Special Topic 2: Ply-Based Failure Criteria

ST2.1 — Overview

- Audience: primarily those taking the course or who have the book
  - some aspects are **theoretical in nature** (tangential topic)
  - **optional as part of the course**
  - course and the book provide the necessary background
  - may also be relevant to those familiar with composites (background knowledge required)

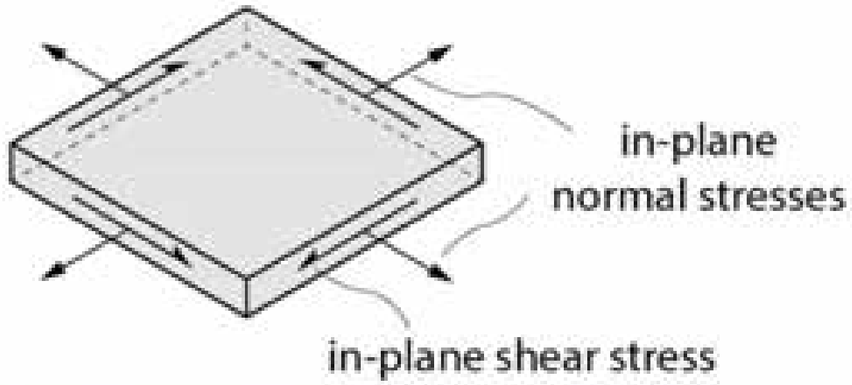
- **Offered as a Free video/PDF and part of the course**
  - *use of ply-based failure criteria is often a source of confusion for the analysis of composites*
  - contains some additional information not in the book

- Goals

1. Better understand the limitations of ply-based approaches for failure prediction of composite laminates
2. Demonstrate an effective approach for practical and accurate strength predictions

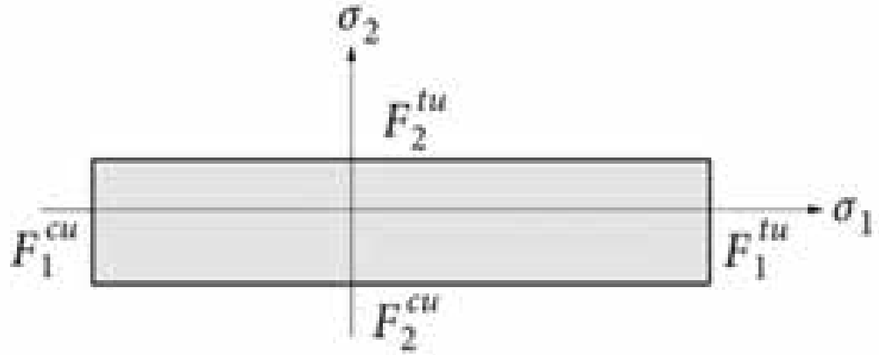
ST2.2 — Academic Objectives

- Ply-based criteria (2D)
  - use the in-plane (2D) stresses/strains in each **ply**
  - attempt to determine the strength of a **laminate**
  - for this discussion, consider the **ultimate strength prediction** (max load capability of a laminate) and not small scale "micro failures"



plane stress components in a ply

- Ply-based criteria commonly taught in academia
  - Max Strain, Max Stress (non-interactive)
  - Tsai-Hill, Tsai-Wu (interactive)
  - Other criteria

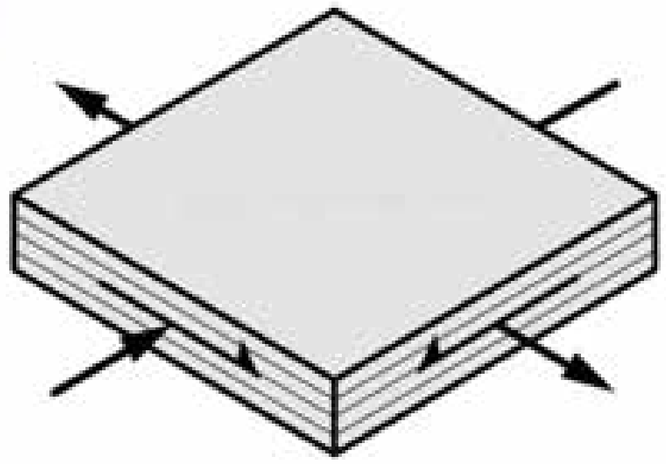


max stress criterion example for bi-axially loading of a ply (2D ply-based)

