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MET TOWER DETAILED DESIGN

DESIGN SUMMARY

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REVISION HISTORY					
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1 INTRODUCTION

1.1 General

The Maryland Offshore Wind Energy Area development requires a meteorological test tower (hereafter referred to as met tower) to be installed approximately 11.5 miles from Ocean City, Maryland as depicted in Figure 1-1. Keystone Engineering Inc. (KEI) is employed by US Wind Inc. (USW) to perform the detailed engineering design of this steel lattice met tower.

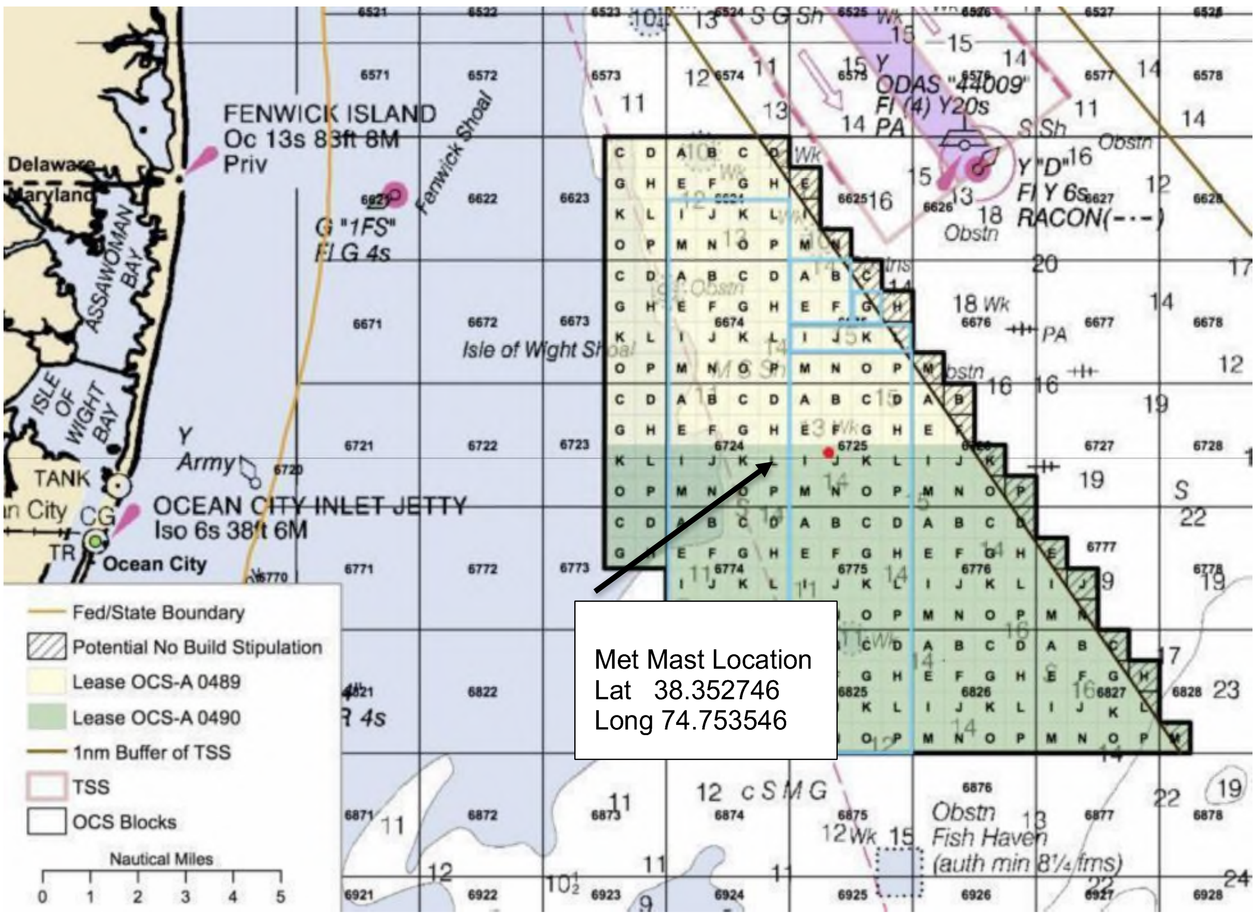


Figure 1-1: Maryland Offshore Wind Farm Location

1.2 Objective

The objective of this document is to describe the criteria and methodology used in the structural design of the met tower and to present the results of the structural analyses performed.

