

Mechanistic Design Framework for Concrete Crosstie and Fastening System



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**U.S. Department of Transportation
Federal Railroad Administration**

Mechanistic Design Framework Outline

- Overview of Mechanistic Design
- Design Process
- Define Load Inputs
- Define Design Thresholds
- Component Design Process
- System Level Verification
- Design Process Example - Insulator



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)

Improving Current Standards

- Due to failures in the field, a push has been made for modifications to the current design processes
- 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

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

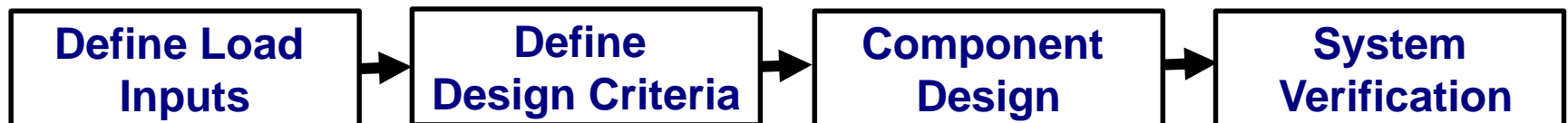
2. Define Design Criteria

- Material
- Geometric
- Assembly

3. Component Design

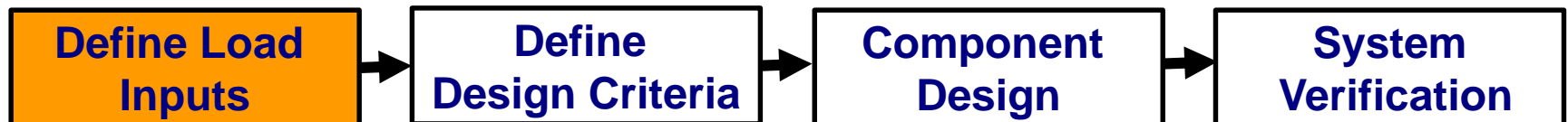
- Material
- Geometric
- Assembly

4. System Verification



Load Characterization

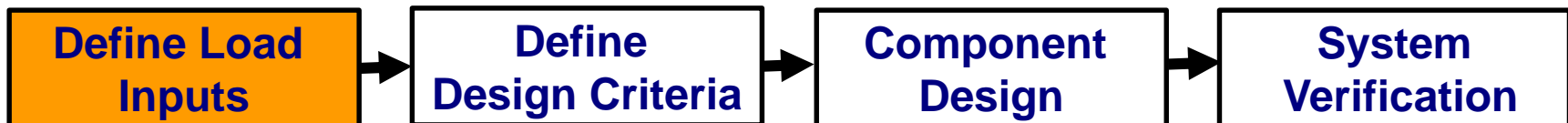
- Load magnitude will vary according to:
 - Traffic type
 - Train speed
 - Track geometry and condition
 - Vehicle health
- Each component of the input load must be considered
 - Vertical
 - Lateral
 - Longitudinal
- A complete understanding of the input loads can lead to optimized component and system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



Load Threshold Approach

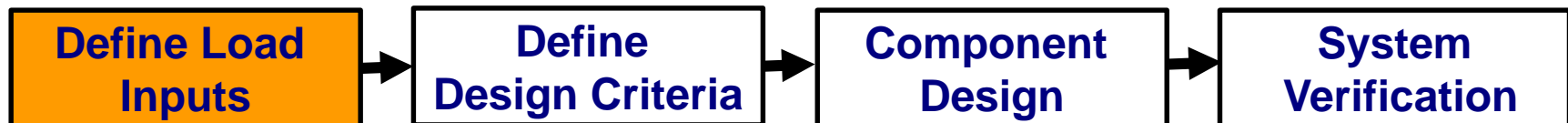
- Load distributions can be analyzed to develop design thresholds
 - 99.5% would be a threshold that is only exceeded by 0.5% of all wheels
- Engineers can set this threshold based on their economic model
 - Optimize between initial capital costs and operating costs
 - Low thresholds could yield more loads exceeding the design value which could result in accelerated wear and/or component failure
- Thresholds will be high percentiles due to large quantity of wheel loads

Threshold Level	Conservative	—————>	Less Conservative
Percentile Load (%)	99.5	97.5	95



Vertical Load Characterization

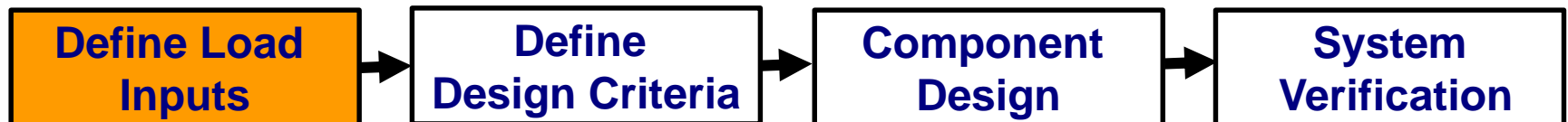
- Vertical loads can be characterized using data from WILD sites
 - Provide average load and peak load for each wheel at each site
- WILD sites only provide a measure for well maintained track
- Useful for determining overall magnitude and variability according to car type
- Causes of vertical load variation 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