- Academic Objectives
  - introduce the student to some of the differences between metals and composites
  - seek "pure" failure criteria (research)
  - *may be different from industry objectives*

ST2.3 — 2D Ply-Based Criteria for Unnotched Strength

- Simple case: consider unnotched (pristine) multi-directional laminates (ultimate strength)
  - general in-plane loading
- Large study* conducted by Hinton, Kaddour, and Soden. Results:
  - estimate to within **± 10% in 40%** of cases*
  - estimate to within **± 50% in 35%** of cases*
  - error greater than **± 50% in 25%** of cases*



laminate with general in-plane loading

60% of cases have a large error

NOTE: For composite aircraft structures, we are usually interested in the ultimate strength because that is often the critical condition (at least for carbon fiber laminates).

Not usually interested in predicting the individual subcritical failure modes for carbon fiber laminates (i.e. matrix failures)

See also Chapter 2 and Chapter 24—Fatigue

*M.J. Hinton, A.S. Kaddour, P.D. Soden, "A comparison of the predictive capabilities of current failure theories for composite laminates, judged against experimental evidence", Composites Science and Technology, 2002, pp. 1725–1797.

ST2.3 — 2D Ply-Based Criteria for Unnotched Strength (cont.)

- Tension dominated failures more accurately predicted
  - more easily predicted by most criteria (tension failure of fibers is straightforward)
  - regardless, may still not be accurate

- In general, compression and shear loading predictions not expected to be accurate for **any** 2D ply-based criterion

- ***General loading: There is no ply-based criteria that is accurate***

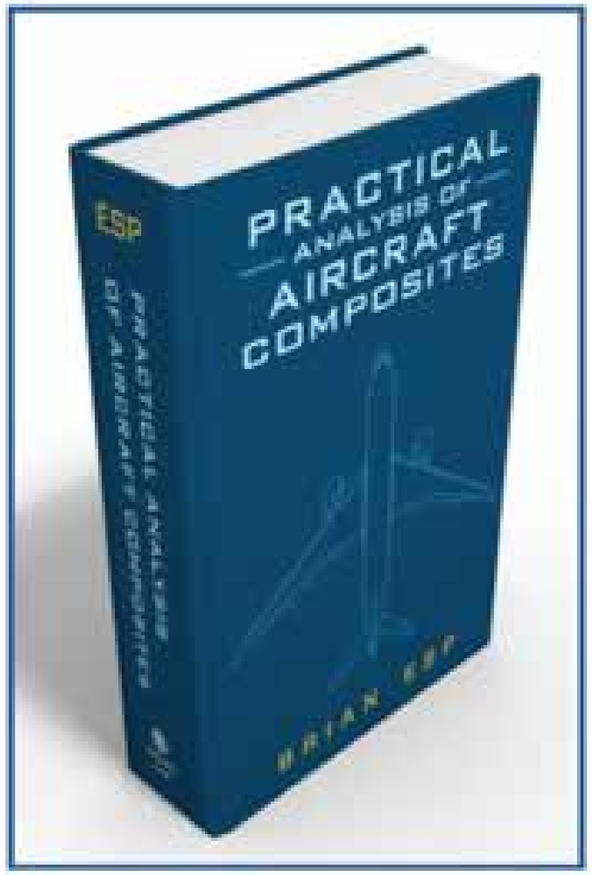
  - estimate to within **± 10% in 40%** of cases*
  - estimate to within **± 50% in 35%** of cases*
  - error greater than **± 50% in 25%** of cases*

  ← **60% of cases have a relatively large error**

*M.J. Hinton, A.S. Kaddour, P.D. Soden, "A comparison of the predictive capabilities of current failure theories for composite laminates, judged against experimental evidence", Composites Science and Technology, 2002, pp. 1725–1797.

