Deliverable D4.1.1 –
State of the art on component level

All Partners WP4 Task 4.1

October, 2013

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2 INTRODUCTION

Levelised cost of energy (LCOE) is one of the main decision drivers for or against offshore wind exploitation. Recent projects indicated actual LCOEs of around 165 € per MWh [01]. A reduction is highly desired, if not even necessary, for a further deployment of offshore wind energy. A study by the Crown Estate [01] indicates possible reduction up to under 100 € per MWh until 2020, which would be a reduction of 37.5%. Various fields were identified, which might contribute achieving this goal. Innovations regarding the support structure was one of those. Therefore, a reduction of costs of at least 20% is aimed for in the description of work during the course of this project [02] to significantly contribute to the realisation of the goal in cost reduction. Furthermore, risks and possibilities will be assessed.

The prospects of completely new concepts are expected to be minor, wherefore the focus in task 4.1. is on "Innovations on component level". Relevant topics for future cost-effective, mass-producible designs were identified, such as new foundation types (without grout and/or piling), soil-structure-interaction of large piles or suction buckets, innovative transition piece designs or designs using hybrid materials never employed in wind energy before. In addition, design integration using jacket-specific controls and innovative fabrication and installation processes shall complete the overall cost saving potentials.

This deliverable shall not only reflect the current state of the art in the identified fields. The actual state of the art will be extended throughout this project from the current 5MW turbine class to 10-20 MW. To realise this step, upscaling will not be sufficient anymore. Issues will arise due to the cubic law, when increasing the rotor diameter and heading for a larger water depth. An identification of the development needs and prospects especially for the InnWind.eu reference turbine is therefore necessary and will be found in the subsections.

The following fields of interest, illustrated by Figure 2-1, are found in the sections of this report:

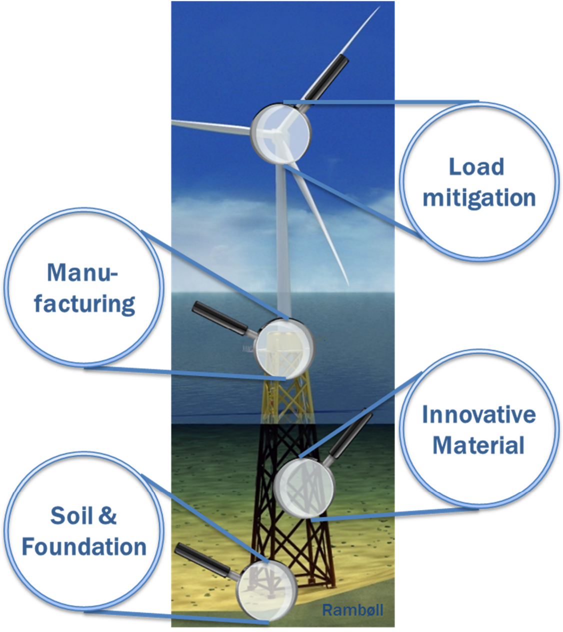

Figure 2-1: Subfields in task 4.1.

Innovative materials:

Hybrid materials, such as sandwich structures are introduced in section 3 by the partners Leibniz University of Hannover (LUH) and Knowledge Centre Wind turbine Materials and Constructions (WMC).

Soil & foundation:

Improvements in the modelling and numerical simulation of the soil structure interaction as well as innovative support structure and foundation designs are treated in section 4 by the Fraunhofer Institute IWES Hannover (FhG-H), the Danish Technical University (DTU) and Aalborg University (AAU).

Load mitigation:

Concepts for load mitigation, such as jacket-specific and structural control are investigated in section 5 by the Fraunhofer Institutes LBF Darmstadt (FhG-DA) and IWES Kassel (FhG-KS), as wells as by the Danish Technical University (DTU) and ForWind Oldenburg (FORWIND-OL).

Manufacturing:

Rambøll (RAMBOLL) is focusing on innovations in manufacturing, mass-production and installation in section 6.

The references used in the partners' contributions are listed directly subsequent to the particular subsection.

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[01] The Crown Estate, "Offshore Wind Cost Reduction: Pathways Study", 2012
[02] InnWind.eu, "Annex I - "Description of Work"", Grant agreement no: 308974, 2012

3 INNOVATIVE MATERIAL

The support structure accounts for over 20% of the CAPEX for an offshore wind turbine, and this number increases when moving to deeper waters. Offshore substructures are exposed to severe environmental conditions. For an estimated service-life of approximately 20 years, they have to withstand up 10^9 load cycles from wind and wave actions. Available steel substructures are depicted in Figure 3-1 and summarized in Table 3-1.

Figure 3-1: Substructures for Offshore Wind Turbines: Monopile, Tripod, Suction Bucket, Jacket, and Floating (f.l.t.r.) [02]

Table 3-1: Type of substructure related to water depths [02]

Substructure	**water depth**					
	small (0 to 25 m)		**average (25 to 50 m)**		**large (>> 50 m)**	
Monopile	■	■	▒	□	□	□
Tripod	□	▒	■	■	□	□
Suction bucket	■	■	■	■	□	□
Jacket	□	▒	■	■	■	▒
Floater	□	□	□	□	□	■ >100 m

■ : well ▒ : fair □ : poor

A key factor in the decision for the type of support structure is the water depth. For waters beyond 40 meters water depth the jacket is seen as the most suitable bottom mounted support structure [01]. There are no technical limits to expanding the jacket design to water depths of several hundred meters and jackets are already being used in such water depths in the offshore oil and gas industry. However, this versatility of the jacket design comes at a price, and the challenge in developing jackets for offshore wind turbines in deeper waters is in bringing the cost of jackets down. Especially the weight-to-stiffness ratio of jackets is beneficial in comparison to Tripods or Monopiles.

A typical jacket consists of 4 legs that are connected by braces to provide stability. The braces commonly form a repeating pattern, the so called panels. The legs are placed at an angle to increase the footprint of the jacket and thus provide stability and effectively counteract the overturning moment of the wind and wave actions. Because of this angle the panels of the jacket increase are larger towards the bottom of the jacket. The number of panels in an important parameter of a jacket as it defines the number of nodes. The nodes of a jacket are commonly welded joints and whereas the complex welds are important contributors to the fabrication costs.

The basic design of a jacket is not expected to see any revolutionary changes. Therefore cost reduction has to be achieved reduced material use and reduced fabrication costs. Reducing material use requires optimization of material use and the use of materials with higher loading capacity. High strength steels can withstand higher stresses and enable the use of thinner walled members. However, the minimum wall thickness does not only depend on the allowable stress, but also on the resistance against buckling or wrinkling. A way to circumvent this limit is to move to a sandwich structure especially with regard to large water depths and longer span width of chords and braces. In paragraph 3 research on sandwich materials for support structures will be discussed.

Another challenge when moving to higher strength materials is to achieve sufficient joint strength. Often the joints are the critical parts in a truss structure, especially when considering fatigue loading. In a welded structure the fatigue life of the structure is commonly governed by the fatigue life of the welds. Welding also proposes a challenge in the use of high strength steels, as the weld fatigue strength hardly improved for higher strength steels. Therefore, to utilize the higher (fatigue) strength of such steels better joining methods have to be developed.

Next to a higher loading capacity another challenge is to bring the cost of joints down. The high number of joints in a jacket is an important contributor to their cost and the main reason why jackets are only an attractive solution for larger water depths. Therefore joining methods have to be developed that do not only address the strength requirements, but are offer potential for cost savings.

Figure 3-2: Welded nodes in a jacket structure (source: www.foundocean.com)

The use of sandwich material provides both challenges and opportunities for joining. For a sandwich structure both faces of the sandwich have to be joined, which increases complexity. On the other hand the sandwich structure can also be used as an advantage, by utilizing the sandwich core for joining and exploiting the fact that there are two face layers. Joining of sandwich material will be addressed in paragraph 0

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3.1 Sandwich material for tubes (LUH)

3.1.1 Technologies used in industry for current 5 MW class and in other sectors

The stiffness of jacket substructures is influenced by the overall global stiffness of chords and braces. With increasing water depths, the structural stiffness has to be increased due to frequency reasons. In case of using pure steel tubes, the overall substructure weight increase is disproportional assuming a quadratic influence of the water depth. That finally leads to ineffective and uneconomic solutions of steel substructures, but as well as for concrete substructures like gravity foundations. One promising solution is the use of sandwich structures. As proposed by Keindorf [LUH01], sandwich structures for towers can be built with different types of core materials, see Figure 3-3. With regard to spatial substructures like jackets, it is obvious that jacket chords and bracings can also be built as sandwich structures. Compared to typical jackets made of steel tubes, the break-even point of economic efficiency is expected at water depths slightly deeper than 50 or 60 m. There, the ratio between weight reductions due to sandwich structures in relation to installation / vessel costs may show a benefit for sandwich structures. This has to be discussed in on-going research.

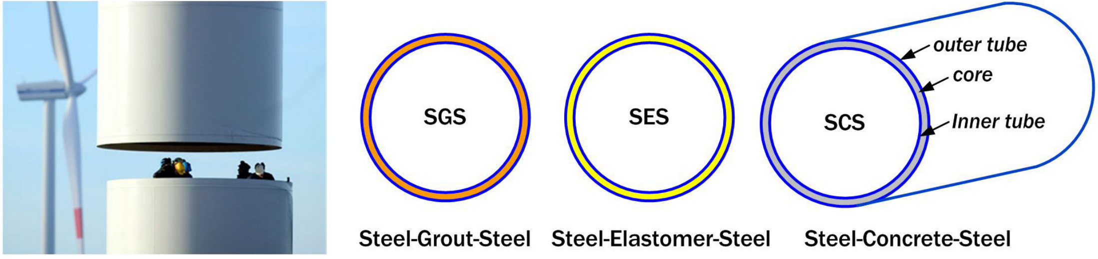

Figure 3-3: Steel- and different types of sandwich structures for towers

Sandwich structures with a concrete, grout or elastomer core have not been used in offshore structures, yet. In standard structural buildings like skyscrapers and multi-storey car parking's, sandwich structures, better known as double-skin composite columns (see Teng et al. [LUH02, LUH03] and Han et al. [LUH04]) have been used quite often, see Figure 3-4 left.

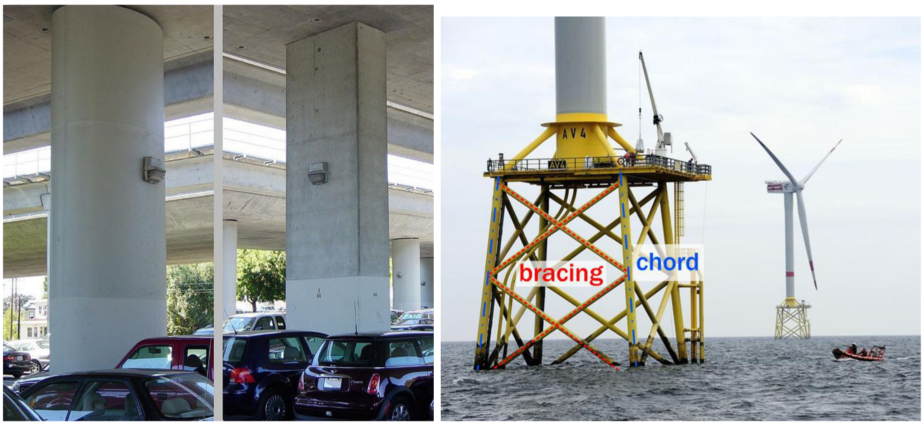

Figure 3-4: Composite and concrete column (© Magnus Manske) (left), Jacket substructure (©DOTI) (right)

With regard to columns, double skin steel sections with fibre reinforced concrete (FRP) filling are commonly used and can be considered as state of the art for columns in buildings, see Teng et al [LUH02, LUH03]. Investigations on columns made from ultra-high performance concrete (UHPC), wrapped with steel tubes were performed by Lindschulte [LUH05] focussing on the influence of confinement effects and compressive strength on the axial ultimate strength. The investigations show that UHPC as core materials offers new opportunities for lightweight and robust structures compared to double skin steel composites with FRP core. First investigations explicitly for wind turbine tower sections were carried out by Keindorf [LUH01]. Besides the ultimate limit state, the influences of cyclic loading conditions were investigated. Nevertheless, no investigations on sandwich structures in Jackets exist.

Core materials

To decrease the costs of offshore structures, it is recommendable to use normal strength steels and cheap core materials. Keindorf [LUH01] suggests cementitious grout or Elastomer core materials. Material parameters of industrial core materials for sandwich structures like young's modulus or uniaxial compressive strength are summarized in Table 3-2. In contrast to grouts and Elastomer, Lindschulte [LUH05] examined Ultra-High Performance Concretes (UHPC) with and without fibres. Material parameters can be taken from Table 3-3. Compared to Elastomer, the material costs of grouts and UHPC are significantly cheaper. But as a drawback, preparation (mixing and pouring) of grout and UHPC is even more difficult. Independent from the core material, the following requirements have to be fulfilled:

- Workability
- Stiffness, elasticity, and ductility
- Bond and compressive strength
- Early age strength
- Durability
- Temperature resistance

Table 3-2: Material parameters of different grout and elastomer core materials

Parameter		**unit**	**Grout**			**Elastomer**	
			Densit Ducorit S5	**Pagel V1/10**	**MC S-Fix**	**Elasto-gran**	**Pagel EH196R**
Young's modulus	E	MPa	55,000	39,800	15,500	820	13,000
Poisson ratio	ν	-	0.19	0.20	0.20	0.36	0.27
Density	ρ	kg/m^3	2,440	2,280	1,780	1,150	1,800
uniaxial compressive strength	f_c	MPa	130	87	42	18	140
tensile strength	f_{ct}	MPa	4	3.49	2.66	16	4.1
bond shear strength	τ_{bond}	MPa	3.64	1.47	0	9.38	1.7
bond tensile strength	f_{bond}	MPa	0.54	0.76	0.55	4.66	3.5
max. aggregate size	d_g	mm	5	1	2	<0.5	0.5

Table 3-3: Material parameters of UHPC core material

Parameter		**unit**	**UHPC**	
			Heat treatment (HT)	HT + steel fibres (2.0 Vol.-%, l/d=6/0.16)
Young's modulus	E	MPa	48,000	50,400
Poisson ratio	ν	-	0.2	0.2
Density	ρ	kg/m^3	2,345	2,511
uniaxial compressive strength	$f_{c,cube100}$	MPa	220	230
flexural strength	$f_{ct,fl}$	MPa	20	26
max. aggregate size	d_g	mm	0.5	0.5

The performance of sandwich structures for offshore substructures is influenced by the bond behaviour between steel shell and core material. Additionally, the stress-strain-behaviour and so the brittleness and ductility of the core materials has an impact on the performance of the sandwich structures. In Figure 3-5, uniaxial stress-strain-relations for steel, elastomer, and concrete are depicted. For comparison reasons, related stress levels as the ratio of stress vs. uniaxial strength have been used.

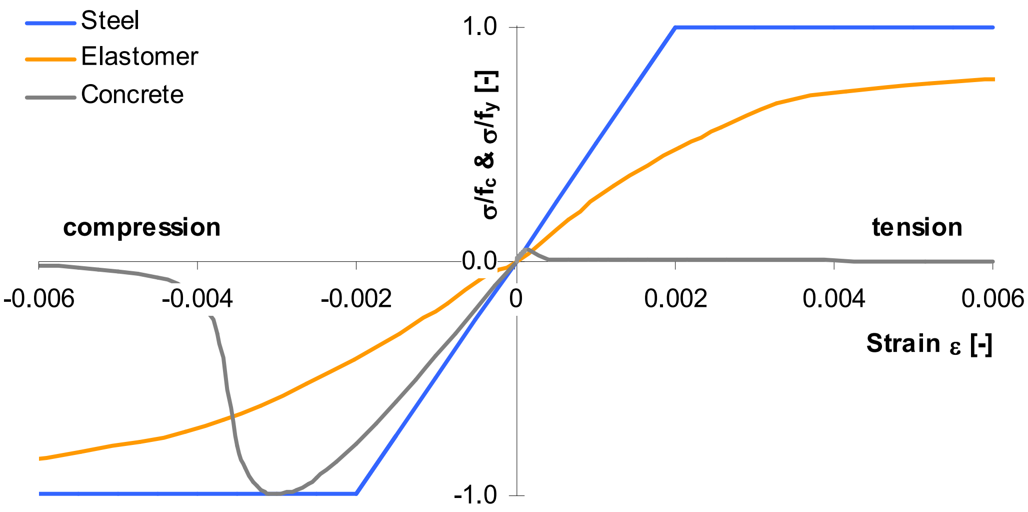

Figure 3-5: Uniaxial stress-strain relation for Steel, Elastomer and Concrete

The stress-strain relation for steel is the typical bilinear approach. In case of stress levels less the yield strength, steel behaves purely linear elastic. By exceeding the yield strength f_y, the material behaviour of steel is considered as ideal plastic. Increased stress levels lead to a disproportional increase in the strain.

Compared to steel, the uniaxial stress-strain-relation of elastomer (which can be found in Keindorf [LUH01]) can be treated as multi linear. For reasons of simplification, a linear approach for small stress levels may lead to sufficient results.

In contrast to Steel and Elastomer, the orthotropic material behaviour of concrete and grout leads to different failure modes under compression and tension, see Figure 3-5 (grey line). Grout and UHPC is characterized by its high strength (>150MPa) and brittle fracture mode. The range of the linear elastic stress-strain behaviour extends with an increasing strength. Thus, in comparison to normal strength concrete, UHPC has a more distinct linear elastic stress-strain behaviour; see König et al. [LUH06]. Brittle failure occurs in unreinforced UHPC, because a high amount of energy is induced during the compression process on account of the high strength and the increased stiffness; see Schmidt et al. [LUH07]. The tensile strength of concrete in general is relatively low compared to the compressive strength and reaches for normal strength concrete approximately 1/10 of the compression strength, see Grübl et al. [LUH08]. With increasing compressive strength this relationship even decreases. For high- and ultra-high strength concretes, this ratio is given as about 1/20, taken from König et al. [LUH06]. In contrast to the characteristic failure under compression load, cracking is the dominant failure mode for concrete under tensile stresses. There are no significant differences in the lateral strain behaviour of concretes with different strengths, if the concrete is loaded only in the linear elastic stress regime. If this is exceeded, the Poisson ratio of the concrete increases disproportionately due to cracking in the microstructure. The tensile strength of the concrete increases disproportionally with increasing compression strength and can be slightly improved by steel fibres as reinforcement. Fibre orientation, which is mainly influenced by the pouring of the concrete, and fibre geometry strongly affect the effectiveness of steel fibres, see Lohaus et al. [LUH09].

Moreover, the stress dependent failure modes as well as the failure behaviour of concretes and grouts are also influenced by shrinkage, swelling and creeping leading to initial (micro-) cracking. They reduce the ultimate fatigue strength significantly. Autogenous shrinkage is the indicative measure of the load-independent deformation value of UHPC. Without external moisture loss (drying shrinkage), autogenous shrinkage can be estimated as about 1.0 mm/m, see Müller [LUH10]. By adding steel fibres to the UHPC composition, autogeneous shrinkage effects can be decreased. Fibres act as reinforcement and prevent the micro-cracking due to restrained stress as a result of load-independent deformation.

The contemplated field of application for UHPC-filled Sandwich components in Jacket substructures for OWT are the chords and the braces. It is appropriate to produce these components as precast elements and integrate a heat treatment. The heat treatment at about 90°C for 48h increases the compression strength while accelerating the setting process. The heat treatment speeds up the production process.

In case of cyclic loadings, the strength of core materials as well as for steel is reduced due to material fatigue, see Almar-Naes et al. [LUH11]. Based on the Miner's rule as linear damage accumulation hypothesis, the damage can be calculated as the ratio of occurring load cycles n to enduring load cycles N for each interval i.

$$D=\sum_i \frac{n_i}{N_i} \le 1 \qquad \text{Eq. 1}$$

The number of occurring load cycles are determined from counting algorithm like Rainflow count or reservoir method. On the resistance side, the number of enduring load cycles is obtained from SN-curves. In Figure 3-6, SN-curves acc. to fib Modelcode [LUH12, LUH13] for high strength concretes and Elastomer acc. to Abraham [LUH14, LUH15] are shown. It can be seen that large stress amplitudes σ_a lead to a loss of fatigue strength of concrete (Figure 3-6 left). With increasing lower stress levels, stress amplitudes are reduced and the fatigue resistance is increased. In contrast to this, the fatigue resistance of Elastomer is reduced if the mean stress level is pure tension or compression, see Figure 3-6 right. In case of fully reversal cyclic stresses the maximum fatigue resistance can be achieved.

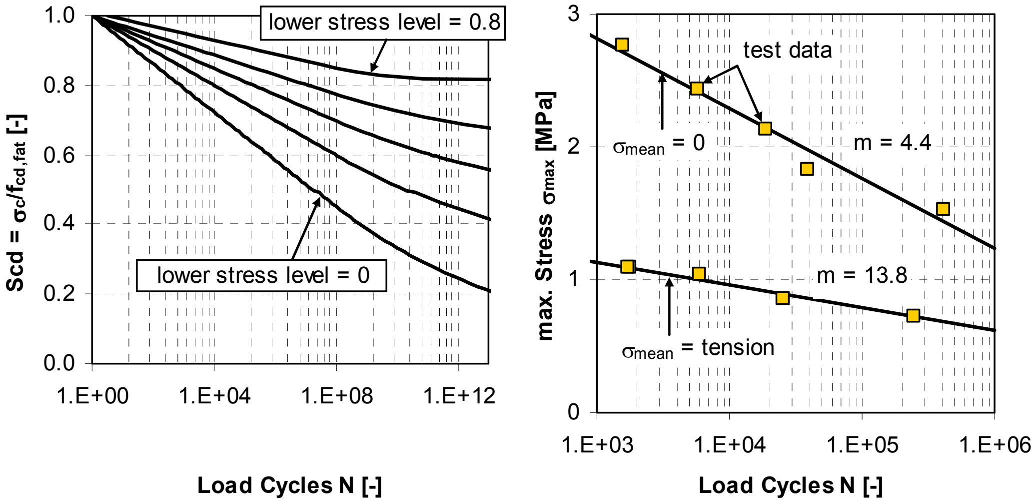

Figure 3-6: SN-curves for high performance concrete (left) and Elastomers (right)

Under consideration of the stress-strain relation shown above, the fatigue performance of grouts and concretes seems to be suitable for dominating compression stress states. In case of alternating stress levels, cracking may reduce the local stiffness and fatigue resistance. Obviously, Elastomer cores seem to be more suitable. But nevertheless, stress ratios, and number of endurable load cycles are significantly smaller than Concrete, Grout or UHPC. For SN-curves for steel sections and joints, reference is made to EN 1992-1-9 [LUH16].

3.1.2 Technologies under current RTD for 5MW class and in other sectors


Figure 3-7: Sandwich structure with UHPC core under ultimate loads acc. to Lindschulte [LUH05]

The global axial bearing capacity of thin-walled steel-wrapped UHPC tubes was investigated during a DFG-Project (funding sign: L0751/13-1). The identification and quantification of influences on the ductility of the construction element were systematically examined in an extensive test program (Figure 3-7). Lindschulte [LUH05] evaluated the effects of cross section geometry and concrete technology such as steel fibers, concrete compressive strength and autogenous shrinkage as relevant parameters to the ductile behaviour and bearing capacity of the examined construction. It was confirmed that a targeted increase in ductility is possible using different arrangements of the internal and external steel plates, depending on the percentage of the steel cross section. The autogenous shrinkage behaviour of UHPC may lead to constraint-induced cracking in the concrete section and showed significant influence on the ultimate load bearing capacity. Based on the experimental results, bearing mechanisms have been identified by analytical investigations and a semi-empirical model has been developed. Both the bearing and the residual capacity of tube configurations can be predicted with sufficient precision.

Investigations on sandwich structures for wind turbine substructures were carried out firstly in the German BMU - research project GROW "Grouted Connections for Offshore Wind Turbines" (funding sign: 0327585). Besides large scale bending tests on grouted joints for Monopiles, scaled tests on the ultimate, buckling and fatigue performance of sandwich structures were carried out. Main achievements and results are summarized in Keindorf [LUH01], Schaumann et al. [LUH17] and Lochte-Holtgreven [LUH18]. All test data are publically available and can be used for numerical benchmarking. Additional tests on grouts and grouted joints are carried out in the BMU-research project "GROWup" (funding sign: 0325290).

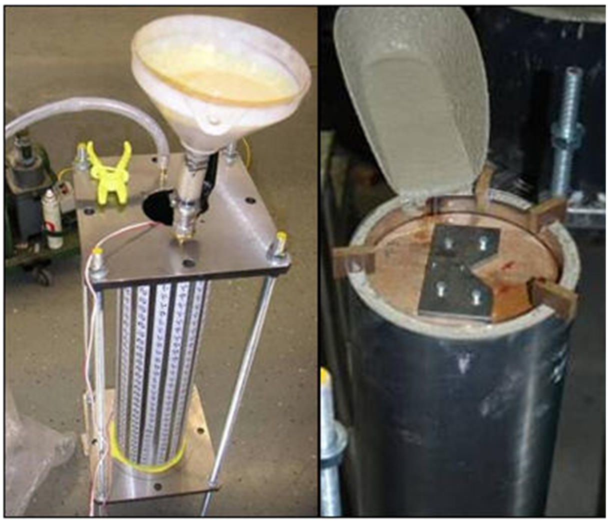
Figure 3-8: Test specimens with elastomer core (left) and grout core (right) acc. to Keindorf [LUH01]

Main objectives of the investigation within GROW were the determination of ultimate and fatigue strength of axially loaded sandwich structures. Two different test specimens can be seen in Figure 3-8.

