Pressure Vessel Damage Tolerance Analyses – Some Issues

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Roy passed away about a year ago
and we miss him and his wise counsel

A Metallic Cylindrical Pressure Vessel (PV)

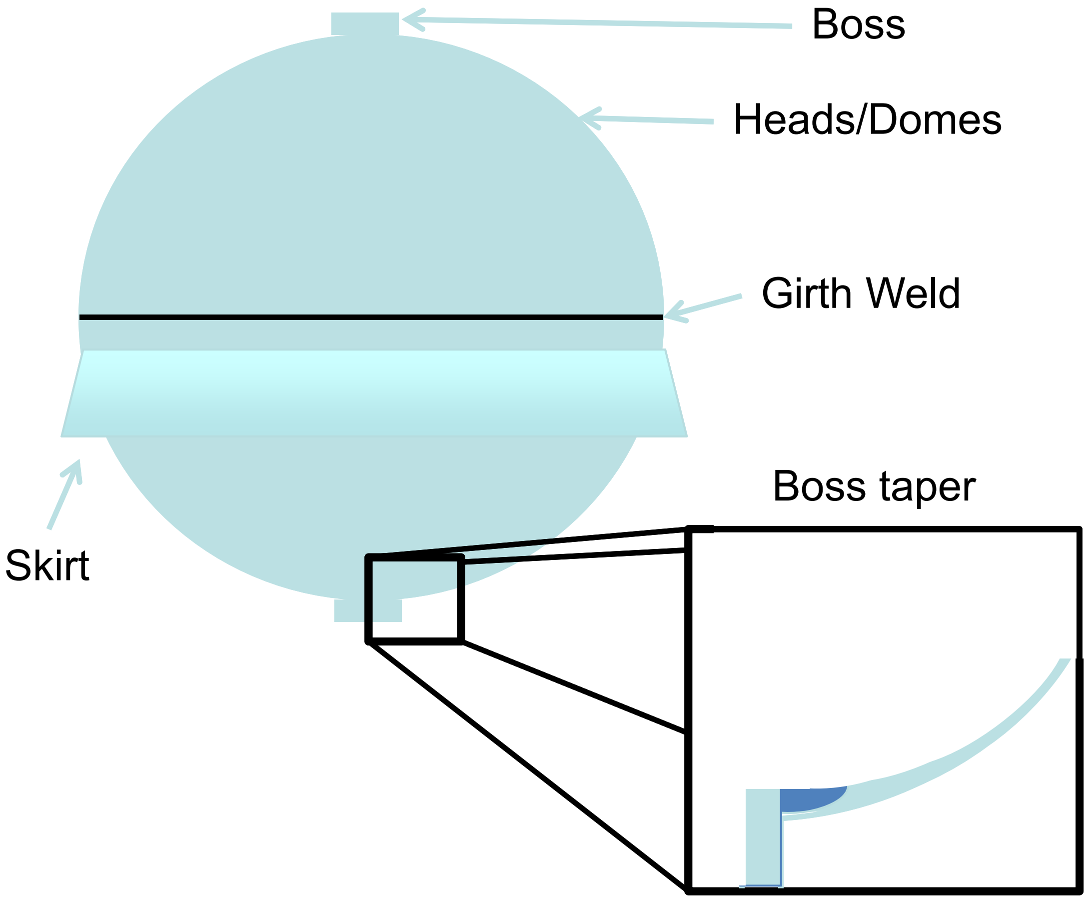
Composite Overwrapped Pressure Vessels (COPVs)

