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# Investigation of Selectively-Reinforced Metallic Lugs

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## ABSTRACT

*An investigation of the effects of material and geometric variables on the response of U-shaped band-reinforced metallic lugs was performed. Variables studied were reinforcement, adhesive and metallic lug mechanical properties, hole diameter, reinforcement and adhesive thickness, and the distance from the hole's center to the end of the lug. Generally, U-shaped band reinforced lugs exhibited superior performance than non-reinforced lugs, that is higher load at the conventional lug design criteria of four percent hole elongation. Depending upon the reinforcement configuration the increase in load may be negligible to 15 or 20 percent. U-shaped band reinforcement increases lug load carrying capability primarily through two mechanisms; increasing the slope of the response curve after the initial knee and restraining overall deformation of the metallic portion of the lug facilitating increased yielding of metallic material between the hole and the edge of the metallic portion of the lug.*

## Introduction

Although aluminum is an excellent structural material its application to aerospace structures requires making important compromises. Aluminum has negligible fatigue crack growth resistance and low fracture strength. Also, the specific buckling load of aluminum panels is typically less than achievable with composite materials. However, an approach to overcome these deficiencies is through the application of selective reinforcement[1,2]. Selective reinforcement has the potential to substantially increase buckling loads, reduce or eliminate fatigue crack growth and increase fracture strength of metallic structures without adversely affecting structural weight.

A broad application where selective reinforcement has not been applied is concentrated load introduction points, such as lugs. This class of structure is part of all vehicles. Examples of lugs integrated into structural components are fittings and beam structures such as depicted in Figures 1 and 2, respectively. Although Figures 1 and 2 depict structural components found on rotorcraft,[3] there are similar structural members on fixed wing aircraft, spacecraft, marine and military ground vehicles. Metallic lugs are typically conservatively designed and are expensive to fabricate because they are frequently machined from single billet of material. To exploit potential benefits of selective reinforcement, that is to reduce design conservatism, it is necessary to first understand fundamental mechanics issues associated with its application and to quantify potential performance benefits.

An analysis-based parametric study is conducted to develop an understanding of the structural and material mechanics issues associated with the application of “U-shaped” band reinforcement to metallic lug structures. Performance gains associated with the application of selective reinforcement is quantified through strength comparisons for reinforced lug and non-reinforced metallic lugs having similar geometry. Material mechanical properties investigated include reinforcement fiber and matrix properties, adhesive properties as well as the metallic lug’s properties. Geometric parameters investigated include lug hole diameter, distance from hole center to pin end of the lug, as well as bond line and reinforcement thickness. Specimen strength is evaluated at four percent hole elongation, conventional lug design criteria, and at initial reinforcement failure.

## Scope of Investigation

To quantify the performance of incorporating reinforcement onto a lug it is necessary to compare its performance with a geometrically comparable baseline. Metallic baseline lugs provide insight into load path related mechanisms, failure modes and strength. These responses are important to developing a comparable understanding for reinforced lugs. Therefore, both reinforced and non-reinforced lugs are evaluated. This section defines the different material and geometric variables evaluated.

### Non-Reinforced Metallic Lugs

Non-reinforced metallic lugs are analyzed for each geometric configuration that is associated with a reinforced lug and the results are used to quantify the magnitude of change in response associated with the reinforcement as well as aiding the development of a mechanics based cause-effect understanding. A single overall lug geometry was used in this investigation for both reinforced and non-reinforced lugs, as depicted in Figure 3. Length, width and thickness of the lug are 5.000, 1.950 and 0.400 inches, respectively. Specimen length, width and thickness was held constant for all cases, both non-reinforced and reinforced. A “baseline” lug configuration has a hole diameter of 0.750 inches with its center located 4.025 inches from the end of the lug away from the pin. In this investigation hole diameter is one of the geometric variables evaluated. Lug hole diameters evaluated are 0.375, 0.500, 0.625, 0.750, 1.000, and 1.250 inches. The distance from the hole center to the pin end of the lug, referred to as the edge- or e-distance, is evaluated in conjunction with variation in hole diameter. The e-distances evaluated are 0.975, 1.350 and 1.725 inches. Specimen width-to-diameter ratio (w/D) ranged from 5.200 to 1.560 and e-distance-to-diameter ratio (e/D) ranged from 0.975 to 3.450. The baseline geometry has w/D and e/D ratios of 2.600 and 1.300, respectively. The majority of the non-reinforced and reinforced metallic lugs are modeled using 7075 aluminum alloy. However, a brief study of the effects of using aluminum-lithium alloy as the lug material is conducted.

### Selectively Reinforced Lugs

A single selective reinforcement architecture was evaluated in this investigation, a “U-shaped” band reinforcement bonded to a metallic lug, such as depicted in Figure 4. The U-shaped reinforcement is a very conservative application of selective reinforcement for a lug as compared to bonding reinforcements to the surfaces of the lug or a combination of surface and band reinforcement. This reinforcement requires the least amount of material and secondary processing to fabricate. Investigation of the associated mechanics issues for this application provides a good foundation for understanding the mechanics of other reinforced lug architectures.

In this investigation the reinforcement and adhesive replaced an equal volume of metal to maintain the same overall dimensions as the non-reinforced lug. The volume of reinforcement and adhesive in a lug is on the order of two to five percent resulting in minimal reduction in lug weight. All reinforcements are unidirectional with reinforcement fiber orientation parallel to the perimeter of the lug. Reinforcement material properties are presented in Tables 1 and 2. Material properties for 7075 and Al-Li aluminum alloys and epoxy adhesive are presented in Table 3.

The baseline reinforced lug geometry and materials, as depicted in Figure 4, or a variant of it was used in many of the subsequent studies. Baseline reinforcement is 0.025-inch-thick Zylon™-epoxy with a 0.007-inch-thick epoxy adhesive between the metal lug and the reinforcement. Hole diameter is 0.750 inches. Specimen geometry has w/D and e/D ratios of 2.600 and 1.300, respectively.

The influence of reinforcement fiber mechanical properties, fiber stiffness and failure strain, on reinforced lug response is evaluated. Since both stiffness and failure strain can substantially vary between structural reinforcement fibers, the mechanical properties of actual fibers were chosen for this investigation. The breadth of fibers chosen for this investigation facilitates the assessment of the influence of stiffness and failure strain on lug response. The reinforcement fibers used in this investigation are Nextel 610™, IM-7 carbon, Zylon™ (baseline reinforcement fiber), Kevlar-49™, and S-Glass™.

It was assumed that an epoxy matrix was used with the reinforcement fibers to form the composite reinforcement. Since it is difficult / impractical to obtain an experimentally based set of three-dimensional composite material data for these materials, the composite constitutive properties were calculated using a micromechanical analysis capability.[4] The baseline reinforced lug geometry was used for this study. Alternative reinforcements were substituted for the baseline (Zylon™-epoxy) reinforcement. Specimen geometry has w/D and e/D ratios of 2.600 and 1.300, respectively.

Matrix stiffness generally has little effect on axial stiffness of composite materials, however it can significantly influence transverse and shear stiffness and strength of unidirectional laminates. Therefore, the effect of matrix stiffness and failure strain on reinforced lug response is included in the investigation. Three perturbations to the baseline matrix properties were evaluated. They consisted of; 1) 50 percent decrease in stiffness with constant yield stress, 2) 100 percent increase in yield stress with no change in stiffness, and 3) a combination of cases 1 and 2, that is 50 percent decrease in stiffness and 100 percent increase in yield stress. Representative stress-strain curves for these matrices are depicted in Figure 5. Three-dimensional constitutive mechanical properties were calculated for these analyses. An aluminum matrix was also added to this study to examine the effect of extreme increase in matrix stiffness and yield stress. It is realized that an aluminum matrix can not be practically incorporated with Zylon™ fibers. This case is evaluated to investigate the effect of this combination of materials to aid in understanding response phenomena. In all of these analyses the baseline reinforced lug geometry, having w/D and e/D ratios of 2.600 and 1.300, respectively, and an epoxy adhesive was used.

The effect of adhesive mechanical properties on the response of reinforced lugs was similarly studied. Two adhesives were incorporated in the study, they are epoxy and 7075-aluminum alloy, the same material used in the metal lug. These materials covered an extreme range of stiffness and yield stresses. To understand whether variations in reinforcement fibers and matrices influenced the properties two matrices, aluminum and epoxy, and three reinforcement fibers, Zylon™, IM-7 carbon and Nextel™ were included. The baseline reinforced lug geometry was used for this study having w/D and e/D ratios of 2.600 and 1.300, respectively.

The effect of adhesive thickness was also studied. Two cases other than the baseline reinforced lug case were studied. They are no adhesive, which is the same as an aluminum adhesive and an epoxy adhesive 0.014-inches thick. The baseline case is the same epoxy adhesive but only 0.007 inches thick. The baseline reinforced lug geometry was used except an increase in adhesive thickness was accounted for in the 0.014-inch thick adhesive case which reduced the amount of aluminum in the lug by the same amount to maintain the same overall geometry. Specimen geometry has w/D and e/D ratios of 2.600 and 1.300, respectively.

Approximately 95 to 98 percent of the volume of material in a reinforced lug is metal. Therefore, it is prudent to quantify how the mechanical properties of different structural alloys of aluminum influence the lug's response as well as whether the mechanics issues associated with reinforcement change when applied to other alloys, in this case Al-Li alloy. The baseline lug geometry was used for both reinforced and non-reinforced lugs having w/D and e/D ratios of 2.600 and 1.300, respectively. Additionally for the reinforced lugs three different reinforcements were evaluated, they are Zylon™-epoxy, IM-7 carbon-epoxy, and Nextel™-epoxy.

Reinforcement thickness is an obvious parameter to study its influence on reinforced lug response. The baseline lug geometry was used. All reinforced cases used Zylon™-epoxy reinforcement with an epoxy adhesive. Four reinforcement thicknesses were evaluated, they are; 0.025 (baseline thickness), 0.050, 0.075 and 0.100 inches. As reinforcement thickness increased an equal volume of metal was reduced to maintain an overall constant dimension. Specimen geometry has w/D and e/D ratios of 2.600 and 1.300, respectively.

Lug hole diameter has a significant effect on lug failure mode therefore it is another important geometrical parameter to quantify its effect on reinforced lug response. Non-reinforced lugs having the same diameter holes were also evaluated and the results were used for comparison purposes. Hole diameters used in this study are 0.375, 0.500, 0.625, 0.750, 1.000, and 1.250 inches. Specimen w/D and e/D ratios relative to these hole diameters were 5.200 /

2.600, 3.900 / 1.950, 3.12 / 1.560, 2.600 / 1.300, 1.950 / 0.975 and 1.560 / 0.780, respectively. The reinforced lug baseline geometry was used with a Zylon™-epoxy reinforcement and an epoxy adhesive for all reinforcement cases.

The final geometric parameter evaluated in this investigation is the e-distance, that is the distance from the undeformed hole's center to the lower portion of the lug, as depicted in Figure 6. This geometric parameter can influence the lug's failure mode so it was deemed important to investigate. The baseline lug geometry was used for this study except e-distance and hole diameters were varied. Zylon™-epoxy reinforcement and an epoxy adhesive were used for all reinforced cases. Three values of e-distance along with three hole diameters were used in this study. The e-distances used are; 0.975 (baseline configuration), 1.350 (baseline e-distance plus radius of baseline hole) and 1.725 (baseline e-distance pluse two times the radius of the baseline hole) inches and the hole diameters are; 0.500, 0.750 and 1.000 inches. The w/D ratios relative to the hole diameters are 3.900, 2.600 and 1.950, respectively. The e/D ratios relative to the hole diameters were 1.950 / 1.300 / 0.975, 2.700 / 1.800 / 1.375 and 3.450 / 2.300 / 1.725, respectively.

## Analysis

Accurate modeling of the response of pin-load reinforced lugs requires accounting for material and geometric nonlinear behavior, interaction between dissimilar materials, material yielding and failure and contact between pin and hole to facilitate accurate load introduction into the lug. Except for the dissimilar materials issues these same modeling requirements are applicable to non-reinforced metallic lugs.

The ABAQUS/Explicit™ version of the ABAQUS™ finite element computer program,[5] is used as the analysis tool for this investigation. Lug mid-plane symmetry is exploited so only one-half of the structure is modeled. Three-dimensional hex-shaped eight-node solid finite elements are used to model the structure. The metallic lug, adhesive, reinforcement and pin are all modeled discretely, as depicted in Figure 7. A uniform end displacement is applied to the end of the lug away from the hole to facilitate accurate load distribution into the lug. The centerline of the pin is constrained to resist vertical, lateral and rotational motion. Reaction forces along the pin's centerline are summed to determine the axial reaction force associated with the uniform end displacement at the other end of the lug.

The pin is modeled using a linearly elastic steel material (E=30 Msi and $\nu$=0.3) and its diameter is slightly smaller than the lug's hole. Contact constraints between the pin and lug's surface were applied to facilitate load introduction into the lug. It was necessary to set the pin diameter slightly smaller than the hole diameter to prevent pin and hole surfaces from violating the contact constraint which when occurs produces inaccurate load transfer between pin and lug. With the pin slightly smaller in diameter than the hole then the contact violation did not occur and load distribution around hole was consistent with expectations.

The metallic lug is modeled using an inelastic aluminum material using true material stress-strain curves,[6] whose data is presented in Table 3. In developing the true stress-strain curves the cross sectional area was allowed to vary as a function of specimen expension. This resulted in higher calculated stresses at high strain levels. Based upon preliminary analysis of a pin loaded hole aluminum coupon specimen, results shown in Figure 8, it was determined that the true material stress-strain curves accurately predicted the specimen's response when large inelastic deformations were produced whereas the traditionally used engineering stress-strain material data resulted in inaccurately predicted response. ABAQUS™ native isotropic inelastic material modeling capabilities were used to incorporate this material into the analysis.

The adhesive material that bonds the reinforcement to the metal lug is represented as an elastic perfectly plastic material. Although many / most adhesives exhibit some nonlinear response, especially in shear, it was assumed for this investigation that the response was linear until the yield stress is reached where its stiffness goes to zero. The adhesive data is also presented in Table 3.

