Spirally Welded Towers

Innovations in the On-site Manufacturing of Tall Wind Turbine Towers

Andrew T. Myers, PhD, PE
Assistant Professor of Civil Engineering
Northeastern University
atm@neu.edu
Mass Wind Working Group Meeting
September 30, 2015

Northeastern University
Johns Hopkins University
Keystone Tower Systems

Outline

- Background
- Research Needs and Project Goals
- Large-scale Experiments
  - Imperfections
  - Strength
  - Buckling characteristics
  - Complementary GMNIA analyses
- Future Work

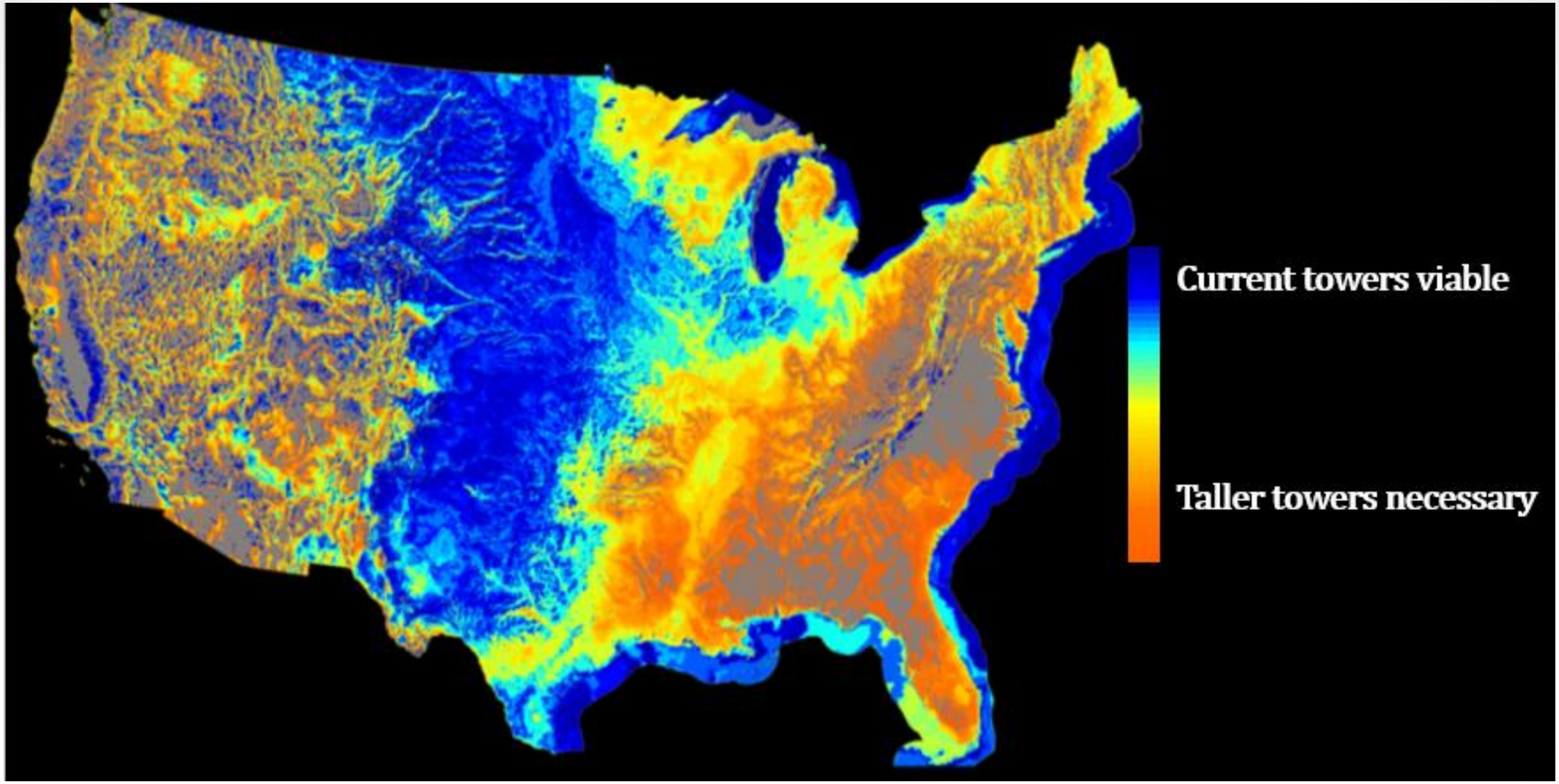
Spirally Welded Towers

Background

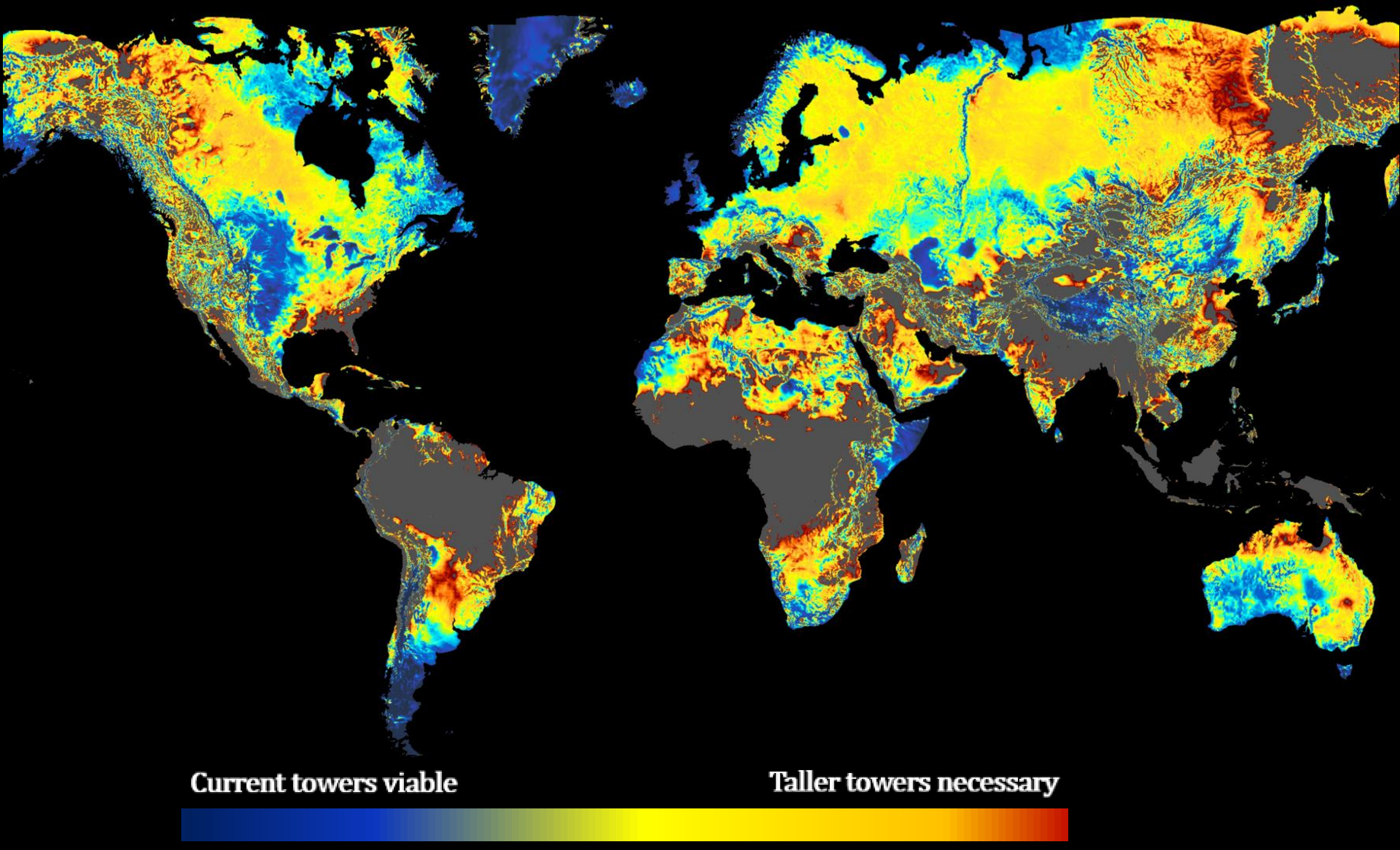
Northeastern University

Johns Hopkins University

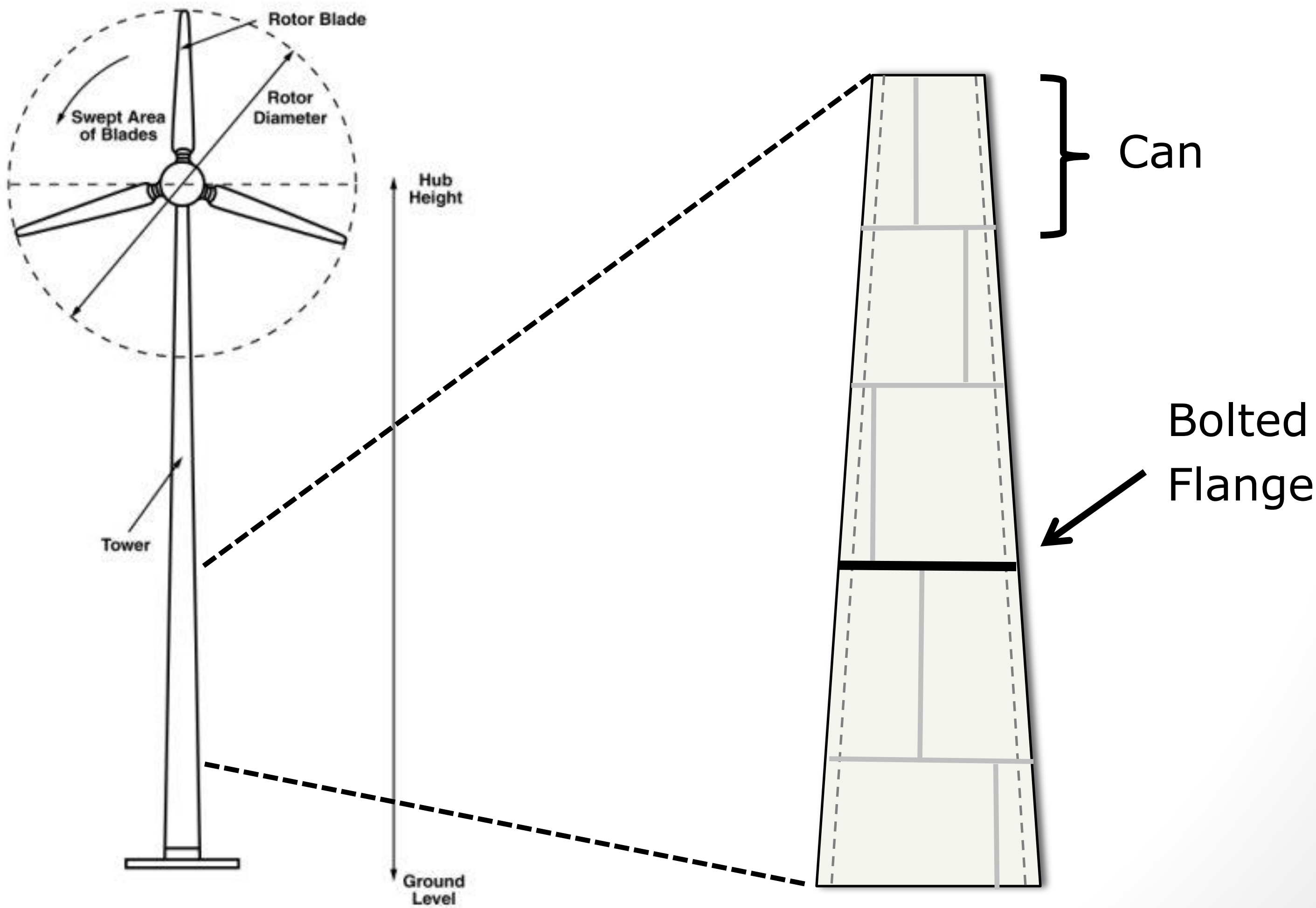
Keystone Tower Systems



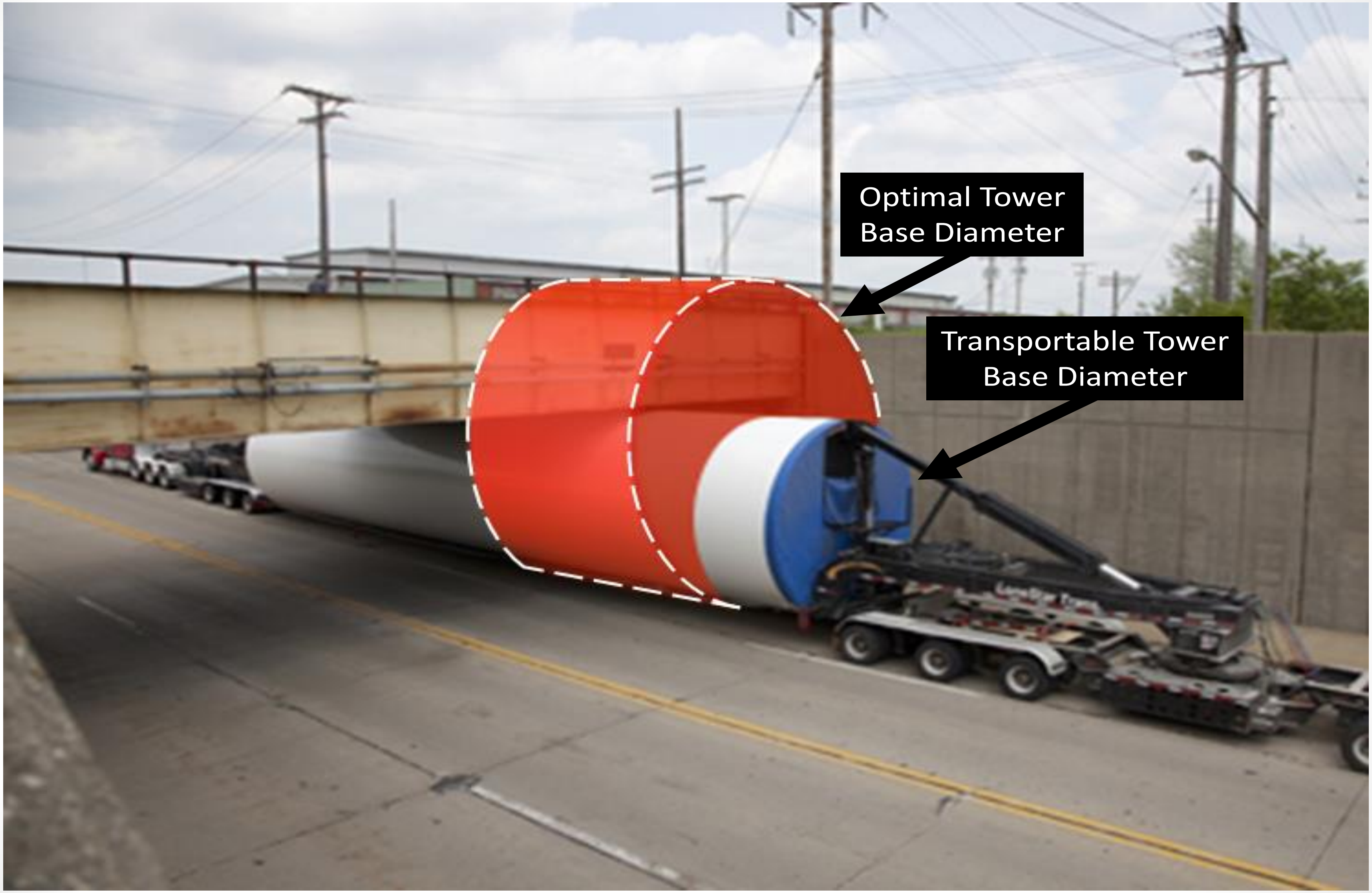