Cylindrical COPV

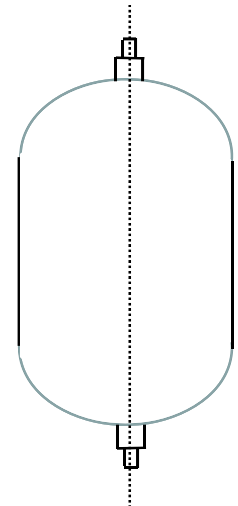
Spherical COPV

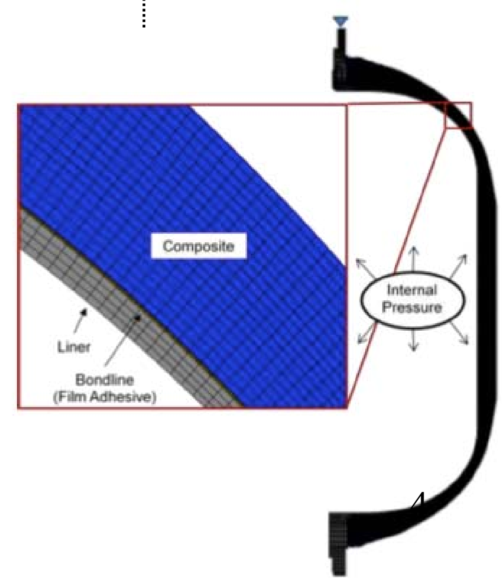
Spherical and Cylindrical COPVs

Spherical

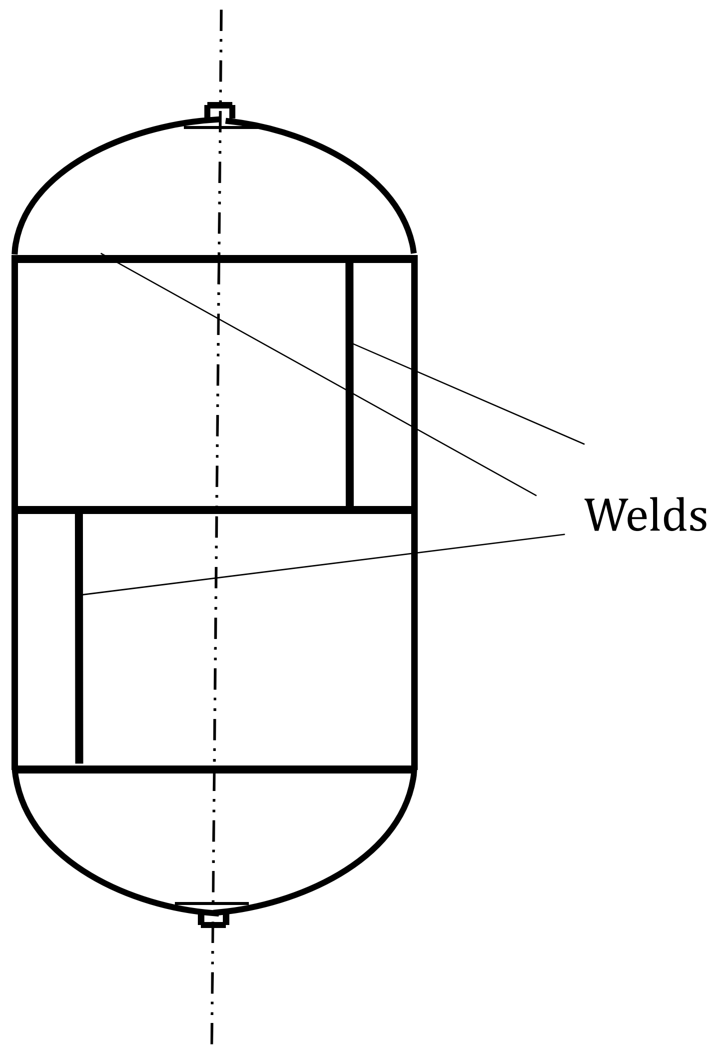


Cylindrical





Welded PV



Pressure Vessels

- PVs and COPVs are used to carry fuels in spacecraft
- Fuels are under high pressure
- Loss of containment and loss of mission can occur if PVs or COPVs fail
- Structural integrity of these very important
- Stringent Damage Tolerance (DT) requirements
  AIAA - S080 for metallic PVs and
  AIAA - S081, S081A for COPVs

General Requirements in S080

- Qualification of a design is based on both analytical and test data

- Analytical:
  - Strength, Stiffness, Thermal
  - Stress Analysis
  - Fatigue
  - Safe-Life (damage tolerance life)
  - Leak before burst (LBB)

- Tests:
  - Material data (K_{1E}, K_R, K_{IC}, da/dN, K_{1EAC}) and allowables (A basis)
  - S-N
  - Safe-life (damage tolerance life) if not by analysis
  - LBB if not by analysis

- Qualification tests are performed on a representative pressure vessel to provide evidence that the design will meet structural requirements and acceptance tests show that an individual flight pressure vessel is “in family” with the design

Fracture Control requirements in S 080

Fracture Control: The application of design philosophy, analysis method, manufacturing technology, quality assurance, and operating procedures to prevent premature structural failure due to the propagation of cracks or crack-like defects during fabrication, testing, transportation and handling, and service.

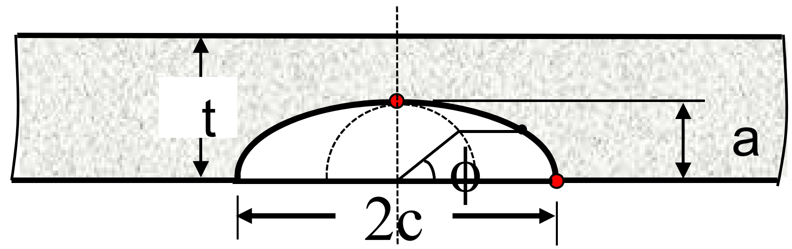
Two methods for demonstration of fracture control: leak before burst (LBB) or damage tolerance (safe-life).

- LBB is about crack stability in the liner for a worst-case NDE defined initial crack.

- Damage tolerance is about crack depth and length growth of an NDE-defined initial crack during 4 mission duty life cycles

Damage Tolerance (Safe) Life

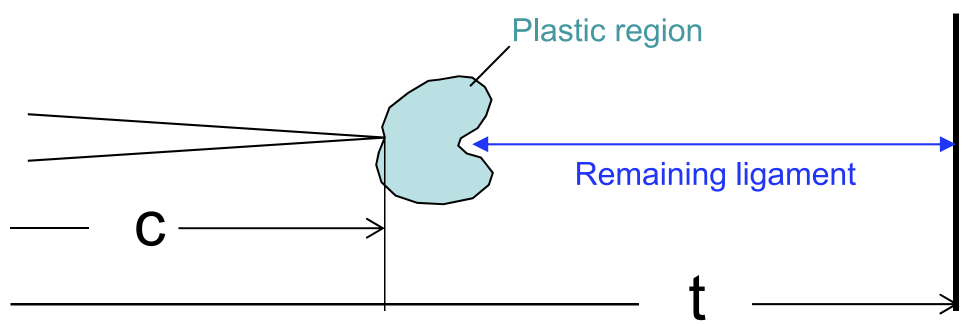
- For both hazardous and non-hazardous fluids where a leak would be catastrophic or would result in loss of the mission
- Damage tolerance means that the number of cycles or period during which a vessel, containing a crack at the NDE limit, is shown by analysis or testing not to fail or leak in the expected service load and environment
- Demonstrate 4x service life with initial crack in the worst case location and orientation and defined by 90/95 POD
- Usually through Linear Elastic Fracture Mechanics (LEFM)



- Initial crack size is set by NDE
- Spectrum contains pressure cycles plus any significant combined or external loads
- Growth must also consider environment

LEFM- Assumptions

- Material of vessel away from crack tip/front is undergoing elastic deformations
- Plastic region ahead of the crack tip/front is small in comparison to the length of the crack
- Deformations outside the small plastic regions, are presumed to remain elastic
- Material is presumed to have a grain structure such that the integrated effects of the grains in these regions acts like a continuum



