Tolerances for Prefabricated Bridge Elements and Systems (PBES)

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WHY ARE TOLERANCES IMPORTANT?

Photos courtesy of CME Associates, Inc.
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Photos courtesy of FHWA
WHAT WE WANT

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Two major tasks:

1. Development of PBES Tolerance Guidelines
   - To be discussed today

2. Development of Guidelines for Dynamics during Bridge System Installations
   - Future Webinar (next month)

Both guidelines are near complete
- To be published by NCHRP this year
NCHRP PROJECT 12-98

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- Senior Program Manager/Implementation Coordinator

Project Team:
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  - Jen Pixley
- Marvin W. Halling, PhD, S.E., Utah State University
  - Marc Maguire
  - Paul Barr
  - Sattar Dorafshan
  - Kris Johnson
- Dennis Mertz, PhD
• AASHTO SCOBS has approved a Guide Specification for ABC
  • Guide Specifications for Accelerated Bridge Construction
  • Developed under NCHRP Project 12-102
  • To be published in the next year
• These guidelines supplement that document
  • Includes references to this work
Industry Participation:
- Guideline has been sent to industry partners for review and suggestions
  - PCI Tolerance Committee
  - PCI Bridge Producers Committee
  - PCI Northeast Bridge Technical Committee
  - Other industry participation

This tolerance guideline primarily covers **Concrete Elements**
- Steel tolerances are already covered in other specifications
- There is not sufficient data on other materials to develop a specification
EFFECT OF ELEMENT TOLERANCES

- Tolerance issues are one of the most common sources of problems with prefabricated construction
- Engineers and Contractors need to understand that........
  - Nothing is fabricated to exact dimensions
  - Nothing is erected to exact dimensions
  - All details and construction methods must account for this
TYPES OF TOLERANCES

• Element Size and Shape Tolerances
  • Forming
  • Shrinkage (elastic shortening if prestressed)
  • Bar bends

• Location of Element Insert and Void Tolerances

• Horizontal Erection/Setting Tolerances

• Vertical Erection/Setting Tolerances
NCHRP PROJECT 12-98

Document Format:
AASHTO Guideline Format
- Guidelines on Left
- Commentary on Right
- Many Details

Sections:
1. Introduction
2. Fabrication Tolerances
3. Erection Tolerances
4. Joints and Connections
WORKING POINTS AND LINES

Measure all construction from a common location
- Working Line
- Working Point
- Used to eliminate the build up of errors due to tolerances

Not new in the construction industry
- Batter boards
- Use of coordinates

Graphic by CME Assoc. Inc.
WORKING POINTS AND LINES

Measure all construction from a common location

Photos courtesy of CME Associates, Inc.
WORKING POINTS AND LINES

Measure all construction from a common location

Photo courtesy of FHWA
WORKING POINTS AND LINES
Measure all construction from a common location

Photos courtesy of FHWA
METHODS OF LAYOUT

Center of Element Method & Face of Element Method

Graphic by CME Assoc. Inc. with permission from NCHRP
Concept of Dimensional Growth

NOTE 1: PROJECTING REINFORCING STEEL SET TO A CENTER TO CENTER TOLERANCE OF ±3/8".

NOTE 2: DOWEL POCKET SPACING SET TO A TOLERANCE OF ±3/8" MEASURED FROM WORKING LINE.

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ELEMENT TOLERANCES

Should be specified in the contract plans.
ESTABLISHMENT OF ELEMENT TOLERANCES

PCI and ACI both have existing tolerance guidelines

Original NCHRP 12-98 Plan

▪ Obtain actual fabrication dimensional data from ABC projects
▪ Complete a statistical analysis of the data to establish a REASONABLE tolerance specification.
1. Obtain data values that represent the deviation from specified dimensions for a population of products.
2. Sort the occurrence of the data into specified bins, and plot that data set using a histogram.
3. Calculate the mean and standard deviation of the data set.
4. Calculate the 95% confidence limit for the data set by adding or subtracting two standard deviations from the mean.
Example of Determining Appropriate Tolerance Based on Statistical Analysis