- Wind generated-energy in the Great Plains among the cheapest energy sources in the country.
- Elsewhere, harvesting wind energy becomes economical only at higher elevations.


Current towers viable
Taller towers necessary

- Predominant wind tower design is a slender steel monopole with diameter-to-thickness (D/t) ratios, ~100-300.
- Utility-scale towers are tapered.
- Manufactured by “can-welding.”



- Great! Let's make taller towers!



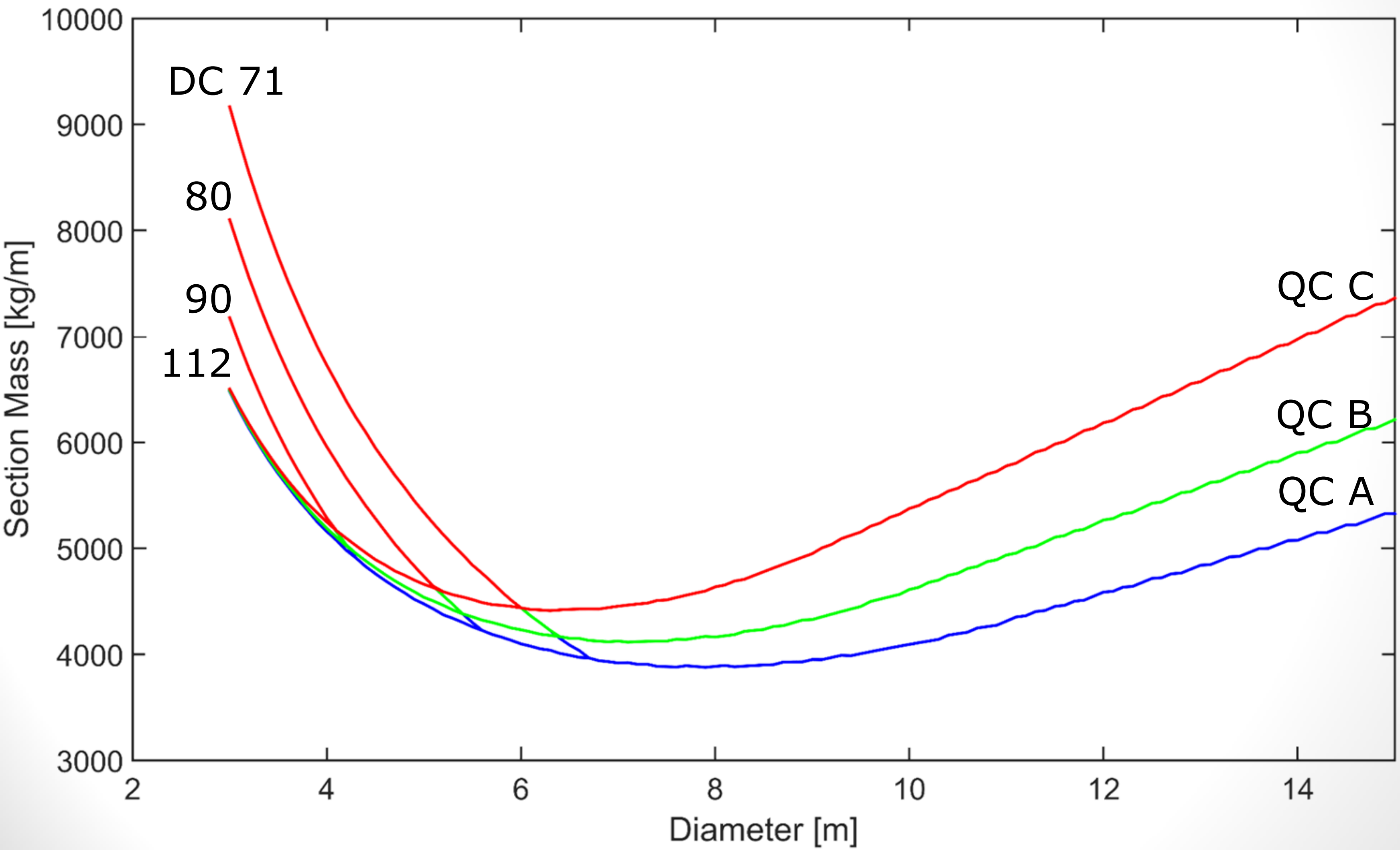
- One innovative solution, patented by Keystone Tower Systems, is to make tapered tubes with automated spiral welding.

Patent:US8720153…

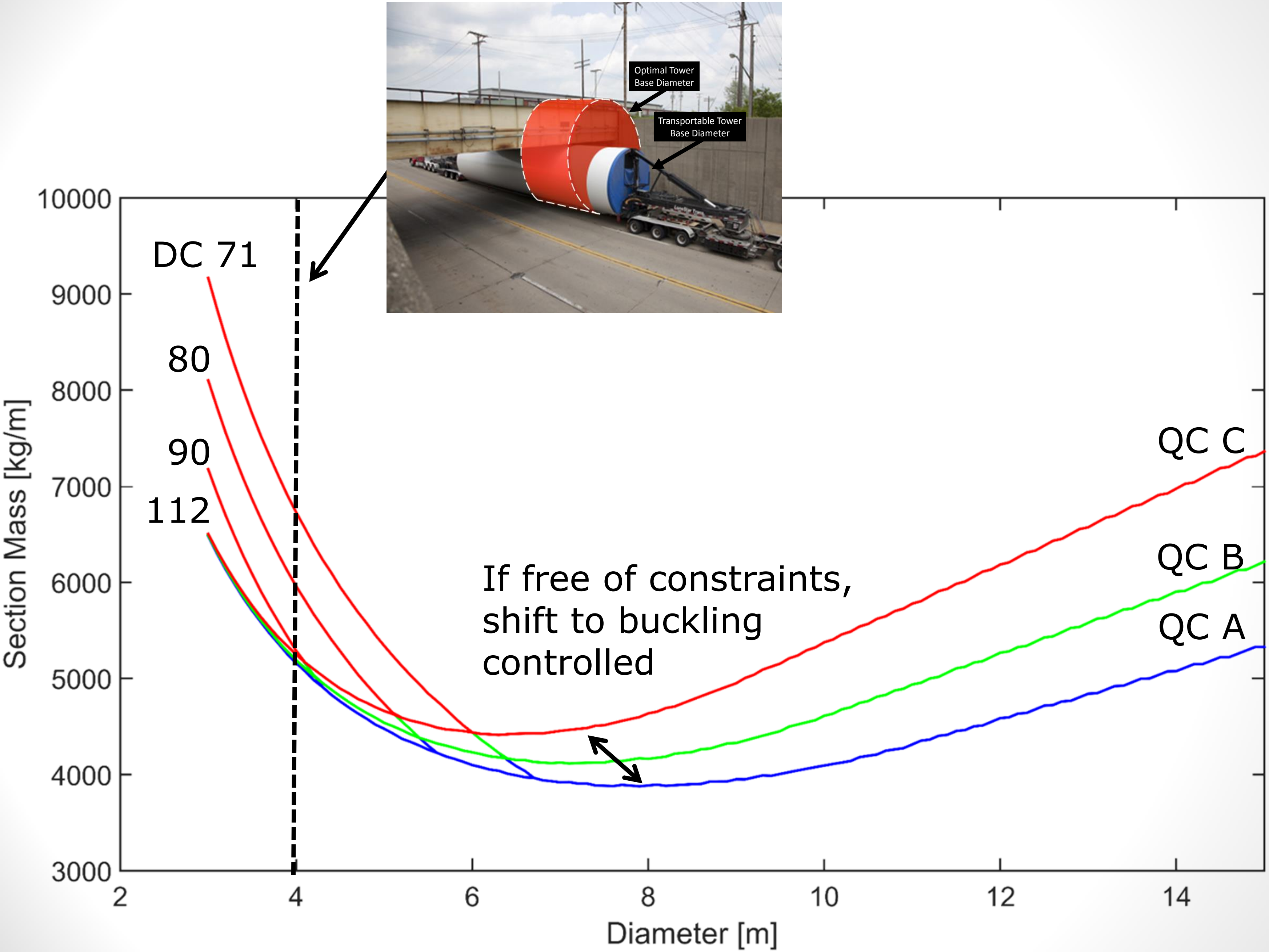
Research Needs and Project Goals

Base cross-section designed to EN 1993-1-6 for typical base loads of 140m, 3MW tower:

