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Chapter 2: Analysis Overview and Composites Versus Metals

- Chapter 1 discussed some **general** differences between composites and metals.
- Chapter 2 gives a **brief overview** of some **structural analysis** related differences between composites and metals.

Chapter 2: Analysis Overview and Composites Versus Metals

- 2.8 — Mechanically Fastened Joints
- 2.9 — Bonded Joints
- 2.10 — Post-Impact Strength
- 2.11 — Mechanical Properties
- 2.12 — Environmental Effects
- 2.12 — Fatigue Loading
- 2.14 — Damage Tolerance
- 2.15 — Structural Sizing
- 2.16 — Other

2.1 — Accuracy and Risk of Failure

- Structural analysis efforts are **a function** of at least:
  - required accuracy
  - risk of failure
  - cost of testing
- Failure acceptable?
  - some commercial applications
  - less analysis (or no analysis) required
- Overdesign (conservatism) acceptable?
  - excess weight OK?
  - less analysis and more testing may be appropriate

2.1 — Accuracy and Risk of Failure (cont.)

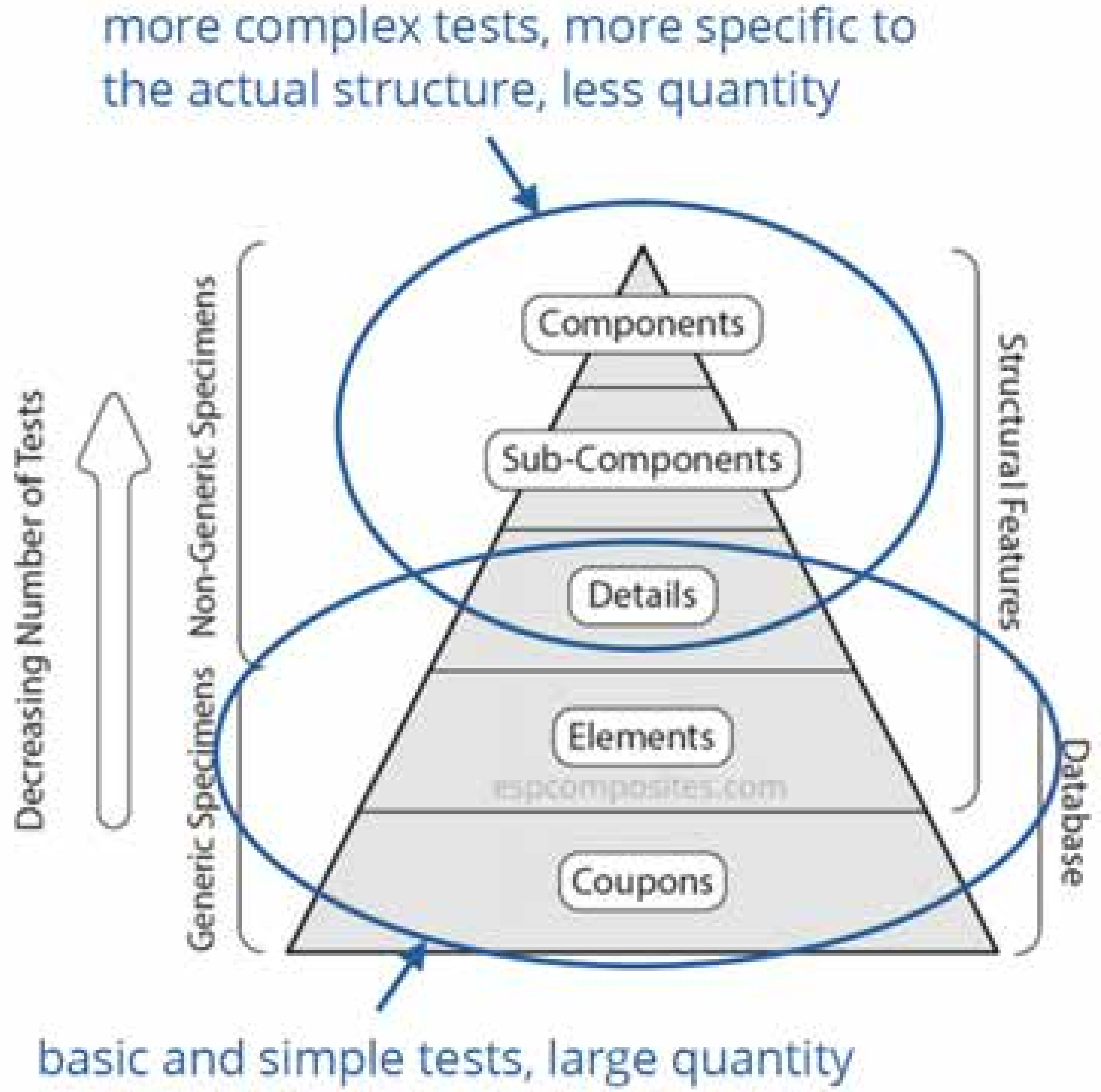
- Inexpensive testing?
  - less analysis (or no analysis) required
- *Minimize weight **and** failure is unacceptable?*
  - competing demands
  - in general, relatively large amount of analysis and/or testing
  - many aircraft structures
- Primary aircraft structures
  - usual case = high accuracy and low risk of failure
  - use typical approaches within the industry
  - large transport aircraft may use:
    - **building block testing**
    - **validated analysis methods**