3.1.3 Development needs and prospects for the preliminary design of the reference support structure and consequences for the work program in task 4.1.

The use of sandwich structures in offshore substructures is part of on-going research. It seems to be a promising solution to reduce costs and weight of offshore substructures for large water depths and increase the efficiency. For the special case of jacket substructures, loading conditions in chords and braces deviate from those which have been investigated in the recent years. Future research work is required. The following topics have to be addressed:

- Experimental investigations on sandwich structures under combined loading (bending and axial loads)
- Development and validation of numerical tools
- Benchmark of numerical models with large (scaled) component tests
- Derivation of a validated pre-design-model

Available experimental investigations neglect combined loading conditions (axial loads and bending). For jacket substructures, local joint flexibilities and so partly clamped chords and braces lead to an interaction of axial forces and bending moments. Under consideration of cyclic stress conditions, bending and axial stresses has to be assumed for the design. Due to the fact, that experimental investigations on sandwich structures under combined loading do not exist, tests become necessary. The test results can be used for the benchmark of numerical models, parameter studies and the derivation of a simplified design approach.

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3.2 Sandwich material for connections and joints (WMC)

3.2.1 Technologies used in industry for current 5 MW class and in other sectors

The introduction of sandwich and other innovative materials solutions for wind turbine support structures does not only impact the material selection, but affect many other aspect of the support structure design. E.g. switching to lighter materials will reduce the gravity loads and change the dynamics. Optimal use of the new material will require a complete redesign of the support structure. For truss structures, sandwich tubular sections are likely to promote the use of larger diameter tubes and a reduced number of braces. Furthermore, sandwich tubes may require different joining methods and promote a different joint design than single walled tubes.

Current support structure design is based on welding as the primary joining technique. For joints during installation bolted flanges and grouted joints are commonly used. The welds on a support structure and tower range from the axial welds joining rolled sections to form a tube, circumferential welds joining tubular sections together, welded flanges, to more complex shaped welds such as T, Y, K and X joints in braced towers or jackets, a welded transition piece for a jacket etc.

The design procedure for welded structures is well established. Design guidelines [WMC01] for offshore support structures and for fatigue evaluation of welded structures [WMC02] provide guidance for the strength and fatigue assessment for different weld profiles and joint configurations. Fatigue design curves are available for different weld profiles and environmental conditions. Typically welds are critical in the fatigue life of a structure. Where the stress level for the fatigue limit of steels is typically about half the yield stress of the steel, the allowable stress for the weld is much lower, typically well below 100 MPa.

Welding limits the gains the can be made by the use of higher strength steels. For high strength steels the fatigue limit typically increases with the yield strength of the steel. However, much if not all of this gain is lost when considering the fatigue strength of a welded part. This fact has a direct impact on the use of sandwich tubes, as these will promote the use of higher stress levels and higher strength steels. This may highlight fatigue strength of welds as a design driver for support structures based on sandwich tubes.

Alternative solutions that eliminate welds do exist. A notable example is the bolted tower by Andresen Towers, used by Siemens. This design reduces the part size for transport, allowing the use of lighter trucks and making more remote and inaccessible locations easier to reach. Apart from the logistic benefit, the bolted design also eliminates welds as a crack initiator and enables the higher fatigue strength of high strength steels to be exploited. Indeed the design uses higher strength steels and lower material thicknesses. However, such a solution is impractical for application in an offshore support structure where the large number of components and the bolted connections are a drawback due to the limited accessibility and challenges in corrosion protection.

3.2.2 Technologies under current RTD for 5MW class and in other sectors

Within current research on joining many topics can be distinguished. Firstly there is research on fabrication methods and joining technologies that allow large volume production and reduce cost. Examples of this include the research on cast nodes for jackets or on higher deposit rates for welding. Second there is research on the performance of joints and their ability to withstand fatigue loads, such as research on grouted joints and on the fatigue resistance of welds specifically for offshore wind energy. Logistics and installation also come into play, especially offshore where vessel time is an important cost factor. An example is the slip joint which aims to simplify and speed up the installation process. Below recent research efforts will be highlighted.

One joining method that has attracted considerable attention in recent years is the grouted joint (Figure 3-9. In a grouted joint two the annulus between two tubular sections with different diameter is filled with a grout to form a permanent joint. It is used as a joining technique during installation to join piles to a support structure or to join different parts of the support structure. It has been used for offshore wind turbines for joining the transition piece to the monopile. Early designs did not use any mechanical interlock, using plain steel faces on monopile and transition piece/tower. Slippage of the joint in such designs in offshore wind farms in the UK, the Netherlands and Denmark sparked research on repair methods and modification of the design to enhance bearing strength [WMC03]. Alternative designs with mechanical interlock by shear keys on the steel faces of or a conical shape of the monopile and tower were proposed and are now accepted method for offshore turbines.

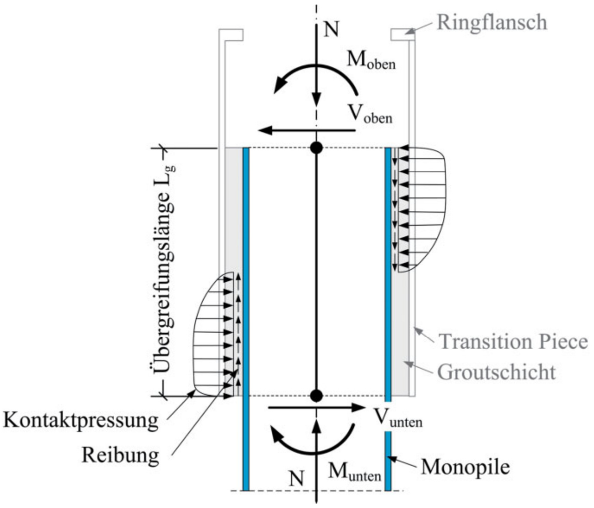

Figure 3-9: Model of a grouted joint(from [WMC03])

The 'Slip joint' is conical joint for tubular sections. It consists of two mating conical sections that slide over each other without the use of bolts, grout or welding [WMC04]. This joint has successfully been applied as a joint for tower sections by the Dutch wind turbine manufacturer WindMaster. Currently this joint is investigated as a transition piece to monopile joint in the Dutch research programme FLOW (www.flow-offshore.nl). An experimental programme aim to validate the performance of the joint, see Figure 3-10. Within this project theoretical models on the behaviour of the joint will be validated experimentally, evaluating the behaviour during installation and for extreme loads as well as the long term behaviour under dynamic loading.

Benefits of this joint design would be a much reduced installation time, by eliminating the time needed for grouting or bolting, and eliminating the risks associated with grout. A drawback is that this joint does not offer any possibilities to correct the vertical alignment of the tower. Furthermore corrosion protection is a point of attention as coating of the interface may be difficult.

Figure 3-10: Experimental set-up from the FLOW slip joint project

Welded flanges are a straightforward alternative for installation joints, however they are costly to manufacture and the weld of the flange to the tubular section has relatively poor fatigue strength. Within the HISTWIN project an alternative connection for tower joints was proposed that used slotted holes and relies on friction [WMC05], see Figure 3-11. It was found that this type of connection shifts the design drivers to other aspects of the tower, enabling material and cost savings.

Adhesive bonding has also been considered as a proposed as an alternative to welded flanges for tower joints [WMC06]. Simple lap joints were studied and the can wall thickness and adhesive thickness were found to be key parameters for limiting the stress peaks in the adhesive for such a connection. Although experimental validation is lacking, this work indicates that adhesive bonding could be a viable alternative to welded flanges with improvements in fatigue strength.

Cast nodes are investigated for jacket support structures to eliminating complex welded nodes [WMC07]. With cast nodes the weld of the braces to the nodes consists of simple circumferential welds, improving weld fatigue life and enabling automated welding processes. Drawbacks are that there is less design flexibility, as for cast nodes it is desirable to use the equal nodes to reduce the number of different castings. For larger series cast nodes seem an attractive solution as they facilitate automated production and may increase throughput in production by reducing weld time.

Research on welding has seen renewed interest specifically for offshore wind energy applications. The expansion of the design limits of monopiles with current XL monopiles with very large diameters and high wall thicknesses, mover the weld volume far beyond the welds which were used to establish the current weld fatigue design curves. Furthermore the large material volume means that small gains in design allowables can give significant cost savings. Within the "Structural Lifecycle Industry Collaboration" (SLIC) project [WMC08] the weld performance of such welds will be re-evaluated.

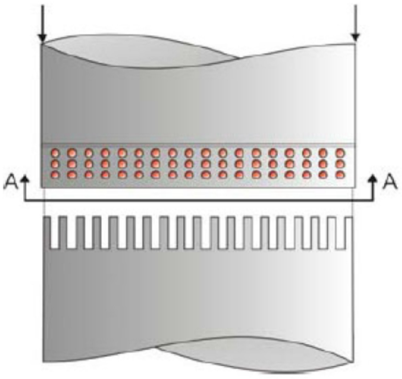

Figure 3-11: The HISTWIN tower joint

3.2.3 Development needs and prospects for the preliminary design of the reference support structure and consequences for the work program in task 4.1.

Specific requirement for joining of sandwich tubes

Sandwich materials present specific challenges but also new opportunities for joining. The use of sandwich materials to prevent buckling will allow higher stresses in the face material, which will increase requirements on the joint and may affect the fatigue resistance. In case both faces are load bearing, both faces need to be joined.

Welding is faced with several challenges when applied to sandwich tubes. Firstly the inner face may difficult or impossible to access on smaller diameter tubes or more complex structures. Second, the fatigue resistance of the weld is likely to be a limiting factor for sandwich tubes. The higher stress levels promoted by the sandwich construction may simply not limited by the fatigue resistance of the weld. More so, only single sided welds can be used because of the sandwich construction, and well improvement techniques can only be applied to one the surface side of the facing material, the sandwich side is inaccessible.

Welded flanges for bolting face the limitation in strength of the weld. Other than that they are relatively similar to flanges for solid materials. At the flange both the inner and the outer face of the sandwich are accessible for welding. Thick sandwiches will require thick flanges with sufficient stiffness to transfer the load also to the inner shell. This will further increase the cost of the flange, increase weight and negate at least some of the gains made by using a sandwich tube.

In the Oil & Gas industry shrink fitted flanges and tubular connections are also used, in part to eliminate the limitations of welding. Shrink fits however have high requirements on machining and are generally more suitable for small diameter, high wall thickness tubes. For support structures generally bigger diameters and smaller wall thickness are used, where the circumferential stresses may present a bottleneck.

Adhesive bonding for sandwich tubes

In adhesive bonding of metals an overlap is required because the strength of the metal is generally much higher than that of the adhesive, and load transfer is achieved by shear stresses in the adhesive and substrate surface. For sandwich materials adhesive bonding is helped by the fact that the two face sheets of a sandwich double the available surface area. Based on this adhesive bonding could turn out to be a favourable joining method especially for sandwich tubes.

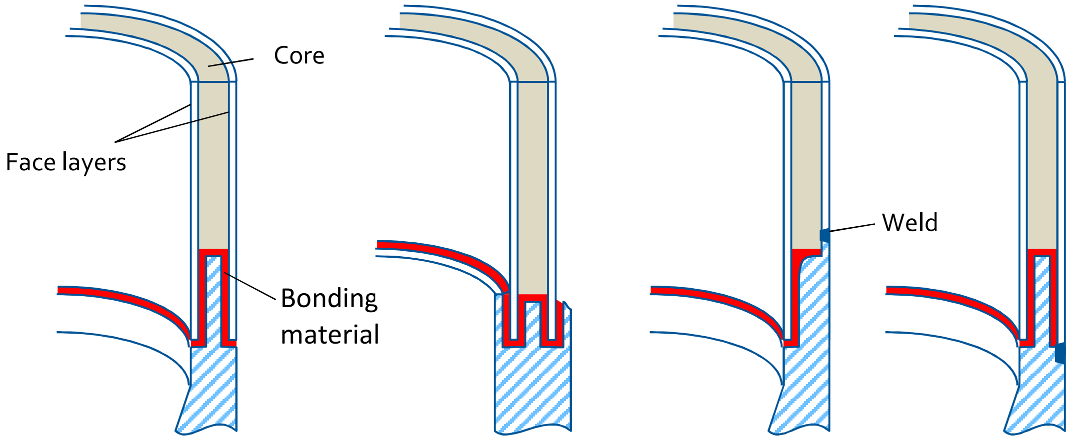

Figure 3-12: Bonded and hybrid joint concepts for sandwich tubes

Many joint configurations are possible for bonded joint. Some concepts are shown in Figure 3-12. The joint could use and insert between the faces of the sandwich for bonding, or could use both the inner and outer surface, although this leads to a complex design. Next to bonded joint also hybrid joint concepts could also turn out attractive. In, next to two bonded joints, also hybrid joints are shown, one featuring a welded outer face and bonded inner face and one for which the outer face is both welded and bonded. The latter concepts could have benefits in manufacturing and in sealing the bonding material from environmental influences. The optimum joint configuration will depend on the application and on the performance parameters of the adhesive joint. Therefore, improved knowledge on the performance of adhesive joints is needed before the joint layout can be optimized.

In a braced structure sandwich tubes will significantly add to the complexity of node design. In combination with adhesive bonding cast nodes however would provide a good option and node design could be adapted to various joint configurations. An advantage of adhesive bonding here is that the material requirements for the castings are reduced as the weldability of the casting in no longer of concern. Sleeved joints would also be a good option for joining to a sandwich tubes, as a sleeve around a continuous sandwich section would not cause large stress concentrations and therefore allow the use of high stress levels in the tube.

Load carrying bonded joints are relatively rare for steel to steel joints, but are commonly encountered for joining fibre reinforced plastics. For wind turbine blades the bondlines connecting the blade shells and the bonded root inserts are key elements of the designs. Uncertainty about the behaviour of adhesives in this application has sparked research using subcomponents to verify the performance of adhesives in a configuration resembling the actual application [WMC09]. Contrary to traditional adhesive joints were bondline thicknesses of a few tenths of a millimetre are used, bondlines in wind turbine blades are often very thick, up to 10 mm. This results in bondlines with multi-axial stress states and consideration of this stress state is vital for understanding of the behaviour of such bondlines [WMC10]. A bi-axial failure envelope of a typical epoxy bonding paste is shown in Figure 3-13.

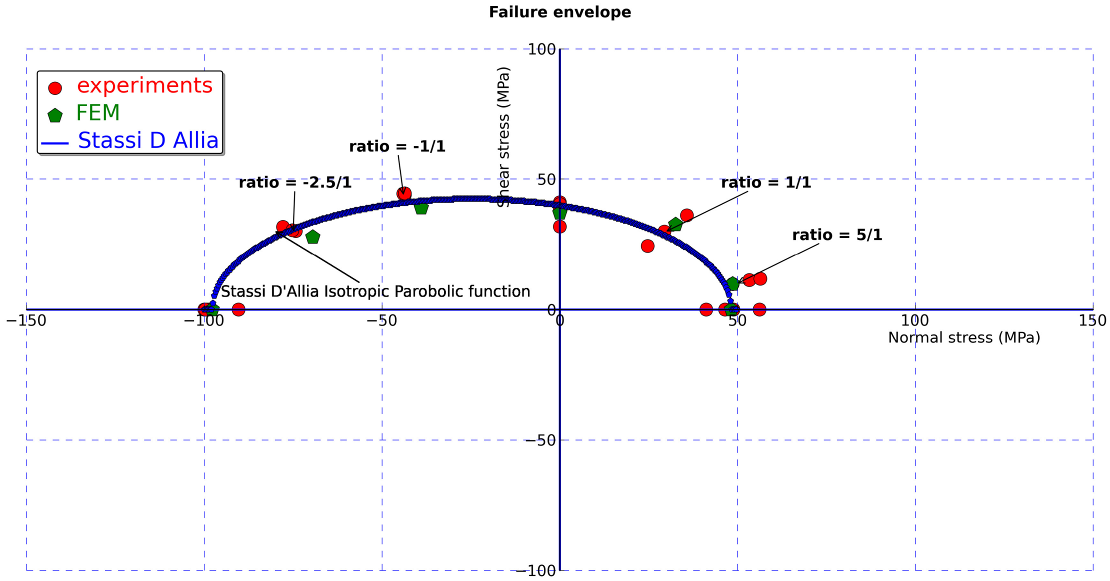

Figure 3-13: A bi-axial failure envelope for an epoxy based adhesive (from [WMC10])

Tubular bonded lap joints are also used in composite tubular structures such as drive shafts or piping systems. Tubular lap joints are used to join composite pipe to metal appendages. For joining composite pipe sections also butt joints are used with an overlap coupler to increase joint strength. Next to strength criteria also a fracture mechanics approach has been used to evaluate the fracture and delamination behaviour of adhesively bonded pipes [WMC12].

The strength of adhesive lap joints suffers from the stress peaks at the joint edges. Modelling of lap joints has developed from classical one-dimensional models that only consider shear deformation in the adhesive and longitudinal deformation in the adherends, which results in the well-known bathtub curve for the stress distribution; see Figure 3-14. More advanced models take effects into account such as the zero shear stress at the adhesive surface, variations in the stress distribution over the thickness, adhesive peel stresses or shear deformation of the adherends. Depending on the characteristics of the adhesive it can be important to take into account non-linear elastic behaviour of the adhesive, particularly for thicker adhesive layers.

Restricting the adhesive joint to an overlap joint there are many parameters that can be varied and can drastically affect joint performance. There is a large range of adhesives that could be applied for and adhesively bonded joint for sandwich tubes, ranging from grouts to high end adhesives like epoxy or acrylic based adhesives. The choice of a suitable adhesive will not only depend on the structural performance of the adhesive but also on the foreseen manufacturing process. Different adhesives will bring different requirements for joint design surface treatment and process control. Joint made in a fabrication yard will allow much better process control than in situ joint made offshore. This makes it likely that different solutions may come forward as the best option depending on the loading requirements and fabrication conditions.

Then there is the joint geometry. Overlap joints exist in may configurations,

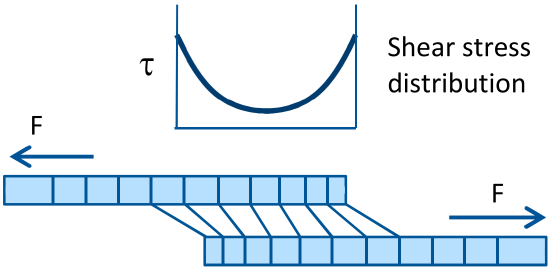

Figure 3-14: Shear stress distribution in a lap joint

mostly aimed at improving the strength of the joint by reducing the peak stress at the joint edges. Examples are shown in Figure 3-15. Within a given geometry there are many parameters that can be varied, such as the thickness of the adhesive layer and the adherents, the overlap length, chamfers, etc. For sandwich tubes the number of options increases even further as there are two faces to join. Not only can the joint be optimized for the sandwich structure, but the sandwich structure can also be adapted to optimize joining. Asymmetric sandwich structures where one face carries a major part of the load may simplify joining techniques, as only the load bearing face then needs to be joined.

Although bonding has been used for metals has seen considerable application in e.g. the automotive and aerospace industry, this commonly concerns joining of thin plates or for low loads. Boyes [WMC12] investigated strength and fatigue performance of lap joints of (thin) stainless steel plates. Compared to spot welding or laser welding adhesive bonding can provide a much improved fatigue resistance [WMC13]. A point of concern is that a dramatic reduction if fatigue strength was observed for epoxy joints in stainless steel after aging in distilled water, with over 50% reduction in fatigue strength after 48 weeks of aging.

For the use of bonding as a joining method for the large, heavily loaded tubular connections with much higher wall thicknesses encountered in the offshore wind industry, very little theoretical background is available and experimental validation is lacking. Experience in other industries shows that adhesive joints can provide excellent joint properties and fatigue strength but it is unsure how this will translate to a large scale joint in an offshore foundation. Therefore first model development on adhesive bond behaviour for these applications is needed, after which these models can be used to develop a suitable joint configuration. This results in the following research needs:

Development and validation of numerical tools for large adhesively bonded steel to steel joints with thick adhesive layers

Current models for adhesive joints are largely based on thin adhesive layers. With the increase in joint size and adhesive thickness the full stress state of the adhesive will need to be considered and, depending on the adhesive, nonlinear behaviour will need to be accounted for. Given the importance of fatigue loading for support structures, this will need to be incorporated in numerical tools. The scale of the application means that joint imperfections will be far more common than in small scale joints. Therefore damage initiation and progression over the lifetime of the components will need to be considered.

Screening and experimental characterisation of bonding materials

There are many candidates for the bonding materials to be used in adhesive joints. Suitable candidates range from high end materials such epoxy based bonding pastes as currently used in wind turbine blades to much lower cost materials such as grouts. The optimum for material will be closely related to the joint configuration and parameters such as overlap length, as well as the design of the sandwich tube. An experimental characterisation of their performance in steel to steel joints is required, taking into account the material thickness and stress states that will be encountered in the actual application.

Experimental investigation of the strength and durability of adhesive joints for large steel structures

An experimental validation of the performance of adhesive joints for sandwich structures is needed to evaluate their potential. The performance under fatigue loading needs to be assessed to validate that a performance increase over welded joints can be achieved. The experiments will need to consider the combinations of axial and bending loads such as encountered in an offshore jacket.

The results of this research will not only assist in enabling the application of sandwich materials in jacket support structures but will have broader applicability. For example bonding could just as well be used for single walled tubes but also beyond the support structure, such as to properly evaluate the potential of bonding for tower joints.

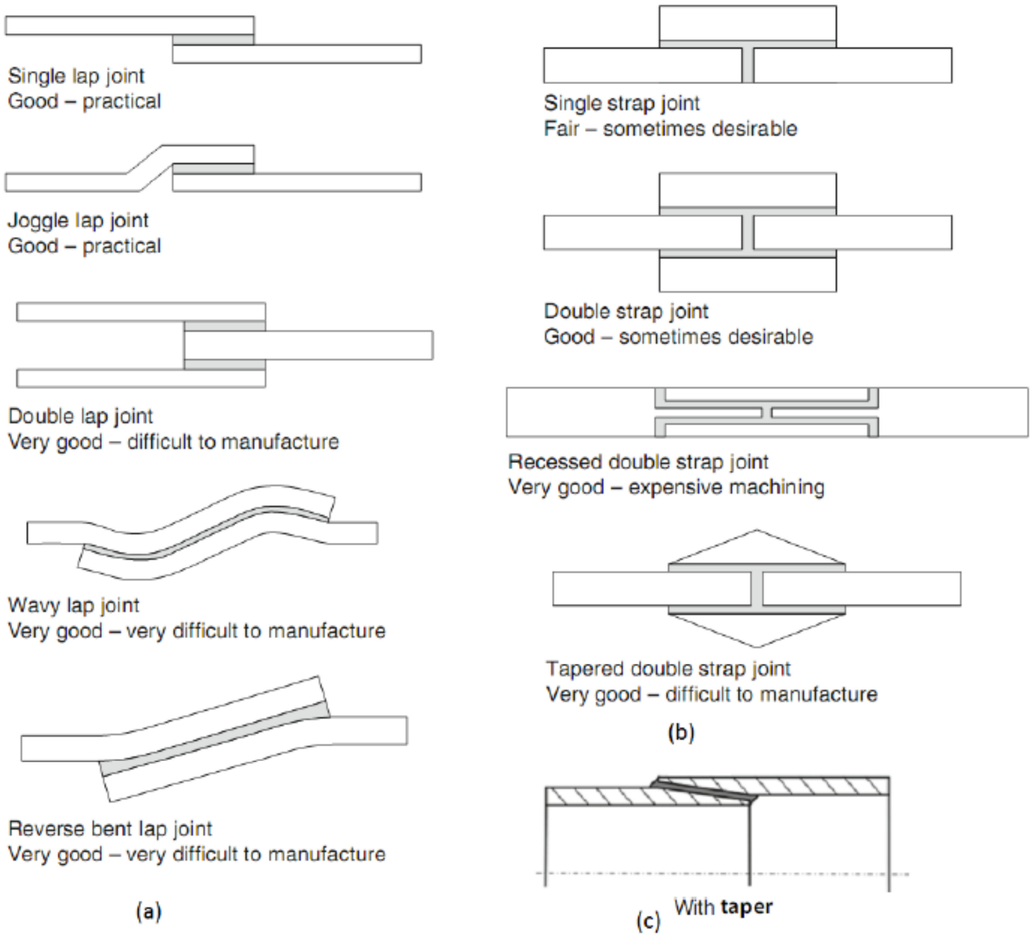

Figure 3-15: Lap joint geometries (from [WMC06])

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4 SOIL & FOUNDATION

The development of innovative designs of support structures for larger offshore wind turbines requires a broad understanding of the behaviour of sub-structure, foundation and soil as well as their interacting processes. These may be geometrically and physically non-linear especially in view of the coupling effects of transient or cyclic loading, and the resulting long term behaviour.