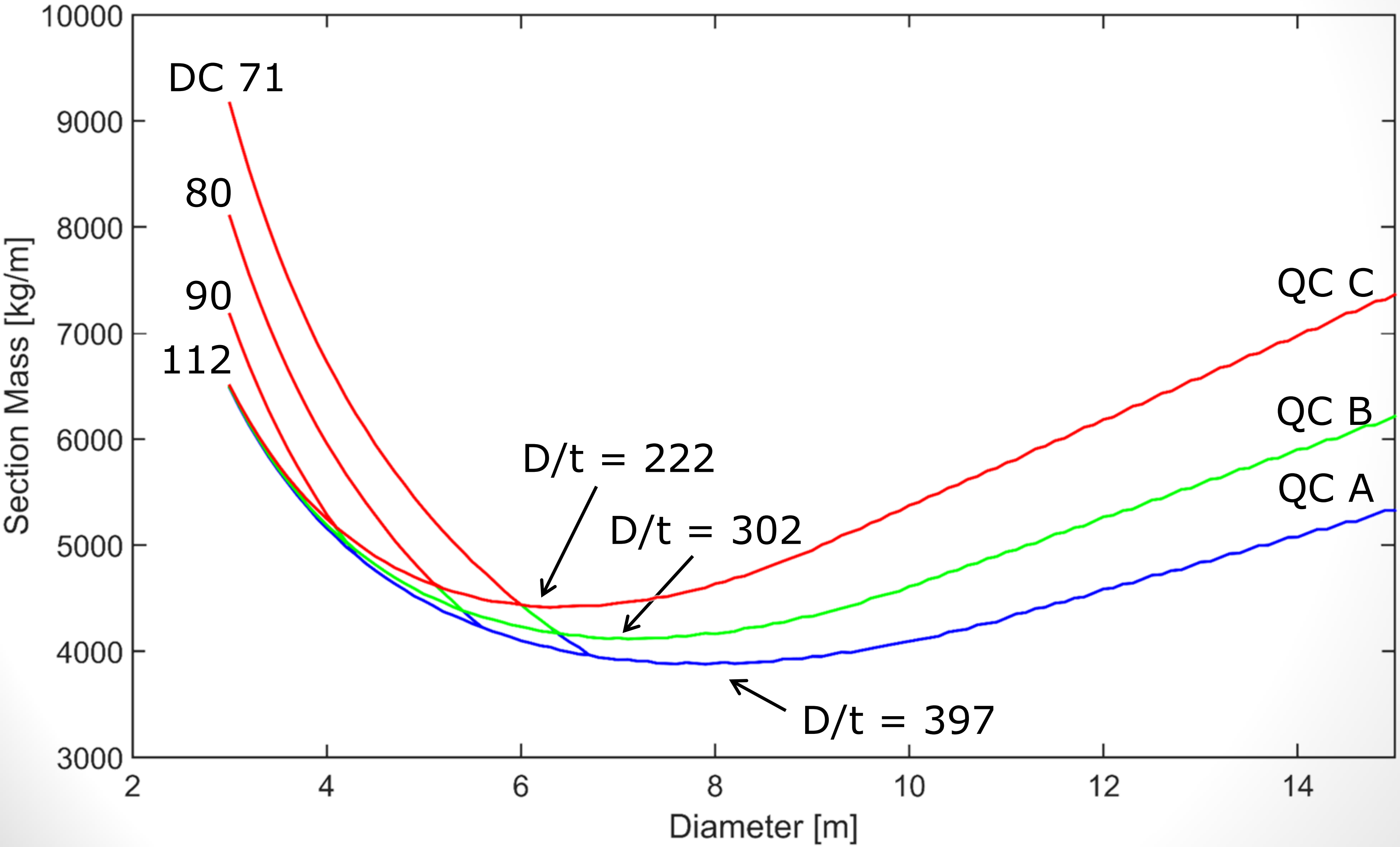
Ultimate Moment = 160 MN-m
Damage Equiv. Moment = 40 MN-m (at 1e7 cycles; m = 4)



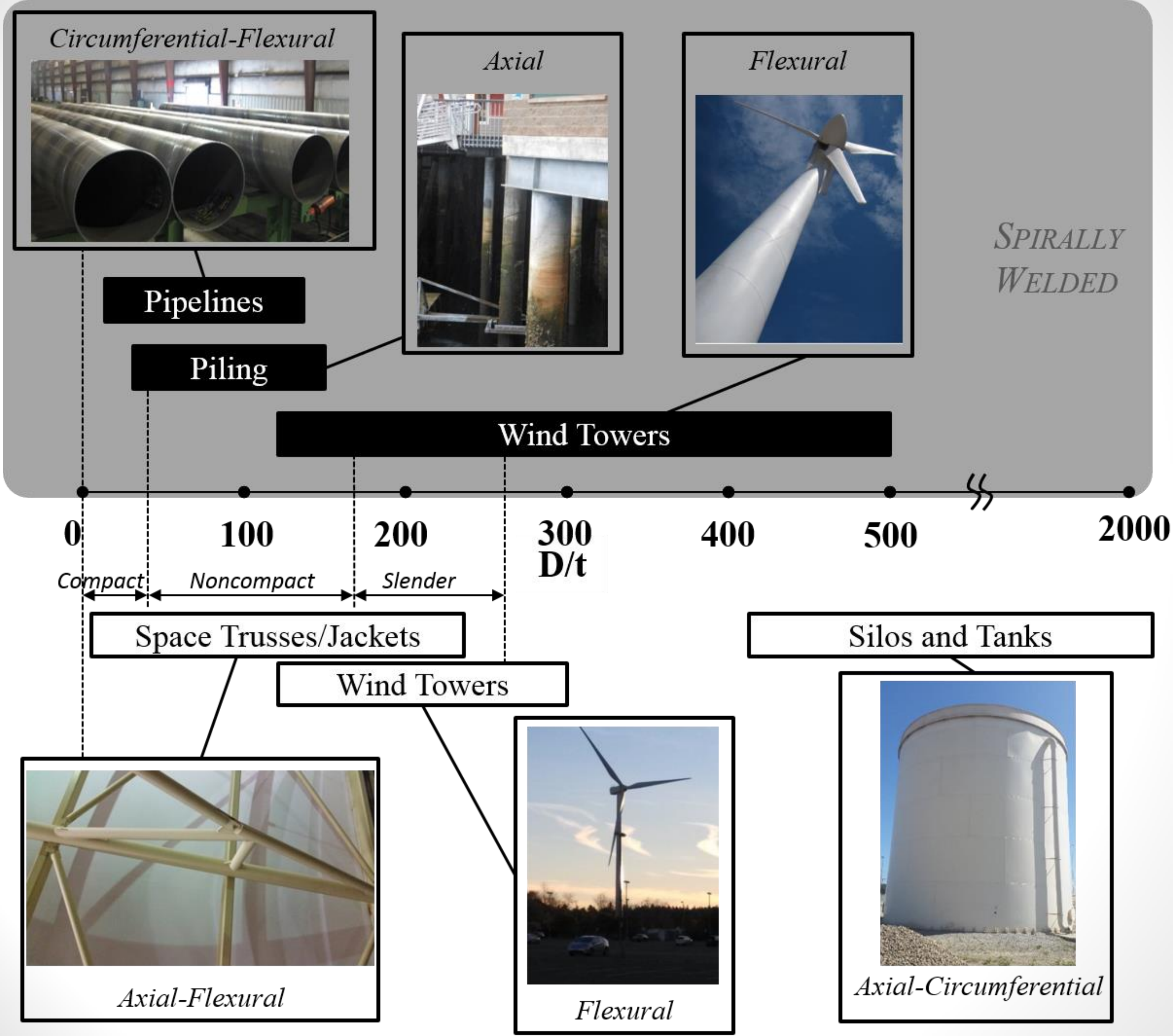
Today, fatigue controlled

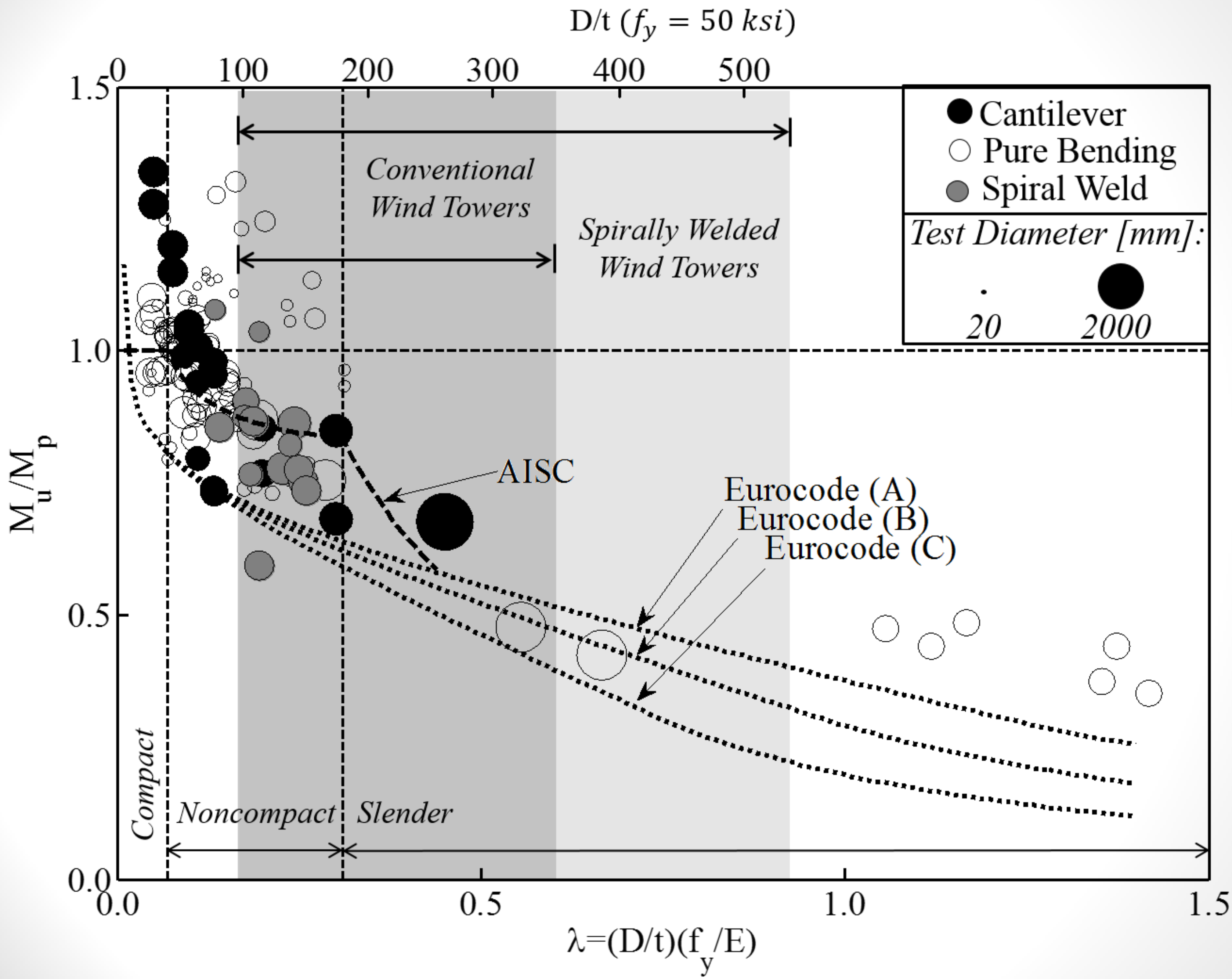


Need to understand buckling for flexure and high D/t



Buckling of a wind tower


Circumferential-Flexural
Axial
Flexural
SPIRALLY WELDED
Pipelines
Piling
Wind Towers
0
100
200
300
400
500
2000
D/t
Compact
Noncompact
Slender
Space Trusses/Jackets
Wind Towers
Silos and Tanks
Axial-Flexural
Flexural
Axial-Circumferential


D/t ($f_y = 50\ ksi$)
0
100
200
300
400
500
1.5
1.0
0.5
0.0
Cantilever
Pure Bending
Spiral Weld
Test Diameter [mm]:
20
2000
Conventional Wind Towers
Spirally Welded Wind Towers
AISC
Eurocode (A)
Eurocode (B)
Eurocode (C)
Compact
Noncompact
Slender
M_u/M_p
0.0
0.5
1.0
1.5
λ=(D/t)(f_y/E)

Current State of Affairs

- As steel tubular towers become taller with larger base diameters, the buckling limit state becomes more important and tower sections become more slender.
- No AISC design equation for moment strength of very slender circular hollow sections ($\lambda > 0.45$).
- Eurocode provides equation, but, at high slenderness, it is based on compression tests not bending.
- Insufficient test data to justify bending design equation.
- Buckling of circular hollow sections is highly imperfection sensitive.
- Eurocode's GMNIA method is promising, but challenging.
- Need for large-scale tests, imperfection measurements and complementary GMNIA simulations.

Project Goals

- Validate Eurocode buckling for:
  - High D/t
  - Flexure
  - Imperfection field from new manufacturing process
- Develop GMNIA protocols to enable greater optimization.
- Establish basis for design in the U.S.

