The Use of Measurement/Metrology & Survey Tools to Build Bridge Structures
Semi-robotic manufacturing, engineering analysis, measurement/metrology and survey tools are increasingly utilized to control geometry when building bridges in accordance with the New York State Steel Construction Manual (NYSSCM), as well as AASHTO/AWS D1.5 Bridge Welding Code Dimensional Tolerances.

Example:
semi-robotic total station may be used to check falsework geometry as bridge erection progresses, especially where tape access is difficult.

Note as 2nd girder is erected, profile changes and existing features/poss. backsights are obscured.
Robotic Total Stationing: some Lessons Learned

Must take care to know what you’re shooting

When in doubt, Pythagoras can help 😊

Getting one’s “bearings” (msmts at distance)

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<td></td>
<td>2</td>
<td>3</td>
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<tr>
<td>X</td>
<td>259.67</td>
<td>280.33</td>
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<tr>
<td>Y</td>
<td>624.75</td>
<td>617.42</td>
<td></td>
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<tr>
<td>Z</td>
<td>0.17</td>
<td>0.08</td>
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<td></td>
<td>Pier 2</td>
<td></td>
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<tr>
<td>X</td>
<td>186.07</td>
<td></td>
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<td></td>
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<tr>
<td>Y</td>
<td>(416.05)</td>
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<tr>
<td>Z</td>
<td>0.35</td>
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OK, my shots reversed.
A resection (location tie-in) of the instrument may be used via two reliable back-sight, & a properly plumbed vertical axis of the coordinate system for the assembly being measured.

Once the instrument has located itself, foresights & stakeouts may be made to check the position of structural members & their control points.
Verifying Yard Assembly Alignments

Here, the robot re-sections (backsights) to two benchmarks nearly 300 ft away, through a "forest" of false work & splice cages.
Multi-girder Bridges

Example of Horizontal & Vertical control for a two-span, curved & skewed multi-girder bridge with rigid end diaphragms

Assembly Diagram
SR 1014 over Brush Creek, Beaver Co. PA

For this project, the support diaphragms at the two abutments & pier are quite rigid and are therefore being reamed in assembly. Intermediate diaphragms, being lighter channel members, are drilled full-sized and only placed into the assembly as needed to assist us with achieving horizontal & vertical control.
Multi-girder Bridges

Measuring no-load, steel dead load & total dead load position

See AASHTO/NSBA Steel Bridge Collaboration Paper “Skewed and Curved Steel I-Girder Bridge Fit”
  - https://www.aisc.org/nsba/nsba-publications/technical-resources/

For sample (geometric only) single span web layover calculations, please refer to:
  - http://www.highsteel.com/technical-resources2/technical-library/
  - Erection of Skewed Bridges: Keys to an Effective Project 2007 International Bridge Conference
When in doubt regarding the geometry or structural behavior of a bridge, it’s usually good practice to check with different method/instrument.
For this bridge, a robotic total station was used to locate bearing points and field splices; manual level run was used to adjust elevations.
Multi-girder Bridges

**IxIxIxI**

Typical output when working to fit a rigid plate diaphragm, adjusting for thermal ratcheting, found settlement & dimensional tolerances.

<table>
<thead>
<tr>
<th>Axis</th>
<th>$\sigma_{i1}$, in</th>
<th>$T_1$ °F</th>
<th>$\sigma_{i2}$, in</th>
<th>$T_2$ °F</th>
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</thead>
<tbody>
<tr>
<td>N</td>
<td>1/8</td>
<td>100</td>
<td>1/2</td>
<td>80</td>
</tr>
<tr>
<td>E</td>
<td>1/8</td>
<td></td>
<td>3/8</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>1/4</td>
<td></td>
<td>1/4</td>
<td></td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Point</th>
<th>$\Delta_{Chord}$, in</th>
<th>$\Delta_{LATERAL}$, in</th>
<th>$\Delta_{ELEV}$, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>3/4 ↓</td>
<td>3/8</td>
<td>1/8 ↓</td>
</tr>
<tr>
<td>15</td>
<td>1/8 ↑</td>
<td>1/4</td>
<td>1/8 ↓</td>
</tr>
</tbody>
</table>
Multi-Girder Case Study: assembled to no-load profile, released to steel DL Profile & re-erected in field.
Both Robotic Total Station & manual level runs were used to establish horizontal & vertical control, respectively (NL & Steel DL Profiles)
Comparison of Yard & Field Assembly Sequences
Given the difference in site conditions, season, erection sequence, means & methods, the author finds the overall reproducibility of the structure quite striking.