The reinforcement is modeled as a unidirectional orthotropic material having matrix created material nonlinearities and implemented as effective stress-strain curves[7]. A user written routine called VUMAT,[5] handles updating orthotropic material properties at the element level. A maximum stress failure criterion is incorporated in the VUMAT analysis to determine when a reinforcement element fails. When failure has been defined the element stress is set to zero which effectively eliminates any subsequent structural contribution. Accurate progressive failure modeling of selectively-reinforced specimens is beyond the scope of this investigation, especially since there is no experimental data to validate such an analysis. Also, initial failure typically occurs at substantially higher percent hole elongation than a lug is designed to meet.

Constitutive material data for the variety of reinforcement materials used in this investigation could not be obtained from experiment or published literature, therefore predicted values were obtained through a material micro-mechanical analysis[4]. Fiber direction properties were assumed linear to failure whereas the transverse and shear properties were heavily controlled by the matrix properties. Material data used in the lug analyzes is presented in Tables 1 and 2.

## Results and Discussion

An analysis-based parametric study U-shaped band selectively reinforced lugs is conducted. Through varying material properties and specimen geometry a mechanics based understanding of the response mechanisms is developed. An attempt is made to quantify the effect of each variable on the lug response and relate its impact to conventional lug design. Load as a function of the applied displacement response curves along with stress contours of the lug at key load conditions are produced to develop this understanding. Also, initial failure refers to the failure of the reinforcement or the adhesive layer between the reinforcement and the lug as denoted by an abrupt drop in load carrying capability. Post-failure response parallels that of the non-reinforced metallic lug. Another important point of interest is related to load magnitude at four percent hole elongation which corresponds to conventional lug design criteria. For the selectively-reinforced cases studied, this load point typically occurs at higher than four percent hole elongations.

## Effects of Reinforcement Fiber Mechanical Properties

A study of the effect of reinforcement fiber mechanical properties on the response of lugs is performed. Lug geometry is consistent with the baseline lug having a 0.750-inch-diameter hole having a w/D and e/D ratios of 2.600 and 1.300, respectively, and an epoxy adhesive layer attaching the reinforcement to the metal lug. Five different fiber reinforcements were used: Nextel™, IM-7 carbon, Kevlar-49™, S-Glass™ and Zylon™ each in the same epoxy matrix. Each of these fiber types have different tensile stiffness and failure strains and it is assumed that the fibers exhibit a linear elastic tensile response to failure. Because of the different stiffness and failure strains exhibited by these fibers this study is not a pure investigation of a single material mechanical property. Rather these reinforcements were chosen because they provide a range of typical mechanical properties from commercially available fibers.

The load-displacement response of the reinforced lugs as well as the non-reinforced metallic lug is presented in Figure 9. Initial failure of the reinforced lugs is denoted by the significant discontinuity in the load-displacement response. Each reinforcement type had a unique initial failure load and displacement value. Except for the Nextel reinforced lug case all reinforced lugs failed beyond the conventional design level of four percent hole elongation. Carbon fiber reinforced lug exhibited the highest load at four percent hole elongation, which was less than 10 percent higher than the non-reinforced lug’s response. Also, the higher the reinforcement’s tensile failure strain the higher the lug’s load and applied displacement at initial failure.

The next step is to assess the influence of fiber stiffness on the response. Although it is difficult to see from the overlapping of response curve symbols in Figure 9, elastic lug response is proportional to fiber stiffness. The slope of the post-knee response is a function of the reinforcement stiffness because, after the knee, most of the metallic load carrying material has yielded so the reinforcement is the primary load carrying mechanism. High stiffness alone does not result in high load as seen by the Nextel™ reinforced lug, it is the combination of stiffness and failure strain. For instance, the Zylon™ reinforcement has a lower stiffness than the IM-7 carbon reinforcement but since the Zylon™ reinforcement has a substantially higher failure strain than the carbon fiber, the Zylon™ reinforced lug has a higher initial failure load than the carbon reinforced lug.

## Effect of Reinforcement Matrix Mechanical Properties

A study on the effect of matrix mechanical property on lug response was conducted. Specimen geometry has w/D and e/D ratios of 2.600 and 1.300, respectively. Zylon™ reinforcement was used as the reinforcement fiber in this study. Two baseline cases were analysed that utilized an epoxy or an aluminum matrix. The aluminum matrix case has a transverse stiffness more than an order of magnitude higher than the epoxy case and provides an upper bound on how matrix properties influence the lug’s response. Three cases of perturbations on stiffness and yield strain were examined for the epoxy matrix. They are: 1) the transverse elastic stiffness of the reinforcement ($E_{22}$) was reduced by 50 percent, 2) the transverse yield strain ($\varepsilon_{22}$) was increased by 100 percent and 3) a combination of materials 1 and 2 that is the transverse stiffness of the reinforcement was reduced by 50 percent and the yield strain was increased by 100 percent and depicted in Figure 5.

The response curves are presented in Figure 10. The response of all five materials was similar up to their respective initial failure. Relative to conventional design practice of designing lugs to a four percent hole elongation there was no significant effect on response relative to these changes in matrix properties. However, there were changes in initial failure load and displacement. A 50-percent reduction in the transverse reinforcement stiffness ($E_{22}$), Case 1, resulted in approximately three percent reduction in maximum load and approximately 22-percent reduction in failure displacement relative to the baseline case. The failure mode for the baseline and the reduced transverse stiffness cases were interlaminar shear.

The response curves for material Cases 2 and 3 were essentially identical and both reinforcement materials exhibited a fiber tension failure mode at the bottom of the lug. The common matrix mechanical property was yield stress, whereas they had different elastic stiffness and yield strain. The overall response of these materials produced a failure load that was approximately 8-percent higher and had a 42-percent greater displacement at initial failure than the baseline reinforced case.

The Zylon™ reinforced aluminum material exhibited a slightly stiffer response curve than the other materials except it exhibited approximately a 10-percent higher failure load and a 53-percent higher displacement at failure. The failure mode was a simultaneous matrix shear and fiber failure. The slightly stiffer response reinforcement is attributed to the higher axial stiffness of the aluminum matrix. The larger displacement at failure and corresponding increase in load relative to the failure load of Cases 2 and 3, is related to an increase in transverse or shear matrix properties.

As shown in Figure 11, the Von Mises stress contours for material Cases 2 and 3 and the Zylon™ reinforced aluminum case exhibited extensive yielding beneath the hole relative to that experienced by the baseline reinforced case. This higher degree of yielding of material is attributed to the constraining action of the reinforcement resulting in a higher initial failure load and displacement, as compared to the baseline reinforced case. Case 1 and the baseline case exhibited similar regions of yielding at initial failure at the bottom edge of the lug as the baseline reinforced lug. Based upon these cases changes in matrix transverse stiffness has a small effect on the initial failure load. However, the increase in lug displacement at failure is attributed to the higher matrix yield stress.

**Effect of Adhesive Mechanical Properties**

A study of the affect of adhesive mechanical properties on reinforced lug response consisted of comparing the responses of three different reinforcement fibers in three combinations of matrices and adhesives. Considering that the role of the adhesive is to transfer load from the metal lug to the reinforcement and the function of the matrix is to transfer load into the fibers it was felt that examining a combination of matrix and adhesives with different reinforcements was required. The aluminum and epoxy matrices and adhesives bound the stiffness properties and provide insight in to the effect of yield strain. The matrix and adhesive combinations that are examined with each reinforcement fiber are; an aluminum matrix with an aluminum adhesive, an aluminum matrix with an epoxy adhesive and an epoxy matrix with an epoxy adhesive. The fiber types were Nextel™, IM-7 carbon and Zylon™. These fiber types bound the stiffness and failure strain range of the reinforcement fibers that have been used in this investigation. Although the use of aluminum as a matrix material is impractical with IM-7 carbon and Zylon™ reinforcement, it provides an upper bound for potential matrix properties. The baseline reinforced lug geometry having w/D and e/D ratios of 2.600 and 1.300, respectively, is used for this study.

The response curves are presented with respect to the reinforcement type and each of the results of the three matrix and adhesive combinations are presented with a particular reinforcement. The response curves for the Zylon™, IM-7 carbon and Nextel™ reinforced lugs are presented, respectively, in Figures 12 thru 14. Only the Nextel™ reinforced lugs failed to exceed conventional lug design requirement of four percent hole elongation because of its low fiber failure strain.

For all reinforcement types the order of the highest maximum load to the lowest is aluminum matrix with epoxy adhesive followed by epoxy matrix with epoxy adhesive and finally the lowest is the aluminum matrix with aluminum adhesive. The matrix stiffness correlates with the pre- and post-knee slope of the response curve, that is response curve stiffness increases with increasing reinforcement matrix stiffness. Comparing the post-knee slopes of cases having aluminum matrix and aluminum adhesive with aluminum matrix and epoxy adhesive, adhesive mechanical properties seems to have some effect on response. The higher stiffness adhesive (aluminum) seems to facilitate load transfer into the reinforcement resulting in a fiber failure at a relatively low displacement. However, the epoxy adhesive allowed for more local straining to occur in the metal lug adjacent to the reinforcement resulting in substantially higher displacement around the hole which ultimately produced a higher initial failure load.

**Effect of Adhesive Thickness**

A study of the effect of adhesive bond thickness between the metal portion of the lug and the reinforcement on lug response was evaluated. Three cases were analyzed, a case with no adhesive and two epoxy adhesive cases having thicknesses of 0.007 and 0.014 inches. The no adhesive case creates a situation where there is a stiff interface between the reinforcement and the metal portion of the lug. The baseline reinforced lug geometry having w/D and e/D ratios of 2.600 and 1.300, respectively, is used for this study.

The load-displacement response for the lug cases is shown in Figure 15. All reinforced cases exhibited a stiffer response than the non-reinforced case. The load-displacement response of the no-adhesive case is slightly stiffer in both the pre- and post-knee response regions. Failure of the no-adhesive case occurred slightly beyond the four percent hole elongation point and the failure mode was an interlaminar shear failure in the reinforcement. The stiffer response is consistent with having a stiffer more efficient load transfer mechanism between the metal and the reinforcement.

The reinforced lug with a 0.007-inch-thick epoxy adhesive layer had a less stiff response than the no adhesive case but a slightly stiffer response than the 0.014-inch-thick adhesive case. This is consistent with respect to volume fraction of adhesive in the lug as well as load transfer through a thinner adhesive region to the reinforcement. Ultimately, the difference in responses between the 0.007- and the 0.014-inch-thick cases were small.

**Effect of Metallic Lug Material**

The effect of changing the metallic lug material from 7075-Al, baseline case, to Al-Li aluminum alloy was performed. The baseline reinforced lug geometry having w/D and e/D ratios of 2.600 and 1.300, respectively, is used for this study. The reinforcement fibers used in this study are the same as used elsewhere in this investigation that is Zylon™, IM-7 carbon and Nextel™.

The load-displacement curves for the 7075-Al and the Al-Li reinforced lugs are presented in Figures 16. The only reinforced lug that did not achieve the four percent hole elongation was the Nextel™-epoxy reinforced 7075-Al lug. All others met or exceeded this conventional design requirement. The elastic stiffness and knee of the Al-Li aluminum alloy response curves was higher for each of the reinforced and non-reinforced cases than the cases with 7075 aluminum alloy. This trend was anticipated due to the ten percent higher stiffness of the Al-Li alloy than the 7075-Al material. Also, the maximum load of the reinforced Al-Li alloy lugs prior to initial failure was higher than the corresponding 7075-Al reinforced cases, although the lug displacement at failure was similar between corresponding 7075-Al and Al-Li alloy cases. The percentage increase in maximum load, that is load at initial failure, was 21.3, 16.6, and 31.0 for IM-7 carbon, Zylon™, and Nextel™ reinforced lugs, respectively. Initial failure modes in the Al-Li cases showed a trend to change from interlaminar shear failure in the reinforcement to a fiber tension failure mode.

Another difference is reinforcement rank in carrying maximum load. In the 7075-Al baseline case the rank ordering of reinforcement by maximum failure load is Zylon™, IM-7 carbon and Nextel™. For the Al-Li case the order is IM-7 carbon, Zylon™ and Nextel™. This difference is related to the percentage of load reacted by the Al-Li alloy lug. The stiffness and yield stress of the Al-Li alloy is higher than the 7075-Al so more of the total load is reacted by the Al-Li alloy than by the 7075-Al. The knee in the load-displacement curve for the Al-Li alloy case is approximately 32-percent higher resulting in a proportionately higher elastic strain energy being reacted by the metal portion of the lug.

An applied displacement loading condition is used in all of these analyses and the corresponding load on the specimen is the sum of the pin reaction forces. Using this modeling approach it is possible to predict the negative slope of the response curve such as that exhibited by the non-reinforced Al-Li alloy lug. Based upon the post initial failure response of reinforced specimens paralleling the non-reinforced lug response, it is possible that the initial failure of the

Zylon™-epoxy reinforced Al-Li specimens will result in a catastrophic failure of the lug. The slope of the non-reinforced lug when initial failure occurs for the IM-7-epoxy reinforced Al-Li specimen is approximately zero so it is also plausible that when initial failure occurs this specimen will also exhibit a catastrophic failure. The Nextel™-epoxy reinforced Al-Li specimen may not produce a catastrophic failure at initial failure because the slope of the non-reinforced Al-Li lug is positive at this displacement. It is not anticipated than any of the lugs composed of 7075 aluminum alloy will exhibit a catastrophic failure because the slope of the non-reinforced lug is positive.

**Effect of Reinforcement Thickness**

Four reinforcement thicknesses (0.025, 0.050, 0.075, and 0.100 inches) were evaluated to determine the influence of reinforcement thickness on lug response. Zylon™-epoxy reinforcement was used with an epoxy adhesive layer between the metallic lug and the reinforcement for all cases. The baseline reinforced lug geometry having w/D and e/D ratios of 2.600 and 1.300, respectively, is used for this study except the thickness of the reinforcement was increased while the corresponding metallic lug dimensions were reduced to maintain constant geometrical dimensions.