Tolerance Data

<table>
<thead>
<tr>
<th>Tolerance Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
</tr>
<tr>
<td>0.24</td>
</tr>
<tr>
<td>0.12</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>-0.2</td>
</tr>
<tr>
<td>-0.22</td>
</tr>
<tr>
<td>-0.05</td>
</tr>
<tr>
<td>-0.06</td>
</tr>
<tr>
<td>0.04</td>
</tr>
<tr>
<td>0.02</td>
</tr>
<tr>
<td>0.21</td>
</tr>
<tr>
<td>-0.23</td>
</tr>
<tr>
<td>0.02</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-0.01</td>
</tr>
<tr>
<td>-0.21</td>
</tr>
<tr>
<td>-0.14</td>
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<tr>
<td>-0.08</td>
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<td>-0.06</td>
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<td>0.03</td>
</tr>
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<td>0.1</td>
</tr>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.03</td>
</tr>
<tr>
<td>-0.07</td>
</tr>
<tr>
<td>-0.03</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Standard Deviation: 0.125962
Mean: -0.0022
Mean plus 2*SD = 0.249725
Mean minus 2*SD = -0.25412

Tolerance Result = ± 1/4" 95% of the data fits within this value
HORIZONTAL ERECTION TOLERANCE

Should be Specified on the Plans

Based on Working Lines and points

P = Plan location from working line
L = Top elevation from nominal top elevation
  Maximum Low
  Maximum High
U = Maximum plumb variation in any 10 feet
V = Jog in alignment of matching elements

Graphic by CME Assoc. Inc.
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Width of Joints are based on tolerances
- Element Tolerances
- Erection tolerances
VERTICAL JOINT WIDTH

Vertical Joints must account for:

▪ The possibility that one or both of the adjacent elements will be fabricated wider or longer than detailed, but within the specified element tolerance.
▪ The possibility that one or both of the adjacent elements will be erected closer together than detailed but within the specified erection tolerance.
▪ The possibility that the elements are out of square or have surface irregularities
▪ The minimum width of the joint must accommodate the joint filler material after all tolerances are accounted for
PROBABILITY OF OCCURRENCE

- Joints need to be able to accommodate tolerances
- We can develop an equation for joint width based on all tolerance variables
- If all maximum tolerances occur at the same time, the joint widths would need to be very large
- We need to determine the probability of occurrence of multiple tolerances at one time
- **Solution: Monte Carlo Simulations**
  - Used to determine the probability of occurrence of multiple variables
  - Outcome: Probability curve for the tolerance equation
  - Use $2\sigma$ (95% probability)
\[0.5(A_L + A_R + L_{HL} + L_{HR}) + \text{maximum of } (D_L + D_R), (H_R + H_L)\]

\[\pm 0.34 [0.5(A_L + A_R + L_{HL} + L_{HR}) + \text{maximum of } (D_L + D_R), (H_R + H_L)]\]
## MONTE CARLO SIMULATIONS

<table>
<thead>
<tr>
<th>Description</th>
<th>Horizontal Joint Thickness Tolerance $T_{HJ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td></td>
</tr>
<tr>
<td>Column Panel</td>
<td>$\pm 0.52 \ (A_U + D_V + H_H + L_{VL})$</td>
</tr>
<tr>
<td>Column Pier Cap</td>
<td>$\pm 0.52 \ (C_U + D_V + H_H + L_{VL})$</td>
</tr>
<tr>
<td>Column Prestressed Cap</td>
<td>$\pm 0.52 \ (C_U + D_V + H_H + J + L_{VL})$</td>
</tr>
<tr>
<td>Panel</td>
<td>$\pm 0.52 \ (C_U + H_H + H_V + L_{VL})$</td>
</tr>
<tr>
<td>Backwall</td>
<td></td>
</tr>
<tr>
<td>Backwall Approach Slab</td>
<td>$\pm 0.74 \ (C_U + H_H)$</td>
</tr>
</tbody>
</table>

Note: more variables lead to higher probability of occurrence of maximums
4.5.1 SPECIFIED JOINT WIDTH OR THICKNESS

The designer should specify the joint opening defined on the plans that accounts for the minimum tolerable joint opening plus the tolerances of the two adjoining elements.

Specified vertical joint width (side-by-side elements):

\[ S_{jw} = t_{\text{min}, jw} + T_{jw} \]  
(4.5.1-1)

Specified horizontal joint thickness (stacked elements):

\[ S_{jt} = t_{\text{min}, jt} + T_{jt} \]  
(4.5.1-2)

where:

- \( S_{jt} \) = specified joint thickness (in.)
- \( S_{jw} \) = specified joint width (in.)
- \( t_{\text{min}, jt} \) = minimum tolerable joint thickness (in.)
- \( t_{\text{min}, jw} \) = minimum tolerable joint width (in.)
- \( T_{jw} \) = joint width tolerance (in.)
- \( T_{jt} \) = joint thickness tolerance (in.)