Lancaster, Pennsylvania

For a more complete report of the fabrication methods used to build this structure and test it to steel dead load deflection profile is provided in the proceedings of the AISC/NASCC World Steel Bridge Symposium 2016 “Using Fabrication & Metrology Advances to Unite a Canal-Divided City with a skewed, curved, pre-erected Multi-Span Pedestrian-Park Bridge”
Project Team

Owner: New York State Thruway and Canal Authority

Designer: Amman & Whitney (Architectural Drawings by Saratoga Associates)

Contractor: Kubricky Construction Corporation

Erector: D.A. Collins Companies

Fabricator: High Steel Structures, LLC

Structural Steel Detailer: Lancaster Country Drafting Services
Whether a bridge structure is large, curved & flexible, or short and stiff, it is remarkable that similar tolerances may be applied to each for bearing alignment, camber & sweep.
The New York State Steel Construction Manual (AASHTO/AWS D1.5 Bridge Welding Code) provide assembly tolerances which generally are achievable goals. These were the targets used for MVGO Yard Steel DL Camber Verification Assembly.

1214.2 Deviation from Specified Camber of Single Erection Pieces.

a) Stringers, girders and floorbeams:
   1) at bearing locations ± ½” (3 mm)
   2) at midpoint -0, + ¾ inch [19 mm]
   3) at intermediate points -0, + ¾ inch x No. of feet from nearest end or + ¾ inch, whichever is less
      10

For the MVGO structure, the above Shop tolerance was achieved for the individual girder field sections (no-load profile).

1104. ALIGNMENT OF MEMBERS DURING SHOP ASSEMBLY.

All steel required to be shop assembled for line camber and/or profile verification, reaming, drilling from the solid, or weld joint preparation shall be aligned so that the control points (bearing locations or support points) are within ± ¼ inch [3 mm] from the locations shown on the approved shop drawings. This tolerance shall apply to the X, Y, and Z coordinates, i.e., in all three dimensions.

1214.3 Deviation from Specified Camber in Assembly

-0, +½ x No. of feet of length from nearest support (bearing or pin), or ¾ inch, whichever is less
   10
Using Measurement/Metrology Tools to assemble large bridge components

Designers visualizing the final bridge both structurally and architecturally

For an expanded discussion of the construction of the Ohio River Bridge, please see ASCE Magazine July-August 2017

Edge Girder Transport vehicle
(Double “sharkfin” anchorage configuration shown)
Laser Sighting was used to align stay-cable anchorages

Edge Girder Fabrication
(Slanted I Girder, “Sharkfin” Gusset, Cable Anchorage “Can”)

Measuring girder in shop for Virtual 3D Checks
Robotic Total Station is able to pick up the following when the Edge Girder is flipped in the Shop:

- Elastic sag in the sharkfins ~ 1"
- Elastic Twist in the girder if not uniformly blocked

**GOOD NEWS:** It will fit in the field (twist to match floorbeam connections)

**BAD NEWS:** Twist throws enough of the benchmarks out of the (1/32") tolerance that we must start this survey over to get the bottom flange & web-to-floorbeam connections.
Local Survey re-sections were used for progressive assembly

Yard Assembly Survey

Edge Girder Measurement
(Shop Fabrication Checks, Yard Line Assembly)
Accumulated Length of the upstream & downstream edge girder assemblies was carefully controlled. Tolerance was maintained via built-in field splice adjustment.
A Robotic Total Station was used to check assembly, with conventional heat-straightening calculations to fine tune cable anchorage lateral alignments.

“Shark-fin” Alignment Adjustment
(Support & jack point for heat-adjust)
Discreet & also point cloud survey measurements were taken to check 3D alignment of complete bridge segments at approximate erected (Steel DL) fit.

Deck Grillage Segment Unit Assembly
(3-D Scan, Left & Robotic Total Station Measurement, right)
Typical 3D Metrology Instrument Results.
### Assembly Width Checks

**Dwg SA14 Assemblies**

<table>
<thead>
<tr>
<th>Assembly 1 G4U-D</th>
<th>Assembly 2 G5U-D</th>
<th>Assembly 3 G6U-D</th>
<th>Assembly 4 G7U-D</th>
<th>Assembly 5 G8U-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHE RHE Δ, inch</td>
<td>LHE RHE Δ, inch</td>
<td>LHE RHE Δ, inch</td>
<td>LHE RHE Δ, inch</td>
<td>LHE RHE Δ, inch</td>
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<tr>
<td>Dec Ft</td>
<td>Inches</td>
<td>Dec Ft</td>
<td>Inches</td>
<td>Dec Ft</td>
</tr>
<tr>
<td>107.10 107.07 0.227</td>
<td>107.05 107.09 0.040</td>
<td>107.09 107.08 0.220</td>
<td>107.07 107.10 0.010</td>
<td>107.09 107.09 ---</td>
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<tr>
<td>1,285.165 1,284.876</td>
<td>1,284.649 1,285.074</td>
<td>1,285.114 1,285.016</td>
<td>1,284.796 1,285.144</td>
<td>1,285.134 1,285.076</td>
</tr>
</tbody>
</table>

**Required width:**

- 107”-0 3/4”
- 1,284.750 inches
- 107.06 Dec Ft

**Note:** The above are not temperature corrected, due to non-uniform (varied) orientations of sun relative to assemblies.
For an interesting article on the Ohio River Bridge, please see ASCE Magazine July/August 2017 “Attractive Alternative” (pp.54 etc)
Greenfield Bridge over I-376 (Pittsburgh)