The load as a function of applied displacement is presented in Figure 17 for both reinforced and non-reinforced cases. The pre- and post-knee stiffness of the reinforced specimens was slightly greater than the non-reinforced specimen. Although it can not be clearly discerned from the Figure, due to overlapping of symbols, the thicker the reinforcement the stiffer the pre-knee response. These trends are consistent with increasing reinforcement volume fraction in the specimen. Beyond the knee of the load-displacement curve a significant difference in slope occurs between the non-reinforced and reinforced specimen's response. This trend is related to the reinforcement becoming the primary load carrying component in the lug while the volume of yielded metallic material increases resulting in less load carrying capability. Post-knee slopes of the reinforced lugs are proportional to the reinforcement thickness.

Displacement at initial failure of the reinforced lugs is inversely proportional to reinforcement thickness. More load is transferred through the adhesive interface with increasing reinforcement thickness resulting in higher stress in the adhesive and initial failure at lower displacement. The inverse relationship between reinforcement thickness and displacement at initial failure is related to a change in yield mode in the lug. As seen in Figure 18, the yield mode for the 0.025-inch-thick reinforcement is a combination of bearing and shear-out, similar to the non-reinforced case, whereas for the 0.100-inch-thick reinforcement it is a more bearing yield mode beneath the hole extending more quickly to the edge of the lug with increasing reinforcement thickness. Based upon these stress contours, lug displacement at failure is inversely proportional to reinforcement thickness. However, all of these failure displacements exceed the four percent hole elongation criteria.

**Effect of Hole Diameter**

The effect of hole diameter on the response of reinforced lugs was investigated. The lug hole diameters analyzed were 0.375, 0.500, 0.625, 0.750, 1.000 and 1.250 inches. Specimen w/D and e/D ratios relative to these hole diameters were 5.200 / 2.600, 3.900 / 1.950, 3.12 / 1.560, 2.600 / 1.300, 1.950 / 0.975 and 1.560 / 0.780, respectively. The baseline geometry of the lug, other than hole diameter, and the reinforcement (Zylon$^{TM}$-epoxy) was constant for all specimens. Non-reinforced metallic lugs having the same hole diameters were analyzed for comparative purposes.

Load as a function of applied displacement for the reinforced cases is shown in Figure 19. Response trends were similar to other results presented in this study, that is the response curve is initially linear followed by a knee in the curve with a linear but inelastic post-knee response. However, load magnitude did not change in proportion to changes in hole diameter.

To help explain these trends, load as-a function-of-hole diameter response curves are presented in Figure 20 for non-reinforced and reinforced cases at four-percent hole elongation and initial failure. The reinforced and non-reinforced lugs exhibited similar response curves, that is load increased with increasing hole diameter and then at a hole diameter of approximately 0.625 inches decreased with continued increase in hole diameter. Although the shape of the response curves were similar the magnitude of the reinforced curves for the same hole diameter were higher, except for the lugs with 0.375-inch-diameter holes. In the case of the 0.375-inch-diameter hole the maximum load in the non-reinforced specimen was less than one-percent higher than the load in the reinforced specimen. Due to the small hole size relative to the width of the lug the reinforcement had little or no effect on restraining the deformations of the specimen.

Based upon the response trends, shown in Figure 10, and stress contours, seen in Figure 21, associated with the non-reinforced lugs it is obvious that the size of the hole relative to the lug's edge (pin end of lug and sides) of the lug influences the load path and yielding of metallic material. For instance, upon examination of the non-reinforced case having a hole diameter of 0.375 inches, load introduction at the hole almost resembles that of a point load. Yielding occurs along the lower portion of the hole resulting in a bearing type failure mode. The stress contours are low in magnitude, for the 0.375-inch case, along the sides of the lug. Based upon these stress contours it is speculated that if the distance from the center of the hole to the pin end of the lug (e-distance) was greater, the sides of the lug would have no influence on lug response. As hole diameter increases the proximity of the lug sides relative to the hole influences the region of material yielding. The yielding region begins to move toward the sides of the lug creating a combined bearing and shear-out failure mode such as exhibited by the non-reinforced lugs having 0.625- and 0.750-inch-diameter holes. As the hole diameter further increases the combined modes transition to a shear-out mode where the yield region further rotates away from the lug's longitudinal axis, such as depicted by the 1.000-inch-diameter-hole case. As the hole diameter increases the ligament of material between the hole and the sides of the lug decreases thus reducing the load carrying path of the lug, as seen in Figure 21, for the 1.250-inch-hole-diameter case. The yield region rotates up the side of the lug until the high stress regions extend almost horizontally producing a net-tension mode. The combined yielding mode exhibited by the 0.625- and 0.750-inch-diameter-hole cases seem to produce a higher maximum load than exhibited by either a pure bearing or shear-out mode. The higher maximum load capability may be related to the higher volume of yielded material for these two cases.

The Von Mises stress contours, see Figure 22, for the reinforced specimens at four percent hole elongation exhibited similar stress state as found for the non-reinforced case at the same hole elongation, as seen in Figure 21. As in previous reinforced cases the load at the same magnitude of displacement was higher for the reinforced lugs than the non-reinforced lugs because the reinforcement restrained the overall deformation of the lug causing the metal to yield more around the hole.

**Effect of e-Distance**

A study was conducted investigating the effect of the e-distance from the center of the hole to the pin end of the lug. The geometry of the reinforced lugs is the baseline case used in this investigation. Three different e-distances were used, e=0.975 (baseline), 1.350 and 1.725 inches. Hole diameters used in this study were 0.50, 0.75, and 1.00 inches. The w/D ratios relative to the hole diameters are 3.900, 2.600 and 1.950, respectively. The e/D ratios relative to the hole diameters were 1.950 / 1.300 / 0.975, 2.700 / 1.800 / 1.375 and 3.450 / 2.300 / 1.725, respectively. A single type of reinforcement Zylon™-epoxy 0.025-inches-thick was used in this investigation including an epoxy adhesive bonding the reinforcement to the metallic portion of the lug.

The response curves for these 9 cases are presented in Figures 23-25. Response curves for cases having the same value of e are presented on the same Figure. Three of the nine cases were not analyzed to initial failure because the analysis would have taken an excessive amount of time and sufficient information was obtained to understand the load transfer and failure mechanisms without taking the analysis to failure.

Through all nine cases similar response trends developed as seen in other studies in this investigation. There were, however, a few anomalies that needs further explanation. The failure displacement of all cases evaluated exceeded the four percent hole elongation conventional design criteria. Another general trend is all selectively-reinforced lugs exhibited higher loads than their non-reinforced counterparts and the displacement at initial failure is inversely proportional to hole diameter for specimens having the same value of e. The mechanics of this response are related to the metal yielding mode (bearing, shear-out and net-tension) in the vicinity of the hole. These modes and direction of propagation of yielding material are influenced by the proximity of the hole to the edge (pin end and / or sides) of the lug in both reinforced and non-reinforced lugs. When the yielded metallic material propagates to the edge of the metallic material, then failure occurs in the reinforcement or the adhesive at approximately that location.

For small holes, such as the 0.500-inch-diameter hole cases, the yielding tends to propagate from the base of the hole towards the pin end of the lug which coincides with a bearing like response, as seen in Figures 26-28. The 0.750-inch-diameter hole cases exhibited a combined bearing and shear-out yielding mode. Typically, the yielded material propagates downward from the base of the hole as well as along a diagonal from the hole to the side of the lug. As the e-distance increases, the magnitude of the stresses diminish the closer one gets to the pin end of the lug. The proximity of the lug's side has a dominant influence on the progression of yielding resulting in the reinforcement failure location progressing up the lug's side. The largest hole cases, those with a 1.000-inch diameter, typically exhibited a combined yielding mode of shear-out and net-tension that was also a function of e-distance. For the smallest value of e-distance a shear-out mode was present and changed to a combined shear-out and net-tension yielding mode for the e=1.350 inch case and became a net-tension failure at e=1.725 inches. As previously mentioned, as e-distance increases the influence of the lower portion of the lug decreases.

Another interesting trend is related to the response curve associated with the 1.000-inch-diameter hole cases for all e-distances, see Figures 23-25. For the two larger e-distances, 1.350 and 1.725 inches, the response curve to initial failure associated with the 1.000-inch-diameter hole cases, is very similar to that produced by the 0.750-inch-diameter hole cases. However, for the e-distance of 0.975-inch hole case the response curve for the 1.000-inch-diameter hole case is similar to that produced by the 0.500-inch hole case. A response that sheds light onto the mechanism associated with the different response curve is the overall reduced stiffness of this case relative to the 0.750-inch-diameter hole case, as depicted in Figure 23. The reduction in stiffness is caused by the yielding of material in the vicinity of the hole which dramatically reduces the amount of load carrying metallic material. This case, e=1.350 inches, has the smallest distance between the hole and the side of the metallic lug, thus any yielding of material around the hole has a significant effect on the overall response. Upon comparing the Von Mises stress contours at failure for the e=1.350-inch case, the yielded material reached the side of the lug at a lower load than the other 0.500 and 0.750-inch-diameter hole cases.

Relative to the 0.500- and 0.750-inch hole diameter cases having e=1.350 inches, neither of these cases were analyzed to the point of initial failure. Their response curves are shown in Figure 24. However, after examination of the Von Mises stress contours shown in Figure 27 it is evident that the yield stresses are closer to the side of the lug for the 0.750-inch-diameter hole case than the 0.500-inch-diameter hole case. From this observation it is plausible to assume the 0.750-inch-diameter hole case would fail prior to the 0.500-inch-diameter hole case, which is consistent with the previous trends.

The next trend discussed is related to the 0.500-inch-diameter hole cases for e=1.350 and 1.725 inches having substantially less stiff response curves than the response curves for 0.750- and 1.000-inch-diameter holes. In both of the cases having 0.500-inch-diameter holes the smaller the hole, hence smaller the pin, the higher the local stresses for the same applied load. Extensive amount of local yielding occurs about the lower portion of the hole, as seen in Figures 27 and 28, resulting in reduced overall stiffness and the lower overall response.

The final trend is related to the 0.750-inch-diameter hole case response with an e=1.725 inches, as seen in Figure 24. In this case the initial failure load was less than the anticipated initial failure load for the e=1.350-inch case, see Figure 24, even though the e=1.725-inch case exhibited a stiffer response. As previously seen the larger the e-distance the trend is for the yield points at the lug edge to move up the lug. In the e=1.725-inch case the specimen exhibits a combined bearing yielding mode beneath the hole with a shear-out and net-tension yield mode toward the sides of the lug. The distance to the side of the lug was the shortest path to the reinforcement, thus resulting in initial failure of the reinforcement and failure at a lower load and displacement. Upon comparing the stress contours in Figures 27 and 28 for the 0.750-inch-diameter hole cases, higher stresses occur at the side of the lug for the e=1.725-inch case. Initially the lug reacts the load in bearing at the bottom of the hole. As load increases if the lower boundary of the lug is close, then it influences stress field beneath the hole. If the hole diameter is small relative to the width of the lug then the sides of the lug have little or no effect on increasing local stresses. As hole diameter increases these boundary effects begin to influence the stress state around the hole. It seems as if the lower boundary becomes a prominent contributor to the stress state around the hole before the side boundaries. However, if the e-distance is larger than the distance to the side then the lower boundary has decreasing influence as the e-distance increases. Then as the hole diameter increases the side boundaries contribute. The extreme situation is the e=1.725-inches case with a large hole. The side boundaries are an immediate contributor in the evolving stress field because the e-distance is very large. In the case of e=1.350 inches with a hole diameter of 0.750 inches, the lower boundary and the side boundaries are at a unique combination of distances from the hole such that they both begin to influence the stress field in such a way as to promote greater local displacement before the global displacements cause failure in the adhesive or reinforcement.

## Summary

An analysis based investigation of the effects of material and geometric variables of U-shaped band reinforced metallic lugs response was performed. The variables studied were fiber stiffness and failure strain, matrix stiffness and yield stress, adhesive mechanical properties, hole diameter, reinforcement thickness, adhesive thickness, lug material properties, and e-distance. In all cases the analysis of comparable geometry non-reinforced lugs was also performed for comparison purposes. A mechanics based cause-effect relationship was developed for how these variables influenced changes in lug response.

In general U-shaped band reinforced lugs exhibited superior performance, that is load at the conventional lug design criteria, four percent hole elongation. Depending on the reinforcement configuration the increase in load may be negligible to 15 or 20 percent. The percent increase in load at failure for the reinforced lugs increased relative to end displacement. The function of the reinforcement in increasing lug load carrying capability is related to restraining overall lug deformations which facilitates increased yielding of metallic material in the vicinity of the hole. Initial failure in reinforced lugs is a shear failure in the adhesive, an interlaminar shear failure in the reinforcement or a fiber-tension failure in the reinforcement. Failures frequently occur where the metallic material yield zone reaches the edge of the lug. The exception occurs with low failure strain fiber reinforcements, such as Nextel™, where the fiber has a lower failure strain than the metallic lug's yield strain. Initial failure load for most reinforced lugs was generally higher than the load at the same end displacement for comparable non-reinforced lugs. Also,

initial failure in reinforced lugs typically occurred at displacements that correspond to multiples of the conventional design criteria of four percent hole elongation. Therefore, it may not be practical to design to these high hole elongations.

Reinforcement fiber stiffness influenced the pre- and post-knee response of reinforced lugs. Fiber failure strain affected the magnitude of post-knee displacement response and thus it contributes to the magnitude of the initial failure load. Matrix stiffness has no effect on the pre- and post-knee slope of the response curve; however matrix yield stress and failure strain had an effect. The higher the yield stress and failure strain the more metallic material yielding occurred resulting in higher maximum load.

The influence of adhesive stiffness on lug response has to be taken into context with fiber and matrix properties. A combination of stiff low-failure-strain fiber with a stiff matrix and adhesive can result in a very efficient load path into the reinforcement that promotes a tensile failure in the fibers at a relatively low load and displacement. Another combination is a stiff fiber with a higher failure strain, a stiff matrix (aluminum) with a conventional stiffness adhesive (epoxy). In this scenario the stiff fiber creates high pre- and post-knee slopes and its higher failure strain allows for increased fiber elongation. The flexible adhesive allows more deformation in the metal lug ultimately resulting in a higher initial failure load albeit at a very high end displacement.