ST2.3 — Ply-Based Criteria for Unnotched Strength (cont.)

- Why aren't predictions better for simple unnotched laminates?
  - many complex damage mechanisms (Chapter 9)
  - **Physical limitations** of ply-based criteria
  - Section 9.8 of the book
    - 10 physical reasons with 10+ supporting publications
  - See also Chapter 9 (part of the course)
- Testing by Hinton, Kaddour, and Soden demonstrated lack of accurate predictions (prior discussion)
- Skip to slide 14 for a useful engineering approach
- Otherwise, continue with a theoretical discussion about ply-based shortcomings for practical scenarios of laminates with holes and impact damage
  - *goal is to gain further insight about the challenges and complexity of failure prediction for composites*



ST2.4 — Hypothetical 2D Criterion for Practical Scenarios

- **Assume** a "perfect" 2D ply-based failure criterion exists (does **not** currently exist) that accurately predicts the unnotched strength of a laminate (general in-plane loading)

- However, unnotched laminates are not of practical concern for most aircraft structures, so consider **two practical scenarios** that were introduced in Chapters 1 and 2:

  1. **Small open hole** (further discussed in Chapter 10)
  2. **Post-impact strength** (further discussed in Chapter 20 of the book)

- What could be done with this perfect hypothetical 2D ply-based criterion?
  - could the "perfect" criterion be useful for practical aircraft scenarios?

ST2.4 — Hypothetical 2D Criterion for Practical Scenarios (cont.)

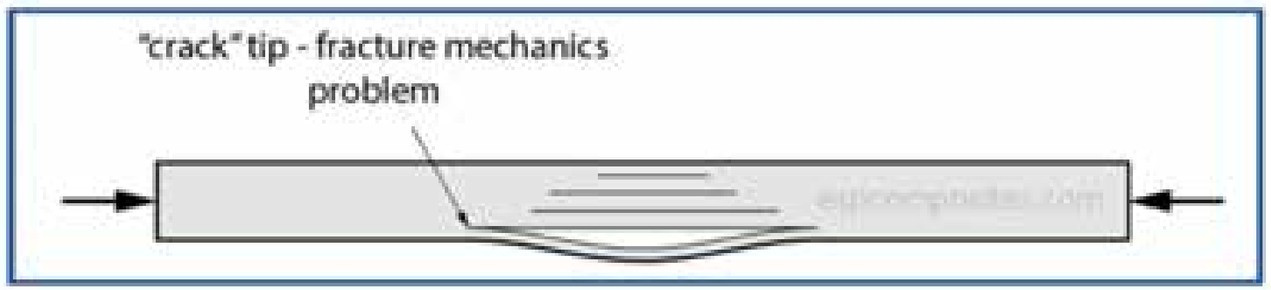
- **Notched laminates (consider a small open hole)**
  - Initially presented in Chapters 1, 2, and detailed discussion in Chapter 10
  - Conservative solution: Possible by using the peak stress concentration
    - overly conservative: composites would not able to compete with metals
  - Accurate physically consistent solution: **Not possible** because a significant effect is "pseudo-plasticity", which is **3D in nature (interlaminar stresses)** (See Chapters 8 and 10)
    - 2D ply-based criteria assume **plane stress (2D)**

SIDE NOTE: One can still develop a validated analysis method for notched laminates by using a ply-based criterion. This would be done by "correcting" the solution with test data (perhaps large corrections) and "backing out" the design values (See the ST1 video).

However, some would consider this to be physically inconsistent and not considered best practice. It may also be confusing/misleading since it implies that a ply-based criterion is able to capture the important failure mechanisms for notched laminates (which is impossible).

ST2.4 — Hypothetical 2D Criterion for Practical Scenarios (cont.)