Design Vertical Wheel Loads

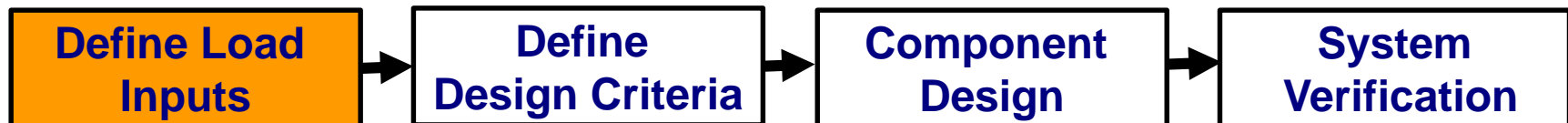
Car Type	Nominal Load (kips)				
	Mean	95%	97.5%	99.5%	100%
Unloaded Freight Car ¹	7	10	11	14	15
Loaded Freight Car ¹	34	40	41	42	46
Intermodal Freight Car ¹	21	36	37	40	51
Freight Locomotive ¹	34	37	38	39	44
Passenger Locomotive ²	27	36	38	40	43
Passenger Coach ²	15	19	19	21	46

Car Type	Peak Load (kips)				
	Mean	95%	97.5%	99.5%	100%
Unloaded Freight Car ¹	11	21	27	40	101
Loaded Freight Car ¹	43	57	66	85	157
Intermodal Freight Car ¹	28	47	55	75	142
Freight Locomotive ¹	43	54	58	69	110
Passenger Locomotive ²	39	50	54	64	94
Passenger Coach ²	24	36	43	59	109



Lateral Load Characterization

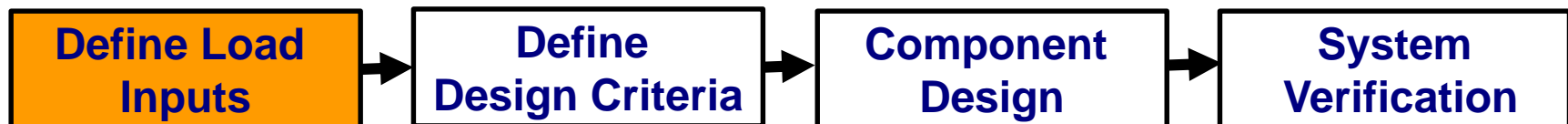
- Lateral loads in curves can be characterized through the use of truck performance detectors (TPDs)
 - TPDs are similar to WILD sites, but found in curves
- Lateral loads must be characterized and distinguished by:
 - Track curvature (tangent vs curve)
- Causes of lateral load variation could include, 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



Design Lateral Wheel Loads (TPD)

Car Type	Lateral Load (kips)				
	Mean	95%	97.5%	99.5%	100% (Max)
Unloaded Freight Car	1.1	4.4	5.2	6.9	22.4
Loaded Freight Car	2.7	10.1	12.1	15.9	33.5
Intermodal Freight Car	1.9	6.2	7.4	10.1	22.8
Freight Locomotive	3.9	13.3	15.6	20.5	34.4

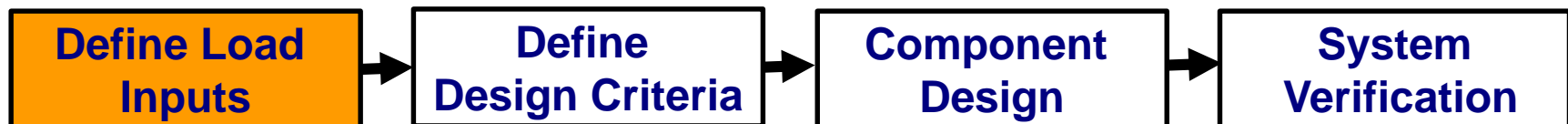
Car Type	L/V Ratio				
	Mean	95%	97.5%	99.5%	100% (Max)
Unloaded Freight Car	0.15	0.44	0.50	0.64	4.00
Loaded Freight Car	0.11	0.35	0.41	0.52	1.46
Intermodal Freight Car	0.12	0.39	0.46	0.59	1.61
Freight Locomotive	0.11	0.38	0.44	0.56	0.81