Adhesive thickness has insignificant affect on pre- and post-knee slope. It seems to have more effect on displacement at initial failure and through that result in increased failure load. This is a variable that should not be tampered with once an acceptable adhesive thickness has been developed for a class of problems.

The metallic lug's mechanical properties have a significant effect on lug response because it is the increased yielding of metallic material that results in higher magnitude response. The higher the stiffness of the metallic lug the steeper the pre-knee slope. The higher the yield stress of the metallic lug material the higher the response curve's knee. If the non-reinforced lug's post knee slope becomes negative then a catastrophic failure of the reinforced lug can occur.

The effect of hole diameter on lug response is related to the load paths and yield modes that are created in the metallic lug. Reinforcement has virtually no effect on lugs with very small holes. The small hole almost creates a concentrated load response resulting in primarily a bearing yield mode beneath the hole. Generally, initial failure occurs because the yielded material region propagates to the edge of the lug. Frequently, the initial failure load is low in magnitude.

At the other extreme, large holes create small ligaments of material beside the hole for load transfer. Typical yield modes are shear-out or a combination of shear-out and net-tension. Generally, the net-tension type of mode results in a low initial failure mode. The highest initial failure load is typically produced by a medium size hole (width-to-diameter ratio of approximately 2 to 3). The yield mode is a combination of bearing directly under the hole and shear-out. This yield mode consumes a large percentage of usable material.

Initial failure load and displacement decreases as hole diameter increases for specimens having a constant value of e-distance. However, the maximum load typically increases as e-distance increases for specimens having a constant hole diameter. The proximity of the lug boundaries (pin end of lug and sides) relative to hole size influences mode of yielding and location of reinforcement failure. In all of the aforementioned cases initial failure occurred beyond the conventional four percent hole elongation design criteria and selectively-reinforced lugs exhibited higher failure loads than non-reinforced lugs of comparable geometry.

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Table 1. Mechanical properties of reinforcement materials used in analyses.

| | Nextel-Epoxy | Nextel-Al | IM7-Epoxy | IM7-Al | S-Glass-Epoxy | Kevlar-Epoxy | Zylon-Epoxy | Zylon-Al |
|---|---|---|---|---|---|---|---|---|
| E11 | 32660000 | 35000000 | 24200000 | 25000000 | 7760000 | 11600000 | 15800000 | 18000000 |
| E22 | 1946043.165 | 19000000 | 1927710.84 | 16000000 | 1787234.043 | 1853658.537 | 1890909.091 | 14444444.44 |
| E33 | 1946043.165 | 19000000 | 1927710.84 | 16000000 | 1787234.043 | 1853658.537 | 1890909.091 | 14444444.44 |
| v12 | 0.27 | 0.25 | 0.27 | 0.275 | 0.27 | 0.27 | 0.27 | 0.275 |
| v13 | 0.27 | 0.25 | 0.27 | 0.275 | 0.27 | 0.27 | 0.27 | 0.275 |
| v23 | 0.45 | 0.3 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| G12 | 749255.5917 | 6840000 | 742459.397 | 6201550.39 | 690221.857 | 714957.667 | 728801.6819 | 5615550.756 |
| G13 | 749255.5917 | 6840000 | 742459.397 | 6201550.39 | 690221.857 | 714957.667 | 728801.6819 | 5615550.756 |
| G23 | 671049.3674 | 3850000 | 664727.877 | 5517241.38 | 616287.6009 | 639192.5988 | 652037.6176 | 4980842.912 |
| | | | | | | | | |
| Sig_11_T | 259589.6488 | 278188.54 | 451935 | 466875 | 412634.9206 | 262526.3158 | 510461.5385 | 581538.4615 |
| Sig_22_T | 8000 | 30000 | 8000 | 30000 | 8000 | 8000 | 8000 | 30000 |
| Sig_33_T | 8000 | 30000 | 8000 | 30000 | 8000 | 8000 | 8000 | 30000 |
| Sig_11_C | 259589.6488 | 278188.54 | 451935 | 466875 | 412634.9206 | 262526.3158 | 510461.5385 | 581538.4615 |
| Sig_22_C | 32000 | 49400 | 32000 | 49400 | 32000 | 32000 | 32000 | 49400 |
| Sig_33_C | 32000 | 49400 | 32000 | 49400 | 32000 | 32000 | 32000 | 49400 |
| Tau_12 | 13500 | 10150 | 13500 | 10150 | 13500 | 13500 | 13500 | 10150 |
| Tau_13 | 13500 | 10150 | 13500 | 10150 | 13500 | 13500 | 13500 | 10150 |
| Tau_23 | 13500 | 10150 | 13500 | 10150 | 13500 | 13500 | 13500 | 10150 |

Table 2. Effective stress-strain data for epoxy and aluminum matrices.

| Epoxy | | | Aluminum | |
|---|---|---|---|---|
| Strain (in/in) | Stress (psi) | | Strain (in/in) | Stress (psi) |
| 0.00000 | 7961.90 | | 0.00000 | 13864.34 |
| 0.00040 | 8668.43 | | 0.00008 | 15144.84 |
| 0.00140 | 10140.82 | | 0.00048 | 18201.41 |
| 0.00260 | 11555.68 | | 0.00148 | 21516.47 |
| 0.00420 | 13085.63 | | 0.00408 | 25394.54 |
| 0.00600 | 14502.95 | | 0.00958 | 29329.91 |
| 0.00900 | 16426.70 | | 0.02708 | 35031.72 |
| 0.01900 | 20908.67 | | 0.10208 | 44009.95 |
| 0.07000 | 32021.62 | | 0.19987 | 49409.65 |
| 2.00000 | 32023.00 | | 2.00000 | 49410.00 |

Table 3. 7075-aluminum, Al-Li alloy and epoxy adhesive data.

| 7075 | | | Al-Li | | Epoxy Adhesive | |
|---|---|---|---|---|---|---|
| True Stress-Strain Data | | | True Stress-Strain Data | | Engineering Stress-Strain Data | |
| Strain (in/in) | Stress (psi) | | Strain (in/in) | Stress (psi) | Strain (in/in) | Stress (psi) |
| 0.00000 | 0.00 | | 0.00000 | 0.00 | 0.00000 | 0.00 |
| 0.00400 | 42050.00 | | 0.00859 | 94500.00 | 0.01000 | 5000.00 |
| 0.00560 | 55980.00 | | 0.40000 | 100000.00 | 0.10000 | 5000.00 |
| 0.00700 | 63570.00 | | | | | |
| 0.00900 | 67470.00 | | | | | |
| 0.01500 | 69960.00 | | | | | |
| 0.11000 | 84000.00 | | | | | |

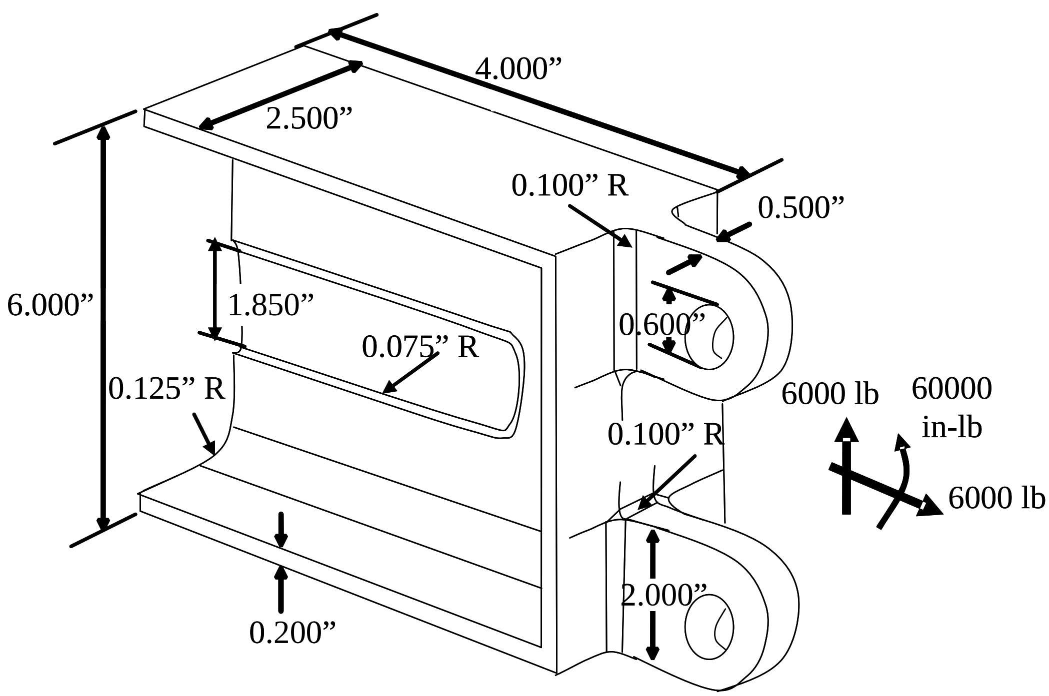


Figure 1. Fuselage keel beam with integral lugs.

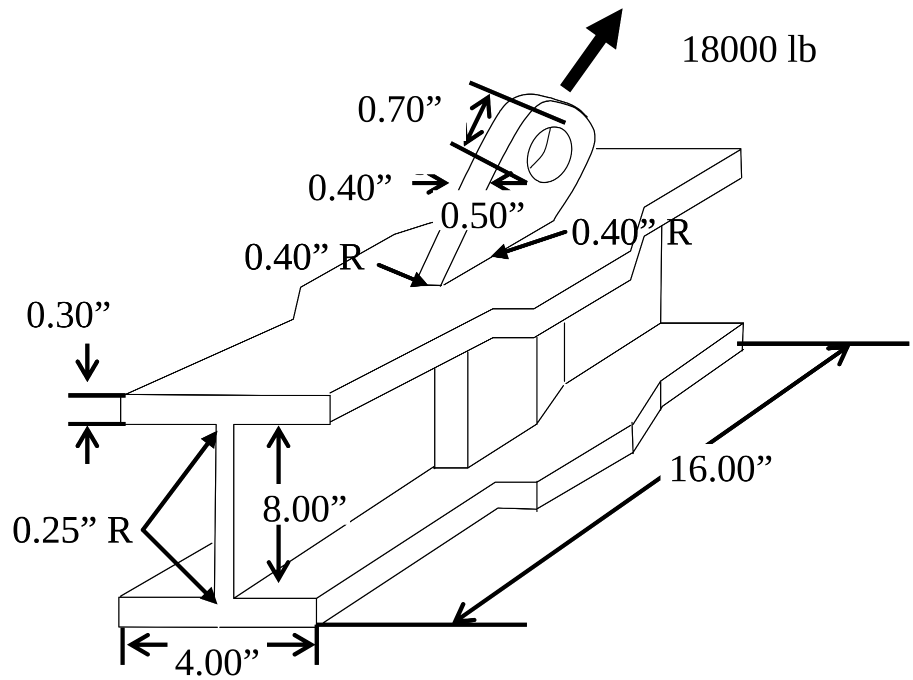


Figure 2. Transmission support beam with integral lug.

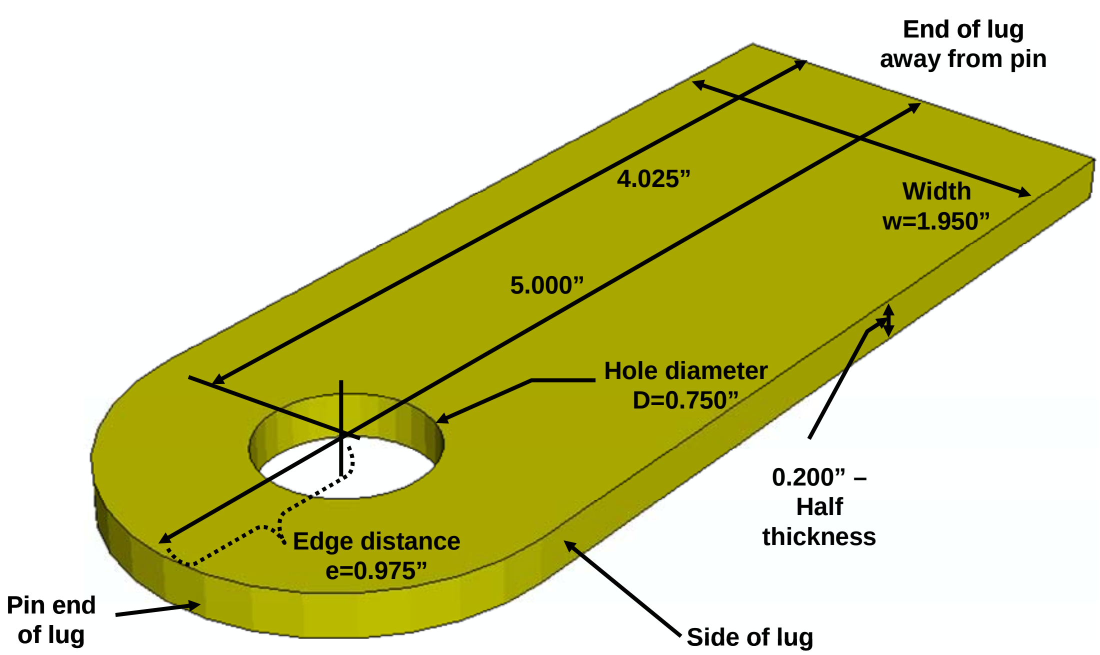


Figure 3. Baseline lug geometry.

