NIAR Research on Certification of Composite-Metal Hybrid Structures

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NIAR Research on Certification of Composite-Metal Hybrid Structures

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Motivation & Key Issues

• Damage growth mechanics, critical loading modes and load spectra for composite and metal structure have significant differences that make the certification of composite-metal hybrid structures challenging, costly and time consuming.

• Data scatter in composites compared to metal data is significantly higher requiring large test duration to achieve a particular reliability that a metal structure would demonstrate with significantly low test duration.

• Metal and composites have significantly different coefficient of thermal expansion (CTE)

• Mechanical and thermal characteristics of composites are sensitive to temperature and moisture

• Need for an efficient certification approach that weighs both the economic aspects of certification and the time frame required for certification testing, while ensuring that safety is the key priority
Outline of the Presentation

- CMH-17 Rev. G
  - Overview of updated contents in Chapter 12 (Damage Tolerance Chapter)

- CMH-17 Rev. H
  - New Topics in Chapter 12 (Damage Tolerance Chapter)

- Overview of Hybrid Studies
  - Multi-LEF
  - Deferred Severity Spectrum
  - Sequencing Effects
12.6 Durability and Damage Growth Under Cyclic Loading

12.6.1 Influencing factors
12.6.2 Design issues and guidelines
12.6.3 Test issues
  12.6.3.1 Scatter analysis of composites
    12.6.3.1.1 Individual Weibull method
    12.6.3.1.2 Joint Weibull method
    12.6.3.1.3 Sendeckyj equivalent static strength model
  12.6.3.2 Life Factor approach
  12.6.3.3 Load Factor approach
  12.6.3.4 Load Enhancement Factor approach
    12.6.3.4.1 Description
    12.6.3.4.2 LEFs for complex structure
    12.6.3.4.3 Testing Requirements
    12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure
  12.6.3.5 Ultimate strength approach
  12.6.3.6 Test spectrum development
  12.6.3.7 Test environment
  12.6.3.8 Damage growth
Fatigue Scatter Analysis Techniques

- Individual Weibull
- Joint Weibull
- Sendeckyj Equivalent Strength Model

\[ \sigma_s = \sigma \left[ \frac{\sigma_i}{\sigma_j} \right]^{1/3} + (N_j - 1) \cdot C \]

NADC Fatigue Scatter Analysis
\( \alpha_i > \alpha_j > \alpha_s \)

NAVY LEF APPROACH IS NOT RESTRICTED TO THESE SCATTER ANALYSIS METHODS
Life Factor Approach

Structure is tested for additional fatigue life to achieve the desired level of reliability

- Life Scatter Factor (LSF)

Newer composite materials/processes indicates significantly lower life factors
Load Enhancement Factor (LEF) Approach

Increase applied loads in fatigue tests so that the same level of reliability can be achieved with a shorter test duration

- Combined load-life approach
  Whitehead, et. al (NAVY/FAA research for F-18 certification)

- Load Enhancement Factor (LEF)

\[
LEF(N) = \left( \frac{N_F}{N} \right)^{\frac{\alpha_z}{\sigma_z}}
\]

\[
LEF(N) = \left\{ \begin{array}{l}
- \ln(R) \cdot N^{\alpha_z} \\
\frac{\ln(2)}{2N^\alpha_z}
\end{array} \right.
\]

- LEF is a function of test duration (for various confidence levels)
- New materials/processes
- Not an SN curve

LEF is a function of the test duration
12.6.3.4.2 LEFs for complex structure

- Modal analysis
- Current industry practice
  - Use of “traditional” LEF values (1.15) unless substantial test databases are developed to support use of lower LEFs
    - Less data required to verify that traditional values are conservative
  - Use a single LEF for the complete test duration
  - Use a single LEF for the complete test spectrum
    - Possibly not apply LEF to fatigue loads in cases where resulting load would be at or above Limit Load
  - Select LEFs based on modal analysis
  - Validation for failure modes with LEFs higher than that selected via modal analysis performed at element or subcomponent tests.
Guidance on Development & Application of LEF

12.6.3.3 Load Enhancement Factor using Scatter Analysis

Method 1: Life Factor Approach

\[ N_1 = N_2 = N_3 = \ldots = N_i = NF \]

\[ \Rightarrow \text{LEF}_1 = \text{LEF}_2 = \text{LEF}_3 = \ldots = \text{LEF}_i = 1.0 \]

