Proof Testing Aluminum and Titanium Thin-Walled Tubes for Aerospace Applications

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Proof testing aerospace components aids in verifying the structural integrity of flight hardware. This process is often an important step in the certification process for critical parts. Though proof testing is a common practice at NASA and in industry, there is often a need to understand better the effectiveness of proof testing pressure systems discovering cracklike flaws or defects. Often proof tests are used in requirements and in practice as technical rationale for screening critical defects in a part in lieu of performing a non-destructive inspection. The intent of this work is to define proof test failure envelopes for thin-walled tubes composed of two materials: aluminum and titanium. Both materials are common in aerospace thin-walled tubing applications which is why these were the materials chosen for this study. The fracture mechanics software NASGRO was used to perform a parametric study on the effect of defects in thin-walled tubes subjected to proof testing. For both materials, the parameters varied in the NASGRO analyses were aspect ratio, proof test pressure, thickness, diameter, and flaw multiplier. With each case defined as a through crack or failure, the results were then pulled into MATLAB in order to parse through the data and produce failure envelope plots. Failure envelopes were created by meshing a surface in between the minimum proof pressure failing data points. As expected, based on material properties, the plots indicated the aluminum material would fail at much lower proof tests than the titanium. The parametric data and failure envelopes may be used as general qualitative insight on the effectiveness of proof testing thin-walled tubes of similar alloys.

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I. Nomenclature

%t	=	flaw multiplier	K	=	stress intensity factor
a	=	initial flaw size	P	=	pressure
a/c	=	aspect ratio	t	=	thickness
D	=	diameter	σ_h	=	hoop stress

II. Introduction

Understanding the structural integrity of spaceflight components is pivotal to prevent catastrophic failures from occurring and proof testing aids in informing subject matter experts (SMEs) of the limits of structures. There are many different approaches for screening parts for defects including non-destructive evaluation (NDE) and proof testing. Even in the realm of NDE, there are many options for screening materials to determine defects that may reduce a structure's ability to perform as intended. For pressurized hardware such as thin-walled tubes, proof testing is often used in practice. This study uses NASGRO, a fracture mechanics and a fatigue crack growth software, to simulate the propagation of a defect in a tube wall. In considering the many different variables inherent in the proof testing of a thin-walled tube, this analysis investigated hundreds of design configurations to determine a failure envelope for thin-walled pressurized tubes.

Additionally, the results of this work should serve as a reference for other SMEs, industry, and applications of proof testing thin-walled tubes. The parametric failure envelopes provided in this paper should be a quick check if a certain set of design parameters including a defect could result in a through crack or structural failure. The particular alloys investigated in this analysis are aluminum-6061-T6 and titanium-3Al-2.5V. With aluminum and titanium being used in many aerospace tubing systems, this will serve as a valuable resource as a preliminary assessment for whether a thin-walled pressurized tube will fail during a proof test with a defect present. The results of this study are intended to influence the designs of propellant and environmental life support system lines in (human) spaceflight applications.

III. Background

Proof testing is especially helpful for verifying the strength and understanding the limitations of hardware. For aerospace applications, proof testing is often employed for pressure vessels, habitable modules, thin-walled tubes for propellant and life support system lines, and other pressurized components. For many industries, structural parts are also put through proof testing to determine whether defects in hardware could propagate to failure. Depending on the function, different sets of proof testing approaches will be necessary [1]. For certain structures, proof testing procedures have yet to be standardized. This is the case for additively manufactured structures, which can reduce the overall cost by manufacturing major portions of a structure as a single piece, but there are concerns this method could disguise defects and failures [2]. Another study looked at honeycomb structures with destructive proof testing and an NDE approach [3]. This study used Abaqus for 3D modeling flaws in determining critical flaw sizes for honeycomb (unvented) structures. While this is a useful technique, often there is a need for more testing to accurately assess hardware for defects [4].

Proof testing in some cases can detect flaws through failures induced by proof loads. Confidence in the hardware is gained by loading parts beyond their design pressure and observing no failures or leaks. Straining and opening flaws so they are more visible post-proof test also aids in post-proof NDE detectability. The results of proof testing verify the structural integrity, inform quality assurance, and can build confidence beyond NDE. To assess a proof test, the hardware is analyzed with different initial flaw sizes and proof pressures beyond the design limit to understand if/where failures may occur. Up until 1959, neither standards nor interpretations of the results for proof testing were clear. Tiffany and Masters [5] provided a report on applications of proof testing as well as how to account for fracture mechanics in the proof test assessment. This can involve consideration of stress intensity factors of hypothetical defects in a part and predictions on whether or not the defects would cause a failure under proof loads.

