

WETI c/o Fachhochschule Flensburg

Postal Address:

**Kanzleistraße 91-93
24943 Flensburg, Germany**

Visitors:

**Nordstraße 2
24937 Flensburg, Germany
Tel: +49 (0)461 805-1660
+49 (0)461 48161-108**

Final Report: Prototype Design of an Energy-efficient Guyed Tubular Steel Tower Concept for Wind Turbines targeting 50 % savings in Steel and associated CO₂ Emissions

(Endbericht: Prototypentwicklung eines energieeffizienten, abgespannten Stahlrohrturm-Konzeptes für Windenergieanlagen bei ca. 50 % Reduktion der Stahlmenge und der CO₂-Emmission)

Project Engineer, Author: Robert Rudolf, M.Sc., M.Eng

Manager: Torsten Faber, Prof. Dr.-Ing.

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ABSTRACT

This report documents the basic design of an exceptionally lightweight prototype guyed tower for a modern 2.5 MW wind turbine. The goal of this work is to assess the potential of the guyed tower with strut (GTS) concept to reduce the material content and associated costs and emissions of wind energy. A rigorously optimized design study with safety factors and analysis according to industry standards was performed in order to fairly assess the material savings potential of the concept. The resulting configuration has an estimated mass of 199 tons and costs 593 t€, achieving its goal of 50 % material savings versus a comparable monopole steel tower. Thus, the GTS has potential to substantially reduce the greenhouse gas (GHG) emissions associated with wind turbine manufacturing and, more importantly, offset fossil fuel emissions by reducing the cost of wind energy. The project was funded by the Foundation for Energy and Climate Protection in the state of Schleswig Holstein, Germany (abbreviated EKSH) and led by the Wind Energy Technology Institute at the Flensburg University of Applied Sciences. Technical assistance and secondary funding were provided by the renowned wind turbine consultancy aerodyn Energiesysteme GmbH.

Dieser Report dokumentiert die Basisauslegung eines besonders leichtgebauten Prototyps eines abgespannten Turms für eine moderne 2,5 MW Windturbine. Das Ziel dieser Arbeit ist das Potential des Konzeptes eines mit Seilen abgespannten Turms (guyed tower with strut = GTS) zu bewerten, um den Materialaufwand und die damit verbundenen Kosten und Emissionen der Windenergie zu senken. Es wurde eine präzise Parameter-Design-Studie mit Sicherheitsfaktoren und Auswertungen nach Industriestandards durchgeführt, um das Potential der Materialersparnis zu quantifizieren. Die resultierende Struktur hat eine geschätzte Masse von 199 Tonnen und Kosten von 593 t Euro und erreicht das Ziel einer 50 %-igen Materialersparnis im Vergleich zu einem üblichen, freistehenden Stahlrohrturm. Dadurch hat der GTS Potential die Treibhausgas-Emissionen bei der Herstellung der Windturbine erheblich zu reduzieren und den Klimaschutzbereich der Windkraft gegeben anderen Arten der Energieproduktion weiter auszubauen. Das Projekt wurde finanziert durch die Stiftung für Energie- und Klimasicherung Schleswig-Holstein, Deutschland und von dem Wind Energie Technologie Institut der Flensburger Fachhochschule durchgeführt. Technische Assistenz und weitere Finanzierung wurden von dem Unternehmen aerodyn Energiesysteme GmbH bereitgestellt.

EXECUTIVE SUMMARY (GERMAN)

Windkraftanlagenstürme bestehen hauptsächlich aus einem Kragarm und sind deshalb von Biegebelastungen dimensioniert. Der konventionelle Stahlrohrturm mit seinem kreisförmigen Querschnitt hat deswegen eine schlechte Materialausnutzung, da die Spannungen in den Biegeebenen konzentriert sind, das Restmaterial hingegen relativ wenig belastet ist. Das GTS-Konzept bietet hier eine viel effizientere Struktur, da das Biegemoment direkt auf Seile und Stäbe, als reiner Zug bzw. Druck, übertragen wird. Diese Lasten sind gleichverteilt auf den Querschnitt und ermöglichen so eine maximale Materialausnutzung. Zudem sind Material und Geometrie der Seile besonders für Zug und der Stäbe besonders für Druck ausgelegt. Kommerzielle und öffentliche Institutionen begannen vor über einem Jahrzehnt GTS zu entwickeln. Einer dieser Türme ist bereits in Produktion, jedoch nur für eine kleine Garten-Windturbine. Das Konzept für größere Windturbinen schaffte den Markteintritt nicht, da die erhöhten Kosten der nicht optimierten Kabelsysteme die Kostensparnis durch Materialeinsparung aufheben. Heute ist das Potential der Einsparung durch GTS noch attraktiver, da Windkraftanlagen deutlich größer (und massiver) geworden sind und die Materialersparnis des GTS mitskaliert. Es gibt zudem einen erheblichen Fortschritt in der allgemeinen Designmethode für Leichtbau (z.B. für die Luft- und Raumfahrt) und es wird angenommen, dass diese Methode zu einem sehr wirtschaftlichen GTS führen könnte.

Das Ziel dieser Studie ist es das Konzept des GTS für eine moderne Turbinenstruktur zu optimieren und das Kostensparnispotential dieses Konzeptes zu quantifizieren. Der Fokus dieser Arbeit liegt in der Auswahl von 19 (Haupt-) Designvariablen, welche, wegen der signifikanten Auswirkungen auf das Materialvolumen (Kosten) und/oder die strukturellen Lasten des abgespannten Turmsystems, einen großen und korrelierenden Einfluss auf die finanzielle und strukturelle Realisierbarkeit des Designs haben.

Die Designaufgabe ist herausfordernd, da die Variablen die Dynamik Response der Windturbine plus Turmsystem beeinflussen, was neue Lasten und Sicherheitsfaktoren (die sich traditionell aus sehr rechenintensiver Analysis ergeben) hervorbringt. Die Aufgabe ein optimiertes Design gewiss den zahlreichen Möglichkeiten zu finden, wurde mit einem neuen und einzigartigen, voll automatisiertem Parameter Study Tool und einer beschleunigten Lastberechnungsmethode, als Teil der Doktorarbeit des Autors, bewältigt. Diese Methode, welche den optimierten Algorithmus zielgerichtet auf minimierte Turmkosten anwendet, ermöglicht eine schnelle Analysis tausender potentieller GTS-Designs.

Das Projekt setzt sich aus 4 Hauptschritten zusammen, welche hier aufgelistet und im folgenden Abschnitt näher ausgeführt sind.

- 1) *Definition der Annahmen und der Grundbedingungen des Designproblems,*
- 2) *Entwicklung des Software Tools zur automatisierten Parameterstudie,*
- 3) *Ausführung der Parameter-Studie zur Findung einer optimalen Struktur und*
- 4) *Prüfung der Sicherheit des finalen Designs.*

Jedes Design eines Turms ist nur für ein bestimmtes Modell einer Turbine und spezielle Standortbedingungen gültig. Im Folgenden wird gemäß dem modernen Trend der "übergroßen" Rotordurchmesser (im Vergleich zur Nennleistung) und höheren Nabenhöhe das "aeroMAster aM 2.5/118" Turbinendesign aus dem Portfolio der aerodyn GmbH ausgewählt. Dieser "Up-scaling" Trend reflektiert den populär steigenden Markt der "low wind" Standorte, entsprechend werden Wind Typ und Turbulenzklasse gewählt.

Die Hauptgestaltung und Querschnittsparameter des optimierten Designs sind so spezifiziert, dass eine genaue Abschätzung der Materialkosten möglich ist. Dazu sind die Materialausnutzungsfaktoren für wichtige Stellen und Lastfälle dokumentiert, welche zeigen, dass der Stahl des vorgeschlagenen Designs an Seilen und Turmwand sehr effektiv eingesetzt ist. Die Stahlmenge für einen konventionellen Stahlrohrturm wird konservativ geschätzt und zeigt eine 50 %-ige Materialeinsparung für den GTS. Dieses Resultat erfüllt die anfänglichen Schätzungen und ist hoch ermutigend! Obwohl einige zusätzliche Kosteneinsparungen mit Verbundwerkstoffen oder hochfesten Stählen eventuell möglich wären, wurden konventionelles Material und Herstellungsmethoden für das Kabelsystem und die rohrförmigen Komponenten des GTS ausgewählt.

Es wird empfohlen, einen Prototyp im Detail auszulegen und zu konstruieren, um das Potential des Konzeptes des GTS bezüglich des Materials, der Kosten und der Treibhausgas-Emissionen zu beweisen. Es verbleiben einige bedeutende Designaufgaben für die Konstruktion eines solchen GTS-Prototyps, welche von dem Bereich dieser Studie ausgenommen wurden. Dies betrifft die detaillierten Designs von beispielsweise Flanschverbindungen, Türöffnungen, Plattformen, Leitern/Aufzügen und Seil-Turm-Anbindungen. Die zur Verfügung stehenden Ressourcen erlaubten keine genauere Ausarbeitung dieser Einzelheiten, was für den Zweck der Bewertung einer Durchführbarkeit dieser GTS auch nicht notwendig ist. Ebenso sind das Design der Fundamente, der Nachweis und die eventuelle Anpassung des Rotor-Maschinenhauses und der Turbine-Controller nicht berücksichtigt. Schließlich wurde das Design der obersten Turmsektion (von dem Schnittstellenpunkt 80 m oberhalb des Grundes bis zum Maschinenhaus) nicht weiter im Detail optimiert oder analysiert.

BACKGROUND & MOTIVATION FOR GTS DESIGN STUDY

Basic physics suggest that the GTS should be a much more efficient structure than conventional monopole towers because it transfers bending loads into structural members acting in and optimized for tension and compression. Commercial and public intuitions began developing GTS concepts more than a decade ago and one such tower is already in production, albeit for small wind turbines. The concepts for larger wind turbines have failed to enter the market, however, in-part because the added cost of the cable system outweighed the material savings [1]. In the decade since these studies were made, the typical rotor diameter and hub height of wind turbines has grown significantly. Today the potential savings of the GTS are even more valuable, especially considering that transport constraints have limited conventional monopole tower cross-sections to suboptimal diameters. There have also been considerable advances in the design methods for wind turbine towers, and it is believed that these cost-engineering methods could lead to a much more attractive GTS. The goal of this study is to optimize the GTS concept for a modern turbine configuration and re-evaluate the cost-savings potential of the concept.

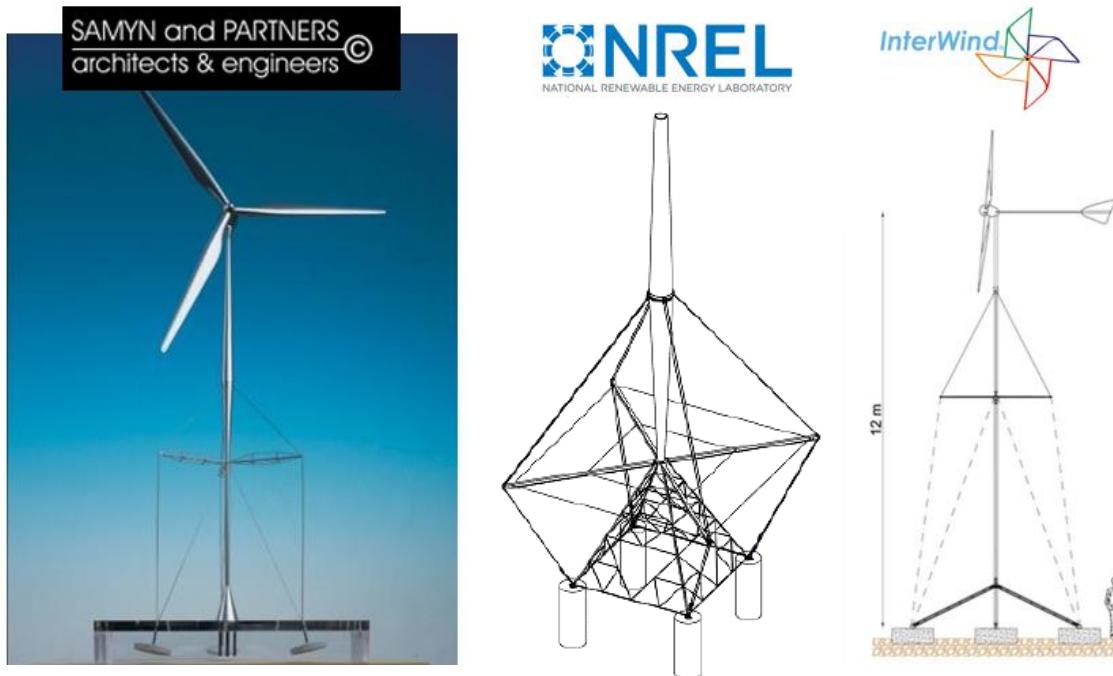


Figure 1: (Left) Original GTS concept from Samyn for 750 kW turbine [2]

Figure 2: (Center) NREL prototype design study for 1.5 MW turbine [1]

Figure 3: (Right) Commercially-available GTS for 4.5 kW small wind turbine [3]

PROJECT SCOPE

The goal of this research is to produce a cost-optimized guyed tower design with sufficient documentation detail to apply for prototype certification as per the “C-design assessment” standard described in the GL wind turbine design guideline [4]. The heart of this work concerns the selection of 19 major design variables which have a large and correlated influence on the financial and structural feasibility of the design. This is due to their significant impact on the material volume (cost) and/or the structural response (loads and safety factors) of the guyed tower system, respectively. The design task is challenging since the variables influence the dynamic response of the turbine plus tower system, resulting in new loads and safety factors (which are traditionally analyzed in a computationally- and human-intensive process). The challenge of finding an optimized design among the numerous possibilities was overcome with a new and unique, fully-automated parameter study tool developed by Rudolf [10] as part of his Ph.D. research. It enabled the rapid analysis of thousands of potential GTS designs selected using optimization algorithms with the objective of minimizing tower cost.

