Purpose of this Presentation

- Take a fresh look at crane loads used to design crane runway girders and supporting building structure.
- Historically, in U.S., we have based these loadings on:
  - AISC Specification for Structural Steel Buildings (up to 1989 AISC ASD Specification)
  - ASCE 7, Minimum Design Loads for Buildings and Other Structures (for current designs)
Response and Loadings on Building Structure

- Note that since many of these forces are dynamic (vary with time), the response of the crane runway and building structure truly becomes a structural dynamics problem.
Crane Vertical Loads

- Dynamic forces are associated with two operations
  - Hoisting of the load (dynamic force is a function of hoist acceleration)
  - Travel of the bridge – dynamic forces are generated when the crane wheels encounter discontinuities in the supporting rail system
    - Rail offsets at splices
    - Rail vertical discontinuities created by wear issues
    - Uneven wheel wear leading to wheels that may not be perfectly round
    - Vertical dynamic loads associated with general motion of the crane
Crane Vertical Impact Forces Due to Bridge Travel

SOME VERTICAL IMPACT SOURCES ASSOCIATED WITH BRIDGE TRAVEL

1. CRANE WHEEL MOTION
   RAIL OFFSET

2. CRANE WHEEL MOTION
   VERTICAL DISCONTINUITIES IN RAIL (e.g., FRETTING)

3. CRANE WHEEL MOTION
   WHEEL NOT PERFECTLY ROUND OR BEARING SURFACE OF WHEEL UNEVEN DUE TO WHEEL WEAR
Crane Vertical Impact Forces Due to Bridge Travel

SOME VERTICAL IMPACT SOURCES ASSOCIATED WITH BRIDGE TRAVEL

1. CRANE WHEEL MOTION
   - RAIL OFFSET

2. CRANE WHEEL MOTION
   - VERTICAL DISCONTINUITIES IN RAIL (eg. FRETTING)

3. CRANE WHEEL MOTION
   - WHEEL NOT PERFECTLY ROUND OR BEARING SURFACE OF WHEEL UNEVEN DUE TO WHEEL WEAR
Crane Lateral Inertial and Dynamic Forces

- Tractive forces from trolley
- Braking forces from trolley
- Bumper forces due to trolley impacting stop at end of bridge
- Skewing forces
- Lateral forces due to dynamic asymmetry
- Lateral forces due to non-vertical lift
Skewing Forces

Skewing forces or forces associated with oblique travel are generated as the bridge travels and skews due to:

- Non-synchronized drive mechanisms for each bridge end truck
- Axles for end truck wheels are not parallel
- Misaligned crane rail
- Wheels for one end truck are slightly different in diameter than other end truck
- Non-uniform braking forces applied to each end truck
Forces associated with bridge skewing

- Sequence of events
  - Crane assumes skewed position for reasons noted on previous slide
  - Eventually a flange of one of the leading endtruck wheels comes in contact with the side of the crane rail. Horizontal frictional forces also develop at all wheels since steering force is trying to change the orientation of the crane
  - The lateral force from this wheel on the side of the rail increase (to $P_{OT}$ referred to as the steering force), the girders deflect as a result of this force and eventually the bridge rights itself. At some point, flanges of other wheels will engage the side of the rail to assist with righting the bridge
Crane Skewing and Resulting Horizontal Forces on Crane Girders

$P_{OT}$: Steering Force

$Y_{ij}$: Frictional Forces on Wheels
Crane Skewing and Resulting Horizontal Forces on Crane Girders

\[ P_{OT} : \text{STEERING FORCE} \quad Y_{ij} : \text{FRICIONAL FORCES ON WHEELS} \]
Lateral Forces Due to Dynamic Asymmetry

- These forces occur as the crane is accelerating or decelerating.
- Generated if the center of mass of the crane including lifted load does not align with the centroid or resultant of the tractive forces from endtruck wheels.
- The tractive forces are causing the crane to accelerate or decelerate.
- Results in torsional force on bridge, similar to skewing forces previously discussed.
Dynamic Asymmetry

$R_T$: RESULTANT TRACTIVE FORCE

TORSIONAL MOMENT = $R_T \times J$

CM = CENTER OF MASS OF CRANE + LIFTED LOAD
Lateral Forces Due to Non-Vertical Lifts