The process of foundation design and the underlying current rules and guidelines are based on analytical models as well as empirical data from laboratory and field tests, mainly at smaller scale. Therefore, the applicability of the design algorithms and their specific data has to be verified for the application at larger scales. This can be done by numerical simulations or by experimental tests on series of specimens of different geometric properties. The experimental and numerical investigations have to be defined in detail according to the requirements of the reference design. The soil is multi-layered and can include different components such as clay, sand, gravel etc. Relevant soil properties such as lateral and axial stiffness, strength and damping are to be accurately estimated from the measurements. Another key properties of the soil that is very important for support structure design is the damping and the long term deformations, which is still inadequately understood. The ABS Offshore Wind Turbine Installations 2010 standard states that the soil internal and radiation damping should be considered in the foundation model of the dynamic system. Further the ABS [01] states that the dynamic simulation of the wind turbine system should include all Soil-structure interaction effects that impact the overall dynamic behaviour of the Support Structure. As soil/clay properties vary a lot during cyclic loading, it is important to investigate the effects of variation of the properties on the behaviour of the support structure. To account for hysteresis, a Deterioration of Static p-y Curve (DSPY) method is sometimes used whereby a static p-y curve is modified for cyclic loading, by increasing the lateral modulus of the soil with depth. With more gained knowledge, better sophisticated numerical models can be developed and validated. Finally, a subset of simplified models of improved reliability can be derived for the application in the design process. Based on time domain simulations and modal analyses, the developed support structure can be investigated and an optimum set of design parameters can be achieved.

The DNV offshore standard [02] describes both lateral stiffness (p-y) curves, as well as axial resistance (t-z) curves. Though for monopile type structures, it is common to consider only the p-y curve characteristics, for jacket and tripod piles, the axial resistance of the pile sand (t-z) is also important. The axial resistance of the soil is strongly dependent on the skin friction and when jacket piles are considered, sufficient axial pile capacity in the ULS must be ensured for each pile.

The topic of soil-structure interaction of axially loaded piles still incorporates substantial uncertainties in the prediction of the cyclic bearing behaviour. The uncertainties in the soil properties is also heightened by the fact that only limited soil sample measurements are taken at a wind farm site and large variations in the soil properties can take place between different wind turbine locations in the farm. Depending on the type of sub structure whether jacket, monopile, bucket or gravity based, a large uncertainty on the natural frequencies of the support structure is possible due to the uncertainty in the soil properties and the understanding of the influence of the pore water.

Therefore in this task, a sensitivity study of the soil structure stiffness effects of jacket and bucket sub structures is investigated and where the coupling between the axial and bending direction is also included in the study of the jacket. Further, the sensitivity of cyclic effects with respect to long term deformations should be investigated in more detail. For this reason a parameter study is planned to be carried out. The aim of this study is to identify the main issues arising from the application of single piles of larger diameter and buckets. It could also analyse the sensitivity of geometric properties on the structural behaviour and the significance of potential hydraulic-mechanical interaction. Additionally, experimental studies at different scales are planned. They shall be based on the numerically gained findings and aim to reduce the remaining uncertainties. The experiments should give the opportunity to focus on selected topics of soil-structure interaction and might incorporate the influence of different installation methods.

In order to define both, the numerical and the experimental investigations a review on current design and installation methods is given in the subsequent section. Finally, suggestions of aims and prospects of meaningful investigations are given with respect to potential novel foundation design and installation techniques.

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4.1 Suction-bucket foundations (AAU)

4.1.1 Technologies used in industry for current 5MW class and in other sectors

The bucket foundation (also referred as to suction caisson or suction bucket) have been extensively used as anchors, principally in clays, and have also been used as foundations for a small number of offshore platforms in the North Sea, Tjelta (1995) [AAU01], or as a support for jackets; Bye et al. (1995) [AAU02]. Over the last decade the monopod bucket foundation has been considered as a suitable foundation concept for offshore wind turbines. A fully operational 3.0 MW offshore wind turbine was installed on a prototype of the bucket foundation in Frederikshavn in October 2002 and has been in operation since; Ibsen (2008) [AAU03]. In 2009 the bucket foundation was used as Met mast foundation at Horns rev II and in 2013 three foundations were installed at Dogger Bank and Firth of Forth wind parks. The water depth ranging from 16 to 34m see Figure 4-1.

Figure 4-1: Three Bucket Foundation for Met masts ready to be installed into the North Sea (Belfast January 2013.)

The aim of the development of the Bucket foundation has been to reduce the cost and time regarding establishment of offshore wind farms and introduce industrialization by:

- Reducing the amount of steel used compared to monopiles, and use simple geometric welded steel structures. The structure is omnidirectional symmetrical with respect to the vertical axis.
- Few offshore operations, with utilizing smaller equipment/vessels during installation than is used in connection with other foundation types. No seabed preparation an no or reduces need of scour protection.
- Adjusting the upper part of the shaft to fit the standard wind turbine tower or met masts. The load introduced by waves and current is reduced compared to the monopile with transition piece.
- Simple decommissioning.

By installing the foundation by suction, the following environmental benefits are achieved:

- No pile driving hammers or drill drives are used.
- The seabed is kept intact to a large extent. The use of excess material for scour protection is reduced or not necessary.
- All steel materials can be retrieved from the seabed and recycled when the foundation is decommissioned.
- Minimum noise impact. No pile driving hammers or drill drives are used
- No grouted connections.
- Minimum disturbance to the existing seabed
- The use of excess material for scour protection is reduced or not necessary

The Bucket Foundation is described as a next generation novel foundation concept that is potentially capable of delivering significant cost reduction to offshore wind farms. In 2009, The Bucket Foundation interred a global competition, "Carbon Trust's Offshore Wind Accelerator (OWA)" foundations competition, aimed to identify innovative, cost-effective, and robust foundation designs that could be used for the challenging conditions that will be encountered at Round 3 in the English sector: water depths of 30-60m, complex soils, and harsher met ocean conditions. The competition attracted more than 100 entries from all over the world, from leading civil engineers and naval architects to marine experts in the oil and gas industry. The Bucket foundation came out as one of two winning concepts. Recent studies in Carbon trust's Offshore Wind Accelerator (OWA) program Stage II has shown that the Bucket Foundation can carry an 8 MW turbine at a water depth of 55m. The Carbon Trust's OWA industrial partners are eight international energy companies.

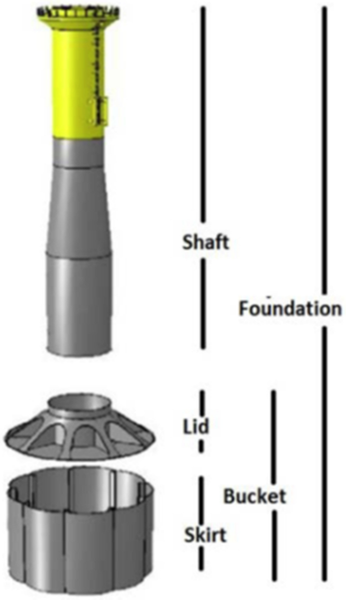

Figure 4-2: Bucket Foundation structure

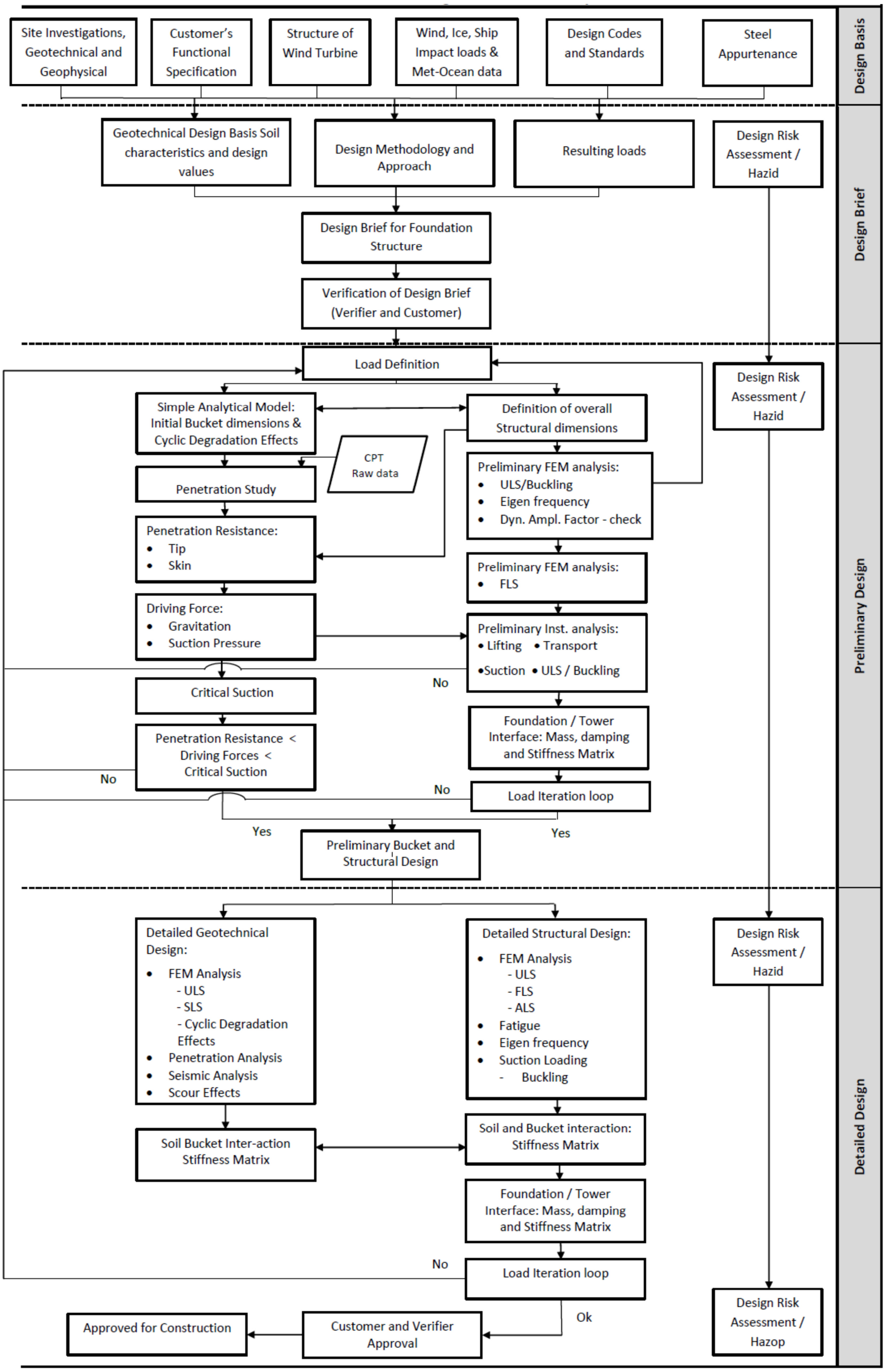

Figure 4-3: Design process for the Bucket Foundation

Figure 4-2 presents a view of the mono bucket foundation illustrating all features that build up the support structure. The lowest part of the structure is composed by the bucket caisson, the only structural member that will interact with the soil. Subsequently the transition between upper and lower parts of the foundation structure is composed by the element so-called "Lid" combined with a number of stiffeners called bulkheads and inside brackets. The shaft is the element that connects the interface platform located above water surface and lower structural members i.e. bucket caisson, conus and bulkheads.

DESIGN PROCEDURE: In order to handle the design process, a design procedure has been developed in cooperation with the certifying party in order to maintain a standard approval procedure for the design, see Ibsen (2008) [AAU03]. The design procedure for the bucket foundation can be divided into a number of parts. In Figure 4-3 the design process is illustrated schematically. As seen the design process are divided into four main bodies. The design analyses comply with DNV-OS-J101. In general the calculations are based on the partial safety factor method. In ULS the safety levels is calculate to ensure that design load effect is smaller than the design resistance. In SLS the plastic deformation/rotation is calculate to ensure that it is below the design requirements.

PRILIMINARY DESIGN: The dimensions of the bucket, i.e. the diameter D and the skirt length d are determined based on simple analytical models. A penetrability study is performed to ensure that the bucket can be installed at the location. The load acting on the bucket are typically given from a structural model, where the bucket and surrounding soil is modelled as springs reflecting torsion, rotation and displacements. The springs are initially uncoupled, based on assumption on vertical, horizontal and rocking movements. Later in the design the springs are coupled reflecting the interaction between the different responses (stiffness matrix is changed). The bucket dimensions are determined based on the load combination and Limit State (ULS, SLS, FLS), which results in the largest dimensions.

The moment capacity of the foundation is obtained by traditional eccentric bearing pressure in combination with the development of resisting earth pressures over the height of the bucket shirt, see Figure 4-4. Hence, the design can be carried out using a design model that combines the well-known bearing capacity formula with equally well-known earth pressure theories. The foundation is designed so that the point of rotation lies above the foundation level, i.e. in the bucket, and the bearing capacity rupture happens as a line failure, which develops below the foundation. The present design is additionally documented by numerous laboratory and large model tests, which allows for optimisations within the framework of the above mentioned design model; Ibsen (2008) [AAU03]. Figure 4-4 shows the earth pressure and reaction of the bearing capacity for the point of rotation located above the foundation level. When calculating the bearing capacity of the bucket (with large eccentricity) the rupture figure is a line rupture as shown in the figure at right, with a rotation point inside the bucket. Therefore no overturning moment is carried by the soil inside the bucket. The moment capacity is carried by earth pressure outside the bucket as illustrated with red arrows in the Figure 4-4.

It is necessary to perform a penetrability analyses of the bucket to ensure that the driving force is larger than the resistance from the soil, see Figure 4 3. The penetration analysis is done on the basis of CPTu tests. Furthermore the driving force consists of the load acting on the bucket and the applied suction; hence it is necessary to check that the suction limits are not exceeded. The applied suction must be controlled during the entire installation. If any of the suction boundaries are exceeded the installation cannot proceed and reach the target depth.

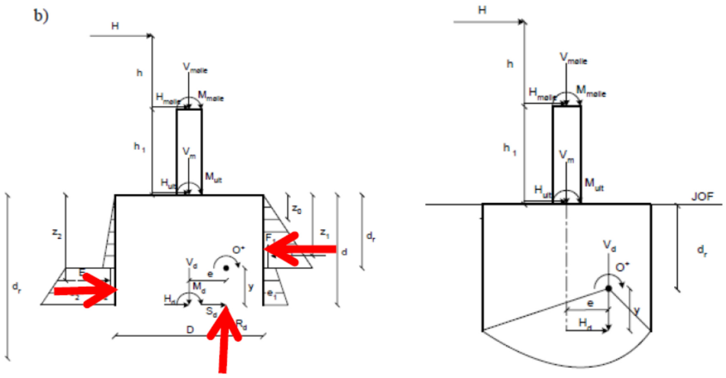

Figure 4-4: Design model for bearing capacity of bucket foundation

The limit for applied suction is controlled by four scenarios:

1. Buckling on the Bucket skirt during installation or any local damage due to applied suction.
2. Maximum pumping capacity to avoid cavitation.
3. Piping channels generated near Bucket skirt when installing through sandy layers
4. Plug heave inside the Bucket during installation through clayey layers.

DETAIL DESIGN: During this phase Finite element analysis of the bucket and surrounding soil is established. The design load cases are resolved to ensure that the bearing capacity is sufficient and the load-deformation performance acceptable. The Finite element analysis shall include constitutive soil models and pore pressure development (consolidation routine). In this way the serviceability limit state, (SLS) can be verified. The interaction between the bucket and the soil has to be investigated in details and the stiffness matrix is established. During this phase changes to the design may occur. To verify the used FE –analysis model test's has been back calculated. Figure 10 shows a FE – analyse of the soil structure interaction.

Hot spots for fatigue in the steal and in the soil have to be investigated to verify the Fatigue Limit State (FLS). The fatigue in the soil has up to now only been verified on the basis of model tests.

4.1.2 Technologies under current RTD for 5MW class and in other sectors

Bucket foundation is currently being considered as foundation supporting jacket structures as an alternative to the normal used piles. Currently design methods are available for axially loaded piles, such as API (American Petroleum Institute, 2007) [AAU04] and DNV (Det Norske Veritas, 2010) [AAU05]. However the conditions of axially loaded pile are different from bucket, basically because of different shape and depth of embedment. Rather simple calculations for static uplift capacity of the spread-out buckets are proposed by Rahman et al. (2001) [AAU06]. Houlsby et al. (2005) [AAU07] have developed a simplified theory for tensile capacity of suction caissons under rapid loading, which mainly depends on the rate of pulling out as well as the ambient water pressure which determines whether the cavitation appears.

Some experimental investigations on vertically loaded small scale suction caissons are performed by Byrne and Houlsby (2002) [AAU08]. Small scale cyclic loading tests in dense sand were presented by Kelly et al. (2004, 2006), [AAU09], and [AAU10] where a conclusion was drawn that only small tensions can be permitted on the caisson foundations. Pull out capacity of suction caissons is also investigated by Iskander et al. (2002) [AAU11]. After small scale tests with many cycles, i.e. 160 000, it was found that the cyclic pull-out capacity depends on the same parameters as for static load. A larger scale test was run in artificially prepared sand test bed near Luce Bay, in Scotland. Houlsby et al. (2006) [AAU12] has investigated behaviour of a cyclically axially loaded caisson and its pull-out capacity. A certain ultimate tensile resistance was generated during the test, but it was led by large displacement.

However, not much research is carried out within the field of cyclical vertical loading on bucket foundations in long term. Most of the present experiments are performed on small scale suction caissons.

Studies regarding the long-term behaviour of moment carrying structures are rare. Numerical models, Achmus et al. 2009 [AAU13] and physical models LeBlanc et al. 2010 [AAU14], Peralta 2010 [AAU15], Tas¸an et al. 2011 [AAU16] have been recently attempted for offshore pile foundations. Fewer studies concerned long-term lateral cyclic response of bucket foundations has been performed one is Zhu et al. 2013 [AAU17].

4.1.2 Development needs and prospects for the preliminary design of the reference support structure and consequences for the work program in task 4.1.

Both the mono bucket and the bucket foundation for the jacket support structure have to fulfil requirements of both transient and long term loading. Another key property there is very important for support structure design is the damping. These three issues affect both the preliminary and the detailed design. Unfortunately these issues are still inadequately understood.

Recommendations for further investigation

The transient load bearing behaviour of both mono bucket and the bucket foundation for the jacket support structure should be investigated in order to predict its influence on the bearing capacity

The development of excess pore water pressure has been experimental investigated with respect to bucket diameter/skirt length and hydraulic conductivity. Within this topic it should be investigated if and to what extent soil-structure interaction and cyclic behaviour interact with significant values of excess pore water pressure and resulting hydraulic transport processes of grain particles. This can lead to better understanding of the damping and stiffness properties of the soil/structure interaction.

It is also recommended to establish a data base of long term cyclic loading of the bucket foundation both for horizontal and vertical loading. On this basis the design rules for long term buckets could be enhanced.

From the above mentioned topics the recommended experimental tests to be carried out are as follows:

- Investigation the long term effects of the influence of horizontal and vertical loading of the bucket.
- Investigation of cyclic degradation under cyclic loads
- Investigation transient load effects (Boot effect)
- Investigation the damping effects of pore water pressure especially in view of pore water flow inducing a relocation of small grain particles

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4.2 Soil-structure interaction / axial pile loading (FhG-H)

4.2.1 Technologies used in industry for current 5 MW class and in other sectors

Introduction

This section reviews the design of pile foundations under predominant axial loading. For multipod support structures like tripods or jackets the experience gained in conventional offshore technology can be applied. Nevertheless, attention has to be paid due to the cyclic loading occurring not only in compression but also in tension. Jacket support structures are dedicated to be taken into consideration as reference support structure within this project. In most of the wind farms currently developed and erected driven piles are being used as foundation elements.

The state of knowledge regarding the foundation design is presented in this section with respect to lateral as well as to axial loading. Especially concerning cyclic lateral loads, which are dominant in monopile support structures but also are non-negligible in case jacket support structures, a final answer to the question to their influence on the bearing behaviour does still not exist. Due to the continuously increasing turbine capacities, the accurate prediction of the pile bearing capacity and deformation behaviour is important to improve the cost effectiveness.

The monopile foundation, being the favoured support structure for current offshore turbines in water depth of up to 30 m, has triggered lots of research projects in the last decade. Furthermore a trend to monopole foundations applied in water depth up to of 35 m is obvious.

According to the project's goal to design and optimize a jacket substructure for a reference 20 MW turbine the horizontal pile loads expected on a single pile foundation are of a magnitude that is comparable to those of a monopile support structure of a current 5 MW turbine. In contrast to the monopile, the overturning moments of a jacket are transferred to a vertical couple of forces. Thus, vertical cyclic loads will become dominant. The residual bending moments in the pile will dependent on the stiffness of the substructure and its pile sleeves.

Consequently, the driving design parameters will not only be the vertical bearing capacity but also the horizontal one which might be influenced by the vertical deformation and vice versa. The design requisites therefore can be summarized as follows:

- Vertical bearing capacity
- horizontal bearing capacity,
- cyclic behaviour due to vertical and horizontal loads or possibly in combination,
- and deformation characteristics.

Current support structures with multi-pile technology are tripiles, tripods or jackets. They are installed in water depths of 25 m to 50 m. The single piles of these structures applied so far have diameters of about 1.5 m to 3 m or even more. During extreme events, the wind and wave loadings cause an overturning moment that has to be supported by a force couple according to the current foot print of the structures. The resulting axial compression and tension forces in the pile have to be transferred into the ground. The latter often is design driving for the required pile length.

Piles foundations under axial loading

The components of the bearing capacity are the pile base resistance and the shaft friction which are treated separately in the design calculation. The large diameter piles applied offshore usually are steel pipe piles. Their bearing capacities result from the outer and inner shaft friction as well as the base resistance on the steel cross-section of the pile. The latter is influenced by possible plugging. The characteristic resistance of a compression pile in the ultimate limit state (ULS) is calculated with the characteristic value of base resistance and shaft friction:

$$R_{b,k} + R_{s,k} = q_{b,k} \cdot A_b + \int_z q_{s,k}(z) \cdot A_s(z)\,\mathrm{dz} \qquad (4\text{-}1)$$

where:

$q_{b,k}$	characteristic value of the pile base resistance (kN/m²)
$q_{s,k}$	characteristic value of the local pile shaft friction in depth z (kN/m²)
A_b	base area or cross section of the pile (m²)
A_s	shaft area referred to the relevant diameter (m²/m)
$R_{b,k}$	characteristic value of the pile base resistance (kN)
$R_{s,k}$	characteristic value of the pile shaft resistance (kN)

In the applicable standards of the offshore engineering several procedures for estimating the characteristic values has been established ([FhG-H01], [FhG-H02], [FhG-H03], [FhG-H04], [FhG-H05],).

The tensile bearing capacity consists of the weight and the outer and inner skin friction. In case of plugging the latter is limited to the total weight of the soil plug inside the plug. The common method for calculating shaft friction capacities for offshore piles is the *β*-method given in API RP 2A, 2007 [FhG-H01]. The skin friction is

$$q_{s,k}(z) = \beta \cdot \sigma'_v(z) \leq q_{s,k,\max} \qquad (4\text{-}2)$$

whereσ'_v is the effective overburden pressure, while $q_{s,k,\max}$ is the limiting skin friction and *β* is the shaft friction factor given in Table 4-1: Design parameters for cohesionless siliceous soil (API RP 2A, 2007) [FhG-H01], respectively. The pile base resistance is

$$q_{b,k} = N_q \cdot \sigma'_v(z) \leq q_{b,k,\max} \qquad (4\text{-}3)$$

where$q_{b,k,\max}$ is the limiting base resistance.

Table 4-1: Design parameters for cohesionless siliceous soil (API RP 2A, 2007) [FhG-H01]

Relative density	Soil	β	$q_{s,k,\max}$	N_q	$q_{b,k,\max}$
(-)	(-)	(-)	(kN/m²)	(-)	(kN/m²)
Medium dense	Sand-silt	0.29	67	12	3
Medium dense	Sand	0.37	81	20	5
Dense	Sand-Silt				
Dense	Sand	0.46	96	40	10
Very dense	Sand-Silt				
Very dense	Sand	0.56	115	50	12

According to the regulations of the Germanischer Lloyd ([FhG-H03]) the skin friction applicable for pull out or tensile loading has to be reduced to $2/3\ q_{s,k}(z)$.

This simple method has been supplemented by more advanced methods using cone penetration tests (CPT) results. They are also applicable in cohesionless soils and their results are closer to pile load test results. The recommended four CPT-based methods are as follows:

- Simplified ICP-05
- Offshore UWA-05
- Fugro-05
- NGI-05

All CPT methods consider the effect of frictions fatigue which leads to a reduction in skin friction especially at the pile head where the soil is in permanent contact with the pile during installation.

Investigations by Achmus & Müller (2011) [FhG-H06] show that these are not sufficiently reliable for the standard piles to be applied for jacket foundation structures with small slenderness and in dense to very dense sands typical North Sea conditions. Based on the limited data the ICP and UWA approaches seem to be most suitable for the application.

Pile foundations under horizontal loading

According to typical subsoil conditions in the North Sea the bearing capacity under horizontal loading is relevant for the design of piles with a diameter of more than 2-3 m. The horizontal load and bending moments of a pile are transferred into the soil by lateral bedding.