Original spectrum is repeated for life factor; example \((NF) = 5\)

\[ N_1 = N_2 = N_3 = \ldots = N_i = 1 \]

\[ \Rightarrow \text{LEF}_1 = \text{LEF}_2 = \text{LEF}_3 = \ldots = \text{LEF}_i = \text{LEF}_{@N=1} \]

Original Spectrum is multiplied by LEF with Load Factor \((N = 1)\) for \(\text{LEF}_1 = \text{LEF}_2 = \text{LEF}_3 = \text{LEF}_4 = \text{LEF}_{@N=1}\)

Method 2: Load Factor Approach

\[ N_1 = N_2 = N_3 = \ldots = N_i = 1 \]

\[ \Rightarrow \text{LEF}_1 = \text{LEF}_2 = \text{LEF}_3 = \ldots = \text{LEF}_i \]

Original Spectrum is multiplied by appropriate LEF with combined load-life factor (example: \(N = 3 < NF\) for \(\text{LEF}_2 = \text{LEF}_3 = \text{LEF}_4 \neq \text{LEF}_1 = 1.0\) with \(N = NF\))

Method 3: Combined Load-Life Factor (LEF) Approach

\[ N_1 = N_2 = N_3 = \ldots = N_i \]

\[ \Rightarrow \text{LEF}_1 \neq \text{LEF}_2 \neq \text{LEF}_3 \neq \ldots = \text{LEF}_i \]

Original Spectrum is multiplied by appropriate LEF with multi combined load-life factor (example: \(N = 3 < N_i\) for \(\text{LEF}_2 = \text{LEF}_3 = \text{LEF}_4 \neq \text{LEF}_1 = 1.0\) with \(N = NF\))

Method 4: Multi Load-Life Factor (multi-LEF) Approach

\[ N_1 \neq N_2 \neq N_3 \neq \ldots \neq N_i \]

\[ \Rightarrow \text{LEF}_1 \neq \text{LEF}_2 \neq \text{LEF}_3 \neq \ldots = \text{LEF}_i \]

Original Spectrum is multiplied by appropriate LEF with multiple combined load-life factors (example: \(N = 3 < N_i\) for \(\text{LEF}_2 \neq \text{LEF}_3 \neq \ldots \neq \text{LEF}_1 = 1.0\) with \(N = NF\))
Multi-LEF Approach for Hybrid Structures

Clipping Level for Metal

LEF

Multi-LEF

Repeated for required N

Repeated for required N

Spread high load cycles throughout the spectrum (may require additional crack growth analysis for hybrid structures)

Original Spectrum Blocks

Test Spectrum Blocks after LEF

Damage Tolerance Certification of Composite Structures  11
Multi-LEF Approach for Hybrid Structures

Load Enhancement Factor using Scatter Analysis

**Method 4: Multi Load-Life Factor (multi-LEF) Approach**

\[ N_1 \neq N_2 \neq N_3 \neq \ldots \neq N_i \]
\[ \Rightarrow LEF_1 \neq LEF_2 \neq LEF_3 \neq \ldots = LEF_i \]

LEF = 1.0 (high load block is repeated 5 times within the overall test spectrum since \( N_s = 5 \))

Original Spectrum is multiplied by appropriate LEF with multiple combined load-life factors (example: \( N = 3 < N_s \) for \( LEF_2 = LEF_3 = LEF_4 \neq LEF_5 \) = 1.0 with \( N = N_s \))
12.6.3.3 Load Enhancement Factor using Scatter Analysis

CMH-17 Rev. H
New Topics in Chapter 12 (Damage Tolerance Chapter)

• **Boundaries of LEF Curve**
  
  • Test duration must be greater than 1 DSG
    
    • Hybrid (metal-composites) structures: minimum 2 DSG \( \rightarrow \) LOV for Metals (LOV for Composites?)

  • LEF must be greater than 1.0

<table>
<thead>
<tr>
<th>n = 1</th>
<th>n = 5</th>
<th>n = 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composites Alpha = 1.25</td>
<td>13.558</td>
<td>9.143</td>
</tr>
<tr>
<td>Metals Alpha = 4.0</td>
<td>2.093</td>
<td>1.851</td>
</tr>
</tbody>
</table>

Damage Tolerance Certification of Composite Structures
12.6.3.3 Load Enhancement Factor using Scatter Analysis

Fidelity of Modal Analysis & Substantiation of Using NADC LEF

Failure modes with large scatter shall be interrogated at element/sub-component level(s).