2.2 — Building Block Testing

- Testing at various levels of structural completeness
- Each level "builds" on itself
- Often used for large civil aircraft programs
  - successful history of use
- For structural substantiation and/or to develop validated analysis methods
- Especially important for some composite problems
  - discover unanticipated failures early
- See also Section 2.3 of the book

Chapter 28 of the book has additional information about building block testing

Example building block pyramid



2.3 — Validated Analysis Method

What happens when classical solutions alone are not able to generate an accurate and/or practical solution?

- **Validated analysis method (*key concept*)**
  - **engineering** approach
    - May be used for **all** analysis solutions (simple or complex) and (metals or composites). Especially useful when classical solutions have shortcomings, physical limitations, or not practical to implement
    - in general, **an "exact" analytical solution is not necessary** (does not require that the actual physical behavior be captured)
  - consists of a **blend** of analysis and testing in a specific manner
    - *testing compensates for analytical shortcomings*
    - also, limit the method to an appropriate design space (bounds of the test matrix)
    - semi-empirical (or empirical) approach if "pure" theory is insufficient or too complex to implement
    - analysis/test blend is based on a variety of factors (objectives, analytical resources, test resources, acceptable amount of conservatism, etc.)
    - *many possible methods* for the same problem (companies may have different approaches)
    - further discussion in the next 3 slides

2.3 — Validated Analysis Method (cont.)