Longitudinal Load Characterization

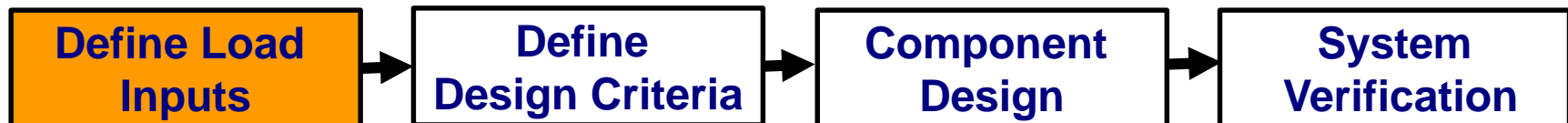
- No comparable wayside technology to WILD or TPD sites to measure longitudinal load
 - Some Instrumented Wheel Sets (IWS) can measure longitudinal load
- Longitudinal loads must be characterized and distinguished by:
 - Track curvature (tangent vs curve)
 - Track topography (mountains vs flats)
- Causes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

	Mainline Freight	Light Density Freight	High Speed Passenger
Longitudinal Load (kips)	50	30	25

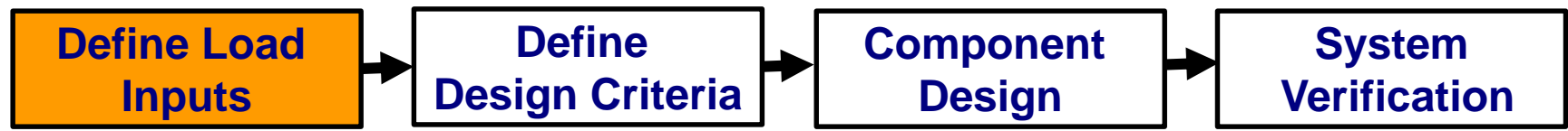
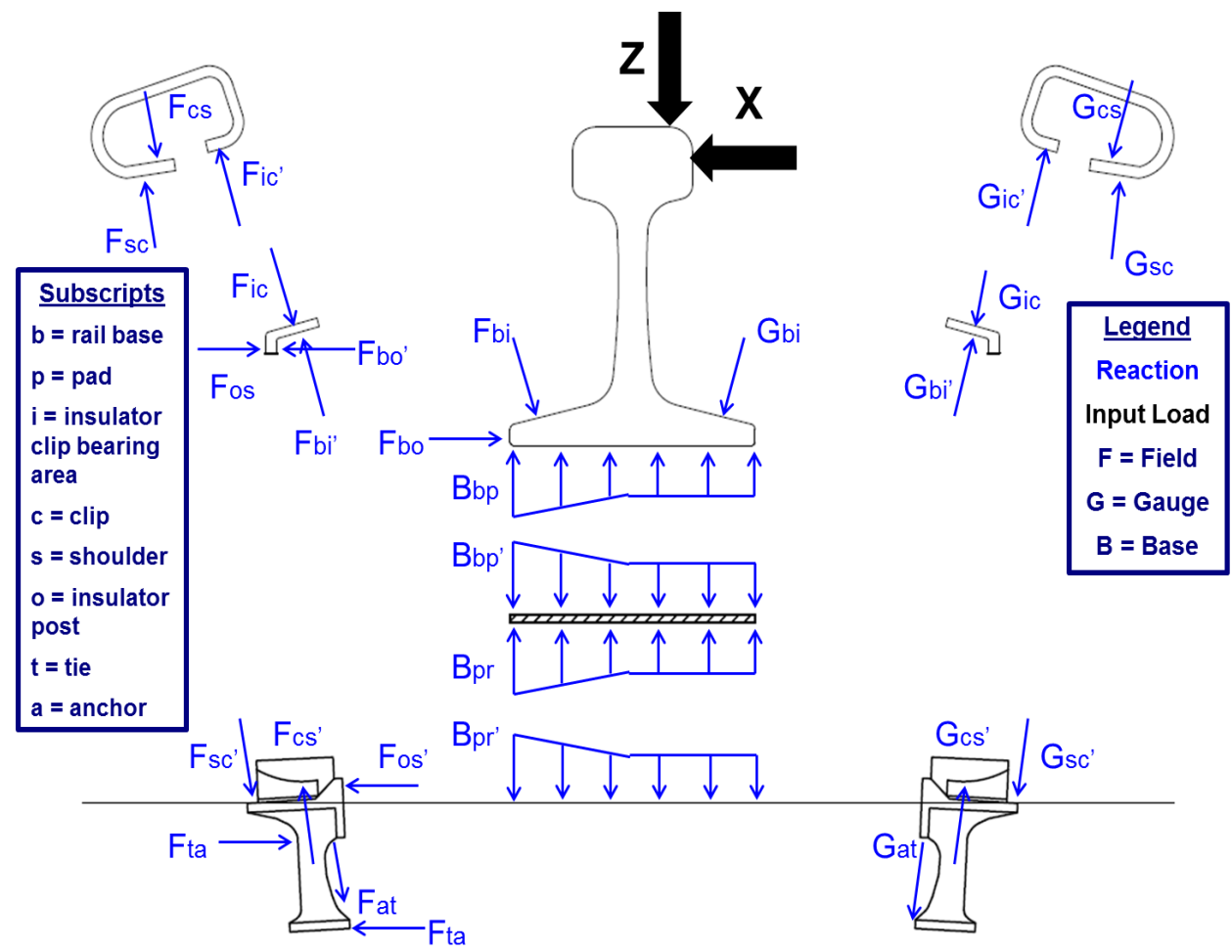