For proof testing, there is a wide range of approaches depending on the material being looked at (brittle vs. ductile) as well as the destructiveness of the tests. In terms of ductile materials, it has been surmised that proof testing would be a poor indicator of their defects. Due to their high strength and tolerance to flaws, a NASA report suggests ductile materials would be better described by NDE for screening defects [6]. Nevertheless, proof testing is widely used on tubes of many materials, so it is of interest to quantify the effectiveness of this approach.

NASA outlines proof testing guidelines in NASA-STD-5019 according to the Fracture Control Requirements (FCR) for acceptance testing of hardware [1]. Proof tests serve to shed light on defects that may not be present at the surface. NASA emphasizes that the test should provide confidence in the hardware, a safety margin (via initial flaw size) should be established, a minimum proof load of at least 1.5 times the maximum design pressure for all materials used with *pressurized* hardware should be used, and that proof testing screen all design configurations. Through this approach, one can gain confidence that the part will not fail during the mission by screening overall quality and the presence of underlying defects.

IV. Methods

The method utilized in this study is to investigate proof testing tubes with defects and develop parametric failure envelopes. The approach for executing a parametric study was to create an analysis matrix of cases to run in NASGRO encompassing several variables associated with characterizing thin-walled tubes with defects. Then with the NASGRO results, three-dimensional plots were generated to define the failure envelopes of both aluminum and titanium tubes.

A. Parametric Study Design

This study looked at an external, longitudinal, surface, cracklike defect in a thin-walled pressurized tube with an internal uniform pressure applied. In NASGRO, in the NASFLA module, the SC04 case was used, as shown in Figure 1. For the parametric study, the variables investigated were aspect ratio, flaw multiplier, proof pressure, tube diameter, and tube thickness. Figure 2 illustrates each of these variables in the context of this analysis.

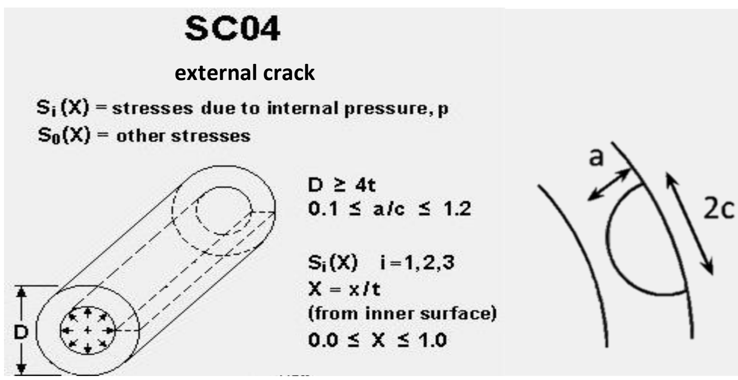
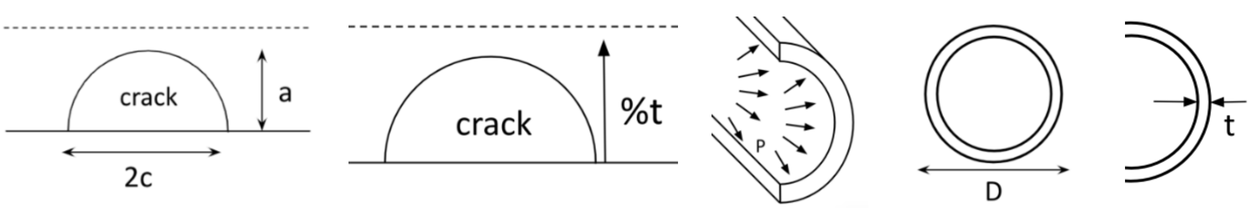


Figure 1. NASGRO NASFLA Test Case.



Aspect Ratio (a/c) *Flaw Multiplier (%t)* *Pressure (P)* *Diameter (D)* *Thickness (t)*

Figure 2. Variable Schematics.

The design pressures being considered for this analysis are listed in Table 1. Determining the failure thresholds for titanium was especially difficult due to its high material strength. The most realistic case is an aspect ratio of 1.0, but the worst cases are also important to understand. In the case of titanium, so few cases were failing due to the high strength that substantial failures were only apparent at a crack aspect ratio of 0.1. The values parsed through with respect to each variable in NASGRO NASFLA cases are shown in Table 1.

Table 1. Parametric Study Variable Parameters.