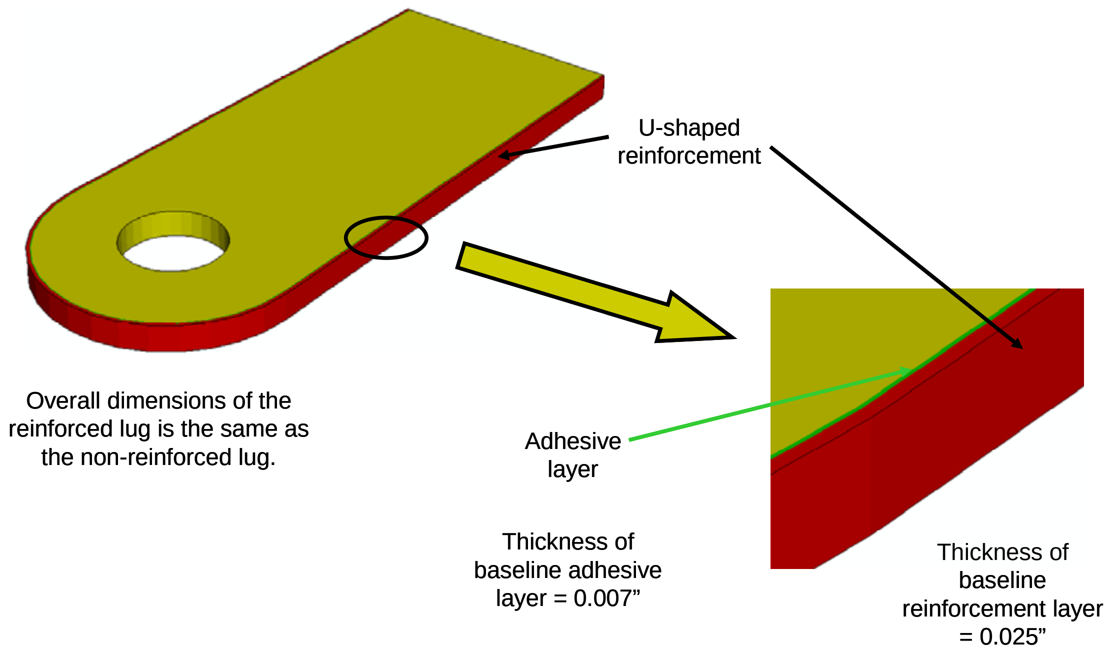


Figure 4. Reinforced lug geometry.

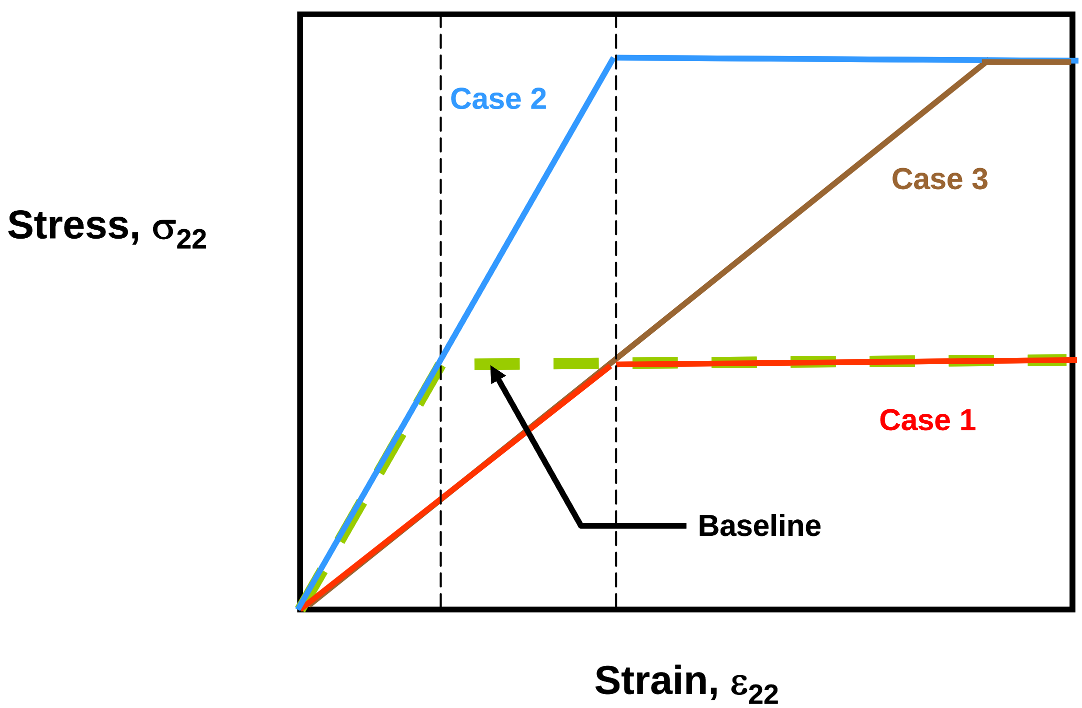


Figure 5. Matrix Stress-strain curves for evaluating the effect of matrix properties on lug response.

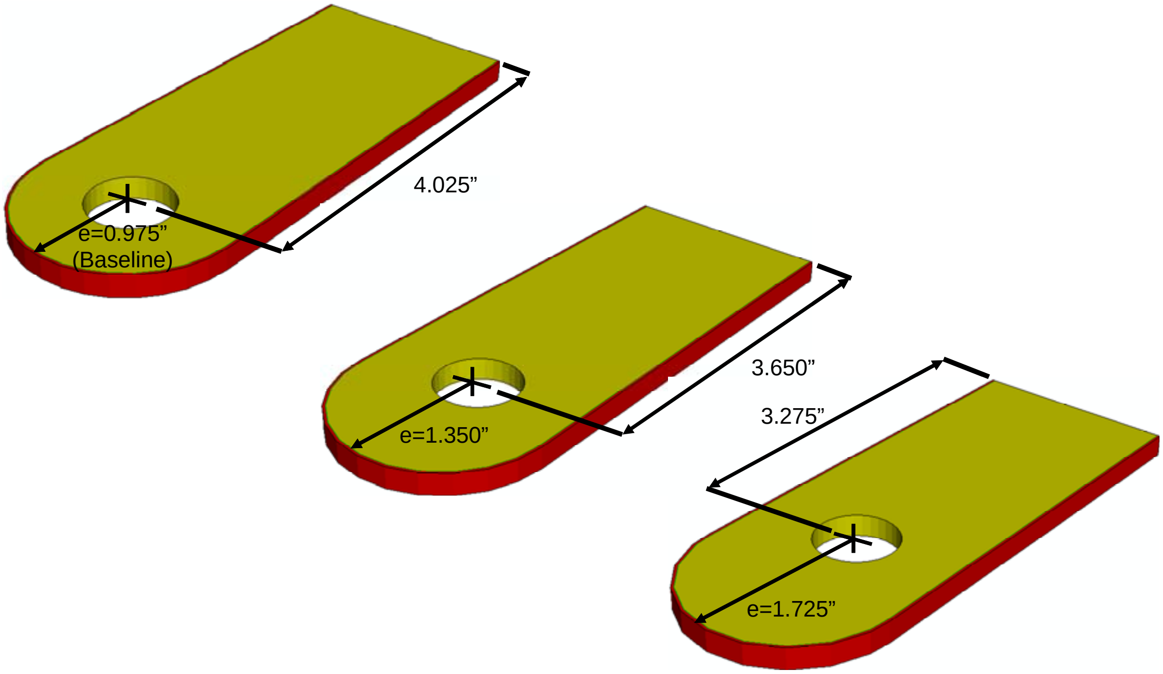


Figure 6. Lug geometry showing e-distance.

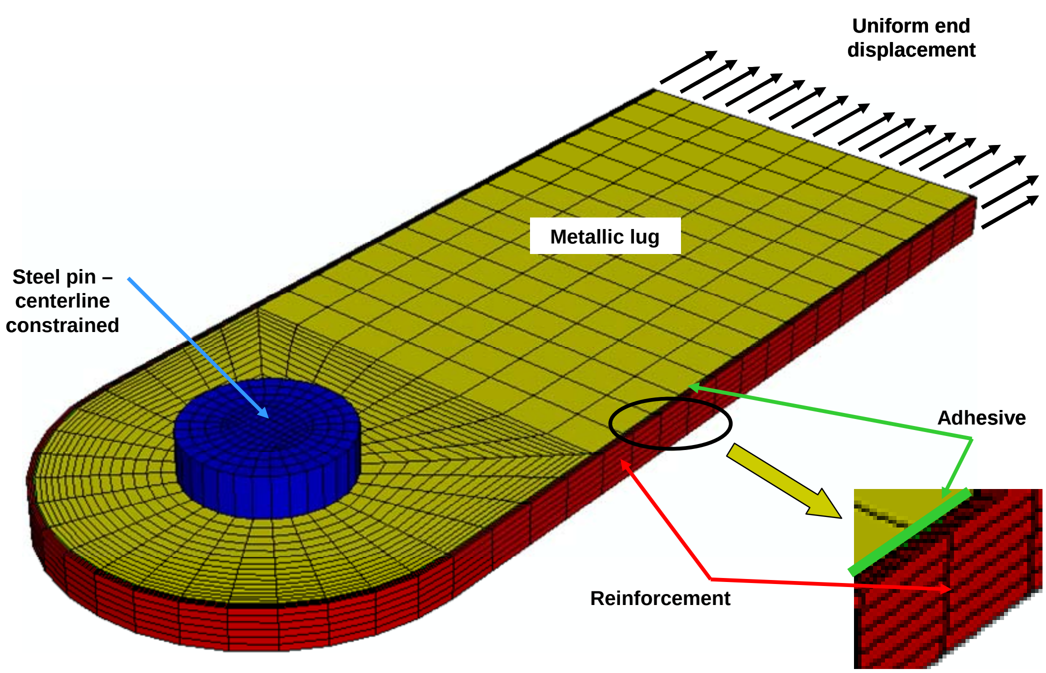


Figure 7. Finite element model of lug with pin, adhesive and reinforcement.

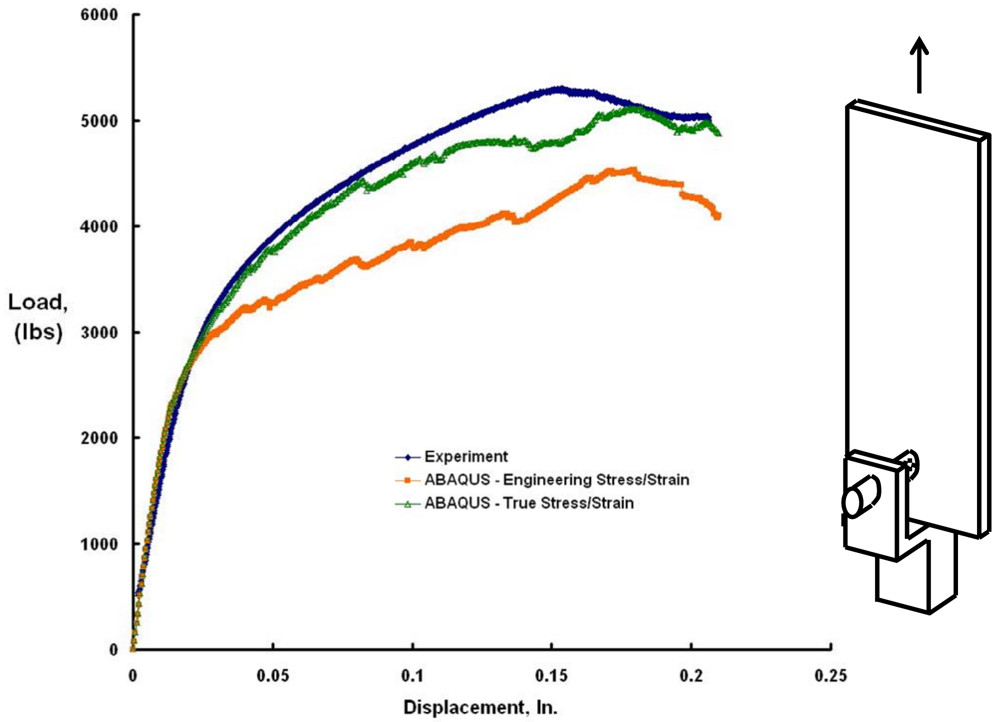


Figure 8. Load-displacement response of 2014-aluminum pin-loaded-hole specimen.

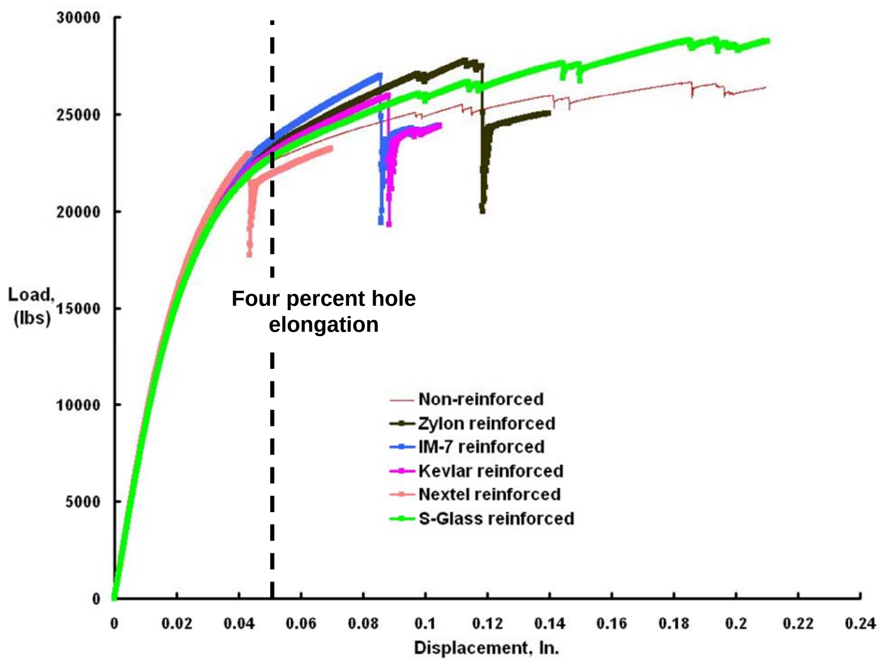


Figure 9. Load-displacement response showing the effect of composite fiber reinforcement mechanical properties.