Project Goals

Initial imperfection scan

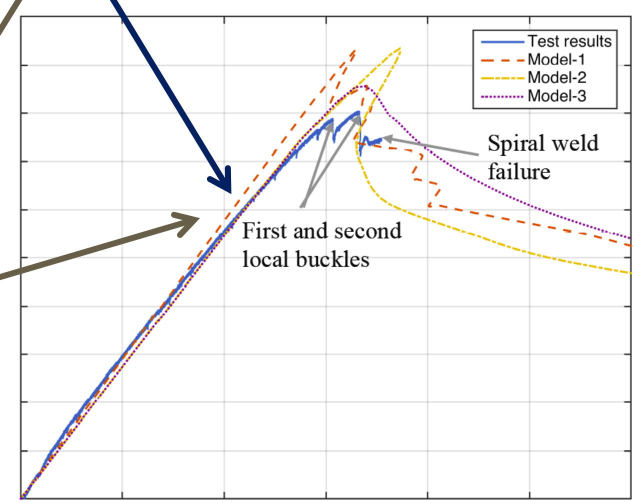
(laser, full 3d)

GMNIA FEA

Ultimate load testing in flexure

Simultaneous surface scan (laser, compression face)

Load curve (moment v. rotation)



Spirally Welded Towers

Large-scale Experiments

Northeastern University

Johns Hopkins University

Keystone Tower Systems

Test Matrix

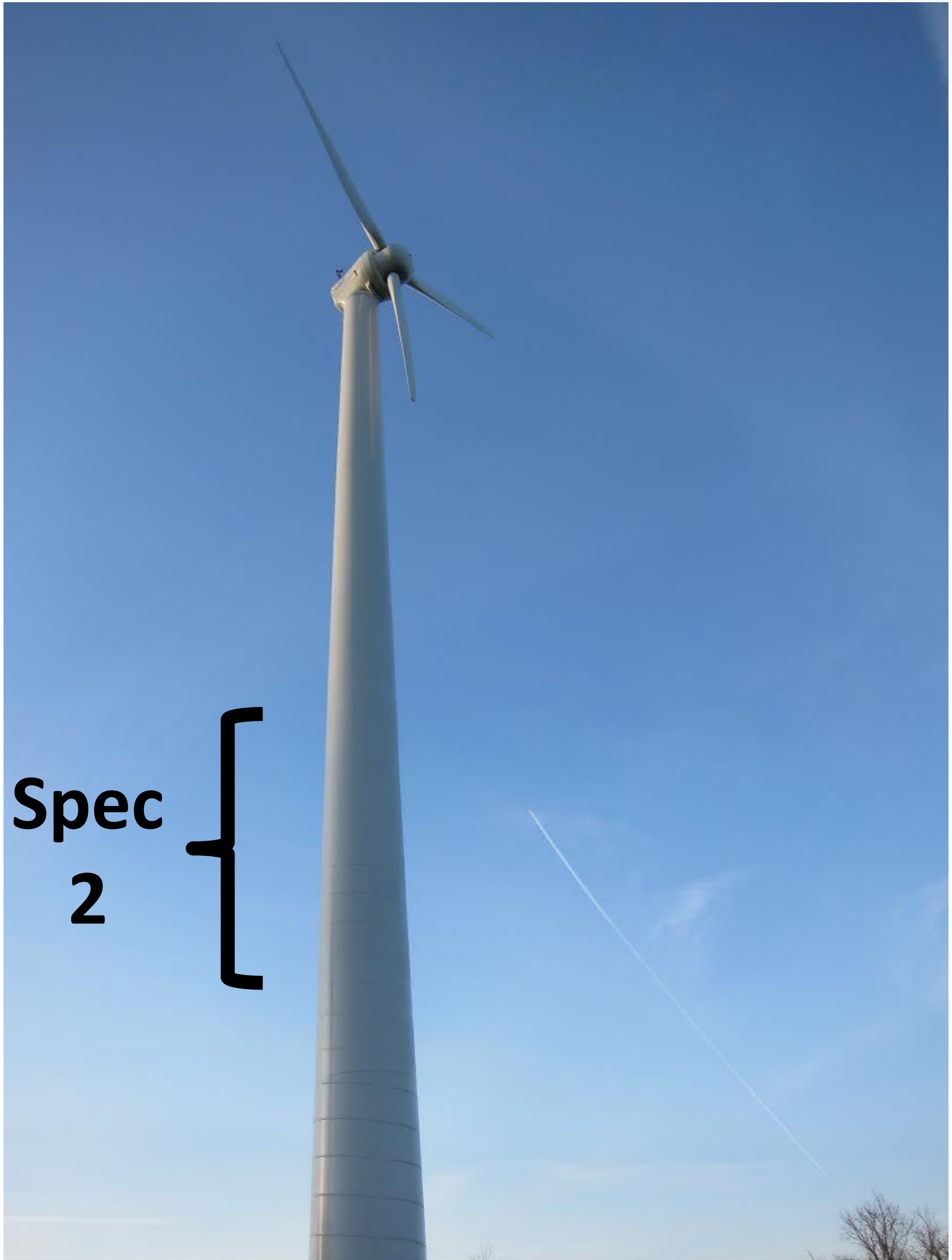
Spec. #	Min D/t [-]	Max D/t [-]	D_{min} [mm]	D_{max} [mm]	Gauge	t [mm]	L [m]	α [-]
1	195	224	663	762	10	3.40	3.43	0.83°
2	127	139	815	892	--	6.43	3.37	0.65°
3	235	260	812	897	10	3.45	3.38	0.76°
4	283	308	864	940	11	3.05	3.40	0.82°
5	283	308	864	940	11	3.05	3.38	0.82°
6	283	308	864	940	11	3.05	3.40	0.82°
7	316	350	965	1067	11	3.05	3.40	0.86°
8	316	350	965	1067	11	3.05	3.40	0.86°
9	316	350	965	1067	11	3.05	3.40	0.86°
10*	68	154	800	975	--	6.35	3.40	0.90°

Overview

- Specimens #1-4 and #6-7 finished
- Specimens #5, #8-10 will be tested this fall

Test Matrix

Spec. #	Min D/t [-]	Max D/t [-]	D_{min} [mm]	D_{max} [mm]	Gauge	t [mm]	L [m]	α [-]
1	195	224	663	762	10	3.40	3.43	0.83°
2	127	139	815	892	--	6.43	3.37	0.65°
3	235	260	812	897	10	3.45	3.38	0.76°
4	283	308	864	940	11	3.05	3.40	0.82°
5	283	308	864	940	11	3.05	3.38	0.82°
6	283	308	864	940	11	3.05	3.40	0.82°
7	316	350	965	1067	11	3.05	3.40	0.86°
8	316	350	965	1067	11	3.05	3.40	0.86°
9	316	350	965	1067	11	3.05	3.40	0.86°
10*	68	154	800	975	--	6.35	3.40	0.90°