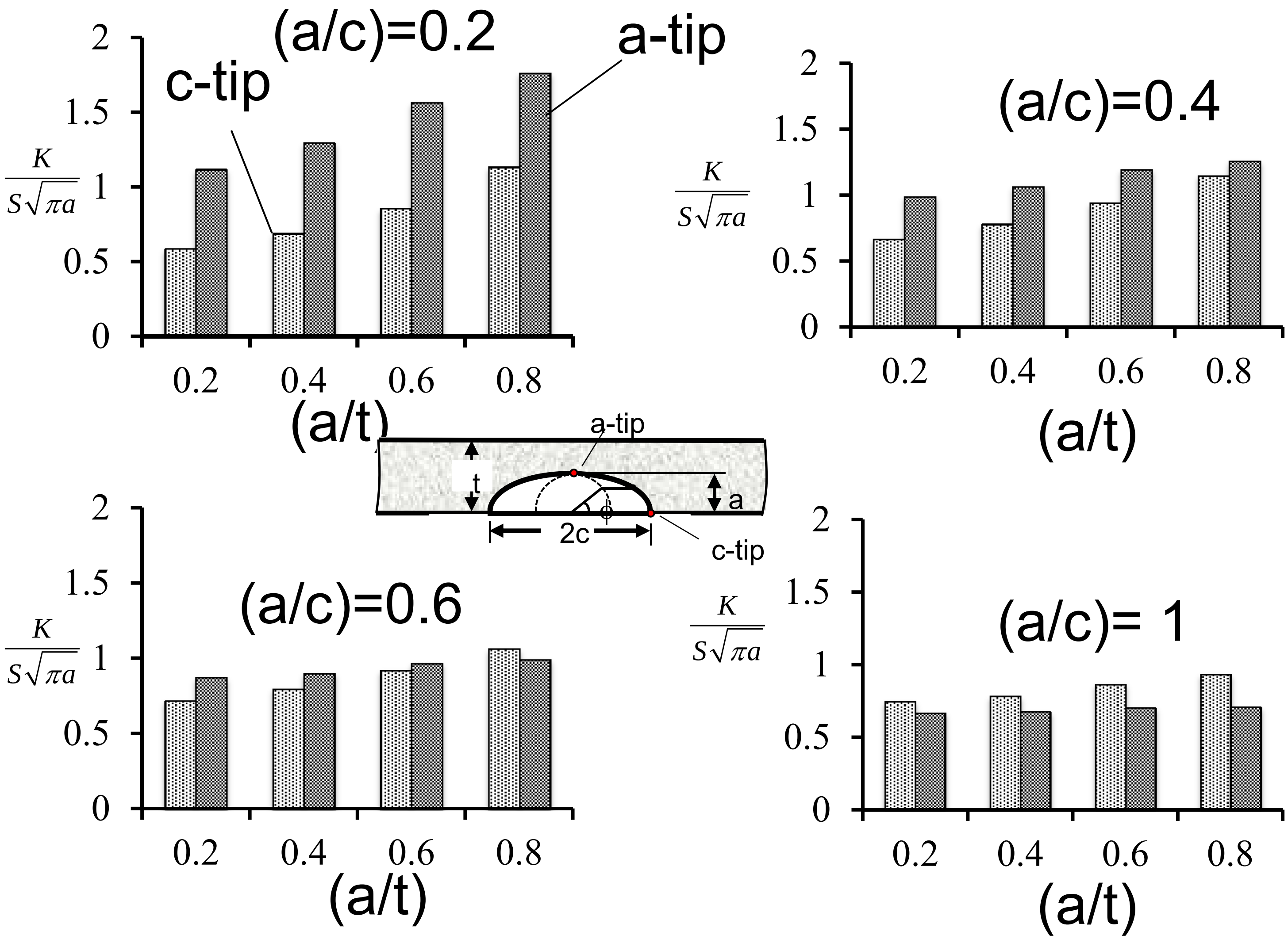
Critical questions and Objectives

While the standards S080 and S081 appear to be clear, various questions arise at the time of implementation

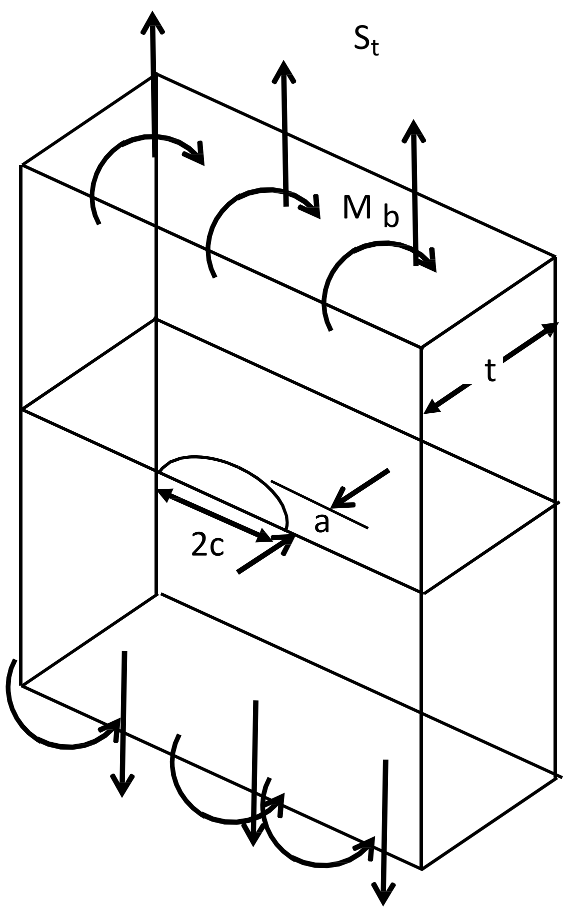
- How is the statement 'examine cracks in the range of (a/c) = 1 and 0.2 interpreted?'
- Does the K-values need to be examined at every point on the crack front?
- Where is the K-value maximum along the crack front?
- Are conclusions drawn for a particular liner region thickness, valid for the entire liner?
- If not, in what range are these conclusions valid?