Use of historic Navy LEF curve must be substantiated with a reduced LEF test matrix.
12.6.1.2 Cyclic stress ratio (R-ratio) and spectrum effects

Effects of Layup Sequence and R-Ratios
12.6.3.6 Test spectrum development

Exceedance Curves & Test Spectrum Development

- Flight/taxi test data are converted to exceedance curves for different events.
- Exceedance curves are then converted into load spectra.
- Spectrum (sequence) is developed.
- Analysis spectrum is then modified for cyclic test:
  - Truncation & clipping high loads to avoid retardation/plasticity.
  - Life factor to account for uncertainties in usage.
  - Load-enhancement factor to reduce test duration for composites.

Industry support is needed.
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

• Current industry practice generally avoids addressing metallic and composite fatigue with the same article.

• Emerging approaches that may enable addressing metallic and composite fatigue with the same article (for composite-dominant designs):
  • Drive LEFs low enough (either via increasing the test duration and/or via thorough testing to substantiate lower values) to avoid overload concerns in metal.
  • Multi-LEF Approach.
  • Deferred Spectrum Approach.
Certification Cost & Time

~ Certification Cost

- Full-Scale
- Sub-component
- Details
- Elements
- Laminate
- Lamina

~ Certification Time

Full-scale test is a significant portion of the overall budget. Improvements to full-scale test duration \(\Rightarrow\) Reduction to overall test timeline
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

**Single Article for Composite-Metal Hybrid FSFT**

**Considerations:**
- LOV
- Type certificate (FTA remain ahead of fleet)
- Effects of LEFs (crack growth retardation in metals)
- Sequencing effects
- Effects of additional test duration on metals
- Invalidation of metal test when high loads are applied (life extension)
- Competing failure modes
- Effects of CTE mismatch
- Effects of environment

**Load-Life Shift:**

\[
\frac{N_{T,LEF_1}}{N_{R,LEF_1}} + \frac{N_{T,LEF_2}}{N_{R,LEF_2}} + \ldots + \frac{N_{T,LEF_n}}{N_{R,LEF_n}} \geq 1.0
\]

Load-Life Shift

• A mechanism to apply different LEFs for multi-phase test programs for a given reliability level to substantiate design lifetime.

\[
\frac{N^T_{\text{LEF}_1}}{N^R_{\text{LEF}_1}} + \frac{N^T_{\text{LEF}_2}}{N^R_{\text{LEF}_2}} + \ldots + \frac{N^T_{\text{LEF}_n}}{N^R_{\text{LEF}_n}} = \sum_{i=1}^{n} \frac{N^T_{\text{LEF}_i}}{N^R_{\text{LEF}_i}} \geq 1.0
\]

• Simplified (two-step) version:

\[
N^T_2 = \left(1 - \frac{N^T_1}{N^R_1}\right) \cdot N^R_2
\]

12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

Deferred Spectrum for Hybrid FSFT

Method 1: Life Factor Approach

Method 2: Deferred High Loads

Method 3: Deferred High Loads with Load Life Shift

Life factor ($N_0$) = 5
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

Deferred Spectrum for Hybrid FSFT (contd.)

Metals:
- Severe flight loads result in crack-growth retardation.

Composites:
- Severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life.

Cycles below composites truncation level (green) are eliminated after 3 DSG.
**Separate Metal and Composite Certification Test Articles**

### Considerations for Metal/Composite Hybrid Structure

#### Load-Life Shift:

\[
\frac{N_{LEF_1}^T}{N_{LEF_1}^R} + \frac{N_{LEF_2}^T}{N_{LEF_2}^R} + \ldots + \frac{N_{LEF_n}^T}{N_{LEF_n}^R} \geq \sum_{i=1}^{n} \frac{N_{LEF_i}^T}{N_{LEF_i}^R} \geq 1.0
\]