Example flowchart:
For strength analysis where there is a **"base allowable"**

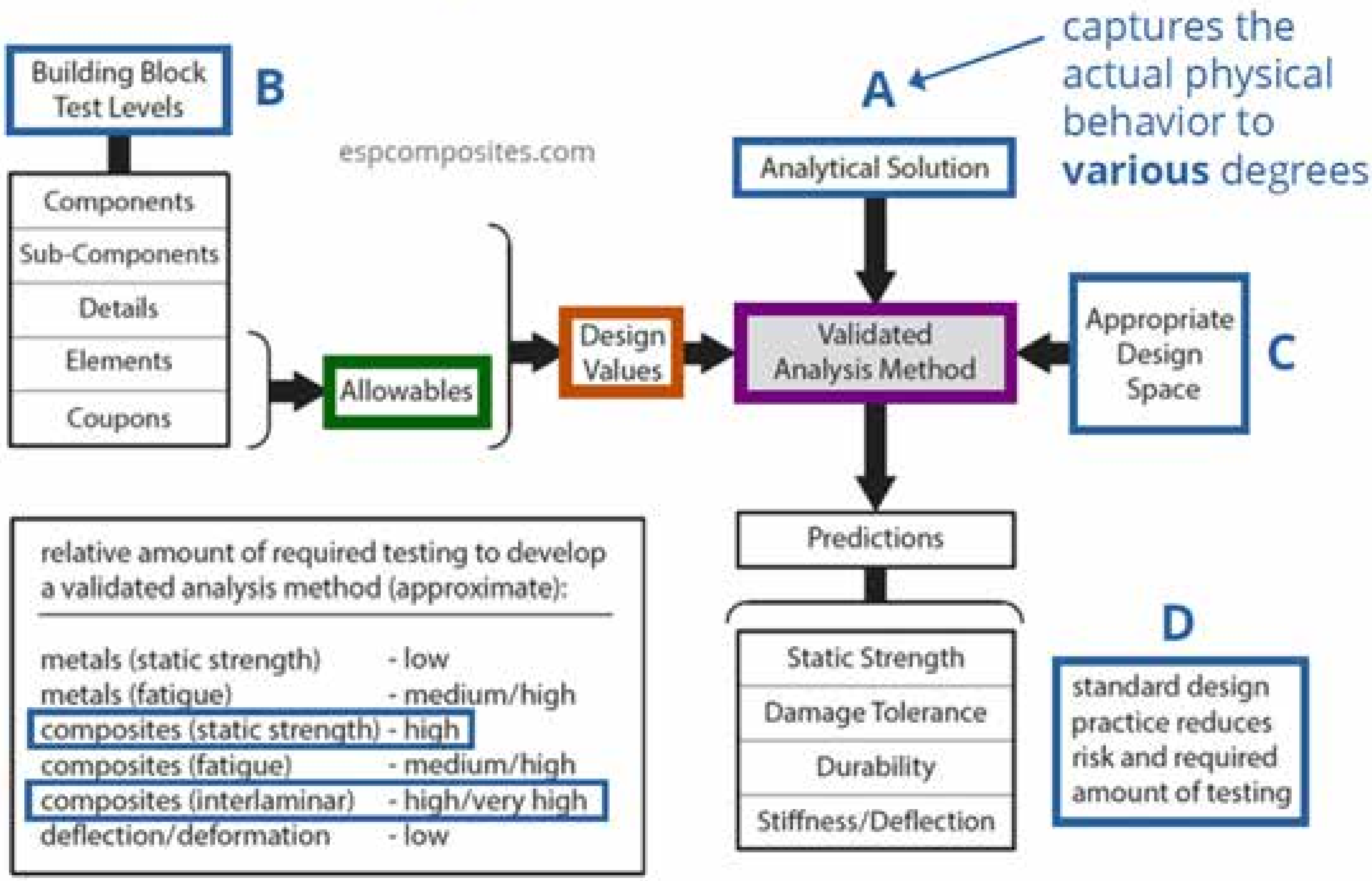
Validated Analysis Method

A: analytical solution

B: building block testing

C: limited to a specific design space

D: standard design practice preferred



Allowables: Statistically based values determined from lower level testing (i.e. OHC, OHT, FHC, FHT, etc.)

***Design values*:** Allowables combined with **correction factors, adjustments, cutoffs, etc.**
Determined from both lower level and higher level testing.
Feeds into the validated analysis method (correlates test data to the analytical solution).

2.3 — Validated Analysis Method (cont.)

VALIDATED ANALYSIS METHOD (GENERAL NOTES)

- Useful for composites
  - general strength prediction
  - no amount of "pure" analysis, regardless of fidelity, can fully capture some of the complex failure mechanisms of composites (discussed in Chapters 8, 9, ST2, and 10)
  - especially appropriate when interlaminar stresses drive results
- Analytical solution should not go beyond its ability to be useful
  - **compensate analytical shortcomings with test data**
- Some basic objectives:
  - use a validated analysis method to "fill in" the design space (but do not exceed the design space)
  - test some cases and analyze untested load cases (possibly hundreds or thousands)
- NOTE: *Do not attempt to use complex analysis or excessive testing to compensate for poor design practice*. Standard (and good) design practice reduces risk and also the required amount of testing.

2.3 — Validated Analysis Method (cont.)

VALIDATED ANALYSIS METHOD (GENERAL NOTES)

- The concept of a "validated analysis method" will be a recurring theme (ST1, Chapters 8, 9, 10, ST2)
- Recommend: Read Section 2.4 of the book for additional discussion (part of **free excerpt at www.espcomposites.com**)
- **View the free ST1 video after completing this video**
  - principles for how to **develop** a validated analysis method
  - further discussion to enhance understanding