Load Distribution in Fastening System

- 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

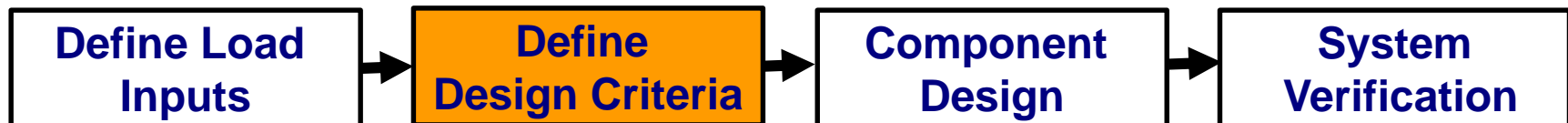


Load Path Example – Safelok I



Limit State Component Design

- Design component based on load-related 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



Design Criteria Methodology

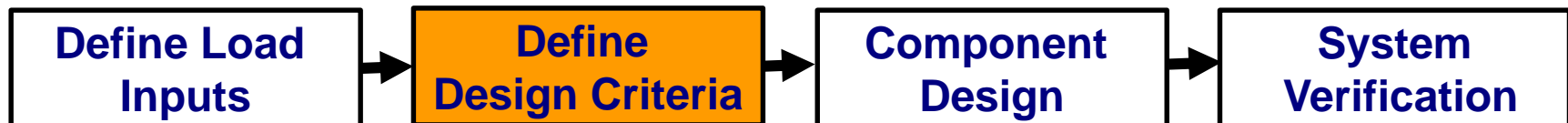
$$S_r = \alpha * S_n$$

where,

S_r = Required Strength α = Reduction Factor

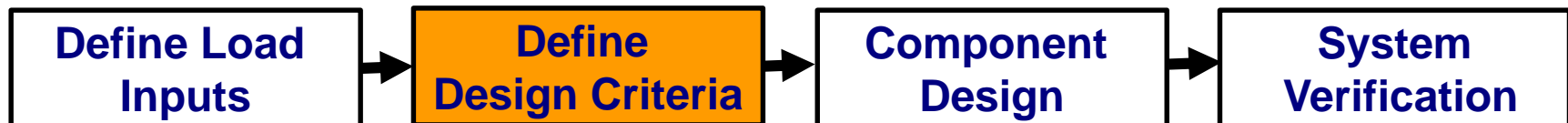
S_n = Nominal Strength

- Required Strength: strength necessary to resist demands on component
- Nominal Strength: estimated component strength using lab testing and stressing to failure
- Reduction Factor: accounts for relative severity of failure modes and component variability



Material Design Criteria

- Define limits for properties of materials used to build components
- Independent of fastening system type
- Critical properties to evaluate are:
 - Compressive Strength
 - Tensile Strength
 - Flexural Strength
 - Shear Strength
 - Stiffness
 - Wear Resistance
 - Fatigue
- Contributing factors include environment and tonnage
- Example of existing material tests:
 - ASTM tests regarding material properties of rail pads, described in Ch. 30 section 4.9.1.15 of AREMA



Material Design Failure Modes

- Exceeding the design criteria for material properties can result in several types of failures
- These failures could be sudden, or a gradual failure over time