For the design the subgrade reaction is applied which idealizes the system by a beam and an elastic foundation. In the classical subgrade reaction method the subgrade modulus which has to be specified over the depth is linear with respect to the deformation and consequently a linear correlation between the subgrade reaction *p* and the horizontal displacement *y* results.

In order to take into account the non-linear behaviour of the soil the p-y method has been developed which uses p-y curves that define the subgrade reaction *p* as a function of horizontal pile displacement and depth z. The p-y method has been accepted as a standard design procedure in rules and guidelines for offshore wind energy turbines. An overview of the compilation of p-y curves is given in Lesny (2010) [FhG-H07] Nevertheless, it has to be mentioned that the p-y curves given in the guidelines are based on field tests with limited number of piles with a relatively small diameter.

While the p-y method is based on an one-dimensional approach in view of the beam and the elastic soil, the strain wedge model (see Figure 4-5) has been developed for different layers of soil, see e.g. Ashour et al. (1998) [FhG-H08] and Ashour and Norris [FhG-H09]. It also takes into consideration a three-dimensional stress-strain behaviour of the soil, the excess pore water pressure and the influence of pile groups.

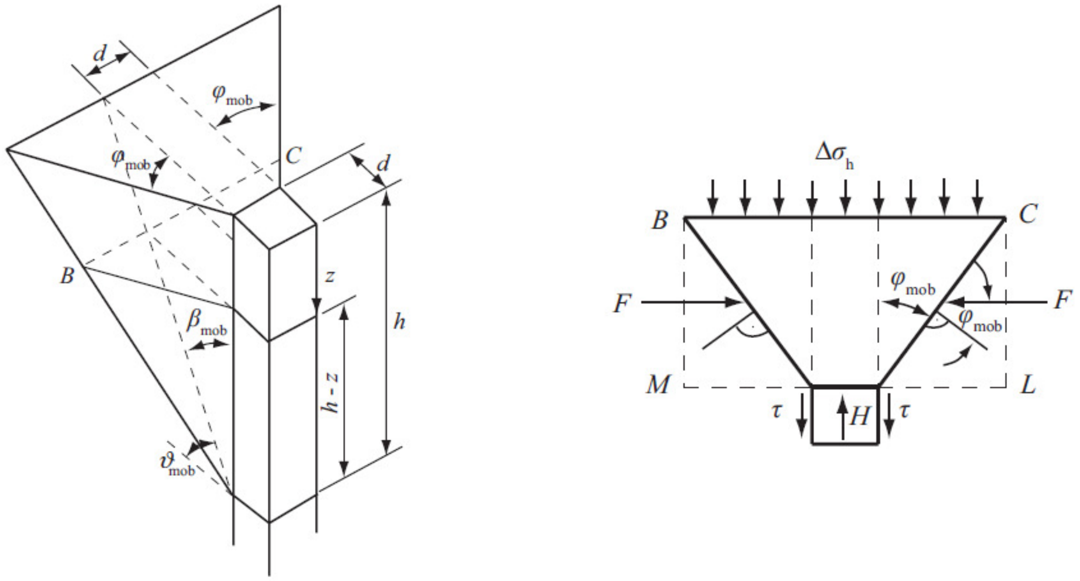

Figure 4-5: Mobilized earth pressure wedge in the strain wedge model

Pile foundations under combined horizontal and loading

The above mentioned design approaches for the axial and lateral bearing capacity are generally applied independently. That means that the algorithms used for the prediction of axial and lateral deformations are applied separately according to axial and lateral loads, respectively. The advantage of disregarding of combined loading ensures a more clear approach in the regulations and guidelines. Nevertheless, two important interaction phenomena should be taken into consideration:

- The behaviour of axially loaded piles is known to be dependent on the normal stresses on the piles shaft. These can be affected by lateral loads and may result in cyclic effects.
- The opening at the upper part the pile may induce pore water pressure and soil mobilisation due to pore water flow that may influence the axial pile behaviour.

4.2.2 Technologies under current RTD for 5MW class and in other sectors

Pile installation methods

According to the installation procedure of piles the noise emission during pile driving is a severe problem. Especially for monopile foundations but also for single piles of jacket support structures the maximum pile diameter and pile length is limited. The problem has not yet been solved but different concepts have been investigated within several research projects, see e.g. the German study on noise mitigation concepts [FhG-H10]. The following developments tried to face the problem by innovative installation techniques:

- The installation method of pile driving is replaced by a drilling technique. The method has to be further developed to be applicable for steel pipe piles of large diameter and greater water depth. The offshore foundation drilling concept (OFD®), as it is developed e.g. by Hochtief and Herrenknecht is illustrated in Figure 4-6. Application tests are planned to investigate the applicability.
- Vertical drilling was also conducted by Fugro Seacore Ltd (FSCL) in 2009 to construct the marine shaft element for the outfall of the European Pressure Reactor (EPR) Flamanville 3.
- Drilled piles of smaller diameter arranged in a pile group might also be a suitable variant. A proposed application is the so-called PREON® marine foundation system by Vallourec. It uses steel threaded injection piles.

Pile types with innovative enhancements

Compared to the standard steel pipe pile, further pile type might be favourable and had been investigated within a German research project "InnoPfahl" [FhG-H11]. With this project different innovative pile improvements have been investigated by experiment and numerical simulations, respectively.

Compared to the standard pipe pile, piles with additional welded components like wings or concentric rings have been proposed to be promising for further research. But it should be taken into account that the rising impact energy for pile driving has to be considered as well. Numerical simulations have been carried out as well. In spite of having any reliable model for cyclic loading at hand, the numerical analyses were performed using a hypoplastic model under a reduced number of cycles. Here, further research has been recommended in terms of model tests at greater scale and the development of better constitutive models for further investigations.

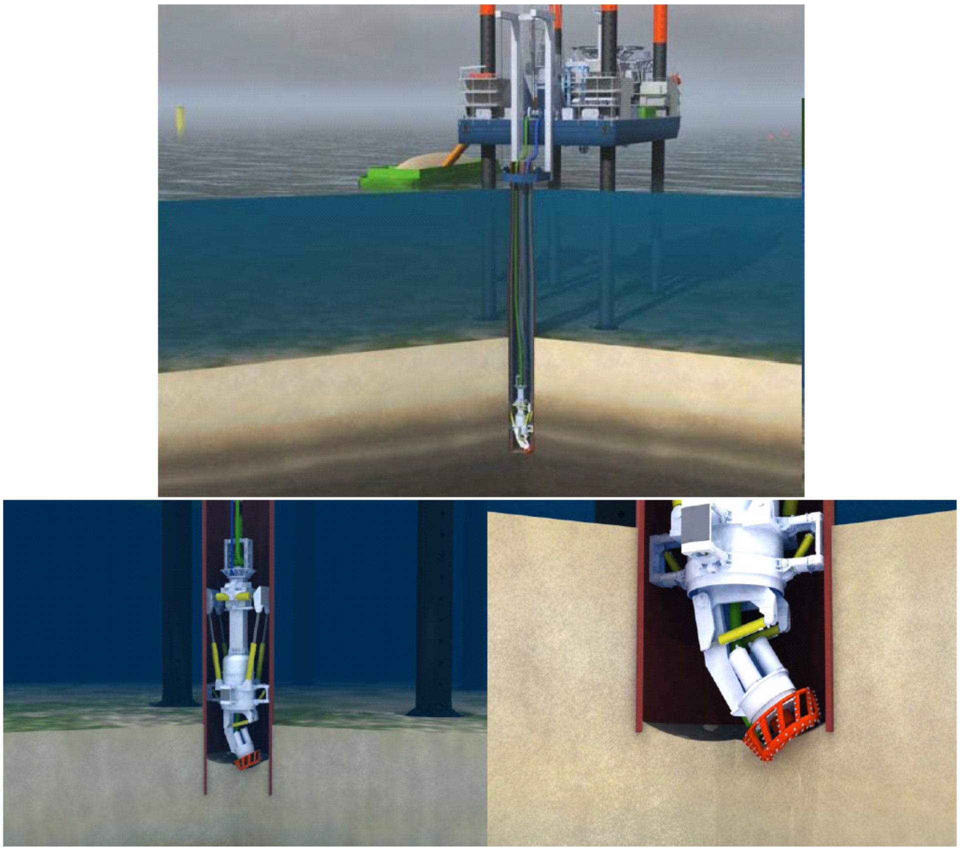

Figure 4-6: Schematic of the Offshore Foundation Drilling (OFD) concept (Source: Hochtief Solutions, Essen)

Pile arrangement

Multiple piles which have been widely used in the offshore oil and gas industry, c.f. Figure 4-7 (left) [FhG-H12]. Offshore piles in groups commonly have close spacing, and the overlapping effects, depicted in Figure 4-7 (right), are significant. The installation of pile groups and the fabrication of pile sleeve construction are assumed to be less cost effective from the current point of view.

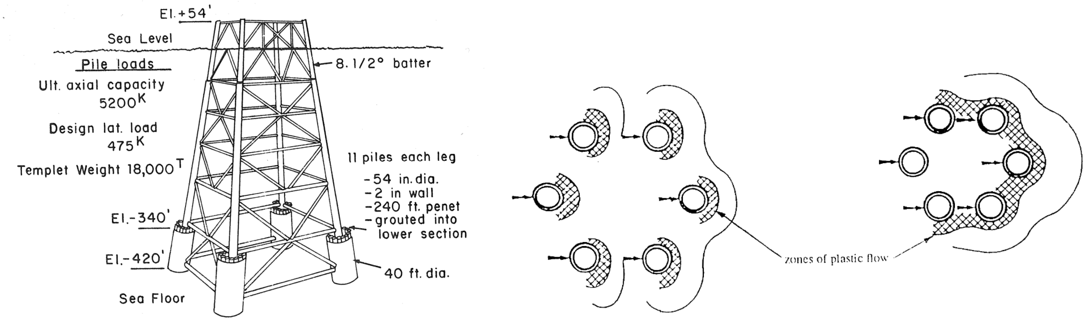

Figure 4-7: Pile foundation for jacket structures in deep water (left).Schematic illustration of pile group under lateral loading in case of wide (left) and close (right) spacing (right)

4.2.3 Development needs and prospects for the preliminary design of the reference support structure and consequences for the work program in task 4.1.

Requirements on foundation components

The piles of the foundation for the jacket support structure have to fulfil several requirements. The pile design should lead to a low impact on cyclic degradation effects resulting in the following requirements on the design of the support structure:

- A low lateral loading compared to axial loading is necessary to reduce lateral deformation and resulting cyclic effects.
- The foundation component has to ensure a sufficient self-healing capacity, i.e. that the foundation structure should have a sufficient robustness against extreme loading combined to the ability to recover accumulated deformations during periods of lower excitation.

Suitable pile foundations to be investigated for the design of the support structure are summarized as follows:

- Single piles should have an optimized bearing behaviour (capacity, deformation) and low noise emission during installation.
- The application of piles in a group is usually more expensive due to the sophisticated pile sleeve structure but might be an option to reduce the noise emission during installation.
- The installation of bored piles instead of driven pile could be applied. The cost effectiveness and the technical feasibility have to be proven or optimized.

Recommendations for further investigation

The transient axial load bearing behaviour along a single pile should be investigated in order to predict its influence on the cyclic behaviour of larger piles. With the upscaling to larger jacket structures the foundation's behaviour will be different from those of currently installed jacket support structures.

The development of excess pore water pressure at monopiles has been investigated numerically by Tasan (2011) [FhG-H13] with respect to pile diameter and hydraulic conductivity. Within this topic it should be investigated if and to what extent soil-structure interaction and cyclic behaviour interact with significant values of excess pore water pressure and resulting hydraulic transport processes of grain particles.

Combined loading effects (c.f. [FhG-H14] amongst others) as well as scale effects should further be investigated with respect to the optimal steel pipe pile geometry according to length, diameter and wall thickness taking into account the relation of lateral and vertical loads on the pile head.

It is also recommended to extend the data base of pile tests by available data from dynamic load testing of offshore piles. On this basis the design rules for axially loaded piles could be enhanced by a statistically enhanced size of the data base.

From the above mentioned topics the recommended experimental tests and numerical analyses to be carried out are as follows:

- Investigation of the influence of installation methods on the cyclic pile behaviour
- Investigation of the development of the bearing behaviour under cyclic loads
- Investigation of interaction effects due to combined lateral and vertical loading
- Investigation of effects of pore water pressure especially in view of pore water flow and relocation of soil particles

Due to the limited budget for experimental tests, the above mentioned research objectives should mainly be carried out within numerical simulations in which validated modeling approaches have to ensure the reliability of the predictions. The main focus of the analyses will be the cyclic behaviour of the foundation system and the sensitivity of its bearing capacity with respect to an increasing pile diameter.

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4.3 Hydrodynamically transparent structures (DTU)

4.3.1 Technologies used in industry for current 5 MW class and in other sectors

Many types of steel structures used as offshore sub structures for wind turbine installations can be considered to be hydrodynamically transparent that is, they significantly reduce the wave loading, which would normally accrue on bluff body structures of their size. A typical example is a jacket sub structure, which though occupying a significant volume of water, has considerable porosity due to its assembly of slender members. However jacket members are still subject to wave loading, which due to the slender size of the links can be computed using the Morison equation. The Morison equation for hydrodynamic loads is usually considered valid if the diameter of the structural member is less than 20% of the wave length, which is the case for hydrodynamically transparent structures. The UpWind Project report on offshore support structure design [DTU01] provided an overview of the jacket designs being used today and the potential in the near future.

4.3.2 Technologies under current RTD for 5MW class and in other sectors

Comparison of 3 and 4 legged jacket designs

In order to minimize the cost of energy of offshore wind energy at moderate water depths, it is essential that the cost of the sub structure is reduced. Of specific interest, is the material cost savings that can be made, if a three legged jacket is constructed instead of the more widely used four legged design. The three legged jacket structure is similar in configuration to a 4 legged jacket, but consists of 3 leg assemblies in a triangular arrangement as depicted in Figure 4-8 below. The three legged jackets have lesser volume subjected to hydrodynamic loading and can use lesser material than 4 legged jackets.

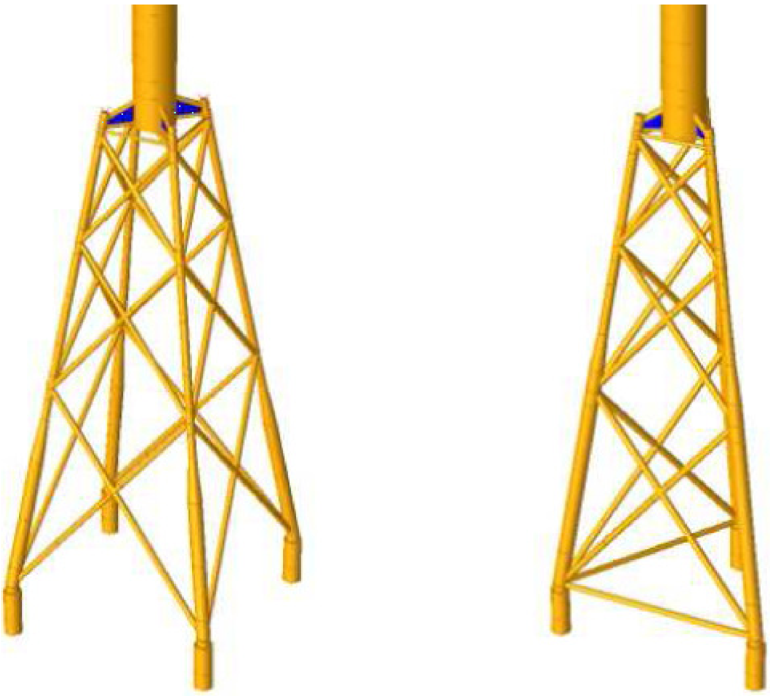

Figure 4-8: Schematic of 3 and 4 legged jacket type sub structures

However, the legs of the jacket need to be stiffened to support greater loading and often the foundation piles need to be driven to a greater extent. It is also possible that the braces of the 3 legged structures are subject to increased fatigue loading [DTU02].

The three legged sub structure can have significant differences in the modal frequencies than 4 legged structures, but the fundamental frequency of the sub structure is designed so as to be in between the p frequency 3p frequency of the turbine, where p is the rated speed of the rotor. One of the main advantages of the three legged structures is that the reduced wave loading can mitigate the effects of wind/wave misalignments, which often is a primary cause for high fatigue loading in wind turbine sub structures. Another obvious advantage that reduces the labour cost of jacket manufacturing is that the number of welded joints can be reduced, which can be further enabled using optimal design to minimize stress hot spots. The design of the joints of the three legged structure will be specifically performed in this task.

A key problem with hydrodynamically transparent structures such as jackets is that they can cause immense sea ice accumulation in waters with ice floes [DTU03] and efficient barriers to ice accumulation must be made if jackets are to be deployed in ice prone areas. Further the boat landing and other accessories must be carefully designed so that there are no boat impacts on the main structure as boat collisions with the jacket structure can be damaging.

Overview of soil condition models used in sub structure design

The soil is a highly stratified material with varying properties at different layers. However for the purposes of wind turbine sub structure design, aero-hydro-elastic load simulations need to be performed to compute the design loads on the sub structure, which many a time do not encompass detailed nonlinear soil mechanics. Three different soil-pile interaction models that are commonly applied in aeroelastic software for the investigation of the wind turbine sub structure response are a distributed springs model, apparent fixity model and coupled springs model [DTU04]. These models are derived from the basics of a Winkler foundation and from measurement of lateral stiffness (p-y curves), soil strength and cohesive properties. The extreme and fatigue loads on sub structure design especially for monopile structures are very sensitive to the soil stiffness and damping, especially in the presence of nonlinear hydrodynamic excitation [DTU05] and the same can apply to jacket structures, unless the members of the structure are made slender and hydrodynamically transparent.

Often the soil is comprised of clay and sand, both of which have different stiffness and strength properties. The modeled soil properties like stiffness, cohesion strength and plastic resistance have a significant influence on the response of the wind turbine foundation and tower. A 10% decrease in the clay stiffness properties is seen to cause about a 3% change in the natural frequency of the sub structure [DTU06]. Therefore accurate measurements of soil properties and a detailed soil mechanics model may be required in appropriately predicting the wind turbine dynamic response. However an offshore wind farm spans several kilometres and detailed soil testing is perhaps carried out in two or three locations in the wind farm. Therefore the wide variation in soil properties over a large area is a significant physical uncertainty which a high fidelity soil model may not mitigate. Figure 2 describes the qualitative frequency spectrum of an offshore wind turbine support structure as obtained from strain gauge measurements on the site and compared with computer models of the wind turbine with a distributed spring soil model and with a rigid soil model [DTU07]. The distributed spring soil model used soil data from a measurement done at an undisclosed location on the site. From Figure 4-9, it can be inferred that the stiff/rigid soil model was able to better match the measured strain frequency, than the distributed spring soil model.

FFT analysis on M_x at transition piece bot

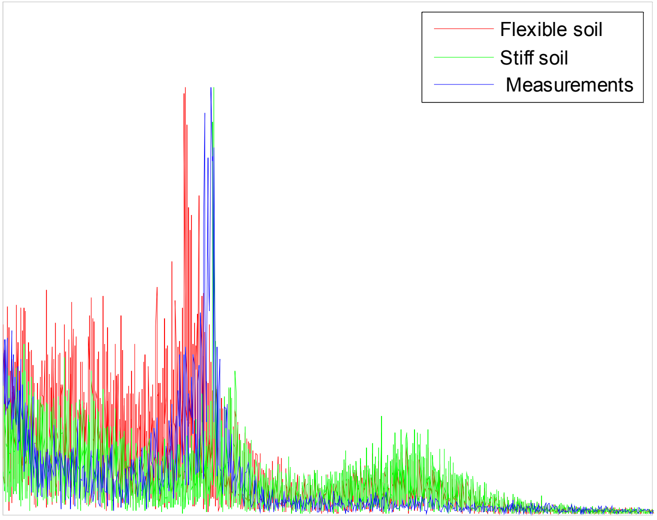

Figure 4-9: Qualitative comparison of Sub structure natural frequency between model and measurements [DTU07]

This indicates that the soil model cannot compensate for the physical uncertainties on the soil properties and if adequate soil measurements are not available, a stiff/rigid soil representation is not worse than an uncalibrated soil model. For 3 or 4 legged jacket structures, it is not only the lateral bending characteristics of the soil that can cause uncertainty in the design loads, but also the axial load response (t-z) of the soil. Further due to the fact that bending can cause axial displacement, the axial and bending stiffness of the soil may be coupled. This aspect also needs to be investigated so as to minimize the uncertainty in design loads on the jacket legs due to the soil model.

4.3.3 Development needs and prospects for the preliminary design of the reference support structure

Two types of hydrodynamically transparent sub structures are investigated by DTU in this project, 1) Slender structures designed for reduced cost.
2) A slender monopile type structure with an articulated joint at the sea floor

- The details of three legged jacket design have been explained in the previous section. The three legged jacket with slender members will be developed for the 10M reference turbine and at 50m water depth. It would be designed using structural optimization techniques under aero-hydro-elastic interactions. The structural optimization of frame structures under dynamic loads has been an area of research since the 1970s; see e.g. the review article Kang, Park, and Arora [DTU08]. The application of systematic numerical structural optimization in the wind energy sector is however fairly limited and only a few research articles in the literature address numerical structural optimization of support- and sub-structures. One example of application for support structures is presented by Zwick, Muskulus, and Moe [DTU09] where optimization was used to design full-height lattice towers for offshore wind turbines. Structural optimization of offshore monopiles is also described in Thiry, et al. [DTU10]. Models and methods for optimal structural design of wind turbine steel towers are presented in Uys et al. [DTU11], Negm and Maalawi [DTU12], and Yoshida [DTU13]. The slender jacket members to be designed herein will use these published approaches of structural optimization to minimize fatigue loading under different operating conditions such as under wind/wave directional misalignments. The braces of the structure will also be designed so as to facilitate minimized fatigue loading and to reduce the number of welded joints required. The dynamic excitation of sub structures is of concern to the reliability and lifetime of the structure. Sub structures are known to have poor damping characteristics and depend on the damping provided by the soil and from the wind turbine aerodynamics. It is therefore of interest to introduce active and passive means to dampen the oscillations of the sub structure. Active damping is usually provided using the turbine control system, which is using the blade pitch or the generator torque. Such an active control is beneficial to monopile type sub structures, but may not be as effective for jacket sub structures due to the interaction of the different members of the jacket with the wind turbine structure. Active damping using liquids that are controlled by electric or magnetic fields can be a viable alternative, if such dampers are embedded within the links of the substructure. Such dampers are termed as electro-rheological or magneto-rheological as based on the embedded material. This application is discussed in more details in the following section.

- The slender monopile on an articulated joint will be studied at varying water depths from 50m to 100m. The monopile is fixed to the soil with a universal joint that does not allow translational motion, but allows all 3 rigid rotary motions. Hence along with the soil joint, it is also required to tether the monopile with catenary type mooring lines to reduce the rotary movement of the sub structure. The articulated joint sub structure as shown in Figure 4-10 also requires a buoyancy chamber and under some conditions a ballast chamber. Investigations have been made at DTU, which showed that such a semi floater arrangement is possible at depths of the order of 120m for wind turbine installations at 5MW capacity [DTU14]. It was found that the system performance was more efficient than the floating spar buoy system and has lower extreme loads at the tower base. The cost and design of such a sub structure with universal joint at the foundation will now be investigated at moderate water depths of 50m and above and with turbine capacities of 10MW and higher. The mechanics of the universal joint and the required mooring will also be analysed and published.

