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Enhancing fatigue lifetime through initial investments

A case in wind energy

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Abstract

In this short note I will try to explain the reasoning behind the idea that the design lifetime of a structure can often be efficiently extended. In fact, there has been an informal saying that "the lifetime of a structure can be doubled with only a 10 percent increase in mass". I will show that this is true, under reasonable assumptions, for a cantilever beam subject to transversal loading, i.e., when considering fatigue due to bending moments. This case is relevant for tall towers with horizontal loads. This applies, in particular, to wind turbine towers or offshore wind turbines on monopile support structures. I will also show that the different failure mode of fatigue under axial vibrations has similar, though slightly worse scaling behavior. Here an increase of roughly 20 percent of structural mass is needed to double the lifetime. This result is relevant for structures with a predominantly axial transfer of loads, such as jacket support structures for offshore wind turbines.

The analysis is simplified and neglects changes in dynamics due to the additional strengthening. I simply look at the scaling behavior of lifetime under the most commonly used damage model, based on standardized SN-curves and linear damage accumulation. The results could probably be strengthened more by considering other relevant factors, e.g., including wave loads or dynamic amplification, but this is left to future work.

The point of this note is to highlight the potential for designing for larger lifetimes in an efficient way, and not to provide detailed pathways for realizing this in practice. There are other, mainly economical reasons why these pathways are currently not taken, leading to a larger and more complex discussion. However, to provide a basis for such a discussion, it is important to realize that there seem to be no inherent, engineering difficulties to design wind turbines with longer lifetimes.

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1 Introduction

Every engineering structure that is being built has a certain lifetime it is designed for. This is a consequence of it being exposed to environmental actions. Loads from wind or waves excite vibrations, and these in turn damage the structure: existing micro-cracks grow and develop into larger cracks [1]. At some point this can lead to structural failures. While this fatigue damage can often be detected and potentially repaired before actual failure, it is better — and often required by existing regulations — to design structures with sufficient fatigue reserves. This is why the notion of the *design lifetime* of a structure has been established.

For highly dynamic structures, e.g. wind turbines, the fatigue failure mode is typically driving the design. On the other hand, often large investments are made in terms of infrastructure surrounding and interacting with the actual structures themselves. For wind turbines, e.g., an electrical connection to the power grid is required. These costly factors contribute to the overall project economics and ultimately, in the case of wind turbines, to the price of electricity. For years it has therefore been an on-going discussion if current design lifetimes are appropriate.

In the following I will focus on wind turbines and, more specifically, on turbines in the context of offshore developments. Current design lifetimes are 20-25 years. Notably, offshore wind energy is a relatively recent development and it is only since a few years that the first offshore wind farms have reached their end of life stage. Some of these wind turbines have been decommissioned as planned, though sometimes slightly earlier, e.g. due to fatigue concerns. In most cases, however, wind farms that are approaching the end of their design lifetime undergo an assessment to understand if there is a business case for extending the lifetime [2]. Such *lifetime extension* can take different forms [3, 4]. It can be the case that wind farms can simply continue business as usual for another couple of year, but other options are exchanges of components up to the replacement of the complete wind turbine (re-powering) [5]. The decisions are made in light of increasing maintenance costs and potential failures, and are ultimately based on an economic model.

A compelling rationale for lifetime extension, especially re-powering solutions, is the existence of sufficient fatigue reserves in some other components, such as the supporting structure and foundations. These parts are designed with a certain conservatism, e.g. conservative assumptions about the length of particularly damaging situations, such as maintenance periods or extreme weather periods. Most wind turbine supports experience less damage in reality than they were designed for [6, 7], which unlocks potential for continuing operations.

How costly is this conservatism in the tower, platform and foundation? Interestingly, it is commonly said in engineering circles that structural reserves are "cheap". Personally, I have heard the claim that "one can double the lifetime with only 10 percent higher structural costs". The goal of this short note is to investigate and, as we will see in the next section, more or less confirm this claim.

But before doing so, we should address another important question: Why are wind farms not designed for a longer lifetime from the start, if the structural components can be made longer-lasting with very little increase of capital costs? The answer to this is likely multi-factored, but I suspect three strong reasons at play here. First, while most of the supporting structure of a wind turbine can be strengthened in a cost-efficient way, this is not necessarily the case for the rotor. Moreover, the power production of a wind turbine is sensitive to the quality of its blades. Degradation, e.g. through collision with rain drops (at surprisingly high speeds!), means that it makes sense to replace blades after a certain period of operation. And since the blades are a major component of the turbine, it can even make sense to replace the entire turbine. In some sense this re-powering scenario is a simple way to guarantee that the turbine will continue to perform satisfactorily. This scenario can be economically attractive. It is additionally expected that more modern turbines are more performant and cost-efficient than the ones initially commissioned 20-25 years ago.