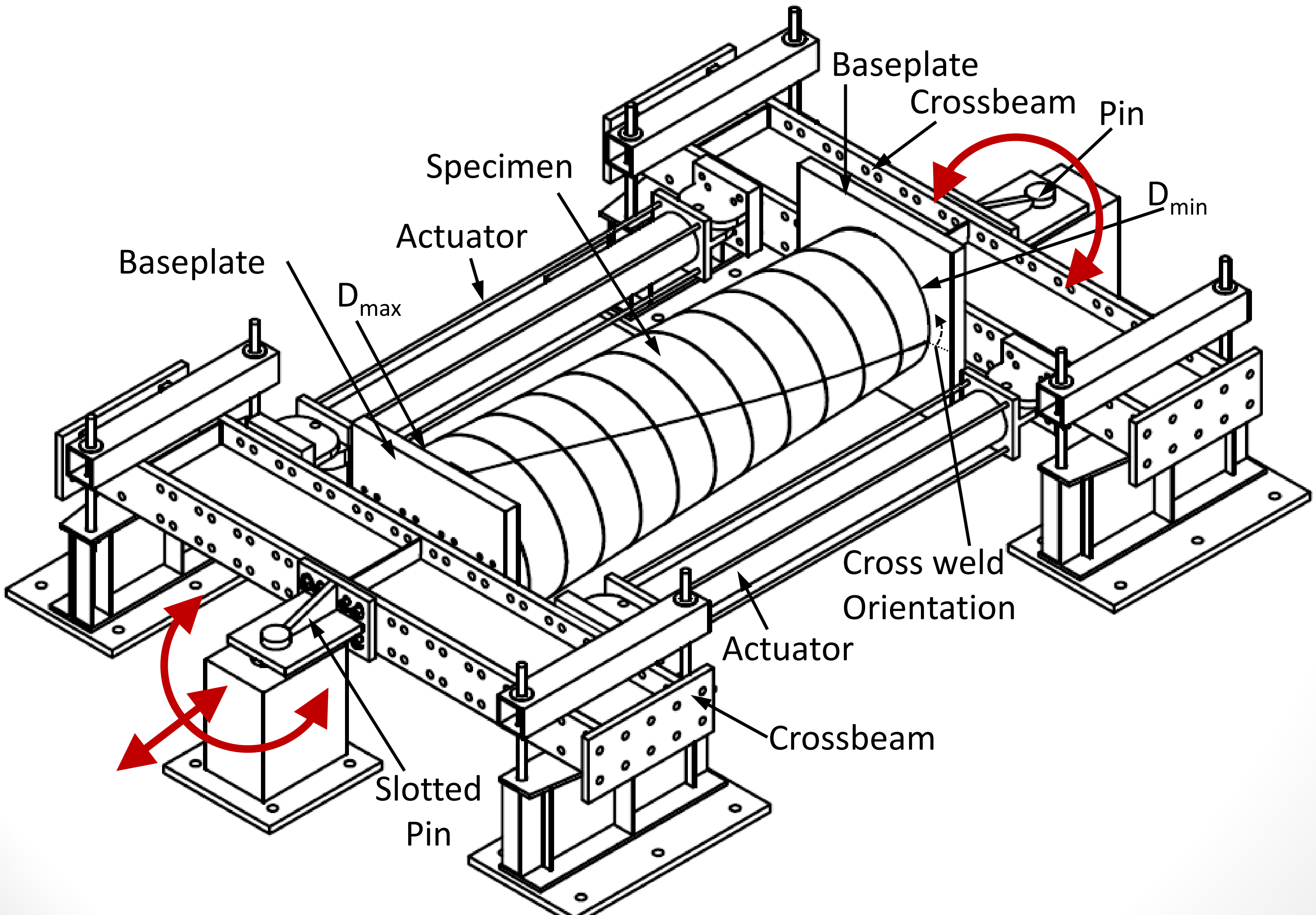

Spec
2

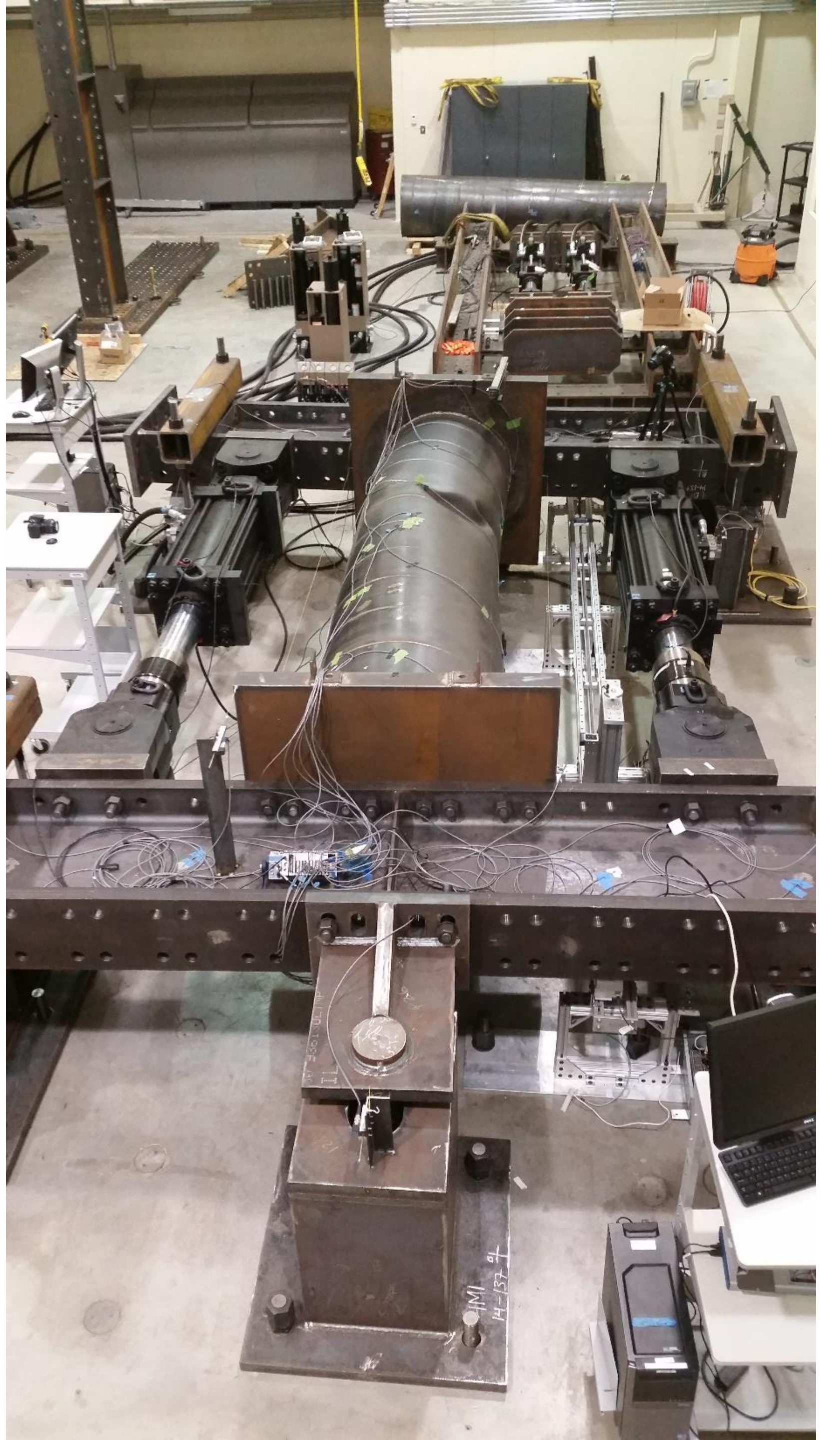
Test Matrix

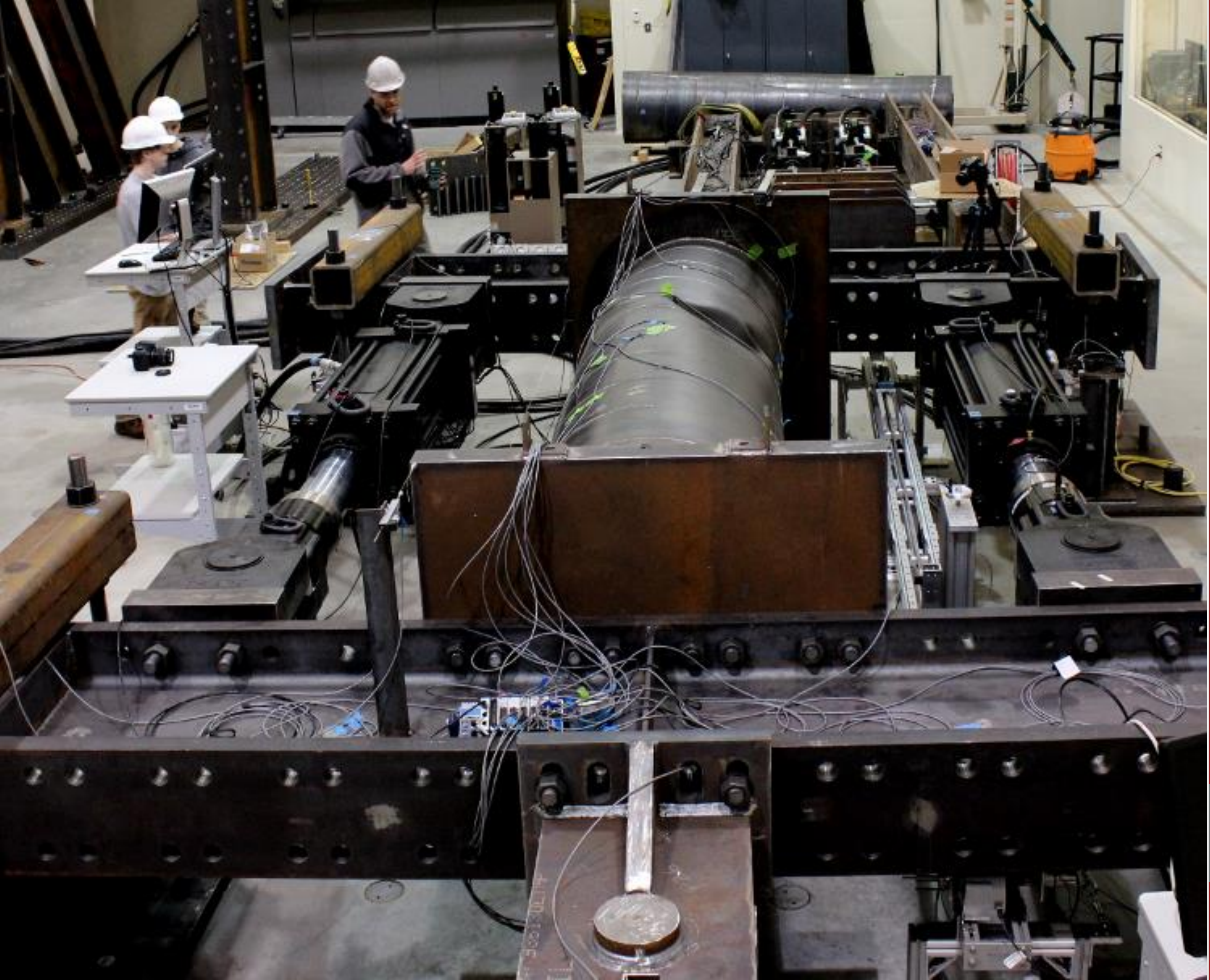
Spec. #	Min D/t [-]	Max D/t [-]	D_{min} [mm]	D_{max} [mm]	Gauge	t [mm]	L [m]	α [-]
1	195	224	663	762	10	3.40	3.43	0.83°
2	127	139	815	892	--	6.43	3.37	0.65°
3	235	260	812	897	10	3.45	3.38	0.76°
4	283	308	864	940	11	3.05	3.40	0.82°
5	283	308	864	940	11	3.05	3.38	0.82°
6	283	308	864	940	11	3.05	3.40	0.82°
7	316	350	965	1067	11	3.05	3.40	0.86°
8	316	350	965	1067	11	3.05	3.40	0.86°
9	316	350	965	1067	11	3.05	3.40	0.86°
10*	68	154	800	975	--	6.35	3.40	0.90°


Spec
10

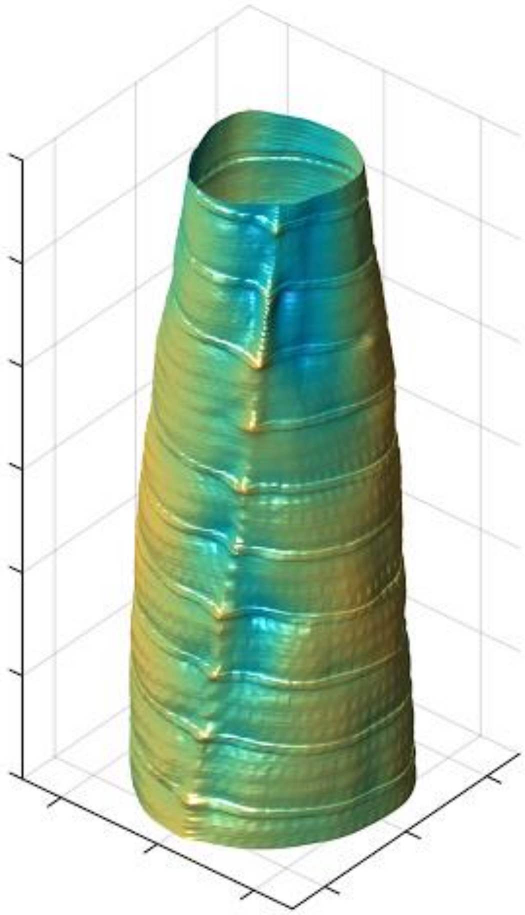
- Pure bending, pure compression and bending-compression
- 3300 kN-m max moment
- 10° max end rotation
- 3000 kN max tension, 2000 kN max compression
- Specimen welded to 100 mm thick end plates



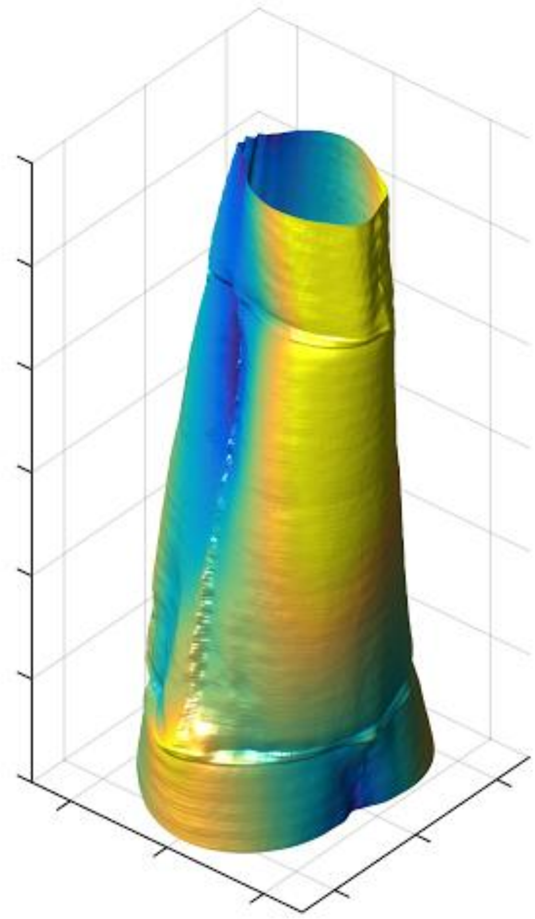




Initial Imperfection Scans



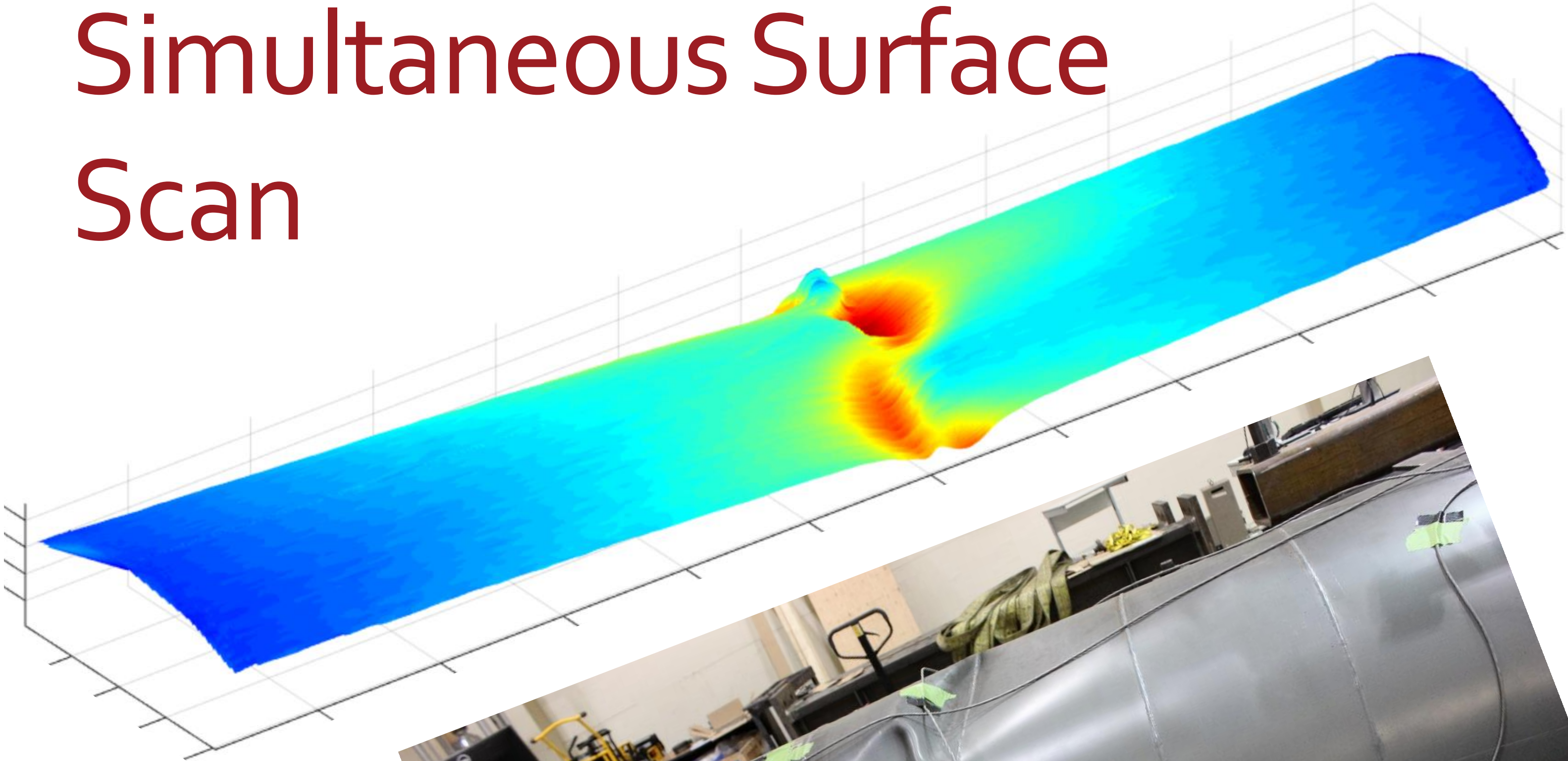
Tapered spiral welded (Specimen #4)