1.3 Background

The met tower shall be installed on a substructure which shall provide adequate support and access to the tower. The tower interface with the substructure is at (+)72 ft elevation above Mean Lower Low Water (MLLW). Design of substructure is not included in the scope of this work.

2 DESIGN PREMISES

2.1 Purpose of Met Tower

The purpose of the met tower is to support meteorological data acquisition equipment at appropriate elevations. The tower was designed for the following data acquisition equipment:

- Anemometers at elevations (+)104'-6", (+)175'-3", (+)249'-10", (+)319'-7" above MLLW installed on booms. Boom lengths were determined based on the met tower solidity ratio.
- Microwave dish antenna with 4 ft^2 surface area at elevation (+)330'-0" above MLLW.
- Work platforms at all instrument boom elevations.

Additionally, the met tower shall provide support and access to equipment required for the operation of the met mast. This includes, at a minimum, the following items:

- Ladder and fall protection system
- Lighting fixtures
- Aviation hazard lights

2.2 Regulations, Codes and Standards

The Maryland Offshore Wind Energy Area Farm met tower shall meet all applicable regulatory requirements of the State of Maryland, United States Bureau of Ocean Energy Management (BOEM), the United States Coast Guard (USCG), the Environmental Protection Agency (EPA), the Federal Aviation Administration (FAA), the Occupational Safety and Health Administration (OSHA), United States Bureau of Safety and Environmental Enforcement (BSEE), and other federal regulatory requirements for operation.

United States codes and standards govern most structural design. However, no US standard addresses offshore tubular lattice met tower design. Therefore, BS EN 1993-3-1 [1] was adopted for design of the met tower. US metocean conditions are developed per API RP 2A [2].

2.3 Design Life

The met tower was designed for a service life of 30 years which is in line with the design life of the corresponding substructure and foundation.

2.4 Design Limit States

The following limit states were evaluated for the design of the met tower:

2.4.1 Ultimate Limit State (ULS)

The purpose of this analysis is to demonstrate that the met tower will resist environmental conditions with a return period of 50 years without exceeding the allowable capacity of any primary steel members or joints.

2.4.2 Robustness Check

The purpose of this analysis is to demonstrate that the met tower will resist environmental conditions with a return period of 500 years without failure or collapse.

2.4.3 Service Limit State (SLS)

The purpose of this analysis is to demonstrate that the deflection and vibration of the met tower, under environmental conditions with a return period of 1 year, are within acceptable range.

2.4.4 Fatigue Limit State (FLS)

The purpose of this analysis is to confirm that the main structural steel connections and the primary steel members have a predicted fatigue life greater than the design life stated in Section 2.3 with appropriate safety factors.

2.5 Reliability Classification

The met tower will be installed on an unmanned substructure in the open seas and failure would not be likely to cause injury to people. Therefore, the met tower structure was classified as Reliability Class 1. The design of the met tower considered the parameters for a Reliability Class 1 structure per BS EN 1993-3-1 [1].

2.6 Safety Factors for Loads and Resistance

Safety factors and allowable stresses used in the design of the met tower conform to guidelines set forth in BS EN 1993-3-1 [1]. Table 2-1 outlines the load factors to be used for ULS, FLS, SLS, and Robustness Check.

Table 2-1: Partial Load Factors

Limit State	Specification	Load Action	Partial Load Factor Permanent Actions	Partial Load Factor Variable Actions
ULS	BS EN 1993-3-1 [1]	Unfavorable	1.1	1.4
		Favorable	0.9	0.0
FLS	BS EN 1993-3-1 [1]	Fatigue	1.0	1.0
SLS	BS EN 1990 [3]	Serviceability	1.0	1.0
Robustness	API RP 2A [2]	Robustness	1.0	1.0