Variable	*Test Values*
Aspect Ratio (a/c)	0.1, 0.2, 1.0
Flaw Multiplier (%t)	50t, 69t, 99t
Pressure (P, ksi)	2, 4, 6, 8
Diameter (D, in)	0.25, 0.45, 0.65, 0.85
Thickness (t. in)	0.003, 0.009, 0.015

For each material, over 400 cases were run in NASGRO in the analysis matrix described in Figure 3. For each material, all variations of the unique combinations of parameters were tested, meaning each aspect ratio went through each value of the variables all the way through to the thickness variations. This thorough testing matrix led to a large set of data points creating failure envelopes for each material based on whether or not a failure occurred in one proof load cycle. In some instances, more cases were run to better understand the of the failure envelope.

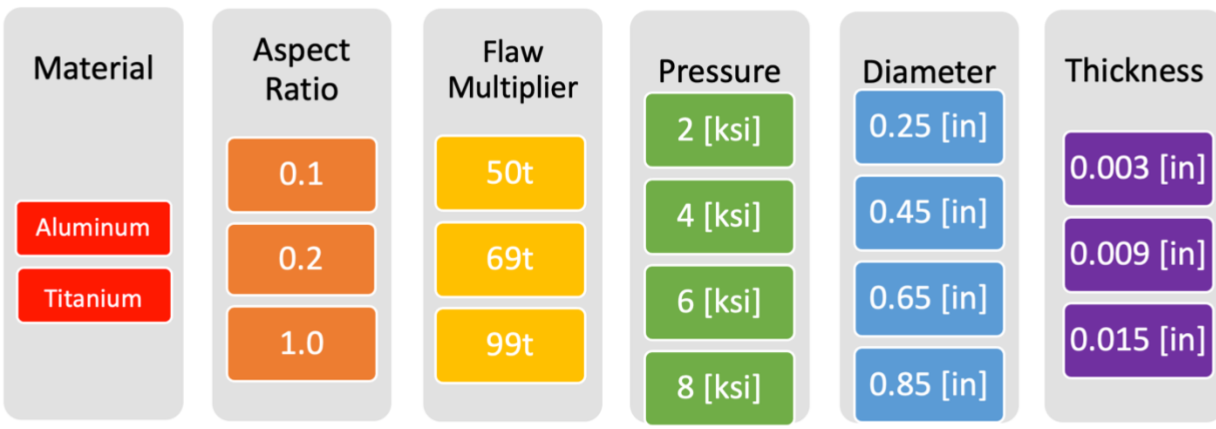


Figure 3. Parametric Study Test Matrix.

B. Parametric Study Procedure

The NASFLA section of NASGRO was utilized to analyze each case defined in the analysis matrix. For these analyses, only the SC04 external crack was used. Previous parametric analyses with other crack cases (e.g., SC05) and internal cracks showed either that there was not much variance in the results obtained or that SC04 was in fact the worst case. To accurately detect when failures occur, the worst-case stress was also used. Hoop stress for thin-walled tubes can be represented by Equation 1 where *P* represents the proof pressure. The longitudinal stress is half of the hoop stress, and so for the purposes of this study, cracks aligned such that they are loaded by longitudinal stress only are neglected. Equation 2 represents the initial flaw size which is input into NASFLA.

$$\sigma_h = \frac{P * (\frac{D}{2} - t)}{t} \tag{1}$$

$$a = \%t * t \tag{2}$$

Aluminum cases were run with properties for Al-6061-T6, T62 [13AB1] and titanium cases were run with properties for Ti-3Al-2.5V [33AB1]. NASGRO results were extracted based on if the crack would cause a failure including Net Section Stress (NSS) Yield, transition to through crack, and unstable Facture failure when subjected to repeated proof load cycles. For the cases that transitioned to a through crack beyond the first load cycle, the number of cycles until the transition to through crack from the initial conditions was also recorded. The cycles indicated how fast the case tested would result in a through crack – for higher proof pressures and flaw multipliers (as well as lower aspect ratios due to the inverse relationship), the cycles to failure are expected to *decrease*. The cycles to failure were obtained for reference, but the criterion for whether the proof test would screen the defect under consideration is based on if a failure is predicted in *one* load cycle.

After initial failure envelopes were determined in the parametric study, additional analyses were performed to refine accuracy. For all combinations of the variable parameters, an initial pressure was calculated such that the hoop stress generated was within 5 ksi of the yield stress of the material. Then, the crack case was run under this initial test pressure. If the NASGRO results displayed a non-zero number of cycles to failure, the initial test pressure was increased by 50 psi. The increase in test pressure was iterated until NASGRO showed failure under the first cycle. If the NASGRO results displayed the opposite, i.e. failure under the first cycle, then the initial test pressure was decreased by 50 psi and iterations were run until NASGRO showed a non-zero number of cycles until failure. This methodology complimented the initial understanding gained in the parametric study by increasing the accuracy of the predicted failure envelopes.