Building an Arch using robotic Measurement Methods
Metrology is a useful tool in locating control points along curved members, especially when machined fit is used e.g., baseplates.
Once the contract fit requirements are understood, a measurement plan can be developed, similar to station-offset layout of horizontal curves.
For this bridge, the two ends of the arch were fabricated entire. The central “keystone” (shown upright) was then iteratively matched-measured then trimmed to length and holes drilled.
Robotic total stations were used to locate arch columns. Connections were then semi-robotically customized where needed. Limited scanning was also used to check fit.
Robotic total stations were used measure pin-to-pin distance across the span of this railroad through truss structure. Results were found to be within anchor bolt alignment tolerances. OK 😊
When measuring bridge structures of significant length, it is prudent to take both ambient and steel surface temperatures. Here, a weighted average temperature is used as the sun advances.

### Steel Temperature Readings

<table>
<thead>
<tr>
<th>Location</th>
<th>Top</th>
<th>Bottom</th>
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<tbody>
<tr>
<td>L0</td>
<td>66</td>
<td>65</td>
</tr>
<tr>
<td>U3</td>
<td>65</td>
<td>63</td>
</tr>
<tr>
<td>L4</td>
<td>63</td>
<td>60</td>
</tr>
<tr>
<td>U5</td>
<td>65</td>
<td>62</td>
</tr>
<tr>
<td>L10</td>
<td>64</td>
<td>63</td>
</tr>
</tbody>
</table>

**Average Steel Temperature (Avg T<sub>STL</sub>):** 63.6 °F

**Desired Temperature (Des T<sub>STL</sub>):** 60 °F

**ΔT (Temperature Difference):** 3.6 °F

**Ambient Conditions:** Cloudy/showers

### As-measured Pin-to-pin (raw reading)

<table>
<thead>
<tr>
<th>Point</th>
<th>Dimension</th>
<th>Inches</th>
<th>Ft</th>
<th>In</th>
<th>Fraction of Inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0F</td>
<td>LOL10N</td>
<td>3,238.175</td>
<td>269.85</td>
<td>269</td>
<td>10 2 8</td>
</tr>
<tr>
<td>C10F</td>
<td>LOL10F</td>
<td>3,238.240</td>
<td>269.85</td>
<td>269</td>
<td>10 1 16</td>
</tr>
</tbody>
</table>

**Measured Length (adjusted for temperature):**

<table>
<thead>
<tr>
<th>Ft</th>
<th>In</th>
<th>Fraction of Inch</th>
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<tbody>
<tr>
<td>269</td>
<td>10</td>
<td>1 16</td>
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</table>

**Required Pin-to-Pin Dimension (Theo. Des.):**

<table>
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<tr>
<th>Ft</th>
<th>In</th>
<th>Fraction of Inch</th>
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<tbody>
<tr>
<td>269</td>
<td>11</td>
<td>1 16</td>
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</table>

**ΔL = (0.963) Inches** short
It is a rewarding thing to be able to advise the crew which way to move (fine tune) a 25 ton structural member with certitude.
It is challenging, yet satisfying to measure a bridge, then observe it dismantled and shipped to make way for the next bridge assembly.
Q & A

And now….wait for it 😊

It’s quiz time!

Question 1: What are potential sources of false metrology/survey readings when using a robotic total station?
- low-angle measurement of adjacent substructures (e.g., piers) with duplicate targets (concurrent trades). Reflectorized vests.
- It is therefore prudent to check measurements that don’t make sense (independent method; hand calc if you have span lengths handy).

Question 2: What is the minimum number of points used for resection using a robotic station?
- two if using reliable benchmarks & accurately plumbed (vertical axis)
- four points are often used for resection/bundling if the points have significant imperfection, or is subject to thermal “ratcheting”, settlement, displacement by construction activities and equipment, or obscuring by subsequent activities and constructed features.
- larger resection length may reduce error of the measured work.

Question 3: How might an out-of-tolerance/outlying measurement be validated?
- Performing standard check/calibration of the instrument; use a different instrument
- Verify via separate instrument and independent method to see if measurement can be reproduced.
Question 4 (extra credit): Why might fabricators prefer full-sized hole (vs. reaming) and check/virtual assembly? What is necessary for success using this practice?

- Reaming is a hazardous operation; many bridges can be manufactured using full-sized hole practice.
- Today’s measurement tools can often measure pieces within bridge assembly tolerances.
- Pre-planned, for a tighter tolerance than specification generally makes it easier to hit tolerance (sometimes not feasible on tight-schedule rush projects).

When contract specifications & geometry permit, we generally prefer to hold a tighter fabricated camber tolerance & use full-size holes with check assembly of one girder line.
Any Questions?

Thank you for your attention 😊

Photo courtesy of: D.A. Collins Companies & Kubricky Construction Corporation