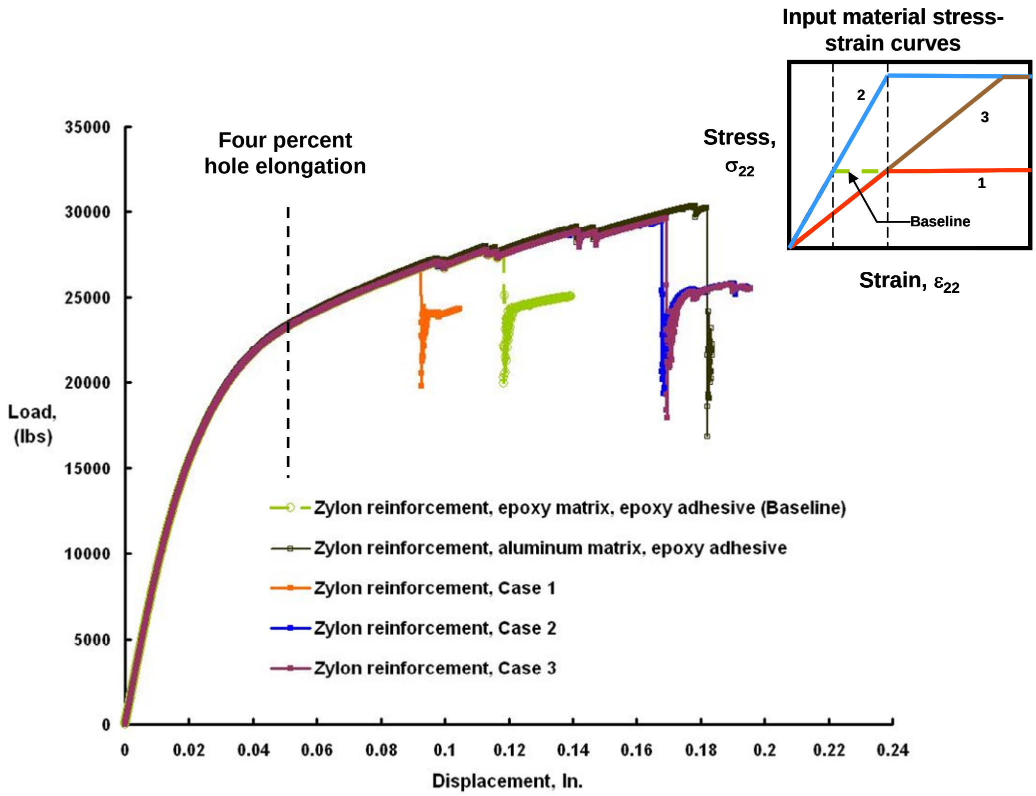


Figure 10. Load-displacement response of Zylon™-epoxy reinforced lugs with variation in matrix properties.

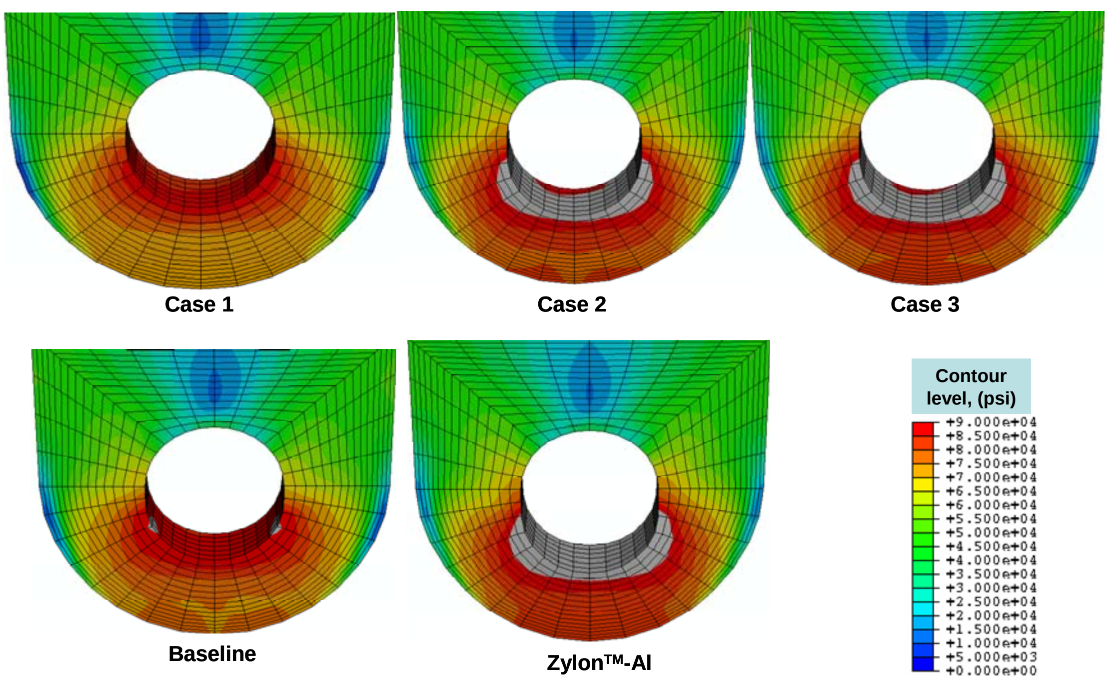


Figure 11. Von Mises stress contours of metallic portion of Zylon™-epoxy reinforced lugs showing effects of matrix properties relative to baseline.

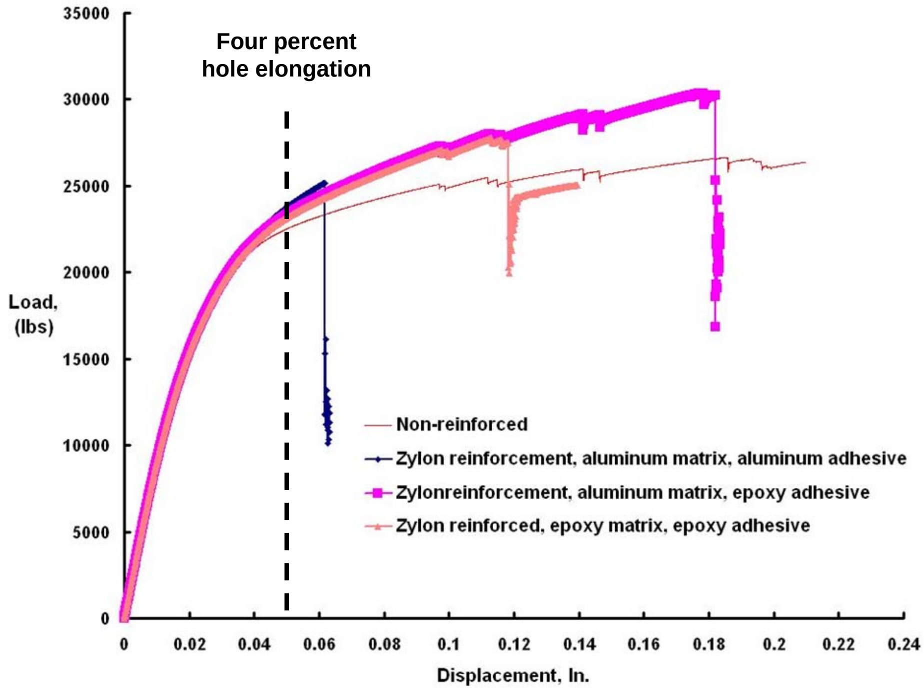


Figure 12. Load-displacement response of Zylon™-epoxy reinforced lugs with aluminum / epoxy matrix and adhesive.

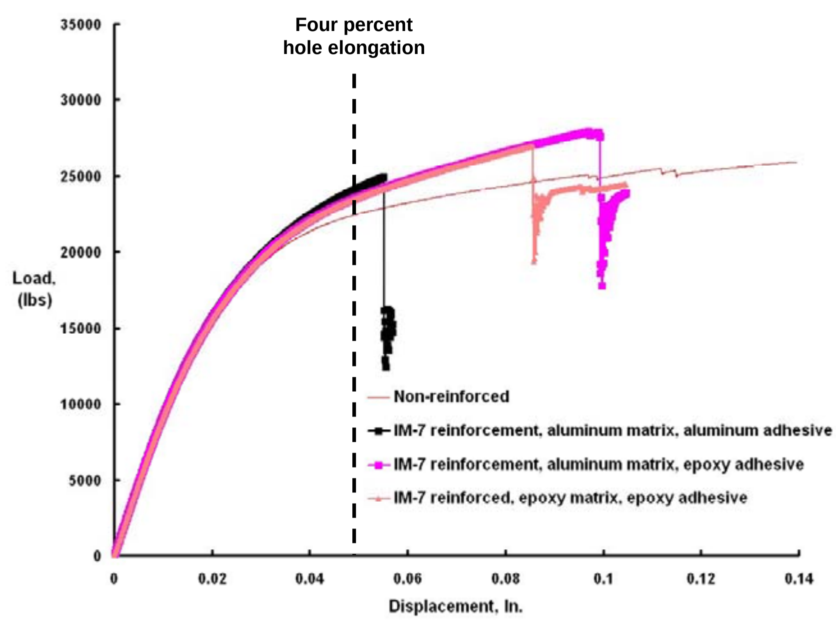


Figure 13. Load-displacement of IM-7-epoxy reinforced lugs with aluminum / epoxy matrix and adhesive.

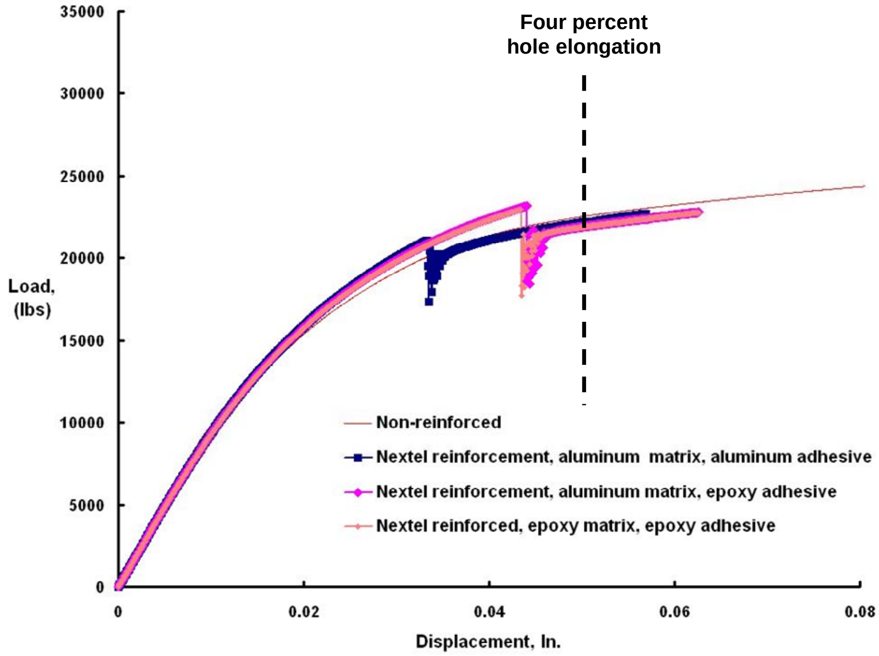


Figure 14. Load-displacement response of Nextel™-epoxy reinforced lugs with aluminum / epoxy matrix and adhesive.

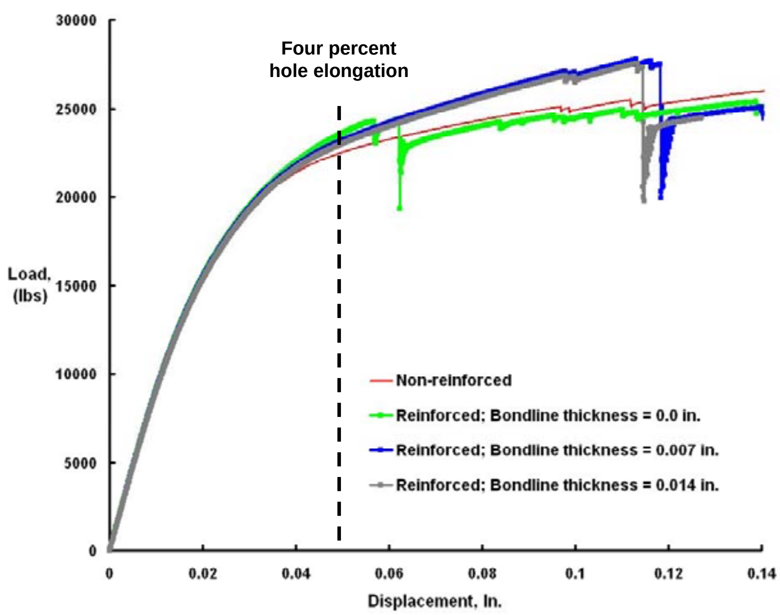


Figure 15. Load-displacement response demonstrating the effect of adhesive bond line thickness on Zylon™-epoxy reinforced lug.

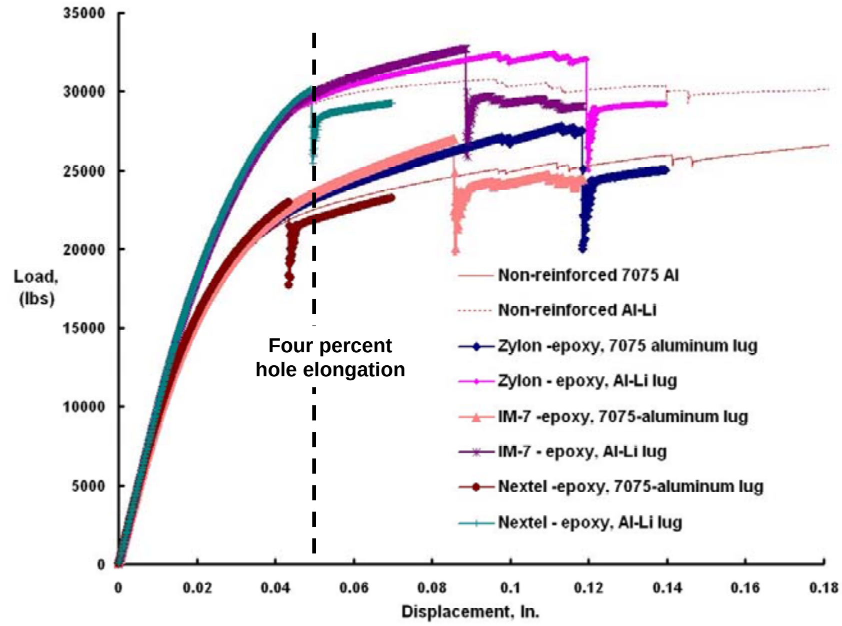


Figure 16. Load-displacement response of 7075-aluminum and Al-Li reinforced lugs.