Table 2-2: Material Resistance Factors

Specification	Limit State	Component	Action	Resistance Factor
BS EN 1993-3-1 [1]	ULS	Members	Yielding	1.0
			Buckling	1.0
		Connections	Tensile Rupture at Bolt Hole	1.25
			Bolts/Welds/ Plates in Bearing	1.25
			Slip Resistance	1.25
BS EN 1993-3-1 [1]	SLS	All	All	1.0
BS EN 1993-1-9 [4]	FLS	All	Low Consequence	1.15
API RP 2A [2]	Robustness	All	All	1.0

2.7 Deflection Criteria

The deflection and vibration criteria used in the met tower design are based on BS EN 1993-3-1 [1] and previous project experience, and are shown on Table 2-3:

Table 2-3: Deflection Criteria

Element Type	Allowable Deflection
Maximum displacement at the tower top	Tower height / 500
Members supported at both ends	Span/200
Members supported at one end - cantilevers	Span/150

2.8 Corrosion Protection

Hot dip galvanization was selected as the appropriate method for the met tower corrosion protection. The service life of the corrosion protection shall meet or exceed the design service life of the met tower. The corrosion protection shall be based on API RP 2A [2] and in accordance with NACE SP0108 [5].

2.9 Analysis Software

Bentley Systems SACS V8i 5.7 structural analysis package was used to develop a space frame model that represents the mass and stiffness of the primary steel members of the met tower. All the required static and dynamic analyses of the primary steel were performed using SACS. Evaluation of the ULS, SLS, and FLS limit states, and Robustness Check were performed using SACS per the requirements of the aforementioned governing codes and standards.

SACS does not perform code checks on bolted connections. For those connections member-end forces were extracted from the SACS outputs and used as input for manual/spreadsheet calculations. Additionally, SACS does not perform wind loading calculation per Eurocode [1]. In this case, overall wind loading on tower was calculated manually and the wind speed input in SACS' API [2] wind loading option was calibrated to match the total wind loading per Eurocode.

2.10 Structural Steel Properties

Structural steel for the various components of the met tower and appurtenances was selected according to the requirements of ISO 19902 [6] and API-RP-2A [2] based on their function, criticality and lowest anticipated service temperature (LAST). Steel specification is presented in KEI drawing 6977A15-KEI-002, Table A.

Welds were designed and shall be implemented according to the American Welding Society D1.1/D1.1M standard [7].

3 ENVIRONMENTAL CONDITIONS

The environmental conditions used in the design of the met tower are based on A.H Glenn and Associates Services reports [8] and [9].

3.1 Water Levels

The design water depth for this site is 88.6 ft. (MLLW).

3.2 Wind Speeds

Omnidirectional wind speeds for 50-year and 500-year return periods are presented in Table 3-1. The 10-min mean wind speed for 1-year return period was calculated from the 50-year wind speeds using BS EN 1993-3-1 [1].

Table 3-1: Wind Speeds

Wind Speed (+32.8 ft Ref. Elevation)	Unit	Return Period (years)		
		1	50	500
1-hour Mean Wind Speed	mph	---	94	114
10-min Mean Wind Speed	mph	61	107	130
1-min Mean Wind Speed	mph	---	122	145
3-sec Gust	mph	---	144	174

3.3 Atmospheric Icing

ISO 12494 [10] was used to determine the requirements of atmospheric icing for the met tower. The parameters in Table 3-2 were used for analysis.

Table 3-2: Atmospheric Icing Parameters

Parameter	Value
Ice Type	Glaze
Ice Density	56.2 lb/ft^3 (900 kg/m^3)
Ice Class	G3 (Glaze Class 3)
Ice Thickness (for Ice Class G3)	1.2 in (30 mm)
Formation Around Member	Constant Thickness
Variation with Height	Constant
Wind Drag Coefficient	Tubular Members = 1.04
	Flat Surfaces = 1.44

3.4 Temperature

The lowest anticipated service temperature (LAST) of air for this site was estimated base on previous project experience and NOAA buoy 44009 data near site location.

Table 3-3: Lowest Anticipated Service Temperature (LAST)

Water Level	Temperature (C°)
Air	-15

3.5 Seismic Conditions

According to API RP 2EQ [11], the Maryland Offshore Wind Energy Area site is located in Seismic Zone “0”. Therefore, no seismic evaluation is required.

