

## PROJECT SUCCESS AND COMPETITIVE SUBSTRUCTURES THROUGH SIMULTANEOUSLY EFFICIENT AND ACCURATE FOWT FATIGUE DIRECT COMPUTATION

Julien Pélé<sup>1</sup>, Laurent Mutricy<sup>1</sup>, Raffaello Antonutti<sup>2</sup>, Alexis Martin<sup>3</sup>, Jang Kim<sup>4</sup>, Johyun Kyoung<sup>4</sup>,  
Youjin Yim<sup>4</sup>, Hyungtae Lee<sup>4</sup>

<sup>1</sup>Ekium, Brest and Nantes, France; <sup>2</sup>Qair, Montpellier, France;  
<sup>3</sup>STAPEM Group, Brest, France; <sup>4</sup>Front Energies, Houston, TX, US

### ABSTRACT

*Floating wind substructure engineering requires a different mindset compared to offshore Oil&Gas. Alongside the serial fabrication and installation topics, absent in the conventional floating offshore platform space, these structures must be designed to host a very lively payload: a large wind turbine generator. A narrow vision of a floater withstanding the static burden of a topside, perhaps subjected to a peculiar wind load, is far from reality.*

*Hopefully, most of the substructure's life will be spent with the turbine in production, largely determining cyclic loading. Experience shows that fatigue governs the design of major steel structures and mooring components and thus, must be incorporated into the process early and robustly. Adding to marine environment fatigue, turbine-related fatigue is quite sensitive to delicate parameters such as mechanical flexibility, structural damping, and controls.*

*In power production conditions, system mechanics are strongly coupled; hence, good prediction can only derive from time-domain coupled analysis. Coupled simulation-based fatigue assessment is advocated early on for quick design convergence, and risk and cost minimization. With up to tens of thousands of Design Load Cases (DLCs) involved and the need to process time series in full to compute damage, an efficient end-to-end calculation chain going from wind-wave-current to local stresses is essential for project success.*

*Ekium's vision in this respect is presented, based on technical and project track record in floating wind substructure design and industrialization, mainly located within the former Naval Energies team. This is embodied by an in-house tool chain built around the Front Energies TRUST software, with the following key features:*

- *All steps (global sizing to local verifications) automated and repeatable, allowing parametric optimization.*
- *Incorporates substructure flexibility in the coupled analysis for accurate global (tower)bending frequencies and reliable 3P response.*

- *Hydrodynamics relying on proven and versatile 1st and 2nd order diffraction/radiation plus distributed Morison drag.*
  - *Quickly derive structural detail stresses i. from thousands of DLCs, ii. in the time domain from coupled analysis outputs, iii. virtually everywhere in the structure, accurately represented by shell finite elements, iv. for a low CPU cost.*
  - *Compatible with different coupled solvers (OrcaFlex, OpenFAST, etc.) for prompt redeployment in varying project settings.*
  - *High process efficiency enabling to apply it from conceptual and preFEED phases to advanced FEED and detailed design.*
- All these features combined are a new feat and hold the promise of more competitive and reliable floating wind system designs.*

Keywords: FOWT, Fatigue, ILA, Structural, Calculation, Simulation, Chain, Design, Loops

### NOMENCLATURE

DLC	Design Load Cases
FEED	Front-End Engineering Design
FEM	Finite Element Method
FLS	Fatigue Limit State
FOWT	Floating Offshore Wind Turbine
ILA	Integrated Load Analysis
QA/QC	Quality Assurance / Quality Control
ULS	Ultimate Limit State
WTG	Wind Turbine Generator

### 1. INTRODUCTION

From a substructure designer's perspective, floating wind engineering demands a different approach compared to traditional offshore oil and gas. In addition to considering serial fabrication and installation, these structures must be designed to fully integrate a living payload: a large wind turbine generator.

Most of the operational life of the substructure and mooring system will be spent with the turbine generating power, significantly influencing fatigue (cyclic) loading. It is well-known that under these conditions, the system's mechanics are highly interconnected. Therefore, accurate fatigue assessment can only be achieved through coupled load analysis.