2.4 — Elasticity

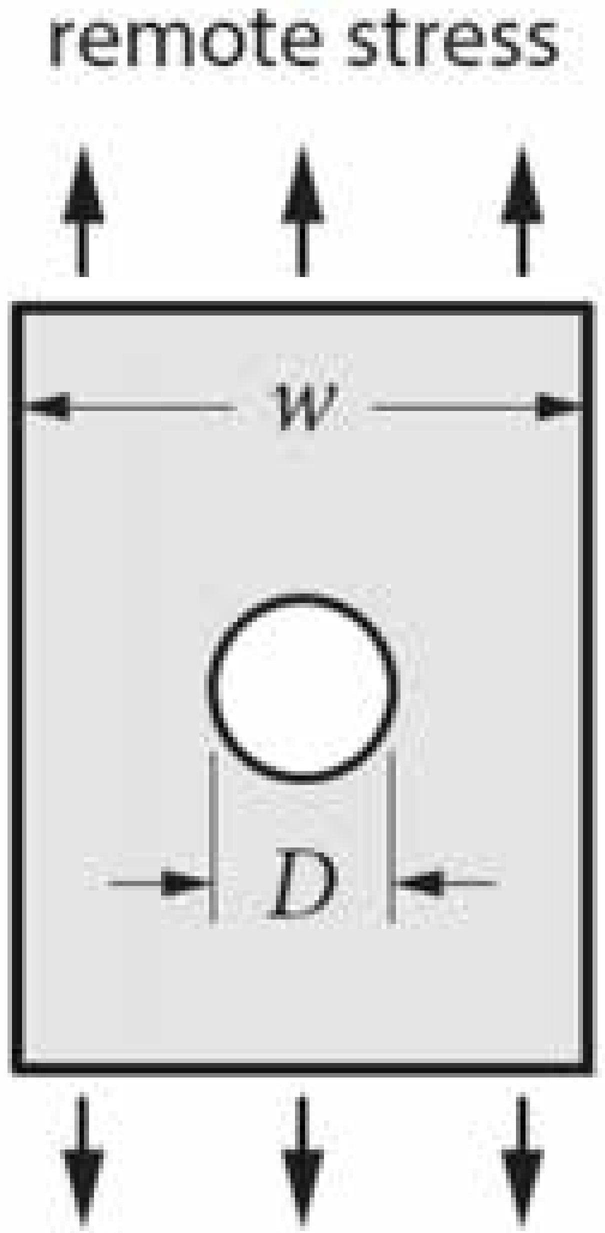
- Elasticity
  - properties/values within the elastic limit (range where no permanent deformation occurs)
  - stiffness/compliance, modulus, deformation, stress/strain
- Metals
  - elastically isotropic = **same elastic properties in all directions**
  - metals are isotropic (or nearly so)
  - elastic properties are simple to characterize
- Composite laminates
  - elastic properties are a **function of the layup**
  - additional analysis required to determine elastic properties
    - CLT (Classical Laminate Theory) used
  - special laminate: "quasi-isotropic" = same elastic properties in the plane
  - Chapters 3–6 (stiffness/compliance of materials/laminates)

2.5 — Unnotched Strength

- Unnotched specimen = pristine condition (no significant defects/damage/stress concentrations)
- Consider the static ultimate strength (in-plane loading of a metal plate and a composite laminate)
- Metals
  - nearly isotropic in strength (static ultimate strength similar in all directions)
  - relatively simple and well-accepted failure criteria
- Composite laminate (in-plane unnotched strength)
  - in-plane static ultimate strength is a **function** of the layup
    - may be a large difference of strength in each orientation
  - **Point 1: Many complex failure mechanisms** (microscopic and macroscopic)
  - **Point 2: No well-accepted physical based failure criterion** (many proposed)
  - industry approach may be different from academic approach to compensate for the lack of a well-accepted failure criterion
    - ***validated analysis method***
  - Chapter 9 (discuss both academic and industry approaches)

