Mechanistic Design Framework for Concrete Crosstie and Fastening System

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Mechanistic Design Framework Outline

• Overview of Mechanistic Design
• Design Process
  1. Define Load Inputs
     • Vertical Load
     • Lateral Load
     • Longitudinal Load
     • Load Distribution
  2. Define Design Thresholds
     • Material
     • Geometric
     • Assembly
  3. Component Design Process
  4. System Level Verification
Overview of Mechanistic Design

• Design approach utilizing forces measured in track structure and properties of materials that will withstand or transfer them

• Uses responses (e.g. contact pressure, relative displacement) to optimize component geometry and materials requirements

• Based on measured and predicted response to load inputs that can be supplemented with practical experience

• Requires thorough understanding of load path and distribution

• Allows load factors to be used to include variability due to location and traffic composition

• Used in other engineering industries (e.g. pavement design, structural steel design, geotechnical)
Design Process Sequence

• Design process consists of four stages
• To facilitate understanding of where each stage fits into the design process, the following graphic will be utilized

1. Define Load Inputs
   • Vertical
   • Lateral
   • Longitudinal
   • Distribution

2. Define Design Criteria
   • Material
   • Geometric
   • Assembly

3. Component Design
   • Material
   • Geometric
   • Assembly

4. System Verification
Load Characterization

• Load magnitude will vary according to:
  – Traffic type
  – Train speed
  – Track geometry
  – Vehicle and track health
• Each component of the input load must be considered
  – Vertical
  – Lateral
  – Longitudinal
• A complete understanding of the input loads can lead to optimized component and system designs
  – (e.g. as load magnitude and frequency change the design of the crosstie and fastening system should change)
Load Threshold Approach

- Design thresholds must be determined
  - Low thresholds could yield greater loads exceeding the design value which could result in accelerated wear and/or component failure
- Load distributions can be analyzed to better understand thresholds
  - 99.5% would be a threshold that is only exceeded by 0.5% of all wheels
- Engineers can set this threshold based on their economic model
  - Optimize between initial capital costs and operating costs

<table>
<thead>
<tr>
<th>Threshold Level</th>
<th>Conservative</th>
<th>Less Conservative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentile Load (%)</td>
<td>99.5</td>
<td>97.5</td>
</tr>
</tbody>
</table>

Define Load Inputs → Define Design Criteria → Component Design → System Verification
Vertical Load Characterization

- Vertical loads can be characterized using data from WILD sites
  - Provide average load and peak load for each wheel at each site
- WILD sites only provide a measure for well maintained track
- Useful for determining overall magnitude and variability according to car type
- Causes of vertical load variation could include, but are not limited to:
  - Speed
  - Temperature
  - Location (geographic)
  - Position Within the Train
  - Track Geometry
  - Vehicle Characteristics
  - Curvature
  - Grade
- Additional causes in load variation due to other conditions can likely be accounted for using a safety factor
### Vertical Wheel Load Tables

#### Nominal Load (kips)

<table>
<thead>
<tr>
<th>Car Type</th>
<th>Mean</th>
<th>95%</th>
<th>97.5%</th>
<th>99.5%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded Freight Car¹</td>
<td>6.6</td>
<td>9.6</td>
<td>11.0</td>
<td>13.6</td>
<td>15.0</td>
</tr>
<tr>
<td>Loaded Freight Car¹</td>
<td>33.4</td>
<td>39.5</td>
<td>40.2</td>
<td>41.4</td>
<td>45.5</td>
</tr>
<tr>
<td>Intermodal Freight Car¹</td>
<td>20.5</td>
<td>35.3</td>
<td>36.8</td>
<td>39.8</td>
<td>50.6</td>
</tr>
<tr>
<td>Freight Locomotive¹</td>
<td>33.6</td>
<td>36.6</td>
<td>37.2</td>
<td>38.5</td>
<td>43.5</td>
</tr>
<tr>
<td>Passenger Locomotive²</td>
<td>27.0</td>
<td>35.8</td>
<td>37.2</td>
<td>39.3</td>
<td>42.6</td>
</tr>
<tr>
<td>Passenger Coach²</td>
<td>15.0</td>
<td>18.3</td>
<td>19.0</td>
<td>20.1</td>
<td>45.4</td>
</tr>
</tbody>
</table>