4 DESIGN RESULTS

The results for each of the analyzed limit states are summarized in this section. Figure 4-1 depicts the SACS model of the met tower.

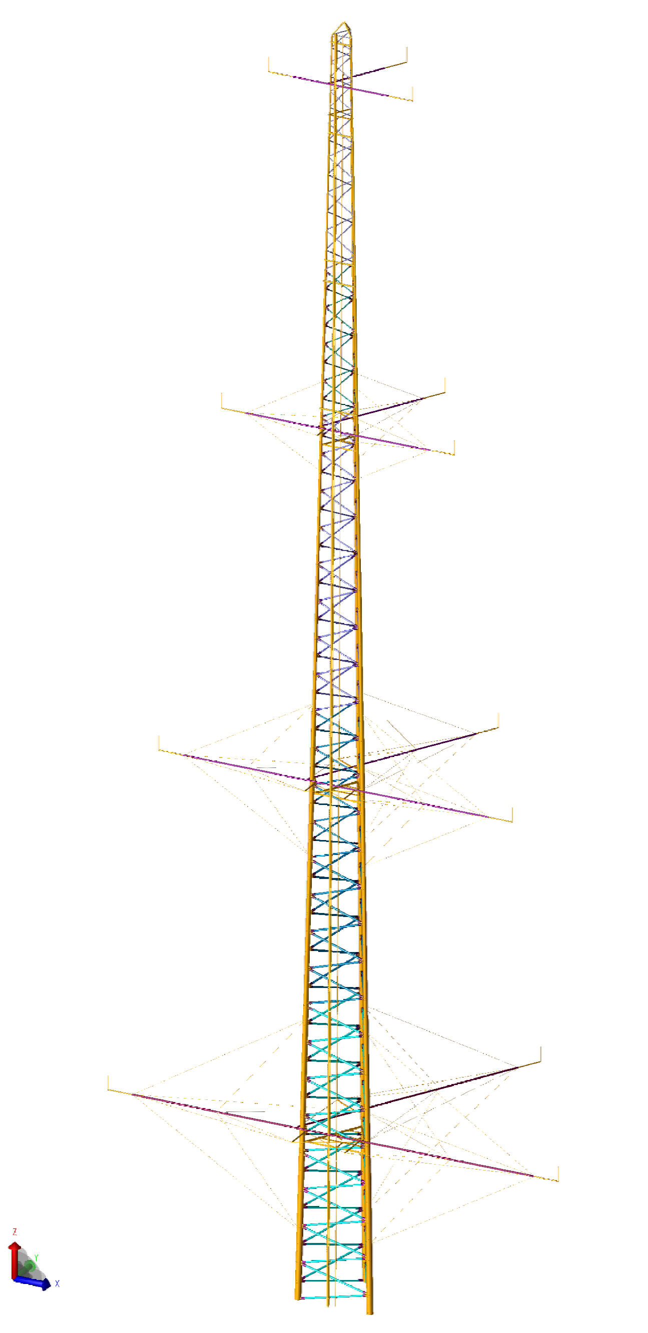


Figure 4-1: SACS Model of Met Tower with Instrument Booms – Isometric 3D View

4.1 Ultimate Limit State (ULS)

The ULS analysis demonstrates that the tower has acceptable utilization ratios. Figure 4-2 and Figure 4-3 show member utilization ratios throughout the tower and instrument booms, respectively. Maximum member and joint utilization ratios are listed in Table 4-1.