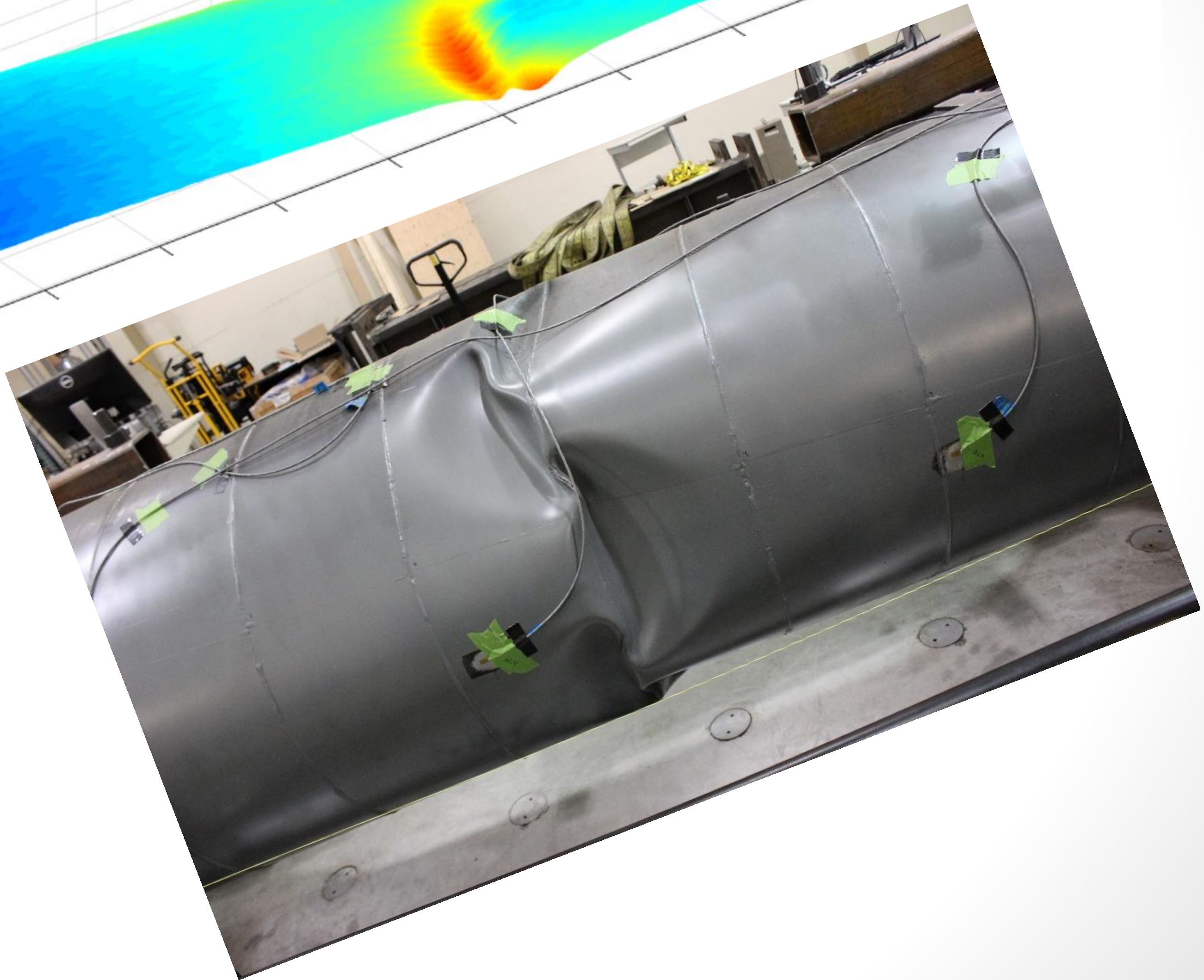


Can welded (Specimen #10)

Imperfections amplified 20x; Both specimens ~1m in diameter, ~3m long

Simultaneous Surface Scan

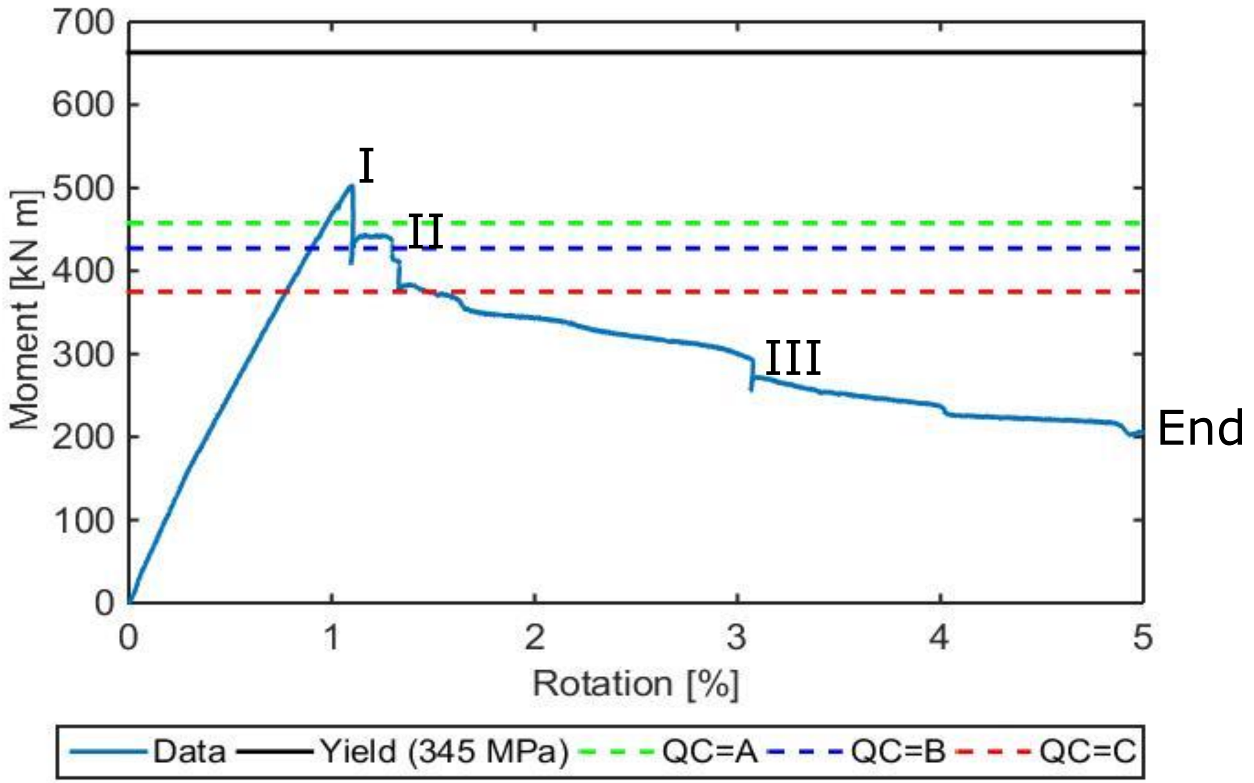




Specimen 4 Results

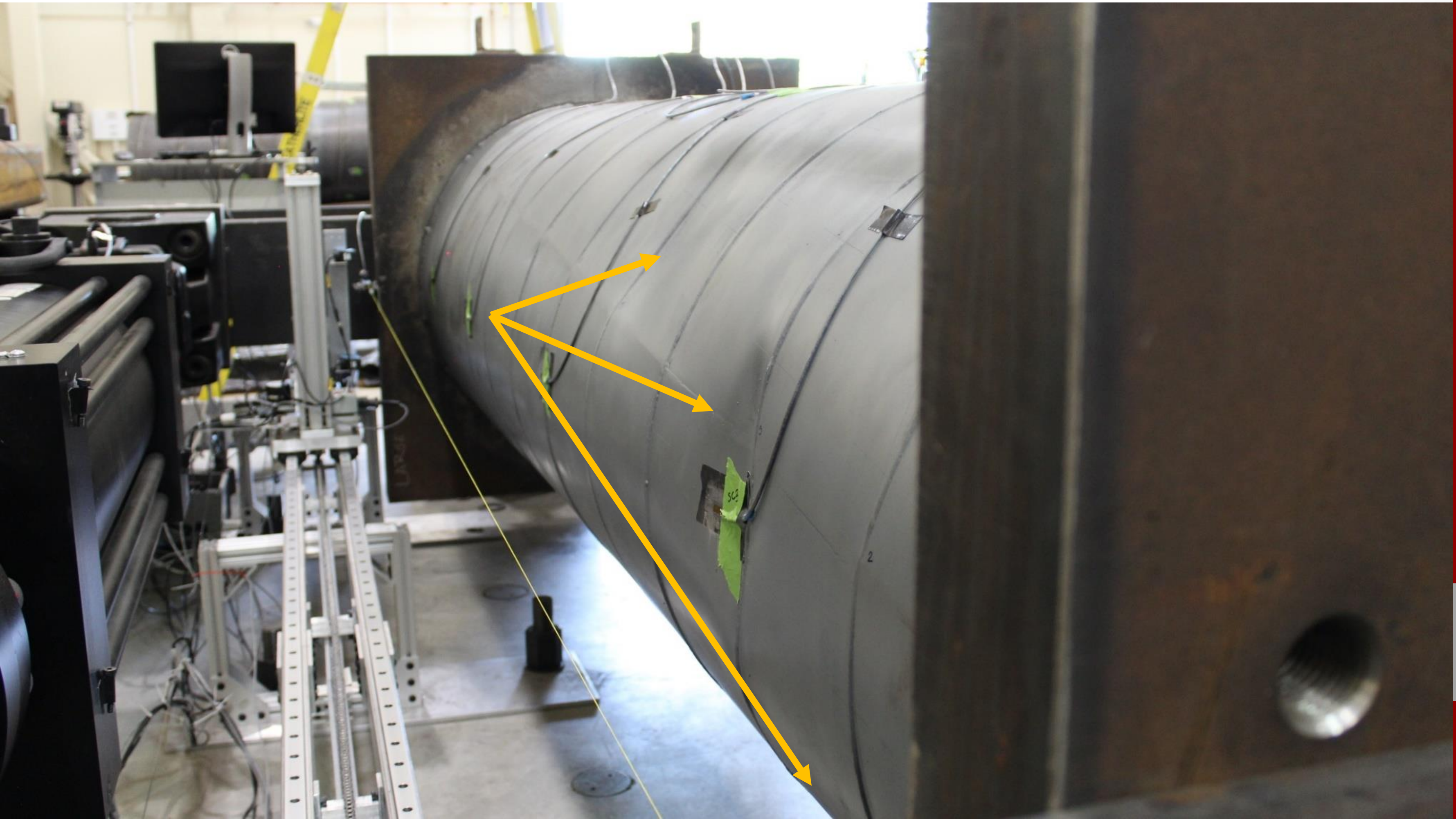
Spec. #	Min D/t [-]	Max D/t [-]	D_{min} [mm]	D_{max} [mm]	Gauge	t [mm]	L [m]	α [-]
4	283	308	864	940	11	3.05	3.40	0.82°