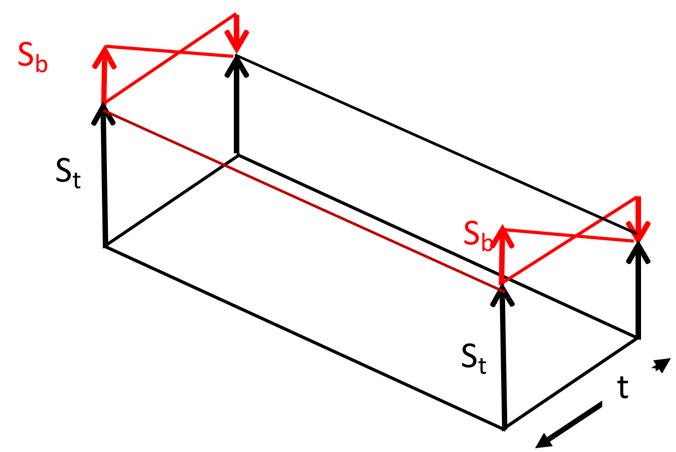
This work tries to answer some of these questions

Maximum value of K



Loadings

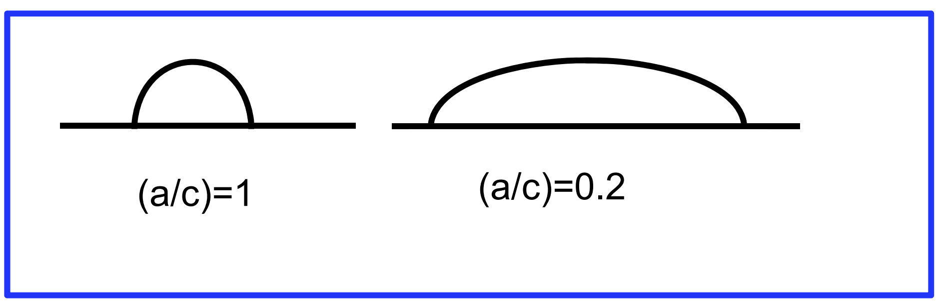


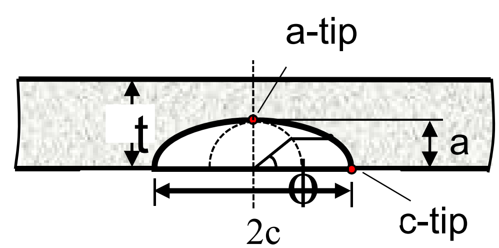


Remote Tension S_t and Bending S_b

NDE Detectability Limits
NASA-STD-5009

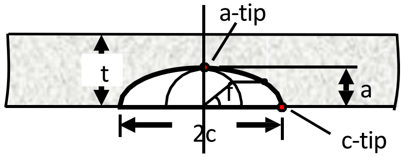
	a, in.(mm)	c, in.(mm)	(a/c)
	Eddy Current		
	0.02 (0.51)	0.10 (2.54)	0.2
	0.05 (1.27)	0.05 (1.27)	1.0
	Penetrant		
	0.025 (0.64)	0.125 (3.18)	0.2
	0.075 (1.91)	0.075 (1.91)	1.0
	Ultrasonic		
	0.030 (0.76)	0.150 (3.81)	0.2
	0.065 (1.65)	0.065 (1.65)	1.0
	Radiography		
t < = 0.107	0.7t	0.075 (1.91)	
	0.7t	0.7t	



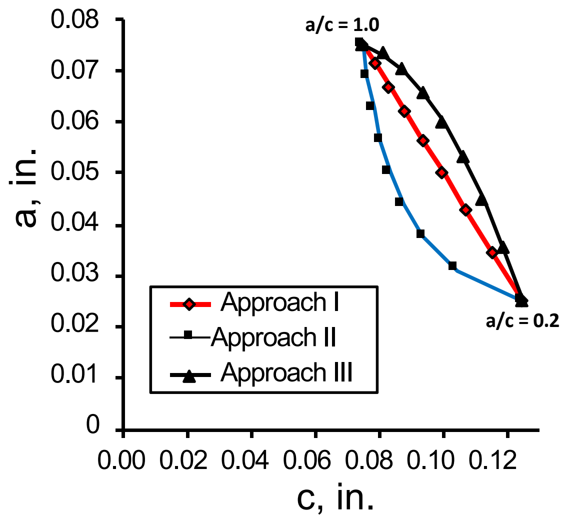


(a/c) range and interpolation

(a/c) range is 0.2 to 1



- Approach I: a is a linear function of c => a = *m* c + *r*
- Approach II: a is a linear function of (a/c) => a = *m* (a/c) + *r*
- Approach III: c is a linear function of (a/c) => c = *m* (a/c) + *r*