C. Generating Failure Envelope Plots in MATLAB

The analysis case results were recorded as transition to through crack (passing after one loading cycle) or, one of the other failing cases (NSS Yield or unstable fracture failure in the first load cycle), and the results were imported into MATLAB 2020. Two types of plots were generated, one with diameter vs. thickness vs. pressure, and the other with diameter-thickness ratio vs. flaw multiplier vs. pressure. Both types of plots use one aspect ratio, the first plots (D vs. t vs. P) is also respective of a specific flaw multiplier. First, the MATLAB code parsed through and found the minimum failing pressure points for every diameter and thickness pair or each flaw multiplier and diameter-thickness ratio pair, respective to the output graph type. With these points, a meshed surface was created to only define the minimum failing points. This surface represents a boundary between failing and passing cases, wherein all cases below the surface will pass (transition to through cracks at lower proof tests after *one* loading cycle), and the cases on or above the surface will define either of the three types of failing cases for the thin-walled tube. The surface was then adjusted slightly to improve accuracy using the final iterative steps described in the previous section. Note, in a proof test application, if a critical defect is present in a part, it is desirable for the test to failure in one load cycle so that the failure mode of the defect is discovered.

As shown in Figure 4, there are three key takeaways from the graph. The blue points below the meshed surface are configurations that did not fail after one loading cycle and transitioned to a through crack. The red points on and above the surface are configurations that failed, as in either experienced NSS yield, or unstable fracture failure in a single load cycle. The red points located on the surface are the minimum failing points for the sets of diameters and thicknesses with respect to pressure. The surface shows the failure envelope for a specific flaw multiplier, aspect ratio, diameter, thickness, and material.

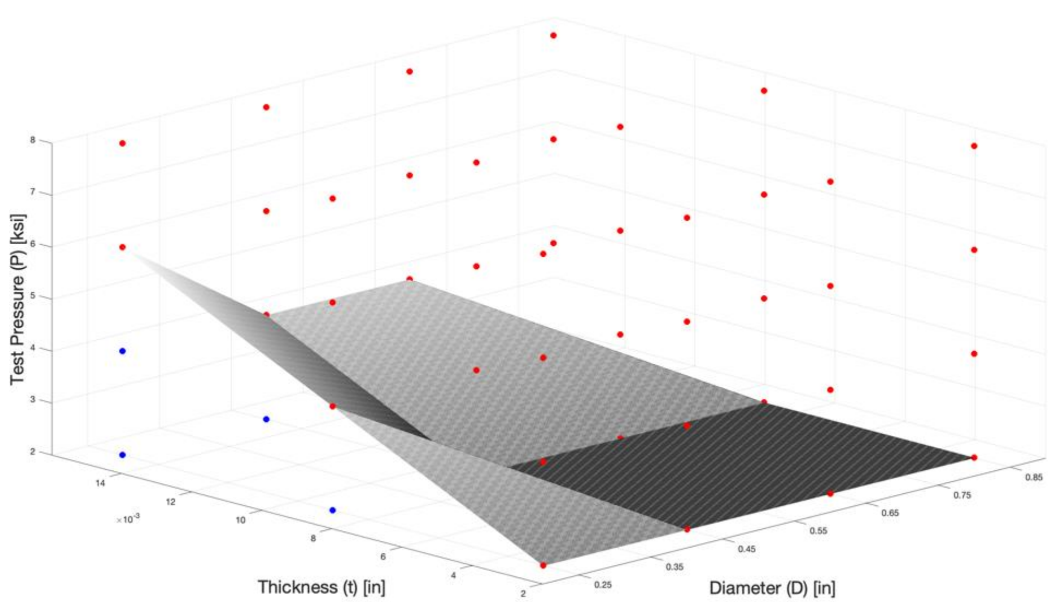


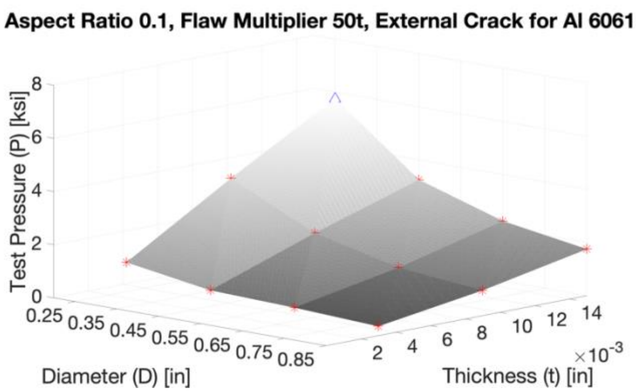
Figure 4. Example MATLAB Output Plot.