2.6 — Small Notch Strength

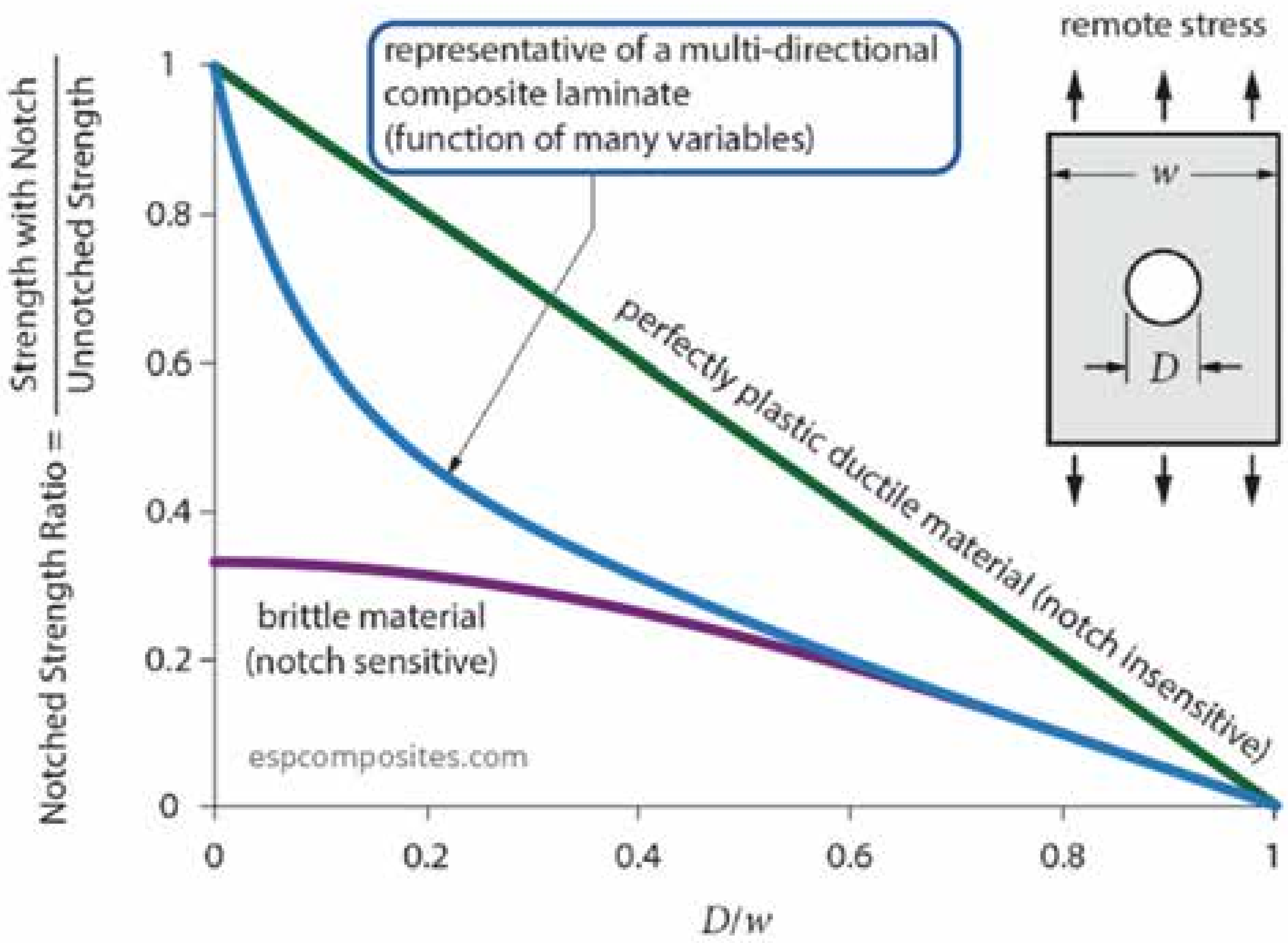
- Small Notch Strength (ultimate strength for in-plane loading)
  - consider a specimen with a small open hole



- Metals (ductile)
  - **notch insensitive:** stress concentration has a minor influence on the ultimate load capability (stress redistribution at the stress concentration)
  - can determine the part's ultimate load capability with simple formulas and basic material properties
- Metals (brittle)
  - **notch sensitive:** ultimate load capability is affected by the stress concentration factor
  - can determine the part's ultimate load capability with simple formulas and basic material properties

2.6 — Small Notch Strength (cont.)

- Multi-directional composite laminates – **neither brittle nor ductile**
  - somewhere **in-between** brittle and ductile (sensitive to notches)



2.6 — Small Notch Strength (cont.)