The project consists of 4 main steps which are listed below and elaborated upon in the following sections:

- 1) defining the assumptions and boundary conditions of the design problem,
- 2) developing software tools to enable an automated parameter study,
- 3) executing the parameter study to find an optimum structure, and
- 4) verifying the safety of the final design.

There remain many major design tasks necessary for construction of a GTS prototype that were excluded from the scope of this study. These include the design of details such as flanges, door openings, platforms, ladder/elevator, cable-tower connections, etc. The available resources did not allow for this work and these items are also not required for C-design assessment. Similarly, the design of the foundation and the tailoring of the rotor-nacelle assembly and turbine controller to the tower are also not considered. Lastly, the design of the top tower sections (from interface point, 80 m above ground, to the top flange at 137.04 m above ground) was not optimized or analyzed in detail. This is because this portion of the tower is essentially a monopole tube tower, for which the design is rather trivial and assumed independent of the design of the guyed portion of the tower. Please refer to Appendix 1 for detail on the assumptions for the top tower sections that were necessary for this feasibility study and a brief explanation of their origin.

BOUNDARY CONDITIONS FOR THE GTS DESIGN TASK

The following sections define and explain the basic assumptions and conventions used to design the GTS.

Wind Turbine & Site Specifications

Each tower design is only valid for a certain turbine model and specific site conditions. Following the modern trend of “oversized” rotor diameter vs. nominal power rating and higher hub heights, the “aeroMAster aM 2.5/118” turbine design was selected from aerodyn’s portfolio. Similarly, the chosen wind type and turbulence class (as specified in the GL 2010 Design Guideline [4]) correspond to the increasingly popular market of “low wind” sites. (These locations benefit most from the improved energy yield and cost savings of tall, material-efficient towers such as the GTS.) The main turbine and site specifications are provided in Table 1, below. Further details about the aM 2.5 turbine can be found at aerodyn’s website [5].

Table 1: Turbine & Site Specifications for GTS study

Model	aM 2.5/118
Rated Power	2500 kW
Rotor Diameter	118 m
Wind Type Class	3
Wind Turbulence Class	B
Rated Rotor Speed	12.14 RPM
Cut-in Wind Speed	3 m/s
Rated Wind Speed	9.7 m/s
Cut-out Wind Speed	22.0 m/s
Short-time Cut-out Wind Speed	30.5 m/s
Hub height	140 m
Foundation Ground Spring-Torsional (Rx)	3.0E+14 Nm/rad
Foundation Ground Spring-Bending (Ry, Rz)	3.0E+8 Nm/rad

Material Specifications & Manufacturing Methods

Although some additional cost savings might be possible with composites or high-strength steels, conventional materials and manufacturing methods were chosen for the cable system and tube-like components of the GTS tower. This decision reduces the complexity of the design problem and corresponds with the material choice for similar

guyed wind turbine structures designed by aerodyn, NREL [1], Vergnet [6], and Mervento [7]. A summary of the material properties used in the finite element modeling is provided in Table 2, below.

Table 2: Properties of materials used in the GTS

Constraints & material properties	Maximum allowable stress [Pa]		Density	Young's modulus	Poisson's ratio
	Extreme	Fatigue	[kg/m ³]	[N/m ²]	n/a
Tower segment	3.14E+08	7.10E+07	8.50E+03	2.10E+11	0.3
Strut	3.14E+08	2.29E+08	8.50E+03	2.10E+11	0.3
Cables	1.52E+09	1.04E+08	7.75E+03	1.60E+11	0.3

Note: "PFEIFFER" catalogue reports 1570 MPa instead of 1520 MPa (Fatzer Catalog [8]) for equivalent "VVS 3" cable

Note that the density of the steel has been increased from its typical value of 7.85E+03 kg/m³ to 8.5E+03 kg/m³ to account for the added mass of paint, flanges, fasteners, etc. in the FEM and ASE modeling. This follows the assumption suggested in other feasibility studies [9] to account for the added mass of flanges, fasteners, surfaces coatings, etc.

TUBULAR SECTIONS (TOWER SEGMENTS AND STRUTS)

The tower segments and struts are specified as grade S355 J2G3 steel. This material has become the reference for wind turbine towers because it has an attractive fatigue strength-to-cost ratio, is easily rolled and welded into tubes, and widely and globally available.

WIRE ROPE

The cable system is comprised of wire rope, connecting elements (sockets), and sometimes also tensioning elements (turnbuckles). Only the material properties for the wire rope, however, are relevant for the FE and ASE simulations. This is because the connecting and tensioning elements are relatively short and low-mass compared to the wire rope and designed to exceed the extreme and fatigue strength of the wire rope.

PIN CONNECTIONS FOR CABLES AND STRUTS

All connections are envisioned as bolted joints with 1 degree of freedom in the main direction of rotation, however, this is not very stiff in the other axes of rotation and the structure is modeled as pin joints with all rotational degrees of freedom in the FEM simulations. Sheet metal tabs with extra reinforcement for fretting are envisioned to accept the socket bolts on the mast and the outside ends of the strut. The detailed designs for these connections are out of the scope of this project, however, undimensioned drawings describing the general concepts are provided in Appendix 5.

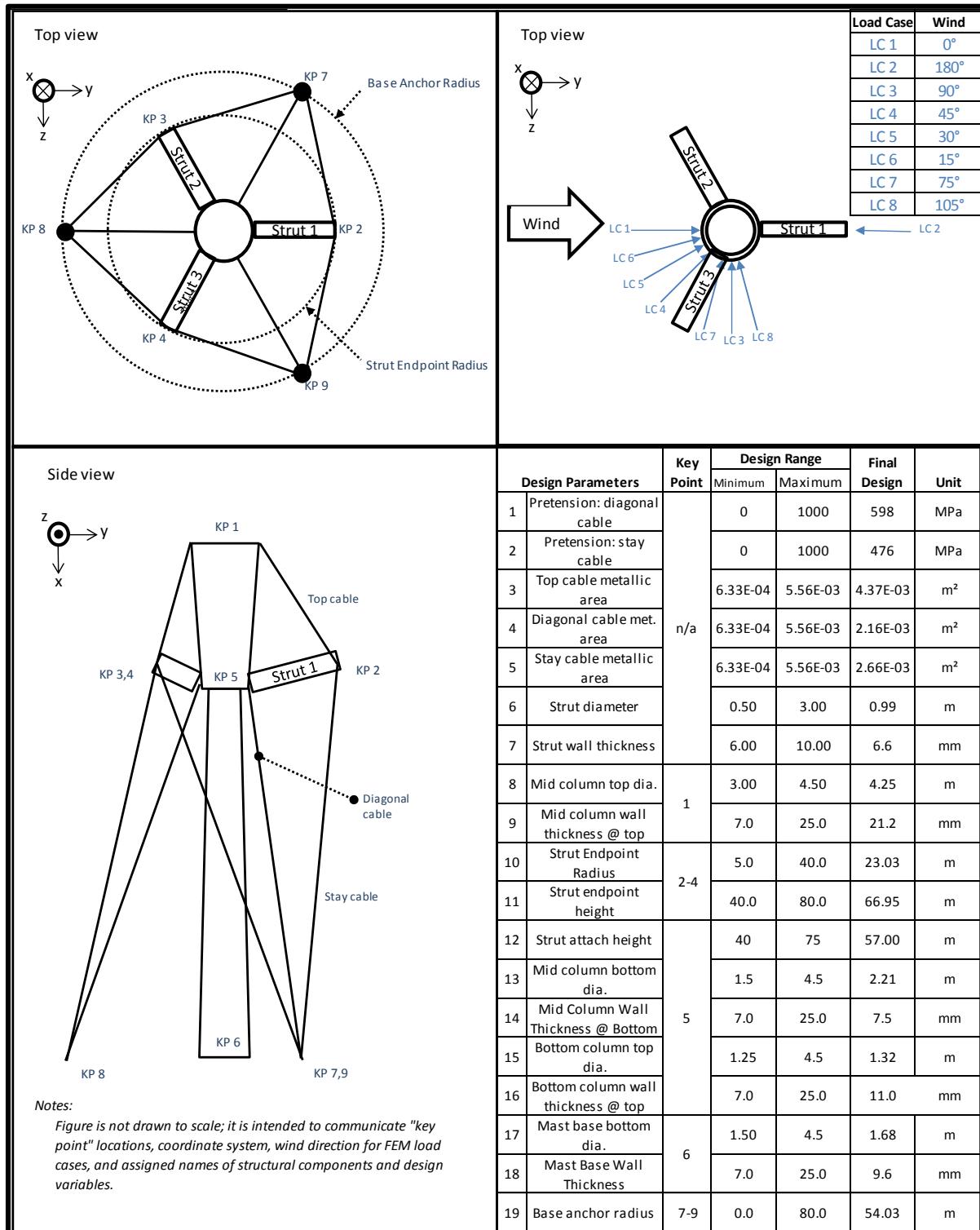
Design Variable Selection

A total of 19 parameters are considered within the scope of the design problem. They are located and listed in Figure 4, below, together with the associated upper and lower bounds and the values of the final design. The inclusion of any more parameters would greatly increase the complexity of the design problem. Accordingly, reducing the number of design variables could result in heavier, more expensive tower designs due to an insufficient number of degrees of freedom for optimizing the stiffness and material distribution in the design.

Careful attention is paid to selecting bounds that were sufficiently large to capture a wide range in design topology (to increase the chance of finding the global optimum configuration) without allowing for designs that are unpractical or obviously a poor use of material. The minimum section diameters for the mast, for example, must be large enough to allow human access for maintenance yet the maximum diameter is constrained to 4.5m for easier overland transport. The struts have smaller loads and do not require human access, allowing for smaller dimensions, whereas the optimal mast dimensions just below the top guy attachment are known to be in a range near those for the unsupported monopole tower section just above that location.

Note that the optimum design values are not at any of the variable bounds. Although this does not prove that the variable bounds were chosen large enough to capture the global design, if one of the variables were at the limit for the optimum design, it would imply that the design is constrained to a suboptimal-cost configuration due to the parameter limits.

Figure 4: Final Optimized Design Parameters for GTS Study



OPTIMIZATION-BASED DESIGN METHOD

The challenge of finding an optimized design among the numerous possibilities was overcome with a new and unique, fully-automated parameter study tool developed by Rudolf [10]. It enabled the rapid analysis of thousands of potential GTS designs selected using optimization algorithms with the objective of minimizing tower cost.

Cost-based Objective Function

Although the simplest structural optimization efforts concentrate on minimizing mass, the expensive cables and connecting elements in guyed towers necessitate a cost-based approach. This accounts for the difference in mass-specific cost between the wire rope and the S355 steel as well as the cost of the open-spelter sockets, which is a function of cable area (not volume).