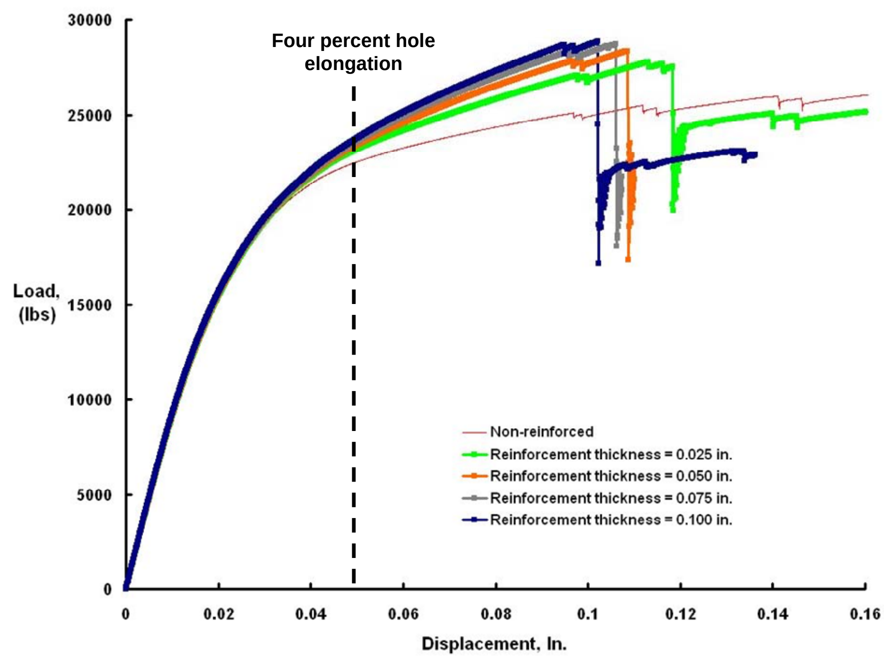


Figure 17. Load-displacement response of Zylon$^{TM}$-epoxy reinforced lugs with various reinforcement thicknesses.

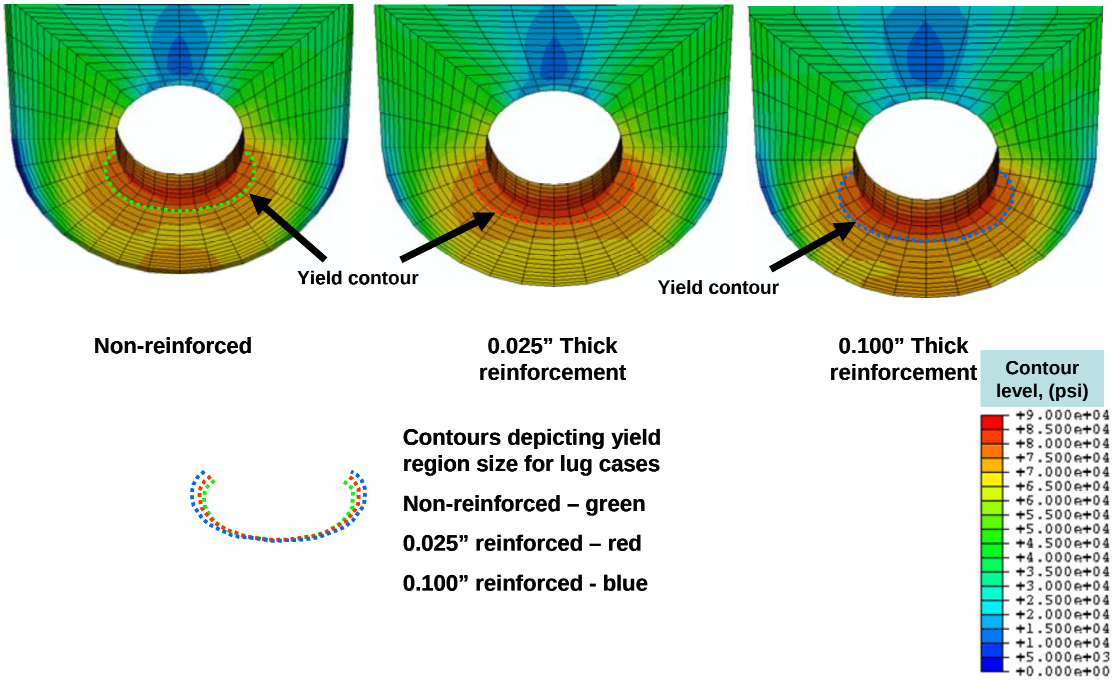


Figure 18. Von Mises stress contours of non-reinforced and Zylon™-epoxy reinforced lug specimens at four percent hole elongation.

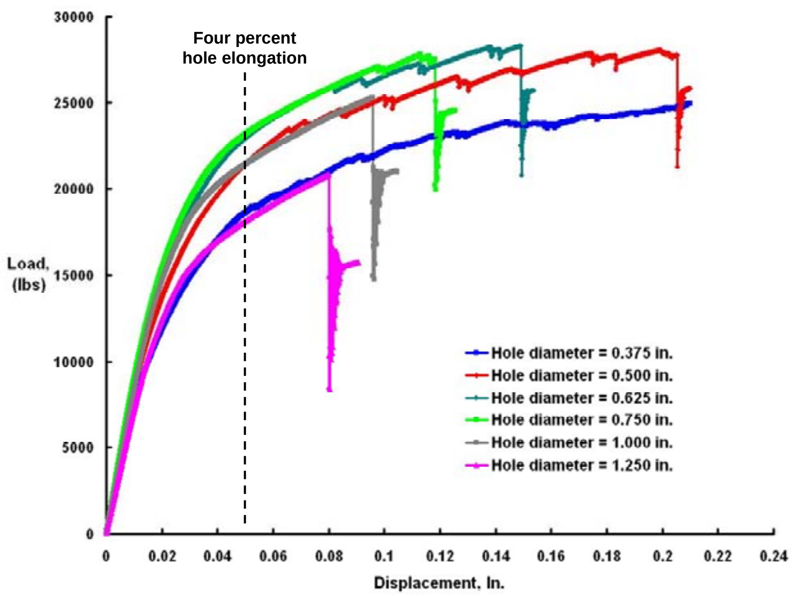


Figure 19. Load-displacement response of Zylon™-epoxy reinforced lugs for different hole diameters.

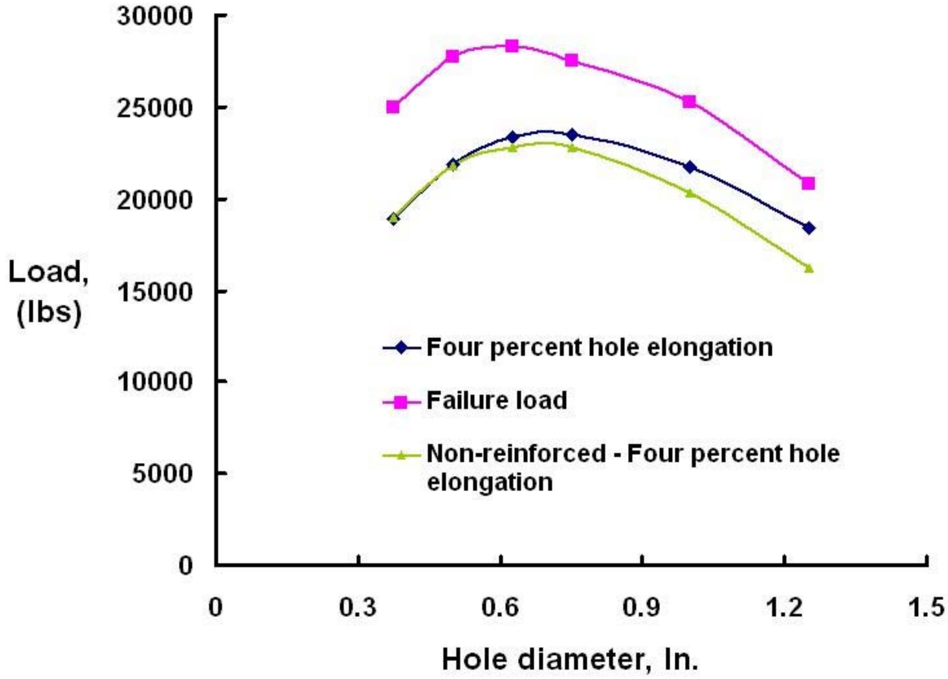


Figure 20. Load hole-diameter response for Zylon™-epoxy reinforced and non-reinforced lugs.

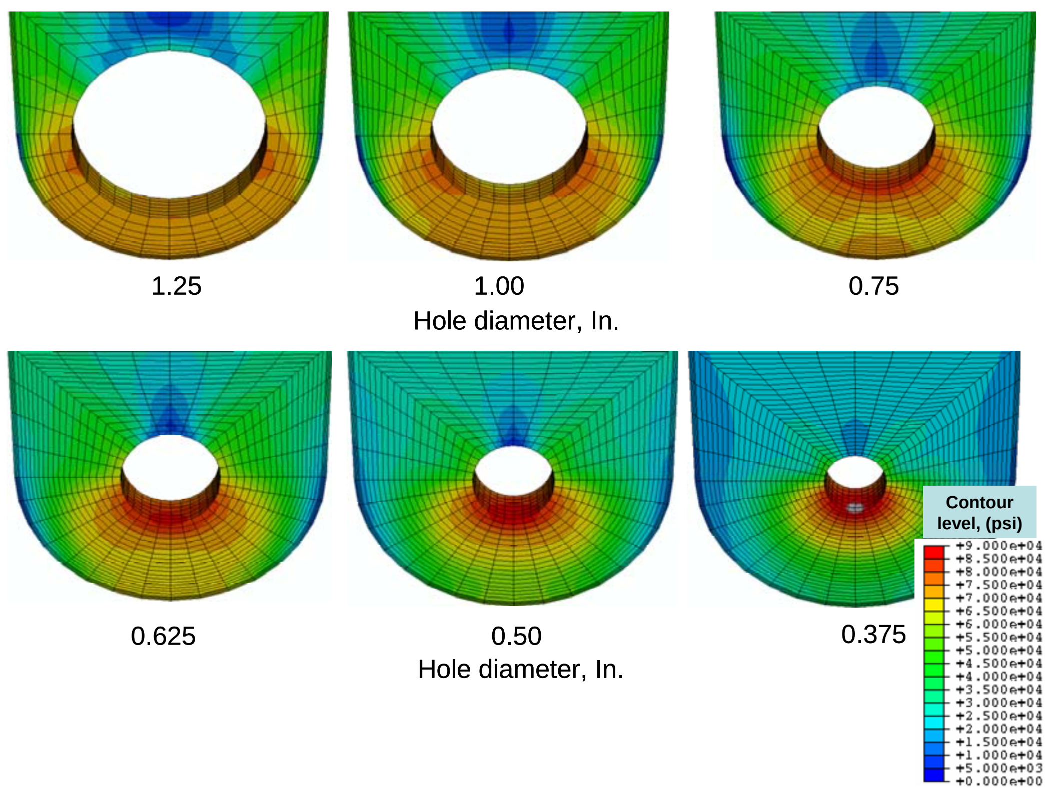


Figure 21. Von Mises stress contours at four percent hole elongation for non-reinforced lug specimens.

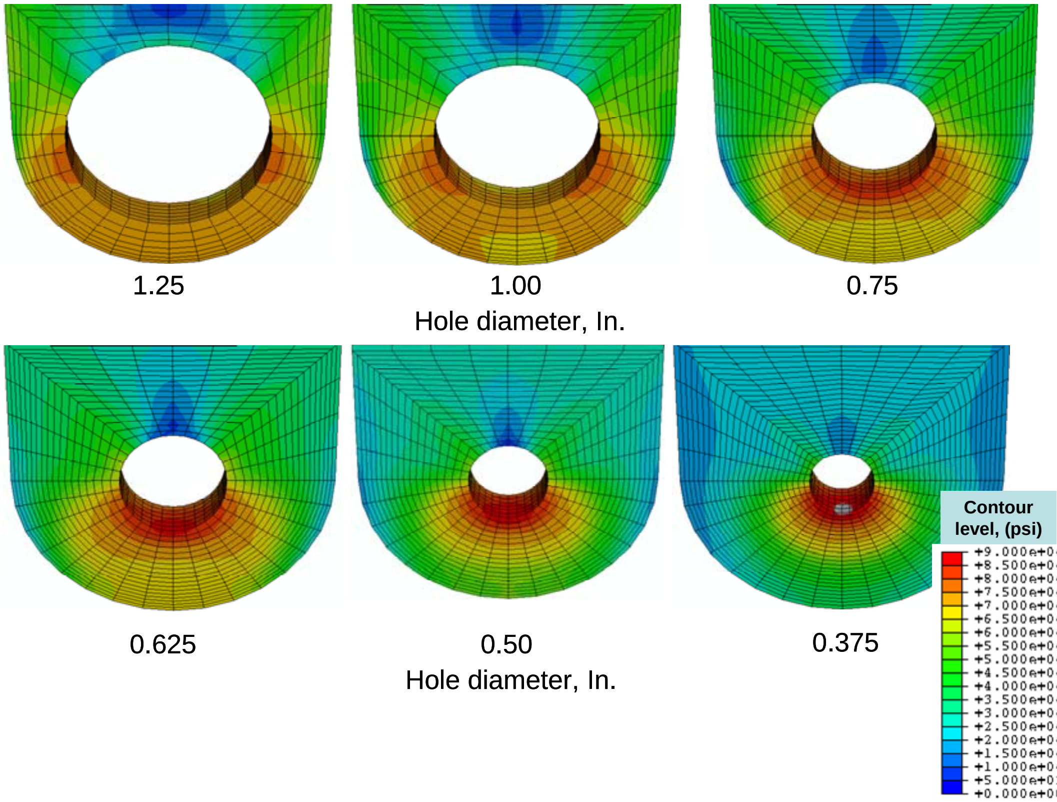


Figure 22. Von Mises stress contours at four percent hole elongation for Zylon™-epoxy reinforced lug specimens.