#### Peak Load (kips)

<table>
<thead>
<tr>
<th>Car Type</th>
<th>Mean</th>
<th>95%</th>
<th>97.5%</th>
<th>99.5%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded Freight Car¹</td>
<td>10.8</td>
<td>20.5</td>
<td>26.4</td>
<td>39.7</td>
<td>100.8</td>
</tr>
<tr>
<td>Loaded Freight Car¹</td>
<td>42.3</td>
<td>56.2</td>
<td>65.3</td>
<td>84.7</td>
<td>156.6</td>
</tr>
<tr>
<td>Intermodal Freight Car¹</td>
<td>27.5</td>
<td>46.8</td>
<td>54.3</td>
<td>74.8</td>
<td>141.9</td>
</tr>
<tr>
<td>Freight Locomotive¹</td>
<td>42.8</td>
<td>53.9</td>
<td>57.5</td>
<td>68.8</td>
<td>109.6</td>
</tr>
<tr>
<td>Passenger Locomotive²</td>
<td>38.1</td>
<td>50.0</td>
<td>53.6</td>
<td>63.4</td>
<td>94.0</td>
</tr>
<tr>
<td>Passenger Coach²</td>
<td>23.2</td>
<td>35.3</td>
<td>42.9</td>
<td>58.5</td>
<td>108.8</td>
</tr>
</tbody>
</table>

¹Source of data: Union Pacific Railroad; Gothenburg, Nebraska; January 2010
²Source of data: Amtrak; Edgewood, Maryland, Hook, Pennsylvania, and Mansfield, Massachusetts; November 2010
Lateral Load Characterization

- Lateral loads in curves can be characterized through the use of truck performance detectors (TPDs) and/or instrumented wheel sets (IWS)
  - TPDs are similar to WILD sites, but found in curves
- Lateral loads must be characterized and distinguished by:
  - Track curvature (tangent vs curve)
- Causes of lateral load variation could include, but are not limited to:
  - Speed
  - Location (geographic)
  - Position Within the Train
  - Track Geometry
  - Vehicle Characteristics
  - Curvature
  - Grade
  - Rail Surface Condition
  - Superelevation
  - Low or High Rail
Lateral Load Wheel Load Distribution

- Percent Exceeded (%)
- Lateral Load (kips)

Legend:
- All Rolling Stock
- Cars
- Locomotives
- Empty Cars
Mechanistic Design Framework

Longitudinal Load Characterization

- No comparable wayside technology to WILD or TPD sites to measure longitudinal load
  - Some IWS can measure longitudinal load
- Longitudinal loads must be characterized and distinguished by:
  - Track curvature (tangent vs curve)
  - Track topography (mountains vs flats)
- Causes of load variation could include, but are not limited to:
  - Speed
  - Temperature
  - Location (geographic)
  - Position Within the Train
  - Track Geometry
  - Vehicle Characteristics
  - Curvature
  - Grade
Mechanistic Design Framework

Load Distribution in Fastening System

• Determine load transferred to individual component of the system
• Use the load at a specific interface as the design load
• Fastening system and wear dependent
  – As component geometry varies (as a result of design or wear), the load path will vary
• Circular relationship with component design
  – Load distribution guides design of components
  – Component design changes load distribution
• Quantification techniques
  – Laboratory and field experimentation
  – Analytical modeling
Lateral Load Restraint

Tangent Track, TLV

- Lateral Input Load
- Estimated Friction Forces
- Sum of Lateral Bearing Forces

Force (lbf):
- 0
- 5,000
- 10,000
- 15,000
- 20,000
- 25,000

Force (kN):
- 0
- 5,000
- 10,000
- 15,000
- 20,000
- 25,000

L/V Ratio:
- 0
- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6

178 kips

L kips
Improving Current Standards

- Recommended practices and standards have areas which can be improved to meet mechanistic design requirements
  - Justify or explain the origination of limit states for tests
    - Maximum allowable moments for concrete crossties (AREMA)
    - Provide limits for all critical properties
      - Lateral rail base displacement limit for insulator
    - Develop a design process for all components
      - Several pad choices are given, but no process for design
  - Examining current standards gives clarity to what is missing or what aspects need improvement
Limit State Component Design