Penetrant NDE Detectible LImits

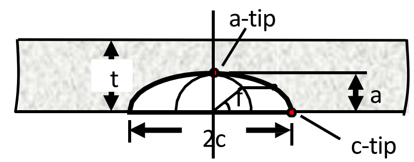
(a/c)=0.2 a=0.025, c=0.125

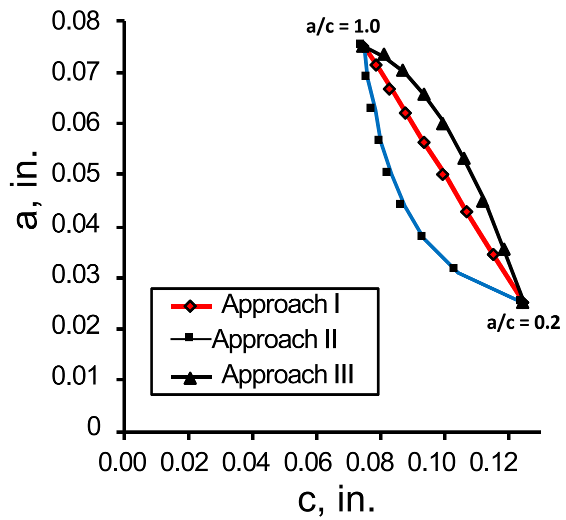
(a/c)=1 a=0.075 c=0.075

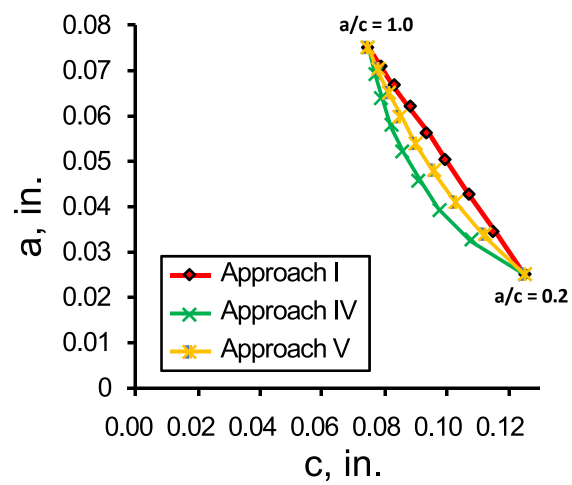
(a/c) range and interpolation

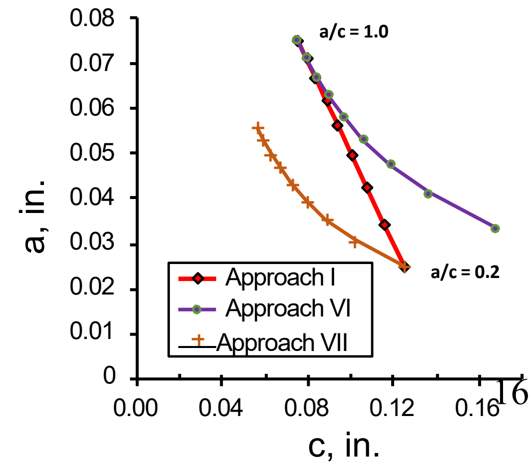
(a/c) range is 0.2 to 1

- Approach I: a is a linear function of c ===> a = *m* c + *r*
- Approach II: a is a linear function of (a/c) => a = *m* (a/c) + *r*
- Approach III: c is a linear function of (a/c) => c = *m* (a/c) + *r*
- Approach IV: crack area is linear function of a
- Approach V: crack area is linear function of c
- Approach VI: crack area is constant based on the value at (a/c)=1
- Approach VII: crack area is constant based on the value at (a/c)=0.2







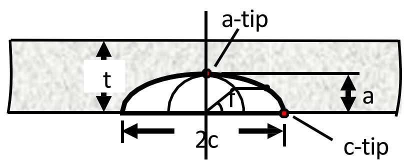


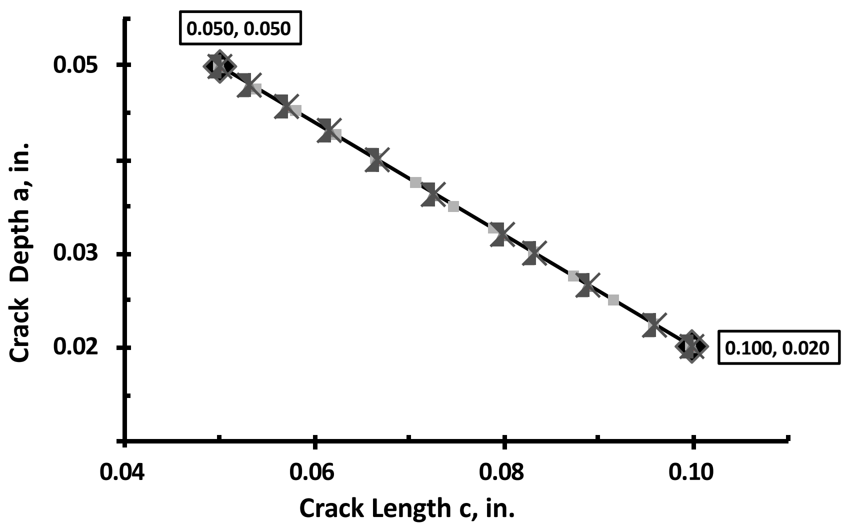
Life Calculations

- LEFM is assumed, NASGRO is used
- Al 6061-T6 Plate that is 3 in-wide is used
  Surface crack solution SC30 from NASGRO is used for K-solutions
  Remote 20 ksi tensile loading with R=0.1 at constant amplitude loading
- Starting from the surface crack (PTC) the crack is grown until the PTC transitions to a through crack (TC)
  $a => a + \Delta a$; $c => c + \Delta c$; leads to new crack shape (a/c) => new K-values, ….
- All available failure checks (K_{IC}, net section stress, plastic limit load) used
- All analyses predicted failure after the transition to a TC. All life is normalized by the smallest life

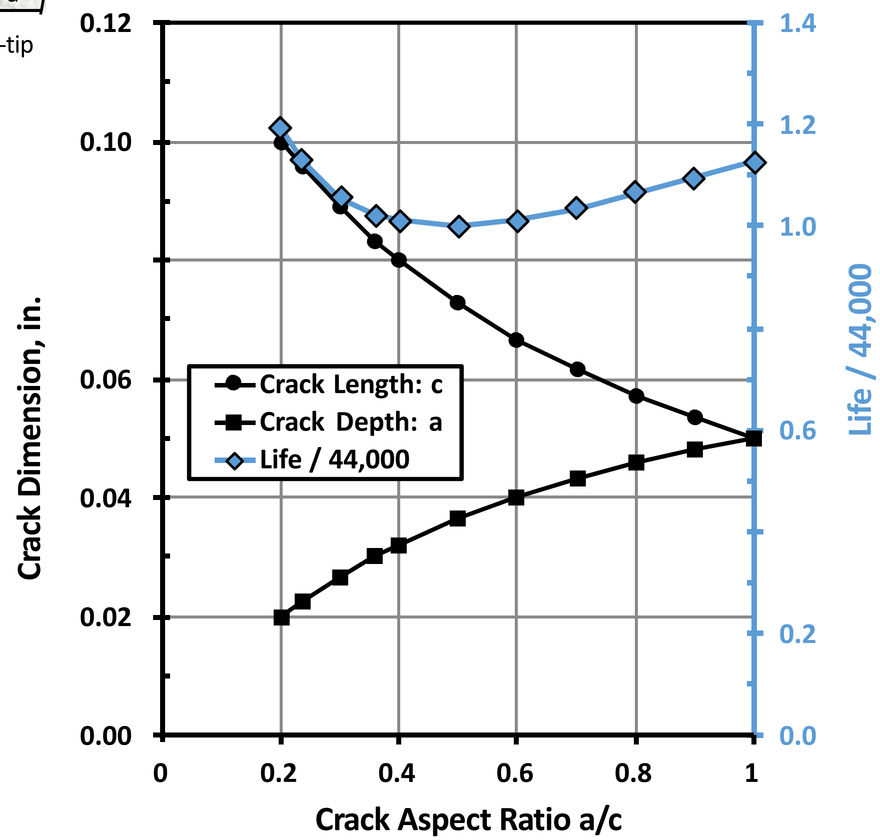
Remote tensile loading 20 ksi, t=0.1 in.