Following the assumption made in the Elforsk study [9], a specific cost of 2.3 €/kg was used to assess the cost of all tube sections. This accounts for material and value-added manufacturing cost, as well the cost of fasteners, flanges and coatings. Note that the cost is also influenced by the increased density assumption of 8500 kg/m³ (vs. 7850 kg/m³) for the S355 components explained in the material properties section. Both the density and the specific cost is taken from the Elforsk study, however, so the specific cost is assumed to be calibrated for the increased density.

The wire rope and socket costs are calibrated from a small matrix of quoted diameters and lengths provided by the sales department at Fatzer AG in 2013 (for reference only). The rope cost was assumed to be linearly correlated to length, and both the rope cost and socket cost were found to have similar respective costs per unit metallic area over the quoted range of rope diameters. This coincided with the minimum and maximum bounds assigned to the metallic area design parameters. The rope and socket cost are calculated using linear terms equivalent to the average rope and cable costs per metallic area (with no constant terms).

The assumptions within the cost-based objective function can be referenced in Table 3, below, which also summarizes the mass and cost of the constituent components of the final design.

Table 3: Mass and cost summary of final GTS design

Costs	Total	Diag	Stay	Top
Cable Area (mm2)	n/a	2159	2661	4372
Cable Length, each (m)	n/a	78.5	85.7	26.5
Rope Cost (€/mm3 cable volume)	n/a	0.0000356	0.0000356	0.0000356
Rope Cost, each (€)	n/a	6039	8,123	4,120
Socket Cost, each (€/mm2 cable area)	n/a	1.172	1.172	1.172
Socket Cost, each (€)	n/a	2530	3118	5123
# Cable Sets per tower	12	3	6	3
Rope Cost	79213	18117	48735	12361
Socket Cost	83334	15182	37416	30736
Total Cable System Cost (=Ropes + Sockets)	162547	33299	86151	43097

Mass	Total	Diag	Stay	Top
Rope Mass (kg/mm3 cable volume)		8.35E-06		
Rope Mass, each	n/a	1416	1904	966
Socket Mass, each	n/a	87	116	230
Rope Mass, tons	19	4.2	11.4	2.9
Socket Mass, tons	3	0.5	1.4	1.4
Total Cable System Mass in tons	22	4.8	12.8	4.3

Mass & Cost Summary	Mass (kg)	Cost (€)
Tower Mast (ground to 80m)	52,062	119,742
Struts	12,987	29,871
Cabel System	21,857	162,547
Substructure Subtotal (ground to 80m)	86,906	312,160
Tower Top (80m to top flange)	112,902	281,176
Total Tower (ground to top flange)	199,808	593,336

Stress Constraint Evaluation

The constraints used to evaluate the feasibility of each design were limited to the allowable stresses in the guyed portion of the tower; they were evaluated using static FEM under both fatigue and extreme load cases and multiple wind directions. As seen in Figure 4 (previous section), 8 wind directions were considered. These load cases cover every wind direction with a 15 degree resolution due to the 120 degree rotational symmetry of the GTS structure.

The stresses in each cable, the maximum stress for all section points in each strut, and the maximum stress for elements at specific positions in the structure are automatically extracted for each load case. (Refer to Table 7 in Appendix 4 for example stress constraint evaluation data.)

The axial stress in each cable element was constrained to be positive (to prevent slack cables) and below the allowable yield stress for all extreme load cases. The Mises stress criterion was used to evaluate the extreme stress constraint for the struts, bottom column, and mid column.

The stresses for the fatigue load cases were evaluated based on their magnitude of deviation from the stresses in the “apply preload” load case, for which only gravity and pre-tension loads act on the structure. This corrects for the mean-stress level induced by these static forces. Note that the allowable equivalent fatigue stress is higher for the struts than for the bottom and mid columns of the guyed mast. This is because the “no-compression” (positive axial stress) constraint on the cables forces the strut to remain in compression. Therefore the strut material receives the fatigue stress bonus permissible in the applicable design codes.

Load Calculation

The applied loads were calculated from the reduced mass and stiffness matrices of the guyed tower FEM model using a neural network (NN) approximation. The NN was calibrated by a parameter study of the “aeroFlex” aero-servo-elastic (ASE) load simulation model. This method, termed the “Reduced-Order Structural Surrogate” or “ROSS” approach, was developed by Rudolf for the GTS design task and introduced at the Wind Structures group in the 2015 World Congress for Structural Optimization in Sydney [10]. The ROSS method and optimization process will be documented in detail in Rudolf’s EKSH-funded Ph.D. dissertation.

OPTIMIZATION

The design process is conducted following the “improved method” depicted in Figure 5, below. It incorporates the ROSS accelerated load calculation together with a fully-automated workflow and optimization algorithms. In this way, brute computing power is used to rapidly explore promising regions of the design space, orders of magnitude faster than possible without the automation and algorithms. Without ROSS, such a massive parameter study is wholly impractical because the data would either be (1) too inaccurate under the static loads assumption or (2) too computationally expensive to generate using standard ASE simulations.

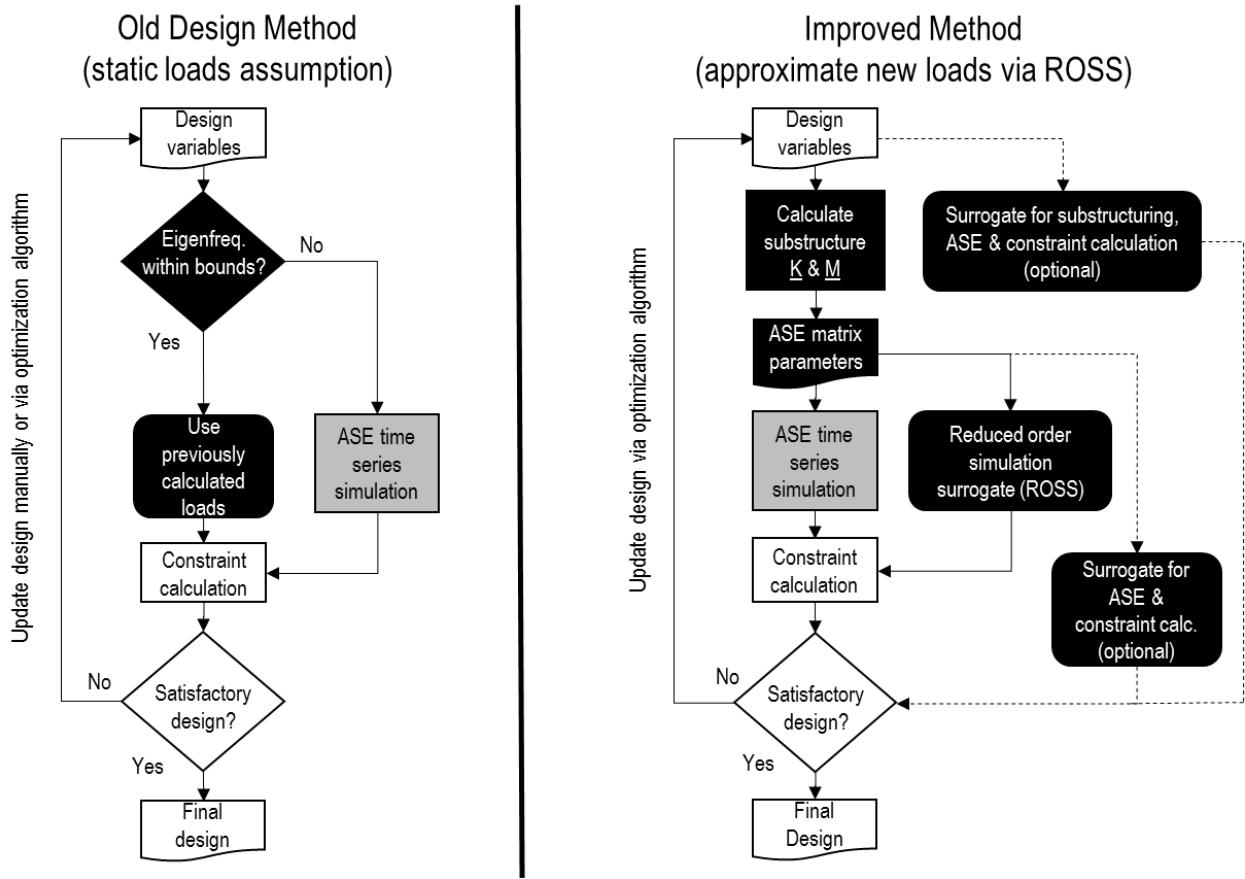


Figure 5: Wind turbine optimization process flow (with vs. without ROSS)

The optimization was implemented using iSight optimization software. Each integration of the design loop takes approximately 20 seconds using a standard business laptop equipped with an Intel Core i7 2 GHz CPU and 10 GB RAM.

Although it may likely be possible to apply a single algorithm or simple, predefined strategy to automatically arrive at a better design in less time, the GTS design presented in this work was developed using less elegant processes. Due to the realities of bugs in the new process and time constraints, a series of parameter studies was executed using Design of Experiments techniques in addition to algorithm-driven stochastic, deterministic, and hybrid search strategies. At each step the dataset was mined and engineering intuition was applied to refine the bounds of the design space and modify the search technique. In this manner, tens of thousands of tower design candidates were evaluated using the accelerated and enhanced “improved Method” enabled via ROSS to arrive at feasible, refined design. In addition to the impressive mass and cost of the final configuration, the efficacy of this new design method is evident in the high level of material utilization (as seen in Table 4, below).

Table 4: Material utilization of final GTS design at select hot spot locations

Summary	Load Case	Wind angle	Mast Base	Mast Midway Below Strut	Mast Below Strut	Mast Above Strut	Mast Midway between Strut	Mast Below Top Cable	All Struts Max	All Top Cables max	All Stay Cables max	All Diag. Cables max	All Top Cables min	All Stay Cables min	All Diag. Cables min
Pretension Stress	194	200	210	69	28	15	186	571	476	598	571	476	598	571	476
PT vs. Yield Stress	62%	64%	67%	22%	9%	5%	59%	38%	31%	39%	38%	31%	39%	38%	31%
PT vs. Fatigue Ref.	273%	282%	296%	97%	39%	21%	81%	549%	458%	575%	549%	458%	575%	549%	458%
Extreme	1	0°	87%	91%	90%	75%	93%	69%	68%	60%	50%	42%	13%	11%	34%
	2	180°	87%	91%	92%	74%	92%	69%	79%	54%	47%	54%	8%	6%	15%
	3	90°	87%	91%	92%	75%	93%	69%	92%	63%	54%	56%	14%	12%	15%
	4	45°	88%	92%	95%	63%	70%	51%	74%	53%	45%	58%	8%	6%	17%
	5	30°	87%	93%	95%	69%	82%	61%	81%	59%	49%	61%	9%	7%	20%
	6	15°	86%	93%	94%	73%	90%	67%	86%	63%	53%	63%	13%	10%	25%
	7	75°	88%	89%	92%	73%	90%	67%	87%	60%	51%	51%	10%	8%	14%
	8	105°	85%	93%	94%	73%	90%	67%	93%	65%	55%	60%	20%	16%	18%
Fatigue	1	0°	9%	15%	12%	53%	62%	47%	33%	91%	71%	66%	17%	4%	27%
	2	180°	9%	15%	12%	53%	62%	47%	45%	89%	83%	65%	19%	20%	28%
	3	90°	9%	15%	12%	53%	62%	47%	35%	92%	84%	59%	32%	37%	6%
	4	45°	8%	13%	11%	54%	64%	49%	33%	86%	75%	61%	5%	1%	12%
	5	30°	9%	13%	11%	51%	57%	43%	32%	94%	72%	60%	30%	21%	5%
	6	15°	9%	15%	12%	48%	53%	40%	31%	95%	74%	65%	41%	24%	22%
	7	75°	9%	15%	11%	55%	67%	51%	32%	94%	87%	64%	43%	40%	23%
	8	105°	9%	15%	12%	49%	53%	40%	38%	84%	77%	62%	8%	17%	11%
All load cases			88%	93%	95%	75%	93%	69%	93%	95%	87%	66%	8%	6%	14%

Note: all stresses reported in MPa.

VERIFICATION OF THE FINAL DESIGN

Although the best feasible design produced by the aforementioned process meets cost and material-savings goals without violating optimization constraints, three additional analysis were completed before the design is ready for C-design assessment:

1. Verification of approximated quasi-static fatigue and extreme loads using ASE analysis—instead of neural network approximation—using the reduced mass and stiffness matrices from the proposed design and the entire set of design load cases specified in IEC 61400 design standard.
2. Verification of stresses in guyed tower under fatigue and extreme load cases using loads from (1)
3. Verification that the results from (1) are acceptable for the rotor and nacelle assembly.