Advocating for coupled analysis-based fatigue assessment early in the project is crucial for rapid design convergence and minimizing risks and costs. Given the numerous load cases involved and the necessity to fully process each time series for damage calculation, an efficient time-domain calculation process is essential for project success.

As an evolution of our former internal tool chain, which mainly relied on our own past developments in a pioneering environment, Ekium's new offshore wind tool frame is a complete redefinition of our expectancies from the ground-up: now combining a state-of-the-art and innovative market solution (TRUST by Front Energies, see [1]) with high performance in-house developments (global sizing and scantling tool, pre/post-processing tools, metocean analysis and DLC definition), to create a proper end-to-end floating calculation chain, with the following features:

- Holistic view incorporating the entire lifecycle in the upstream design choices to optimize overall costs: fabrication, T&I, O&M, etc.
- End-to-end vision: consistency, no silos, built for efficiency + scalability + accuracy + repeatability (for QA/QC).
- Incorporates substructure flexibility in the modal analysis for accurate global (and thus tower) bending frequencies and reliable 3P/vibrational response.
- Dual-ILA platform, allowing to choose between OpenFast or OrcaFlex, to deal with every industrial scenario.
- Innovative “lodal” approach which uses linear combinations of unitary responses, allowing to derive stress time-series for each local mesh element of a full floater model with great simulation time efficiency compared to compared to a typical offshore FEM-based workbench.
- Adaptive: we developed an array of adaptive calculation methods calibrated to the complexity of each phase, from simplified approaches (see [2]) early on, to fully fledged models for more detailed phases.

## 2. FLOATING WIND FATIGUE DESIGN

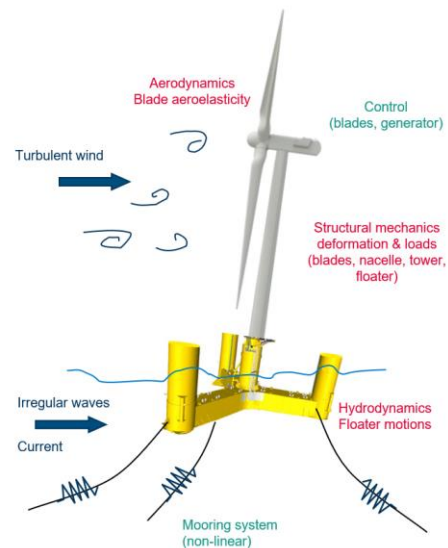
Floating offshore wind turbine (FOWT) substructures, similar to traditional offshore structures, experience cyclic wave and wind loading throughout their operational life, necessitating proper sizing and verification.

The operation of a wind turbine generator (WTG) induces a new loading regime on the substructure, distinct from that of a conventional floating platform:

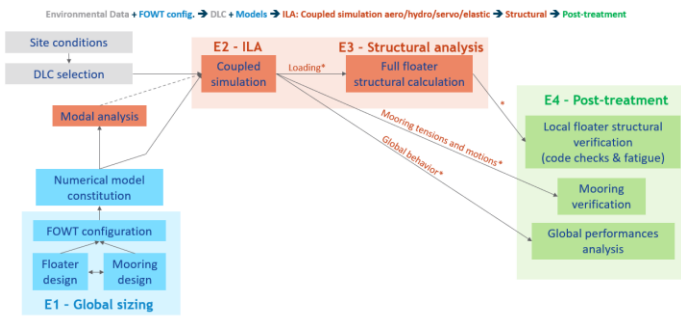
**TABLE 1: LOADING AND RESPONSE IN FOWT VS. CONVENTIONAL FLOATING STRUCTURES**

NEW ITEM	FOWT LOADING SIDE	FOWT RESPONSE SIDE	CONVENTIONAL FLOATING STRUCTURES
Detailed wind	Wind becomes an important loading process, high sensitivity to turbulence	Low-frequency cycles from wind: thrust, gravity actions due to inclination, mooring tensions	Generally insensitive to wind loading details
Vibration	WTG aero-servo-elastic loads, esp. 3P and 6P synchronous excitations below 1 Hz	Synchronous excitations introduce vibrations, amplified by fore-aft & side-side tower bending resonances	No significant global vibrations (excluding ringing and springing)
Coupling	Strong coupling of all loadings through WTG controller and moving parts	Wave-induced motions and wind turbulence affect control, which has knock-on effects on motions and vibrations  Aerodynamic damping from revolving rotor & control	Fairly decoupled loading processes, wave dominated