**Total Test Duration for Corresponding LEF’s Using Load-Life Shift Hybrid Approach (One Test Article)**

<table>
<thead>
<tr>
<th>Option</th>
<th>LEF</th>
<th>Required Test Duration without LLS</th>
<th>Required Test Duration with LLS</th>
<th>Total Test Duration</th>
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<td>1.000</td>
<td>5.0</td>
<td>2.0</td>
<td>5.0</td>
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<td>2</td>
<td>1.016</td>
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<td>4.6</td>
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<td>3</td>
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<td>3.0</td>
<td>1.2</td>
<td>4.2</td>
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<td>4</td>
<td>1.058</td>
<td>2.0</td>
<td>0.8</td>
<td>3.8</td>
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<tr>
<td>5</td>
<td>1.088</td>
<td>1.3</td>
<td>0.5</td>
<td>3.5</td>
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*NIAR (FAA-LEF Data)*
## 12.6.1.2 Cyclic stress ratio (R-ratio) and spectrum effects / 12.6.3.8 Damage growth

### Load Sequencing Effects – Open Hole Tension/Compression (UNI )

<table>
<thead>
<tr>
<th>NAME</th>
<th>n=0 Reference</th>
<th>70% - n=3,000</th>
<th>40% - n=403,010</th>
<th>55% - n=519,340</th>
<th>40% - n=919,350</th>
<th>55% - n=1,035,680</th>
<th>Load Block 5</th>
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<tbody>
<tr>
<td>UNI-EX-11</td>
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<tr>
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</tbody>
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### Fatigue Profile 5

<table>
<thead>
<tr>
<th>NAME</th>
<th>n=0 Reference</th>
<th>40% - n=400,010</th>
<th>55% - n=536,340</th>
<th>40% - n=916,350</th>
<th>55% - n=1,032,680</th>
<th>70% - n=1,035,680</th>
<th>Load Block 5</th>
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<tbody>
<tr>
<td>UNI-EX-11</td>
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### High-Low

<table>
<thead>
<tr>
<th>Spectrum Block</th>
<th>% of Ultimate</th>
<th>Number of Cycles in Block</th>
<th>Spectrum Block</th>
<th>% of Ultimate</th>
<th>Number of Cycles in Block</th>
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<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>3000</td>
<td>1</td>
<td>40</td>
<td>400010</td>
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<tr>
<td>2</td>
<td>40</td>
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<td>55</td>
<td>116330</td>
</tr>
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<tr>
<td>4</td>
<td>40</td>
<td>400010</td>
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<td>55</td>
<td>116330</td>
</tr>
<tr>
<td>5</td>
<td>55</td>
<td>116330</td>
<td>5</td>
<td>70</td>
<td>3000</td>
</tr>
</tbody>
</table>

### Low-High

<table>
<thead>
<tr>
<th>Spectrum Block</th>
<th>% of Ultimate</th>
<th>Number of Cycles in Block</th>
<th>Spectrum Block</th>
<th>% of Ultimate</th>
<th>Number of Cycles in Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>400010</td>
<td>1</td>
<td>70</td>
<td>3000</td>
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<td>2</td>
<td>55</td>
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<td>400010</td>
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<td>400010</td>
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<tr>
<td>5</td>
<td>70</td>
<td>3000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Lower level building-blocks of testing:

1. **Sequencing effects for validation of deferred spectrum**
2. **Mismatch of CTE’s**
3. **Environmental issues for composite (ex., hot-wet)**
4. **Hot spots (ex., ILS/ILT for composites)**

6 spec. survived profile 5

4 spec. failed and 2 spec. survived profile 6

Failed at 1,035,455 cycles

Failed at 1,033,152 cycles
### Load Sequencing Effects – Open Hole Tension/Compression (PW)

#### Fatigue Profile 5

- **Reference**: 70% - n=1,040
- **Load Block 1**: 40% - n=401,050
- **Load Block 2**: 55% - n=415,610
- **Load Block 3**: 40% - n=815,620
- **Load Block 4**: 55% - n=830,180

- **PW-OH-27**: Failed at 823,523 cycles
- **PW-OH-1**: Failed at 827,830 cycles
- **PW-OH-6**: Failed at 816,002 cycles

#### Fatigue Profile 6

- **Reference**: 40% - n=400,010
- **Load Block 1**: 55% - n=414,570
- **Load Block 2**: 40% - n=814,580
- **Load Block 3**: 55% - n=429,140
- **Load Block 4**: 70% - n=430,180

- **PW-OH-3**: Failed at 815,550 cycles
- **PW-OH-4**: Failed at 822,849 cycles
- **PW-OH-6**: Failed at 816,002 cycles
Load Sequencing Effects - Compression After Impact

