Evaluation of Progressive Failure Analysis and Modeling of Impact Damage in Composite Pressure Vessels

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NASA White Sands Test Facility (WSTF) is leading an evaluation effort in advanced destructive and nondestructive testing of composite pressure vessels and structures. WSTF is using progressive finite element analysis methods for test design and for confirmation of composite pressure vessel performance. Using composite finite element analysis models and failure theories tested in the World-Wide Failure Exercise, WSTF is able to estimate the static strength of composite pressure vessels. Additionally, test and evaluation on composites that have been impact damaged is in progress so that models can be developed to estimate damage tolerance and the degradation in static strength.

Nomenclature

WSTF: White Sands Test Facility
CPV: Composite Pressure Vessel
PFA: Progressive Failure Analysis
FE or FEA: Finite Element or Finite Element Analysis
WWFE: World Wide Failure Exercise
σ: Stress
    Subscripts: l = longitudinal; h = hoop or transverse; x,y,z = local coordinates
τ: Shear
    Subscripts: x,y,z = local coordinates
p: gauge pressure
d: diameter of the pressure vessel
t: wall thickness of the pressure vessel

I. Introduction

Composite pressure vessels (CPVs) offer a significant weight reduction and gain in strength that makes them ideal for high performance aerospace applications including commercial space transport and International Space Station. CPVs perform the task of holding a fluid under pressure, and in many cases they utilize a metallic or polymer liner to prevent leakage. The most common types of composites used in CPVs are fiber-reinforced polymers with glass, Kevlar®[1] or carbon filaments. The ability to hold fluids at higher pressures with reduced weight compared to traditional metallic pressure vessels comes with additional structural complexity. CPVs are critical components in commercial and aerospace applications; therefore, it becomes important to model how they respond to pressure as well as external forces.

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[1] Kevlar® is a registered trademark of E. I. Dupont de Nemours and Company, Wilmington, Delaware.

II. Basic Modeling

CPVs are composed of a composite material with or without a metallic liner, and due to anisotropic material properties are more complicated to evaluate than metallic pressure vessels. Of the five common types of CPVs, the Type III CPV (fiber-reinforced vessel with metallic liner) is the most commonly used in aerospace since it offers a balance between low weight and low manufacturing cost. In the case of a basic thin shell model, the stress in the hoop direction is twice the stress in the longitudinal direction (Figure 1). Since the walls of a metallic pressure vessel need to be adequately thick to carry the load of the stress developing in the hoop direction, they are inefficient. This makes a metallic pressure vessel heavy compared to a CPV. In the case of composite materials, the fibers are strong normal to the fiber direction; therefore, with careful composite pattern design a CPV can be significantly lighter than a metallic pressure vessel for the same pressure rating. Using thin shell theory, stresses can be approximated as:

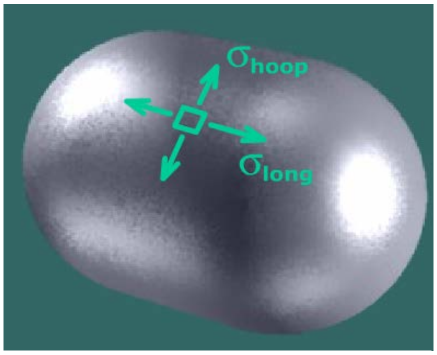

Figure 1: Thin Shell Model

1) $$\sigma_1 = \frac{pd}{4t}$$

2) $$\sigma_h = \frac{pd}{2t}$$

A common assumption for CPV thin shell models is that the walls of the pressure vessel are less than one-tenth of the radius of the vessel and, more importantly, that the stress through the thickness of the wall is negligible. Demonstrated with equations 1 and 2, a typical thin shell model lacks a third component of stress acting normal to the CPV inner surface and accounting for the gauge pressure contained in the vessel. A thick shell model assumes that the stresses through the thickness of the vessel wall will vary. Thick shell models are a step closer in accuracy for CPV analysis; however, both thick and thin models generally assume homogeneous, isotropic, and linear elastic material properties. Due to this fact, neither modeling approach is accurate for a CPV.