Eddy Current NDE





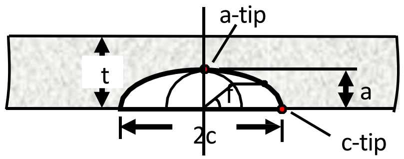
Eddy current aspect ratio endpoints and interpolated shapes using Approach I

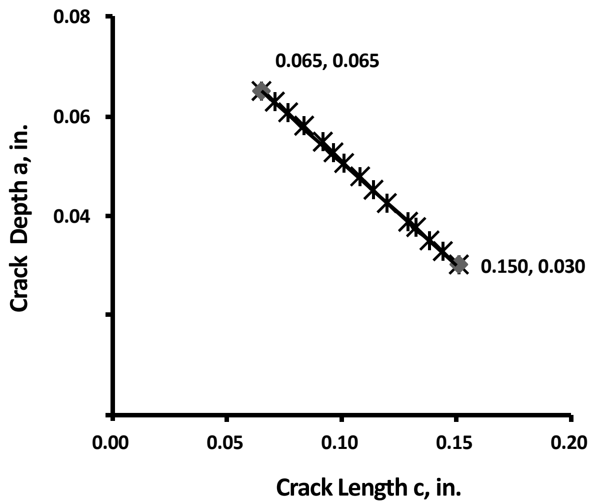


Calculated lives for interpolated crack sizes using Approach I

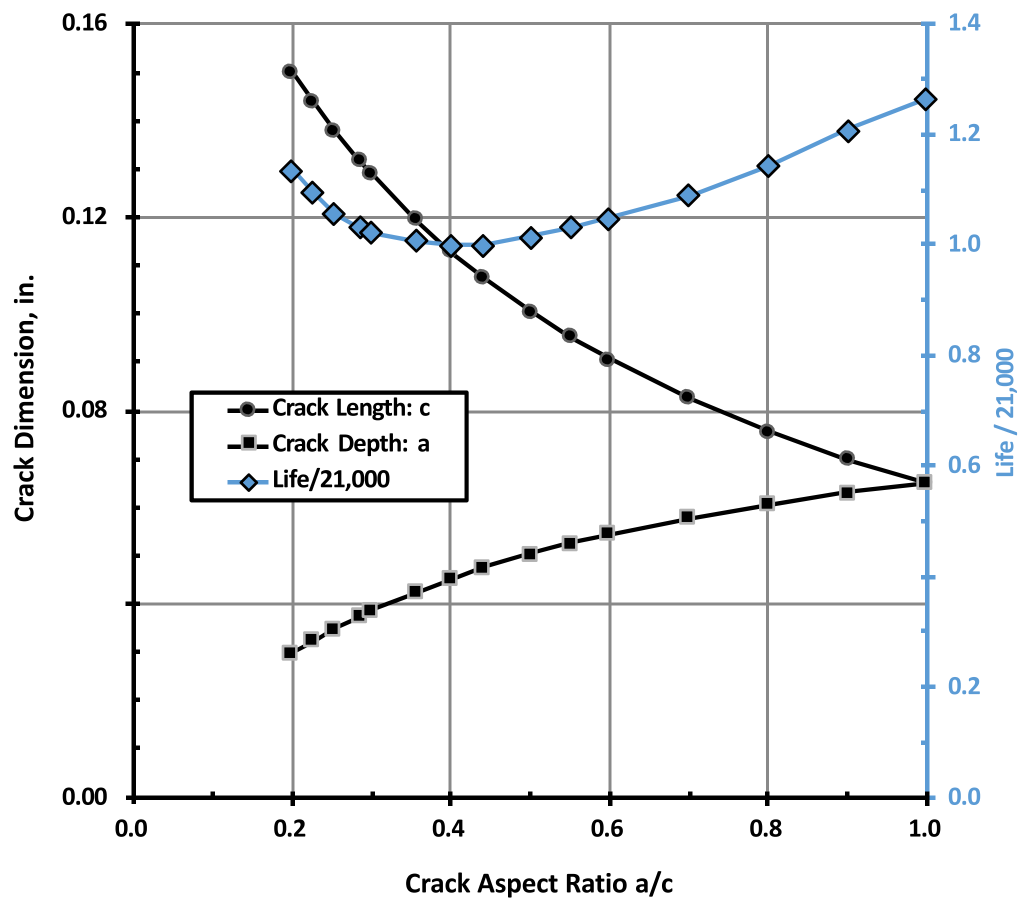
Remote tensile loading 20 ksi, t=0.1 in.