12.6.1.2 Cyclic stress ratio (R-ratio) and spectrum effects / 12.6.3.8 Damage growth

Constant Amplitude (70% CAI SS)

<table>
<thead>
<tr>
<th>Stress Level</th>
<th>Percentage [%]</th>
<th># of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL1</td>
<td>80</td>
<td>3000</td>
</tr>
<tr>
<td>SL2</td>
<td>50</td>
<td>400010</td>
</tr>
<tr>
<td>SL3</td>
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<tr>
<td>SL5</td>
<td>65</td>
<td>116380</td>
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</table>

Spectrum Fatigue

<table>
<thead>
<tr>
<th>Stress Level</th>
<th>Percentage [%]</th>
<th># of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL1</td>
<td>50</td>
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<tr>
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<td>116380</td>
</tr>
<tr>
<td>SL5</td>
<td>80</td>
<td>3000</td>
</tr>
</tbody>
</table>

1 spec. failed at n=403,011
1 spec. survived n=1,035,680
3 spec. survived n=1,035,680
Operating Stress/Strain Levels

Operating levels for composites are significantly low

→ No sequencing effects

Ref: Whitehead, et. al. (1986), NADC-87042-60

Open Hole 25/50/25 Out-of-Autoclave Material

- $R=5$
- Stress Level: 50% of Mean Static (~25 ksi)
- Runout: After 26 million cycles @ $f=5$ Hz
Development of Hybrid Spectrum

- Differences between composite and metallic spectrums
  - Metals: severe flight loads result in crack-growth retardation \(\Rightarrow\) Clipping
  - Composites: severe flight loads significantly contribute to flaw growth in composite structures and reduce the fatigue life
  - Flaw growth threshold for metals may be lower load level than that for composites
    \(\Rightarrow\) Different Truncation Levels
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

**Composite-Metal Bolted Joints**

- 2 x 3 0.25-inch fasteners with 0.5-inch pitch
- 2 metallic splice plates
- Anti-buckling fixture for compression loading

- Competing failure modes
- Sequencing effects
- Miner’s Rule or an alternative (???)
- Effects of LEFs
- Effects of additional test duration
- Effects of CTE mismatch
- Effects of environment
Composite vs. Metal - Sensitivity

- Notch Sensitivity (Composites)
- Notch Sensitivity (Metals)

CTE Mismatch

Damage Tolerance Certification of Composite Structures
12.6.3.4.4  Considerations for Metal/Composite Hybrid Structure

**ASIP 2010-11**
Fatigue Life Assessment of F/A-18 A-D Wing-Root Composite-Titanium Stepped-Lap Bonded Joint

**ASIP 2012**
Durability of Composite Wet Layup Repair on Metallic Leading Edge of F/A-18 Trailing-Edge Flap

**ASIP 2013-14**
Full-Scale Fatigue Testing of F/A-18 A-D Inner Wing

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**Graphs and Tables:**
- Load vs. Number of Test Lifetimes
  - Tension Dominant Fatigue Spectrum
  - Compression Dominant Fatigue Spectrum
  - Inspections after 10 lifetimes

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**Repair Results:**
- Crack survived 5,523 lbf
- Repair survived 6,785 lbf
- Repair After 1 Test Life survived 6,785 lbf

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**Announcement:**
*Damage Tolerance Certification of Composite Structures* 31

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*9/16/2015*
12.6.3.4.4 Considerations for Metal/Composite Hybrid Structure

F/A-18 Wing-Root Stepped-Lap Hybrid Bonded Joint

Viscoelastic Behavior of TRS due to Hygrothermal History

Transverse Residual Stress

Decrease in temperature

Moisture induced swelling

Stress relaxation

Moisture desorption

Summary

- CMH-17 Rev. H contents will be discussed during meeting in Wichita (October)
- Research findings will be presented at next FAA Joint Advanced Materials & Structures (JAMS) workshop
  - Hybrid fatigue study with thermal effects
  - Load sequencing studies
  - Hygrothermal history
- Multi-LEF Approach can be applied to hybrid structures to prevent metal overloads
  - Case studies
- Deferred spectrum
  - Composite-dominant design
  - Need analysis/tests to justify spectrum modifications
  - Case studies
Questions

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