Complexities generally arise with the use of composite materials, especially in the case of a Type III CPV. The metallic liner is approximated as a homogeneous material that is isotropic and linear-elastic. The composite material is composed of semi-continuous filaments embedded in a polymer matrix resulting in a non-homogeneous and non-isotropic layup that has a viscoelastic mechanical response. The combined material types and anisotropy of the assembled CPV requires significantly complex calculations in trying to estimate structural response, ultimate strength and stress rupture. Further, the geometry of the vessel adds to the complexity of the analysis. Vessels can be spherical, cylindrical, toroidal, or other shapes. Cylindrical vessels have end domes of elliptical or hemispherical shape, and these geometric shapes are significant in the performance of the vessel.

A CPV can be evaluated and analyzed using several methods, some being more accurate than others. Two common methods are either a netting analysis or quasi-isotropic analysis. Both methods use simplifying assumptions in order to obtain solutions. “Netting analyses assume that all loads are supported by the fibers only, neglecting any contribution by the matrix and any interaction between the fibers" [1]. "A quasi-isotropic laminate is one that approximates isotropy by orientation of plies in several or more directions in-plane" [2]. Figure 2 shows the general trend of both a netting and quasi-isotropic analysis as a function of pressure. In the general case of a CPV, failure never occurs at the ultimate tensile strength of the fiber. There is a combined stress state that is much more complex; therefore, both the netting and quasi-isotropic analyses tend to overpredict the global failure strain of a CPV. Both methods subsequently need "knockdown" factors to estimate the strength of a vessel. Both methods do, however, provide a quick approximation of the performance of a CPV.

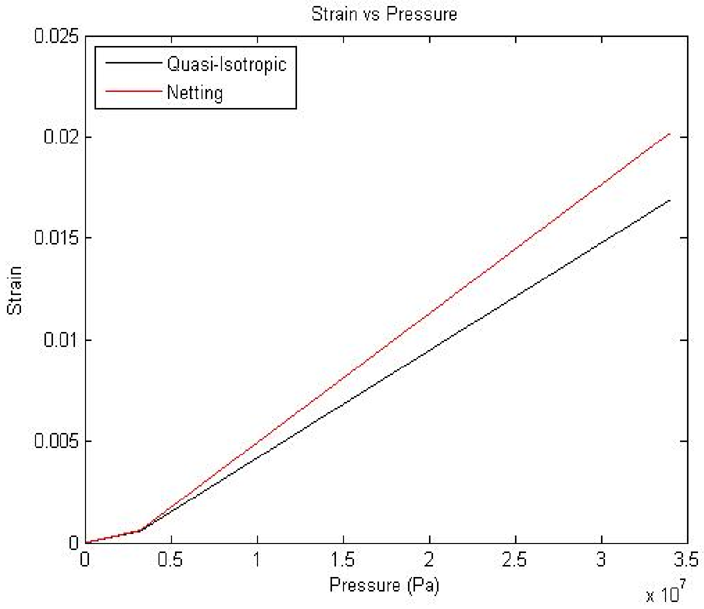

Figure 2: Quasi-isotropic vs. Netting Analysis
[A modified program written by Jeremy Bruggemann showing a comparison of netting and quasi-isotropic analysis]

It quickly becomes apparent that a much more accurate method of analysis is needed to describe the mechanical response of CPVs. Several other more rigorous methods can be used for the design process and design evaluation, including finite element analysis (FEA). FEA can be more accurate in estimation of mechanical response than previously mentioned approaches, yet still requires considerable improvement to provide accurate blind predictions without "knockdown" factors. FEA is currently being used along with many destructive and nondestructive methods for evaluation of CPVs through design and through the design confirmation process. CPV FEA uses numerical mathematics methods and composite failure theory to predict stress and failure based on relationships between forces applied, material properties, and local rotations and displacements.

III. Failure Theories

Many theoretical failure criteria have been developed with varying levels of accuracy, with most being specialized to their specific engineering origin. As an example, in the 1970s engineers in the aeronautical industry were interested in the use of carbon fiber as a lightweight, high-performance replacement for aluminum aircraft components. At the time, a ply pattern of

[0˚, +45˚, 90˚,-45˚] was used to produce a quasi-isotropic material with a Youngs modulus similar to aluminum in all directions. One of the important assumptions was that the fiber was the dominant load bearing component, so the matrix was ignored. This method is adequate for many high factor-of-safety aeronautical applications; however, in a case where matrix failure plays a significant role in the structure, this assumption can overestimate the ultimate strength of a laminate, leading to safety issues [3]. From the "World-Wide Failure Exercise" (WWFE), leading theories of composite failure criteria were evaluated against data including those from Puck, Cuntze, Bogetti, Zinoviev and Tsai. A summary of failure theory assumptions is given in Table 1.