Ultrasonic NDE





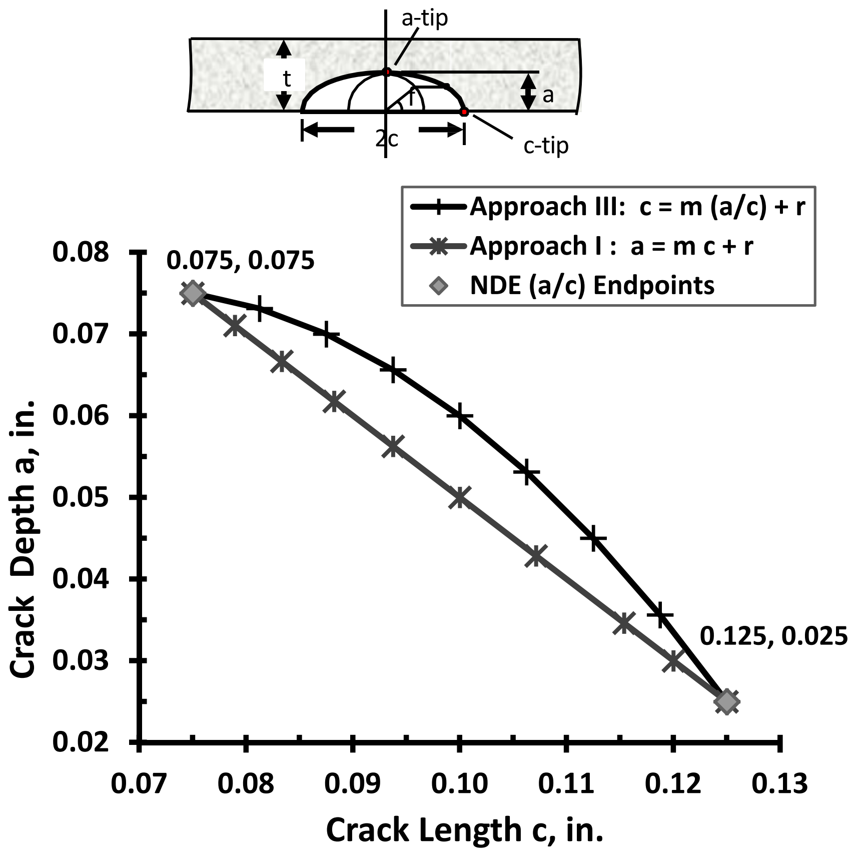
Ultrasonic aspect ratio endpoints and interpolated shapes using Approach I



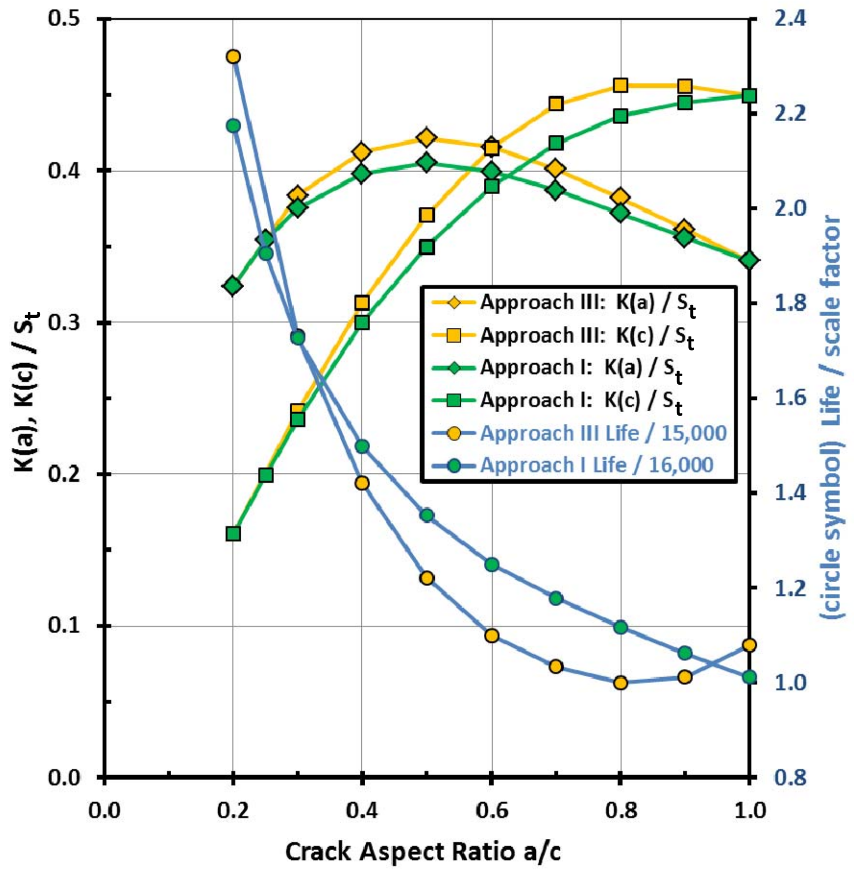
Calculated lives for interpolated crack sizes using Approach I

Remote tensile loading 20 ksi, t=0.1 in.

Penetrant NDE



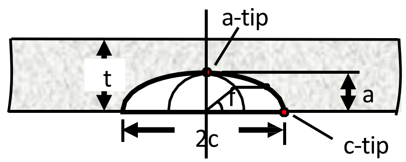
Penetrant aspect ratio endpoints and interpolated shapes using Approaches I and III