- Eurocode QC strengths calculated for "equivalent" diameter

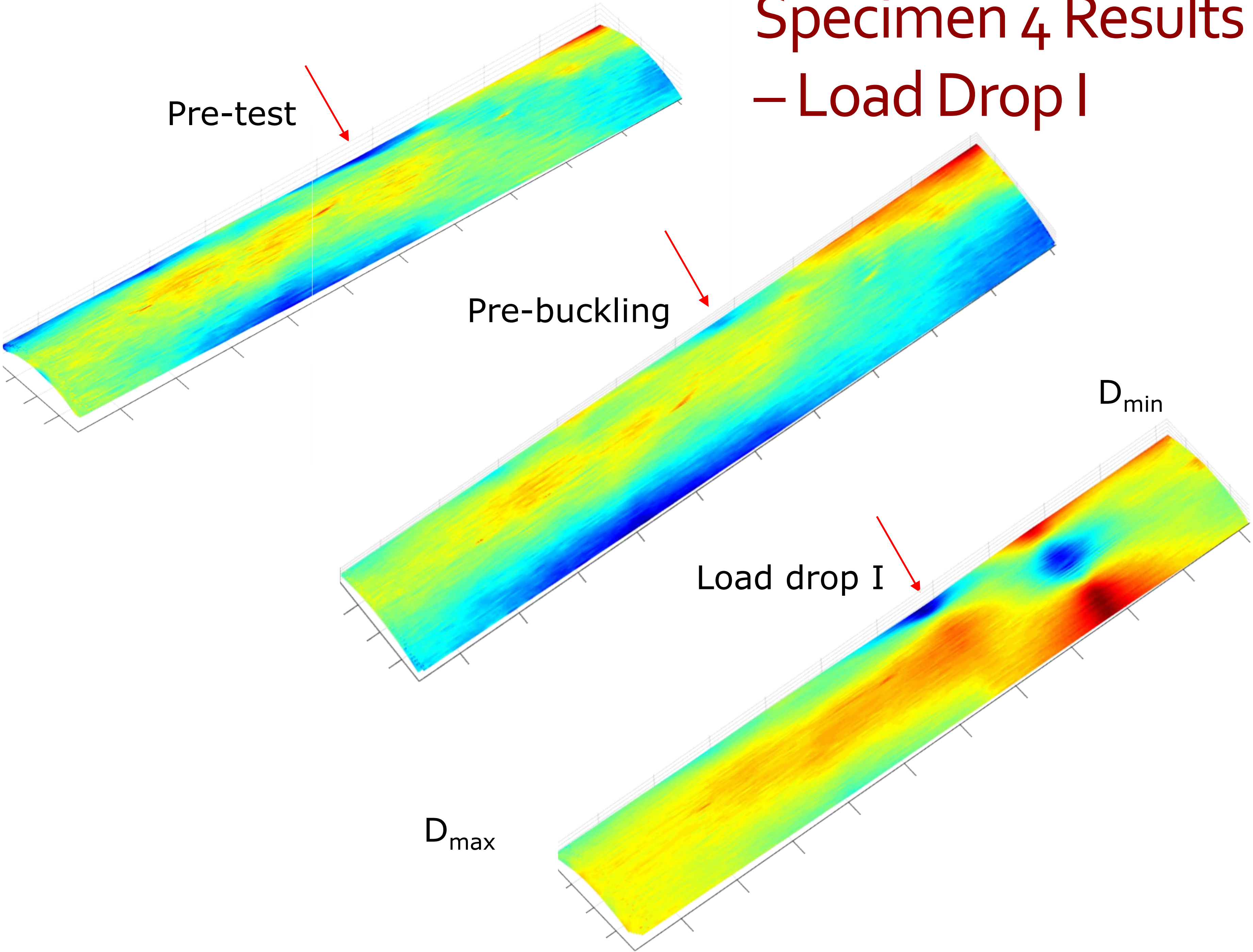


Specimen 4 Results – Load Drop I

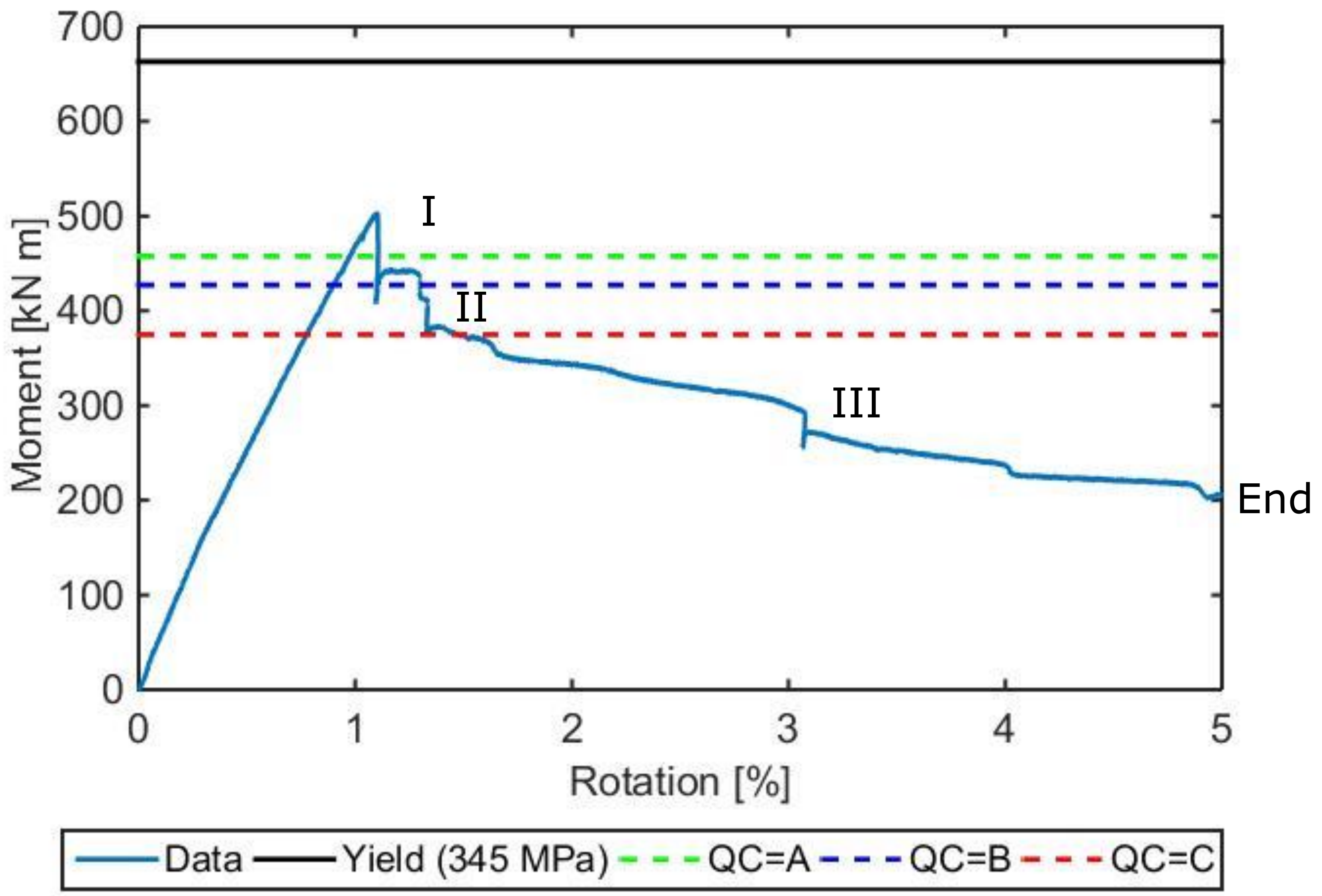
- First test to buckle simultaneously at three different cross-sections. Buckling initiated near the end with minimum diameter.