- **Small notches (composites):** ***can not*** accurately determine a laminate's capability via the basic strength properties from either the ply or the fiber/matrix
  - also the case for mechanically fastened joints, which have a notch
- In turn, the analysis treatment of small notches is one of the most important analytical distinctions between metals and composites
- Further discussed in Chapter 10 (also ST2)

Notes about practical composites for large civil aircraft:

- The unnotched strength is rarely (if ever) used. Must consider open holes, fastened joints, repairability, impact damage, etc.
- These considerations/requirements are discussed in Chapters 23 and 25 of the book.

2.7 — Interlaminar Strength

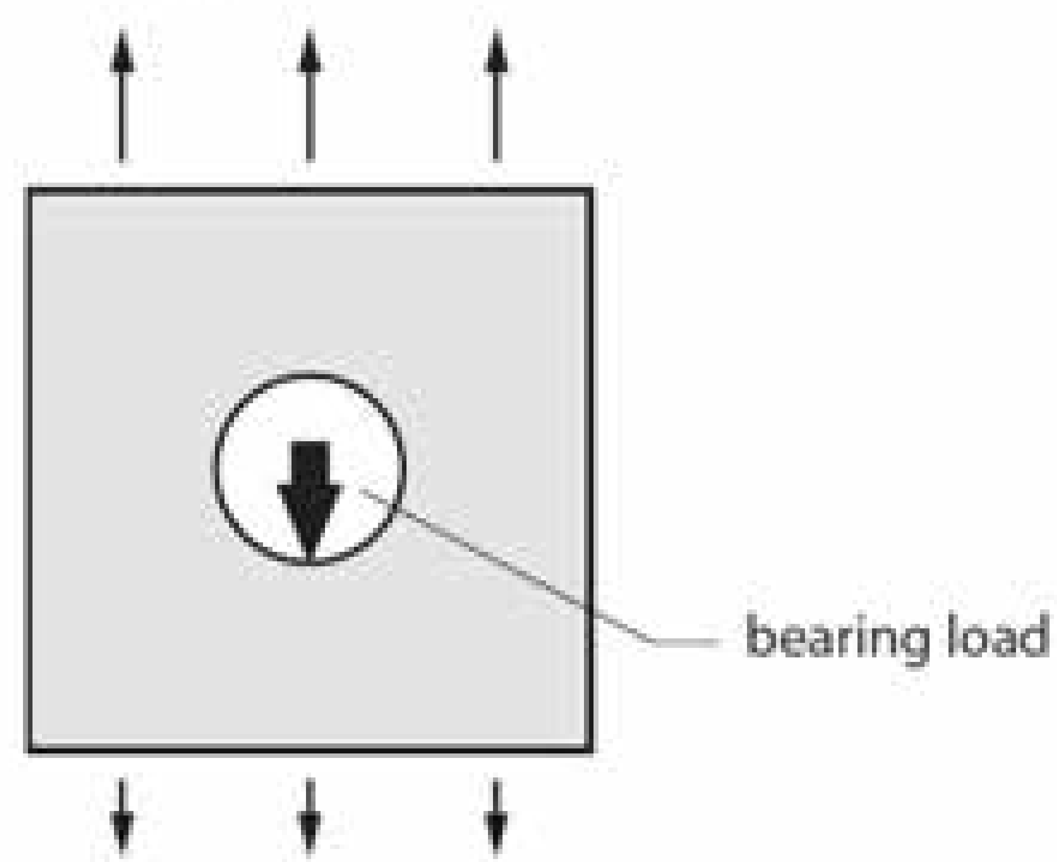
- Metals
  - delamination not possible (assuming it is not a laminated metal structure)

- Laminated composites – interlaminar stresses/strength
  - interlaminar stresses may exist at the **ply-to-ply interface**
  - fibers are not oriented to resist the interlaminar stresses
    - interlaminar strength is low (function of only the strength of the matrix)
  - **responsible for delamination (and delamination growth)**
  - in general, may be responsible for a reduction of a structure's load capability (compared to if delamination was not possible)
  - not easily (or impossible) to predict the effects with analysis alone
    - use validated analysis method (analysis + testing) + good design practices
  - **distinct and important aspect to consider about laminated composites**
  - discussed further in Chapter 8

2.8 — Mechanically Fastened Joints

- Metals — static ultimate capability (shear joints)
  - bearing failure mode is **independent** from the net section tension failure mode
    - *simple analysis solutions for both modes*
  - if bearing critical = uniform fastener load distribution (*simple calculation*)

- Composites — static ultimate capability (shear joints)
  - bearing stress and bypass stress are **interactive**
    - known as the **"bearing-bypass"** failure mode
    - can not use "pure" analysis (specific test data of laminates with fasteners and use a validated analysis method)
    - relatively complex analysis (compared to metals)
    - *there is also an independent bearing mode (like metals)*
  - limited fastener load redistribution
    - fastener load share analysis usually required
  - Chapter 11 of the book



2.8 — Mechanically Fastened Joints (cont.)