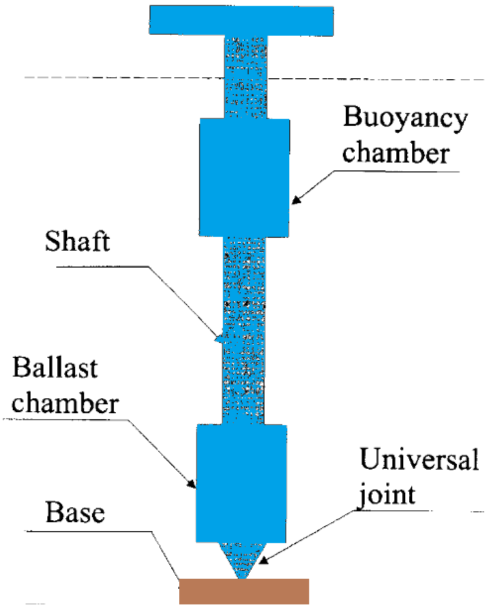

Figure 4-10: Schematic of a semi floating foundation with a universal joint at the sea floor [DTU15]

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5 LOAD MITIGATION

Increasing wind turbine sizes alter the requirements and the load ranges significantly. As known from literature [01], the thrust increases with the rotor diameter squared, the tower base moments increase in addition with the consequently higher hub height. The static loads in the structure are cubed in relation to the increase of the rotor radius. These higher loads lead to larger required stiffnesses in the support structure. On the one hand, the higher stiffness subsequently changes the natural frequencies. In most cases, depending on the change in mass, they increase. On the other hand, larger rotor diameters lead to a decrease in rotor speed and therefore to periodic excitations in lower frequencies. This results in resonances, i.e. interferences of excitation and natural frequency, and therefore in larger amplitudes of oscillations. In addition, the wind turbine experiences various excitations, such as turbulent wind and waves and also altering or imprecisely defined soil conditions change the turbine's properties. To overcome these limitations and to breach the cubic up-scaling law, three approaches may be considered in the wind turbine design:

- Innovative materials with strongly improved characteristics
- Better estimation of precise soil characteristics
- Mitigation of the effects of various excitations

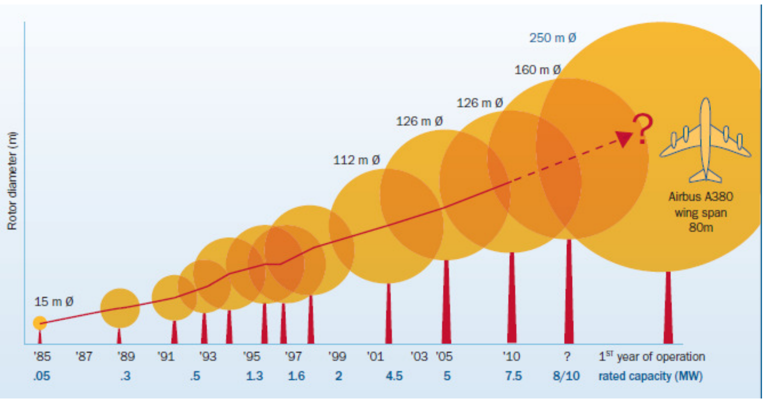

Figure 5-1: Trend in wind energy regarding turbine size and power [02]

The first two approaches are already in the focus of chapter 3 and chapter 4, where improvements in material characteristics and better predictability of soil conditions are discussed. This subsection emphasizes the last approach of achieving relevant enhancements on the loads side and lists advantages and opportunities of load mitigating concepts. The mitigation of extreme and fatigue design loads on the sub structure is crucial to decrease its cost. Mitigation of the design loads requires increased damping of the sub structure response, either by active or passive means.

The total damping of the support structure depends on the wind and wave direction. However most of the net damping is from the rotor aerodynamics and thereby the excitation of a monopile in the cross direction or a jacket link is readily possible since the structural and soil damping are often assumed to be less than 1% critical. The GL- note on engineering guidelines [03] describes the net damping of a wind turbine support structure minus aerodynamics to be of the order of 1.2% critical. This leads to high excitations of the sub structure due to wave excitation, rotor excitation or in some cases a coupled mode of a jacket brace with a higher mode of the blades.

Promising concepts are mainly based on two principles: assuming the rotor-nacelle-assembly as being an actuator or the integration of additional energy dissipating devices in tower or nacelle, i.e. exerting counter-acting forces or to increase structural or aerodynamic damping. Therefore active and tuned passive damping mechanisms that can attenuate precise modes of sub structure excitation, not only at the fundamental model are required, Further, these damping mechanisms should be robust in performing under a small variation in the excitation frequency.

The Fraunhofer Institute LBF introduces in the following section the state-of-the-art on component level for passive structural and distributed devices, widely used e.g. in civil engineering or automotive. Nonetheless the achieved results are promising, the transfer is rather complex and therefore applications in the field of wind energy are rare up to now. Possible concepts, their prospects and limitations are found in subsection 5.1. ForWind – Oldenburg focusses on semi-active and active devices but also gives an overview over chosen passive devices and control concepts. Semi-active and active devices are also used in civil engineering, like the earlier mentioned passive devices, but some obstacles have to be overcome. DTU studies the ability to embed MR dampers on the braces of jackets with a cost benefit analysis on its potential for lowering the cost of jacket structures. The main challenges are the simulation of all relevant effects on the wind turbine system, the overall effect on fatigue and extreme loads, the realisation and the economic benefit. More details are found in subsection 5.2. IWES Kassel summarises control and regulation concepts of different complexity. Some of them have already been tested on wind turbines and proved a lot of potential in load reduction for the support structure. However, the synergies or interferences as well as the feasibility in terms of economic effectiveness of the different concepts are of high importance. The concepts are described in subsection 5.3 and development needs and chances are defined.

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5.1 Passive damping devices (FhG-DA)

5.1.1 Technologies used in industry for current 5 MW class and in other sectors

Passive vibration absorbers (PVA) are commonly used to suppress disturbing vibrations in different industrial areas, like automotive, railway and in manufacturing. Furthermore PVAs are applied to high rise buildings and bridges. For these applications PVAs enables a larger comfort and greater security on these structures.

The reduction of vibrations leads to decreased displacements in the structure. Therefore the host structure run smoother and quieter in their operating state. Using PVAs, resonances of the structure are eliminated and the operating frequency range can be enlarged. The fatigue life is probably extended too, when disturbing vibrations are deleted and the stress on the devices is reduced.

As already described by Frahm in his patent application in 1909 [FhG-DA01], a tuned vibration absorber consists of a spring-mass-oscillator connected to the structure. While being mostly concerned with problems of ship building, he predicted the usefulness of tuned vibration absorbers in other sectors as well. With the determination of optimal parameters for the tuned absorber in the case of application to a single-degree-of-freedom system, the design of such device is a straightforward task [FhG-DA02]. The design of a PVA mostly uses a significant amount of damping, while the absorber resonance is tuned to a structural resonance.

A further approach can be used to adjust the resonance frequency of vibration absorbers by adapting the absorber stiffness and/or absorber mass, either physically or virtually by means of dynamic feedback force (see Figure 5-2). For reasons of simplicity, most tuned vibration absorber (TVA) adapting their tuning by changing the properties of the spring. The adaptation of the spring stiffness can be done in many ways, using a wide range of actuator types. Actuators range from electric motors to novel smart materials such as Shape Memory Alloys, magnetorheological materials, and piezoelectric ceramics. The application of a TVA device to a tram to reduce the vibration of the compressor of an air-conditioning unit is shown in [FhG-DA03]. The authors used a piezo ceramic based approach with a feedback controlling.

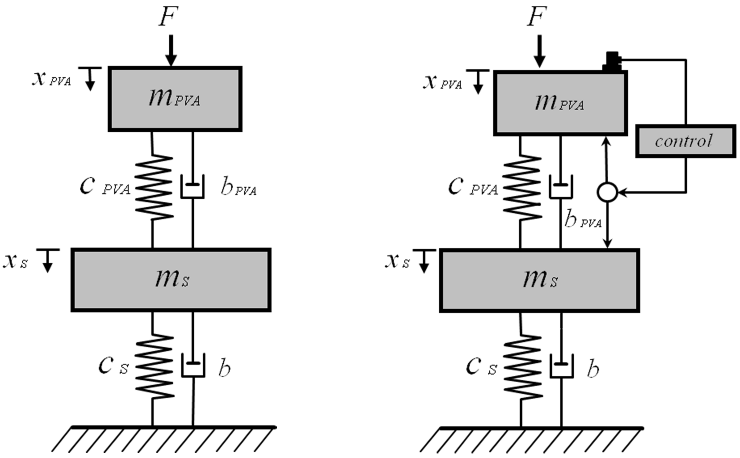

Figure 5-2: mode of operation of a PVA at a host structure

The application of PVAs to bridges is frequently considered problem. Since a bridge is a slim structure with an excitation at a similar frequency range, solutions can be transferred to wind turbines. A great overview on passive and liquid vibration absorbers (LVA) and their numerical and experimental application to a bridge is given in [FhG-DA03]. There are two considered excitations; they are induced by pedestrians and wind, respectively. Moreover the effects of the horizontal and vertical positioning of the PVAs and LVAs to the structure are covered. The author used a direct solution approach, namely a simplex search method of Lagarias to optimize the devices' parameters.

In [FhG-DA04] the authors give a considerable overview on the implementation of PVAs to public bridges (i.e. the Millennium Bridge, London) and buildings (Burj Al Arab, Dubai). To solve realistic problems, which occur at low frequencies up to 10 Hz, distributed PVAs are used. Also the implementation of a circular PVA wrapped around a flue is presented. At the flues top deflections of up to 70 cm were measured. Within the wrapped PVA the deflections were reduced such that less than 15 cm deflections occur. This approach can be numerically analysed to lower torsional modes occurring between the jacket and the monopile structure. Therefore also the different kinds of loads have to be taken into account.

For example the company Maurer Söhne shows in [FhG-DA05] PVA devices and their application to bridges, towers and slim steel structures. The positioning as well as the used large amount of masses is predicted by experience and basic numerical considerations, respectively. They provide different concepts of PVAs. At most of the showed applications more than one PVA is applied to the host structure.

Another company that researches, constructs and installs PVAs to large host structures is Gerb. They also provided PVAs for an offshore 5MW wind turbine at the test plant in Bremerhaven, as well as a transformer station of an offshore wind park [FhG-DA06].

Also other companies investigated in the production and application of PVAs to wind turbines, like Stop Choc or ESM GmbH. The latter ones applied PVAs to an onshore wind turbine to reduce the first bending mode that lies between 0.3 and 3 Hz. The PVA in Figure 5-3has a weight of 500 kg.

Figure 5-3: left: novel PVA to reduce monopiles. Right: PVA under the turbine of a 1MW onshore wind turbine [Source: www.esm-gmbh.de]

Some authors are examining on vibration reduction with PVAs or liquid PVAs for rise buildings.

The authors in [FhG-DA07] focus on an offshore platform with jacket support structure and applied PVA. The damped vibrations are ice-induced. They constructed a tuned mass damper that acts on the top of the platform. The reduction of reflection is about 35%, while just 2% of the overall mass is used. The PVA is applied on the top of the offshore platform and works in a horizontal position.

In [FhG-DA08] the optimum parameters of one tuneable PVA in order to reduce responses of a building under earthquake loadings (El Centro, 1940) are investigated. To determine the optimal parameters a harmony search approach is used. The results are compared with results of other authors that also used an evolutionary approach. The presented setting lead to better results than a genetic algorithm while having numerically smaller parameters.

Hitchcock et al. equipped a tall steel frame communications tower with multiple liquid tuned vibration absorbers. It turns out, that from a maximum amount of 20 individual LVAs, using more than 5 LVAs do not lead to significant better results. The wind-induced accelerations are almost halved by mean of wind speeds of approximately 20m/s [FhG-DA09].

5.1.2 Technologies under current RTD for 5MW class and in other sectors

One of the treated support structures for wind turbines is a jacket structure. In the literature a variety of truss structures are considered. In [FhG-DA10] the authors discovered a truss incorporating active members. The active members are struts with integrated piezoelectric ceramic material. A truss structure with applied piezoelectric struts is also a matter of interest in [FhG-DA11]. Here the authors focus on the electric circuit, where a negative capacitance is used to shunt the piezoelectric material. In [FhG-DA12] a truss structure with applied adaptive vibration neutralizers is considered. The distributed neutralizer system is controlled with feedback loops. Each of the four vibration neutralizers is equipped with four piezoelectric ceramics. The measured results show improvements of the vibration suppression, where the adapting neutralizers perform better than the passive neutralizers (see Figure 5-4).

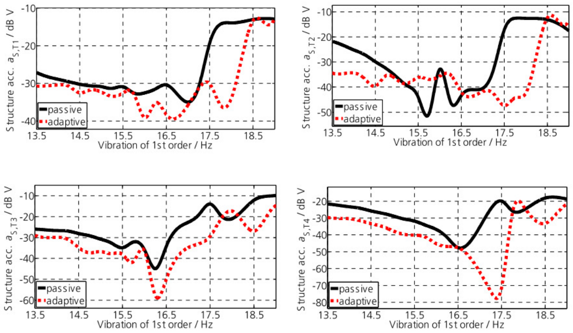

Figure 5-4: measured results showing the wide-band effects achieved with real-time adaptive vibration neutralizers applied to a truss structure

At a more extended truss structure the authors in [FhG-DA13, FhG-DA14] optimized and realized the distributed, passive and adaptive neutralizers. The neutralizers attached to the structure are optimized within a sequential quadratic programming (SQP) approach. The authors compared two different positioning settings of the devices. On one hand one neutralizer at the excitation position is considered and on the other hand four distributed devices are observed. Passive and adaptive devices were compared. It turns out that with optimized distributed adaptive neutralizers same or better results than with a single device at the optimized position can be achieved, namely about 4 dB reduction. Within this setting the used mass of the distributed devices is just 25% of the single device. The results were partially checked on the real structure with designed devices. The amount of reduction is approved within measurements (see Figure 5-5).

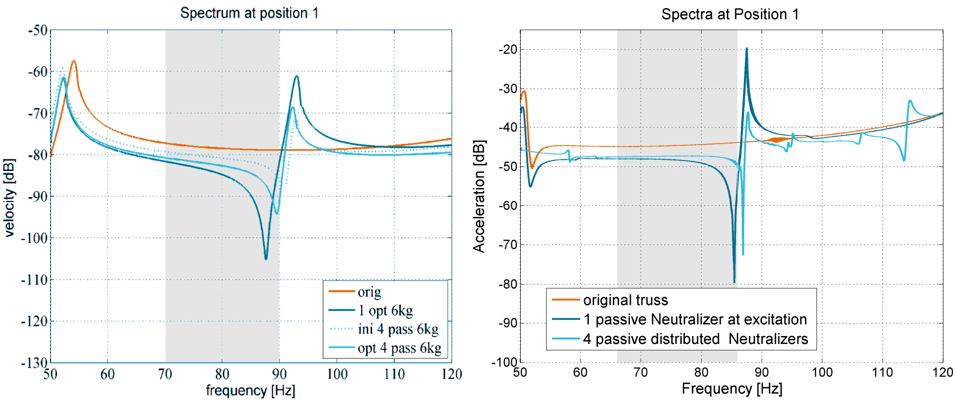

Figure 5-5: Spectra of numerically optimized neutralizer left and measured results at the same position [FhG-DA 14]

For elastic structures, the PVAs are likely to be implemented by distributed devices over the structure. Thus, numerical optimization methods have to be applied to the problem in order to design a well performing vibration control system of multiple oscillators with a limited amount of additional mass. Thereby the coupling and the interchanging of energy is taken into account.

The authors Chang and Qu derived analytically unified design formulas for five different passive dynamic absorbers for wind induced vibrations at tall buildings [FhG-DA15]. The unified equations lead to optimal properties and damping ratios for the considered five dynamic absorbers. The formulas are tested at a thirty-nine-story building. It turns out, that the suppression of acceleration is very effective, while on the other hand no significant reduction in the total displacement and the total shear forces are achieved. Four of the five treated devices contain liquids and have therefore a nonlinear characteristic.

Research on sophisticated concepts and approaches for optimizing passive distributed absorbers are often done on very simplified structures, e.g. on spring-mass-oscillators [FhG-DA16] or beams [FhG-DA17]. In [FhG-DA 16] the authors consider multiple tuned mass dampers (MTMDs) to control the structural vibrations. The MTMDs are a large number of small tuned mass dampers (TMD) whose natural frequencies are distributed around the resonance frequency of the structure having unwanted vibrations. Li and Ni attached the non-uniformly distributed MTMDs to a single spring-mass-oscillator (see Figure 5-6).

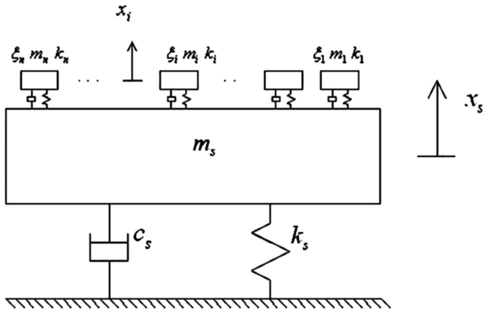

Figure 5-6: Analyzed setting of host structure *s* and *n* applied MTMDs [FhG-DA 16]

As an optimization algorithm, they used multiple objectives and a gradient-based method. The objective function differs from other authors, because they consider the maximum displacement of the main structure, than the root-mean-square response, which is often treated. Moreover non-uniformly as well as uniformly distributed devices are compared and error estimation of the structural natural frequency and damping ratios are taken into account. It turns out that non-uniformly distributed MTMDs are more effective than uniformly distributed devices while having some restrictions on the frequency spacing and damping.

Approaches using active techniques for multiple absorbers are although analysed on spring-mass-oscillators [FhG-DA18] as well as for beam structures [FhG-DA19]. Here the concepts of distributed absorbers are hardy transferable to complex structures, due to capacity disadvantages of the algorithms. For complex structures often heuristic approaches are used, that take positioning, topological and controlling difficulties into account, e.g. genetic algorithms or simulated annealing. An overview is given by Begg and Liu in [FhG-DA20] and [FhG-DA21].

In [FhG-DA20] the structure and controller variables are both taken into account as independent design variables. Generally the structural sizing as well as the structural layout in terms of shape and topology is distinguished. This results in a typical multidisciplinary optimization problem. They point out, that the objectives are settled to meet robustness, controllability and observability. Moreover the objective functions can take quadratic performance index, structural weight, energy dissipation and as well as the before mentioned measure of robustness into account.

The structural as well as the controller design variables can be discrete or continuous, which often raises the complexity of the optimization problem. The actuator/sensor placement falls into the class of combinatorial optimization. Thus for large problem sizes the solution is exceedingly intractable. For these problem types often heuristic-based approaches are used, where it is not guaranteed to retrieve the global optimal solution. One advantage of a heuristic-based approach is the possibility of iterating from a local optimum to the global optimum.

In the companion article the authors present in [FhG-DA21] several algorithms, as guided random search technique, sequential mathematical programming and their mixtures for the solution of the multi-objective optimization. Simulated annealing as well as hybrid sequential linear/quadratic programming turned out to solve the topological program best.

5.1.3 Development needs and prospects for the preliminary design of the reference support structure and consequences for the work program in task 4.1.

Passive vibration absorbers often have a large amount of percentaged mass of the host structure and work narrowband. Using distributed PVAs the reduction working in a small frequency range can be extended. In communications with companies, mentioned beforehand, it turned out, that the distribution of devices as well as the apportioning of masses is made by two steps. One step is made by basic numerical investigations to have a good ratio between the host structure mass and the added PVA masses. Also the eigenfrequencies of the host structures are taken into account, whereas they are mostly measured. The other large step is the experience that are integrated and which composes the companies' success.

The 10 MW reference wind turbine as well as the 20 MW wind turbine are elastic and complex structures. When the occurring eigenfrequencies are determined, also all important load cases need to be considered. Hence the problem of positioning and configuring the distributed devices becomes rather complex. Therefore the optimization of distributed PVAs needs further investigations. Using an evolutionary optimization approach it is in long term also possible to take further parameters into account. For example an approach using adaptive devices could be extended such that the adaption parameters are also treated. Since this procedure is coupled to a variety of further aspects, like a controlling system, only distributed PVAs are considered in a first step. Within these considerations also the different load cases need to be focused.

In own further researches the optimization strategies are chosen in a first step such that nonlinear behaviours of the devices are not taken into account.

It is useful to investigate in the design and dimensioning of a structure with numerical simulations to influence the dynamic behaviour of wind turbines positively. Especially for elastic and complex structures with a variety of loads and different mode of actions the application of distributed PVAs need to be tested numerically beforehand. Only when taking numerical optimization into account, it is ensured to add a small amount of mass. Also the test phase, where the devices are installed and measurements are taken, is than short.

If the installation of an optimization setting is assembled, the vibrations of the wind turbine are reduced. This possibly extends the fatigue life of the concerned devices. Hence the numerical optimization of distributed PVAs can decrease the overall costs of a wind turbine.

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5.2 Semi-active and active damping devices (FORWIND-OL)

Passive, semi-active and active damping devices used for structural control are widely used in civil engineering since decades. However, the main purpose for application of structural control is the excitation of buildings by earthquakes. More rarely, the devices are also used to mitigate wind induced loads where inter-story drift is used to dissipate energy either by transfer in heat or countermovement. The main challenge about wind induced vibration in structures is that there are only small displacements.

Furthermore, devices for structural control are used whenever problems during operation such as resonances occur. A famous example is according to [FORWIND-OL01] the Millennium Bridge in London, where passive tuned mass dampers (TMD) and viscous dampers were installed after resonance problems arose after construction.

The following sections will focus on semi-active and active damping devices used in industry, both wind and civil engineering or in research. Although passive devices are more commonly used, they are not automatically adapting, like active dampers, to different operational domains, altering structural properties such as degradation of soil and material or are limited to smaller bandwidths for instance tuneable mass dampers. Semi-active devices combine the advantages of both active and passive devices such as reliability and adaptability while avoiding the disadvantages such as high power consumption. Recent research showed the potential of semi-active and active damping devices especially in wind engineering where broadband excitation due to changing rotational speeds, turbulence and wave excitation dominates. Challenges are still costs, limited lifetime and reliance on external power [FORWIND-OL01]. In most cases, stability and endurance of the structure has to be proven in case of failure of the devices, which might become up to now highly ineffective from an economic point of view.

5.2.1 Technologies used in industry for current 5 MW class and in other sectors

Displacement amplification devices

A major challenge in using dissipative devices is the comparably small relative displacement in the structure due to wind excitations and turbulence. In civil engineering, various displacement amplification devices are used in these cases. Berton, e.g., [FORWIND-OL02] introduced a mechanism which connects rigidly a damper device to a relatively flexible structure. Under use of a lever arm, the displacement of the flexible structure is amplified and the stroke of the damper therefore increased. Not only is the dissipation of energy by dampers such as viscous or frictions types consequently increased, also the damper requirements and consequently price is lowered. Figure 5-7 shows a displacement amplification device as proposed by Berton [FORWIND-OL02]. The amplification is realised with a lever arm (20), which is connected to the rigid structure (18a & 18b), the flexible structure (10a & b) and to the dampers (26a &b).

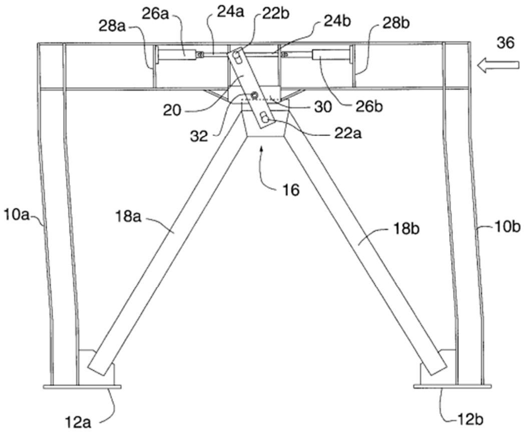


Figure 5-7: Displacement amplification method and apparatus for passive energy dissipation in seismic applications [FORWIND-OL02]

Other concepts are based on toggle braces, which are diagonally installed in a frame and leads to a stroke of the damper which is a multiple of the structure's displacement. However, flexibility and precision in the mechanisms and joints defines the effectiveness of the system. An example for a toggle braced system is the so-called "scissor jack" configuration, proposed by Constantinou [FORWIND-OL03]. Figure 5-8 shows on the left braces installed inside of a frame of a building. On the right, the effect on the dynamics of the structure over frequency is shown and the potential of the displacement amplification apparatus is clearly indicated.

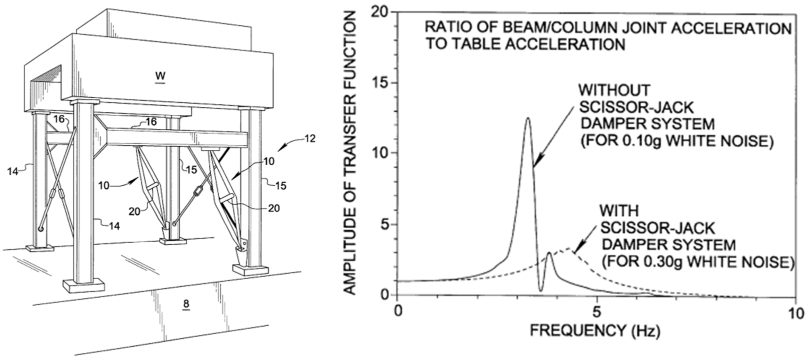


Figure 5-8: Integration of scissor-jack damper system (left) and amplitude of transfer function of tested structure with and without system (right) [FORWIND-OL03]

Tsouroukdissian [FORWIND-OL04] gives an overview over different displacement amplification configurations and their possible amplification factors. Figure 5-9 shows three different damper configurations. The upper and lower configurations are two different toggle configurations. The amplification factor is depending on the angular installation and can be around 2 to 3. The configuration in the middle is the so-called scissor jack as presented in [FORWIND-OL03]. As can be seen, another important advantage especially when applied in the field of wind energy is the reduction in space requirements as this is the limiting factor in slender towers. The quantity and alignment of damper mechanisms can be varied according to the specific needs. An optimal configuration might be using three dampers with a shift of 120° and all pointing towards the centre of the tower or a four-damper diamond-shaped arrangement, which might

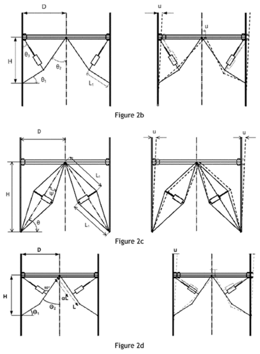


Figure 5-9: Displacement amplification configurations [OLD04]

also mitigate torsional loading. Additional investigations to estimate the effect of different settings shall be done.