- **Post-Impact Strength** (damage state **unknown**)
  - for large civil aircraft structures, it is required to assume there is undetectable damage (discussed in Chapter 25 of the book)
  - without knowing the actual damage state, there is no way to directly analyze (**testing of laminates is required**)
- **Post-Impact Strength** (damage state **known**)
  - damage (such as delamination) may be determined via NDI
  - delamination scenarios require a **fracture mechanics** solution (still evolving)
    - delaminations are effective "cracks"
    - Chapter 13 of the book discusses ILFM (interlaminar fracture mechanics)
  - stress/strain solutions **not appropriate** for "crack-like" behavior
    - can not use 2D ply-based failure criteria



ST2.5 — Hypothetical 3D Criterion for Practical Scenarios

- Now assume a "perfect" **3D ply-based** failure criterion exists for unnotched laminates (does not currently exist)
  - 3D criteria consider the interlaminar stresses (in addition to the intralaminar stresses)

- Post-Impact Strength scenario:
  - same as previous case (test based solution or fracture mechanics analysis)
  - 3D ply-based criteria would not be useful

- Small Open Hole scenario:
  - next slide

ST2.5 — Hypothetical 3D Criterion for Practical Scenarios (cont.)

- Small Open Hole
  - 3D criteria can somewhat address "pseudo-plastic" behavior (a 3D effect). However, we must also consider the "hole size effect" that composites exhibit.
    - further discussed in Chapter 10
    - effect of absolute hole size
  - Ply-based criterion (even if 3D)
    - a physically consistent solution for the hole size effect is **not possible**.
  - Physically consistent criterion
    - must go to the **fiber-matrix level (micromechanics)** to address both "pseudo-plasticity" and the "hole size effect"
    - next slide

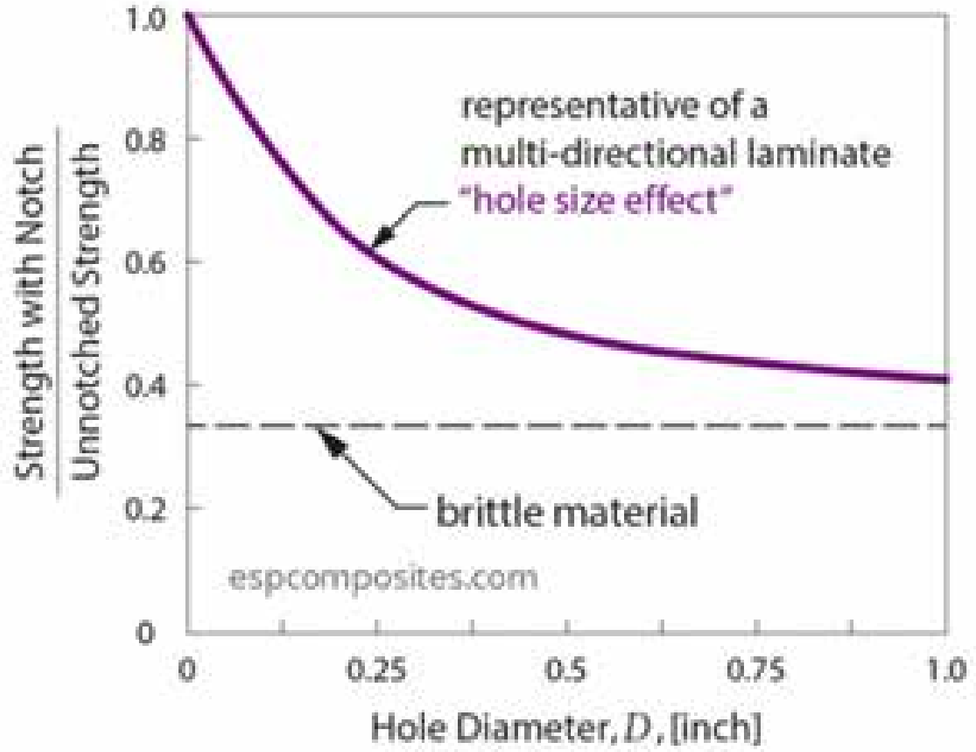
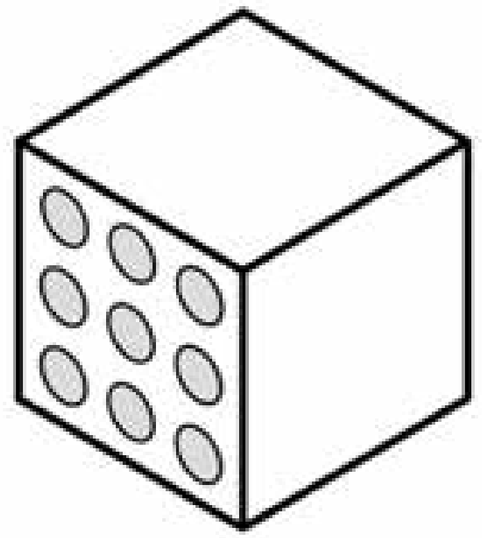