ESTIMATED SAVINGS VS. CONVENTIONAL TOWERS

A simplified cost and GHG emission savings is estimated based solely on the material savings of the GTS concept. The main assumption is that the GHG emissions in the supply chain (processing and transport) are proportional to the material mass. Although the cable system likely has different emissions per mass than the tubular tower sections, the mass of the cable system is an order of magnitude smaller than the tubular tower sections, limiting the influence of this assumption on the estimated savings. Comparing the calculated 200 ton mass of the GTS tower (described in Table 3) with the estimated 500 ton mass of an equivalent steel monopole tower (refer to Appendix 1) suggests that the GTS has potential for 60 % reduction in tower-related GHG emissions.

The aforementioned 60 % mass savings may be less once the details such as the flanges, door opening, platforms, ladders, etc. are included in a subsequent, detailed final design. These are somewhat offset, however, by the 8.2 % increased density assumption (explained above in the material specification section). A bigger source of error in the savings calculation is the mass of the equivalent monopole tower. This was not designed in detail, rather, extrapolated using a polynomial regression from an existing design. As a lower bound (for a conservative savings estimation), a 400 ton equivalent monopole tower is considered for comparison. The resulting 200 ton material savings represents a realistic 50 % tower mass and associated GHG emissions reduction.

Using the cost models explained previously, the material cost of the GTS tower is 593 t€ and the 400 ton reference tower is conservatively calculated to be 55 % more expensive at 920 t€. Although the additional fabrication and assembly cost of the GTS might eat into these savings, these costs would likely be offset by reduced logistics costs (due to less mass and smaller dimensions), especially for the foundation. Although the foundation design of the GTS is out of scope, guyed towers are known to have substantially more economical foundations. For example, the foundation for a guyed tower without strut manufactured by Mervento in Finland (3.6 MW, 125 m hub height, 118 m rotor diameter, wind class IEC IIA [11]) is only 535 tons [7], whereas a standard slab foundation for a similar wind turbine typically requires ca. 5 times more steel-reinforced concrete [9]. Thus, the GTS concept has attractive economic and GHG emissions savings potential.

CONCLUSION

The basic design is presented for a GTS prototype for a modern utility-scale wind turbine. The main geometry and cross-sectional parameters are specified so that an accurate assessment of the material savings is possible. These values were carefully optimized to meet industry design standards with a minimum-cost configuration, to identify the maximum potential of the GTS concept. The conservatively-estimated 50 % material savings meet the initial estimate and is highly encouraging; it is recommended that a full-scale prototype should be designed in detail and constructed as a proof of

concept to validate and market the material, cost, and GHG emissions potential of the GTS.

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APPENDIX 1: DESIGN OF GTS TOP SECTIONS

(portions above top guy attachment location)

For ASE simulation and cost estimation purposes, an existing aeroMaster 2.5 tower design for 90 m hub height and wind class TC3A was truncated from the bottom to the appropriate height of the “top section.” The table on the following page documents the diameter, thickness, and mass distribution of the baseline and truncated towers. Note that the baseline tower is limited in diameter from 67 m below hub height to ground level. Fortunately, the truncated tower has a maximum thickness of 4.05 m (and is therefore not limited by transport constraints to a suboptimal diameter with reduced structural efficiency). As with the mast and struts of the GTS, the material for the top sections is also S355, however, with assumed density of 7.85 kg/m³.

The baseline tower is also used to estimate the mass of a taller (140 m hub height) tower for cost and mass comparisons against the GTS. Considering that such a tall tower would be limited to a maximum diameter for transport reasons, the baseline design is extended using the diameter-limited curve fit from the data points more than 67 m below hub-height using a second-order polynomial regression of the baseline tower. As shown in Figure 6, below, the resulting mass is 496 tons. Accordingly, the cost is 1.14 M€ using the same 2.3 €/kg assumption explained in the GTS cost model.

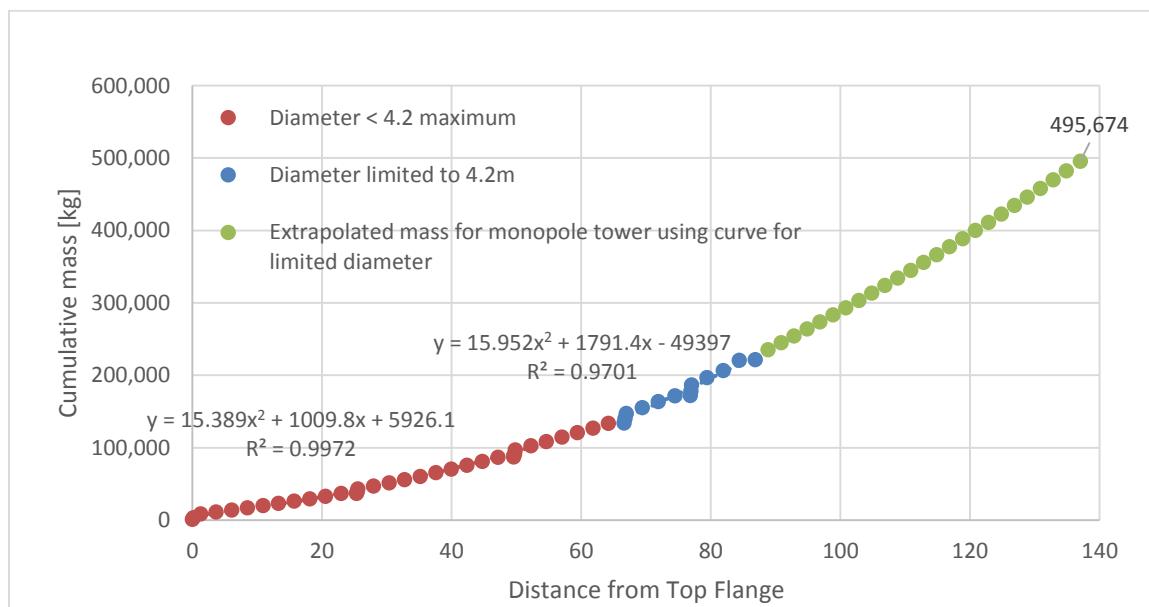
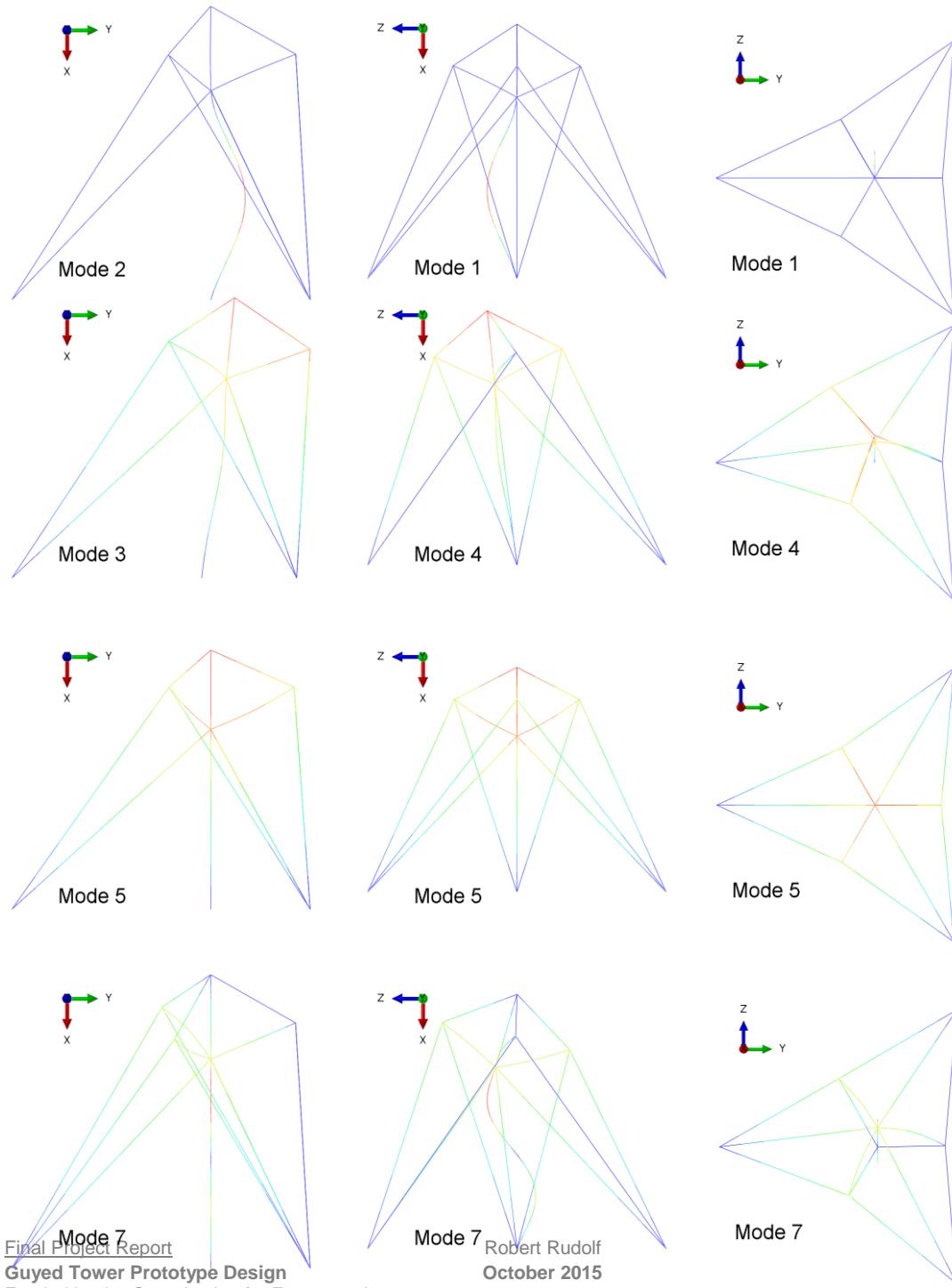


Figure 6: Extrapolation of baseline monopole tower mass to 140 m hub height

APPENDIX 2: EIGENFREQUENCY & EIGENFORM ANALYSIS

The Abaqus FEM solver was used to calculate the eigenfrequencies and modes of the GTS substructure (ground to top guy). NOTE: Analysis is without equivalent point mass/inertia representing tower & Rotor-Nacelle assembly.



