FATIGUE RESISTANT FOUNDATION SYSTEM

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ABSTRACT

A fatigue resistant gravity based spread footing under heavy multi-axial cyclical loading of a wind tower having a central vertical pedestal, a substantially horizontal continuous bottom support slab with a stiffened perimeter, a plurality of radial reinforcing ribs extending radially outwardly from the pedestal and a three-dimensional network of post-tensioning elements that keep the structural elements under heavy multi-axial post compression with a specific eccentricity that is intended to reduces stress amplitudes and deflections and allows the foundation to have a desirable combination of high stiffness and superior fatigue resistance. The foundation design reduces the weight and volume of materials used, reduces cost, and improves heat dissipation conditions during construction by having a small ratio of concrete mass to surface area thus eliminating the risk of thermal cracking due to heat of hydration.
BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

This invention relates to a method for building fatigue resistant foundations for supporting columns, towers and structures under heavy cyclical loads such as wind turbines. Large wind turbine manufacturers have successfully developed large wind turbines with rated power ranging from 1.5 to 10 MW. Several wind turbine manufacturers are planning mass production of large multi-Megawatt turbines for onshore and offshore installations. The installation of the E-126 model turbine by Ethcon with a 7 MW rated power required a 20 meter diameter circular foundation with 1,400 cubic meters of concrete and 200 tons of rebar. The installation of the 5.0M by RePower with a 5 MW rated power required a 23 meter diameter circular foundation with 1,300 cubic meters of concrete and 180 tons of rebar. The task of building such large foundations is monumental and requires a great deal of construction planning and logistics. The proposed foundation designs and their associated construction methods provide cost-effective solutions for such challenging foundation projects.

[0004] Several wind turbine foundations, that have been constructed in the last 10 years in the US and Europe, have structural problems stemming from thermal cracking during construction or from fatigue cracking and required repairs. The present invention improves the geometry of the foundation in order to enhance dissipation conditions for the due to the typical temperature rise after casting and also provides a cost effective fatigue resistant design.

[0005] 2. Description of the Related Art

Conventional gravity style foundations for large wind turbine usually comprise a large, thick, horizontal, heavily reinforced cast in situ concrete base; and a vertical cast in situ cylindrical pedestal that is installed over the base. There are several problems that are typically encountered during the construction of such foundations.

[0007] Fatigue resistant of such conventional footings is achieved by over sizing the structural concrete elements and the reinforcing elements such that the resulting stress amplitudes are small enough for the structural elements to resist fatigue design checks.

[0008] The main problem is the monumental task of managing large continuous concrete pours, which require sophisticated planning and coordination in order to pour more than four hundred cubic yards of concrete per footing, on average, in one continuous pour, without having any cold joints within the pour.

[0009] Another problem is logistics coordinating with multiple local batch plants the delivery plan of the large number of concrete trucks to the job site in a timely and organized manner.

[0010] A further problem is the complexity of installing the rebar assembly into the foundation which requires assembling two layers of steel reinforcing meshes that are two to six feet apart across the full area of the foundation, while maintaining a strict geometric layout and specific spacing. This rebar assembly is made of extremely long and heavy rebar which requires the use of a crane in addition to multiple workers to install all components of the assembly. The rebar often exceeds forty feet in length, thus requiring special oversized shipments which are very expensive and usually require special permits. That labor intensive and time consuming task requires large number of well trained rebar placing workers.

[0011] Another important problem is the fact that majority of the construction process consist of field work which could be easily compromised by weather conditions and other site conditions.

[0012] Another problem is thermal cracking of concrete due to overheating of the concrete mass. When concrete is cast in massive sections for wind tower foundations, temperature can reach high levels and the risk of thermal cracking becomes very likely. Thermal cracking often compromises the structural integrity of the foundations as reported in many projects in Europe and North America.

[0013] Multi-cell caissons used in offshore installations always lack multi-axial post-tensioning elements and their fatigue resistant rely completely on heavily reinforced oversized concrete elements which involves expensive and labor intensive construction.

BRIEF SUMMARY OF THE INVENTION

[0014] It is desired to have cost-effective foundation system that can reduce construction materials and labor for large wind turbines. The wind turbine foundations can then be built to the standards of the Fatigue Resistant Foundation System which uses concrete rib stiffeners, with a cast in place slab on grade element and a central pedestal to build an integral foundation that will behave structurally as a monolithic foundation structure. Other concrete components can be included such as secondary and perimeter beams, diaphragms, or intermediate stiffeners and rib stiffened or flat slab sections. The foundation system relies on the use of many prefabricated components including rebar meshes and cages, pedestal cage assembly, pre cut post-tensioning strands, preassembled strand bundles, pre-cut post-tensioning duct sections and prefabricated concrete forms.

[0015] The present invention pertains to a fatigue resistant foundation for wind towers which comprises a plurality of components, namely a central vertical pedestal, a substantially horizontal continuous bottom support slab with stiffened perimeter, a plurality of radial reinforcing ribs extending radially outwardly from the pedestal and a three-dimensional network of vertical, horizontal, diagonal, radial and circumferential post-tensioning elements embedded in the footing that keeps all the structural elements under heavy multi-axial post compression, reduces stress amplitudes and deflections and allows the foundation to have a desirable combination of high stiffness and superior fatigue resistant while improving heat dissipation conditions during construction by having a small ratio of concrete mass to surface area thus eliminating the risk of thermal cracking due to heat of hydration.

[0016] Although the application is written for a wind turbine tower as the column being supported by the foundation, any tower or column can be used on the foundation including but not limited to, antennas, chimneys, stacks, distillation columns, water towers, electric power lines, bridges, buildings, or any other structure using a column.

[0017] In one embodiment, the present invention pertains to a wind turbine foundation having a plurality of components, namely a central vertical pedestal, a substantially horizontal bottom support slab, and a plurality of radial reinforcing ribs extending radially outwardly from the pedestal. The ribs are prefabricated and transported to job site, but the
pedestal and support slab are poured in situ at the site out of concrete. The prefabricated ribs are equipped with load transfer mechanisms, for shear force and bending moment, along the conjunctures with the cast in situ support slab. The prefabricated ribs are also equipped at their inner ends with load transfer mechanisms, for shear force and bending moment, along the conjunctures with the cast in situ pedestal. The ribs are arranged in a circumferentially spaced manner around the outer diameter of the pedestal cage assembly before or after slab reinforcing steel is installed. Forms are then arranged for the pedestal and support slab. The support slab is cast in situ by pouring concrete into the forms and then pedestal concrete is poured over the slab into the pedestal form. When the concrete cures the support slab is united to the prefabricated ribs and the ribs are also united to the pedestal. The final result is continuous monolithic polygonal or circular foundation wherein loads are carried across the structure vertically and laterally through the continuous structure by the doweled and spliced reinforcing steel bars which are integrally cast into the pedestal, ribs and support slab. The combination of the high stiffness of the ribs, solid pedestal and continuous slab construction across the pedestal, and through or under ribs, allows the slab to behave structurally as a continuous slab over multiple rigid supports resulting in small bending and shear stresses in the slab, reducing deflections and increasing the stiffness of the foundation, substantially reducing fatigue as well as allowing for the benefits of rapid construction and economical design.

OBJECTS OF THE INVENTION

[0028] An object of this invention is to provide the wind energy industry with a fast, reliable, yet cost-effective foun-
A foundation system that is suitable for most wind energy projects, including projects using the largest utility scale turbines and tallest towers, while providing a foundation lifespan that is longer than conventional foundation systems.

Another object of this invention is to reduce the cost of wind energy projects by realizing savings in the areas of rebars, concrete pouring and finishing, logistics, man-hours and crane operations.

It is the object of this invention to provide a foundation system suitable for large wind turbines including utility scale turbines ranging from 1.5 MW to 10 MW and larger, wherein the amount of cast in situ concrete work is limited and the number of concrete trucks and the amount of rebar required for the foundation are reduced to a manageable level when compared to conventional gravity style foundations.

Another object of this invention is to improve dissipation conditions for the heat of hydration and the typical temperature rise after casting. That goal is achieved by reducing the ratio of concrete mass to surface area. When concrete is cast in massive sections for wind tower foundations, temperature can reach high levels and the risk of thermal cracking becomes very high unless cooling techniques or special admixtures are applied. Thermal cracking often compromises the structural integrity of the foundations.

A further object of this invention is to improve foundation structural properties due to fabrication of some structural components in a fully controlled environment of a precast concrete plant or a suitable facility at or near project site and to utilize benefit from advancement in concrete construction in areas such as concrete admixtures, special cements and fiber reinforcement.

Still another object of this invention is to utilize desirable features and benefits associated with mass production of precast concrete such as high reliability and uniform consistency and high compressive strength.

Another important object of this invention is to minimize chances for errors in bar placement, spacing and layout by providing pre-marked spacing for splicing slab rebar with existing dowels extending from ribs.

A further object of this invention is to use light weight, small diameter, short and easy to handle rebar for the cast in situ concrete.

A further important object of this invention is to provide the wind energy industry with a solution for all weather foundation construction.

Still another important object of this invention is to improve safety and accessibility around foundations under construction, and reduce hazardous conditions for construction crew.

A further significant object of this invention is to increase productivity and increase the number of footing that can be built in a given time frame using the same number of workers, when compared to conventional foundation designs built under similar conditions.

Another object of this invention is to employ pre-stressing and/or post-tensioning techniques in order to maximize the performance of the foundation, improve its fatigue resistance and extend its life span.

Another object of this invention is to provide the wind energy industry with reliable and readily available designs, and prefabricated components, for every wind energy project wherein foundation designs are pre-approved by and coordinated with turbine manufacturers and certification agencies.