LATERAL FORCE DUE TO NON-VERTICAL LIFT = W_{LOAD} \times \sin \theta

NOTE THAT THE MAGNITUDE OF THIS LATERAL FORCE IS LIMITED BY THE TRACTIVE FORCE THAT CAN BE DEVELOPED BETWEEN THE TROLLEY WHEELS AND RAIL OR THE BRAKING FORCE AND RAIL IF BRAKES ARE PROVIDED FOR THE TROLLEY AND UTILIZED FOR THIS OPERATION.
Crane Longitudinal Forces

- Sources
  - Tractive forces from crane end trucks
  - Braking forces from crane end trucks
  - Bumper forces from crane collision with end stops on runway Lateral forces
Crane Longitudinal Tractive Forces

Tractive force is limited by the maximum frictional force that can be sustained without wheel skid.

Crane designer does not want driven wheel to skid for all loading conditions, so maximum torque is regulated to provide tractive force \( P_{\text{MIN}} = P_{\text{MIN}} \mu m \)

\( P_{\text{MIN}} \) = Minimum vertical wheel load on end truck (i.e. unloaded)
\( \mu \) = Sliding coefficient of friction, estimate as 0.2
\( m \) = Dynamic factor, estimate as 1.5
Maximum Tractive Force

Therefore, the maximum tractive force per end truck

\[ = P_{MIN} \mu mN \quad (N=\text{no. of driven wheels per end truck}) \]

\[ = P_{MIN}(0.2)(1.5)N \]

\[ = 0.3P_{MIN}N \]
Bumper forces are a dynamic force that varies with bridge speed at impact, mass of crane + trolley (typically not including lifted load) and the load-deformation characteristics of the bumper system
Bumper Force Calc. for Linear Load-Deformation Relationship for Bumper

![Graph showing load vs. spring displacement]

**Work done**

\[ \Delta KE = W \]
\[ = \frac{1}{2} m_c v_1^2 \]  \[\text{--- i}\]
\[ = \Delta PE \]
\[ = \frac{1}{2} K_B s^2 \]  \[\text{--- ii}\]

Now, work done

\[ W = P_{BI}.s/2 \]  \[\text{--- iii}\]

Equating i, ii & iii

\[ P_{BI} = \frac{m_c v_1^2}{s} = v_1 \sqrt{m_c K_B} \]

- **P_{BI}** — buffer impact force
- **K_B** — spring constant
- **m_c** — mass of crane
- **s** — spring extension
Hydraulic Bumpers

- Hydraulic Bumpers are very commonly used with heavy and/or fast cranes
- Consult bumper manufacturer’s literature for bumper capacities and force / stroke characteristics.
Crane Forces per Eurocode 2006

- Part 3 of Eurocode 1 draws much from the previous German DIN Standard 15018
- Code is more complex with regard to deriving various inertial and dynamic force components associated with the crane and requires additional input from the crane supplier to calculate these forces
- Although more complex, this code is also more transparent with regards to evaluating forces based on previously noted potential source of these loads
Difference in Behavior for Two Guidance Systems

- Guidance for flanged wheel option provided on both sides of bridge (i.e. resisted by both crane girders)
- Guidance for guide roller option shown on previous slide is focused to one side of the runway girder when friction forces between rails and wheels are exceeded. This system is commonly used by European crane suppliers
- Effect on design of crane rail, rail attachments, crane girder and supporting building structure may be significant
Crane Lat. Forces Due to Acceleration & Deceleration of Crane Bridge

- Reference Section 2.7.2 of EN 1991-3 (this deals with lateral load source previously referred to as dynamic asymmetry)

\[
H_{T,1} = \Phi_5 \xi_2 \frac{M}{a}
\]

\[
H_{T,2} = \Phi_5 \xi_1 \frac{M}{a}
\]
### Table 2.2 — Groups of loads and dynamic factors to be considered as one characteristic crane action