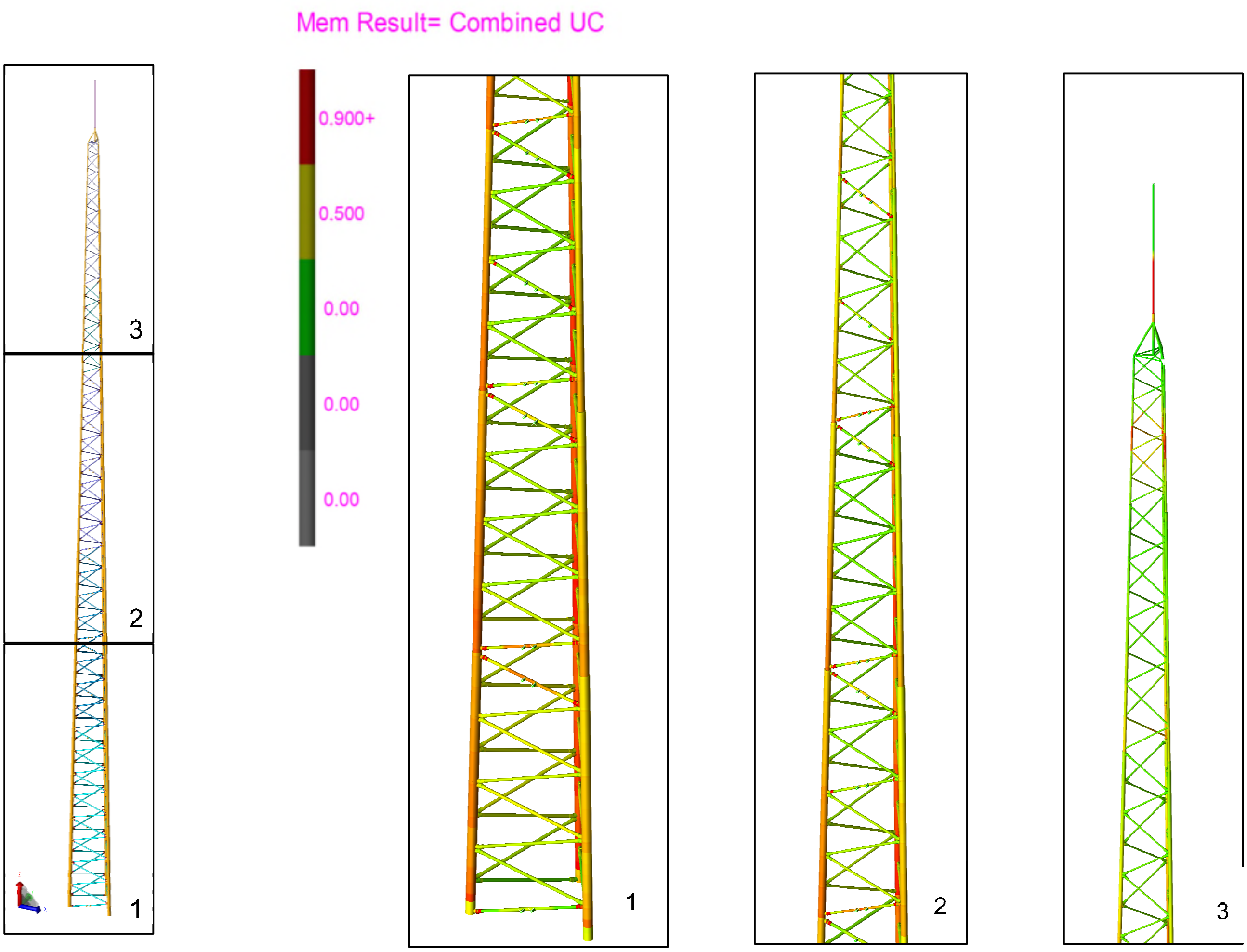
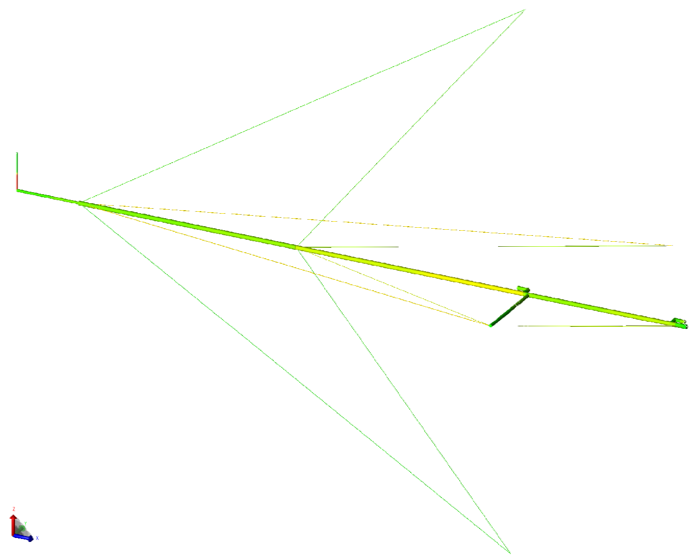
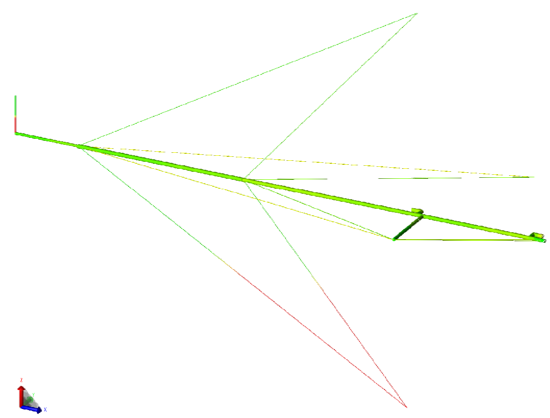