Another object of this invention is to use standard designs to reduce engineering work and simplify the permitting process, as well as improve project construction schedule.

Still another object of this invention is to speed-up construction by using many prefabricated components including rebar meshes and cages, bolt cage assembly, pre-cut post-tensioning strands, preassembled post-tensioning bundles, pre-cut post-tensioning duct sections and prefabricated concrete forms.

It is also the object of this invention to provide wind energy developers with the ability to select pre-approved complete foundation designs for wind turbine foundation based on project and site variables including turbine model and tower height; site geotechnical characteristics; and desired foundation style such as gravity, anchored or piling.

Another object of this invention is to provide foundation contractors with the convenience and economy of using commercially available prefabricated components with complete assembly and detail drawings that can be delivered to any project site with short lead time.

A further object of this invention is to improve the quality and productivity of foundation construction due to experience gained from practicing standard construction techniques with repetitive production steps.

Still another object of this invention is to produce foundation designs suitable for shallow and deep offshore installations.

Another object of this invention is to use the modular foundation system for other tower structures such as chimneys, stacks, distillation columns and telecommunication towers.

Yet another object of the foundation is to improve tower base bearing resistant in concrete pedestals supporting wind towers such that it become possible to build the pedestal and the foundation with concrete having the same compressive strength without increasing the diameter of the pedestal.

Another object of the invention is to build wind tower foundation in one continuous concrete pour.

The final object of the invention is to independently produce prefabricated components for offshore foundations that can be assembled on a barge without having the critical path of completing to a first component before a second component can be constructed.

Other objects, advantages and novel features of the present invention will become apparent from the following description of the preferred embodiments when considered in conjunction with the accompanying drawings.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of the foundation showing the rebar before pouring the concrete.

FIG. 2A is a perspective view of a pedestal and ribs in a second embodiment with a pier for shore applications.

FIG. 2H is a perspective view of a pedestal and ribs.

FIG. 3A is an inner perspective view of a rib showing connections to the pedestal and the slab.

FIG. 3B is an outer perspective view of a rib showing connections to the pedestal and the slab.

FIG. 4 is a perspective view of a rib and forms for forming the pedestal and slab.
FIG. 5 is a perspective view of the bolt assembly and alignment apparatus.

FIG. 6 is a top view of the foundation prior to pouring the concrete showing the rebar and template for the anchor bolts and post tensioning elements.

FIG. 7 is a perspective view of a raised rib having means for raising the rib above the slab.

FIG. 8 is a perspective view of the foundation showing the alignment apparatus and a pedestal forming section.

FIG. 9 is a perspective view of the foundation showing the rebar and rebar cage.

FIG. 10 is a perspective view pedestal cage assembly with anchor bolt and reinforcing.

FIG. 11 is a perspective view of the foundation.

FIG. 12 is a perspective view of the rib for supporting a lattice style tower.

FIG. 13 is a perspective view of the foundation for offshore installation.

FIG. 14 is a perspective view of the foundation for offshore installation.

FIG. 15 is a perspective view of the foundation for offshore installation.

FIG. 16 is an elevation view of the foundation for offshore installation.

FIG. 17 is a perspective view of the foundation for offshore installation.

FIG. 18 is a perspective view of the foundation for offshore installation.

FIG. 19 is a perspective view of the foundation for offshore installation.

FIG. 20 is a perspective view of the foundation with rock anchors.

FIG. 21 is a perspective view of the foundation with rock anchors.

FIG. 22 is a perspective view of the foundation with rock anchors.

FIG. 23 is an elevation view of the foundation with rock anchors.

FIG. 24 is a perspective view of an offshore foundation with micro-piles.

FIG. 25 is an elevation view of an offshore foundation with micro-piles.

FIG. 26 is a perspective view of the foundation.

FIG. 27 is an elevation view of the foundation.

FIG. 28 is a perspective view of rock anchored foundation.

FIG. 29 is a perspective view of rock anchored foundation.

FIGS. 30a-30d show circumferential post tensioning view of the foundation.

FIG. 31a is a plan view of the foundation.

FIG. 31b is a section view of the foundation.

FIG. 32a is a section view of the foundation.

FIG. 32b is a section view of the rib 16.

FIG. 33a is an elevation of rib reinforcing details.

FIG. 33b is a plan view of rib reinforcing details.

FIGS. 34a and FIG. 34b are section views of the rib 16.

FIG. 34c and FIG. 34d are pedestal reinforcing details.

FIGS. 35a and FIG. 35b are section views of the pedestal.

FIGS. 36a and 36b are slab 20 reinforcing plans.

FIGS. 37a and FIG. 37b are elevation and plan views of a rib with unbounded post tensioning elements.

FIG. 38 FIG. is a plan view showing circumferential post tensioning in the foundation.

FIG. 39a-FIG. 41b show details of the a foundation with prefabricated ribs.

FIG. 42a-FIG. 42d show tendon duct arrangements in a pedestal 10.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention pertains to a wind turbine foundation for wind turbines. The foundation comprises a plurality of components, namely a central vertical pedestal, a substantially horizontal bottom support slab, and a plurality of radial reinforcing ribs extending radially outwardly from the pedestal. The ribs may be prefabricated and transported to job site, but the pedestal and support slab are poured in situ at the site out of concrete. Alternately the ribs may be cast in situ.

The present invention pertains to a fatigue resistant foundation 100 for wind towers which comprises a plurality of components, namely a central vertical pedestal, a substantially horizontal continuous bottom support slab with a stiffened perimeter, a plurality of radial reinforcing ribs extending radially outwardly from the pedestal and a three-dimensional network 500 of vertical, horizontal, diagonal, radial and circumferential post-tensioning elements embedded in the footing that keeps all the structural elements under heavy multi-axial post compression, reduces stress amplitudes and deflections and allows the foundation 100 to have a desirable combination of high stiffness and superior fatigue resistance while improving heat dissipation conditions during construction by having a small ratio of concrete mass to surface area thus eliminating the risk of thermal cracking due to the heat of hydration.

A construction site is prepared by excavation and flattening and preparation of soil for the foundation 100. The foundation 100 may be set on pilings, on piers, or have anchors (soil anchors or rock anchors 404 or micro-piles 401 or other types) in a conventional manner. The present invention ensures good contact between foundation 100 and soil, or sub-base, by casting.

The foundation 100 is cast against prepared soil, or crushed stone sub-base, or a mud slab or a membrane sheet in case of offshore foundations assembled on a barge or in dry docks. Known grouting and leveling techniques under precast elements can be employed for ensuring plumb installation and good soil contact.

In one embodiment of the invention the foundation 100 may be set on a mud slab 14 or on compacted granular fill. The mud slab 14 is often a thin plain concrete layer intended to provide a clean and level base for foundation installation. After the foundation site has been prepared, a plurality of three or more precast stiffener ribs 16 are placed on the mud slab 14 or compacted granular fill inside of the excavation pit 12. The precast concrete stiffener ribs 16 may have means for leveling or other leveling techniques can be employed for level and plumb installation. If desired, grouting techniques can be used to ensure complete rib base contact with the mud slab or sub-base. The precast concrete stiffener ribs 16 may have bases 21 with left shear key 38 and/or shear connectors and right shear key 36 and/or shear connectors. The precast concrete stiffener ribs 16 may also have a vertical shear key.
34. The shear keys 34, 36 and 38 and associated dowels 40, 42 and 46 are to ensure continuous connections, with complete transfer of shear and bending loads, between the precast concrete stiffener 16 and the cast in place concrete which is to be poured into the foundation 100. The precast concrete stiffener ribs 16 have upper dowels 40 and lower dowels 42 extending on the right and left sides of the base 21 which interconnect with and spliced to upper mesh rebar 22 and lower mesh rebar 24 installed between the ribs 16 and connected to dowels 40, 42 to form reinforcement for the slabs of foundation 100 when the concrete is poured. The base 21 of the ribs 16 and the top of the rib 16 also have dowels 46 radially entering the pedestal 10 in the center of the foundation.

[0103] Doweling of rebar between ribs and foundation components can be achieved by dowel rebars extending from the prefabricated elements or by using rebar couplers, bar extenders or any mechanical rebar splicing system.

[0104] Arrays of grout or epoxy filled sleeves arranged in the slab 20 could receive corresponding arrays of vertical dowels extending from the bottom of prefabricated ribs or perimeter beams 190 or other prefabricated components.

[0105] Shear keys can be replaced with, or combined with, corbels or shear studs, or other shear connectors such as angled rebar or embedded steel shapes.

[0106] In another embodiment an array of steel beams, are encased into the web of the rib and extend inwardly into the pedestal cavity at the innermost end of ribs, and serve as a suitable shear force transfer mechanism between the rib and the pedestal.

[0107] In another embodiment the foundation 100 comprises a steel frame fully encased in concrete and has a central tower receiving metal cylinder fixed to an array of radially extending steel girders encased in concrete beams and rigidly connected at their outer ends to an array of perimeter beams 190 encased in the concrete foundation and a reinforced concrete slab-on-grade 20 covering the foot print of the foundation 100 and connected to the said steel frame.

[0108] In one embodiment the ribs are treated with concrete bonding agent along surfaces where cast in place concrete is received.

[0109] In another embodiment the foundation 100 is provided with drains around the perimeter and the top surface of the slab 20 is slightly sloped towards the said drains such that water is drained away from foundation 100.

[0110] In another embodiment the ribs or other foundation elements are covered or coated with protective material for extending the life span of the footing.