With this shifting parameter distribution, fatigue analysis gets increasingly more significant and difficult to evaluate with precision. As a risk mitigation measure within FOWT design, a large consensus across certification bodies (most notably IEC [3], DNV [4] and BV [5]) dictates that at all stages of projects, from early to detailed design, these fatigue loads must stem from coupled time-domain simulations (see Figure 1).



**FIGURE 1: COUPLED FLOATING WIND TURBINE SIMULATION AND CONSTITUTIVE PROCESSES**



**FIGURE 2: FOWT SUBSTRUCTURE INTEGRATED DESIGN AND CALCULATION WORKFLOW**

### 3. INTEGRATED CALCULATION CHAIN

As seen in the workflow in Figure 2, applicable for all FOWT projects, the core of the design loads transits through the coupled simulation section. Prior to running the coupled simulation:

- Site conditions are determined and discretized into a set of design load cases (DLC), associated with parked and production states of the WTG.
- A WTG and floating substructure design freeze is made in our in-house global sizing and scantling tool, leading to the creation of 2 types of numerical (aero-hydro-servo-elastic) models:
  - Beam-based models,
  - Full shell models.

The beam-based models are used as a means for performing quick frequency assessments of the hydro-mechanical system, mainly to evaluate the 3P/6P frequency margins, a crucial tool in global sizing to quickly discriminate between large number of models. They also serve as a reference for the tower frequency mode tuning in the ILA model. Simplified hydrodynamic models by sectional hydrodynamic coefficients along the beam models are used.

After the initial design screening, full shell-models are preferred for the structural and hydrodynamic modeling of substructures for more accurate structural and hydrodynamic modeling of the substructure. The 3P/6P frequency margins are re-evaluated from the modal analysis of substructure shell model integrated with the WTG model. Full shell-models are also used for the comprehensive consideration of hydrodynamic load during ILA, where a few hundreds to tens of thousands of coupled simulations are carried out, depending on the project stage. Hydrodynamic modeling for ILA has usually been made assuming rigid substructure. Recently it has been found that dynamic elastic response of the substructure needs to be considered in ILA for certain substructure designs [6]

The ILA is followed by post-treatment, where our full models can be interrogated at each finite-element panel for verifications. The goal of this process is to reach both structure reliability and competitiveness by performing full optimisation, which requires being able to calculate accurately and efficiently

the local extreme stresses and fatigue damage in every part of the structure on a high-resolution (standard) mesh.

It is during the post-treatment phase that the design of the calculation chain determines the feasibility of conducting verifications on time and with a reasonable amount of computational effort.

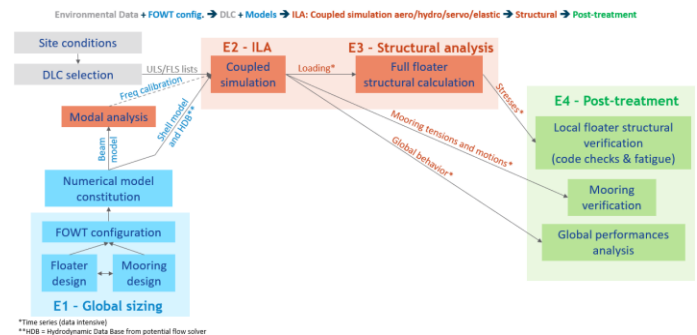
### 3.1 Specific focus on post-treatment

Focusing specifically on fatigue analysis, dictates the following requirements:

- Floating conditions imply long simulations to sample enough low-frequency cycles associated to horizontal station-keeping modes; typically, at least 20-30 minutes per simulation versus 10-minute simulations used for the bottom-fixed offshore wind.
- Within the structure, load effects (mostly stresses) are not readily available from the coupled simulation. A viable method is needed to obtain them from the simulation outputs.
- The entire response time series from each DLC must be processed to enable rainflow counting of the loads (DEL), and especially load effects.
- The sampling rate must be high enough to represent cycles originating from blade passing harmonics, to prevent excessive amplitude shaving. For instance, logging a 0.6 Hz loading process (within the common FOWT vibration frequency range), at sample intervals considered fine for classic wave-frequency analyses can lead to underprediction of damage by up to 40%.