Horizontal joint detail call out = \( S_{jt} \pm T_{jt} \)
Vertical joint detail call out = \( S_{jw} \pm T_{jw} \)
**SPECIFYING JOINT WIDTH**

Table 4.5.2.1 – Vertical Joint Tolerance Values for Side-by-Side Elements, $T_{jw}$

<table>
<thead>
<tr>
<th>Element Description</th>
<th>$T_{jw}$ (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left (except noted)</td>
<td>$\frac{5}{8}$</td>
</tr>
<tr>
<td>Right (except noted)</td>
<td>$\frac{7}{8}$</td>
</tr>
</tbody>
</table>

Example: Wall Panel to Wall Panel Joint
- Minimum Joint width based on grout material = $\frac{3}{4}”$
- Joint Tolerance based on fabrication and erection tolerances = $\frac{5}{8}”$
- Specified Joint Tolerance = $1\frac{3}{8}” \pm \frac{5}{8}”$

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What if a designer wished to specify larger tolerances?
  • The Guideline gives equations to adjust the joint tolerance
    • In commentary
  • Based on same statistical evaluation
### SPECIFYING JOINT WIDTH

<table>
<thead>
<tr>
<th>Element Description</th>
<th>Vertical Joint Width Tolerance $T_{jk}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Approach Slab</td>
<td>$\pm 0.34 \left[0.5(B_L + B_R + L_{HL} + L_{HR}) + \text{maximum of } (D_L + D_R), (H_L + H_R)\right]$</td>
</tr>
<tr>
<td>Right Approach Slab</td>
<td></td>
</tr>
<tr>
<td>Left Approach Slab</td>
<td>$\pm 0.34 \left[0.5(A_L + A_R + L_{HL} + L_{HR}) + \text{maximum of } (D_L + D_R), (H_L + H_R)\right]$</td>
</tr>
<tr>
<td>Right Sleeper Slab</td>
<td></td>
</tr>
<tr>
<td>Left Sleeper Slab</td>
<td>$\pm 0.34 \left[0.5(A_L + A_R + L_{HL} + L_{HR}) + \text{maximum of } (D_L + D_R), (H_R + H_L)\right]$</td>
</tr>
<tr>
<td>Right Sleeper Slab</td>
<td></td>
</tr>
<tr>
<td>Left Pier Cap</td>
<td>$\pm 0.34 \left[0.5(A_L + A_R + L_{HL} + L_{HR}) + \text{maximum of } (D_L + D_R), (H_R + H_L)\right]$</td>
</tr>
<tr>
<td>Right Pier Cap</td>
<td></td>
</tr>
<tr>
<td>Left Panel, Footing, Wall Cap</td>
<td>$\pm 0.37 \left[0.5(A_L + A_R + L_{HL} + L_{HR}) + \text{maximum of } (D_L + D_R), (H_R + H_L), (F_L + F_R)\right]$</td>
</tr>
<tr>
<td>Right Panel, Footing, Wall Cap</td>
<td></td>
</tr>
<tr>
<td>Left Full-Depth Deck Panel</td>
<td></td>
</tr>
<tr>
<td>Right Full-Depth Deck Panel</td>
<td></td>
</tr>
</tbody>
</table>

where:

- $A_L$ = maximum fabrication length tolerance of left element (in.)
- $A_R$ = maximum fabrication length right element (in.)
- $B_L$ = maximum fabrication width tolerance of left element (in.)
- $B_R$ = maximum fabrication width tolerance of right element (in.)
- $D_L$ = maximum fabrication end skew/squareness tolerance of left element (in.)
- $D_R$ = maximum fabrication end skew/squareness tolerance of right element (in.)
- $F_L$ = maximum fabrication sweep tolerance of left element (in.)
- $F_R$ = maximum fabrication sweep tolerance of right element (in.)
- $H_L$ = maximum fabrication smoothness tolerance of left element (in.)
- $H_R$ = maximum fabrication smoothness tolerance of right element (in.)
- $L_{HL}$ = maximum horizontal erection tolerance of left element (in.)
- $L_{HR}$ = maximum horizontal erection tolerance right element (in.)