Bond Failure



Rail Seat Deterioration



Define Load
Inputs

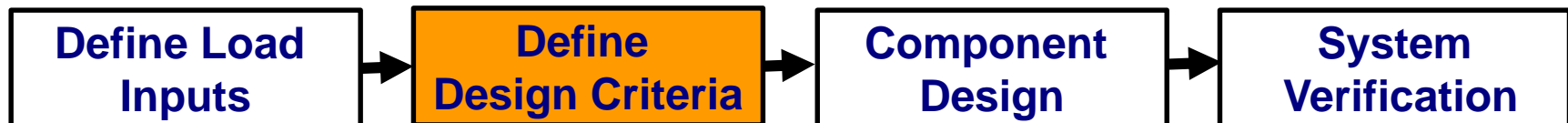
Define
Design Criteria

Component
Design

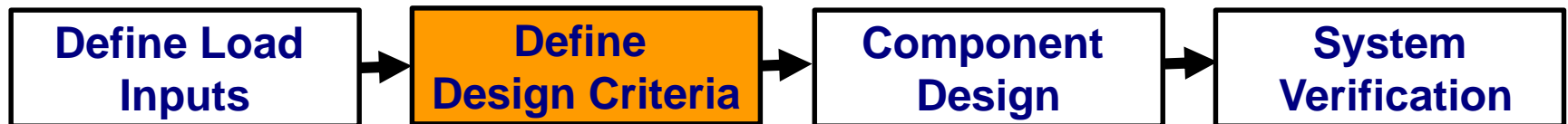
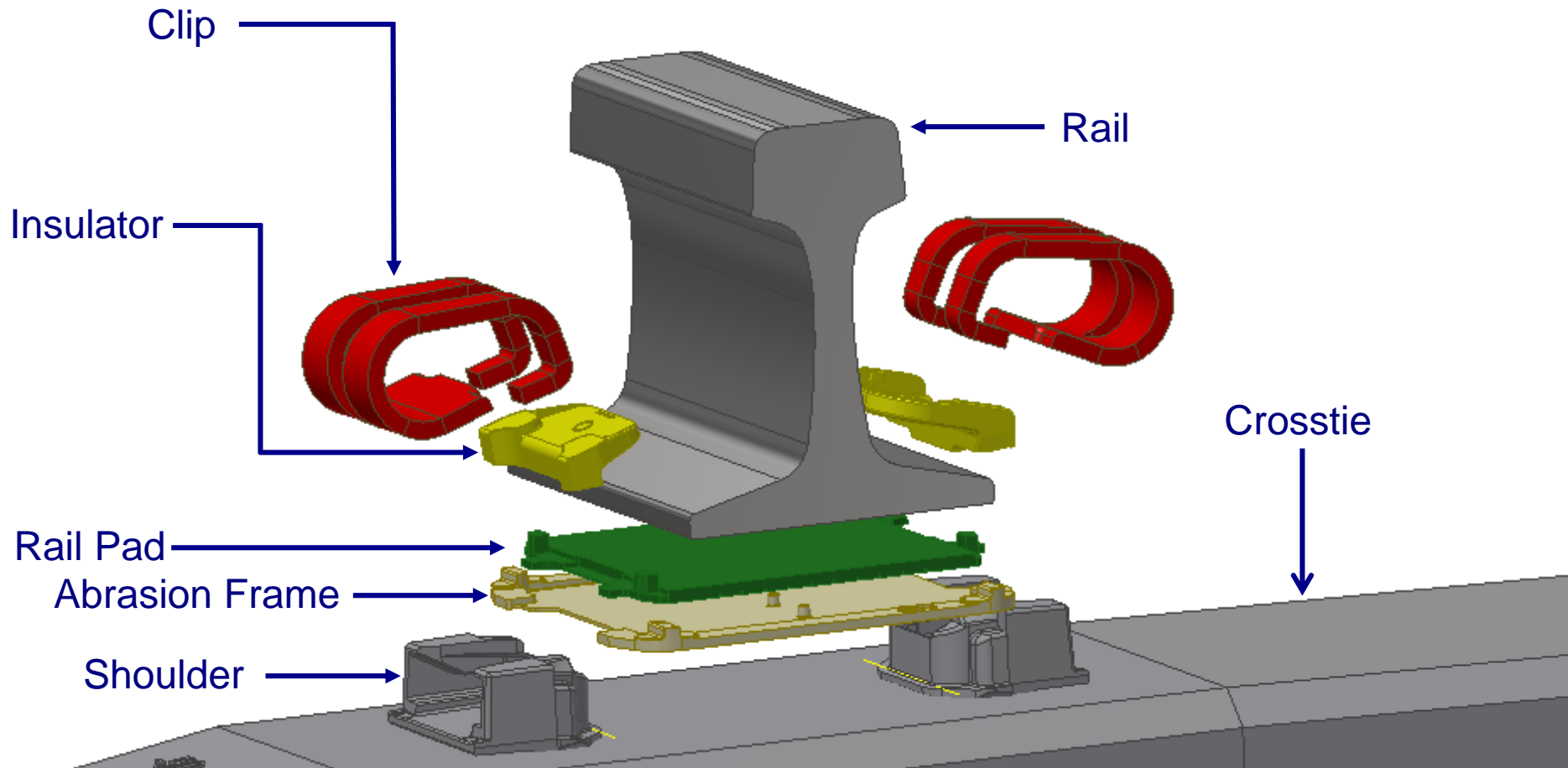
System
Verification

Geometric Design Criteria

- Define 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
 - Required strength based on laboratory and field testing
- No existing examples of geometric design thresholds in AREMA standards