Meeting these criteria for relatively early project phases (e.g. preliminary design or FEED Phase 1) already implies a large amount of structural stress resolutions, in the order of tens of millions of time stamps. Compared to conventional offshore structural engineering and especially when factoring in the time/cost efficiency required by the project stages, this represents a major shift for the designers, which must be addressed by the calculation chain. And this is what is enabled by Ekium's solution.

### 3.2 Ekium's global solution



**FIGURE 3: EKIMUM'S FOWT SUBSTRUCTURE INTEGRATED DESIGN AND CALCULATION WORKFLOW**

As per Figure 3, Ekium's response to the distinctive features of FOW post-treatment is an end-to-end computing framework, combination of:

- The mature FOWT-dedicated software platform TRUST One (developed by Front Energies),
- With critical in-house complements dedicated to engineering tasks: automated global sizing tool, DLC selection tool (see [7]), automated post-treatment tools.

The main framework path is organised as follows:

- Step E1 – Global sizing and scantling (GLOSS):
  - Quick automated model setup for both beam (for modal analysis in full-Morison model) and shell (for ILA with a potential flow model), producing series of floaters and the related analytics,
  - Mooring design,
  - Modal analysis.
- Step E2 – ILA / Coupled simulations with dual solver workflow (within TRUST One), OpenFast or OrcaFlex.
- Step E3 – Structural analysis. Following E2 and the coupled simulations:
  - Creating a “lodal” response database (unitary responses)
    - Punctual loads from mooring lines and tower boundaries (3 or 6 DOFs)
    - Accelerations and gravity as distributed loads
    - Hydrostatic and hydrodynamic load mapping (radiation/diffraction and Morison loads)
    - Hydrostatic load mapping (inertia / radiation loads from elastic modes)
  - Gathering global loads time series: tower loads, mooring loads, Morison element loads
  - Global calculations motions and accelerations, and wave elevation,
  - From all the substeps above: synthesizing step to generate structural response in time domain, by multiplying the unitary response with the load timeseries,
  - This allows for extremely efficient structural analysis while using a detailed full-shell model of the entire floater, with a time ratio between simulation and CPU wall-clock time being about 10 to 100 times faster than traditional time-domain structural analysis methods.
- Step E4 – Post-treatment
  - Regarding regular post-treatment, global performance analysis and mooring verifications are tackled by in-house tools, helping to produce standardized outputs with efficiency,
  - Structural fatigue post-treatment (see dedicated section below).

### 3.3 On the importance of quality assurance

In recent years, the rise of new and innovative FOWT calculation tools is also correlated with a steep increase in the

number of DLCs and the volume of data required by projects. These calculations need to be launched once per phase only, as one cannot afford mistakes that would require repeating costly and timely simulations: the burden of mandatory QA/QC discipline cannot nor must be a manual task left for the ILA teams alone.

Moreover, convoluted calculation processes are not only error-prone, but also often dependent on the skills of the people running them, which is problematic as it makes the design loops non-repeatable.

The need for an assisted and automated global process is paramount, so enablers have been included into Ekium's process:

- Input validations: the input data are clearly parametrized and gathered in specific text-formatted files.
- Semi-automated reports: if errors or anomalies occur, being able to pinpoint their location quickly is capital and must be made easy for the user.
- Aids/results dashboards: being able to follow the process step-by-step and efficiently monitor the desired metrics.

These tools, along with strong self-discipline to follow the imposed line help to reduce the room for error early on, help problem solving and allow for repeatable design studies.