Effect of active and passive control of structures

Using semi-active control in structures does not only mean integration of damping devices but also implementation of appropriate control laws and the effect on the structure. Casciati [FORWIND-OL01] emphasizes, that the passive part of the mechanism might already lead to a redesign of the structure. In addition, the active part has also to be taken into account in the design phase to achieve an improved controllability in terms of structural masses and optimization of amount of energy, which is later necessary to achieve the control goals. Therefore new design processes have to be initiated and integrated design of the overall structure becomes highly desired. In [FORWIND-OL01], an approach for the design process is proposed. The author recommends designing the controller with the structure assumed to be fixed to achieve performance requirements matching the "ideal response" of this initial structure. Later on, an integrated design will assure that objective functions can be optimized and the ideal dynamic response will be achieved.

Structural control can not only be used to achieve a given performance requirement, but can also lead to a certain damage tolerance: An acceptable performance where a damaged structure behaves like an undamaged can be realised. [FORWIND-OL01]

Some applications were realised where actively tuned mass dampers and viscous dampers to prevent inter-storey drift were used in parallel. The equivalent damping ratio in this example identified was to be around 7% with damper strokes of 5.2 mm and 640kN. The increase in damping ratio was therefore around 600%, reductions in displacement to one third of the initial value and nearly eliminations of the response peak of the first natural frequency were found.

Different variations can be realised to reduce inter-storey drift as shown in [FORWIND-OL05]. Mainly accelerometers are used in this study as reliable and inexpensive sensors. A multi-damper configuration was realised with tendon/pulley systems. One of the results was that the response reductions of the multi-dampers system were smaller than of the single-damper system, but it turned out that the required forces were significantly smaller for the multiple-control system. A trade-off is therefore important to determine the optimal configuration.

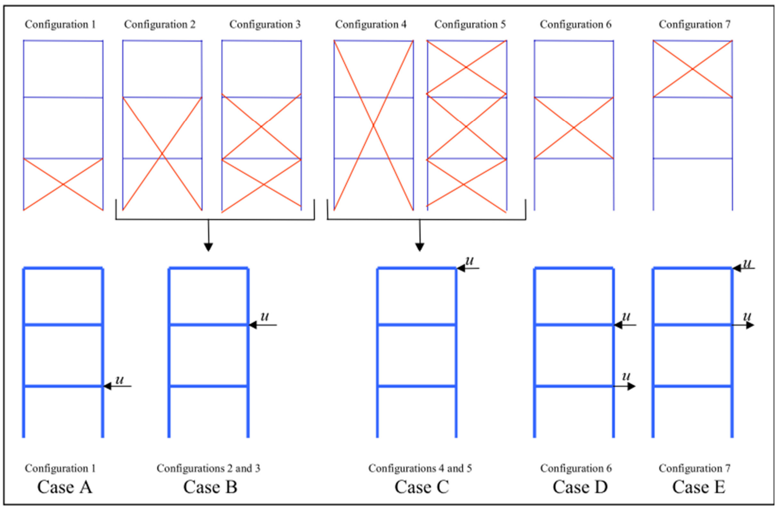


Figure 5-10: Single input control systems [FORWIND-OL05]

Control and regulation for load mitigation

The response of a wind turbine system can not only be influenced by structural control. If the rotor is not only seen as a mean to transfer kinetic energy from the wind into rotation but also as an actuator, different control and regulation concepts can be applied for a resulting force which, in case of optimally applied and counteracting, leads to load reductions. Field tests were carried out for an active tower damping controller [FORWIND-OL06]. Not only a commonly known fore-aft damper was implemented and validated, but also a side-to-side damper based on individual blade angle regulation. It is based on acceleration measurements in fore-aft and side-to-side directions. Whereas the acceleration in fore-aft direction leads to an additional collective pitch demand, the side-to-side acceleration results in an individual pitch demand. The pitch demand is then added to the collective pitch angle, which is defined to maximise the power output. The pitch angle offset among the blades induces aerodynamic imbalance which, though in normal operation undesired, results in counteracting, and therefore desired, forces in lateral direction. Like other control and regulation strategies a limitation of operational range also applies for the tower damping by pitch control. Due to prevention of power loss and care of the pitch actuator it is only used close to and above rated wind speed. However, the effect on fore-aft loads is still large as most of fatigue damage occurs during operation with low aerodynamic damping – during idling and at higher wind speeds than rated. Another aspect is the difference of fatigue loads in fore-aft and sideways direction offshore compared to onshore. Due to the relative small turbulence, missing aerodynamic damping and prevailing wind-wave-misalignment, the fatigue damage in side-to-side direction might be dominating. The individual pitch control tackles these loads and reductions of up to 30% in this direction compared to 10% in fore-aft were found whilst the other parameters stayed constant or increased only slightly, such as the pitch rate standard deviation [FORWIND-OL06].

Another concept was investigated by Gjerlov [FORWIND-OL07] where extreme loads during stand still non-power production state are mitigated. The concept is realised in such a way that the loading on the turbine and blades is monitored and stored in combination with the wind and yaw direction. Sectors are selected where least loads occur. The turbine is then in idling cases with high wind speeds rotated to achieve a position where the yaw-wind direction misalignment is in the sector of least excitation to prevent exceedance of loading and damage to the turbine.

5.2.2 Technologies under current RTD for 5MW class and in other sectors

Fluid dampers

Several publications describe structural control mechanisms which are currently under research both in wind energy but also in other sectors. As first example a variety of fluid or oil dampers is described. Berton [FORWIND-OL02] introduced a displacement amplification method which transfers inter-storey drift into rotational kinetic energy, which is afterwards dissipated by a propeller within a housing filled with viscous fluid.

Argyriadis [FORWIND-OL08], Zheng [FORWIND-OL09], Wilmink [FORWIND-OL10] and Faber [FORWIND-OL11] demonstrated the advantages of the application of fluid dampers in the upper part of the tower or in the nacelle respectively. Especially soft towers and structures subject to variable excitations profit of the added damping. It significantly reduces 1P or 3P excitations. However, also operational situations can be found where the effect is neglectable. Furthermore, one has to assure that malfunction of the dampers are avoided as they can severely damage the turbine. Monitoring might be a necessary measure to guarantee a proper operational state. An example for a fluid damper is illustrated in Figure 5-11.

FIG. 5

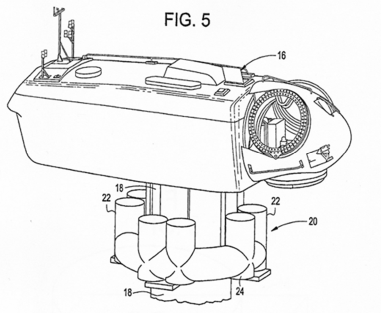


Figure 5-11: Vibration load reduction system located near a top of a tower of the wind turbine [FORWIND-OL09]

A damper is shown which is appropriate for multi-directional damping due to the distribution of columns around the nacelle. The fluid is located partly in the columns and the base, which are connected via valves. The damping effect is based on inertia forces. The valves can in addition be controlled actively to influence the exchange of fluid between columns and base. The location and distance of the columns as well as the quantity of fluid change the characteristics of the mechanism. [FORWIND-OL09]

Wilmink names the minimal space requirements of liquid dampers in comparison to mass dampers as advantage [FORWIND-OL10]. Whereas normal mass dampers need 4% of the total effective mass of the tower, the same amount of damping can be created with 2% as liquid damper leading to a tower base fatigue load reduction of 6% in full simulations. This is due to the fact that in an appropriate arrangement, the flow of the fluid can be redirected to be not only in horizontal but also in vertical direction. This is, due to the space requirements in the upper part of a tower or in the nacelle, a very important advantage. Furthermore, fluid dampers are non-linear, which makes them harder to model but increase in general the effect for larger displacements and hence, makes it more effective.

Faber [FORWIND-OL11] also describes the disadvantages of installing such a system. As expected for a double-mass system, the natural frequency of the tower e.g. is split into two peaks, which might lead to a larger exclusion window for the rotor speed. One has to prove in simulations, that regulations for the exclusion do not apply in these cases as the amplitude of the response is significantly reduced. Moreover, an operational vibration monitoring is necessary to assure proper operation of the damper apparatus. Faber proposed to keep the operational exclusion zone but not greater than in designs without dampers.

Riesberg [FORWIND-OL12] patented a water tank with flow restriction valve in the upper tower part including a sensor and processor and shock absorbers, which are connected inside the tower. Oscillation will then be detected and the processor will control shock absorbers and the flow restriction valve in such a way that they are damped in the range of the natural frequency. Dissipation of energy leads to less oscillations like in the aforementioned examples.

Tuned mass dampers

Lackner [FORWIND-OL13] published a report of passive structural control of wind turbines especially under use of tuned mass dampers. Although the author has a strong focus on the application for floating wind turbines, also bottom-fixed structures were part of investigation. Lackner experienced only minor effects on the loading of a monopile when the damper is tuned for the first natural frequency as the broadband excitation of the waves is dominating which might be in a different frequency range apart from the 1st natural frequency. He concluded therefore that a tuning according to the waves might be more advantageous. As illustrated in Figure 5-12, the effect of added damping can best be seen in a transient event like investigated on left hand side. The damper weight in this example is around 20 tons. The normal operation simulations with an optimal tuned mass damper on the right prove a reduction of 4.5% in the tower fore-aft DEL when compared with the baseline. However, the side-to-side damage equivalent loads are increased by 1.4%. This example clearly shows that load reductions in one component might always lead to increases in other components. An in-depth analysis of the overall system is necessary. Furthermore, possible combined arrangements might be interesting in this case such as the combination of a passive, semi-active or active damper with corresponding control strategies to further mitigate sideways oscillations such as the individual pitch control. A study of the economic impact is then of importance to evaluate the concepts.

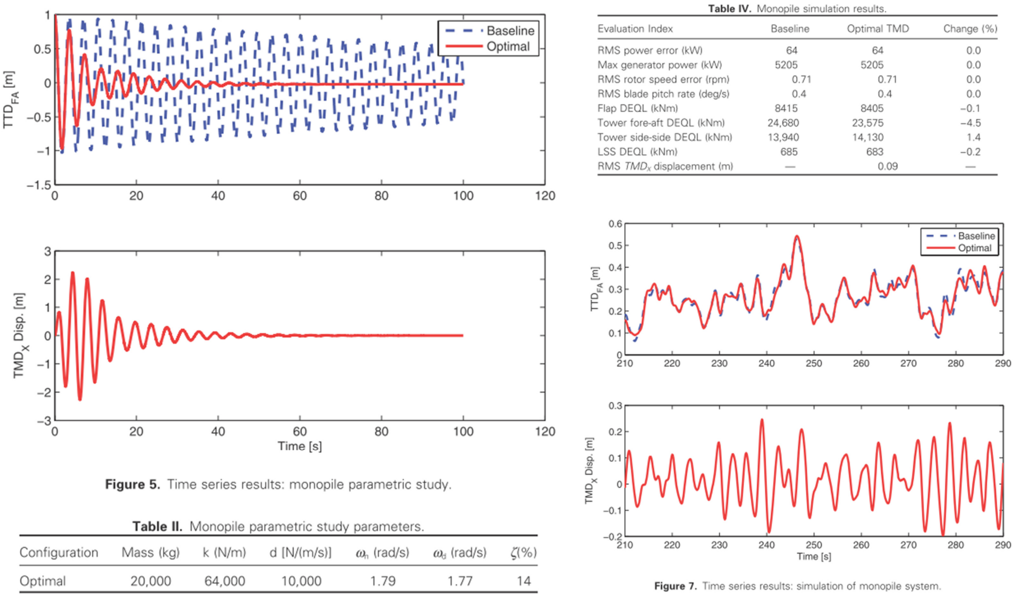


Table IV. Monopile simulation results.

Evaluation Index	Baseline	Optimal TMD	Change (%)
RMS power error (kW)	64	64	0.0
Max generator power (kW)	5205	5205	0.0
RMS rotor speed error (rpm)	0.71	0.71	0.0
RMS blade pitch rate (deg/s)	0.4	0.4	0.0
Flap DEQL (kNm)	8415	8405	−0.1
Tower fore-aft DEQL (kNm)	24,680	23,575	−4.5
Tower side-side DEQL (kNm)	13,940	14,130	1.4
LSS DEQL (kNm)	685	683	−0.2
RMS TMD_X displacement (m)	—	0.09	—

Figure 5. Time series results: monopile parametric study.

Table II. Monopile parametric study parameters.

Configuration	Mass (kg)	k (N/m)	d [N/(m/s)]	ω_n (rad/s)	ω_d (rad/s)	ζ(%)
Optimal	20,000	64,000	10,000	1.79	1.77	14

Figure 7. Time series results: simulation of monopile system.

Figure 5-12: Monopile simulation results – Transient excitation (left) and normal operation (right) [FORWIND-OL13]

Semi-active and active damping devices (DTU)

Passive and semi-active dampers have been proposed and also used in offshore wind turbines. Most passive dampers used in offshore wind turbines are situated at the nacelle and tuned to the fundamental frequency of the support structure so that the motion of the liquid or the movement of a spring mass can mitigate the oscillation of the tower. Many different arrangements of these dampers are possible as in:

1) Mass spring damper [DTU16]
2) Liquid sloshing in a tank [DTU16]
3) Liquid in a U-tube or multiple U-tube arrangements [DTU17]
4) Different types of mechanisms and friction dampers [DTU18]

All of the above dampers can be developed as passive or semi-active devices, if they are actuated by the wind turbine control system under specific conditions such as during rotor over speed or turbine shutdown. Some of the liquid dampers such as the tuned liquid column dampers can provide nonlinear damping and therefore a greater bandwidth for the damping action. However these dampers are tuned to certain structural modes of the wind turbine support structure, mostly the fundamental mode and may not be effective for other excitation frequencies.

It is not clear if such dampers benefit the design of a jacket sub structure from a cost perspective since many different criteria such as the stress concentration at welded joints, the number of welds etc. need to be investigated with regards to their potential to reduce fatigue loads and save material cost. Therefore the potential for semi active dampers to reduce jacket material cost is investigated in this task.

Semi Active liquid dampers (DTU)

Electro rheological (ER) dampers and Magneto rheological(MR) dampers change their characteristics when the rheological fluid is exposed to an electrical or magnetic field, thus changing its stiffness and damping coefficients. The ER and MR fluid possess a hysteretic behaviour with regards to its force-velocity relationship [DTU19] that can be controlled based on the current input to the damper, which makes it possible to be actively controlled

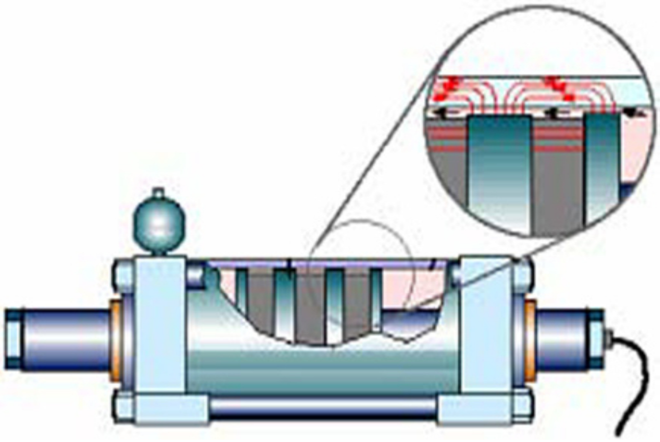


Figure 5-13: MR damper arrangement with coil and cylinder [DTU19]

The MR damper consists of a cylinder with magnetic coils and material with polarizable particles floating on a liquid substratum. The polarizing of the material to change its properties does not require a great deal of energy, with 10W sufficient to produce about 3kN of force [DTU19] in a few milli-seconds. It has also a compact arrangement which can be assembled into several series arrangements within the braces of the jacket structure. The material has high yield stress levels, which prevent failure under normal engineering loads, but requires investigation in wind turbine operational conditions. The dynamics of the MR damper equipped structure can be actively controlled using current signals to the damper to mitigate fatigue loadings or it can be a semi-active arrangement whereby the current is used to actuate the damper to a pre-designed stiffness and damping coefficient under extreme conditions and then de-activated under normal operation. Such an active /semi active damping mechanism will supplement the normal turbine controls which also provide active damping to tower vibrations. The effectiveness of such a damper under different design conditions such as normal operation, storm conditions, extreme sea states etc. are investigated in task 4.1 of this project. The most optimal arrangement of these MR dampers on the sub structure is also investigated.

Semi-active and active structural control in wind energy

Lackner [FORWIND-OL13] also investigated active and semi-active approaches. He concluded that active approaches offer by far the highest potential in load reduction, but also points out the potentially high power requirements. According to the Author, semi-active and active concepts are a relatively new topic in wind energy and are virtually not applied up to now inside the structure.

Arrigan [FORWIND-OL14] published a research paper on the control of flapwise vibrations in turbine blades using semi-active tuned mass dampers. Although this work package 4 focusses on the support structure, this publication is worth being mentioned here. A smart tuneable mass damper was connected to each blade tip and to the nacelle. Simulations were done to estimate the influence on the system and also to investigate changes in the system parameters due to e.g. environmental changes or damage. Significant load reductions were found especially in the flapwise vibrations, which are mainly dominated by the turbulence in the wind.

Tsouroukdissian [FORWIND-OL15] proved that the implementation of viscous dampers, especially magneto-rheological dampers with displacement amplification inside a wind turbine tower might be highly beneficial. Fatigue load reductions around 20% in certain cases and a consequential mass reduction of around 10% were achieved. The advantage of viscous dampers is the large bandwidth in which they dissipate energy so other tower modes besides the 1st, also torsional, can be damped as well. The effect of changing the characteristics of the magneto-rheological damper is however highly depending on the trigger value which is used. It was found out to be beneficial if other values than the acceleration, such as rotor speed, were used in addition. All in all, a reduction of 10% in fatigue loads but also 20% in extreme cases were achieved. Unfavourable are some requirements for the dampers. The high number of cycles might lead e.g. to the fact that replacements might become necessary after a certain number of years in operation.

Control and regulation for load mitigation of wind turbines

If the rotor is seen as a controllable actuator and not only as a mean for the conversion of the kinetic energy in the wind, load mitigation can be realised under use of the control system of the turbine. Duckwitz [FORWIND-OL16] describes large side-to-side oscillation in case of yaw activity. In full load simulations in GH Bladed, the effectiveness of active damping of these oscillations was investigated. The concept used was individual pitch control, where aerodynamic imbalance is purposely employed to generate lateral forces. The Author mentions that disadvantages like increased axial loading and pitch activity necessitate considerations in which operational cases the concept might be applied. Duckwitz proposes the use only near and above rated wind speed and only if an acceleration threshold or a comparable trigger is activated. An advantage is the simple implementation also in already erected turbines. Especially in load cases dominated by sideways oscillations lateral damage can be eliminated almost completely. [FORWIND-OL16] This is not only realised by damping the first natural frequency but also higher ones. In another study, Duchwitz [FORWIND-OL17] summarizes other control and regulations concepts which are based on the regulating variables pitch and torque. Both extreme and fatigue loads could be reduced. Whereas collective and individual pitch control is already described in an earlier section, he further introduces a torque control where 5% of the nominal torque is used. Variation of the torque leads consequently to lateral forces and could be used to counteract lateral oscillations. The effectiveness is depending on the angular displacement of the nacelle in the specific mode. The high dynamics of the torque controller support effectiveness. 10-20% load reduction could be realised.

Shan [FORWIND-OL18] published a report on field testing and practical aspects of the aforementioned control and regulation concepts, including more detailed numbers achieved in load reduction. Table 5-1 summarizes the results for different stations and concepts. He emphasizes that a sophisticated concept when to switch on and off which control concepts will be necessary for optimal operation as not every strategy is suitable in every situation and the use can even have negative effects, both from structural and economical point of view. The concepts will especially be interesting for very large turbines as the yawing and nodding moments will significantly increase with larger rotor areas.

Table 5-1: changes in lifetime weighted DELs for both considered load reducing pitch control modules using Rainflow-Counting method [FORWIND-OL18]

	Yaw and Tilt moment compensation	Active Tower Damping	SN-slope
Blade Root M_{flap}	-13%	+1%	14
Blade Root M_{edge}	0%	0%	14
Rot. Hub M_y	-18%	0%	4
Rot. Hub M_z	-18%	0%	4
Main frame M_y	-4%	0%	4
Main frame M_z	-4%	0%	4
Tower foot M_y	0%	-8%	4

Suryanaryanan [FORWIND-OL19] focuses on the torque modulation for load mitigation which is used as an active damping input. It mainly applies for doubly-fed induction drives, where the torque demand is not necessarily proportional to the slip. The variability of the torque demand can furthermore not only be used for mitigation of drive train loads but also to reduce oscillations and resulting loads for the structure, especially the tower in sideways direction.

Seidel [FORWIND-OL20] presents an additional concept for a specific situation, i.e. the turbine in idling mode. For certain support structures such as monopoles, it was experienced that the share of fatigue damage occurring during idling state is much larger than the actual time share in lifetime of these situations. Due to the missing aerodynamic damping in these cases and a wave spectrum whose dominant frequency lies in the range of the natural frequency of the system, strong excitations occur and results in large fatigue damage. Seidel proposes increased rotational speeds in trundle mode to increase the aerodynamic damping by using a different idling pitch angle. The control concept is preferably slow in order not to significantly increase the pitch actuator requirements.

Influence on natural frequency

Another aspect when using devices which significantly increase the damping is the influence on the natural frequency. An increase in damping alleviates oscillations and amplitudes but also increases the natural frequency, which has to be taken into account in the design phase when exclusion windows are defined [FORWIND-OL03].

Amongst others, the following two publications describe this effect explicitly. Wilmink [FORWIND-OL10] describes the integration of tuned liquid column dampers in wind turbines. A reduction of maximum response was found but the single peak of system response split in two and the location of the local frequency could be influenced. The fact that two peaks occur, increases in most cases the response at the edges of the normally used exclusion window.

Nieuwenhuizen [FORWIND-OL21] describes an alteration of the natural frequency on purpose. Connections inside a tower were established, including damping means, and a control system can alter the tension. The natural frequency is hence moved according to the control algorithm. Using this concept, peak stresses can be reduced and finally extend the lifetime.

5.2.3 Development needs and prospects for the preliminary design of the reference support structure and consequences for the work program in task 4.1.

A state of the art summary was successfully completed, showing different application examples which are used up to now. Moreover, all recent publications indicate large potential in using structural control and control and regulation strategies in terms of load mitigation. However an in-depth analysis of the overall system is necessary to investigate the following aspects:

- Synergies or interferences of different approaches
- Operational range where the concepts are most beneficial
- Structural implementation of additional devices
- Control implementation and effect on the safety system
- Impact on overall costs of the wind turbine
- Influence on required maintenance intervals and eventually periodic need for replacements
- Necessary monitoring systems and additional signals as control variables

To research these aspects, a detailed analysis of the reference turbine, its characteristics with respect to operational regions and occurring design loads will be carried out.

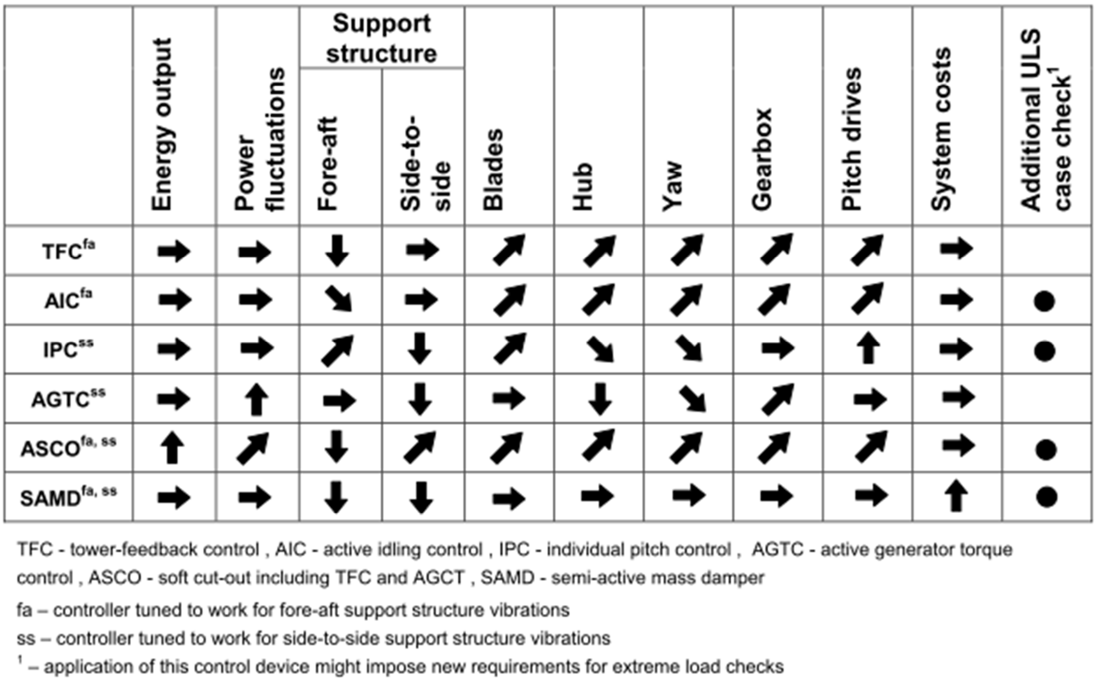
Due to the increase in rated power, water depth and rotor diameter, the characteristics are expected to change significantly. Large tower head masses and low rotor speeds will lead to very specific design conditions for the support structure. It needs to be stiff to sustain static loads but flexible enough to also overcome the dynamic loading. Due to the low rotational speed 3P resonances are possible to occur and as a result of the design of the jacket and possible full truss configurations of the tower, the impact of torsional modes will increase.