A second reason for keeping the design lifetime in this ballpark is the following. Even though, as we will see, it is possible to increase the resistance of structures to fatigue cracking with small increases in mass, we are also changing the dynamics of the structure as a whole. Being highly dynamic structures, wind turbines are sensitive to changes of their vibration frequencies. As is

well known in civil engineering, the design of highly dynamic structures can be counter-intuitive: it is not always the case that strengthening a structure increases the lifetime. The opposite can also happen.

Finally, we come to what is probably the most important reason: it seems difficult to finance commercial projects with a time horizon that is much longer than 25 years. For this design lifetime it takes about 6-8 years before the loans have been effectively paid off and a wind farm starts to generate profits [8]. If the design lifetime were 50 years, it would probably take about 20 years before wind energy projects will start to generate profits. Not only are there few investors with such a long-term horizon, the considerable uncertainties about the future mean that the risk is higher and that potential investors are asking for considerably higher rates of return. In other words, current market mechanisms (or rather, the lack of them) seem to locate the sweet spot for wind farm lifetimes around the effective lifetime of the rotor, when the value of power production starts to become less than the losses due to maintenance costs.

That said, if different mechanisms or other incentives were in place, it seems likely that it would economically make sense to design wind farms for much longer lifetimes, though most likely including a scheduled replacement of the wind turbines themselves.

2 Scaling

Let us consider some relevant cases. The first one is an offshore wind turbine on a monopile. This is a simple support structure type that currently makes up for more than 85 percent of all installed offshore wind turbines. The design is essentially a cylindrical extension of the tower (though typically with different dimensions). With a large horizontal thrust load on the rotor at the top we can consider the support structure to act like a cantilever beam. It is clear that the dominant structural loads are stresses arising from bending of the tower-pile system.

The second case I want to consider is a jacket structure. These support structures, while more complex and costly than monopiles at low water depths, have greatly reduced wave loads compared to monopiles. Jackets therefore become cost-efficient at a certain transitional water depth. The steel members of such a support structure transmit loads mostly axially, so axial stresses play an important and potentially dominant role in such a structure.

Finally, we might want to consider floating wind turbines. Unfortunately the design space for such turbines is rather large, and many different concepts exists or are still potentially viable with current knowledge. We will shortcut these difficulties by considering a highly simplified scenario. A critical location and one of the most likely to fail due to fatigue is at the tower bottom, where the wind turbine tower connects to the floating platform that supports the turbine. The tower can be considered a cantilever again, and this suggests that this case is very similar to the first one. We will therefore consider[2] floating wind turbines to follow the same scaling relationship as monopiles.

2.1 Fatigue lifetime in bending

Consider a fatigue critical detail in a circular member, e.g. at the tower bottom or the mudline location. The member geometry is characterized by an outer diameter D and thickness t. The largest bending stresses occur at the outer edge of the section, so this is where fatigue cracks will initiate and propagate [9]. The value of these stresses is determined by member geometry,

$$\sigma_b = \frac{M_b}{S}, \tag{1}$$

[2]While not strictly true, analyzing this relationship in detail would take us much too far here — such an analysis is therefore left to future work.

where M_b is the bending moment and S is the (elastic) section modulus [10]. For a cylindrical member with thin walls its value is approximately

$$S = \frac{\pi(D^4 - (D-2t)^4)}{32D} = \frac{\pi(8D^3t - 24D^2t^2 + 32Dt^3 - 16t^4)}{32D} \approx \frac{\pi D^2 t}{4}. \tag{2}$$

Note that the section modulus grows fastest in diameter, therefore thin-walled members are structurally more efficient. Of course other structural considerations (e.g., local buckling) also play a role. Therefore we assume that the diameter-to-thickness ratio $\gamma = D/t$ is fixed. This means that the bending stresses scale as

$$\sigma_b = \frac{4}{\pi} M_b \frac{1}{D^2 t} = \frac{4}{\pi} \gamma M_b \frac{1}{D^3} \propto D^{-3}. \tag{3}$$

The structural cost is mainly driven by the mass, which for such a cylinder is approximately

$$m = \rho A = \rho\pi \frac{D^2 - (D-2t)^2}{4} \approx \rho\pi D t = \frac{\rho\pi}{\gamma} D^2 \propto D^2. \tag{4}$$

The fatigue life is calculated from a semi-empirical *SN-curve* (or Wöhler curve) that relates the stress range amplitude to the number of cycles before failure [11]. In its simplest case the number of cycles is expressed as

$$N = \frac{a}{(\Delta\sigma)^b} \tag{5}$$

in terms of the stress range $\Delta\sigma$. The exponent is typically assumed $b = 4.0$ for structural steel details. If we want to be more accurate, the relevant guidelines (e.g. [12]) give more precise values. Notably, these design SN-curves typically feature two different stress regimes, with differing exponents. The low-stress (or high-cycle) regime is usually assumed for stresses that can be sustained during 10^7 cycles or longer. The exponent for these cycles is assumed to be $b_l = 5.0$ in the DNV guidelines. On the other hand, the high-stress regime typically uses an exponent of $b_h = 3.0$.