<table>
<thead>
<tr>
<th>Group (Symbol, Section)</th>
<th>Groups of loads</th>
<th>Ultimate Limit State</th>
<th>Test load</th>
<th>Accidental</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Self-weight of crane</td>
<td>$Q_s, 2.6$</td>
<td>$\varphi_1, 1$</td>
<td>$\varphi_2, 1$</td>
<td>$1, 1$</td>
</tr>
<tr>
<td>2 Hoist load</td>
<td>$Q_h, 2.6$</td>
<td>$\varphi_3, 1$</td>
<td>$\varphi_4, 1$</td>
<td>$1, 1$</td>
</tr>
<tr>
<td>3 Acceleration of crane</td>
<td>$H_L, H_T, 2.7$</td>
<td>$\varphi_5, 1$</td>
<td>$\varphi_6, 1$</td>
<td>$1, 1$</td>
</tr>
<tr>
<td>4 Swinging of crane</td>
<td>$H_S, 2.7$</td>
<td>$\varphi_7, 1$</td>
<td>$\varphi_8, 1$</td>
<td>$1, 1$</td>
</tr>
<tr>
<td>5 Acceleration or braking of crane or hoist block</td>
<td>$H_{TD}, 2.7$</td>
<td>$\varphi_9, 1$</td>
<td>$\varphi_{10}, 1$</td>
<td>$1, 1$</td>
</tr>
<tr>
<td>6 In-service wind</td>
<td>$F_w$, Annex A</td>
<td>$1, 1, 1, 1$</td>
<td>$1, 1$</td>
<td>$1, 1$</td>
</tr>
<tr>
<td>7 Test load</td>
<td>$Q_T, 2.10$</td>
<td>$\varphi_{11}, 1$</td>
<td>$\varphi_{12}, 1$</td>
<td>$1, 1$</td>
</tr>
<tr>
<td>8 Buffer force</td>
<td>$H_B, 2.11$</td>
<td>$\varphi_{13}, 1$</td>
<td>$\varphi_{14}, 1$</td>
<td>$1, 1$</td>
</tr>
<tr>
<td>9 Tilting force</td>
<td>$H_{TA}, 2.11$</td>
<td>$\varphi_{15}, 1$</td>
<td>$\varphi_{16}, 1$</td>
<td>$1, 1$</td>
</tr>
</tbody>
</table>

**NOTE:** For out of service wind, see Annex A.

$\varphi$ is the proportion of the hoist load that remains when the payload is removed, but is not included in the self-weight of the crane.

$\eta$ is the proportion of the hoist load that remains when the payload is removed, but is not included in the self-weight of the crane.
Crane Load Combinations

Considerations – LRFD Combinations

- What are the appropriate load factors to be used for the crane dead and live loads?
- What are the appropriate load factors to be used with each of the inertial or dynamic forces?
- What individual dynamic and inertial forces should be considered simultaneously?
- What are the appropriate load factors to be used with each of these inertial or dynamic forces?
- What other building loads should be considered with crane loads?
- For LRFD Design, what Peak and Companion Load Factors should be considered?
- What about multiple cranes?
Commentary to Section 4.10 states that all support components of moving bridge cranes and monorail cranes shall be designed to support the maximum wheel load of the crane and the vertical impact, lateral and longitudinal forces induced by the moving crane. Also the runway beam end stops shall be designed for crane stop forces.

- This discussion does not appear to exclude any crane dynamic or inertial force from the load combination considering crane loads (i.e. crane loads would consider all of these forces – vertical impact, crane lateral loads and crane longitudinal loads) simultaneously.

- Commentary also references CMAA Specs., MBMA Design Manual and AIST Tech. Report #13 for crane runways supporting higher capacity or higher speed crane systems.
ASCE 7-05 LRFD Load Combinations

1. 1.4D
2. 1.2D+1.6L+0.5(Lr or S or R)
3. 1.2D+1.6(Lr or S or R) + (L or 0.8W)
4. 1.2D+1.6W+L+0.5(Lr or S or W)
5. 1.2D+1.0E+L+0.2S
6. 0.9D+1.6W
7. 0.9D+1.0E

Comments
- Include crane loads anytime you see L
- What crane load should be used for combs. w/ E?
- What crane load should be considered for fatigue design?
- What about multiple cranes?
ASCE 7-05 ASD Load Combinations

1. D
2. D+L
3. D+(L_r or S or R)
4. D+0.75(L)+0.75(L_r or S or R)
5. D + (W or 0.7E)
6. D+0.75(W or 0.7E)+0.75L+0.75(L_r or S or R)
7. 0.6D+W
8. 0.6D+0.7E