V. Results

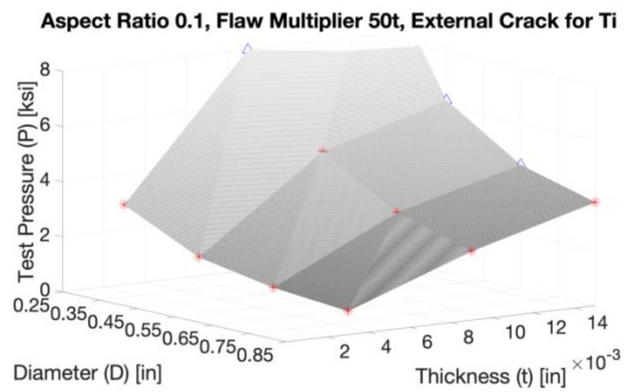
A. Failure Envelope Plots

With all cases input into MATLAB as failing or passing, the output is a three-dimensional failure envelope. When looking at the plots, the different failure modes are distinguished by the plot points. The red asterisk represents an NSS Yield failure, while a blue triangle represents a fracture failure. The difference between the fracture and NSS Yield failure modes can be shown through the hoop stresses. For cases of NSS yield, failure is detected when the hoop stress exceeds the flow stress of the material (flow stress is the average of the yield and ultimate stress of the material). For cases of fracture, failure is detected when the maximum stress intensity factor, K, exceeds the fracture toughness of the material. In the cases of fracture, the hoop stresses at failure are much lower than the hoop stresses required to generate an NSS Yield failure mode.

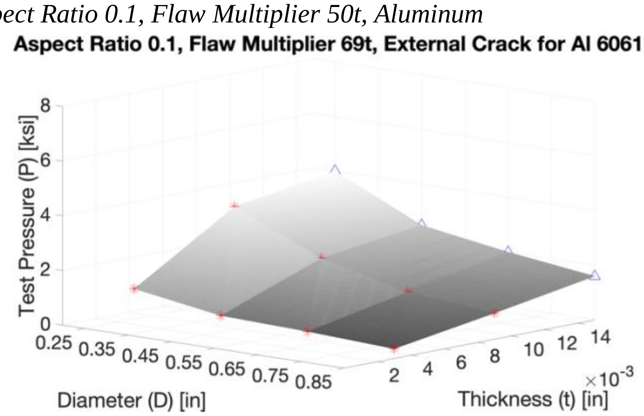
Looking into the failure envelope, one can qualitatively estimate points to determine if the specific thin-walled tube case will fail after one loading cycle in each proof test scenario. The failure envelopes for aluminum (left column) and titanium (right column) are shown in Figure 5 for a crack aspect ratio of 0.1 and flaw multipliers ranging from 50t to 99t. Note that the aluminum material fails at lower proof pressures compared to the titanium and therefore only has a few cases that see a fracture failure mode in a single proof test load cycle. Only one case sees a fracture failure with a flaw multiplier of 0.50t for aluminum. At 0.69t, four cases see a fracture failure and at 0.99t, there are numerous at low D/t ratios. Many more fracture failure modes are seen for titanium. The uppermost points of the titanium data set are not shown due to the pressure axis only going up to 8 [ksi]. The highest failing point is around 15.75 [ksi] for titanium. Fracture failure modes are found to occur generally in cases of higher thickness and lower diameter, as well as lower D/t ratios. There is an interesting phenomenon occurring at the low D/t ratio points for the aspect ratio of 0.1. There are a few points of NSS Yield mixed between the fracture failure cases. This is likely due to the propagations in NASGRO being right on the line between the two failure modes, but it is interesting that both materials have the same behavior.