• Design component based on failure modes
• Determine value of design criteria for critical fastening system properties
  – Highest value a property can reach that still ensures safe system operation
• Limit state design can be decomposed into three categories of design criteria, each which must have criteria limits defined
  – Material
  – Geometric
  – Assembly
• Provides opportunity to split up design process into smaller manageable pieces
  – E.g. - A project could analyze one specific material property

Define Load Inputs → Define Design Criteria → Component Design → System Verification
Material Design Criteria

- Define limits for properties of materials used to build components
- Independent of fastening system type and component geometry
- Determine which properties are critical, and the limiting value of the design criteria
- Critical properties to evaluate are:
  - Compressive Strength
  - Tensile Strength
  - Flexural Strength
  - Shear Strength
  - Stiffness
  - Wear Resistance
  - Fatigue
- Example of existing material tests:
  - ASTM tests regarding material properties of rail pads, described in Ch. 30 section 4.9.1.15 of AREMA
Geometric Design Criteria

- Definite limits for properties dictated by component geometry
- Fastening system dependent
- Critical properties to evaluate are:
  - Compressive Strength
  - Tensile Strength
  - Flexural Strength
  - Shear Strength
  - Stiffness
  - Wear Resistance
  - Fatigue
- Same properties as for material design, but limits will be different
  - Limits based on laboratory and field testing
- No existing examples of geometric design thresholds in AREMA standards
Critical Components

Example: Safelok I fastening system
Assembly Design Criteria

- Define the limits of properties of a fully assembled fastening system
- Simplified testing state that eliminates variation due to support conditions
- Critical properties to evaluate include:
  - Contact Pressure
  - Relative Displacement
  - Wear Resistance
- Primary areas of concern are interfaces between components
  - Interfaces will vary with different fastening systems
- Examples of existing assembly tests include:
  - AREMA Test 6
  - Rail Seat Load Index
Critical Interfaces

Example: Safelok I fastening system
Component Design Process

1. Select load threshold (low, medium, or high)
2. Complete material design process
   - Compressive Strength
   - Tensile Strength
   - Flexural Strength
   - Shear Strength

3. Complete geometric design process
   - Compressive Strength
   - Tensile Strength
   - Flexural Strength
   - Shear Strength

4. Complete assembly design process
   - Contact Pressure
   - Relative Displacement
   - Wear Resistance

Define Load Inputs → Define Design Criteria → Component Design → System Verification

- Stiffness
- Wear Resistance
- Fatigue

• Compressive Strength
• Tensile Strength
• Flexural Strength
• Shear Strength

• Stiffness
• Wear Resistance
• Fatigue

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Mechanistic Design Framework

Component Design Process

1. Define Load Inputs
2. Define Design Criteria
3. Component Design
4. System Verification

- Choose Load Threshold
- Choose Material
- Design Geometry
- Test Assembly
- Test Component
- Test Material

Flowchart:
- Choose Material ➔ Test Material
- Design Geometry ➔ Test Component
- Test Assembly ➔ System Verification
- Choose Load Threshold
- Final System Verification

Flowchart States:
- PASS
- FAIL
Final System Verification

• Look at overall system response to confirm that design is adequate

• Critical properties to evaluate include:
  • Maximum Ballast Pressure
  • Maximum Subgrade Pressure
  • Total Track Deflection
  • Track Modulus

• Typically involves field testing with varied support conditions

• Initial simulations could be performed with FEM model
  – Lower cost and more timely than producing new parts

• Evaluate system by installing in track and examine critical properties after appropriate amount of traffic
UIUC Contribution to Mechanistic Design

- Field Experimentation
- Standards Review
- Mining of Existing Data
- FEM Model
- Lab Experimentation
- Analytical Track Design Tool

Define Load Inputs ➔ Define Design Criteria ➔ Component Design ➔ System Verification
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Conclusions

• Characterizing wheel load distribution of rail traffic will give more realistic values for input loads used to test components and system

• Limit state component design can be used to give greater understanding to what the factor of safety in design is

• Proposed mechanistic design methodology will provide consistent approach even with varying fastening systems

• Framework provides a guide for future research projects to improve the design process
Future Work

- Analyze lateral load data from multiple TPD sites to develop similar load tables to vertical load tables
- Perform more analysis on critical properties, determine if other properties should be included
- Perform literature review to determine existing research on determining values for component properties design criteria
- Include more system level tests, develop ideas for new tests that aren’t currently included in AREMA or other standards
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