These aspects necessitate a review of the concepts described in this report in this new application case. Their impact on the overall system, as well as their potential, needs to be numerically investigated and proven. However, this literature study already showed large potential especially in load cases, which will become more prominent such as yaw misalignment.

Important development needs are the numerical integration of optional structural control into the reference turbine. This will mainly be done in aero-elastic simulations as a first step.

In further steps, the effect on all components will be evaluated. Fischer [FORWIND-OL22] already highlighted the influence of various concepts on economic efficiency. Especially variations in energy yield due to control concepts necessitate at least 4-5% reduction in substructure costs for each per cent in power loss (Fischer assumes a 20-25% share of substructure costs in the costs of energy). The author furthermore emphasizes that, due to hydrodynamic transparency, load mitigating controls might even be useless, which will be investigated in detail during this project. Table 5-2 summarises the main findings in the UpWind.eu project, work package 4, task 4.1. for different load mitigating concepts and their effect on the support structure.

Table 5-2: Qualitative fatigue load influences on system quantities by applying dynamic control concepts [FORWIND-OL21]



	Energy output	Power fluctuations	Support structure		Blades	Hub	Yaw	Gearbox	Pitch drives	System costs	Additional ULS case check[1]
			Fore-aft	Side-to-side							
TFC^{fa}	→	→	↓	→	↗	↗	↗	↗	↗	→	
AIC^{fa}	→	→	↘	→	↗	↗	↗	↗	↗	→	●
IPC^{ss}	→	→	↗	↓	↗	↘	↘	→	↑	→	●
AGTC^{ss}	→	↑	→	↓	→	↓	↘	↗	→	→	
ASCO$^{fa, ss}$	↑	↗	↓	↗	↗	↗	↗	↗	↗	→	●
SAMD$^{fa, ss}$	→	→	↓	↓	→	→	→	→	→	↑	●

TFC - tower-feedback control , AIC - active idling control , IPC - individual pitch control , AGTC - active generator torque control , ASCO - soft cut-out including TFC and AGCT , SAMD - semi-active mass damper

fa – controller tuned to work for fore-aft support structure vibrations

ss – controller tuned to work for side-to-side support structure vibrations

[1] – application of this control device might impose new requirements for extreme load checks

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5.3 Load-mitigating controls (FhG-KS)

5.3.1 Technologies used in industry for current 5 MW class and in other sectors

The primary objective of a wind turbine's control system is to ensure a safe and stable operation while maximising the overall energy output. Ensuring safety is achieved by keeping electrical and mechanical quantities within admissible ranges. Thus, the control system has a substantial impact on the loads experienced by the turbine during its lifetime. This, of course, also applies to the loads on the support structure. It is useful to distinguish between the operational and the dynamic control level.

The operational control deals with supervisory control tasks, e.g. triggering grid-connection when the conditions for power production are fulfilled. Its main inputs are averaged measurements of the wind field and the rotational speed. Based on these measurements it initiates transitions between the turbine's operational states: idling, start-up, power production, normal shutdown, and shutdown due to a fault.

Choosing operational control parameters like the cut-in and the cut-out wind speed does not only affect the annual energy yield. It has also a substantial influence on the loads. Mainly three dedicated load mitigation concepts are currently available on the operational control level: *speed exclusion zones*, *soft-cut out*, and *peak shaving*.

Dynamic control is related to several feedforward and feedback control strategies. Their primary objective is to ensure proper dynamic responses of the turbine, e.g. to changing mean wind speeds, to gusts, or to safety issues. For actuation, the typical basic controller structure uses the generator torque in the region below rated wind speed and the collective pitch angle in the region above rated wind speed. The rotational speed is used as the control input in both cases.

The basic feedback controllers have a tremendous impact especially on the fatigue loads of the tower. For example, most utility-scale wind turbines exhibit a bandwidth limitation for the closed loop system above rated wind speed due to the first tower mode [FhG-KS01, FhG-KS02]. If this is not properly taken into account, the controller design might induce unwanted vibrations that emerge from interaction between controller and tower motion.

The basic control strategy can be enhanced by a large number of methods to actively mitigate loads, see e.g. [FhG-KS03]. Different methods are available for *active tower damping*. Furthermore, *active idling* is an interesting option for offshore turbines. Load mitigation strategies for the 10+MW offshore turbines are being developed in task 1.4 and further developed here as required for different sub structure designs.

Speed exclusion zone

Speed exclusion zones, also called rotational speed windows or tower resonance bridging, can be useful when the rotor speed (1P) or blade passing frequency (3P) excites a structural resonance at a certain operating point, see e.g. [FhG-KS04, FhG-KS05]. Such resonances can be avoided by choosing the turbine's natural frequencies outside the operational excitation ranges. However, sometimes this is not possible. This is shown in the Campell diagram in Figure 5-14, where the frequency of the 1st tower mode lies within the 3p operational range of the turbine. At the red dot, the 3P-line cuts the dash-dotted line indicating the natural frequency. That is, when the system operates near this operating point, a vibration with the 1st tower frequency will be excited.

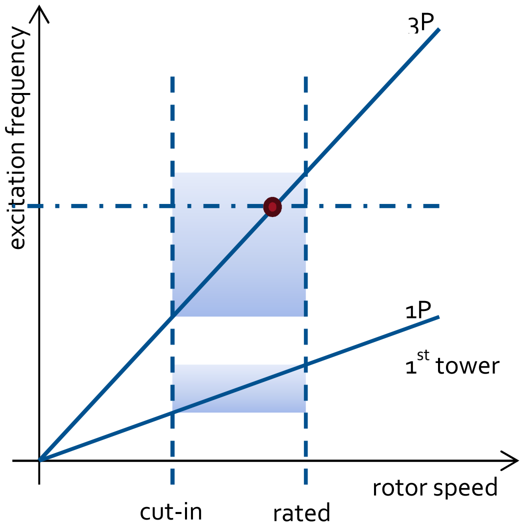


Figure 5-14: Campell diagram. The red dot indicates an operating point where the 1st tower mode is excited by the rotor speed (1P).

A speed exclusion zone can be employed in order to avoid this phenomenon. This means that the control system is modified such that the critical speed range includes no stable operating points. Thus, the rotor speed will rapidly drive though the critical speed range without severely exciting the natural frequency. Usually, this is implemented by modifying the speed-torque curve of the generator, see [FhG-KS04] and [FhG-KS06] for two implementation alternatives.

Soft cut-out

Most turbines shut down at very high wind speeds. Typically, the cut-out wind speed lies around 25 m/s. E.g. when the average wind speed exceeds this limit, a shut-down-procedure is triggered to drive the turbine to the idling state. This straight-forward cut-out strategy is shown in Figure 5-15a. Some sort of hysteresis should be involved before returning to power-production as to avoid heavy switching activities. Regarding the loads there is a trade-off between many factors: loads associated with shut-downs, operation/idling in high wind speeds, number of shut-downs, energy loss.

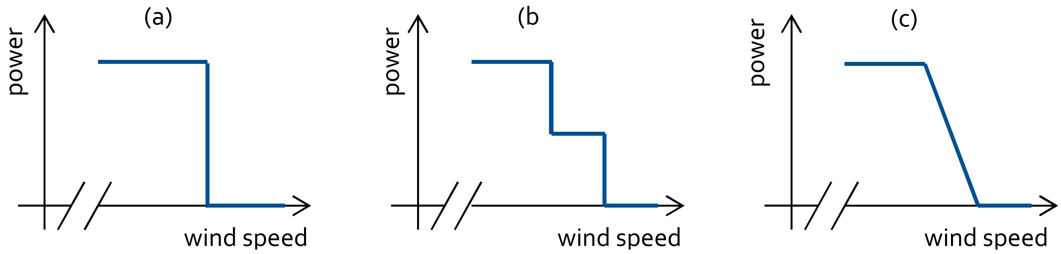


Figure 5-15: Different cut-out strategies: straight forward (a), stepwise (b), continuously (c)

The operation above cut-out wind speed can been enhanced by soft cut-out strategies (also: "gradual" or "extended" cut-out) shown in Figure 5-15b and Figure 5-15c. The power output is gradually reduced either in stepwise (b) or continuously (c). The soft cut-out strategies have been originally intended to improve the behaviour of wind farms in storm conditions by avoiding too many turbines to shut down and disconnect from the grid at the same time [FhG-KS07]. However, they are also useful in terms of load mitigation.

The soft cut-out strategies are particularly interesting for offshore turbines [FhG-KS08]. Because the blades are not pitched to feather position, the aerodynamic damping is increased. This reduces especially wave induced fatigue loads.

Peak Shaving

Following the standard operating strategy (speed-torque curve below rated and speed regulation with collective pitch above rated), the steady state thrust force on the rotor plane peaks at rated wind speed, see the dashed line in the middle plot in Figure 5-16. This usually causes high bending moments in the tower bottom and is critical both in terms of fatigue and extreme loads.

"Peak shaving" or "thrust clipping" is a strategy that reduces the maximum steady state thrust force. The basic idea is to begin pitching the blades slightly below rated wind speed, see the solid line in the left plot in Figure 5-16, which reduces the thrust force in the critical range.

Simultaneously to shaving the thrust force peak the power capture in the transition region is reduced (right plot). Therefore, the design of a peak shaver is strongly subject to the trade-off between load mitigation and energy yield. Since its implementation is very simple it is often used as a last resort e.g. for meeting site-specific requirements. For offshore sites with considerable wave excitation, the reduction of aerodynamic damping must also be taken into account.

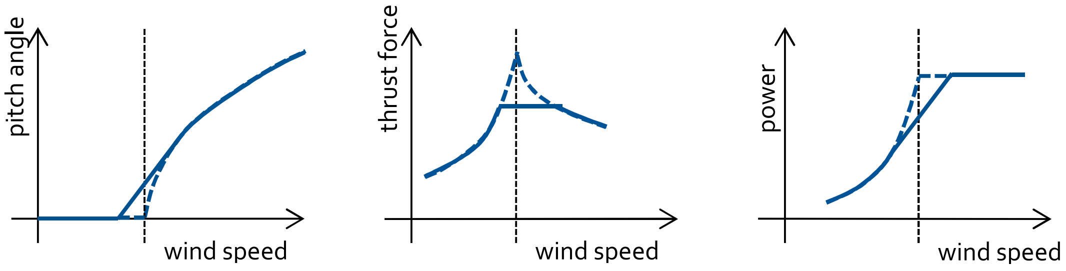


Figure 5-16: Steady operating points with peak shaving (solid line) and without (dashed line).

Active tower damping

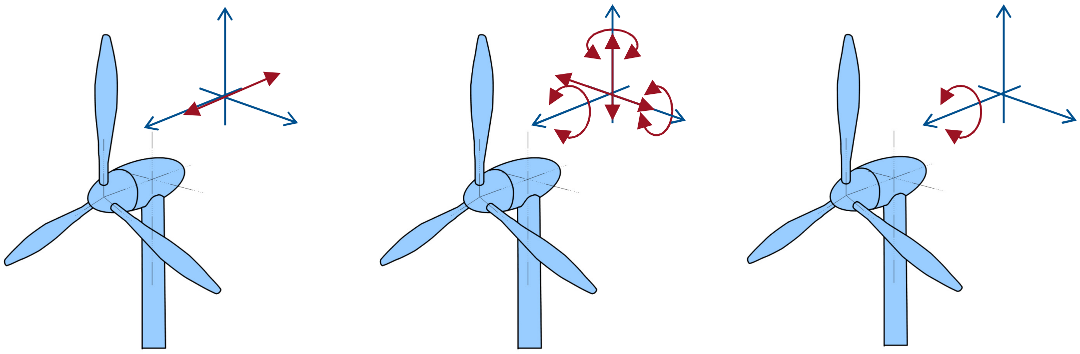
Controlling the pitch angles and generator torque allows for the active damping of vibrations of the support structure. This can be done in the fore-aft as well as in the side-side direction. The actuators are used in a feedback control loop to generate counter-acting forces and moments that reduce the motions of the structure. Usually, the motions are measured by accelerometers mounted on the tower top. To realize a damping effect it is necessary to generate a force that is inversely proportional to the velocity. Hence, the design of the closed loop system includes a filter design to assure an appropriate phasing.

Because the resulting control signals are added to those of the normal operating control loops, the coupling between the different control loops must be taken into account. This is not trivial especially when actuator amplitude and rate constraints are active. Furthermore, active load mitigation is in general subject to a "waterbed effect": When loads in a certain range in the frequency domain are reduced they will be increased in another range. And, more generally, when loads at a certain part on the turbine are reduced they will be increased on other parts. Consequently, different objectives must be balanced, and the application of mitigation strategies for the support structure requires a broad knowledge of the overall turbine design, see also the subsection on integrated design below.

A classification of different variants regarding actuator and motion direction is given in Table 5-3. These are discussed in detail in the following. Figure 5-17 shows how the different actuators affect forces and moments on the tower top.

Table 5-3: Different variants for active tower damping.

Collective pitch angle	✓	✗
Individual pitch angle	✓	✓
Generator torque	✗	✓



collective pitch individual pitch generator torque

Figure 5-17: Different actuators for active tower damping and their effective force/moments on the tower top (red arrows).

The most widely spread variant is the damping of the 1st fore-aft tower mode for fatigue load reduction. For that purpose the fore-aft acceleration is fed back to the collective pitch angle using an appropriate filter. Consequently, a counter-acting thrust force on the rotor plane damps the tower vibration, see Figure 5-17. Changing the collective pitch angle also has an influence on the normal rotor speed regulation. But, this is usually not a major issue because the frequency of pitch angle variations due to the active tower damping is in most cases greater than the bandwidth of the properly designed rotor speed control loops. More critical is the potential coupling with blade flap modes; see [FhG-KS09].

Depending on the specific turbine design, it might be beneficial to mitigate not only the vibrations related to the 1st tower mode. For example, in [FhG-KS10] it is shown that also tower loads related to 3P harmonic excitation can be reduced using the same feedback structure. Another variant is dedicated to the 2nd tower mode. This is especially interesting for offshore turbines because this mode is easily excited by the waves. However, controlling the pitch angles individually is sometimes superior in this case: Depending on the actual shape of the 2nd mode, the tilting of the nacelle might be dominant. Then, an individual pitch control strategy that generates a tilt moment is more effective.

The so called "Individual pitch control" (IPC) has been heavily discussed in literature for quite some time, see e.g. [FhG-KS11, FhG-KS12]. It has been suggested for the reduction of loads on various components, which also includes the support structure. As shown in the middle of Figure 5-17 it offers a wide range of forces and moments on the tower top. The measurements used for feedback include tower top acceleration in side-side direction, blade bending moments, or bending moments measured on the mainframe.

The most obvious idea for the support structure is the damping of the side-side motion [FhG-KS13–15]. This motion is being counteracted by a side-side force or a roll moment on the nacelle. For onshore turbines the tower side-side fatigue loads are usually less important as compared to those in fore-aft direction. In contrast, the support structure of offshore turbines can experience significant fatigue loads in the side-side direction. Especially wind-wave-misalignment induces side-side motion because of the low aerodynamic damping [FhG-KS8].

From the overall control system's point of view the coupling with the rotor speed control loop has to be considered. Furthermore, because the blades are actuated independently, either multivariable control design or a preliminary decoupling by a transformation must be carried out. The non-linear mapping, known under different names as "d-q axis-", "Coleman-", or "multiblade-" transformation, transforms rotating quantities into an non-rotating frame. In both cases significant amount is necessary for addressing issues like extreme loads induced by rotor asymmetry during shut-downs [FhG-KS16] and pitch system amplitude and rate constraints [FhG-KS17]. The latter can be an issue mainly in the operating regime around rated wind speed because large pitch angle variations are necessary.

The active side-side damping is also possible modifying the generator torque [FhG-KS18]. To this end, the side-side acceleration is fed back to the demanded generator torque using an appropriate filter. The generator torque is supported by the main frame and, thus, leads to a counter-acting roll moment on the tower top (Figure 5-17). Due to the couplings between the various subsystems the interaction with the rotor speed control loop and the tower fore-aft loads has to be taken into account.

The enormous number of papers dealing with results from simulation studies contrasts with the little number of field-tests described in the literature. Some creditable exceptions include [FhG-KS16, 19–22]. These studies have been carried out on onshore turbines. Nevertheless, the reported results demonstrate the efficacy of the investigated load mitigation strategies by showing compliance with results obtained from simulations.

Active Idling

The term "active idling" refers to a control loop that is switched on during the idling state. Normally, when the turbine is in the idling state, the rotor almost stands still because the blades are in feather position. This also implicates low aerodynamic damping. The latter can be increased by reducing the pitch angle for a non-zero rotor speed. Consequently, tower vibrations stimulated e.g. by waves will be damped.

Measuring wind speed and/or rotor speed allows for adjusting a certain pitch angle, which, in turn, maintains the rotor idling with a certain, low rotor speed. [FhG-KS8] suggests defining the operating regime of this strategy up to slightly above rated wind speed. Thus, higher loads at higher wind speeds, e.g. due to extreme events, are being avoided. [FhG-KS23] proposes to start this procedure and to actively control the pitch angles depending on additional quantities such as the tower top acceleration. Active idling at higher wind speed is mentioned, although only for extraordinary conditions. The variant presented in [FhG-KS24] explicitly addresses high wind speeds. The main idea can be summarised in applying a "normal" active pitch angle regulation for load mitigation in wind speeds above cut-out wind speed – rather than just increasing the aerodynamic damping by a non-zero rotor speed.

Integrated design

As pointed out several times above, load mitigation strategies for the support structure should be carefully balanced by taking into account the overall turbine design. The numerous strategies can be beneficial for addressing site-specific characteristics. This is especially useful for retrofitting a type certified turbine in the engineering process for offshore project certification, see e.g. [FhG-KS25]. [FhG-KS26] demonstrates an integrated support structure optimisation by means of a reference study. However, integrating the load reduction capabilities of the control system from the start offers new possibilities for the whole turbine design [FhG-KS4, 27].

5.3.2 Technologies under current RTD for 5MW class and in other sectors

This section provides a brief overview of several options that are currently discussed.

LiDAR

LiDAR (Light Detection And Ranging) enables the remote sensing of wind speed by measuring the speed of aerosols, see e.g. [FhG-KS28] for a comprehensive overview. It has become increasingly important not only for resource assessment. Mounted on the turbine and measuring the wind field that approaches the rotor, it also offers a wide range of opportunities for modifying the control system: To a certain extent, it means looking into the near future and renders possible e.g. the anticipation of extreme events.

The simplest integration of the knowledge of the future wind field is via a feedforward structure [FhG-KS29, 30], see Figure 5-18. That is, a feedforward control signal is added on the "normal" feedback control signal. The feedforward algorithm uses the estimated future wind speed to compensate for varying wind conditions in good time. The estimation is subject to low pass filtering as i) the wind field measurement of the LiDAR system involves spatial averaging and ii) the high-frequency content in the wind field changes while it approaches the rotor [FhG-KS31].

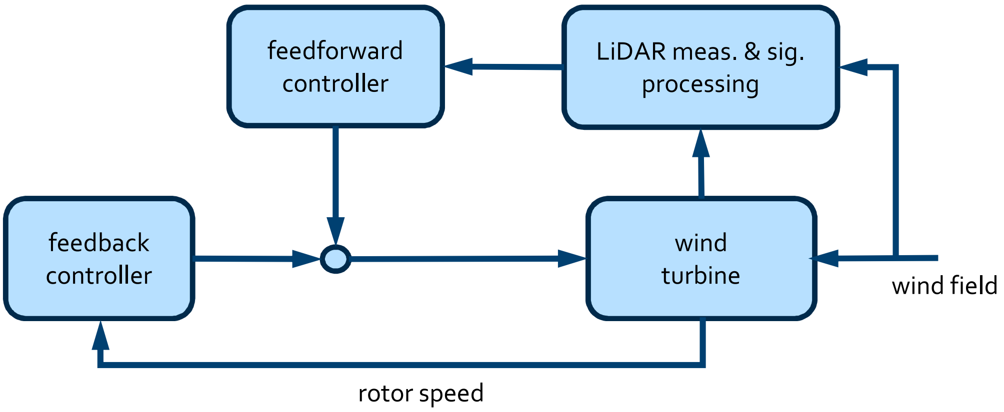


Figure 5-18: Control system integrating turbine mounted LiDAR.

Although apparently appearing to be well suited for decreasing gust sensitivity, recently published results indicate that the most promising application is the reduction of tower fatigue loads [FhG-KS32, 33]. This is achieved by retuning the feedback controller. In short terms, a less "aggressive" feedback controller can be chosen because a part of the control burden is shifted to the feedforward path.

[FhG-KS34] presents preliminary field test results that show that implementation is possible in practice. However, the increased complexity of the overall control system must be carefully balanced with availability issues, and, the main obstacle at present remains the costliness of the LiDAR device.

Advanced control

Common practice in industry is to iteratively close several more or less decoupled single-input–single-output (SISO) control loops. Examples are the strategies for active tower damping discussed above, which are added to the normal controllers.

By considering all the controller inputs and outputs simultaneously, the wind turbine becomes a multiple-input-multiple-output (MIMO) system. "Advanced" control methods lend themselves nicely to addressing the nonlinear, multivariable nature of the control problem. Different approaches are applied in the wind turbine control literature, e.g. Linear Quadratic Gaussian (LQG) controllers [FhG-KS35, 36], controllers based on H_∞-theory [FhG-KS37], feedback linearization [FhG-KS38], or Model Predictive Control (MPC) [FhG-KS39–41], to mention only a few of them.

These methods intrinsically solve issues with nonlinearities, couplings between different physical pathways, and sensor fusion. In a mathematical systematic manner they find a control law that is optimal with respect to a certain cost function. Choosing this cost function however is not that straight-forward. The complexity of the overall turbine design makes it hard to reflect practical design objectives, which, ultimately, are driven by the reduction of cost of energy. Furthermore, the use of additional makeshift methods, e.g. for constraint handling, should be avoided, and the embedding in the supervisory operating system is challenging. See also the discussion on MIMO-controllers for wind turbines in [FhG-KS42].

Model predictive control

A special case is MPC. Assuming a rapid maturing of the nacelle-based LiDAR technology, this advanced control method becomes more attractive because it directly incorporates future values of the wind speed.

The basic principle is to calculate optimal values for the control signals over a certain time horizon in the future. To this end, it uses a dynamic model of the turbine, current measurements to update the state of this model, and the future course of external inputs; the latter being e.g. the rotor effective wind speed measured by the LiDAR system. Given that these elements are sufficiently representing the real system, its behaviour over the time horizon can be calculated depending on the control signals. This is used for determining an optimal trajectory of the control signals by solving a – possibly constrained – optimisation problem with a cost function that reflects the control objectives. The optimal control signals are applied to the system until new measurements and predictions are available. Then the whole procedure is repeated. This repetition makes the feedback controller out of subsequent actions that are individually feedforward.

On the one hand, MPC provides the simple incorporation of actuator constraints and wind speed predictions. On the other hand, solving the optimisation problem in real time is computationally demanding and some of the other obstacles for advanced control methods mentioned above still remain.

A comprehensive study of nonlinear MPC of a 5 MW benchmark turbine is reported in [FhG-KS43]. It considers uncertainty in the LiDAR measurement as well as the operation below and above rated wind speed including transitions between both regions. Promising load reductions were achieved without corrupting other aspects. However, the authors emphasise that, due to the immense computational effort for the online-solution of the optimisation problem, the chosen nonlinear approach should rather be considered as an upper benchmark for other controllers. To overcome issues with real time implementation they suggest investigating other variants of MPC.

[FhG-KS44] presents a real time feasible variant of MPC. A case study has been carried out, where the computational time of the MPC is increased by only 40% as compared to a conventional controller. Although future values of the wind speed are assumed to be constant, the controller achieved considerable extreme and fatigue load reductions on the tower bottom bending moment. The authors mention that, if available, wind speed predictions can easily be incorporated.

Integrated design

An approach for integrating the control design into the overall turbine design, which is very interesting from a theoretical point of view, is presented in [FhG-KS45]. Structural parameters and parameters of an advanced MIMO control strategy are directly optimised using an iterative algorithm. The cost function of the optimisation depends on both parameter sets. The structural design parameters are stiffness and damping coefficients of a lumped parameter model of the turbine.

From a practical point of view this choice is somewhat academic, but the authors point out that their work can be extended to more practical cases, e.g. by including the minimisation of structural mass. Even though the mathematical rigorousness of the approach is appealing – what has been mentioned in the advance control section above also applies for this concept. In general, it is very hard to design a cost function that sufficiently reflects practical design objectives.

Smart blades

Recently there is a strong research focus on so called "smart blades". The basic idea is to design additional aerodynamic actuators directly into the rotor blade. Many different types of actuators have been proposed in literature. A comprehensive overview on the status of development of "smart" rotor blades for wind turbines and helicopters is given in [FhG-KS50].

The main advantage of these new kinds of actuators is that aerodynamic forces can be influenced much faster than with conventional pitch control because only small masses have to be moved. The forces are influenced locally, preferably close to the blade tips where the effect is largest. If several actuators are placed along the span of the rotor blade, also the distribution of forces could be influenced.