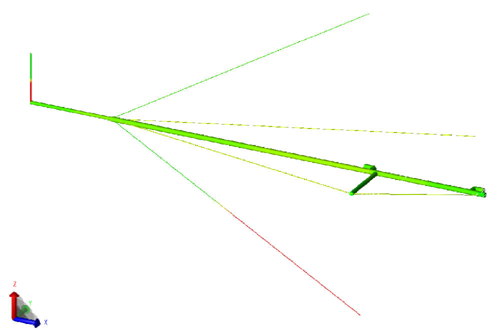
Figure 4-2: Ultimate Limit State Tower Members Utilization Ratios – Color Scale Isometric View



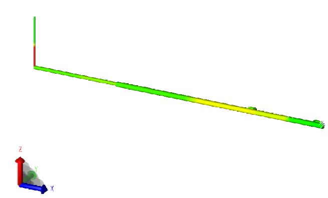
Booms at elev. +104' M.L.L.W



Booms at elev. +175' M.L.L.W.



Booms at elev. +249' M.L.L.W



Booms at elev. +319' M.L.L.W.

(1 boom shown per tower section. Total of 3 booms per tower section)

Figure 4-3: Ultimate Limit State Boom Member Utilization Ratios – Color Scale Isometric View

Table 4-1: Ultimate Limit State Maximum Utilization Ratios

Component	Maximum Utilization Ratio
Tower leg members	0.98
Tower brace members	0.91
Welded joint cans	0.31
Leg to leg bolted connection	0.98
Brace to leg bolted/welded connection	0.97
Boom members	0.50
Boom connections	0.85

4.2 Robustness Check

The robustness check demonstrates that the met tower has acceptable utilization ratios. Figure 4-4 shows member utilization ratios throughout the tower. Maximum member and joint utilization ratios are listed in Table 4-2.