Same Comments as for LRFD Load Combs.
ASCE 7-05 Load Combinations - Problems

- Does not address multiple cranes
- Does not specifically address what to do with crane loads and EQ loads
- Use of regular DL and LL factors for LRFD design is questionable when considering the nature of crane loads discussed previously
- Simultaneous application of all inertial and dynamic crane loads at full value for ASD design and using full LL load factors for LRFD design seems overly conservative
AIST Technical Report #13 – Load Combinations

- Case 1 – For fatigue design
  \[ D + C_{VS} + 0.5C_{SS} + C_{i} \]

- Case 2 – Maximum expected load combinations. Fatigue is not expected because location and simultaneous application of these loads at a single point is not likely
  1. \( D + L + (L_{r} \text{ or } S \text{ or } R) + C_{VS} + C_{i} + C_{SS} + C_{ls} \) (single crane)
  2. \( D + L + (L_{r} \text{ or } S \text{ or } R) + C_{Vm} + C_{SS} + C_{ls} \) (multiple cranes)
ASCE 7-05 LRFD Load Combinations

1. 1.4D
2. 1.2D+1.6L+0.5(Lr or S or R)
3. 1.2D+1.6(Lr or S or R) + (L or 0.8W)
4. 1.2D+1.6W+L+0.5(Lr or S or W)
5. 1.2D+1.0E+L+0.2S
6. 0.9D+1.6W
7. 0.9D+1.0E

Comments
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ASCE 7-05 ASD Load Combinations

1. D
2. D+L
3. D+(Lr or S or R)
4. D+0.75(L)+0.75(Lr or S or R)
5. D + (W or 0.7E)
6. D+0.75(W or 0.7E)+0.75L+0.75(Lr or S or R)
7. 0.6D+W
8. 0.6D+0.7E

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- Simultaneous application of all inertial and dynamic crane loads at full value for ASD design and using full LL load factors for LRFD design seems overly conservative
Section 3.10 discusses load combinations for design of crane runway beams and supporting structures.

Nomenclature for crane loads:
- $C_{vs}$ = vertical loads due to single crane in one aisle
- $C_{ss}$ = side thrusts due to single crane in one aisle
- $C_i$ = vertical impact due to a single crane in one aisle
- $C_{ls}$ = longitudinal tractive forces due to a single crane in one aisle
- $C_{bs}$ = bumper impact due to a single crane in one aisle
- $C_d$ = dead load of all cranes parked in each aisle, positioned for maximum EQ effects
Qualifying notes for load combinations
- Load combinations provided are for ASD design
- Load combinations without cranes are referenced to ASCE 7
- Crane vertical impact loads only apply to design of crane runway girders and supporting brackets
Case 1 – For fatigue design
\[ D + C_{vs} + 0.5C_{ss} + C_i \]

Case 2 – Maximum expected load combinations. Fatigue is not expected because location and simultaneous application of these loads at a single point is not likely

1. \[ D + L + (L_r \text{ or } S \text{ or } R) + C_{vs} + C_i + C_{ss} + C_{ls} \] (single crane)
2. \[ D + L + (L_r \text{ or } S \text{ or } R) + C_{vm} + C_{ss} + C_{ls} \] (multiple cranes)
Case 3 – Represents load combinations that may occur only once or a few times over the life of the structure

(1) \( D + L + (L_r \text{ or } S \text{ or } R) + C_{vs} + C_i + W \)
(2) \( D + L + (L_r \text{ or } S \text{ or } R) + C_{vs} + C_{ss} + 0.5W \)
(3) \( D + L + (L_r \text{ or } S \text{ or } R) + C_{vs} + C_i + 0.67C_{bs} \)
(4) \( D + L + (L_r \text{ or } S \text{ or } R) + C_d + E \)

The total combined effect of the Case 3 load combinations can be multiplied by 0.75
Problems with AIST Load Combinations

- 0.75 factor for Load Case 3 combinations would not be applied to dead load if follow current line of thought of ASCE 7 load combinations
- No load combinations provided for LRFD design
CMAA 70

Load Combinations

- Section 3.3.2.4 of this document discusses load combinations
- Load combinations noted only pertain to the crane and crane runway structure
- Presented for ASD design procedure
Crane Load Combinations

- Consider crane loads as independent load case (separate from LL)
  - Example: 1.2D + 1.0S + 1.6C
- What crane load components do you consider simultaneously?