[0111] In one embodiment the ribs 16 are placed on the mud slab 14 first and then the pedestal cage 50 made of an array of rebar, preferably Z or C shaped rebar and circumferential rebar is assembled around anchor bolt assembly. Alternatively the pedestal cage 50 is assembled first or a preassembled pedestal cage 50 dropped into place first and then the ribs 16 with dowels 46 are slid into place so that dowels 46 and shear connectors fit between the elements of pedestal cage 50 rebar assembly.

[0112] As best seen in FIG. 3a, the precast concrete stiffener rib 16 has lifting lugs 52 to help place the stiffener rib 16 into the excavated construction area. The base 21 has a flat bottom surface such that the ribs may stand on their own on the mud slab 14 or compacted granular fill or during transportation from precast plant to foundation site. The precast concrete stiffener ribs 16 have prestressing elements 58 running through the ribs 16 radially from the outside of the ribs 16 and through pedestal 10. The radial prestressing elements 58 (or post tensioning elements) may be anchored to the opposite side of the pedestal or optionally run through the opposing precast concrete stiffener 16 on the other side of the pedestal 16 and anchored at the end of the opposite rib 16. Once the ribs 16 and the pedestal cage 50 are in place, the dowels 46 extending radially inward from ribs 16 may be connected to, or spliced with, corresponding dowels arranged in the pedestal cage. Inside of a cage 50 are additional rebar dowels 48 which will facilitate the continuity of the structural components through the pedestal 10 as well as resist bearing, shear and bending loads.

[0113] Also inside of pedestal reinforcement cage 50 is a bolt assembly 60 comprising a bolt template 52 an embedment ring 54 and anchor bolts 56 protected by a PVC sleeve 57 or wrapped with a material to prevent bonding between the anchor bolts 56 and concrete to be poured. The anchor bolts 56 have a top portion which is used to attach the base flange 301 of a tower or column to the pedestal 10. A grout trough template 52 at the bottom of the bolt template 52 may be used to create a grout trough 90 to ensure a good connection of the tower or column to the pedestal 10. The grout trough 90 will be formed by removing the bolt template 52 from the anchor bolts 56 after the concrete has been poured. Radial dowels, prestressing elements or shear connectors at the inner end of ribs 16 should be spaced to clear anchor bolts # and other reinforcement arranged in pedestal cage 50.

[0114] In a preferred embodiment, for fully cast in place foundations, slab forms may sit directly on the mud slab and rib forms 16b are supported and kept elevated above slab 20 by elevation by means of adjustable and reusable support legs arranged in the rib forms 16b. Small footings or thickened mud slab areas could be used under rib form support legs. Pedestal forms 102 can be supported by rib forms 16b or by separate support legs.

[0115] When ribs 16 are prefabricated, the bolt assembly 60 is held in place and the anchor bolts 56 are properly oriented by an alignment apparatus 130 can be utilized. The alignment apparatus 130 has a central post 132 with arms 134 attached perpendicularly to the center post and having legs 136 for attachment to the top of the ribs 16 to provide added stability, and bolt circle proper alignment during construction. The legs 136 have an adjustable height relative to the arms 134.

[0116] The arms 134 may have braces 138 attached to the central post 132 for holding the arms 134 straight. The central post 132 may also have rod supports 135 for holding reinforcement rebar such as reinforcement rebar 80 which are spliced to dowels 46. The alignment apparatus 130 also has adjustable support members 140 for attachment between the arms 134 and the bolt template 52 to align the anchor bolts 56 so they are upright. The alignment apparatus 130 can support the bolt assembly 60 without the central post 132 by relying on the legs 136 supported by ribs 16, which allows the lower portion of the central post 132 to be removed if desired. Alignment apparatus 130 can be used as a template to ensure proper location, elevation and orientation of ribs 16.

[0117] The ribs 16 can be of any shape or size depending on the specifications of the tower and loads thereon. For example the ribs 16 may be trapezoidal, rectangular, tee shaped or I beam shaped. The ribs 16 may have intermediate stiffener plates or diaphragms for improved structural performance. The ribs 16 or rib forms 16b may receive ramps or catwalks thereon for easy access to the forms during construction.
Ribs 16, or rib forms 16b, may have means for receiving and supporting perimeter forms 18, such as bolts or threaded inserts for receiving and supporting the pedestal forms 102. The ribs 16, or rib forms 16b, may also have attachment means 15 for holding base forms 17. The pedestal forms 102 may be equipped with platform sections for allowing access around the pedestal and the rest of the footing.

With all the rebar, ribs 16, pedestal 100, bolt assembly frame 80 and optional alignment apparatus 130 in place concrete forms may be attached such that concrete can be poured to form the pedestal and base of the foundation. Pedestal forms 102 may attach to the ribs 16, or rib forms 16b, by bolts 18 or by any other means. Similarly the base perimeter forms 17 may be attached to the ribs 16, or rib forms 16b, by bolts 15 or by any other means. Alternatively the base perimeter forms may be supported to the ground or the mud slab.

With all the parts assembled all the rebar in place and the conduit for the prestressing tendons or rods of the foundation in place, concrete is ready to be poured into the pedestal 10 and between the ribs 16. The pouring of the concrete can be accomplished quickly and slab areas between the ribs 16 can be finished as the pedestal 10 concrete is still being poured. The concrete may be used to build the pedestal 10 and the slab 20 in one pour. Alternatively the base for the entire foot print of the footing can be poured in a first pour then the pedestal 10 can be formed in a second pour.

When bonded multi-strand post tensioning system is used in the foundation 100, the prefabricated components will be fitted with ducts and anchor hardware according to design specifications. The cast in place components will be fitted with matching ducts to facilitate the continuity of tendons across the foundation 100. After the jacking of tendons, duct grouting is carried out as required. If the unbonded, bundled mono-strand system is employed, no duct or grouting is required.

The structural load capacity of the foundation 100 is increased significantly by the combination or radial (or diametric) and circumferential post tensioning 59. Circumferential post tensioning 59 creates a desirable symmetric bi-axial post compression in the slab 20. Circumferential post tensioning 59 is applied at an elevation well below the neutral axes of the ribs 16 thus creating eccentric post compression in the ribs 16 and the pedestal 10 and resulting in increased nominal moment and shear capacity of the ribs 16 as well as improvement in multi-axial fatigue resistant of the pedestal 10, ribs 16 and the slab 20. Radial or diametric post tensioning elements 58 extend from rib to opposite rib across the pedestal 10. Radial post-tensioning is applied with an eccentric load pattern, with higher post compression below the neutral axis of the rib. When all the prestressing elements are jacked, the foundation 100 is kept under heavy multi-axial eccentric post compression stress, thus increasing rib structural capacity to resist soil support reaction and providing low deflections, high stiffness and low stress amplitudes resulting in high fatigue resistant and high durability. Backfill is added over the foundation 100 for increased stability and stiffness of the foundation 100.

After the concrete sets, post tensioning is carried out and the foundation 100 is backfilled with compacted granular fill to stabilize the foundation 100 against overturning.

Alternately the bolt assembly can be replaced by a tower section 56b embedded in pedestal 10 concrete and the embedded section 56b having means 56c for receiving, a tower base by means of a bolted connection arranged at the top of the section. The embedded metal cylindrical tower section 56b encased in pedestal 10 concrete is provided with holes for rebar and post tensioning tendons 58 to extend through the metal cylinder. Post tensioning 58 tendons can extend through holes arranged in the cylinder and across the pedestal 10, through the ribs 16 to be anchored on distal ends of the foundation.

Pedestal 10 can be any size or shape, round, triangular, square, polygon or other shape depending on the specifications of the tower and loads thereon. The ribs 16 can be in any pattern around the pedestal 10. In one embodiment shown in FIG. 2 the foundation 100 may have a square pedestal 10 and ribs 16 at the corners parallel to the faces of the pedestal. The pedestal 10 may have a stepped construction with an enlarged lower cross section to reduce the length of the cantilevered ribs 16.

Pre-assembled reinforcement sections (meshes) of the slab 20 components can be lowered into place in the slab 20 to speedup construction. All rebar dowel or metal shear connectors extending through a construction joints may be galvanized or Epoxy coated to prevent corrosion. The use of mechanical couplers in the foundation 100 shall be limited or avoided. Specified mechanical couplers must be tested and certified for the number of load cycles in the life span of the foundation 100.

In another preferred embodiment, the ribs are cast in place in reusable rib forms 16b. The ribs 16 are cast in place jointly with the pedestal 10 in one continuous pour over the slab. Optionally, the ribs 16, the pedestal 10 and the slab 20 are all jointly cast in one pour. All rib internal components including rebar assembly with dowels and prestressing elements are placed inside the forms then cast in place concrete is poured into the rib forms 16b as well as into pedestal 10 and slab 20 forms.

Rib reinforcing cages can be assembled above grade and lowered into the foundation in one or more sections.

In a preferred embodiment rib forms 16b with internal rib reinforcing cages are preassembled and lowered into the foundation by cranes to mesh with slab reinforcing sections already placed in the foundation. The radial reinforcing panel of the slab 20 enables the meshing rib dowels between slab reinforcing without geometric interference.

Ribs 16 can also be made in segments and eventually united by means doweling or by using segmented post-tensioned construction techniques. Rib anchor zone with anchor trumpets and hardware can be prefabricated separately of higher strength concrete than the rest of the rib.