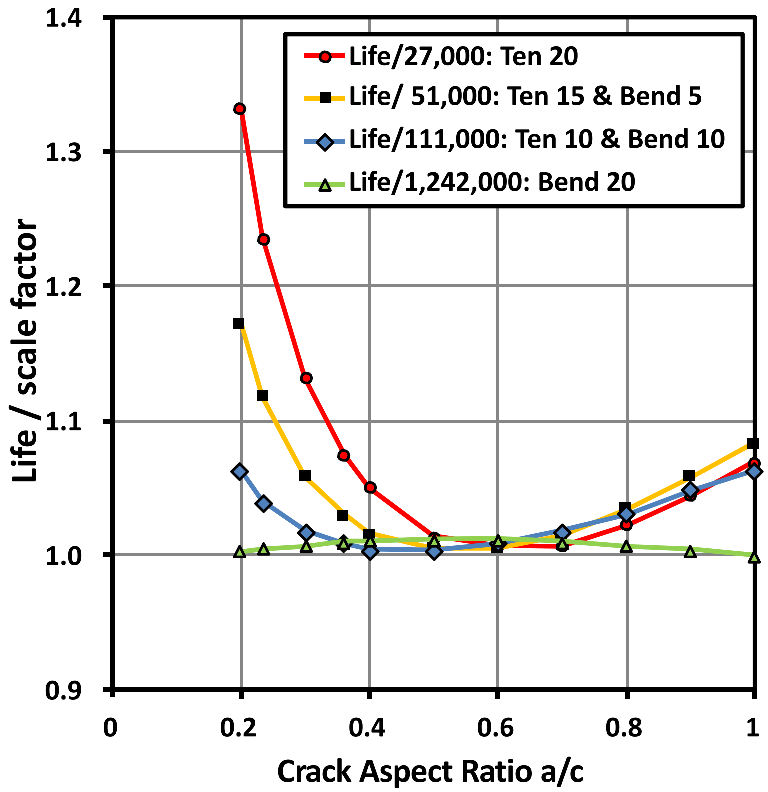


Initial crack tip K(a), K(c) for interpolated crack shapes using Approaches I and III, and computed lives at each aspect ratio

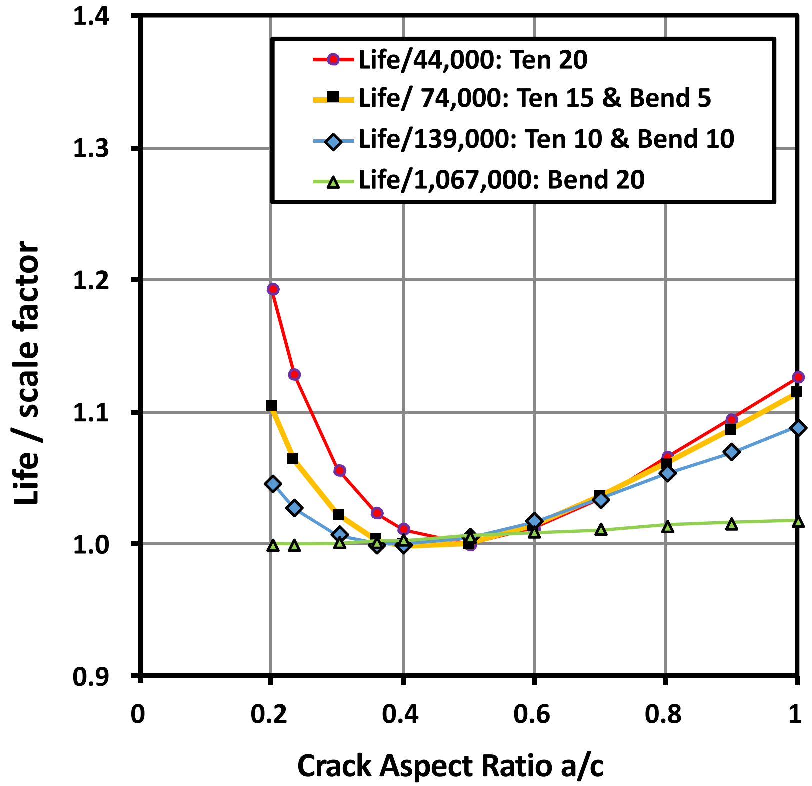
Normalized lives for various loadings

Eddy current- 20 ksi remote tension
and various tension and bending loads





Thickness of plate = 0.075 in.



Thickness of plate = 0.10 in.

Recommendations

The requirement that safe-life be demonstrated for the minimum detectible flaw sizes for specific NDE methods (as assessed by estimated 90/95 POD) requires an interpretation of the initial PTC size between the aspect ratio values (endpoints) listed in the NASA-STD-5009 (generally at an aspect ratio of a/c = 0.2 and 1). The choice of interpolation method for the PTC sizes between the listed NDE endpoints can influence the analytically predicted life.

The following recommendations are made based on the findings of this paper:

Table 1 of NASA-STD-5009 that lists the minimum detectible flaw sizes of various NDE techniques should be updated to include a minimum of three aspect ratios for each technique. It is recognized that this is a significant undertaking, but it is necessary to eliminate the ambiguity present in the current situation.

In the interim, i.e. before Table 1 of NASA-STD-5009 can be updated, the community should adopt a standard approach for the interpolation of PTC sizes from the listed NDE endpoints. There are two possible choices: Approach I or III as discussed in this paper. Without any other information, Approach III, as the most conservative, is a logical choice to be the standard method for interpolation between the listed crack length (c) and depth (a) values.

Summary

- Some observations on DT of PVs and COPVs discussed
- As is customary in DT analyses, minimum detectible cracks are assumed to exist in the PV oriented perpendicular to the maximum tensile principal stress. DT analyses then proceed to demonstrate 4 life times
- NASA STD 5009 is used with EC, PT, UT, and RT NDE methods to choose a part-through crack with (a/c) = 0.2 or 1
- Do we need to interrogate K all along the front? No need to – only the end points
- Where is the K-maximum? Max K occurs either at the surface point (c-tip) or the deepest point (a-tip)
- How is the statement 'in the range (a/c) = 0.2 and 1', interpreted'?

Summary (concluded)

- To answer this question, seven approaches for interpolation are proposed. Of these, two approaches are more conservative than others:
  - a is a linear function of c between the two endpoints (approach I) and
  - c is a linear function of (a/c) between the two endpoints (approach III)
- EC and UT give the smallest life at about (a/c)= 0.4, with approach I and *smallest life occurs away from the endpoints*
- PT gives the smallest life at (a/c)=1 with approach I (*but shifts to 0.7 or 0.8 with approach III*).
- Analyses that only interrogate the two end points (a/c) =0.2 and 1 *likely to result in unconservative life predictions.*
- The standard practice needs to be revised based on the results in this work.