Table 1 [3]

General Theories and Assumptions Used in WWFE

Theory	Lamina Strength Predictions	Non-Linear Analysis	Laminate Strength Predictions	Micro Mechanics	Fiber Failure Predictions	Post Failure Analysis	3D Analysis	Progressive Failure
Bogetti	Y	Y	Y	N	Y	N	Y	Y
Cuntze	Y*	Y	Y	N	Y	N	Y	N
Puck	Y*	Y*	Y*	N	Y	N	Y	N
Tsai	Y*	N	Y*	N	N	Y	Y	Y
Zinoviev	Y	Y**	Y*	N	Y	Y	N	Y

Y: The topic was included in the theory
N: The topic was not included in the theory
*   The predictions performed well in terms of experimental accuracy
** Zinoviev assumed linear behavior until initial damage then went to nonlinear

Based on the results of the WWFE, composite failure theories had significant variability in failure prediction accuracy. Several performed well with experimental error of about 10 % in specific loading cases, yet in other loading cases variability from the test data was much greater. Experimental testing is required to evaluate and develop better composite failure theory. Tsai uses the well known Tsai-Wu theory, which works well for loading cases of bi-axial tension. In the case of a CPV, the dominant force is assumed to be tension, and therefore a Tsai-Wu may be an adequate failure theory to use in CPV FEA. In many cases other than in a bi-axial compression state, Tsai-Wu proved to be fairly conservative and reasonably accurate. In the bi-axial compression state, Tsai-Wu overpredicted the strength of the structure by a factor of 4.15 [3]. Puck and Zinoviev had accurate results in bi-axial tension; however, it is noted that in this state they experienced numerical convergence issues. In general, failure theories were used to predict initial composite failure but did not accurately predict the coupon global failure strength. Using failure theories that predict reductions in material properties due to fiber or matrix failure for structural failure prediction, the modeler must consider that the predicted ultimate laminate strength using WWFE failure theories was in error by factors of up to 50 % [3]. Treatment of composite failure theories is critical in the accuracy of any FEA prediction. Several composite failure theories perform well in specific cases and poorly in others. For a composite FEA approach, it is important to document and understand the limitations of the model and the failure theories used for analysis.

IV. Progressive Failure Analysis Model Building

A progressive failure analysis (PFA) takes the traditional FEA method and adds two features important for the analysis of composite structures. First, a PFA will incrementally load the structure and attempt to track damage as it progresses through the structure, while updating the geometry of the structure as a result of this damage. Second, a PFA will adapt its FE mesh and material properties during the FEA to reflect any damage that appears. An FEA software package will generally incorporate assumptions using a theoretical failure criterion of a composite laminate in order to predict failure. Several commercially available PFA packages intended specifically for composite structures include:

1) Genoa PFA (Alpha STAR Corporation, Long Beach, California)
2) Abaqus® (Dassault Systèmes SIMULIA, Paris, France)
3) FireHole (FireHole Composites, Laramie, Wyoming)
4) HyperWorks® (Altair Engineering, Troy, Michigan)

Some companies provide an FEA package that will perform the evaluation of the composite structure standing alone, and other companies provide packages that will perform composite evaluation and return the resulting data to be processed by an external FEA solver. In the latter case, a failure theory is used to describe the response of the composite structure within the composite evaluation package at a given load.

An additional consideration in FEA modeling is in the accuracy of the user input parameters. The classic saying in FEA is “garbage in, garbage out,” meaning that if the composite properties and approach used to develop the model and input by the user are flawed then the output inherits the associated error. Given many uncertainties in the as-manufactured layup, it is difficult to accurately define the geometric FEA model. Another challenge is in defining the properties of the materials used in the construction of the composite. The mechanical and thermal properties are likely to have variance from the designer’s expectation. Further, variability in the manufacturing process must be addressed. In addition, uncertainties in loading and operating conditions make accurately modeling the CPV a challenge.

Programs like Genoa, Abaqus, and FireHole are widely used, and use advanced modeling techniques specifically tailored for composites. Abaqus provides support for three-dimensional composite structures in addition to compatibility with other popular engineering software packages. FireHole, is not standalone but uses Abaqus or another FEA package to provide a solution. Genoa provides modeling of three-dimensional composite structures with a variety of weave patterns and an advanced micro-mechanics capability. Genoa also has a probability analysis module to account for uncertainties that affect the accuracy of composite FEA models. Genoa PFA has been cited to predict results with a 10 % error, in comparison with experimental data [4].