Prefabricated perimeter beams 190 with post tension ducts could serve as perimeter forms become part of the structure. An array of precast, rectangular or L-shaped beams with means for connecting to the slab 20 and the ribs 16 can be used. The perimeter (edge) beams can rest directly on the mud slab and connect to the slab 20 using horizontal dowels and shear key arranged at its inner side. Optionally the perimeter beam is elevated and connects to the top of the slab 20 using dowels extending from its bottom. The precast perimeter beams 190 may have dowels and shear keys extending from their sides ends for connecting to the ribs 16. In this case the ribs 16 will have corresponding dowels and shear keys for receiving and supporting perimeter beams 190. The connection between ribs 16 and perimeter beams 190 is established using closure pours in small cavity at the connections.

In another embodiment the foundation 100 pertains to hybrid gravity based and rock anchored foundation system.
Ribs 16 can be made with arrangement, mechanisms and connectors for receiving piles 400 or micro-piles 401 or anchors 404 in different configurations. Vertical through holes in the ribs 16 can provide means for receiving a pile or an anchor. Bearing elements and grouting are arranged on top of each rib to establish the required structural connection. An array of bearing plates 404b with tensioning nuts 404c on each soil/rock anchor is used to compress the foundation 100 against supporting soil. Vertical through holes with corrugations for the anchor extend through the foundation. Bearing plates 404b with tensioning nuts 404c can be placed on top of the pedestal 10 or in the foundation 100. If desired ribs 16 may have piers extending vertically from the ribs 16 and the top of pier elevation is raised above grade to make anchor bolts accessible for tensioning and testing. Typical rock or soil anchor construction and grouting methods can be utilized. Another option is to house rock anchor bolts and bearing plates 404b and tensioning nuts 404c in accessible corrosion protection compartments above the foundation 100.

0133 In another embodiment the invention pertains to a foundation 100 that comprises the following elements:

0134 1. A vertically extending pedestal 10 that is cast in situ, out of concrete, the pedestal 10 serving to receive and support the tower structure;

0135 2. A substantially horizontal support slab 20 that is cast in situ out of concrete, the support slab 20 covering an area of ground larger than that covered by the pedestal 10;

0136 3. A plurality of radial ribs 16 extending radially outwardly from the pedestal 10 and spaced around the pedestal 10, each rib being joined along the base thereof to the support slab 20 being joined along an inner side thereof to the pedestal 10, each rib has means for receiving a rock or soil anchor;

0137 4. An optional plurality of perimeter beams 190, or stiffened slab edge 190a, spanning continuously, near the perimeter of the foundation, between ribs 16 and supporting the slab 20 may be employed;

0138 5. An array of soil or rock anchors 404 extending through the foundation 100, preferably through the ribs 16, may extend down into the ground below the foundation, each anchor having a bearing element in or above the foundation 100 and compressing the foundation against support soil when the anchors are tensioned.

0139 The prefabricated components can be molded at a facility under controlled conditions for good quality concrete setting and controlled rebar spacing which is superior to what can be obtained on a job site and at a lower cost. The ribs 16, acting as deep stiff horizontal cantilever support, allow the base of the foundation slabs to have a relatively small thickness using less cast in place concrete and rebar thus lowering the cost for each foundation.

0140 Alternatively ribs 16 can have reusable temporary supports 170, or other means, arranged at the ribs 16 to hold the ribs 16 in place, maintain them plumb during construction and elevate them at a predetermined height over slab reinforcing. This style of ribs 16 is intended to be raised above the ground or mud slab 14 so that the foundation support slab 20 can be poured in place continuously under ribs. Dowels and shear connectors for this style may be arranged at the bottom of the rib for connecting with base slab 20 which extends under the raised rib. When the concrete cures the continuous support slab 20, extending under the ribs, is united to the prefabricated ribs 16 and the ribs 16 are also united to the pedestal 10. The rib inner ends will be partially encased in the pedestal 10 to increase rib torsional end resistance. The final result is continuous monolithic foundation wherein loads are carried across the structure vertically and laterally through the continuous structure by the doweled and spliced reinforcing steel bars which are integrally cast into the pedestal, ribs 16 and support slab 20. The combination of the high stiffness of the ribs 16, solid pedestal 10 and continuous slab 20 construction across the pedestal 10, and under ribs 16, allows the slab 20 to behave structurally as a continuous slab 20 over multiple rigid supports resulting in small flexural and shear stresses in the slab 20, reducing deflections, improving fatigue conditions and increasing the stiffness of the foundation as well as allowing for the benefits of an economical design.

0141 Cast in situ concrete can be shielded from extreme weather, including heat, cold, rain and snow, by simply extending blankets, covers or shields between ribs 16 during construction, and then using heaters or fans as required to regulate temperature, humidity of concrete to allow for proper setting and curing conditions.

0142 Another embodiment of the present invention pertains to a leveling technique that simplifies the tower base leveling process and shortens the number of steps required for grouting under a tower base. The bolt template is provided at the very top of the bolt assembly with at least three sets of additional bolts and corresponding threaded bolt inserts suitable for embedment in the concrete. Such leveling bolts 53 and inserts 53b will be located outside or inside the bolt circle of tower base, but directly under tower base flange. This allows for continuity of grout bed construction and provides an easy access to leveling bolts 53. Small cutouts at leveling bolt locations may be used. Another benefit of this leveling technique is having the ability to apply continuous grout bed that is free of cold joints, under tower base flange in one session as well as having the ability to tension all anchor bolts in one work session.

0143 The foundation design can be reconfigured to support lattice towers comprising multiple columns connections to foundations in a spaced array. The ribs 16 will be provided with column receiving components including embedded anchor bolts (or grouting around embedded element) and an integrated pier design into the rib. The rib geometry may be widened and enlarged at the integral pier. The array of said integrated piers ribs 16 are fitted with means for receiving and supporting the legs or the columns of the lattice tower 200. The integrated piers can extend above final grade elevation, while the top of pedestal 10 may stay below final grade elevation. For this foundation style, pedestal elevation may be depressed and tower receiving components may not be required in the pedestal 10. This configuration may also be used in offshore applications wherein a prefabricated gravity foundation 100 is connected to lattice tower structure 200 that is fitted with a wind tower receiving component at its top. The foundation 100 will be installed over prepared seabed and filled with a suitable backfilling material 13, and surrounded with scour protection 13a.

0144 In permafrost conditions, the foundation 100 may be supported on an array of concrete piers deeply embedded and frozen into the ground. Anchors can be used to secure the ribs 16 to their supporting piers around the perimeter of the foundation. If a slab 20 is incorporated in the design, the slab bottom elevation may be set above grade elevation.
This invention pertains to a fatigue resistant gravity based spread footing for use under heavy multi-axial cyclical loading of a wind tower, which comprises a plurality of components, namely a central vertical pedestal extending radially outwardly from the pedestal and a three-dimensional network of vertical, horizontal, diagonal, radial (or diametric) and circumferential post-tensioning elements that keep the structural elements under heavy multi-axial post compression with specific eccentricities and orientations that are intended to reduce stress amplitudes and deflections and allows the foundation to have a desirable combination of high stiffness and superior fatigue resistance while improving heat dissipation properties during construction by having a small ratio of concrete mass to surface area thus eliminating the risk of thermal cracking due to heat of hydration.

Vertical prestressing of the pedestal can be carried out independently of tower receiving elements. A pedestal may have an array of vertical post tensioning elements that does not connect to a tower, and an embedded tower section boiled to a tower structure.

Radial post-tensioning, extending across the foundation, in pairs of ribs, allows for the desirable structural continuity and the direct transfer of loads from a windward rib into the pedestal and then into the opposing wind rib. Radial and circumferential post compression stresses in the slab and/or perimeter beams allows for a desirable reduction in stress amplitudes the structural continuity between slab spans and/or perimeter beam spans, thus creating a desirable load sharing mechanism between adjacent ribs by forcing more rib to be engaged in resisting tower loads.

The invention pertains to a durable, high-stiffness, fatigue-resistant foundation structure for onshore wind tower installations which comprises:

1. A central pedestal that is made of cast-in-place concrete with concentric vertical prestressing elements and eccentric multi-axial horizontal and/or radial post-tensioning elements;
2. An array of cast-in-place eccentrically post-tensioned radial ribs;
3. A cast-in-place slab with heavily post-tensioned thickened slab edge.

All components are made of high strength reinforced concrete and are rigidly connected to each other to behave as a monolithic spread foundation structure. The structural components are rigidly connected with arrays of rebar dowels (passive reinforcing) or post-tensioning elements extending through the conjunctures. The slab functions as a two-way slab system that is free of construction joints across the footprint of the foundation and spans continuously over multiple ribs. Perimeter post-tensioning or circumferential post tensioning of the slab is applied at an elevation well below the neutral axes of the ribs to cause eccentric loading of the ribs and the pedestal. Radial post-tensioning elements with an eccentric load pattern, with higher post compression at the bottom of the rib, extend from rib end to opposite rib across the pedestal, or to the opposite end of the pedestal. When all the prestressing elements are jacked, the foundation is kept under heavy multi-axial eccentric post compression stress, thus increasing rib structural capacity to resist soil support reaction and providing low deflections, high stiffness and low stress amplitudes resulting in high fatigue resistant and high durability. Backfill is added over the foundation for increased stability and stiffness of the foundation.

Soil support reaction under the slab is transferred from the slab to the ribs and thickened slab edge (or perimeter beams) as in two-way slab systems with more load distribution going to the ribs in the primary span. Perimeter or circumferential post-tensioning are applied, perpendicular to the ribs, in the orientation of the primary span that effectively reduces stress amplitudes and deflections in the slab by keeping the slab under heavy post-compression in the directions of primary slab spans around the foundation. The size, distribution, eccentricity and location of post-tensioning elements in the ribs and the slab are used, by the engineer, to dictate the natural frequencies of the foundation to be in a safe range relative to operating frequencies of the wind generator according to turbine manufacturer recommendations.