Figure demonstrates the "hole size effect"

(See also Chapter 10)

ST2.6 — Hypothetical Fiber/Matrix Criterion for Practical Scenarios

- Small Open Hole
  - must consider the complex mechanisms of "pseudo-plasticity" and the "hole size effect"
  - to capture these effects in a physically consistent manner, a **fiber/matrix level failure criterion is required (micromechanics)**



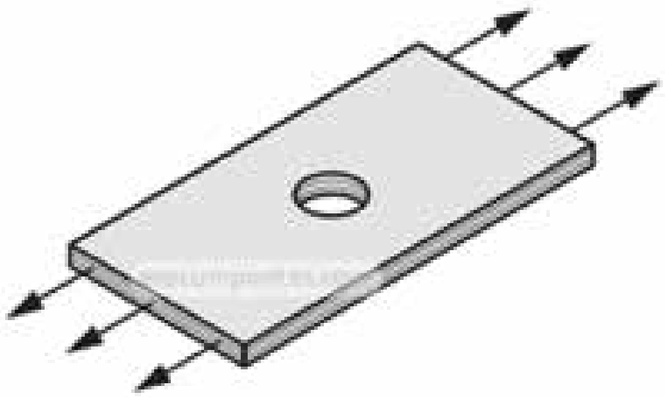
fibers and matrix constituents/properties considered

- SIFT (Strain Invariant Failure Theory)
  - fiber/matrix level criterion
    - theoretically capable of physically consistent predictions for laminates with open holes
  - appropriate fiber and matrix properties required (no standard tests)
  - detailed nonlinear FEA can be used (including damage progression)
  - specialized skill set
  - not currently practical for the vast majority of engineering applications
  - still theoretical (not proven for general use)

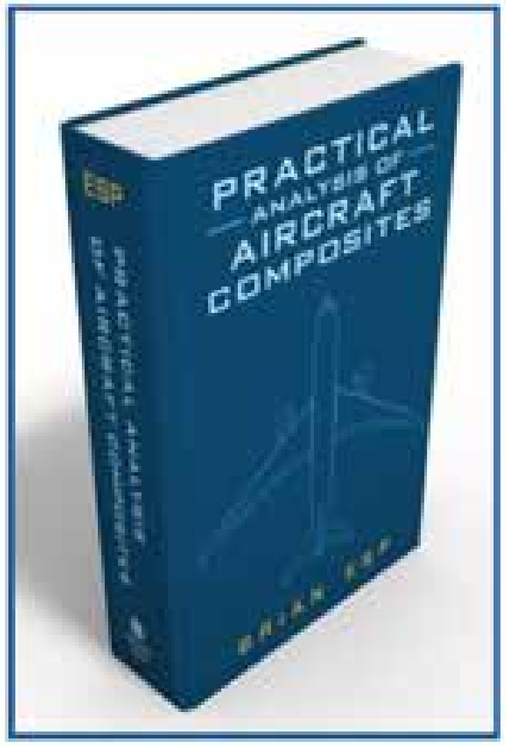
ST2.7 — A Practical Approach to Failure Prediction

- An approach to address the **practical scenarios** of *notched laminates* and *post-impact strength* of laminates:
  - **laminate-level** test data to offset shortcomings of ply-based and micromechanics
    - uniaxial loading (tension and compression)
  - **laminate-level failure criterion** (max strain, or a variation of max-strain)
    - multi-axial loading
  - discussed in the course/book (Chapters 9, 10, 11, other)

allowables are based on laminates that represent the scenario of interest



open hole scenario shown, can also be applied to filled hole, post-impact scenarios, etc



ST2.7 — A Practical Approach to Failure Prediction (cont.)