V. Composite Damage Due to Impact Loading

Damage due to an impact can significantly reduce the strength of a composite structure and therefore is a concern for high performance CPVs. For this reason it is important to know how damage progresses through a CPV and its overall effect on the strength and durability of a vessel. In many cases a CPV is a man-, mission-, and vehicle-critical component, and the understanding of damage due to mechanical, chemical and other environmental factors is critical for safe life.

The ability to model defects due to mechanical damage is important since pressure vessels are typically operated with energy that is high, and its release could cause catastrophic results. Experiments have been performed in which composite laminate plates were impacted with various levels of impact energy. Both thin and thicker laminates were tested with a thin-to-thick ratio of 0.59. After the impact, the plates were visually examined and then deconstructed in order to evaluate damage in the sub-laminate constituents. Nondestructive and destructive evaluation techniques were performed at WSTF to quantify and qualify the effects of damage due to impact, with consideration of how an FEA model can be used to provide an estimate of the ultimate strength [5]. The data generated from tests were archived for input into an FEA model in the future. Cracks were measured with a 6–in. Mitutoyo® Digital Caliper Model #CD-6” CS and recorded. An Olympus® SZX12 optical microscope with a built-in InfinityX camera was used to collect images of the impact induced cracks. Figures 3 and 4 show examples of damage observed in individual plies.

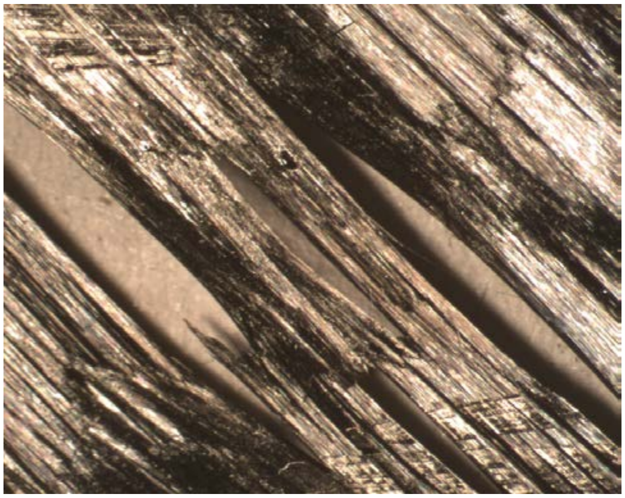

Figure 3: Damaged composite material

Figure 3 shows one of two common types of fractures that appeared in the laminate samples. The ply was deflected and bent into a concave shape, and the cracks that developed can be seen. These types of cracks will be particularly difficult to model since it is not clear exactly how much of the actual fiber has failed in the cracks. Also, it appears that significant gaps after thermal deply make measurement of these partial cracks difficult.

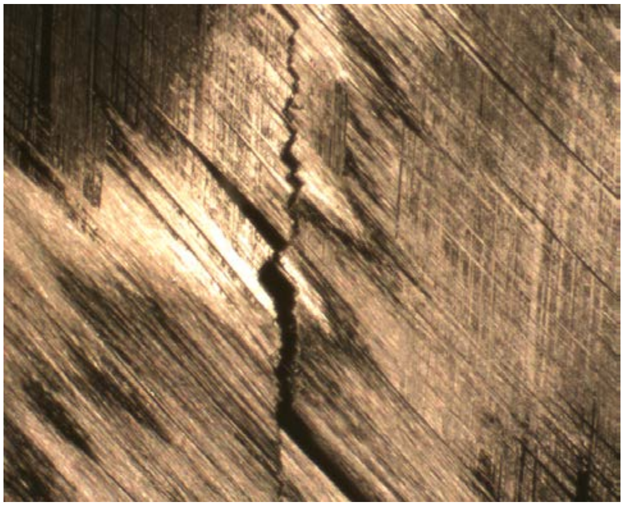

Figure 4: Damaged composite, showing stepped crack progression

The second most common type of ply damage is shown in Figure 4. In this case the crack progresses in a “stepped” fashion in which it travels parallel to the fibers then makes a 90-degree turn and moves perpendicularly to the fibers and follows this trend for the length of the crack. It is also interesting to note that the orientation of the crack is parallel to the orientation of the adjacent ply. The vertical impression of the adjacent ply can be seen and is roughly the same angle as the crack relative to the local fiber direction.