- Composite joints — fastener considerations
  - composite members usually thicker than metal counterparts
  - low transverse shear stiffness
  - fastener bending
  - fastener fatigue

- NOTE: Metal joints under **fatigue loading** (load magnitude much less than the static ultimate load)
  - treated similar to composites (metal fatigue exhibits notch sensitivity)
  - the interaction from the bearing load and bypass load (tension) must be considered (combined effect from stress concentrations)
  - loads are too small to cause large bearing deformations (non-uniform fastener load distribution in shear joints)

2.9 — Bonded Joints

- Metal adherends
  - bondline analysis
  - Chapter 12 of the book
- Composite adherends
  - bondline also analyzed, **but...**
  - **interlaminar failure modes are often the critical mode**
    - separation (delamination) at the ply-to-ply interface and growth propagation
  - Chapter 13 of the book

interlaminar failure modes in composite adherends

2.10 — Post-Impact Strength

Non-penetrative post-impact strength

- Metals
  - minor reduction or no reduction of static strength after a non-penetrative impact event
- Composites
  - may have a significant reduction of strength after an impact (even if there is no penetration or visible damage)
    - **delamination** is the primary cause for reduced residual strength
    - **compression/shear** residual strengths reduced more than tension
    - compression after impact strength (CAI) can be about 50% of the unnotched strength for Barely Visible Impact Damage (BVID)
      - **BVID discussed in Chapters 20 and 26 of the book**

2.11 — Mechanical Properties

- Metals
  - nearly isotropic
    - may have different properties as a function of grain direction (but usually similar in all directions)
  - **centralized database (MMPDS – previously MIL-HDBK-5)**
  - stress based allowables
  - **usually obey simple failure criteria (or nearly so)**
    - less testing required to establish required material properties (at least for the basic properties)

2.11 — Mechanical Properties (cont.)

- Composites (testing/properties are **very different** from metals)
  - Properties are a **function** of the layup (ply orientation and sequence)
  - **No centralized database**
  - **Lack of well-established "pure" failure criterion. To compensate for this, many unique properties and tests are required.**
    - various ***ply-level*** properties
    - various ***laminate-level*** properties
      - open hole tests
      - filled hole test
      - bearing-bypass tests
      - post-impact tests
    - interlaminar effects and associated testing
  - Strain based allowables (typical)
    - however, the bearing allowable is stress based
  - Testing also performed at various temperature/humidity environments
  - Chapter 21 of the book