Components Example – Safelok I



Geometric Design Failure Modes

- Exceeding geometric design properties can result in several specific types of failures
- Geometric design can result in the exceedance of material property limits

Yielded Clip



Worn Insulator



Define Load
Inputs

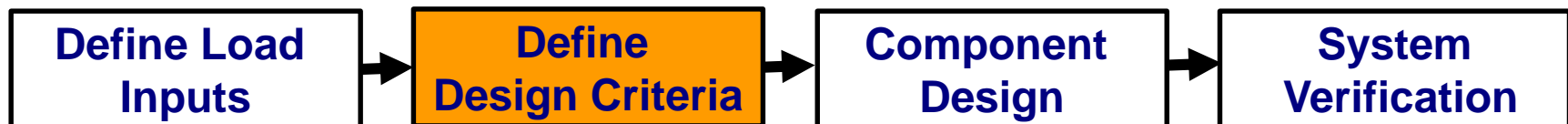
Define
Design Criteria

Component
Design

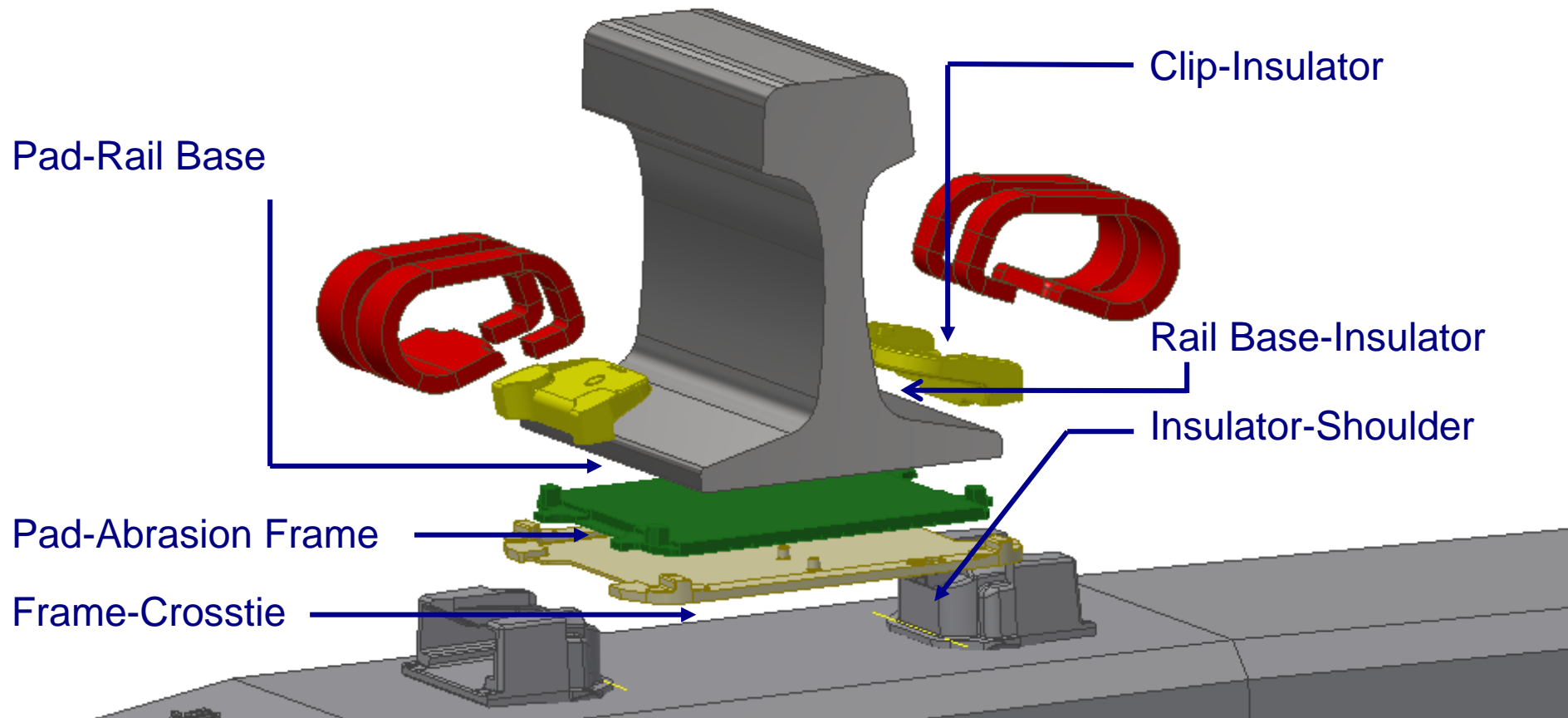
System
Verification

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



System Interfaces Example – Safelok I



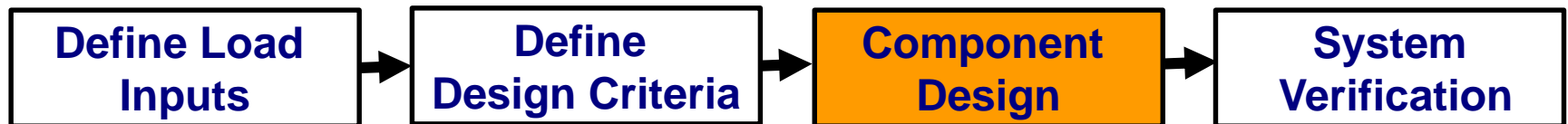
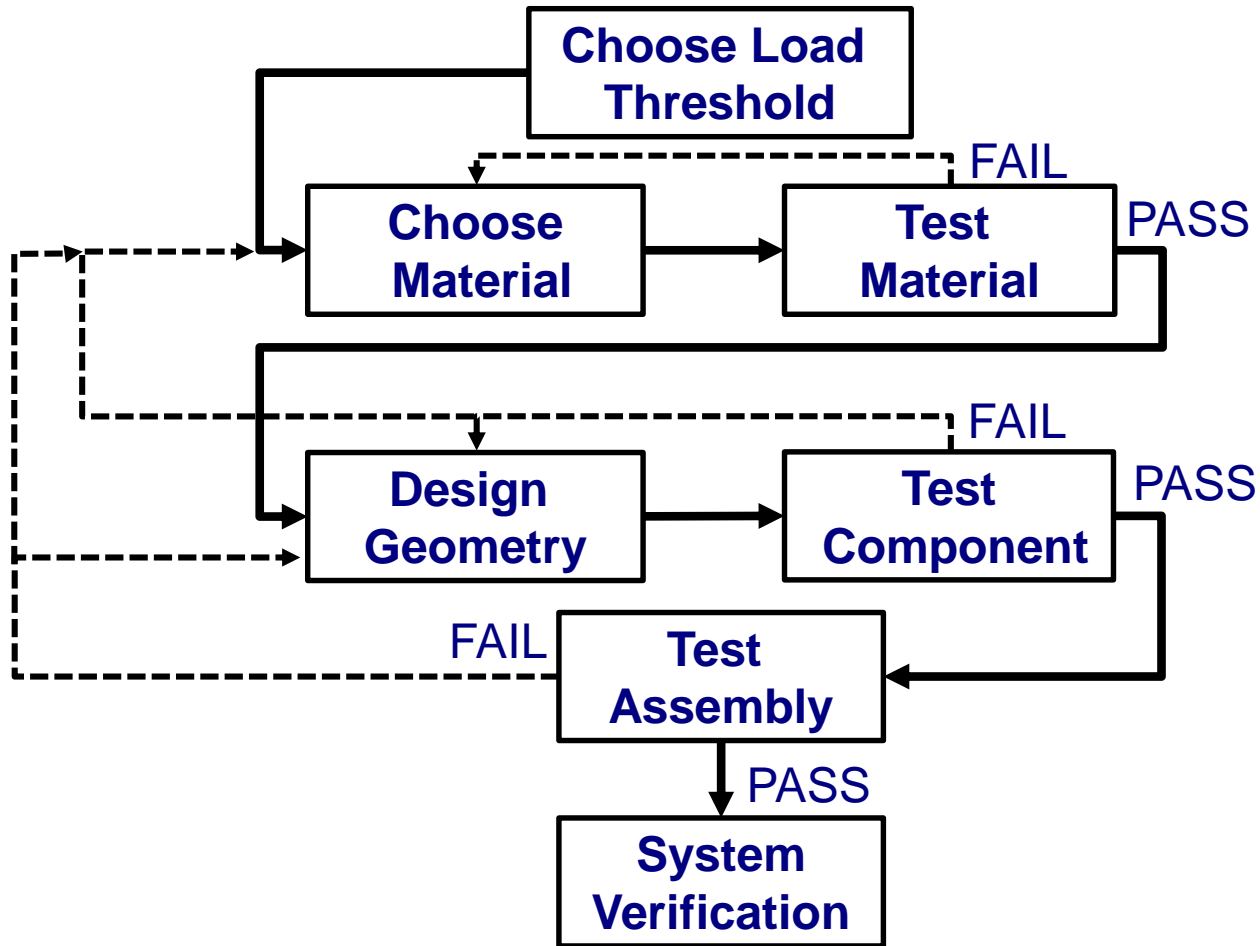
Define Load
Inputs