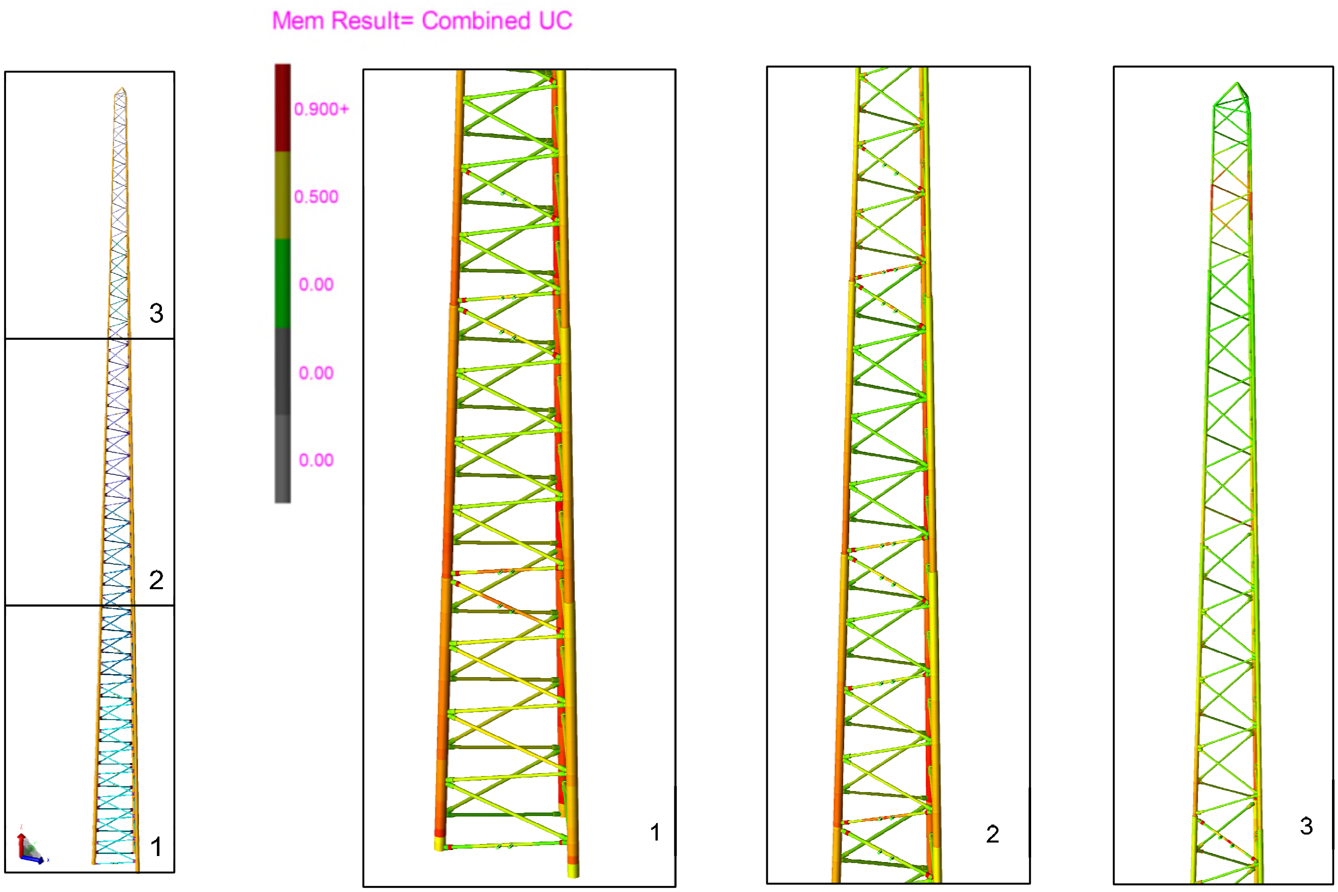


Figure 4-4: Robustness Check Tower Members Utilization Ratios – Color Scale Isometric View

Table 4-2: Robustness Check Maximum Utilization Ratios

Component	Maximum Utilization Ratio
Tower leg members	0.97
Tower brace members	0.94
Welded joint cans	0.32
Leg to leg bolted connection	0.98
Brace to leg bolted/welded connection	0.97

4.3 Service Limit State (SLS)

The Service Limit State analysis shows that the tower deflection is within the allowable limit defined in section 2.7. Figure 4-5 illustrates the deflected shape of the tower under service loads and Table 4-3 presents the tower's natural period.