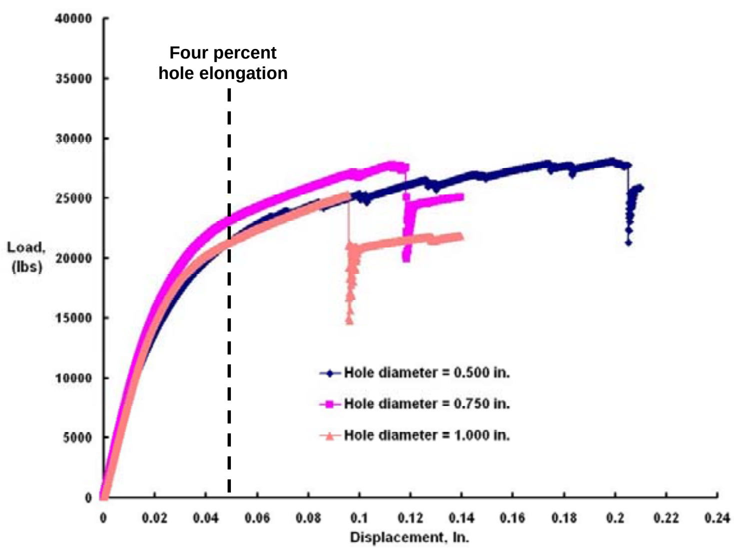


Figure 23. Load-displacement response of Zylon™-epoxy reinforced lugs having different diameters with e=0.975 inches.

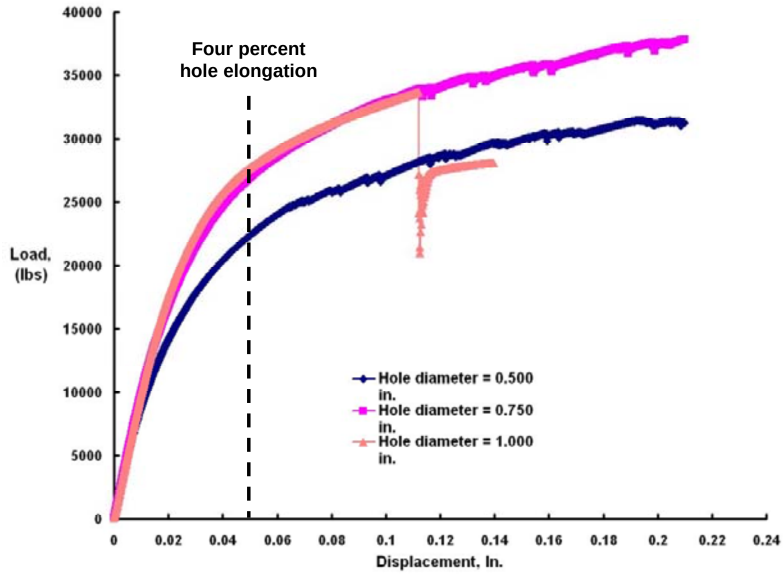


Figure 24. Load-displacement response for Zylon TM-epoxy reinforced lugs having different diameters with e=1.350 inches.

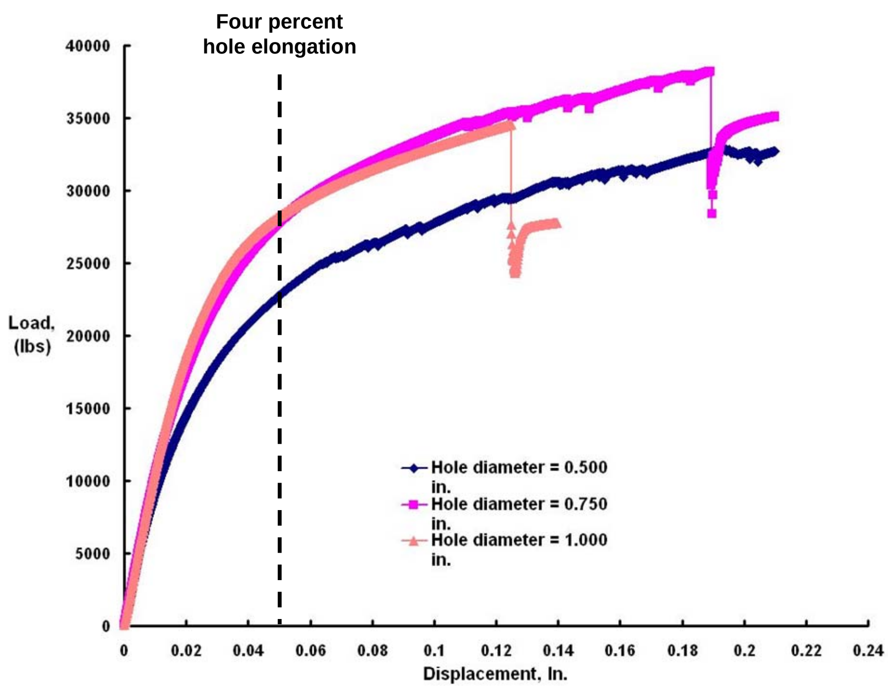


Figure 25. Load-displacement response for Zylon TM-epoxy reinforced lugs having different diameters with e=1.725 inches.

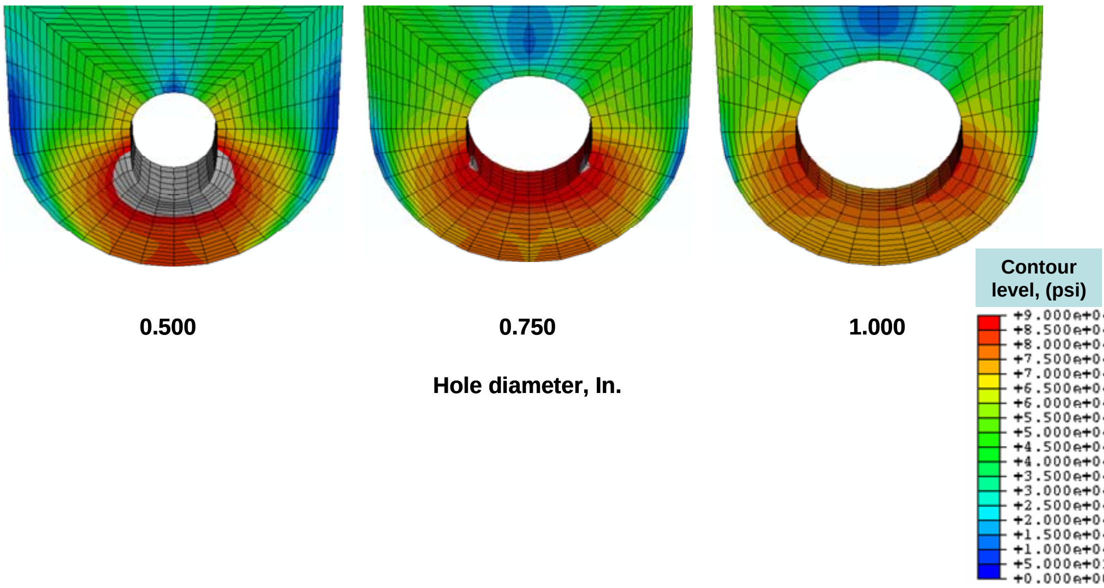


Figure 26. Von Mises stress contours for Zylon™-epoxy reinforced lugs having different hole diameters with e=0.975 inches.

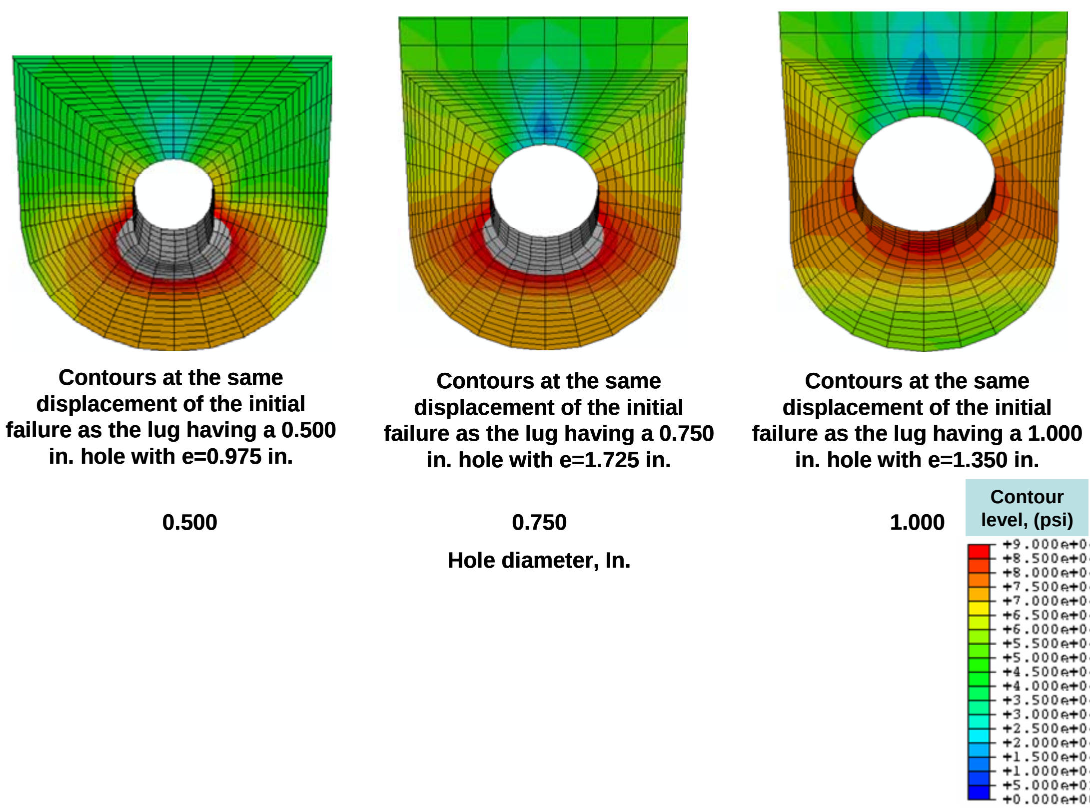


Figure 27. Von Mises stress contours for Zylon™-epoxy reinforced lugs having different hole diameters with e=1.350 inches.

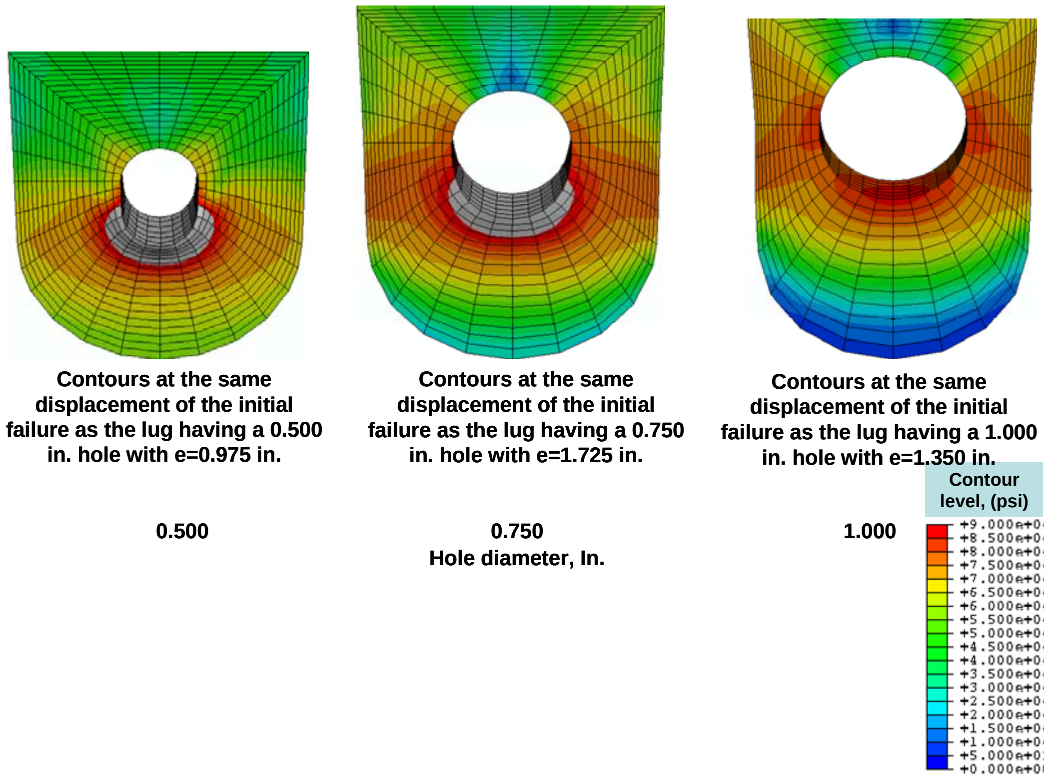


Figure 28. Von Mises stress contours for Zylon™-epoxy reinforced lugs having different hole diameters with e=1.725 inches.

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**14. ABSTRACT**
An investigation of the effects of material and geometric variables on the response of U-shaped band-reinforced metallic lugs was performed. Variables studied were reinforcement, adhesive and metallic lug mechanical properties, hole diameter, reinforcement and adhesive thickness, and the distance from the hole’s center to the end of the lug. Generally, U-shaped band reinforced lugs exhibited superior performance than non-reinforced lugs, that is higher load at the conventional lug design criteria of four percent hole elongation. Depending upon the reinforcement configuration the increase in load may be negligible to 15 or 20 percent. U-shaped band reinforcement increases lug load carrying capability primarily through two mechanisms; increasing the slope of the response curve after the initial knee and restraining overall deformation of the metallic portion of the lug facilitating increased yielding of metallic material between the hole and the edge of the metallic portion of the lug.

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