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## SPECIFYING JOINT WIDTH

### Example of Designer Modified Tolerance Effect on Joint Width Specifications

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Description</th>
<th>Guideline Specifications</th>
<th>Designer Modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Width Tolerance</td>
<td>1/4</td>
<td>1/2</td>
</tr>
<tr>
<td>L</td>
<td>Erection Tolerance</td>
<td>1/2</td>
<td>3/4</td>
</tr>
<tr>
<td>D</td>
<td>End Skew Tolerance</td>
<td>1/2</td>
<td>3/4</td>
</tr>
<tr>
<td>H</td>
<td>Flatness Tolerance</td>
<td>1/4</td>
<td>1/2</td>
</tr>
</tbody>
</table>

\[ \pm 0.34 \left[ 0.5 \left( A_L + A_R + L_{HL} + L_{HR} \right) + \text{maximum of } (D_L + D_R), (H_R + H_L) \right] \]

Modified Joint Width Tolerance = 0.94 inches

- Minimum Joint width based on grout material = \( \frac{3}{4} \)"
- Joint Tolerance based on fabrication and erection tolerances = 1”
- Specified Joint Tolerance = \( 1\frac{3}{4} \)” \( \pm 1 \)”
Similar approach as with joints

- Multiple Tolerances can affect the fit-up of blockouts

Specified minimum width of pocket connection:

\[ S_w = 2t_{\text{min-cl}} + 2T_w + \varphi_b \]  \hspace{1cm} (4.6.2.1-1)

where:

- \( S_w \) = specified minimum width of pocket (in.)
- \( t_{\text{min-cl}} \) = minimum tolerable clearance from face the dowel to the inside face of the pocket, measured perpendicular to the dowel (in.)
- \( T_w \) = pocket dowel location tolerance (in.)
- \( \varphi_b \) = nominal reinforcing bar diameter (in.)

The recommended pocket dowel location tolerance for two or more bars should be:

\[ T_w = 1\frac{3}{4}'' \]
Similar approach as with joints

- Multiple Tolerances can affect the fit-up of blockouts

\[ T_w = 0.65 \left( P + G + L_H \right) \]  \hspace{1cm} (C4.6.2.1-1)

where:

- \( G \) = maximum fabrication reinforcing location tolerance for outer bars (in.)
- \( P \) = maximum fabrication pocket location tolerance (in.)
- \( L_H \) = horizontal erection tolerance of precast member (in.)
Splice couplers

GROUTED SPLICE COUPLER TOLERANCES

| A | SHIM PACK HEIGHT | 1 1/8" ± 3/8" |
| B | DOWEL HEIGHT     | CONSULT MANUFACTURER |
| C | LOCATION OF COLUMN REINFORCEMENT, GROUTED SPLICE COUPLER, AND FOOTING DOWELS, MEASURED FROM A COMMON REFERENCE POINT | ± 1/4" |
| D | GAP BETWEEN DOWELS AND COLUMN REINFORCING | CONSULT MANUFACTURER |

GROUTED SPLICE COUPLER DETAILS

NOTES:
1. USE MATCHING TEMPLATES FOR THE LOCATION OF COLUMN REINFORCEMENT AND GROUTED SPLICE COUPLER PLACEMENT WITHIN THE ELEMENTS TO CONTROL CRITICAL DIMENSION C.
2. CONSULT MANUFACTURER OF THE GROUTED SPLICE COUPLER FOR PROPER DIMENSIONS "B" AND "D" AND FOR TOLERANCE ON THESE DIMENSIONS.
3. BEFORE EXECUTING GROUTED SPLICE COUPLER ASSEMBLIES, ALWAYS SEEK INSTALLATION RECOMMENDATIONS FROM THE MANUFACTURER OF THE GROUTED SPLICE COUPLER USED.
HOW TO PREVENT THIS?

Photos courtesy of CME Associates, Inc.
CONCLUSIONS

Specify tolerances on plans or specification
- Element tolerances
- Erection tolerances
- Joint Width Tolerances

Availability of guidelines
- PCI Tolerance Manual is available now (www pci org)
- PCI Northeast has ABC Tolerance Details (www pcine org)
- NCHRP 12-98 Guideline: 2017
  - Includes more detail than other guidelines
  - Referenced in the upcoming ABC Guide Specifications

Future
- This guideline may be adopted by AASHTO
- PCI may look to include joint tolerances in a future re-write
QUESTIONS