a hole will decrease the initial load drop of bearing strength but have no effect on the ultimate bearing strength. These results are similar to those of 'poorly' drilled holes in which the load at initial drop was slightly decreased due to poor hole quality, but the ultimate bearing strength was unaffected. The results are summarized graphically in figure 10.

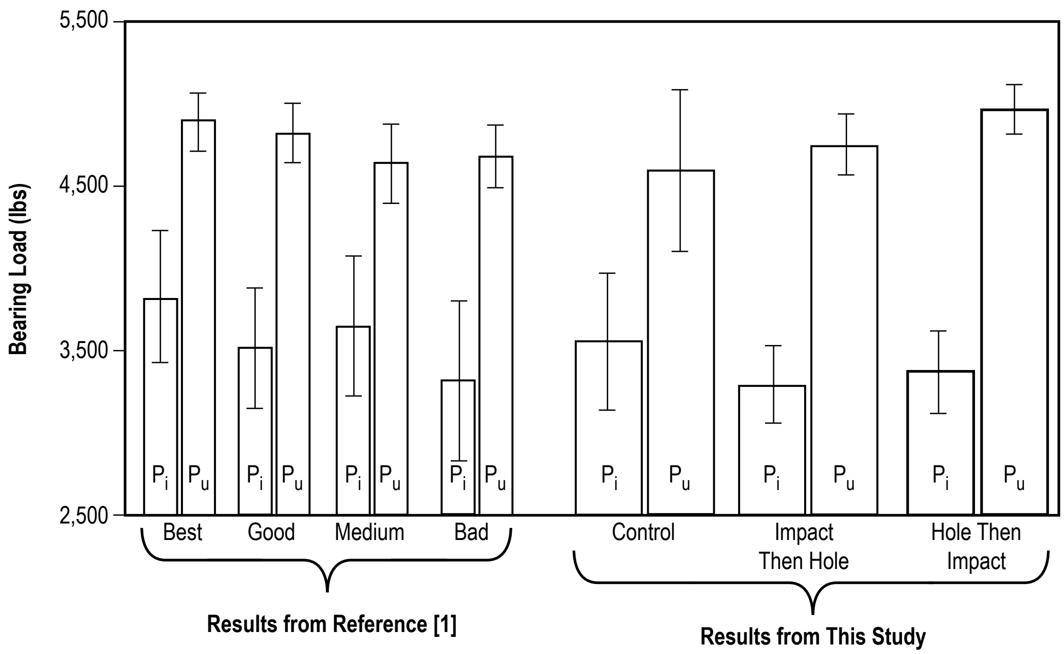

Figure 10. Bar graph summary of results from this study and those from reference 1.

REFERENCES

1. Nettles, A.T.: "The Effect of Hole Quality on the Bearing Strength of Carbon Fiber Laminates," NASA/TM-2019-330134, NASA Marshall Space Flight Center, Huntsville, AL, 2019.

2. Green, E.R.; Morrison, C.J.; and Luo, R.K.: "Simulation and Experimental Investigation of Impact Damage in Composite Plates with Holes," *Journal of Composite Materials*, Vol. 34, No. 6, pp. 502–151, doi: 10.1177/002199830003400604, 2000.

3. Reis, P.N.B.; Santos, R.A.M.; Silva, F.G.A.; and De Mours, M.F.S.F.: "Influence of Hole Distance on Low Velocity Impact Damage," *Fibers and Polymers*, Vol. 19, No. 12, pp. 2574–2580, doi: 10.1007/s12221-018-8376-8, 2018.

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

REPORT DOCUMENTATION PAGE					*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01–12–2019

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
The Effect of Impact Damage Next to Holes on the Bearing Strength of Carbon Fiber Laminates

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A.T. Nettles

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Huntsville, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–1498

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM—2019–220551

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 24
Availability: NASA STI Information Desk (757–864–9658)

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This study was undertaken as a follow-on to a previous one that examined the effect of hole quality in the bearing strength of carbon fiber laminates. The question was raised as to the effects of impact damage next to a hole on the bearing strength of that hole for a good quality hole. While this is an unlikely scenario, it is still possible that this may occur and thus warranted study. From the data obtained in this study, it was evident that impact damage near a hole will have no effect on the ultimate bearing strength.

15. SUBJECT TERMS
composite material, bearing strength, impact damage

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk at email: help@sti.nasa.gov
U	U	U	UU	22	19b. TELEPHONE NUMBER *(Include area code)* STI Help Desk at: 757–864–9658

National Aeronautics and
Space Administration
IS02
George C. Marshall Space Flight Center
Huntsville, Alabama 35812