Due to the non-linearity inherent in the SN-curve it is empirically often the case that the largest structural damage arises from high-stress cycles, for which the exponent is $b = 3.0$. However, since the design lifetime of a wind turbine is nominally 20-25 years, the stresses cannot be too large. Indeed, most tower or support structure damage arises from sustained vibrations at characteristic structural eigenfrequencies. These occur at low frequencies of about 0.2-0.3 Hz. At these frequencies we expect 100 million or more cycles, so we should consider the low-stress regime with an exponent $b = 5.0$ instead. In early design stages, however, an exponent $b = 4.0$ is often used as a compromise. This will be more unfavorable.

For irregular loads, stress cycles are obtained by matching stress minima and maxima, typically using the so-called rainflow algorithm [13, 14]. For each stress cycle $\Delta\sigma$ the damage $d = 1/N$ is calculated and, assuming linear damage accumulation, summed up. Overall, the total damage is

$$d = \sum_i d_i = \sum_i \frac{(\Delta\sigma_i)^{b_i}}{a_i} \tag{6}$$

where the sum runs over all identified stress cycles. Let T be the time period during which this damage is sustained, then the expected lifetime is

$$L = \frac{T}{d} = \frac{T}{\sum_i \frac{(\Delta\sigma_i)^{b_i}}{a_i}} = \frac{aT}{\sum_i (\Delta\sigma_i)^b} \tag{7}$$

$$\propto D^{3b}, \tag{8}$$

since scaling all stresses equally does not change the mapping defined by rainflow counting.

Let us now examine the above mentioned statement. Indeed, assume we want to double the lifetime. How much more structural mass is needed to accomplish this? We assume that the mass is scaled by a factor

$$m \mapsto m' = \kappa m, \tag{9}$$

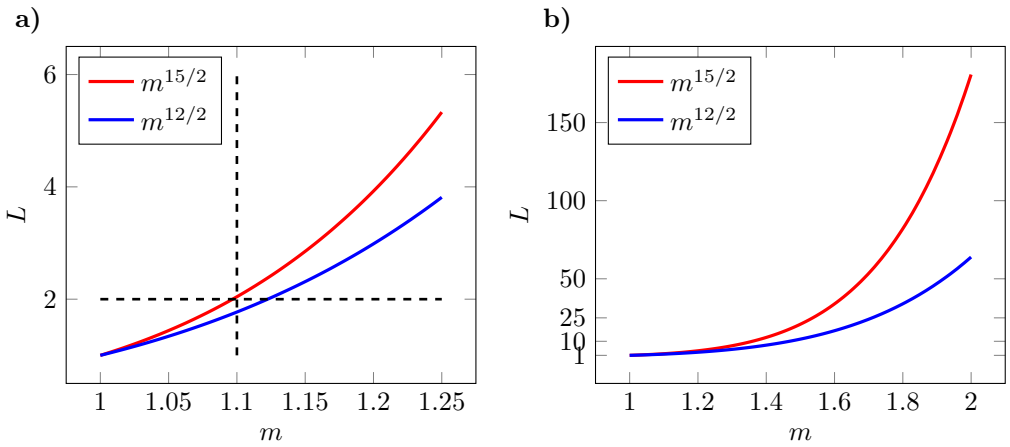

Figure 1: Theoretical scaling of lifetime L with the mass m of a cantilever column subject to fatigue loads from cycles in bending moments. a) Results for small variations of the column mass, for two different exponents corresponding to high-cycle fatigue (red curve) and a more conservative exponent commonly used in preliminary design (blue curve). Both the mass and the lifetime are normalized. The value for which the lifetime doubles is indicated for the first curve (dashed lines). b) Results for larger variations of the column mass to show how nonlinear the effect is.

which implies that

$$D \mapsto D' = \sqrt{\kappa} D. \tag{10}$$

Filling in the formulas, we see that the expected lifetime scales as

$$L \mapsto L' = \kappa^{3b/2} L. \tag{11}$$

With our assumptions $b = 5.0$, and thus we obtain the result that, approximately, $L \mapsto \kappa^{15/2} L$.

Doubling the lifetime then requires

$$\kappa = 2^{2/15} \approx 1.097 \approx 1.10, \tag{12}$$

which corresponds to an increase in mass of about 10 percent. In other words, we have indeed **confirmed that a 10 percent increase in structural mass can result in a 100 percent increase in lifetime**.