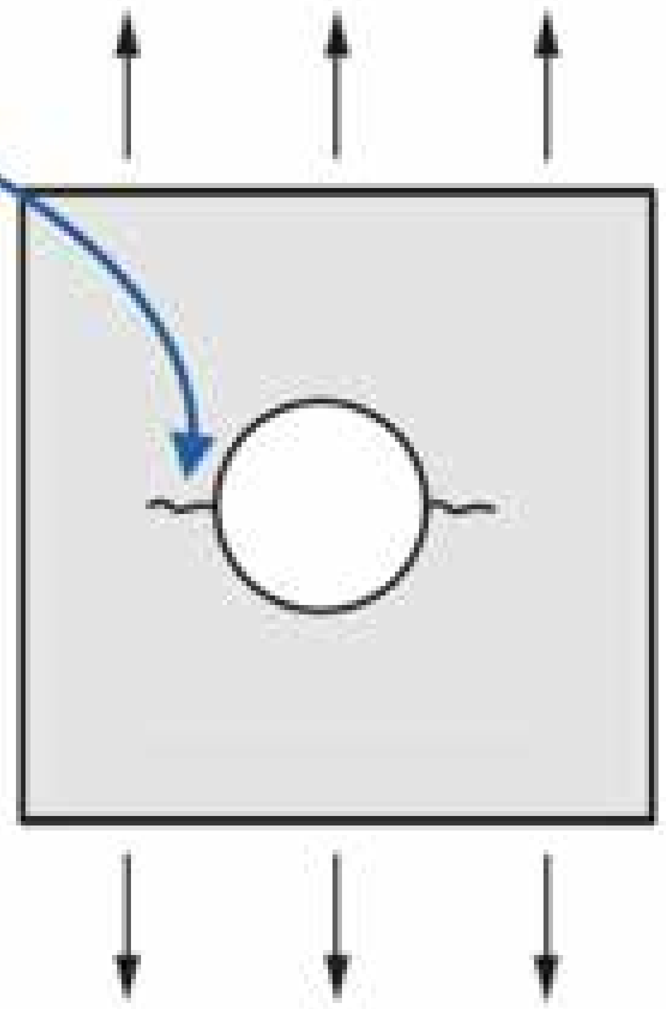
2.12 — Environmental Effects

- **Metal strength/stiffness *not sensitive*** to typical aircraft environments. However, also consider:
  - localized hot areas
  - humidity can contribute to corrosion and stress-corrosion cracking **(long-term effect)**

- **PMC composite laminates *are sensitive* to typical temperature and humidity environments**
  - **immediate** and significant reduction of strength
- polymer matrix is primarily responsible for a laminate's reduced properties
  - fiber properties may also be influenced, but to a lesser degree
- some in-plane strength properties (laminate): reduction of about 15-25%
- some interlaminar effects: up to about 50% reduction of strength in extreme environments
- stiffness properties less affected than strength

2.13 — Fatigue Loading

- Metals
  - concern is a **through-the-thickness** (or well-formed) crack at stress concentrations
  - fatigue often drives the sizing of aircraft structures
  - well-established methods for crack initiation, crack growth (LEFM), residual strength (LEFM)
  - tension loading (or loading that causes tensile stress) is critical



- Composites
  - general degradation (not a well formed “crack”)
  - **resistant to fatigue damage when fibers react the loading**
    - does not usually affect sizing
    - carbon fiber composites are especially resistant to fatigue damage (glass and aramid fibers are less resistant)
    - *may be susceptible delamination growth*
  - no well-established analytical solutions
  - compression/shear loading often critical (delamination growth is a concern)
  - Chapter 24 of the book

2.14 — Damage Tolerance

- Metals
  - through-the-thickness cracks (or well-formed cracks)
    - sources: fatigue loading and corrosion
    - concerned with: presence, growth, and coalescence
    - reduction of stiffness and strength
  - **stable and predictable** crack growth (can use analysis methods)
  - inspection intervals/methods are **deterministic**
    - detect cracks before they reach a critical size
- Composites
  - accidental damage is of primary concern
    - **significant and immediate reduction** of strength from impacts (even if there is not a penetration – delamination)
  - focus on the residual strength in the presence of various types of damage
  - possible to demonstrate that damage does not grow (high threshold for growth)
    - if damage does grow, it may be sudden and **unstable**
  - Chapter 26 of the book (civil aircraft)

2.15 — Structural Sizing (Aircraft Applications)

- Structural Sizing (or just “sizing”)
  - thickness, size, shape, spacing of structural elements, etc
  - drives weight
  - function of: loading, requirements, environment, failure modes, etc.

- Metals
  - sometimes sized by the static ultimate load requirement
  - **often times sized because of fatigue related requirements**

- Composites
  - **usually sized by the static ultimate load requirement**
    - holes, fastened joints, repairability
      (much lower capability compared to the unnotched strength)
    - civil aircraft requirements assume undetectable damage and BVID (barely visible impact damage) – Chapter 25 of the book
  - resistant to fatigue damage (especially carbon fiber composites)

2.16 — Other

- This video addressed the **main** analysis difference between metals and composites
- **Additional** discussion about the differences in the book
  - ***free book excerpt contains the complete Chapter 2***
  - download free excerpt at **www.espcomposites.com**
- Course and book
  - Even further discussion about the differences between metals and composites in the corresponding chapters

End of Chapter 2

Up Next

Special Topic 1: Developing a Validated Analysis Method