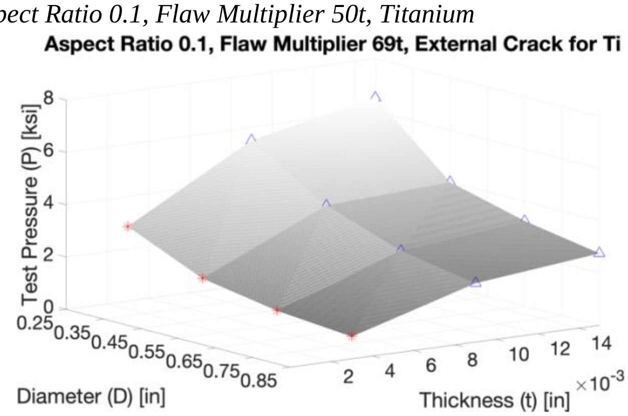
Aspect Ratio 0.1, Flaw Multiplier 50t, Aluminum



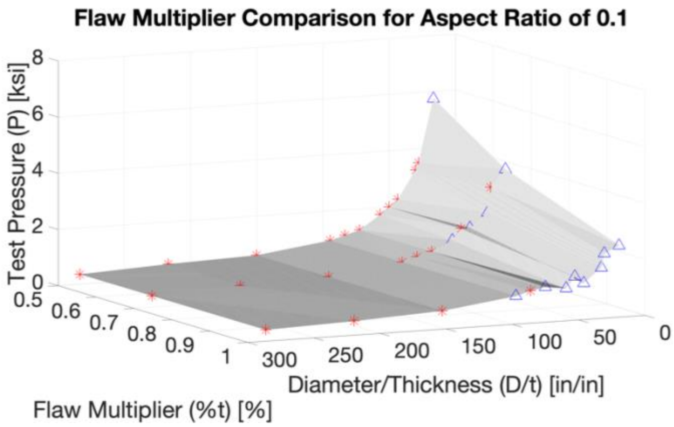
Aspect Ratio 0.1, Flaw Multiplier 50t, Titanium



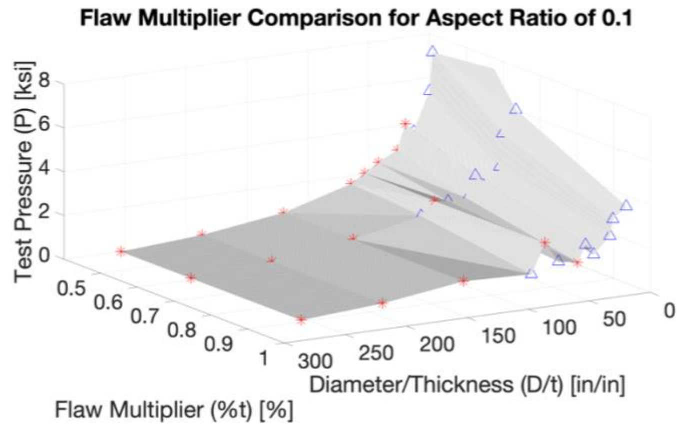
Aspect Ratio 0.1, Flaw Multiplier 69t, Aluminum



Aspect Ratio 0.1, Flaw Multiplier 69t, Titanium



Flaw Multiplier Comparison, Aspect Ratio 0.1, Al

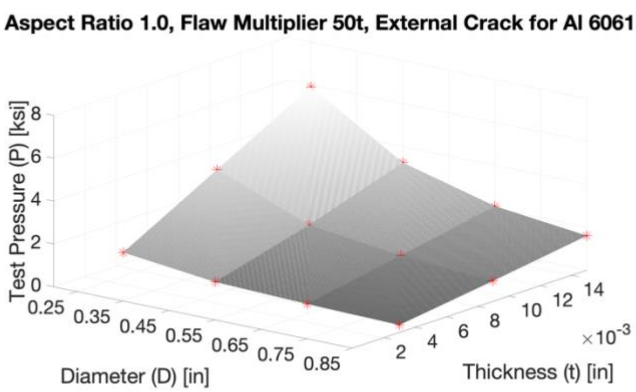


Flaw Multiplier Comparison, Aspect Ratio 0.1, Ti

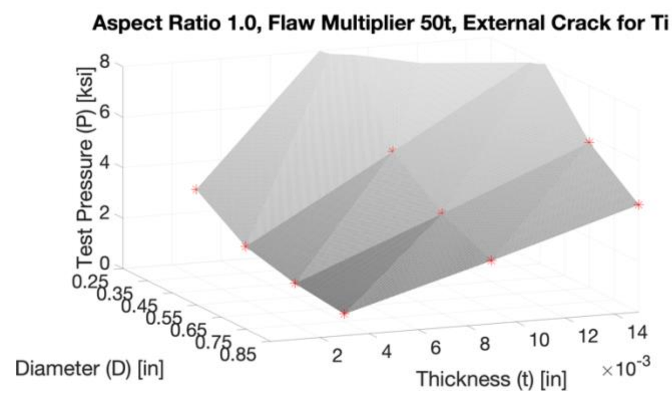
Figure 5. Failure Envelope Plots for Aspect Ratio 0.1.