The said vertical, radial and circumferential post-tensioning in the foundation keep all the structural components (Pedestal, ribs, slab, thickened slab edges (or integral edge beams)) under multi-axial post compression confinement resulting in lower stress range amplitudes thus yielding higher stiffness, more effective crack control, lower deflections and improved fatigue resistance. Superior fatigue resistance and long life-span are achieved by keeping most of the structural elements of the foundation under multi-axial compression while resisting operating loads or even during normal and abnormal extreme loads from the supported structure (wind power generator).

In a preferred embodiment, rib post-tensioning requirement are reduced by engaging fully developed bar dowels from the rib into the pedestal connection as well as extending fully developed radial rebar dowels of the slab into the pedestal, thus allowing passive reinforcing to participate in the said connection especially under extreme loads. Radial slab reinforcing pattern with tapered rib width was found to be very cost effective as the rib to pedestal connection benefits from a large number of top and bottom radial slab reinforcing bars participating in the said connection, as the rib width widens, thus reducing the number of bottom post-tensioning strands required for the said connection.

The structural configuration of the foundation reduces the overall cumulative deflections in the structure under tower loads and significantly improves the rotational stiffness of the foundation which is a key factor in determining the size of foundations in wind turbine installations. The rotational stiffness is also improved by the interlocking between surrounding soil (after backfilling) and the multiple surfaces and vertical faces of the foundation structure. The horizontal stiffness is improved by the passive earth pressure on the multiple faces of the structure. Both rotational and horizontal stiffness achieved by this design are much higher than conventional tapered inverted-Γ gravity spread footings especially onshore foundations installed below grade in an excavated pit because of the increased interlocking surface area and increased passive earth pressure and increased friction on the multiple faces of the fatigue resistant foundation.

The solid-core pedestal comprises a continuous reinforcing cage and a tower receiving component, such as anchor-bolt assembly, with a cylindrical array of bond pro-
ected high strength post-tensioning bolts, for connecting to wind tower base flange 301. In another embodiment and the tower receiving component may comprise an embedded cylindrical metal tower section 56b with means 56c for connecting to a tower section such as a flange with bolt holes for receiving bolts at its top and with an array of holes to allow the passing of rebar and post tension tendons. The anchor bolt assembly ensures structural continuity between the tower 300 and the pedestal 10. The post-tensioning forces of the anchor bolts are selected by the engineer to insure that the tower base flange 301 remains in contact with the pedestal 10 under extreme normal and abnormal load conditions. The bolt assembly includes, at its bottom end, a bearing element that may consist of an embedment ring plate that is made of segments that are welded together.

[0157] Radial post-tension tendons and rebar reinforcing elements extending from the ribs 16 and the slab 20 pass through the pedestal reinforcing cage, or through holes in the embedded metal tower section.

[0158] As shown on the drawings, post-tensioning elements are flared horizontally, profiled vertically, arranged in matrix groups, spaced and draped in a manner that allows for optimum utilization of post-tensioning and ease of installation while avoiding tendon congestion and stress concentrations as tendons cross over in the pedestal 10. The regrouping of tendons to form flat and wide matrix along each axis was found to be effective in avoiding tendon congestion especially in the pedestal 10. The said flat and wide matrix of tendons is placed as high or as low as possible to maximize their moment arms and optimize their contributed moment capacity. For corrosion protection, bonded (multi-strand and grouted) or un-bonded encapsulated (mono-strand) post-tensioning elements and their associated construction techniques can be used in the foundation 100.

[0159] The rib's thickness can be gradually increased at the connection to the pedestal 10 to increase rib flexural, shear and torsional capacity and enhance pedestal confinement. The post-tensioning requirements can be reduced by engaging dowels at rib-to-pedestal connection and by extending fully developed radial dowels from the rib and the slab 20 deep into the pedestal, thus allowing passive reinforcing to participate in the connection.

[0160] In another embodiment, ribs 16 top surface can be tapered to a substantial slope extending vertically to an elevation near the top of pedestal allowing the ribs 16 to benefit from diaphragm action at their inner zone and also provide lateral support for the full height of the pedestal 10 and to provide concrete confinement at the highly stressed zone at the top of pedestal under tower base flange 301.

[0161] The foundation may have a circular or polygonal foot print. The thickened slab edge 190a, 190b (perimeter beam) may extend above or below the foundation. A shallow perimeter beam profile should be selected for ease of backfilling and improved accessibility for roller compactors during the backfilling of the foundation 100. A thickened slab ring beam 190a may be designed to be at an offset distance away from the slab edge allowing the slab segment, outside the ring, to behave as a cantilever. This configuration reduces slab span and deflections as well as the volume of concrete required in the foundation 100.

[0162] As shown on the drawings the size of the slab 20 and its continuous reinforcing including that of the thickened slab is configured to create a rigid composite connection to the ribs 16 with high stiffness which is sufficient to allow adjoining ribs 16 to participate more in resisting the loads and thus reducing local deflections and increasing overall foundation stiffness in addition to reducing the unsupported length of cantilever radial ribs 16.

[0163] In a preferred embodiment, as shown on the drawings, the pairing of the ribs 16 on distal ends and the continuous perimeter beam construction yield a cost effective layout of post-tensioning that uses a small number of tendons and corresponding anchors as well as reduces friction losses by avoiding sharp turns in tendon layout. The tendons of the ribs 16 are anchored in a matrix array at the outer ends of the rib and extend horizontally and diagonally along the rib to split into at least two groups 58a and 58b one near the bottom and the other near the top of the rib as it connects to the pedestal 10. The tendons are more concentrated at the bottom than at the top in a concentric prestressing pattern that is intended to maximize the structural capacity of the foundation and meet the flexure and shear demand of the governing load cases.

[0164] Ribs 16 may have thickened flanges, at their connection to the pedestal 10, that may also house post tensioning anchors for tendons 58 extending from ribs 16 on the opposite side of the pedestal. The ribs 16 may also have post tensioning anchors along their sides or tops if tendon curtailment methods are applied in the design. The ribs 16 may also have embedded loop anchors if loop of tendons is used in the design. Loop anchors could also be used in the pedestal 10 to support precast concrete towers 300.

[0165] As shown on the drawings the tendons in ribs 16 extend horizontally and diagonally to be split into three distinct groups as they enter the pedestal. The first group 58a with more tendons is placed at the bottom of ribs 16 or in the slab to create camber for reducing deflections and improving foundation soil contact as well as meet the high flexural demand from the governing load cases, and the second group 58b slope up diagonally to follow the geometry of the top of the rib as they enter the pedestal 10. The third group 58c is in the middle and it starts horizontal at rib anchor block and diagonally slopes down towards the bottom of the rib to enter the pedestal 10 for optimum use of the tendons. Tendons in the pedestal 10 are fanned and flared into groups to simplify the installation and maximize their utilization by increasing their moment arms measured from the top or the bottom of the structural concrete. Additional post-tensioning groups for shear resistance can be provided by providing tendons that traverse the shear failure plane in the ribs 16.

[0166] In another embodiment the post-tensioning in the ribs 16 consist of three distinctive groups:

[0167] 1. A bottom group 58a that is horizontal at the bottom of the rib 16 and in the slab 20 and may be grouped with slab post tensioning.

[0168] 2. A top group 58b that is diagonally sloped upward to follow the geometry of rib top.

[0169] 3. An optional middle group 58c that starts horizontal at rib outer edge and is diagonally sloped down towards the bottom of the rib to eliminate dead load deflections and keep the ribs 16 and pedestal under post compression during normal operating conditions and also provide the high demand of post-tensioning capacity required at the bottom of the rib for downward load cases, and traverse the shear failure plane for ribs 16 in the governing downward load cases and provide additional shear resisting capacity in each rib, such that the number of strands in the bottom of the rib and the pedestal 10 is much higher than that at the top thus causing a
multi-axial, heavy, eccentric horizontal post compression in the foundation after the tendons are jacked. [0170] Anchor-blocks for perimeter or circumferential post-tension tendons can be placed at perimeter beams 190, (ring beams) or thickened slab or at the edge of the foundation or on top of perimeter beams 190 or on sides of ribs 16. A preferred layout with two anchor blocks on opposite sides of the foundation and with semi-circular (180-degree) tendon arrangement is shown on drawings. Ring tendons with ring anchors 59d (such as dog-bone anchors) can be used to avoid having blisters on the foundation 100. Styrofoam block-outs 59c can be placed in the foundation 100 according to anchor manufacturer recommended dimensions. When the concrete reaches the sufficient strength ring tendons are jacked and ring anchors grouted.

[0171] The foundation is made of a network of prestressed concrete elements that can be structurally analyzed, with the strut and tie method, as to a three-dimensional structure made of an array of vertically and horizontally oriented truss-girders joined at the center, with major tension chords reinforced with prestressing tendons, based on both upward and downward load cases wherein tension forces in the structure are resisted largely by prestressing elements and passive reinforcing and compression forces are resisted largely by the concrete elements. The structure can be analyzed as a circumferential array of vertically oriented trusses that are fixed at their inner ends to the central pedestal 10 and are laterally stabilized at their bottom by a horizontal trussed diaphragm formed by perimeter post tensioning 59a, in the slab or perimeter beam, and radial bottom tendons 58 in the ribs 16 or the slab 20.