For the more conservative exponent $b = 4.0$ we obtain the result

$$\kappa = 2^{1/6} \approx 1.122, \tag{13}$$

indicating a necessary increase in structural mass by 12 percent. These results are visualized in Fig. 1.

2.2 Fatigue lifetime under axial loads

While the design of many structures is governed by bending stresses, this is not always the case. In particular for multi-membered jacket structures, which are more robust and cost-effective than monopiles for larger water depths, the loads are typically transferred through the structure with significant axial components. The scaling behavior is different in cases where axial stresses dominate.

Axial stress σ_a depends on cross-sectional area, and therefore scales as

$$\sigma_a = \frac{N}{A} \propto D^{-2} \tag{14}$$

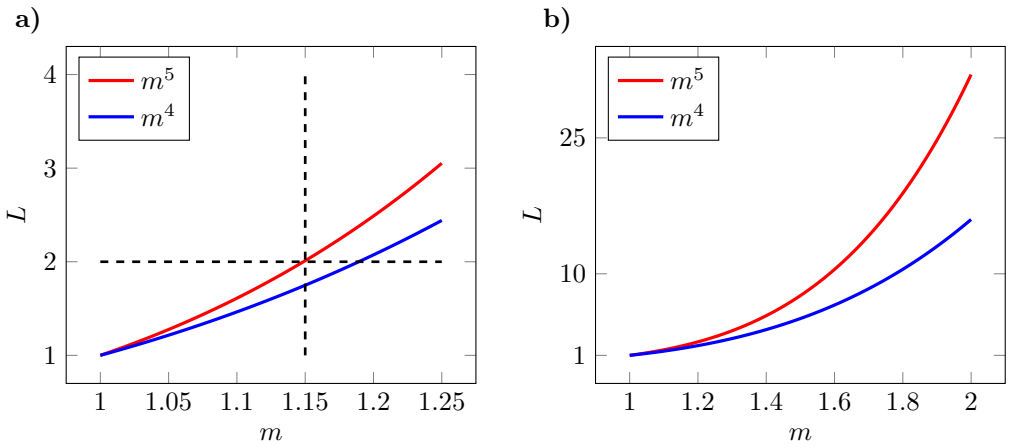

Figure 2: Theoretical scaling of lifetime L with the mass m of a cantilever column subject to fatigue loads from cycles in axial loads. a) Results for small variations of the column mass, for two different exponents corresponding to high-cycle fatigue (red curve) and a more conservative exponent commonly used in preliminary design (blue curve). Both the mass and the lifetime are normalized. The value for which the lifetime doubles is indicated for the first curve (dashed lines). b) Results for larger variations of the column mass to show how nonlinear the effect is. Note that additional loads due to self-weight have been neglected.

for a thin-walled cylinder (with constant diameter-thickness ratio γ). The area thus scales with the same power as the material cost, and the lifetime then scales as

$$L \mapsto L' = \kappa^b L. \tag{15}$$

Doubling the lifetime therefore requires

$$\kappa = 2^{1/5} \approx 1.149 \tag{16}$$

for $m = 5.0$. With the more conservative exponent $m = 4.0$ the factor becomes

$$\kappa = 2^{1/4} \approx 1.189, \tag{17}$$

which is about 19 percent. This means that even though the situation is slightly worse for axial stresses than for bending stress, an increase of 15-20 percent in structural mass still leads to more than twice the fatigue lifetime. These results are visualized in Fig. 2.

3 Discussion

The above results are relatively simple, but nevertheless prove the main point: Structures can often be designed for much longer lifetimes, for relatively little additional cost.

There are obvious limitations of this simple analysis, however. For one, we have neglected the dynamic effects of the change in structural mass when strengthening the structure. Changes in the mass will invariably lead to changes in eigenfrequency and vibration behavior. This can actually lead to a (larger) dynamic amplification and thus to proportionally larger damage than we anticipate here. In practice, however, this will only be significant when the structure eigenfrequency is already close to an excitation frequency. This typically means that the initial structure is either badly designed, or otherwise highly constrained.

We have also neglected local load effects, such as potentially larger wind and wave forces on larger diameter cylinders. Both these loads scale proportional to the diameter of a structure, therefore for a monopile the damage from the resulting bending stresses should scale with an exponent $1/b$ relative to the increase in mass, comparable to what happens to axial stresses in jacket support structures. However, a more detailed analysis seems desired.

How to incorporate the relative benefits of larger design lifetimes into actual practice is not that clear. The economics of wind farms is relatively complex [15–17], and economic incentives drive investors to prioritize short-term returns. That said, approaches exist for data-driven, risk-based design to optimize wind turbine lifetimes based on overall economic considerations (e.g., see [18]).

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