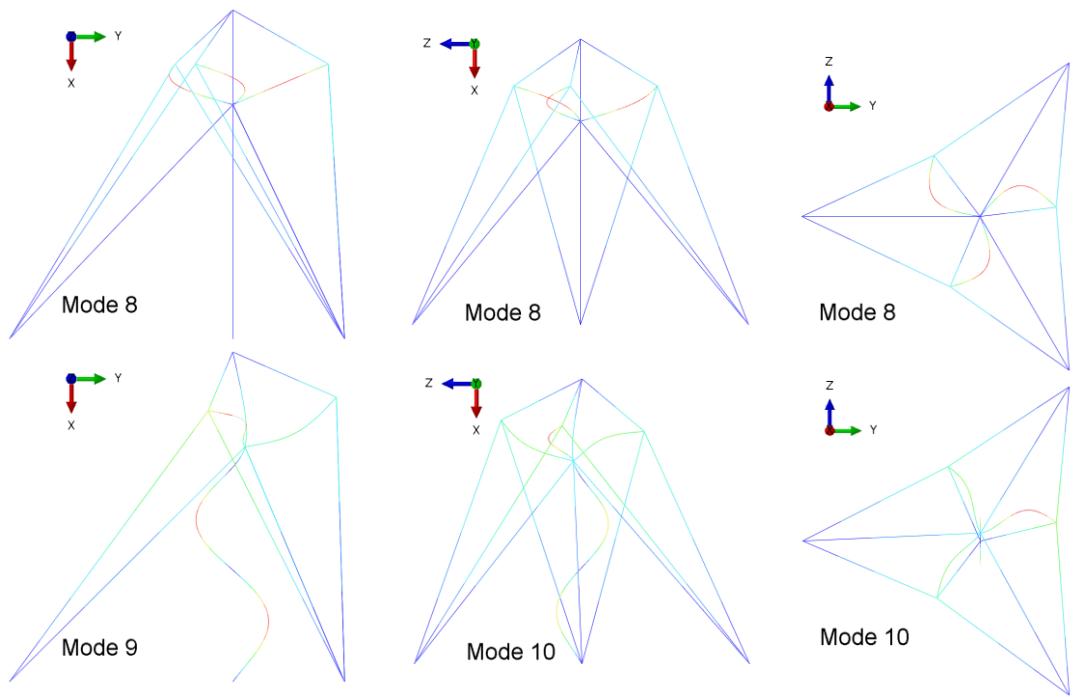


Figure 7: Normalized displacement plots of GTS substructure eigenforms

Table 6: Wind turbine component excitation frequencies calculated using aeroFLEX

Load Case	Unit	A	B	C	D	E	F	G	H	I
WindSpeed	[m/s]	26.25	3	4.675	6.35	8.025	9.7	13.8	17.9	22
PitchAngle	[°]	28.791	0	5.542	8.131	10.205	12.172	16.692	20.964	24.963
Rotorposition	[°]	0.192	0.187	0.216	0.284	0.193	0.086	0.166	0.248	9.597
RotorSpeed	[rpm]	13.012	9.114	13.006	13.005	13.009	13.007	13.011	13.015	12.996
1P	[Hz]	0.217	0.152	0.217	0.217	0.217	0.217	0.217	0.217	0.217
3P	[Hz]	0.651	0.456	0.65	0.65	0.65	0.65	0.651	0.651	0.65
6P	[Hz]	1.301	0.911	1.301	1.301	1.301	1.301	1.301	1.302	1.3
Found:u_x	[Hz]	3.855	3.848	3.847	3.847	3.847	3.848	3.849	3.851	3.853
Found:u_z	[Hz]	1.01	0.969	0.975	0.98	0.983	0.986	0.993	0.999	1.005
Found:fi_y	[Hz]	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249
Found:u_y	[Hz]	0.913	0.898	0.897	0.896	0.895	0.893	0.895	0.918	0.915
Found:fi_z	[Hz]	0.251	0.251	0.251	0.251	0.251	0.251	0.251	0.251	0.251
Found:fi_x	[Hz]	0.437	0.43	0.43	0.43	0.431	0.431	0.432	0.433	0.435
Tower:Long1	[Hz]	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249	0.249
Tower:Long2	[Hz]	7.684	7.648	7.649	7.651	7.653	7.655	7.661	7.668	7.676
Tower:Lat1	[Hz]	3.461	3.434	3.436	3.437	3.437	3.438	3.441	3.445	3.451
Tower:Lat2	[Hz]	8.274	8.276	8.277	8.277	8.276	8.276	8.276	8.275	8.274
TwrNac:yaw	[Hz]	12.137	12.113	12.114	12.115	12.116	12.118	12.122	12.126	12.132
Shaft:rot	[Hz]	0	0	0	0	0	0	0	0	0
Blade1:1-flap1	[Hz]	0.633	0.628	0.628	0.628	0.628	0.629	0.63	0.631	0.632
Blade1:1-flap2	[Hz]	1.78	1.768	1.768	1.768	1.768	1.768	1.76	1.738	1.778
Blade1:1-edge1	[Hz]	1.01	0.95	0.941	0.936	0.932	0.929	0.993	0.999	1.005
Blade1:1-edge2	[Hz]	2.841	3.035	3.049	3.062	3.076	3.092	2.874	2.864	2.854
Blade2:2-flap1	[Hz]	0.699	0.667	0.668	0.67	0.671	0.673	0.678	0.684	0.691
Blade2:2-flap2	[Hz]	2.366	1.827	1.818	1.809	1.802	1.794	1.779	2.44	2.4
Blade2:2-edge1	[Hz]	0.826	0.923	0.918	0.913	0.907	0.902	0.895	0.862	0.844
Blade2:2-edge2	[Hz]	2.841	2.873	2.877	2.879	2.88	2.879	2.874	2.864	2.854
Blade3:3-flap1	[Hz]	0.699	0.667	0.668	0.67	0.671	0.673	0.678	0.684	0.691
Blade3:3-flap2	[Hz]	1.78	1.827	1.818	1.809	1.802	1.794	1.779	1.777	1.778
Blade3:3-edge1	[Hz]	0.826	0.923	0.918	0.913	0.907	0.893	0.88	0.862	0.844
Blade3:3-edge2	[Hz]	3.289	2.873	3.049	3.062	3.076	3.092	3.139	3.189	3.242
Shaft:tors	[Hz]	1.106	1.109	1.109	1.109	1.109	1.109	1.109	1.108	1.107

APPENDIX 3: FEM STRESS VISUALIZATIONS

The following stress visualization plots are organized per load case. Refer to Figure 4 for a definition of which wind directions correspond to which load case numbers. The Mises stress values are intended for the struts and mast and are therefore calibrated to 314 MPa. The S11 axial stresses plots are intended for the cables (because Mises stress criterion would show compressive stresses as positive values). Recall that the stresses in the “Fatigue” load case plots are not corrected for the static mean stress level effects of gravity and pre-stress loads; they can only be referenced against the allowable fatigue stress after subtracting the corresponding element stresses in the “apply preload” step (shown directly below).

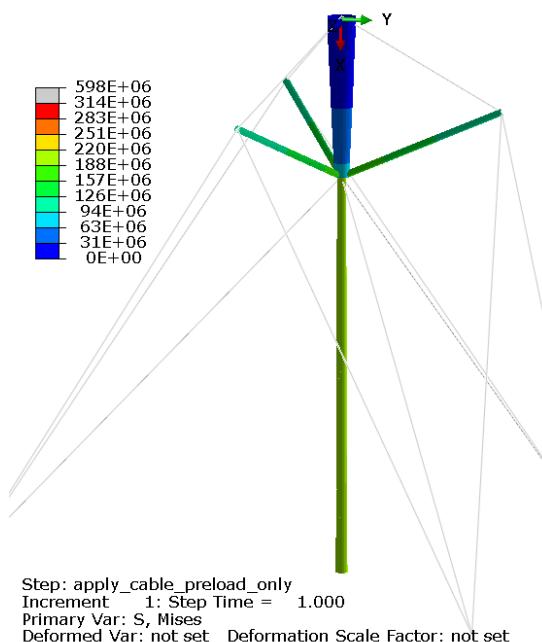


Figure 8: Apply Preload Mises

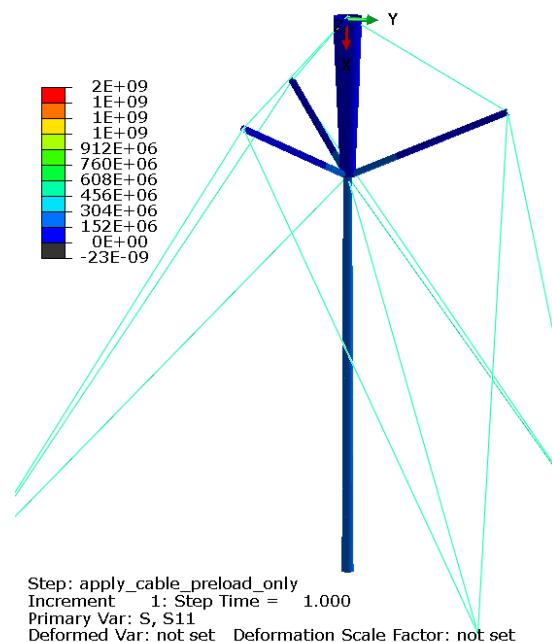


Figure 9: Apply Preload S11

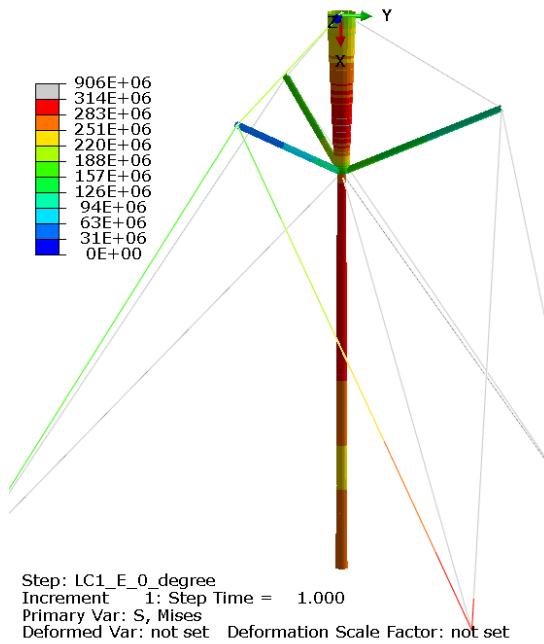


Figure 10: LC 1 Extreme Mises

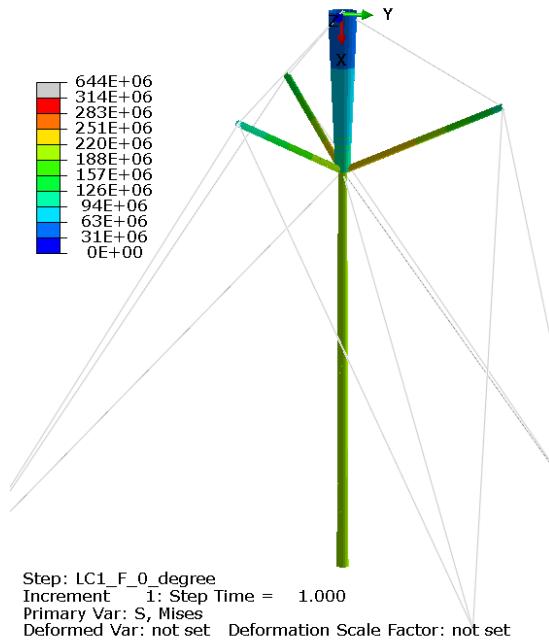


Figure 11: LC 1 Fatigue Mises

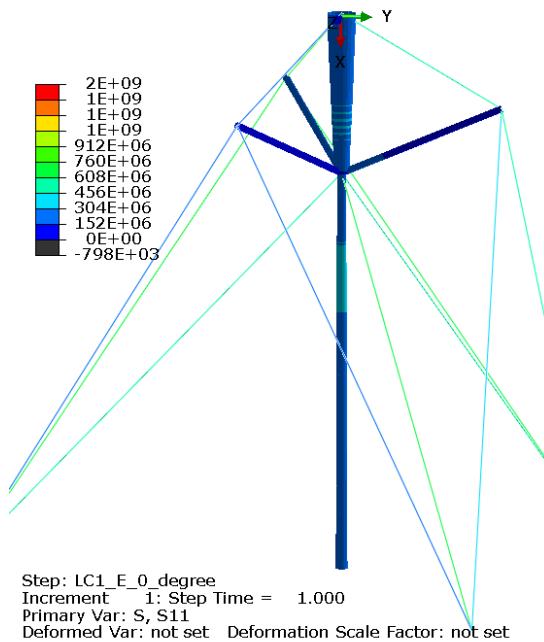


Figure 12: LC 1 Extreme S 11

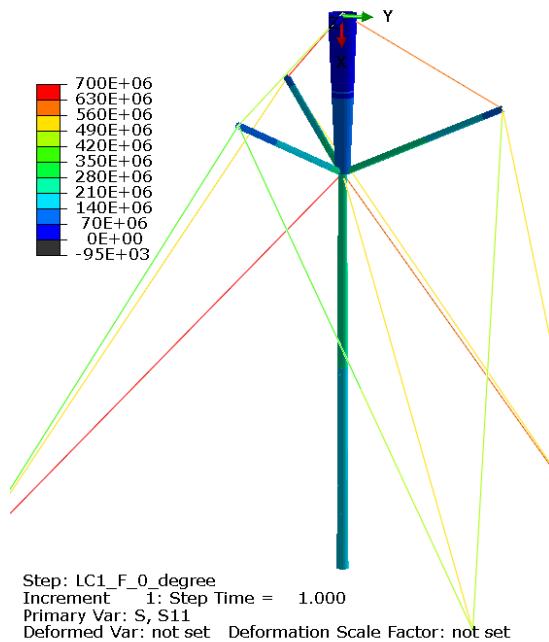
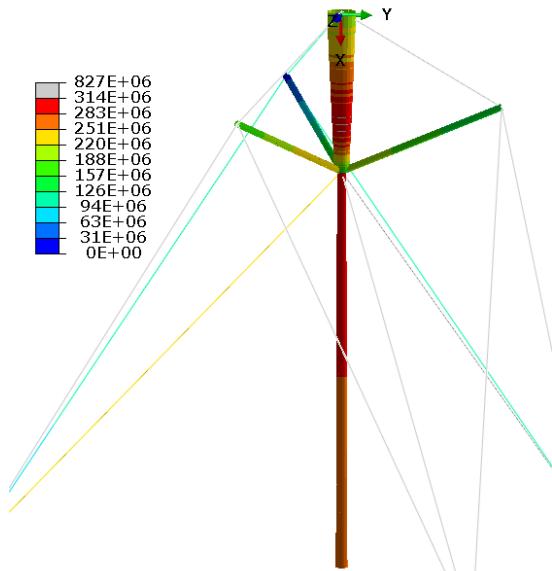
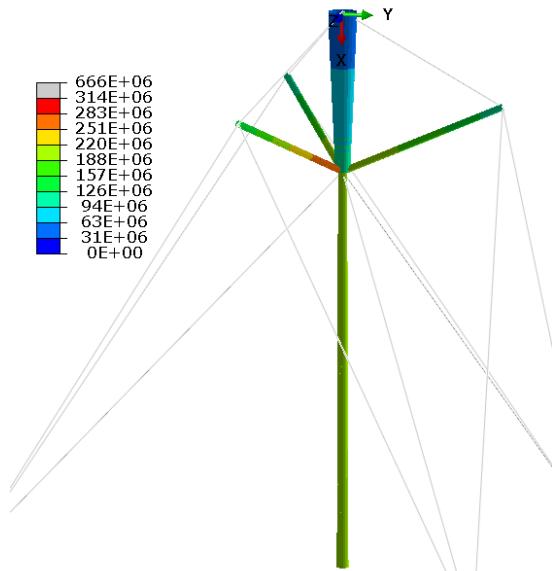