Define
Design Criteria

Component
Design

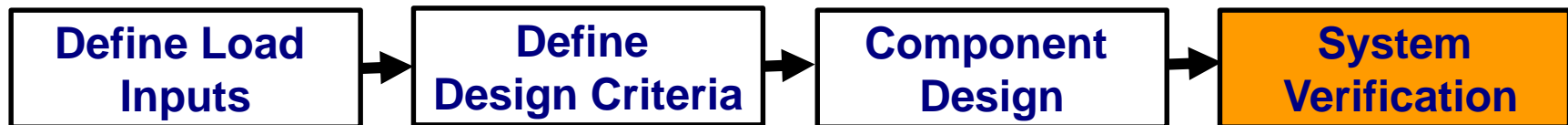
System
Verification

Component Design Process



Final System Verification

- Examine 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 computer model
 - Lower cost and more timely than producing new parts
- Evaluate system by installing in track and examine critical properties after appropriate tonnage



Component Design Example

Insulator – Current Design Standards

- Current Tests
 - ASTM D257 - test electrical properties of insulator material
 - AREMA Test 7 – ensures that minimum electrical impedance values are met
 - AREMA Test 6 – measures lateral rail head displacements
- Shortcomings
 - Electrical properties should be determined before geometry of component is chosen
 - Missing measurement of lateral rail base displacement
 - Limiting values of Test 6 origin appear to be empirically derived, source is not clear

Insulator – Load Threshold Selection

- Select threshold based on requirements of track where insulators will be installed
 - Use field and lab measurements to determine demands

	Peak Load (lbf)				
	Mean	95%	97.50%	99.50%	100%
Force on Shoulder ¹	2,020	5,501	6,414	7,408	7,883

Source of data: Transportation Technology Center; Pueblo, Colorado; May 2013

- Sample Calculation:

Choose 95% confidence threshold

95% of lateral FS forces fall below 5,500 lbf (based on field data)

Design FS force → 8,000 lbf

Insulator – Material Selection

- Select material based on critical properties of insulator
- **Electrical Resistivity** – sample of material must meet necessary resistivity
 - When 10 volts AC, 60 hZ is applied, resistance must exceed 10,000 Ω

$$\frac{\text{Applied Voltage (V)}}{\text{Current Flow (A)}} = R \qquad \frac{10,000 \text{ V}}{0.00094 \text{ A}} = 10,638 \Omega \rightarrow \text{Pass}$$

- **Applied Load** – sample of material must meet load versus deflections requirements
 - When 10,000 lbf is applied 10 times for one second each, the slope of the load versus displacement curve must be less than 150,000 lb/in

$$\frac{\text{Applied Load (lbf)}}{\text{Displacement (in)}} = S \qquad \frac{10,000 \text{ lbf}}{0.0714 \text{ in}} = 140,000 \text{ lbf/in} \rightarrow \text{Pass}$$

Insulator – Geometric Design

- Design geometry based on reducing demands on components, intended component function, and interfaces with other components
- **Stress on bearing areas** – Stress on interface of shoulder and insulator should not exceed limits
 - Typical compressive strength of material is 25,000 psi
 - Actual bearing area must exceed calculated requirement

$$\frac{\text{Applied Load (lbf)}}{\text{Compressive Strength (psi)}} (\text{S.F.}) = A \quad \frac{8,000 \text{ lbf}}{25,000 \text{ psi}} (2) = 0.64 \text{ in}^2$$

- Applied load as determined in load threshold selection
- Compressive strength will vary with material selected

Insulator – System Level Verification

- Evaluate properties of system that depend on design of insulator
 - Eg. Forces and relative displacement at insulator interfaces
- **Actual Pressure at Bearing Area with Shoulder**
 - Pressure at interface must be less than material compressive strength limit (25,000 psi for this example)

$$\frac{\text{Measured Force (lbf)}}{\text{Bearing Area (in}^2\text{)}} = \sigma$$

$$\frac{7,250 \text{ lbf}}{0.68 \text{ in}^2} = 10,662 \text{ psi} < 25,000 \text{ psi} \rightarrow \text{Pass}$$

Insulator – Future Work

- Validate proposed design using data from field and the FE model
 - Determine the exact demands on the insulator
- Perform full-scale testing to learn more about lateral loads and load distribution and the loads imparted on the insulator
- Specifically engineer materials with high strength and high electrical resistivity

Conclusion

Qualitative Comparison of Iterative and Mechanistic Design Processes

Category	Iterative Design (Current)	Mechanistic Design (Proposed)
Ease of development	Already developed	Will require large amounts of capital investment and time
Time required to run analysis	Relatively quick	Requires lengthy analysis process
Accuracy of demand estimates	Variable, could be inaccurate	Highly accurate, based on system specific analysis
Ability to account for specific failure modes	Limited, mostly focused on crosstie failure modes	Design specifically accounts for each failure mode of every component
Potential for design of new systems	Low, may not be accurate	High, very flexible for material or geometry chosen for the system
Safety factor of design	Relatively conservative	More variable according to choice of designer



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Thank You



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