- Laminate-based max strain criterion
  - captures major effects that exist at the *laminate level that are impossible to capture with a ply-based criterion*
  - max strain may not be a perfect fit for the given material system
  - must still validate (and adjust if necessary) through building block testing
    - or use a different laminate-based criterion
    - see also the ST1 video
    - treat as an "effective bulk property" for the given scenario (unnotched, open holes, filled holes, bearing-bypass, post-impact strength/BVID, etc.)
- Why consider the max strain criterion?
  - use of strain versus stress is common for composites (reasons are provided in Chapter 21)
  - max strain is simple to incorporate
  - history of use for unnotched laminates (and the similar truncated max strain criterion)
  - a reasonable criterion to first postulate and then go through the validation process (See the ST1 video)

ST2.8 — Why are Ply-Based Criteria Sometimes Used

- **Why** are ply-based criteria sometimes used in industry?
  - frequently taught in academia, but ***different goals than industry objectives***
  - engineers may continue an academic approach if they are ***not aware*** of the inherent shortcomings of ply-based criteria
  - ply-based criteria only require simple ply properties (vendors or online databases may provide)
    - ***path of least resistance*** (temping to use if laminate level test data is not available)
    - incorporated into FE software (tendency to believe they can be used in a direct manner)
  - initial damage or specific damage modes (fiber or matrix failures)
    - laminate-based criteria can only be used for ultimate failure
    - initial damage/matrix failures (a concern for glass fiber laminates)
    - may not be accurate in the "pure" form (may require additional testing to correct)
  - debatable: ply-based criteria can be "somewhat" useful for the ultimate strength of unnotched laminates (captures many of the most important failure mechanisms)
    - sometimes accurate for tension loading, but may also be very inaccurate (presented earlier)
    - however, ply-based criteria are physically **unreasonable** for notched laminates or post-impact strength scenarios (does not capture some important effects)

ST2.8 — How are Ply-Based Criteria Sometimes Used

- **How** are Ply-based criteria used in the aircraft industry?
  - Validated analysis method has **many solutions**:
    - discussed in Chapter 2 and the ST1 video
    - possible to "correct" **any criterion with enough testing**, even if the criterion is largely arbitrary
  - However, depending on the scenario, some *do not consider this best practice*:
    - may have to "force" the criteria to "work"
    - may be misleading, indirect, and cause confusion
    - may need to be conservative (criterion lacks physical significance for some scenarios)
  - Conservative approach possible (if high accuracy is not required)
  - **Variety** of company objectives and there may be a successful history of use with ply-based criteria (possibly with correction factors)
    - the goal of this video is **general exposure** to shortcomings, challenges, and potential solutions
    - each company may have its own strategy (depends on a variety of factors)
    - **no absolutes** for strength prediction of composites

ST2.9 — Summary

- *Simple case considered for 2D ply-based criteria*: **unnotched** multi-directional laminate with multi-axial in-plane loading (ultimate strength)
  - Physically reasonable for **some** damage mechanisms, but **not all**
  - Accuracy depends on the loading direction and the material system
  - **No accurate 2D ply-based criterion exists** for unnotched laminates with general in-plane loading (ultimate strength prediction)

- Even if a "perfect" 2D or 3D **ply-based** criterion did exist for unnotched laminates, it could not capture the damage mechanisms for open holes or post-impact/BVID scenarios
  - **physically shortcomings** would prevent accuracy
- Fiber/matrix level failure criteria can theoretically address the open hole scenario, but this approach is not yet practical and not well-accepted
  - various complex failure mechanisms have proven to be very difficult to accurately capture in a "pure" manner
- *For practical aircraft structural considerations, **laminate-based** failure criteria are usually the most appropriate (and practical) approach*
  - unnotched, open holes, fastened joints, post-impact damage

End of Special Topic 2

Up Next

Appendix A: Micromechanics