Figure 13: LC 1 Fatigue S 11



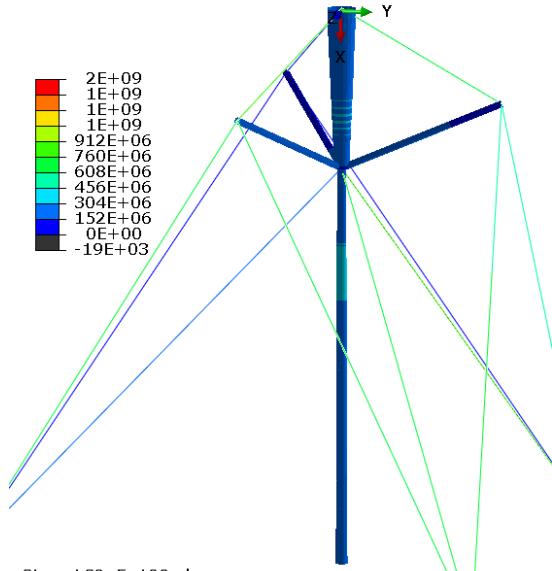
Step: LC2_E_180_degree
Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: not set Deformation Scale Factor: not set

Figure 14: LC 2 Extreme Mises



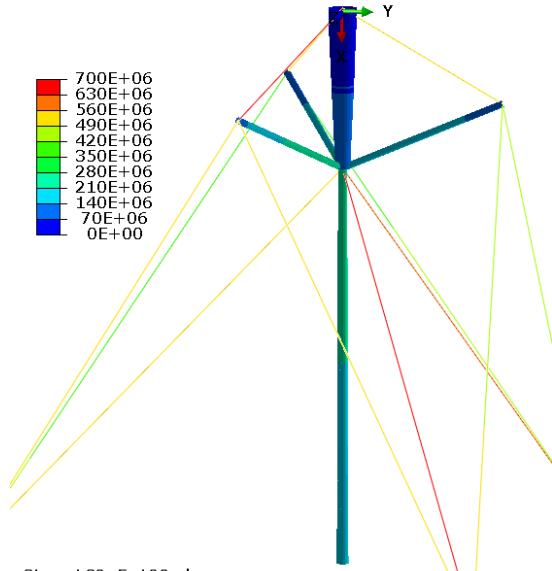
Step: LC2_F_180_degree
Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: not set Deformation Scale Factor: not set

Figure 15: LC 2 Fatigue Mises



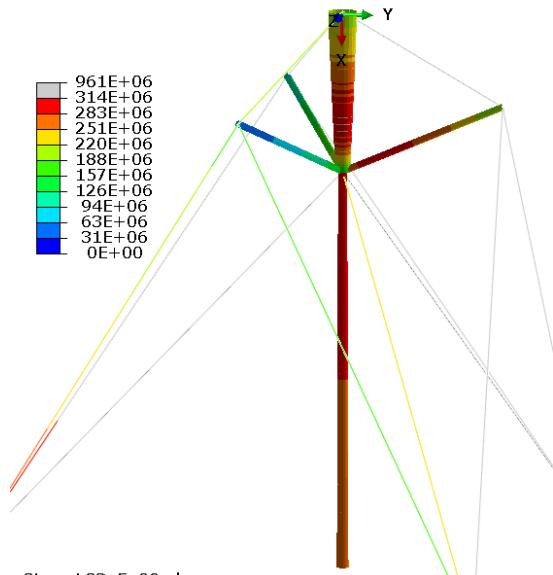
Step: LC2_E_180_degree
Increment 1: Step Time = 1.000
Primary Var: S, S11
Deformed Var: not set Deformation Scale Factor: not set

Figure 16: LC 2 Extreme S 11



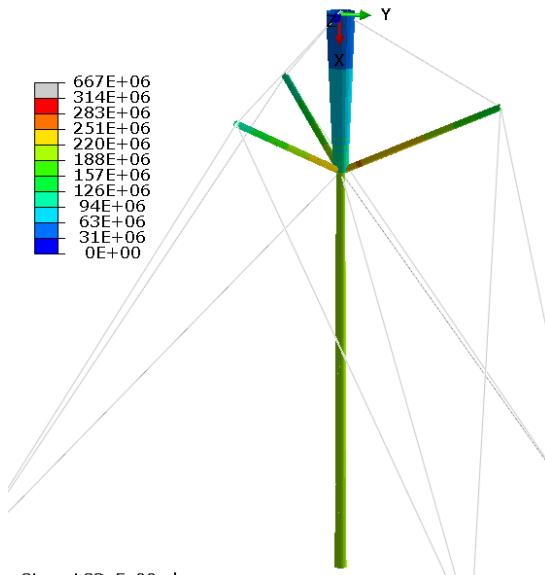
Step: LC2_F_180_degree
Increment 1: Step Time = 1.000
Primary Var: S, S11
Deformed Var: not set Deformation Scale Factor: not set

Figure 17: LC 2 Fatigue S 11



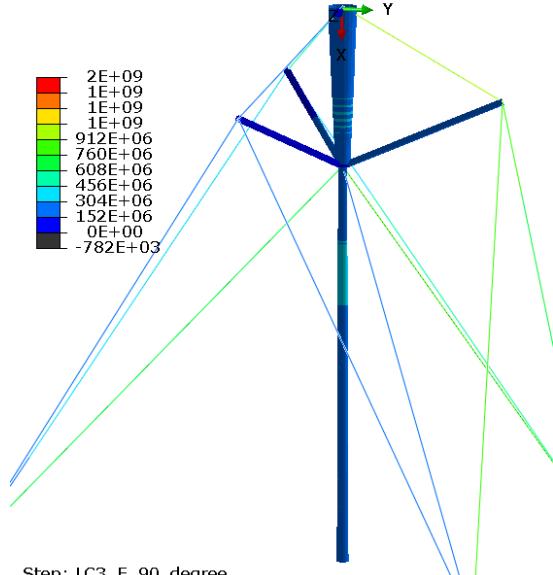
Step: LC3_E_90_degree
Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: not set Deformation Scale Factor: not set

Figure 18: LC 3 Extreme Mises



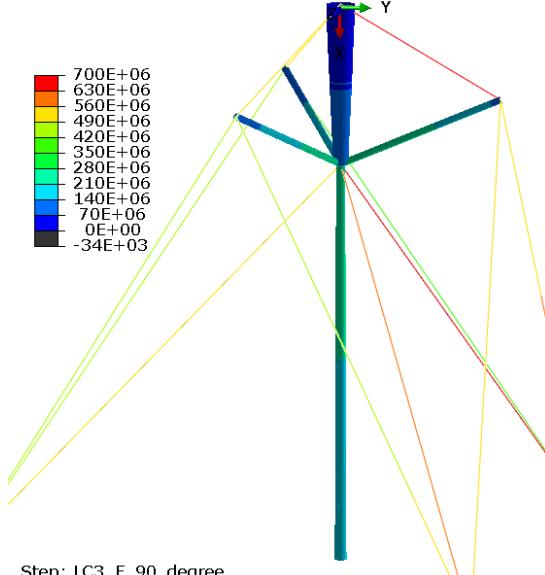
Step: LC3_F_90_degree
Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: not set Deformation Scale Factor: not set

Figure 19: LC 3 Fatigue Mises



Step: LC3_E_90_degree
Increment 1: Step Time = 1.000
Primary Var: S, S11
Deformed Var: not set Deformation Scale Factor: not set

Figure 20: LC 3 Extreme S 11



Step: LC3_F_90_degree
Increment 1: Step Time = 1.000
Primary Var: S, S11
Deformed Var: not set Deformation Scale Factor: not set