The lengths of cracks and any damage within the laminate plate were documented and are given in Figures 5 and 6. The vertical axis represents the ply number, with ply 1 being the ply in contact with the impactor. Many questions were raised from the data gathered in this experiment and several interesting facts observed. In Figure 5, the thin plates show an increasing amount of damage progressing through the thickness of the material. Also, the lower energy impact shows more damage in plies 2, 6, 10, and 14.

In Figure 6, the thick plates show some interesting trends. In the case of the two samples tested at lighter impact energies, no damage is visible at the surface of the laminate, yet the largest amount of damage is observed at ply 7. After this initial spike of damage at ply 7, the damage observed in the following plies is relatively small through the thickness of the laminate. When the impact energy is doubled, the damage increases drastically and the same damage spike is seen at ply 7. In both cases it seems that total damage does not necessarily increase linearly as a function of impact energy. The common trend across all of the thin and thick laminate samples was that the surface damage was generally much less than the subsurface damage, which is consistent with data from an earlier study that WSTF performed for the U.S. Air Force [6].

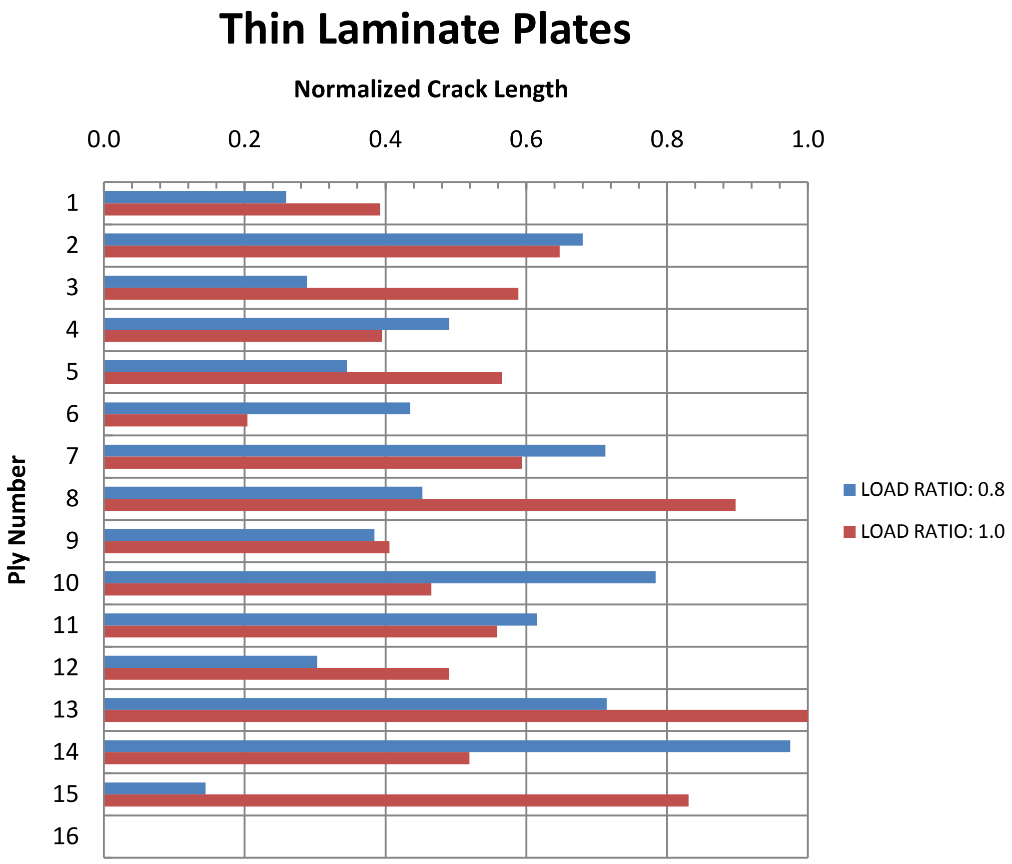

Figure 5: Thin laminate plate data

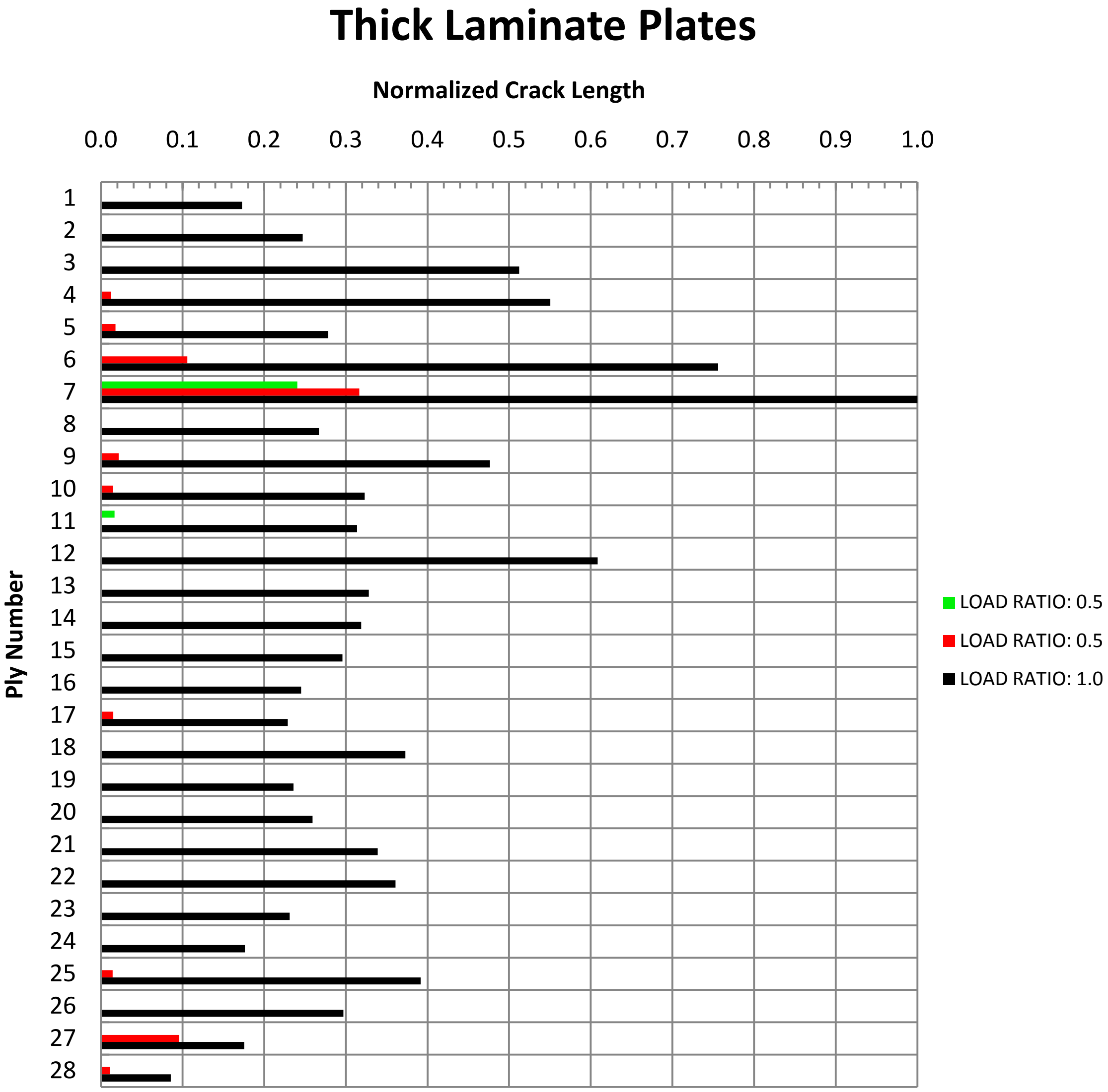

Figure 6: Thick laminate plate data

VI. Conclusions

As a result of the current test and evaluation at WSTF in composite failure theories, progressive failure finite element analysis, and impact damage in composite laminates, it is clear that additional test and evaluation needs to be performed in order to fill gaps in predicting pressure vessel failure. Accurate modeling and failure theories form the basis for PFA approaches, and predictions must be used with awareness of current limitations in accuracy. Adequate safety factors must be included in the design in order to account for uncertainties, and vessels must be protected from mechanical damage until FEA is able to model reductions in strength. Current composite failure theories need to be revised to improve the accuracy of composite FEA predictions and validated with test data. Significant effort is required to model mechanical damage in composite materials, and additional experimental data are needed to validate progressive failure models for CPVs. WSTF is working to develop new data and approaches for modeling composites and mechanical damage durability.

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List of Figures and Tables

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