[0172] In another embodiment the fatigue resistant foundation 100 comprises a circumferential array of vertically oriented eccentrically prestressed cantilevered girders that are fixed at their inner ends to a central pedestal 10 that is laterally supported and confined through most of its height by rib concrete, and the ribs 16 and pedestal 10 are laterally stabilized at their bottom by a horizontal prestressed concrete trussed diaphragm, with a continuous slab 20, and the prestressing is provided by radial tendons in the ribs 16 (or the slab 20) and circumferential post tensioning elements 59. The radial and circumferential tendons provide eccentric prestressing in the ribs 16 and the pedestal 10. The pedestal is vertically prestressed and is structurally fixed to a tower base 301 of a pylon.

[0173] In a preferred embodiment the construction of the foundation 100 may utilize pre-assembled perimeter beam reinforcing cages, built in segments with overlapping spliced bars at their ends, and each having an array of shear resisting vertical ties and flexure resisting horizontal bars as well as local reinforcing at anchor locations as shown on FIG. X.

[0174] As shown on the drawings, the foundation has specific reinforcing groups. The ribs 16 have flexure reinforcing concentrated at the bottom and the top, vertical stirrups for shear reinforcing that are tightly spaced at high shear zone along rib inner end, rib skin reinforcing on ach face and bursting and splitting reinforcing made of horizontal hairpins extending between the said rib skin reinforcing, as well as straight or U-shaped horizontal dowels for embedment into the pedestal 10 and vertical dowels, at the bottom, for composite action with the slab 20. As shown on the drawings the vertical stirrups also function as dowels for composite action of the slab 20. The said dowels are spaced such that they could mesh between slab reinforcing bars without geometric interference, if the rib reinforcing is built in preassembled cages and placed over the slab reinforcing. In order to maximize shear capacity vertical stirrups are placed side-by-side, in pairs, at the inner rib zone where the shear demand is high.

[0175] Anchor zones are provided with heavy reinforcing with trim bar and ties. The ribs 16 may also have horizontal reinforcing dowels, perpendicular to the ribs 16, to facilitate the structural continuity of the supported perimeter beams 190 or the thickened slab, across the width of the rib, by means of splicing the said dowels with perimeter reinforcing.

[0176] The pedestal 10 has a horizontal mesh at the top and skin reinforcing at all faces as well as at least one cage, around the anchor bolt assembly, comprising vertical tightly meshed anti-bursting reinforcing including two cylindrical meshes confining the anchor bolts each comprising horizontal hoops and either C or Z-Shaped bars and a radial array of horizontal hair-pins or stirrups tying both cylindrical meshes or spirals stirrups each housing a number of anchor bolts. The pedestal 10 cage assembly may comprise two concentric tightly meshed cages surrounding the anchor bolts one from the inside and the other from the outside with radial array of anti-bursting and splitting resistant hairpins extending between the two cages # and #. Additionally an array vertically oriented pedestal vertical anti-bursting and splitting resistant reinforcing group, comprising circumferentially spaced vertical hairpins extending between said top horizontal mesh and a horizontal bottom reinforcing mesh in the pedestal 10 or slab 20, is included in the pedestal cage. The vertical hairpins # also function as supports to secure tendons in the pedestal 10 during construction.

[0177] Upper and lower slab reinforcing meshes may have any pattern such as a square grid, a circular array with radial pattern or overlapping pie-shaped segments. Additionally, an array of slab reinforcing locally arranged beneath the ribs 16 and being oriented parallel to the ribs 16 and extending into the pedestal 10 to facilitate composite action. The slab 20 may also be reinforced with post-tensioning elements in any pattern including radial, circumferential, perimeter or a square grid.

[0178] The foundation system relies on the use of many prefabricated components including rebar meshes and cages, pedestal cage assembly, pre cut post-tensioning strands, pre-assembled post-tensioning bundles, pre-cut post-tensioning duct sections and prefabricated concrete forms.

[0179] Reusable rib forms 16b are utilized to form foundation perimeter, the ribs 16 and the pedestal. Forms can be made to be segmented, universal, expandable and adjustable to work for different foundation sizes. As shown on FIG. X rib forms 16b can be made with adjustable supports to elevate the forms above the wet slab concrete during construction if the foundation is built in one pour. Rib forms 16b may sit directly on the hardened concrete slab 20 if the foundation is built in two pours. Rib forms 16b may be made with two side-panels of stiffened non-stick plates and an array of adjustable horizontal spacers between the panels to maintain proper geometry and resist the lateral pressure of wet concrete. Rib and pedestal forms 102 may be fitted with lifting lugs or means for receiving and supporting ladders, catwalks and work platforms to allow for access around the foundation. The forms may have means for securing post-tensioning anchors and hardware at specific spacing during construction. The forms may also have means for hanging an supporting rib reinforcing cages.
The foundation 100 may be supported on piles, or micro-piles 401 or piers 402 or rammed-aggregate piers 405. The foundation 100 may receive rock anchors 404 or soil-anchors in a conventional manner. A construction site is prepared by excavation and flattening and preparation of soil for the foundation. The foundation 100 may be set on a mud slab or on compacted granular fill. The mud slab is a thin plain concrete layer intended to provide a clean and level base for foundation installation.

In one embodiment, After the foundation site has been prepared, slab reinforcing is placed inside slab forms and the slab is poured in place with dowels extending up from the slab 20 to receive ribs 16 and pedestal in a second pour. Rib and pedestal rebar and cage placement with post-tension tendons (or duct) placement are accomplished and forms are installed in place and a second pour is carried out. Alternatively the foundation 100 can be poured in a single pour with the use of accelerators in the concrete mix and by following a well designed concrete pour sequence. A set of small footings, placed within the mud slab, can be used to support and elevate the rib forms 16b and pedestal forms 102 during construction. Slab 20, pedestal and rib reinforcing elements are assembled in the foundation 100. Forms are placed in the foundation around the perimeter, the ribs 16 and the pedestal and the concrete is poured into the foundation in a carefully designed pour sequence. One option is to start with slab 20 and the bottom part of the ribs 16 and the pedestal with accelerator in the concrete mix to seal the bottom of rib and pedestal forms 102 by the time the slab 20 concrete is finished, the ribs 16 and the pedestal are poured jointly in small lifts.

When the concrete hardens to certain strength, post-tension elements are jacked and grouted as required. The tower base flange 301 is then attached to the pedestal 10 and grouted, and the tower anchor bolts are tensioned after the grout reaches sufficient strength.

In a preferred embodiment, the invention relates to a high stiffness, fatigue resistant, wind turbine foundation 100, supporting a wind generator with a multi-megawatt rating and subjected to extremely high cyclical upset loads that comprise the following components:

1. a substantially massive and wide central pedestal 10 with substantially solid core concrete construction that is kept, through most of its height, under a combination of lateral structural concrete supports and confinement, high vertical post-compression stress and high eccentric multi-axial lateral horizontal post-compression stress across its width, provided by said lateral supports and post-tensioning elements that traverse the width of the pedestal 10, through non-segmented concrete construction, along multiple axes in a concentric pattern, and having a set of upright, circumferentially spaced anchor bolts, for providing the said high vertical post-compression stress, extending through said pedestal 10, and having lower ends anchored relative to an anchor ring and upper ends projecting upwardly from said top end of said pedestal, said anchor bolts being substantially bond protected along their length, said upper ends of said bolts project upwardly from the said pedestal 10 through a base flange of an annular tower structurally fixed atop the said pedestal 10, and also having an upright heavily reinforced cage of tightly meshed rebar, and concentrically arranged around both sides of the anchor bolt cage with opening to allow the passing of lateral load transfer elements.

2. a support slab-on-grade 20, cast-in-situ out of concrete against the soil, in an excavation footprint, of continuous construction and covering a footprint substantially larger than that of the pedestal 10 and having a thickness that is much smaller than the depth of the pedestal 10 and having thickened edge made of concrete integral with the support slab 20 and having horizontal post-tensioning elements to keep the slab 20 under heavy multi-axial post compression,

3. an array of concentrically arranged ribs 16 made of deep girder construction, integral with the pedestal and support slab 20, and jointly cast-in-situ with said pedestal 10, and extending vertically, above the slab 20, to an elevation near the top of pedestal 10 such that the pedestal 10 is laterally supported and substantially confined below the said tower base flange 301, and having a width that is substantially smaller than that of the said pedestal, and being arranged such that pairs of ribs 16 outwardly extend from opposite sides of the pedestal with post-tensioning elements inwardly extending from the distal ends of the ribs 16 through the pedestal,

4. reinforcing rebar and prestressed dowels extending from the ribs 16 deep into the core of the pedestal 10 from distal ends, and arrays of dowels, made of rebar, extend between the slab 20 and each of the ribs 16 and the pedestal along their conjunctures,

5. a suitable backfill material 13 placed over the foundation 100, to stabilize the foundation 100 against overturning, followed by tower base installation and grouting.

the foundation 100 is kept under heavy multi-axial post-compression such that tower loads are resisted by pairs of ribs 16, on distal ends of the pedestal 10, wherein each pair of ribs 16 form a high stiffness continuous, non-segmented, laterally supported, post-tensioned girder extending between distal ends of the foundation 100 with continuous uninterrupted composite action from the slab-on-grade 20.

In another embodiment, slab post-tensioning can be arranged at any combination of perimeter, radial or diametric, or other patterns.

In another embodiment, composite action is further facilitated with radially oriented, reinforcing bars locally arranged in the slab 20, beneath the ribs 16, and extended deep into the pedestal 10, in addition to an array of vertical dowels extending between the rib and the slab 20 that function as shear connectors.

In a preferred embodiment, the invention pertains to a foundation 100 for supporting a wind generator with a multi-megawatt rating and subjected to extremely high cyclical upset loads, with increased stiffness and improved fatigue resistant comprising:

1. a support slab-on-grade 20 of non-segmented continuous construction with a circular integral perimeter beams 190 with circumferential post tensioning elements 59 made of two 180-degree tendon segments forming a 360-degree circle, with anchors at the opposite sides of the foundation.