Figure 21: LC 3 Fatigue S 11

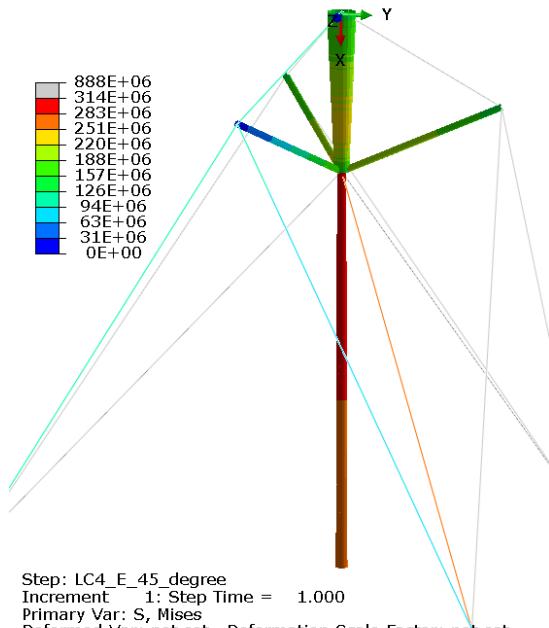


Figure 22: LC 4 Extreme Mises

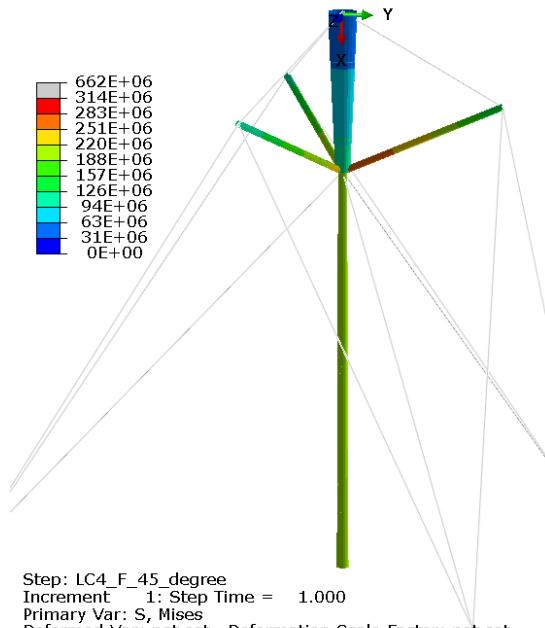


Figure 23: LC 4 Fatigue Mises

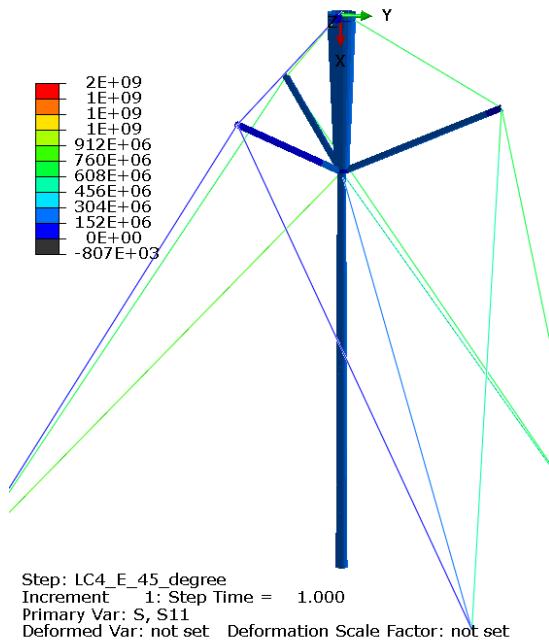


Figure 24: LC 4 Extreme S 11

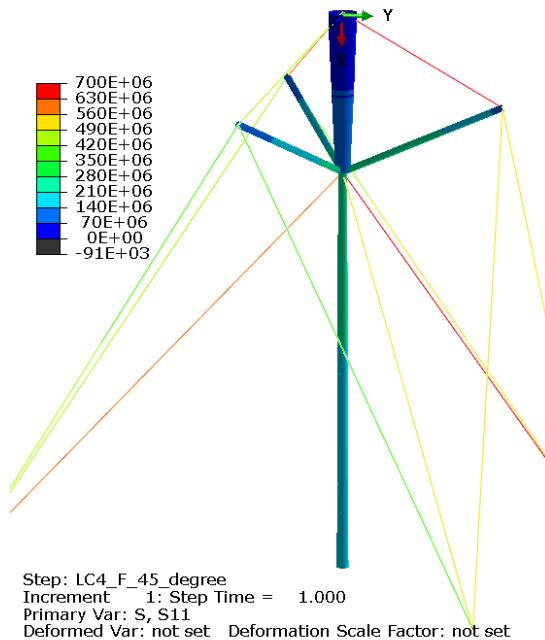


Figure 25: LC 4 Fatigue S 11

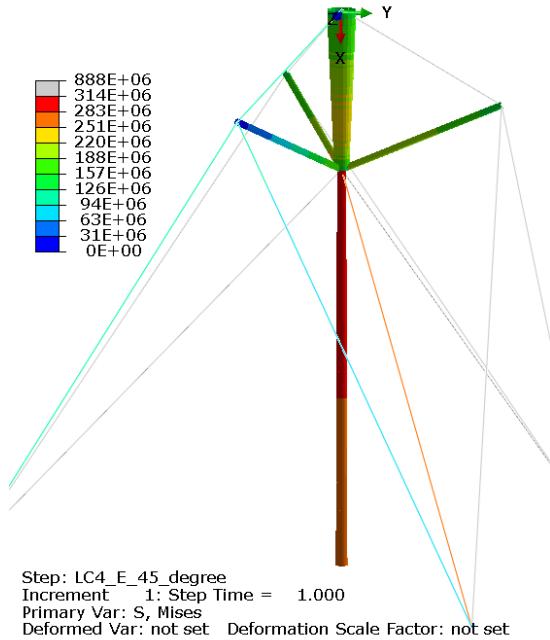


Figure 26: LC 5 Extreme Mises

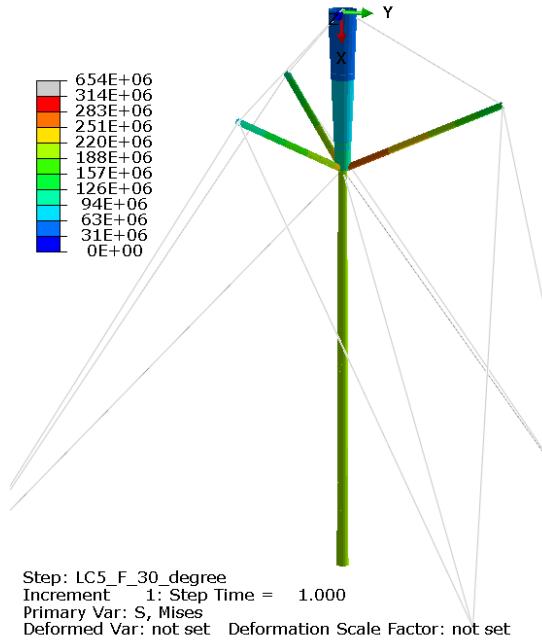


Figure 27: LC 5 Fatigue Mises

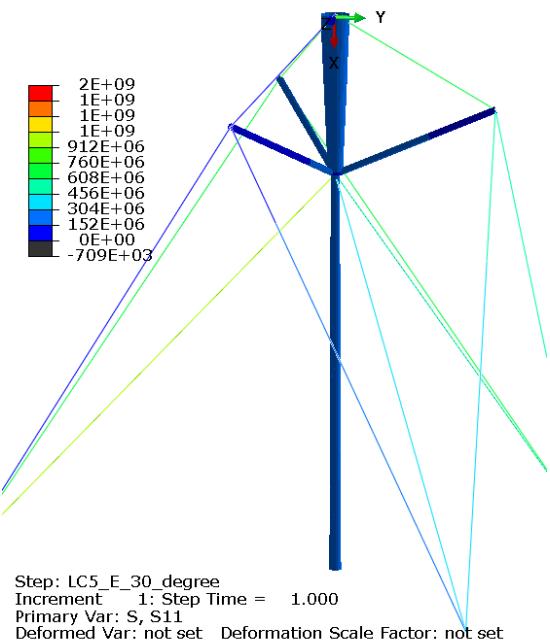


Figure 28: LC 5 Extreme S 11

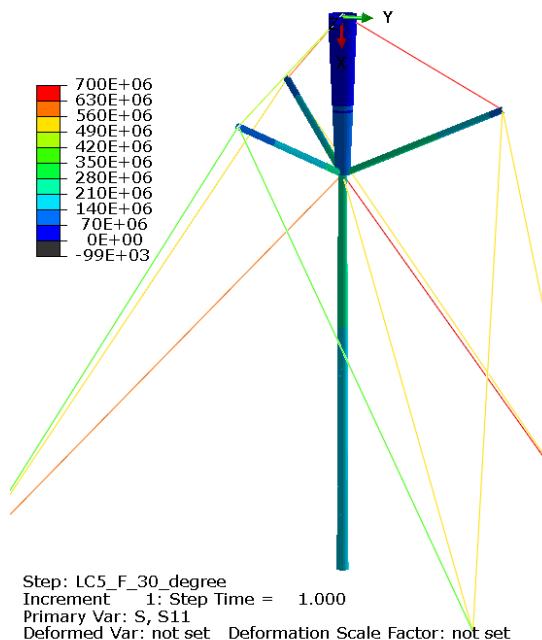


Figure 29: LC 5 Fatigue S 11

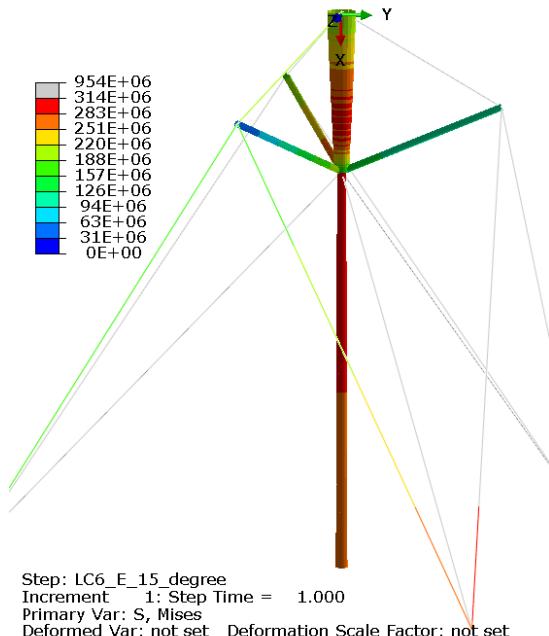


Figure 30: LC 6 Extreme Mises

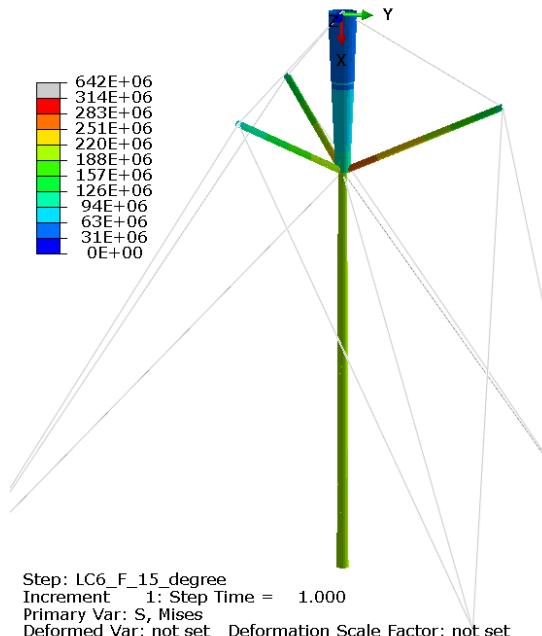


Figure 31: LC 6 Fatigue Mises

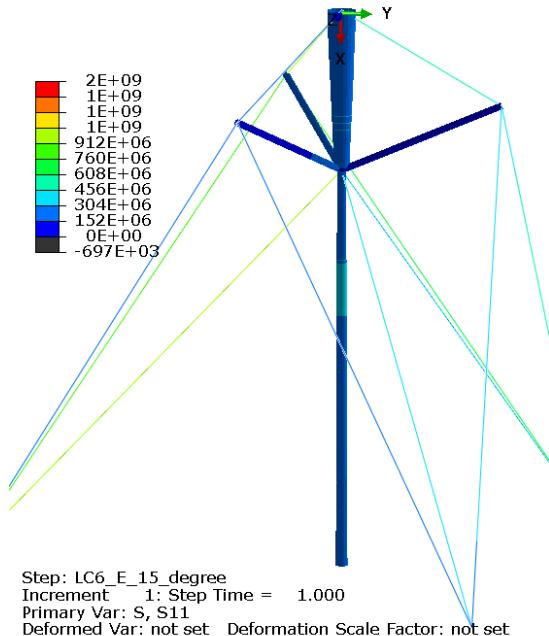


Figure 32: LC 6 Extreme S 11

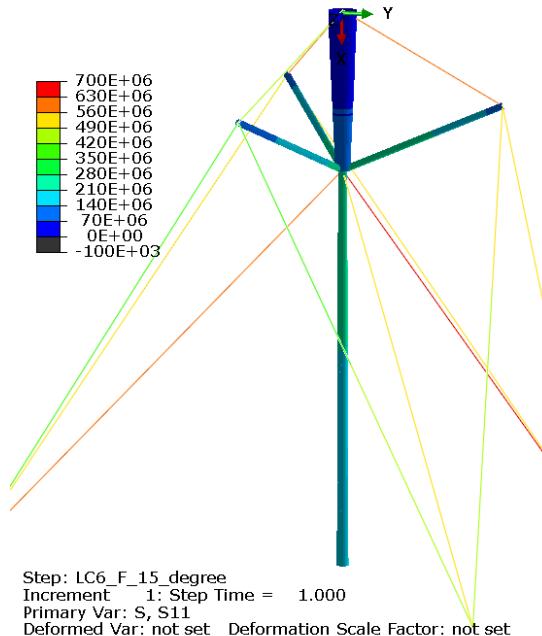
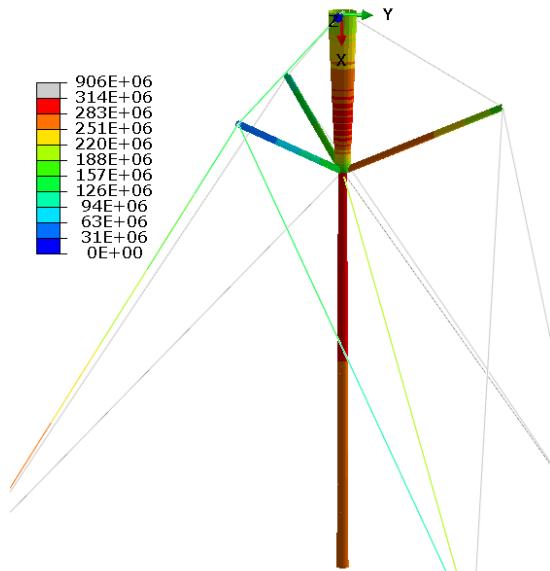
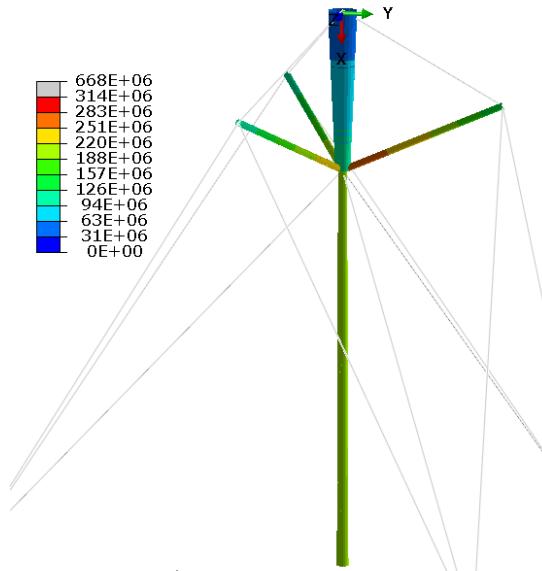