For the aluminum cases, test pressures for screening appear to be near-identical in low thicknesses, regardless of the initial flaw multiplier. Flaw multipliers appear to affect the test pressure at higher thicknesses, where the lower flaw multiplier required a higher test pressure to screen the tube. The inverse is true in the case of comparing flaw multipliers to the diameter/thickness. For higher D/t ratios, the test pressure is near-identical for all flaw multipliers. Higher test pressures to screen the tube appear in the cases of lower D/t ratios and smaller flaw multipliers.

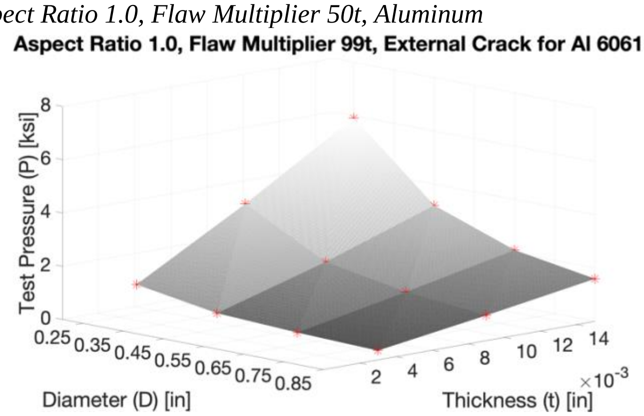
More realistic cases than crack aspect ratios of 0.1 can also be identified through this method and data manipulation. Plotted below are failure envelopes for aluminum and titanium but with crack aspect ratios of 1.0. The results do not predict any fracture failures, but like in Figure 5, indicate flaw screening for different single load cycle proof test scenarios. After examination of the aluminum cases, there appears to be little-to-no difference when varying the flaw multiplier as plots for both the Flaw Multiplier 50t and 99t appear to be the same.



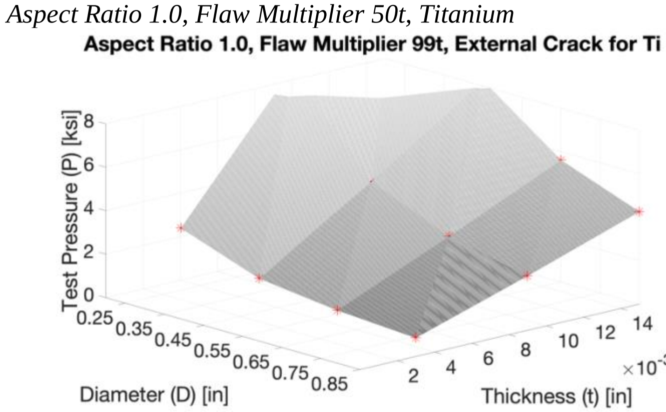
Aspect Ratio 1.0, Flaw Multiplier 50t, Aluminum



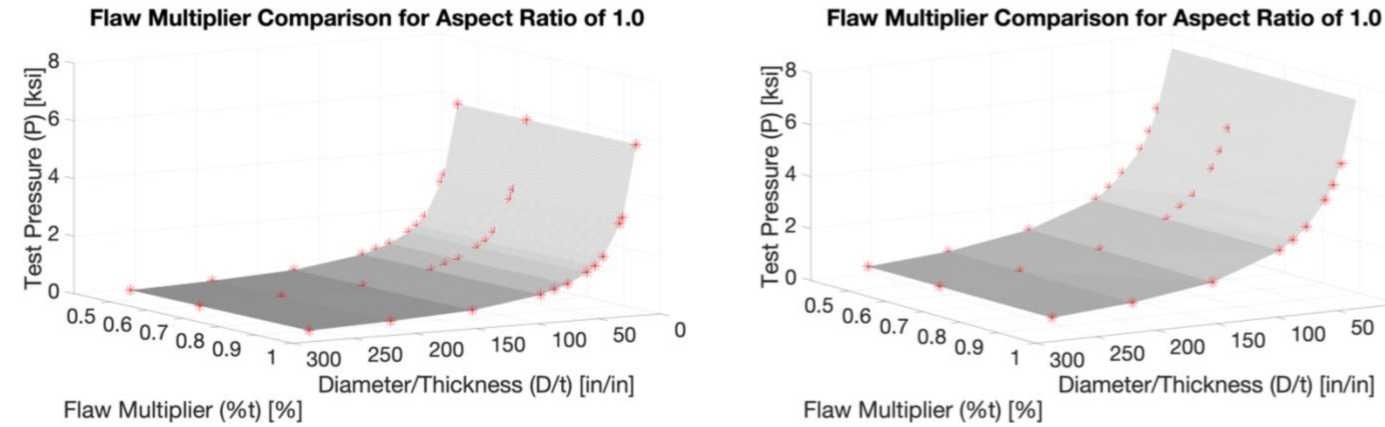
Aspect Ratio 1.0, Flaw Multiplier 50t, Titanium



Aspect Ratio 1.0, Flaw Multiplier 99t, Aluminum



Aspect Ratio 1.0, Flaw Multiplier 99t, Titanium



Flaw Multiplier Comparison, Aspect Ratio 1.0, Al *Flaw Multiplier Comparison, Aspect Ratio 1.0, Ti*

Figure 6. Aluminum Failure Envelope Plots for Aspect Ratio 1.0.