2. a central cylindrical pedestal 10 integral with the support slab-on-grade of solid non-segmented construction and having vertical post-tensioning elements,

3. ribs 16 integral with the support slab and the central pedestal 10, on top of the slab 20, with three or
four pairs of ribs 16 radially extending from opposite sides of the pedestal 10 and post tensioning elements extending axially and diagonally from anchors placed at the distal ends of the ribs 16 through the pedestal 10, such that the ribs 16 and the perimeter beams 190 function as a prestressed trussed diaphragm structure with infill panels, and pairs of ribs 16 on distal ends of the pedestal 10 function continuous post-tensioned girder, that are free of construction joints, with continuous composite action from the slab 20 and the foundation 100 is kept under eccentric multi-axial horizontal and concentric vertical post-compression, and circumferential post-tensioning in the slab 20 effectively reduces stress amplitudes and deflections in the slab 20 by keeping the slab 20 under heavy post-compression in the direction of primary slab spans which is roughly perpendicular to the ribs 16.

[0195] In a preferred embodiment, the rib extends vertically from the bottom of the foundation to an elevation near the bottom of the tower base flange 301 to enable the ribs 16 to participate in resisting bearing loads under the tower base flange by increasing the area of the cross-section involved in bearing resistance under the tower base flange 301 and increasing the permissible bearing strength under the base flange or the grout bed by increasing the bearing area measured at the surrounding faces of the concrete. The geometric configuration and the improvement in bearing resistance, in this invention, allow the engineer to specify concrete with only one relatively low compressive-strength for the entire foundation structure. In contrast, high bearing stresses under the tower base flange 301 in conventional gravity spread footings, force the engineer to specify concrete with higher compressive strength for the pedestal and a lower compressive strength for the base.

[0196] The proximity of inner rib ends to the tower base flange 301 allows the inner zones of the ribs 16 to remain under vertical compression stresses caused by vertical post-tensioning forces between embedment ring 54 and tower base flange 301. The said vertical compression stress zones improves confinement conditions and fatigue resistance in rib inner zones.

[0197] Bonded and grouted multi-strand system was found to be expensive and lengthy and requires an additional step of grouting and may not be economical for some onshore installations. The use of unbonded, encapsulated and monocoal strands, arranged in bundles and installed in the foundation reinforcing prior to concrete casting, which would reduce construction costs and improve construction schedule.

[0198] In a preferred embodiment post-tensioning in the foundation 100 is made eccentric, to create cambers in the foundation 100 that could result in reduced deflections and improved foundation-soil contact. As an example, the eccentric prestressing of the ribs 16 creates a convex shaped camber in the foundation 100 that helps reduce the deflections under turbine weight and operating loads. Similarly cambers can be used in perimeter beams 190 and slab sections to reduce slab deflections and improve foundation-soil contact conditions by ensuring a more uniform bearing pressure under the foundation.

[0199] The vertical profile (elevation) of circumferential tendons in the foundation 100 may be adjusted at mid spans and under supporting ribs 16 to optimize their utilization.

[0200] In another embodiment gradual transition of geometry at the conjunction of the structural elements is employed to prevent stress concentration and fatigue related problems.
is free of construction joints, under tower base 301 in one session and to also have the ability to tension all anchor bolts in one session.

- The present invention improves safety and accessibility around foundations during construction, and reduces hazardous conditions for construction crew. That goal is achieved by using reusable form sections that are fitted with platform sections for forming a access platforms around the foundation, and connect to at least one access ramp extending beyond the edge of the foundation. The platform and the ramp are fitted with slip-resistant walking surface and elevated ramps all provided with guardrails and designed to applicable industry safety standards. The relatively thin slab thickness minimizes the risk of worker injury during construction.

Transformer pad can be supported on a precast concrete post extending vertically from the foundation.

- Pedestal forms 102 will have openings for running electrical and communication conduits thus preventing problems stemming from randomly placing the conduits in areas that could compromise the structural design.

- The ribs 16 may have means for receiving and supporting prefabricated trays (or electrical duct banks) for housing power and communication cables.

- This foundation design can also be adapted for offshore wind turbine projects. In this case the foundation 100 may be assembled on a barge or dry dock then transported or floated to its destination, then lowered into a prepared seabed location. The foundation can be weighed down in place by backfilling it with suitable material. The offshore foundation 100 may be configured to receive any type of offshore piers 404, suction piers 403, piles 400, micro-piles 401, anchors 404 or any combination of the above.

- The invention relates to an offshore concrete foundation 100 with high stiffness and improved fatigue resistant comprising:

- 1. a support slab-on-grade 20 of non-segmented continuous construction covering the entire footprint of the foundation and having (horizontal) diametric and perimeter post-tensioning elements,

- 2. a central pedestal 10 integral with the support slab-on-grade 20 of solid non-segmented construction and having vertical post-tensioning elements and also having reinforcing elements of rebar to carry loads diametrically across the pedestal 10,

- 3. a cylindrical or conical stem 11 extending vertically above the pedestal 10 and being fixed to the pedestal 10, and having a hollow cross section, of equal size or smaller than that of the pedestal 10, and may be constructed with segmented or non-segmented construction methods and could be made with typical cast in place over the pedestal 10 by using typical construction methods for tall cylindrical concrete structures such as continuous forming, successive pours, segmental construction with precast concrete panels or other known construction methods used conventionally for cylindrical concrete structures such as chimneys, and the stem 11 is kept under heavy concentric vertical post-compression stress by an array of circumferentially arranged vertical post-tensioning elements, and the stem 11 may have an ice cone 11b integral with the top of stem 11, and the stem 11 having means for fixing a tower base 301 of a wind tower 300, the stem 11 and the ice cone 11b are vertically and circumferentially posttensioned with vertical and circumferential post tensioning elements,

- 4. ribs 16 integral with the support slab 20 and the central pedestal 10, on top of the slab-on-grade, with pairs of ribs 16 radially extending from opposite sides of the pedestal 10 with post-tensioning elements extending radially and diagonally from the distal ends of the ribs 16 through the pedestal 10 and keeping the ribs 16 and the pedestal 10 under heavy eccentric post compression stress and reinforcing dowels extending from the ribs 16 into the pedestal 10 and spliced with pedestal 10 reinforcing,

- 5. deep perimeter beams 190 extending continuously around the foundation, made of concrete integral with the support slab-on-grade 20 and the ribs 16 and having continuous perimeter or circumferential post tensioning elements.

When the concrete sets, the said post-tensioning elements are jacked and the anchor bolts are post-tensioned the foundation is kept under heavy multi-axial post-compression.

- The offshore foundation 100 is constructed on a barge or in a dry dock and then floated or transported to an offshore installation site and lowered to be placed on a prepared sea bed, a suitable backfill material 13 placed over the foundation 100 to stabilize the foundation against overturning. Scour protection measures 13b are provided around the foundation. The foundation is built with marine cement and marine grout and is kept under heavy multi-axial horizontal and vertical pre-stress using bonded and grouted post tensioning systems rated for double corrosion protection and suitable for marine environment.

- An offshore foundation for wind turbines comprising the following elements:

- 1. A vertically extending pedestal that is cast in situ, on a barge, out of concrete, the pedestal has an integral long stem 11 for receiving and supporting a tower structure;

- 2. A substantially horizontal support slab 20 that is cast in situ, on a barge, out of concrete, the support slab 20 covering an area of ground larger than that covered by the pedestal 10;

- 3. A plurality of radial ribs 16 extending radially outwardly from the pedestal 10 and spaced around the pedestal 10, each rib being prefabricated and being joined along the base thereof to the support slab 20 when the support slab 20 is cast in situ and being joined along an inner side thereof to the pedestal 10 when the pedestal 10 is cast in situ;

- 4. A plurality of prefabricated perimeter beams 190 spanning continuously, near the perimeter of the foundation, between ribs 16 and supporting the slab 20;

- 5. Backfill 13 for weighing down the foundation, resisting tower loads and providing scour protection 13b.

When the concrete sets, the precast components will become integral with a cast-in-place components. Radial post-tensioning tendons extend from rib ends opposite rib ends across the pedestal 10. Vertical post-tensioning is arranged in the pedestal 10 as well. The stem 11 and the ice cone 11b may also benefit from circumferential post-tensioning.

- The pedestal 10 has means for receiving and supporting a tower 300 or pylon. The upper portion of the pedestal 10 (the stem 11) may be made in multiple consecutive cast in situ pours, depending on its height. Alternatively, the
stem 11 may also be made by joining precast segments with circumferential and vertical post-tensioning to form the stem 11.

[0227] In another embodiment of the invention, a wind turbine is fabricated on a barge with precast concrete element as following. The barge surface is prepared with a non-bonding agent or a thin membrane at the foot print where the foundation to be built. Lower slab reinforcing mesh sections are assembled and placed and the pedestal cage reinforcing is assembled at the center of the foundation. Upper slab reinforcing mesh sections may follow after slab post tension duct is placed. Precast concrete ribs 16 are placed in a radial array around the pedestal cage and precast concrete perimeter beams 190 are arranged around the perimeter of the foundation. Post tensioning ducts in the pedestal space and at perimeter beam-to-rib connections are placed to pair with corresponding duct in the precast members. Forms for pedestal and for closure pours at rib-to-perimeter beam connections are installed. Slab concrete is poured followed by pedestal 10 concrete and closure pours at rib-to-pedestal connections. Stem 11 is fabricated possibly in multiple consecutive pours depending on pedestal height. Stem 11 design may incorporate an ice cone 11b at its top. Post tensioning tendons are installed, the jacking and grouting of tendons is carried out. Some pylon sections could be installed earlier prior to transportation. The finished foundation 100 is transported to its offshore installation site using a suitable means of transportation such as towing the barge.