Specimen 4 Results – Load Drop I

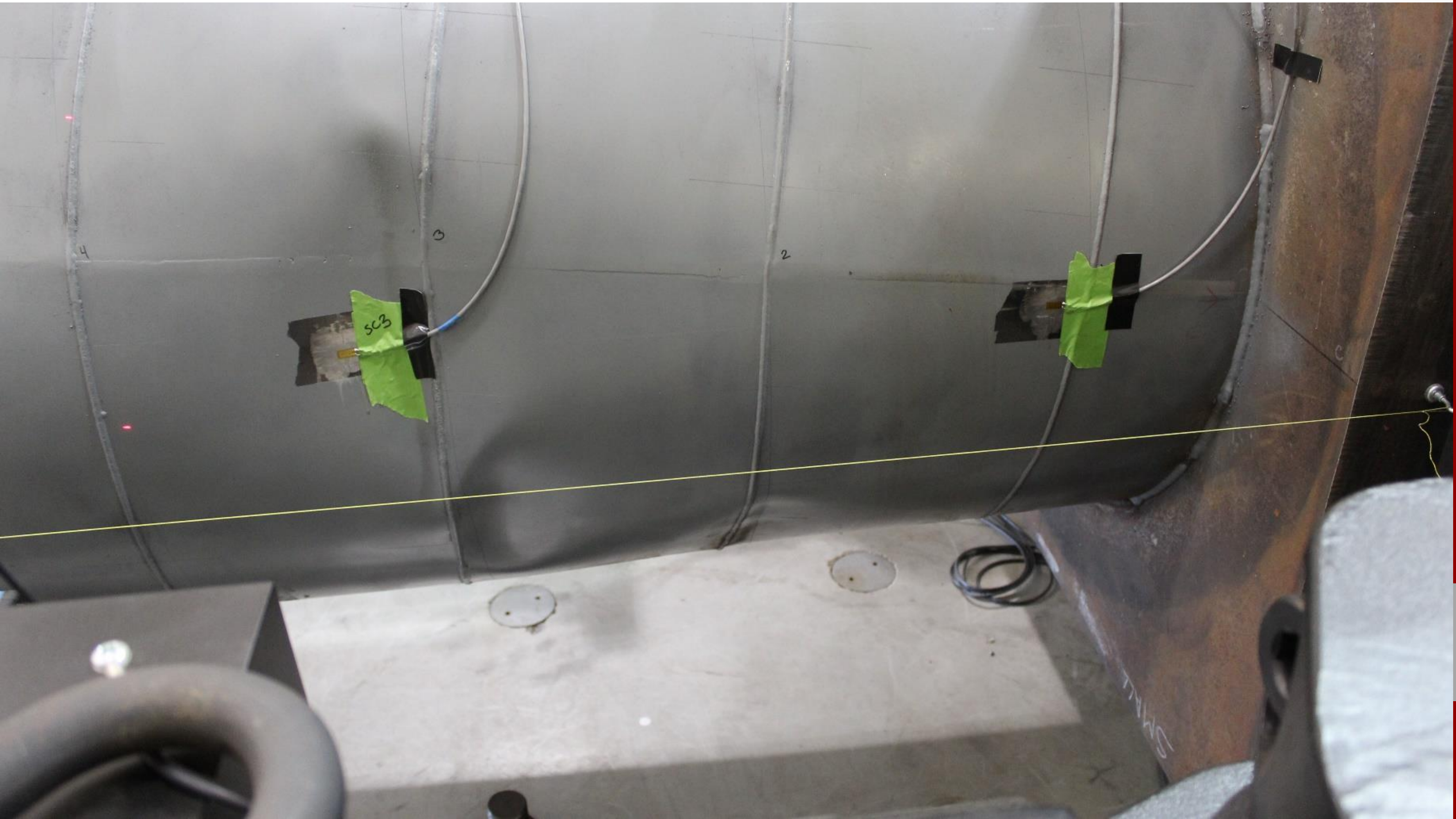


Specimen 4 Results

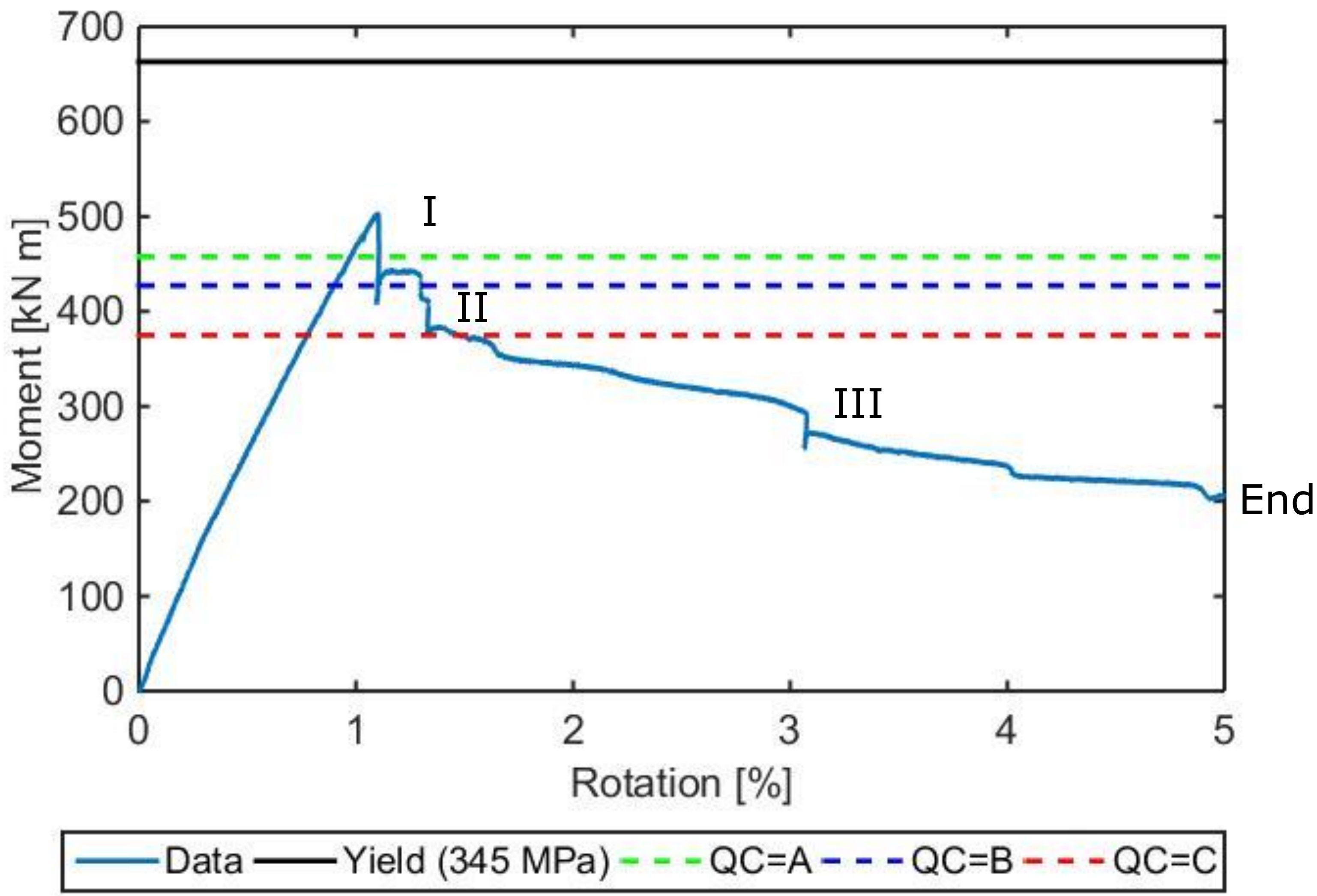


Specimen 4 Results – Load Drop II

- Additional buckling waves on bottom of the second and third sheets



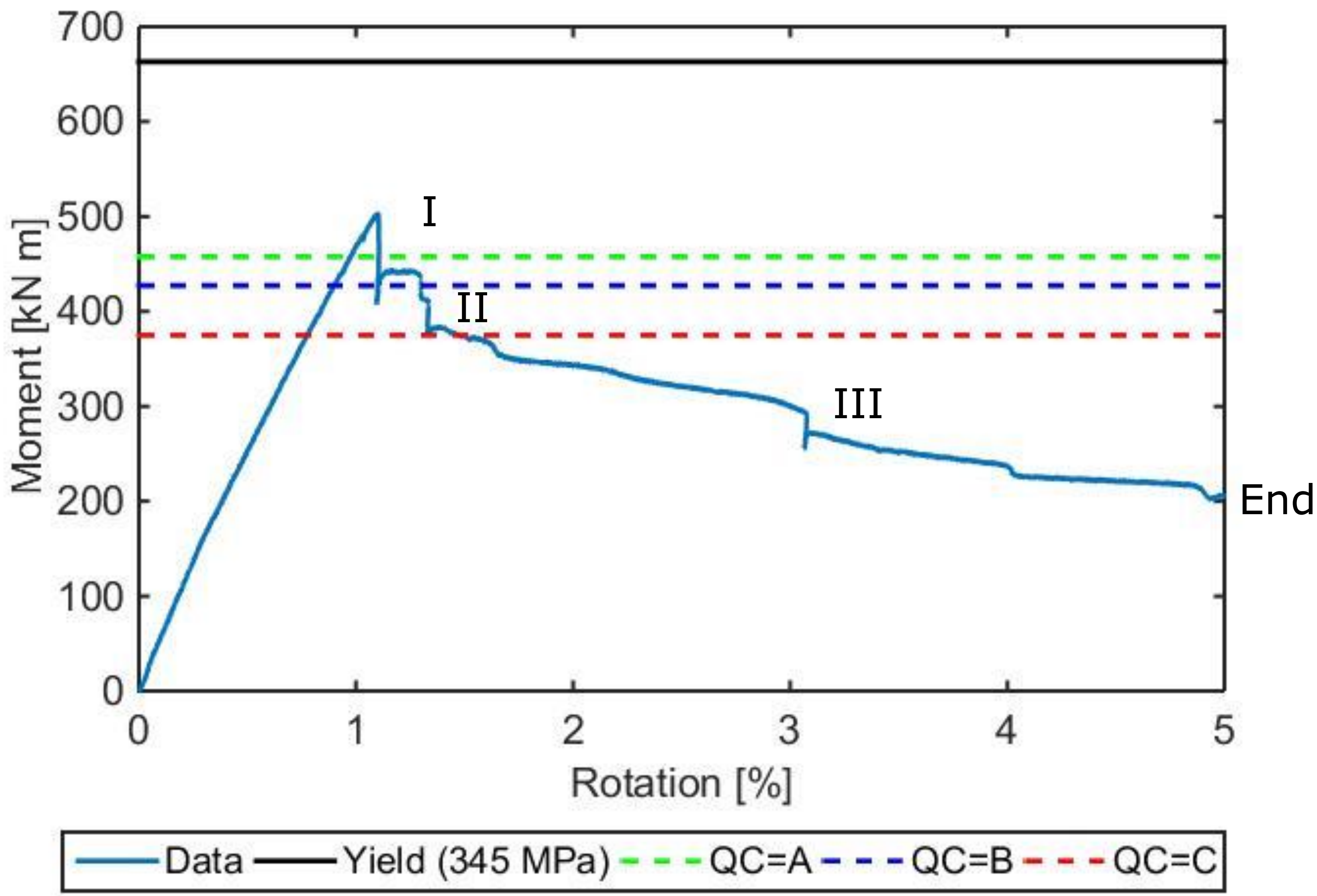
Specimen 4 Results



Specimen 4 Results – Load Drop III

- Additional buckling waves on top of the fifth sheet

Specimen 4 Results

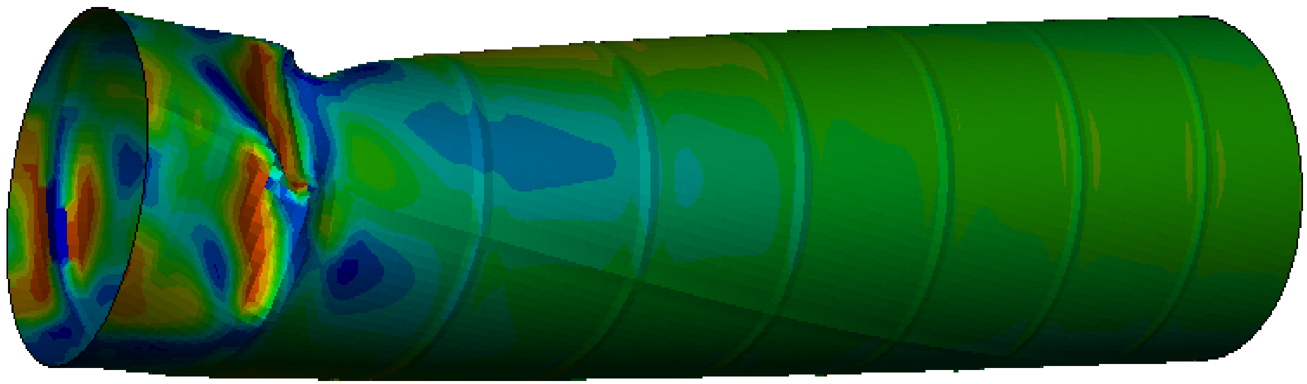


Specimen 4 Results – End

- Buckling pattern somewhat helical in reverse direction as weld

GMNIA Analyses – Convergence Study

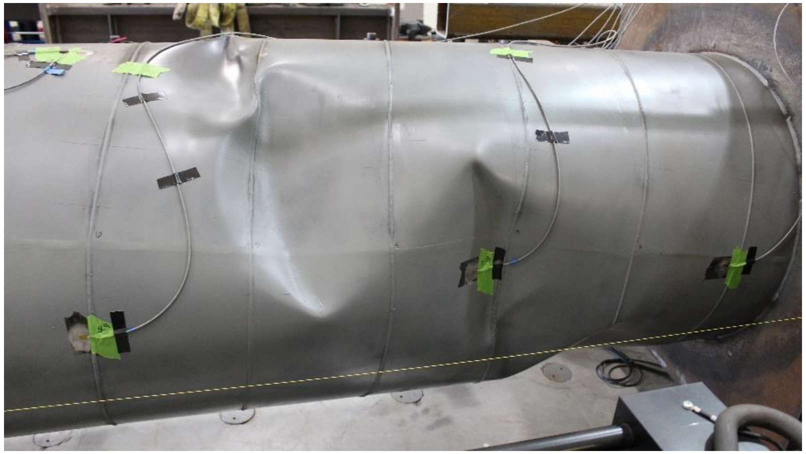
- S4R elements in ABAQUS.
- Nonlinear collapse analysis with Rik's Solver.
- Convergence study on shell element type, aspect ratio, size, orientation (aligned with helix vs normal) and loading (pure compression vs bending).

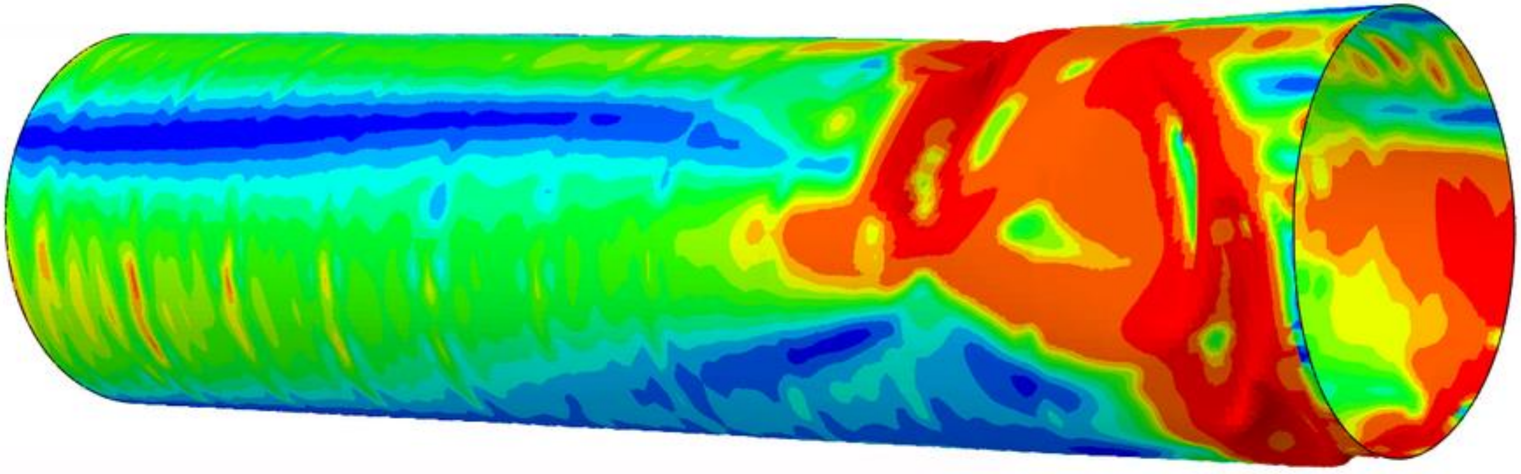


- Results showed convergence for S4R elements, 1:1 aspect ratio, element size = $\sim 0.5\sqrt{Rt}$, elements oriented normally and bending.

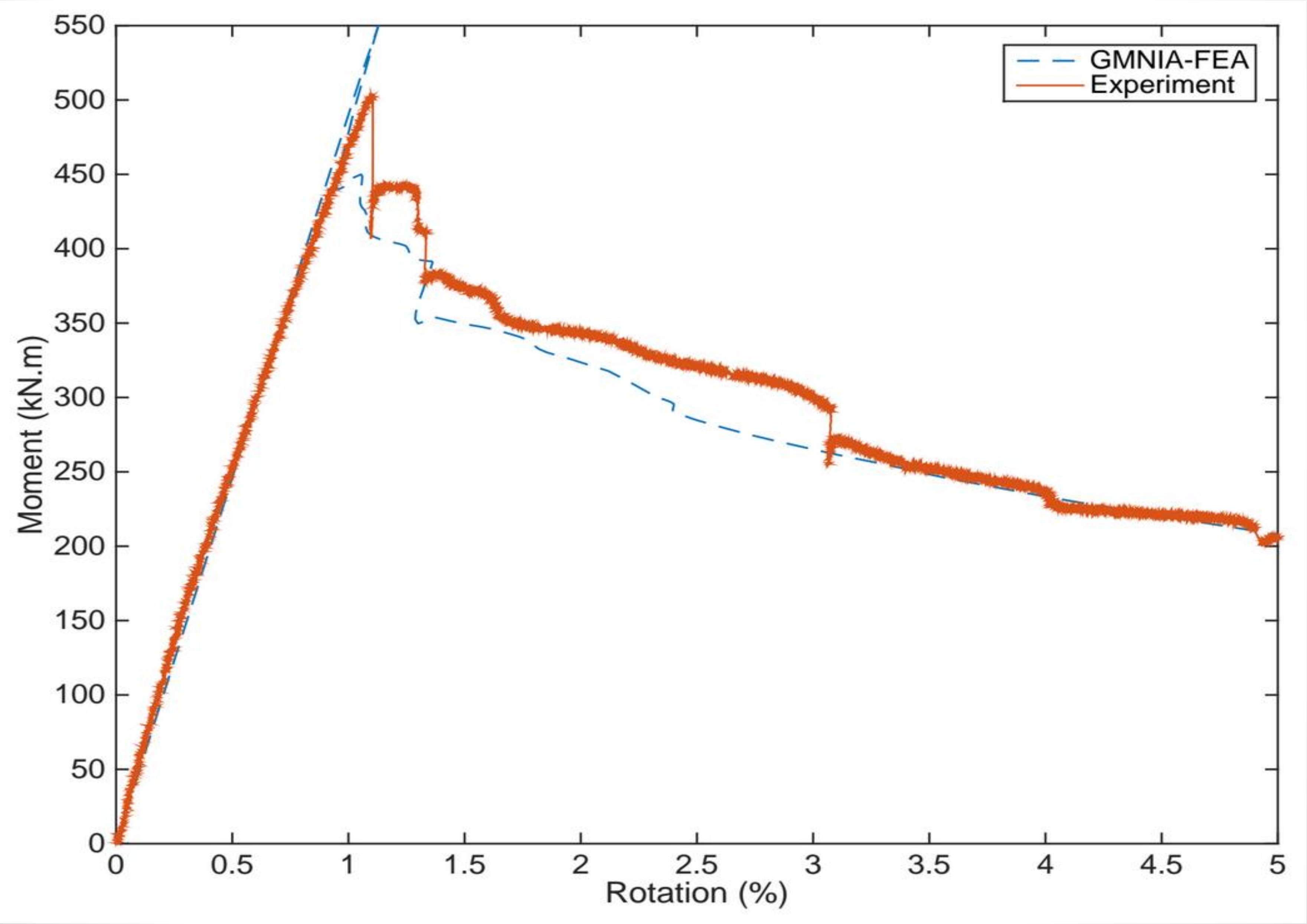
GMNIA Results – Specimen 4

- GMNIA results shown for S4R elements, 1:1 aspect ratio, element size = $\sim 0.5\sqrt{Rt}$, elements oriented normally, bending
- Measured imperfections
- Idealized boundary conditions
- Measured material properties (idealized as bilinear with yield plateau)
- Contours of Von Mises stress





GMNIA Results – Specimen 4



Future Work

- More large-scale tests.
- Probabilistic assessment of initial imperfections.
- FEA sensitivity study of imperfections.
- Combining tests and FEA to develop design equations and FEA protocols for high slenderness steel tubes subject to flexure.

Collaborators

- Eric Smith, Keystone Tower Systems
- Ben Schafer, JHU
- Angelina Jay, NEU
- Robert Rosa, NEU
- Shahab Torabian, JHU
- Abdullah Mahmoud, JHU

Acknowledgements

- NEU STReSS Lab

- Funding by:
  - NSF grant CMMI-1334122
  - NSF SBIR and DOE SBIR
  - Mass Clean Energy Center

Thank You.

Prof. Andrew Myers, PE, PhD
Northeastern University
atm@neu.edu