So far, mainly simulation studies have been published. An exception is the work by Castaignet [FhG-KS51], which provides first field testing results for a modified 225 kW wind turbine, equipped with piezo-electrically actuated flaps and pitot tubes.

The main focus of "smart blades" research so far has been on rotor blade loads. However, also the loads of the support structure could be influenced in a favourable manner with faster, distributed aerodynamic actuators, see for instance [FhG-KS52]. As an example, higher harmonics control of blade bending moments could significantly reduce the 3p component of the tower bending moment. Also the active damping of higher tower bending modes might be feasible.

It must be stated, however, that a lot of research work is still to be done before this kind of technology can enter industrial application. Reliable actuators must be designed that can withstand a high number of actuation cycles. From the control design prospective, new kinds of models must be developed and validated that properly describe the fast aerodynamic effects and the aero-elastic interaction of actuators and rotor blade.

Situational controller adaptation

So far, the proposed additional methods for load mitigation have mostly been investigated as running continuously when the turbine is in a certain operating state. For example, virtually all works about IPC observe that the structural load reduction comes along with significantly increased pitch activity. When IPC is continuously active during power production, the pitch system requires considerable reinforcements, which might cancel out cost savings on other components. For a specific turbine, [FhG-KS16] suggests to select IPC only in the case of certain extreme operating conditions.

This idea is presented more generally in several publications [FhG-KS46–49]. The control system's structure or parameters are adjusted according to certain operating situations. Thus, the controller is optimally adapted to the current operating conditions. This can result in two positive effects: i) loads experienced by different components are balanced, and ii) heavy duty cycles of the actuators are avoided.

5.3.3 Development needs and prospects for the preliminary design of the reference support structure and consequences for the work program in task 4.1.

From earlier projects it became clear, that the successful application of load mitigating control strategies for wind turbines requires the consideration of the overall wind turbine structural design concept. Careful analysis is required to decide which controller strategy can really help to save material and to reduce the overall Cost-of-Energy for a given wind turbine concept, see for instance [FhG-KS52], [FhG-KS53]. Generally spoken, a certain load mitigating controller strategy is never equally beneficial for all types of wind turbines.

Especially the following main points need to be considered jointly with task 1.4:

- The structural load components that are influenced by individual load mitigating control strategies must in fact be design driving in order to achieve effects on material use and turbine cost. Many load mitigating control strategies published in literature aim to reduce the fatigue loading on tower and blades whereas for many wind turbine concepts, especially for locations with high extreme wind speeds and low turbulence, ultimate loads are in fact design driving. On the other hand it is also possible to apply control strategies that can reduce ultimate loads, see [FhG-KS16].
- There is always a trade-off between the achievable load reductions for main structural components like support structure and blades and the additional actuator duty. In [FhG-KS53] it has been shown, that especially for IPC and active tower damping strategies considerable enhancements in the pitch actuator system are required. Besides the rating of the pitch drives especially the fatigue of blade bearing and pitch gears is critical. The related increase in costs can easily reach the order of cost-reductions that can be achieved by material savings in tower and blades.
- Furthermore, in many cases, cross-couplings exist between loads on main structural components. For example, a control strategy aiming at the reduction of support structure loads might increase the fatigue loading of rotor blades.

In the frame of the INNWIND work package 4, first a detailed load and design analysis for the reference jacket support structure will be carried out. From this analysis it should become clear, which design driving load components can be influenced by means of control and which kind of load mitigating control strategies are suitable candidates for application.

From preliminary analysis it seems that fatigue loads determine the design especially for the joints of the jacket structure. The main contribution to this fatigue loading is expected to come from fluctuations in aerodynamic forces. Special care in control design must be put on the avoidance of structural resonances of the support structure. Furthermore, the application of active damping strategies seems appropriate and should be investigated in more detail.

In the second step, an optimization problem must be formulated including all relevant control design, structural design and actuator system variables of the wind turbine. Design and cost models for all involved sub-components of the turbine must be included. The main focus in this work package will be on the support structure; however, important cross couplings to loads in other structural components need to be covered.

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6 MANUFACTURING (RAMBOLL)

6.1.1 Technologies used in industry for current 5 MW class and in other sectors

Pipe Sections for Jacket Structures

Every jacket consists of a large number of steel pipes. These pipes are currently produced individually for each jacket design according to the required cross section properties. Due to the lower costs of standardized pipes a significant amount of fabrication cost saving potential is given. Furthermore it enables a large supply-chain, as there are plenty of suppliers for these pipes on the market where the current manual produced pipes for jackets are often done by a very small set of specialized companies.

Currently, the market provides a considerable amount of different standardised pipes sections. However, rather large cross-section dimensions with diameters of approximately 1000 mm and more are often required for the jacket legs near mud-line. For the lower jacket X- and K-joints thicknesses up to 100 mm and more may be required depending on the turbine and water depth. Such large dimensions are usually not part of the pipe fabricators' standardized product range.

Optimisation Strategies for the Designer

Currently, the optimisation process of jacket designs aims at minimising the structural mass only. This is mainly because no reliable cost models exist which take into account the total costs arising from the different fabrication steps like weld preparation, welding or assembly of the structure. Consequently, the influence on the fabrication costs of different jacket configurations with respect to the number of X- and K-joints on the fabrication costs cannot be taken into account. This is also true for the investment trade-off between material costs and welding/assembly efforts. In addition, the impact of the jacket design on cost drivers like transport and installation is barely considered during the design process.

Structural Flexibility of Jacket Structures

Currently, the jacket geometry parameters like top width, bottom width and brace configuration are designed individually for each location in order to meet the site-specific requirements, e.g. water depth. In general, jacket geometries having a constant batter angle of the legs are designed.

K- and X-joint Fabrication

With respect to fabrication costs of jacket structures a significant amount is considered to be hidden in the fabrication of the X- and K-joints. Welded X- and K-joints impose critical stresses located in the vicinity of the brace-to-chord welds. These so called hot spot stresses lead to relatively short fatigue lives of the joints compared to other welded details like circumferential butt welds.

Weld improvement techniques like grinding reduce the hot spot stresses. If the K- or X-joint weld is made from both inside and outside of the brace the weld toes both on the inside and outside can be treated by weld improvement measures. However, the welds of brace-to-chord connections are often single-sided due to access limitations inside the brace. In the latter case the efficiency of grinding the outside weld toe must be treated with caution since the weld root may be more critical with respect to fatigue cracks than the ground weld toe on the outside, see ref. [Ramboll01].

Welding techniques

In general, many different welding techniques exist. For jackets, one has to distinguish between welding as part of the pipe production process and the welding performed in order to assemble the jacket.

For the production of pipes, the following techniques are commonly used:

- High frequency welding

- Submerged arc welding
- Resistance welding

In order to assemble the jacket, the following welding techniques are performed:

- Arc welding
- Submerged arc welding
- Metal active-gas welding

If labour costs are low, manual welding is an economic solution. However, if labour costs for manual welding are high, it is usually beneficial to apply mechanised or even automated welding techniques. There are developments in the market aiming at fully automated processes, e.g. using welding robots.

Piling Methods

The traditional application of jacket-type structures has always been the oil and gas business. Within this area, there were in principle two ways of establishing the connection between piles and support structure. The piles can be driven through pile sleeves at the bottom of the structure or the piles can be driven through the legs of the structure. In this case the connection is made at the top of the structure. Both methods refer to post-piling installation techniques.

A new technique was then developed for the offshore wind business, where new criteria were present. Installation times with large vessels should be optimized and also cases with pile refusal needed to be considered, a case where post-piles solutions could become difficult or at least very expensive. The outcome is a so-called pre-piled system where the jacket piles a piled into the soil by using a template. After the 3 or 4 piles are piled down, the jacket will be levelled into it and a fixed connection via grout is established.

Transition Pieces

With respect to costs, the transition piece (TP) forms an important part of an offshore jacket structure. Several concepts have already been developed and installed and some have been patented (OWEC Tower, Repower). Besides the patent issue which is still causing uncertainties in the market, open questions regarding the most cost effective solution are still to be answered.

It is noted that the four-strut TP follows the direct force flow pattern and avoids the occurrence of bending in its structural members. However, it might not always be the solution preferred by the client because its geometry imposes restrictions, especially for the external platform setup.

An alternative is the so called box girder TP, which transfers loads from the tower bottom to the jacket legs mainly by bending of its structural members. While the box girder concept is considered less efficient regarding its material demand, it provides more flexibility regarding the external platform setup.

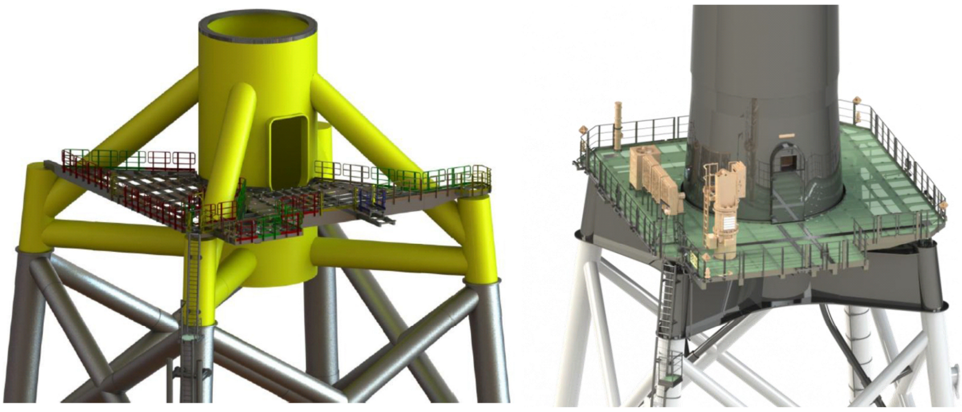

Figure 6-1: Four-strut TP (left) [Rambollo2] and Box Girder TP (right) [Rambollo3].

Assembly of Jacket Structures

Different assembly scenarios for jacket structures exist. Usually, the complete legs consisting of chord cans and pipes are welded together (point-to-point concept). Typically, material optimization is aimed for and consequently the heavily loaded chord cans show increased wall thicknesses compared to the less loaded connecting pipes. After welding of the jacket legs, the jacket is assembled by welding the complete braces manually onto the legs (point-to-point assembly). In this case, the costs for handling are largest since many single elements have to be assembled and welded.

Operation and **Maintenance**

Operation and Maintenance (O&M) is carried out on foundations of offshore wind turbines in order to ensure safe operation and the overall structural integrity of the asset – the 'Balance of Plant'. There are different O&M strategies applied in the market, whereas periodic inspection and corrective maintenance are commonly used for all structural parts of the foundations. The reason lies in the design of structural items which is usually done for the full considered service life of the turbine.

Inspections are mainly carried out to ensure that all assumptions made in the design (e.g. marine growth thickness, corrosion protection) are in compliance with the actual state of the structure. Depending on the design premises, fatigue crack investigations need to be carried out. Only in case of the exceedance of design limits, corrective measures are carried out (this is valid for all primary and secondary steel items, the corrosion protection system, grouted connections and the scour protection) in order to enable the desired functionality of the respective item.

State of the art O&M strategies take the relation of CAPEX (capital expenditure) and OPEX (operational expenditure) into consideration and are often developed from a risk point of view, i.e. building up an inspection plan based on the consequence of a possible failure related to safety, economy and environment. This methodology can, in particular for larger offshore wind parks, reduce operational cost significantly, but still ensure safe operation. Operational costs are, amongst others and related to structural items only, mainly driven by the distance to shore, environmental, operational and loading conditions, the available O&M fleet (e.g. helicopter, service/crane vessels) and personnel, the design of the foundation and the durability of the used protective systems, as e.g. corrosion protection systems. For other items in the system of the offshore wind turbine, as those located in the rotor nacelle assembly or power electronics, cost drivers might be different and need to be investigated individually.

Contributing up to 40 % to the cost of energy of offshore wind parks, the full scope of Operation and Maintenance, from developing an inspection plan to re-tightening bolts, is currently of high interest and under constant investigation in the industry, aiming to optimize processes and thus minimizing risks and reducing cost of energy. Related to offshore wind foundations, topics related to ensuring the full desired service life of nowadays 20 to 25 years are in the focus of research; keeping in mind that the longest track record for a large scale commercial offshore wind farm is just slightly over 10 years.

The main aim of O&M strategies is the so called "Balance of Plant" which guarantees the integrity lifetime of the foundation. Moreover, a cost optimisation takes into account the relation of CAPEX (capital expenditure) and OPEX (operational expenditure).

O&M strategies comprise periodic inspections of the foundation as well as corrective maintenance measures (e.g. exchange of damaged boat landing or repair of the scour protection) if required. In general, it has to be ensured that all assumptions made in the design (marine growth, corrosion protection) comply with the real structure. Furthermore, it is checked whether fatigue cracks have occurred.

The costs for O&M strategies are depending on the distance to shore and the number of foundations. Usually, the number of foundations which are inspected is kept small in order to reduce costs. However, it has to be ensured that the inspected foundations are representative for the total number of foundations within the wind farm.

6.1.2 Technologies under current RTD for 5MW class and in other sectors

Pipe Sections for Jacket Structures

Considering the current product range of standardized pipes, it would be beneficial to design jackets with a large amount of rather small members instead of a small amount of larger members. As an example, it is more likely that four-leg jackets can be fabricated by using standardized pipes compared to a three-leg jacket. However, this only holds true as long as fabricators do not add larger cross sections to their product range.

Optimisation Strategies for the Designer

In order to provide a cost optimised jacket design, future design processes should make use of a detailed cost model. In a first step, the cost model should contain the following main cost contributors:

- Fabrication costs
- Transportation costs
- Installation costs

Based on this cost model, a cost-effective jacket design can be derived and further evaluated by using case studies (as planned in task 4.3).

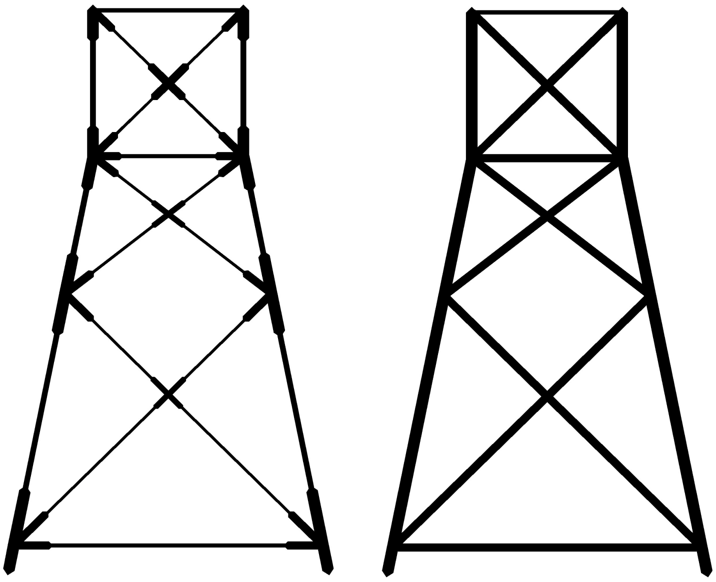

Figure 6-2: Schematic illustration of a jacket with an optimized material demand leading to many welds (left) and a jacket with only a few different (standardized) cross sections showing a larger material demand but less welds (right).

Structural Flexibility of Jacket Structures

For wind parks consisting of several locations with significantly varying water depths, a modular concept for the jacket structure is supposed to be beneficial in terms of costs. One approach would be to have each jacket consisting of two or more modules, the upper module being the standardised part which can be used for every location and the lower part requiring adaptation to the demands imposed by the location under consideration.

Modular concepts also aim at reducing the number of required piling templates which are needed in case of pre-installed piles. This implies a standard footprint width of the jacket for a certain number of locations.

Therefore one major goal, besides the overall optimization of the jacket itself, will also be to come up with a modular solution that enables an application of the developed concept over a wide range of site conditions (water depths and soil types).

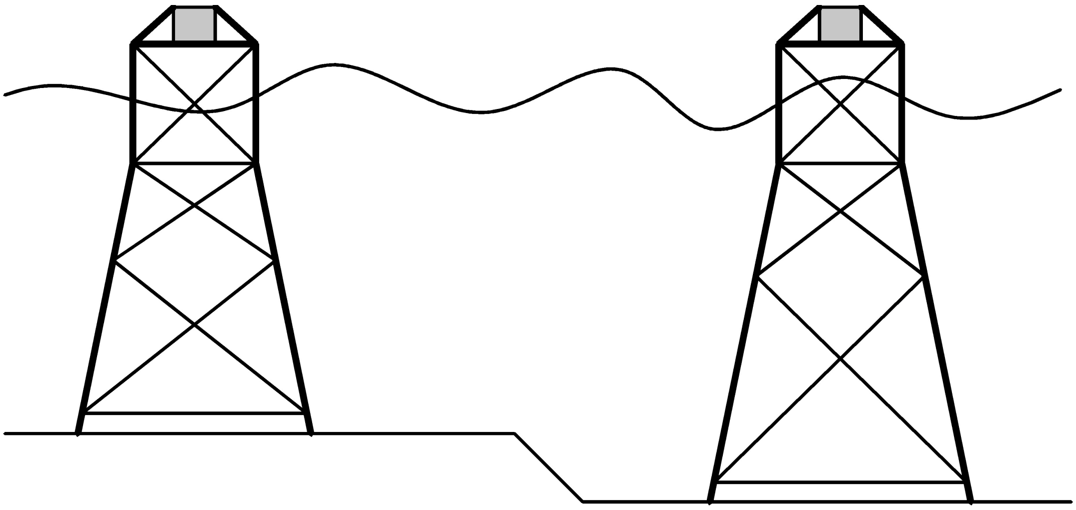

Figure 6-3: Schematic illustration of modular jackets.

K- and X-joint Fabrication

In order to improve the overall fatigue life of welded K- and X-joints the accessibility of the inside brace stub could be facilitated such that two-sided welds can be produced which can both be treated by applying weld improvement techniques. However, this issue is closely related to the restrictions imposed by the fabricator’s capabilities, especially the accessibility of the brace’s inside. Moreover, access of the inside brace stub also implies that short brace stubs have to be used. Consequently, a “point-to-point” assembly (welding of the complete brace onto the leg) is not possible in this case.

An alternative to welded joints is the application of casted joints. However, little experience has been gained so far concerning the trade-off between advantages and disadvantages of casted joints. While hot spot stress areas are relieved due to the absence of welds in the brace to chord transitions, the fabrication costs are higher and the likeliness of production failures is increased.

Welding techniques

For welding of plates with thicknesses up to 90mm and more, many weld layers are required which increase manufacturing time and costs. New welding techniques aim at a deeper welding penetration to reduce the number of layers. On technique following this goal is called Hybrid Welding which combines laser and arc welding techniques.

In general, the following issues should be evaluated carefully in order to reduce costs:

- Cost effectiveness
- Accessibility of the connection
- Geometry of the connection
- Number of connections
- Welding position
- Welding location

Piling Methods

There are still significant challenges and investigations with respect to the connection between piles and jackets (i.e. the grouted connection), but also the levelling of the jacket while the grout is hardening during installation.

Transition Pieces

Current investigations aim at defining advantages and disadvantages of the different TP solutions. This refers to issues like overall costs but also to O&M requirements and installation issues.

Assembly of Jacket Structures

In order to reduce costs for material handling, the legs could be provided to the fabricator as one entire pipe with limited change in cross sectional properties. This implies that no intense material optimization is performed and standardized pipes are used instead. By using only one or two cross sectional properties for the total leg, the number of welds and the costs for material handling are reduced significantly.

Alternatively, the K-joints (the joints at the legs) could be pre-fabricated by welding the brace stubs onto the legs. Subsequently, the jacket is assembled by using circumferential butt welds in order to connect the remaining braces to its stubs. This is supposed to decrease the costs for material handling even more. However, this strategy also introduces critical tolerance issues which have to be investigated.

Since the assembly sequence is supposed to have a significant impact on the fabrication costs, deeper insight into the costs for different assembly strategies would be beneficial. It is also expected that a smaller number of X- and K-joints decrease the assembly time and costs.

In general, the fabrication process should be oriented towards a mass production which includes the use of standardized pipes and mechanized/automated welding techniques.

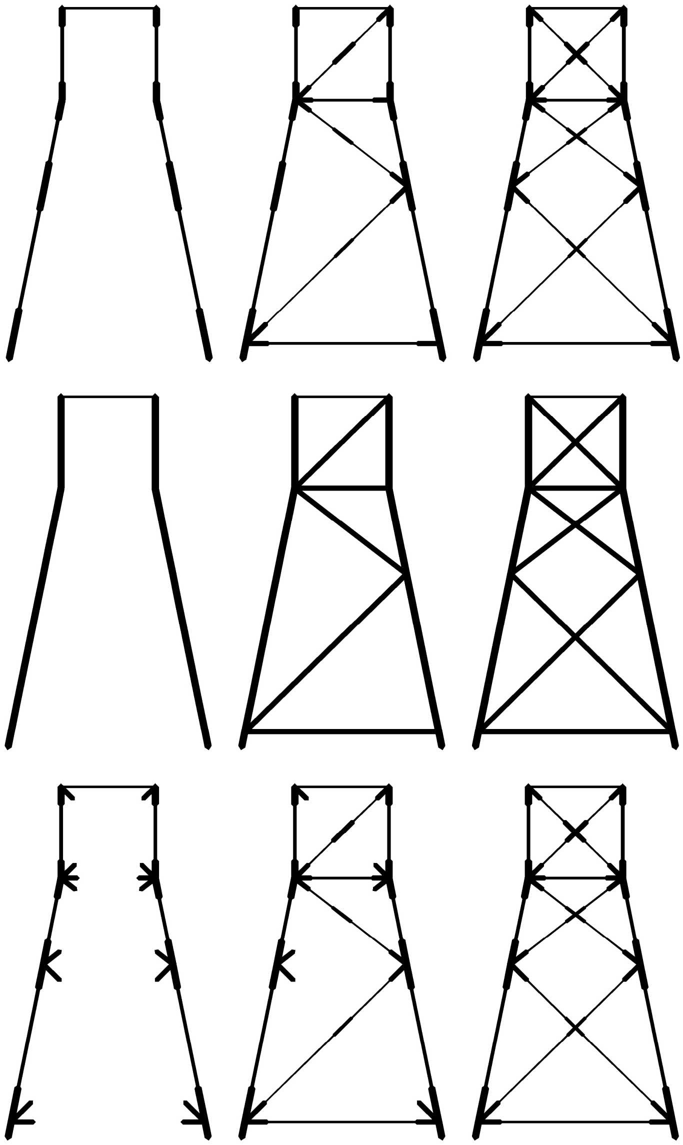

Figure 6-4: Examples of assembling sequences of a jacket: “point to point” assembly including material optimization (top), “point to point” assembly reducing the number of cross-section thickness changes (middle) and pre-fabrication of the K-joints before assembly of the jacket (bottom).

Operation and Maintenance

Typically, no preventing maintenance is considered for offshore foundations. An example for preventing maintenance measures would be the permanent removal of marine growth by mechanical devices or the prevention of colonisation by applying a special coating. Hereby, the assumptions made for the design of the foundation could be adapted accordingly, i.e. material cost savings would be possible due to the absence or permanent reduction of marine growth. This is because the presence of marine growth increases the fatigue damage, especially the fatigue damage of joints connected to the braces.

6.1.3 Development needs and prospects for the preliminary design of the reference support structure and consequences for the work program in task 4.1.

Pipe Sections for Jacket Structures

For upcoming Jacket projects it will be crucial to make use of standardized pipes in order to reduce fabrication costs. Based on a cost model, the advantage of this strategy could be evaluated. In this respect the Reference Jacket which has not been designed by using standardized pipes serves as a reference.

Optimisation Strategies for the Designer

A cost model which enables the designer to account for different scenarios with respect to the jacket fabrication (material, welding, coating, and assembly) should be developed in order to provide cost optimized jacket designs.

Structural Flexibility of Jacket Structures

Different strategies for providing modular jackets should be developed in order to reduce costs for a jacket being part of a large wind farm application.

K- and X-joint Fabrication

Different questions related to the reduction of hot spot stresses at X- and K- joints of jackets should be evaluated. This comprises the evaluation of less conservative numerical models in order to calculate these critical hot spot stresses. Moreover, the application of casted joints could be evaluated.

Welding techniques

As this is closely related to the X- and K-joint fabrication, any improvement of techniques or processes which reduce hot spot stresses at the joints would be of interest. In addition, automate welding processes offer cost savings and their potential could be evaluated.

Piling Methods

Within the here presented work, the connection between piles and jackets (i.e. the grouted connection) should be studied in relation to a more optimized structural connection as well as by evaluating effective and cost-effective solutions for the installation process. In addition, investigations of the levelling process of the jacket while the grout is hardening offers potential for investigations and improvements.

Transition Pieces

Different transition piece concepts could be evaluated in the cause of this project. The focus should lie on a cost effective design.

Assembly of Jacket Structures

In close relation to actual fabricators different assembly strategies should be evaluated. As the assembly strategy is an important part of the whole supply-chain, this offers a considerable potential for cost reduction.

Operation and Maintenance

The potential of preventing maintenance should be evaluated in the cause of this project. Amongst others, this could include the permanent removal of marine growth. Furthermore, different strategies for the cost reduction of inspections could be evaluated.

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