[0228] In another embodiment of the invention relates to an offshore foundation for wind turbines comprising the following elements:

[0229] 1. A vertically extending pedestal 10 that is cast in situ, on a barge or dry dock, out of concrete;

[0230] 2. A substantially horizontal support slab 20 that is cast in situ, on a barge or dry dock, out of concrete, the support slab 20 covering an area of ground larger than that covered by the pedestal 10;

[0231] 3. A plurality of radial ribs 16 extending radially outwardly from the pedestal 10 and spaced around the pedestal 10, each rib being prefabricated and being joined along the base thereof to the support slab when the support slab 20 is cast in situ and being joined along an inner side thereof to the pedestal 10 when the pedestal is cast in situ, each rib has an integral pier for receiving a leg of lattice lower;

[0232] 4. A plurality of perimeter beams 190 spanning continuously, near the perimeter of the foundation, between ribs 16 and supporting the slab 20, optionally each perimeter beam can be prefabricated;

[0233] 5. A lattice tower 200 having a plurality of legs structurally connected to the integral piers 180 in the ribs 16, the lattice tower 200 has, at its top, means for receiving and structurally supporting a pylon or a tower 300;


[0235] When the concrete sets, the pre-cast components will become integral with a cast-in-place components. Radial post-tensioning tendons extend from rib ends opposite rib ends across the pedestal 10. Vertical post-tensioning is arranged in the pedestal 10 as well. The structural behavior is improved by the added compression in all ribs 16, edge beams, slab 20 and center pedestal.

[0236] The lattice tower 200, preferably incorporating 3-dimentional trusses, transfers the pylon loads down to the concrete foundation 100. The lattice tower 200 may get connected to the concrete foundation prior to transportation or it can be connected to the foundation at final offshore installation site.

[0237] In another embodiment of the invention, a wind turbine is fabricated on a barge with precast concrete element as following. The barge surface is coated with a non-bonding agent or covered with a thin membrane at the foot print where the foundation to be built. Lower slab reinforcing mesh sections are assembled and placed and the pedestal cage reinforcing is assembled at the center of the foundation. Upper slab reinforcing mesh sections may follow after slab post tension duct is placed. Precast concrete ribs 16 are placed in a radial array around the pedestal cage and precast concrete perimeter beams 190 are arranged around the perimeter of the foundation. Post tensioning ducts in the pedestal space and at perimeter beam-to-rib connections are placed to pair with corresponding duct in the precast members. Forms for pedestal and for closure pours at rib-to-perimeter beam connections are installed. Slab concrete is poured followed by pedestal concrete and closure pours at rib-to-pedestal connections. A lattice tower 200 structure is prefabricated and mounted atop the concrete foundation 100. The foundation is transported to installation site using a suitable means of transportation. Seabed is prepared for receiving the foundation by placing a sub-base of suitable material such as crushed stone. The foundation is backfilled and scour protection measures 13b are installed.

[0238] In another embodiment of the invention, the stem 11 is prefabricated separately and provided with means for connecting to the pedestal 10, preferably an array vertical post tensioning dowels extended between the pedestal and the stem or other segmental post tensioning joining methods. The pedestal may be fitted with means for receiving the prefabricated stem based on segmental post tensioning and grouting construction methods.

[0239] Piles 400, Micro-piles 401 or piers 402 or suction piers 403 or anchors 404 can be used with the offshore foundation 100 in a similar manner described in the application. In this case vertical sleeves will be arranged in the foundation to receive an array of piles 400 or anchors extending through the foundation, and allow for additional loading capacity and improve stability of foundation. Piles 400 are secured to the foundation by filling the sleeves with marine grout.

[0240] Under some conditions, the use of piles 400, piers or suction piers or anchors may eliminate the slab 20 and/or the perimeter beams 190 from the design.

[0241] Obviously, many modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that, within the scope of the invention.

1. A foundation comprising:
   a concrete support slab having horizontal rebar therein,
   a concrete pedestal integral with the support slab having vertical rebar therein,
   a plurality of concrete ribs on top of and integral with the support slab and integral with the pedestal, the ribs being radial to pedestal, and having connection elements extending from the ribs into the pedestal and from the ribs into the slab,
   post tensioning elements extending from the distal end of the ribs through the pedestal and,
a perimeter beam in the slab having a post tensioning element therein.

2. A foundation as in claim 1 wherein, the ribs positioned in pairs on opposite sides of the pedestal and having the tension elements extending from the distal ends of the ribs through the pedestal.

3. A foundation as in claim 2 wherein, the post tensioning elements in the ribs are eccentrically arrayed for eccentric loading.

4. A fatigue resistant foundation comprising: a horizontally prestressed concrete slab having a structurally continuous horizontal rebar grid for reinforcing the slab and a plurality of horizontal post tensioning elements therein for prestressing the slab, and a perimeter beam proximate the perimeter of the slab, a vertically extending central concrete pedestal having a plurality of vertical post tensioning elements, the pedestal integrally connected to the slab, a plurality of reinforced concrete ribs on top of and integrally connected to the slab with structural continuity between the rib and the slab, the ribs integrally connected to the pedestal, with structural continuity between the rib and the pedestal, at least one post tensioning element running through each rib and the pedestal for providing post tensioning stress in the ribs and pedestal and for connecting the ribs to the pedestal under post compression stress, such that the pedestal, slab and the ribs are connected to each other to form a monolithic foundation with a three dimensional network of post tensioning elements in the slab, pedestal and ribs keeping the foundation under multi-axial compression while resisting operating loads, and during normal and abnormal extreme loads, thus linking the slab and the ribs to the pedestal under vertical, and horizontally eccentric post compression stress, with reduced multi-axial stress range amplitudes in the concrete and steel reinforcing.

5. A foundation as in claim 4 wherein, the perimeter beam comprises a thickened perimeter slab portion.

6. A foundation as in claim 5 wherein, the thickened perimeter slab portion comprises a plurality of slab perimeter reinforcing cages, each cage having a plurality of continuous horizontal bars housed in an array of vertical stirrups extending between the horizontal bars for reinforcing the perimeter slab portion and having a perimeter post tensioning element extending through the plurality of perimeter reinforcing cages to further post tension the perimeter slab portion.

7. A foundation as in claim 4 wherein, the pedestal has a vertical inner reinforcing cage and an outer reinforcing cage with the plurality of vertical post tensioning elements therebetween, the pedestal also having a horizontal bottom reinforcing mesh, and a horizontal top reinforcing mesh, with an array of vertical reinforcing hairpin bars extending therebetween for reinforcing the core of the pedestal.

8. A foundation as in claim 4 wherein, the pedestal has pairs of ribs on opposing sides of thereof and post tensioning elements extending from the distal ends of the ribs through the pedestal to hold the ribs to the pedestal under post compression stress.

9. A foundation as in claim 7 wherein, the pedestal has a vertical inner reinforcing cage and an outer reinforcing cage with the plurality of vertical post tensioning elements therebetween, the pedestal also having a horizontal bottom reinforcing mesh, and a horizontal top reinforcing mesh, with an array of vertical reinforcing hairpin bars extending therebetween for reinforcing the core of the pedestal.

10. A foundation as in claim 9 wherein, the pedestal has pairs of ribs on opposing sides of thereof and post tensioning elements extending from the distal ends of the ribs through the pedestal to hold the ribs to the pedestal under post compression stress.

11. A foundation as in claim 4 wherein, the ribs are cantilevered and have a neutral axis, and the post tensioning elements in the perimeter beam and in the ribs and through the pedestal are spaced relative to the neutral axis of the cantilevered ribs to provide a three dimensional post compression load pattern in the foundation to counter influence the multi-stage and multi-axial fatigue loading of the forces of a wind tower supported thereon when the post tensioning elements are tensioned to the desired stresses.

12. A foundation as in claim 4 wherein, the ribs have a neutral axis and the post tensioning elements in the perimeter beam, in the ribs and through the pedestal are spaced relative to the central axis of the ribs to provide a camber pattern in the foundation to counteract the deformation due to the dead loads on the foundation from self weight, soil weight and the weight of a wind tower supported thereon when the post tensioning elements are tensioned to the desired stresses.

13. A foundation as in claim 4 wherein, the ribs are cantilevered and have a neutral axis such that when perimeter post tensioning elements in the slab are tensioned at an elevation below the neutral axis of the cantilevered ribs it causes an eccentric loading of the cantilevered ribs and the pedestal to satisfy the governing load case of ribs under downwind loading during extreme normal and abnormal load cases when the post tensioning elements are tensioned to the desired stresses.

14. A foundation as in claim 4 wherein, the pedestal is laterally confined by the ribs and the vertical post tensioning elements in the pedestal, and the pedestal further comprises a plurality of bond-protected anchor bolts extending vertically from an embedment ring near the bottom of the pedestal through the top of the pedestal for securing a base flange of a tower in full contact under compression for providing vertical post compression stress in the foundation when the anchor bolts are tensioned.

15. A foundation as in claim 4 wherein, a backfilling material placed over the foundation adds stability and stiffness to the foundation.

16. A foundation as in claim 4 wherein, the size, distribution, eccentricity and location of post tensioning elements in the ribs and the slab are selected to
dictate the natural frequencies in the foundation for a desired safety range selected for the operating frequencies of the wind tower and generator supported on the pedestal.

17. A foundation as in claim 4 wherein, the ribs are prefabricated.

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