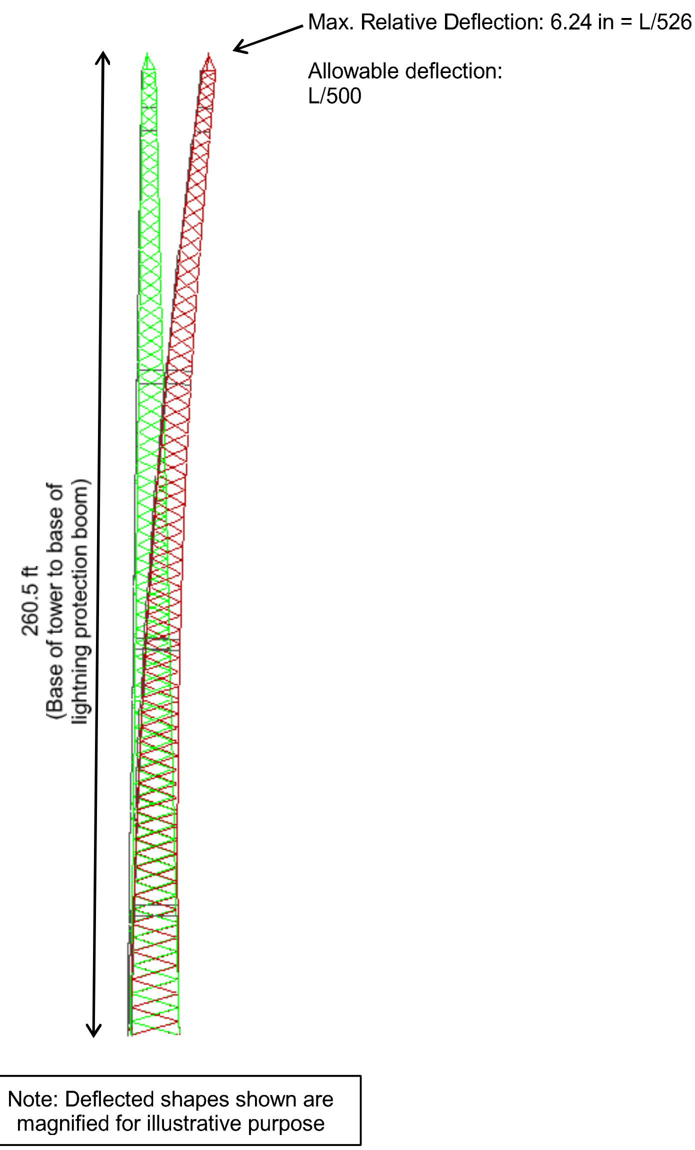


Figure 4-5: Met Tower Deflection – Elevation View

Table 4-3: Met Tower Natural Period

Mode	Natural Period (s)
First	1.248

4.4 Fatigue Limit State (FLS)

The Fatigue Limit State analysis was performed per BS EN 1993-3-1 [1] and BS EN 1993-1-9 [4]. The Fatigue Limit State analysis predicts that the fatigue lives of the tower members and connections are adequate for the intended design life of the structure. The fatigue analysis considered wind loads only. Wave induced fatigue on the met tower is considered negligible. Table 4-4 presents the minimum predicted fatigue lives of the three types of tower connections.

Table 4-4: Met Tower Fatigue Life

Tower Component	Calculated Fatigue Life
Leg to leg connection	198 years
Brace to leg connection (bolted)	125 years
Brace to leg connection (welded)	119 years

5 REFERENCES

[1] British Standard, "BS EN 1993-3-1: Eurocode 3 - Design of Steel Structures Part 3-1: Towers, Masts and Chimneys - Towers and Masts," 2006.

[2] API RP 2A-WSD - Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms – Working Stress Design 22nd Edition.

[3] British Standard, "BS EN 1990: Eurocode - Basis of Structural Design," 2002.

[4] British Standard, "BS EN 1993-1-9: Eurocode 3 - Design of Steel Structures Part 1-9: Fatigue," 2005.

[5] NACE SP0108-2008, Standard Practice: Corrosion Control of Offshore Structures by Protective Coatings, 2008.

[6] ISO 19902 – Fixed Steel Offshore Structures.

[7] American Welding Society, AWS D1.1/D1.1M:2010. Structural Welding Code – Steel. 22nd Ed., 2010.

[8] A.H. Glenn and Associates Services, 50 Year Storm Wind, Tide, Wave, and Current Characteristics, and Combined Wave - Current Forces: 88.6 foot (27 meter) MLLW Depth: approximately 38°21'09.8892"N, 74°45'12.7656"W: Offshore Maryland, Oct. 2015.

[9] A.H. Glenn and Associates Services, 500 Year Storm Wind, Tide, Wave, and Current Characteristics, and Combined Wave - Current Forces: 88.6 foot (27 meter) MLLW Depth: Approximately 38°21'09.8892"N, 74°45'12.7656"W: Offshore Maryland, Oct. 2015.

[10] ISO 12494 - Atmospheric Icing of Structures, 2012.

[11] API RP2EQ - Seismic Design Procedures & Criteria for Offshore Structures.