B. Combined Failure Envelope Plots

The other valuable aspect of this work is the ability to directly compare materials. This helps inform on how the two materials may fail or transition to a through crack. Shown in Figure 6 below is the comparison of aluminum in red and titanium in blue. In accordance with their material properties, the strength of titanium over aluminum is clearly shown as it fails at higher proof pressures compared to aluminum.

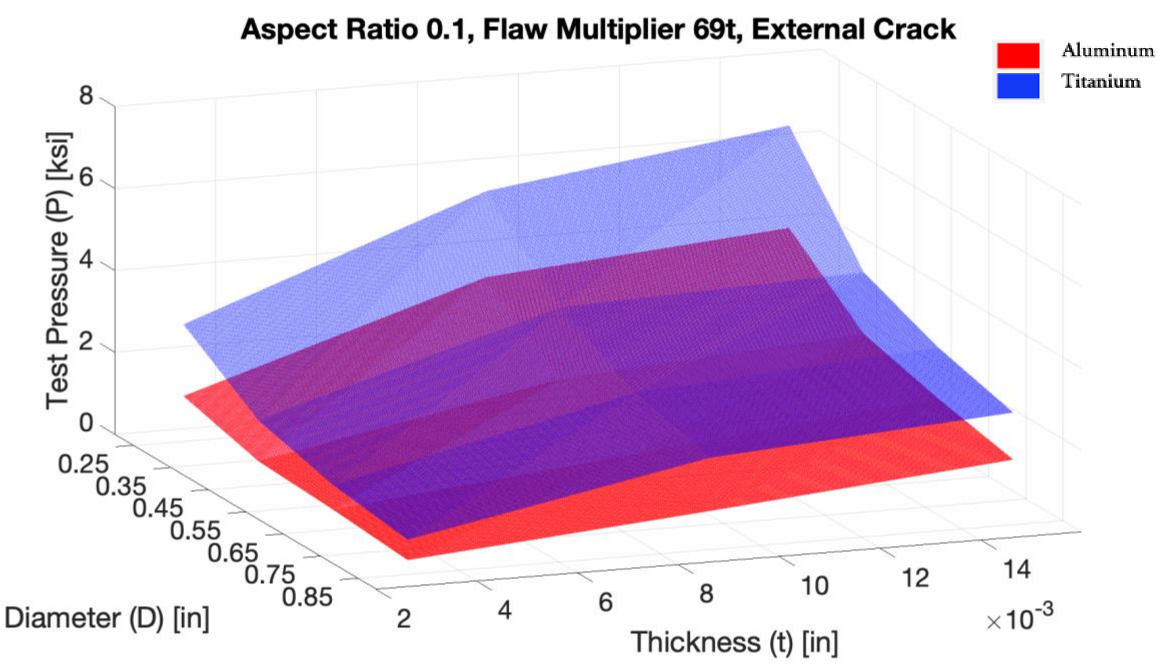


Figure 6. Aspect Ratio 0.1, Flaw Multiplier 69t.

VI. Conclusion

Proof tests are a useful tool to aid in proving structural integrity of a part. They are especially important in defining how defects may result in catastrophic failures. This paper defines failure envelopes of both aluminum and titanium thin-walled pressurized tubes with defects intended for aerospace structures. With these results, structural engineers in all industries can quickly understand if the design parameters of a thin-walled pressurized tube will pass or result in a fracture failure after one loading cycle. The use of NASGRO allows for predictions of crack propagation and fracture failures. This tool can be used prior to testing parts in labs to quantify the effectiveness of a proof test. This insight also may be useful in risk management where proof testing is used for hazard mitigation. Future work includes building failure envelopes encompassing more materials to build a library for SMEs to refer to when quickly analyzing if a specific (thickness, diameter, flaw multiplier, and aspect ratio) thin-walled pressurized tube design is conducive to proof test screening. It is also desirable to eventually validate these analysis results with laboratory tests.

Acknowledgments

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