Figure 33: LC 6 Fatigue S 11



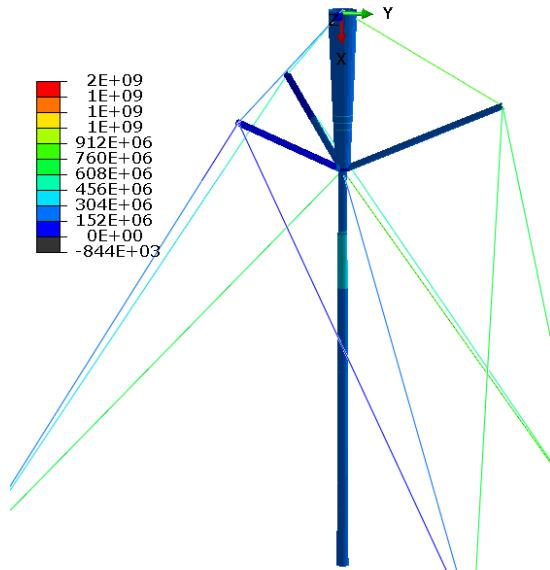
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Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: not set Deformation Scale Factor: not set

Figure 34: LC 7 Extreme Mises



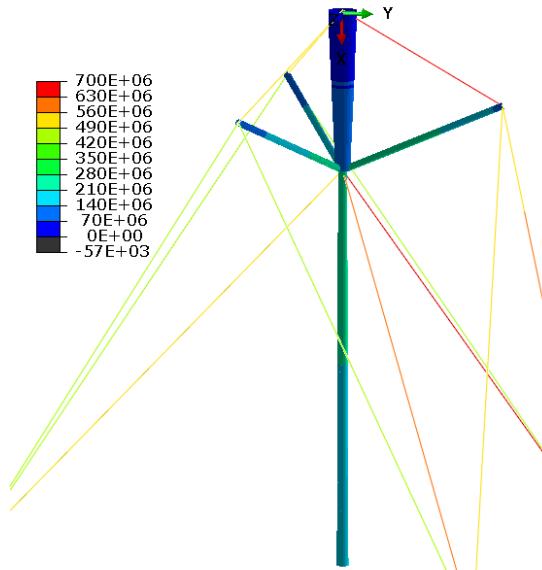
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Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: not set Deformation Scale Factor: not set

Figure 35: LC 7 Fatigue Mises



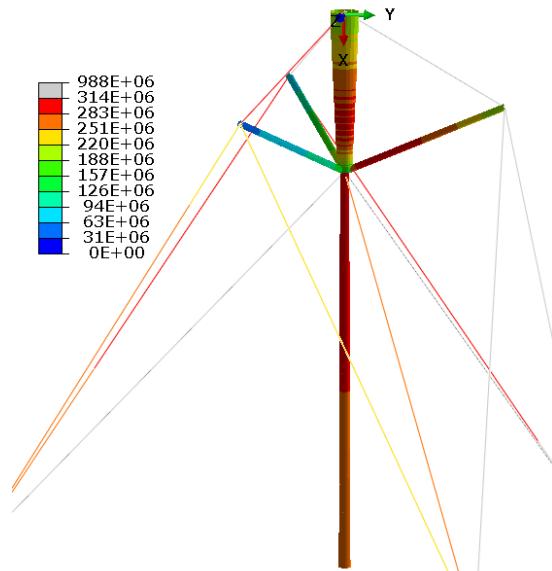
Step: LC7_E_75_degree
Increment 1: Step Time = 1.000
Primary Var: S, S11
Deformed Var: not set Deformation Scale Factor: not set

Figure 36: LC 7 Extreme S 11



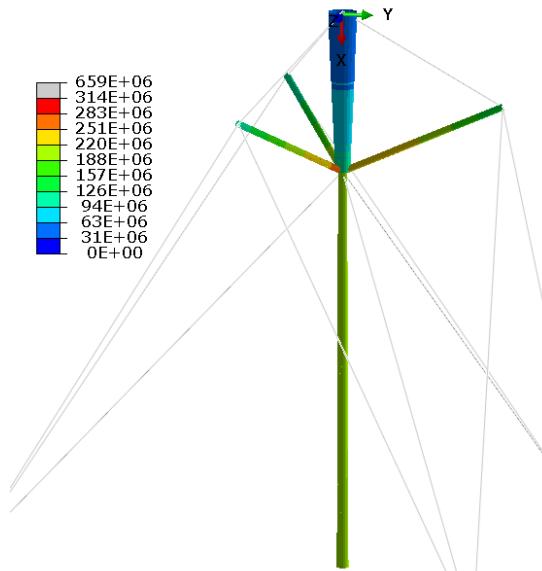
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Increment 1: Step Time = 1.000
Primary Var: S, S11
Deformed Var: not set Deformation Scale Factor: not set

Figure 37: LC 7 Fatigue S 11



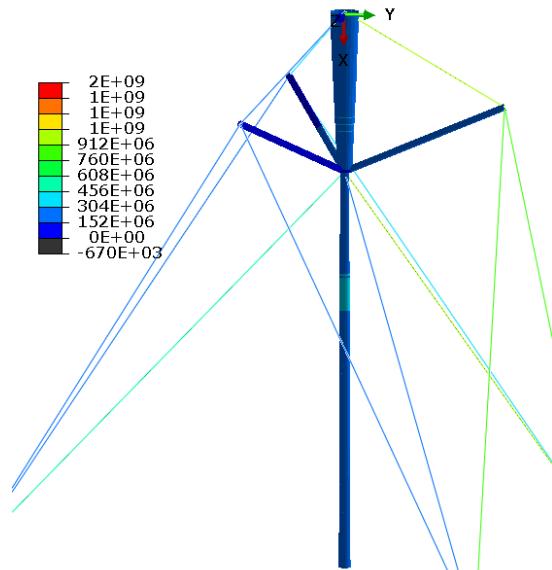
Step: LC8_F_105_degree
Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: not set Deformation Scale Factor: not set

Figure 38: LC 8 Extreme Mises



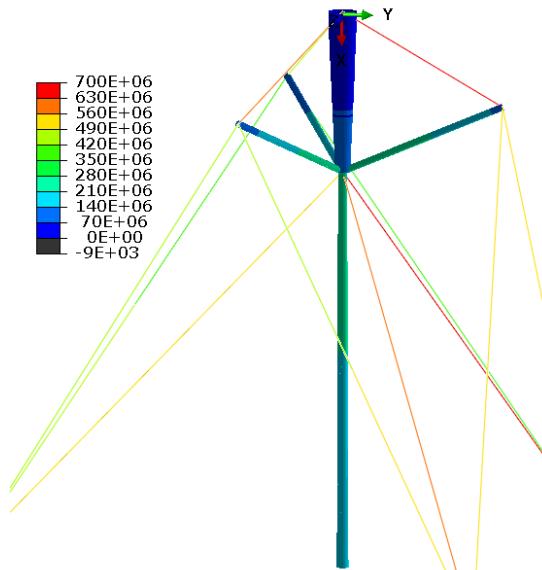
Step: LC8_F_105_degree
Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: not set Deformation Scale Factor: not set

Figure 39: LC 8 Fatigue Mises



Step: LC8_F_105_degree
Increment 1: Step Time = 1.000
Primary Var: S, S11
Deformed Var: not set Deformation Scale Factor: not set

Figure 40: LC 8 Extreme S 11



Step: LC8_F_105_degree
Increment 1: Step Time = 1.000
Primary Var: S, S11
Deformed Var: not set Deformation Scale Factor: not set

Figure 41: LC 8 Fatigue S 11

APPENDIX 5: GUYED TOWER ASSEMBLY DRAWING

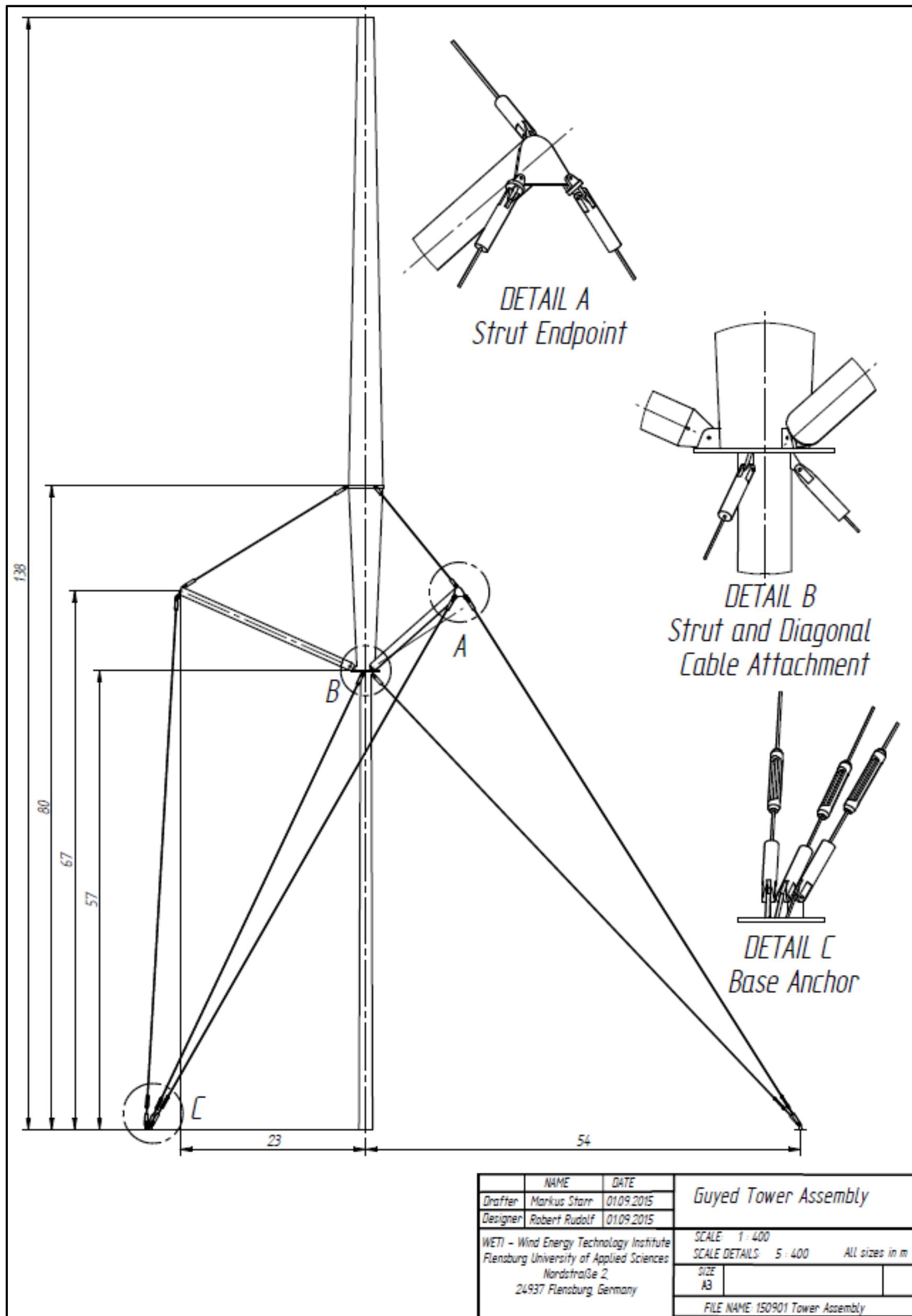


Figure 42: Guyed Tower Assembly Drawing