## 4. DESIGN CONSIDERATIONS

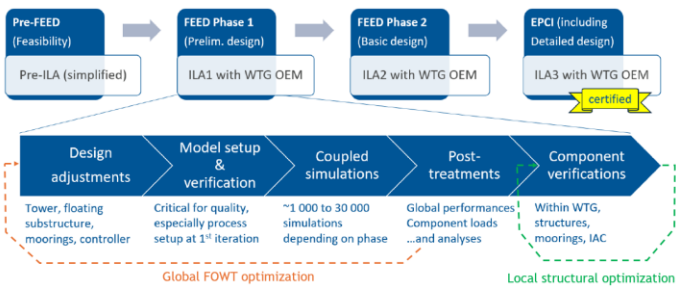
From a designer's perspective, fatigue might initially seem challenging to address, as it is often associated with "detail issues" such as local reinforcements and welds. Additionally, it can require extensive calculations that are not feasible in the early stages of a project. However, as discussed earlier, fatigue significantly impacts FOWTs.

An efficient calculation process is crucial for FOWT substructure design engineers, as it provides early access to:

- Detailed modal analysis in floating conditions, considering the flexibility of the entire system (beams and shells).
- Extreme loads and Damage Equivalent Loads (DELs) in every part of the floater. For example, these values at the tower base can validate tower sizing and WTG integration from the outset, based on actual project data such as wind, waves, current, and water depth.
- Extreme stresses and damage in every part of the structure (including local details), confirming scantling choices and enabling local optimization by iteration.
- Extreme loads and damage in mooring lines, aiding in the definition and optimization of mooring components.

Having access to this information early in the project significantly reduces design cycle risks. It helps avoid vicious cycles, such as reinforcements making the structure stiffer, which can affect bending frequencies and potentially reduce the margin against 3P (or 6P), leading to increased loads.

The FOWT calculation chain built by Ekium allows for early detection of diverging phenomena in the time domain, to then adapt the design to reach the desired performances.



**FIGURE 4:** DETAIL OF FOWT DESIGN PHASES AND ITERATION LOOPS POSSIBILITIES

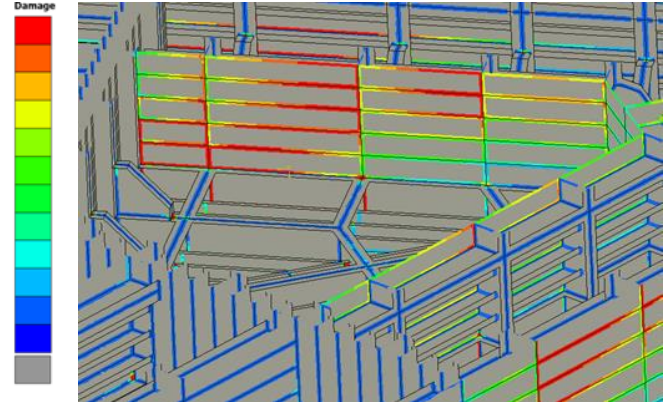
Figure 4 above (see [8] and [9]) shows how each FOWT design phase is subdivided, and how EKIUM’s agile chain allows for different types of iterative design loops:

- Global FOWT optimization enablers:
  - Quick global performance iteration capacity
  - Closed-loop design based on global performance and loads from coupled simulations
- Local structural optimization enablers:
  - Quick structural arrangement iteration capacity
  - Closed-loop component design based on FLS & ULS in time domain

#### 4.1 Structural fatigue

Based on Step E3 outputs, local stress time series (e.g. for cycle counting) are computed in every part of the structure. This yields a direct map of long-term damage in all welds, directly based on the hundreds-to-thousands of fatigue DLC simulations (Figure 4), and is ideal for optimising the structure. One can hence confidently seek: minimal steel plate thickness to reduce material usage; weld type with higher or lower S-N curves for an optimal compromise with respect to fabrication workload and tolerances; etc.

For the fatigue assessment, for an example, stress can be printed only on the elements along the weld lines to evaluate fatigue damage where it matters, as shown in Figure 5. For hot-spot fatigue assessment, the number of elements necessary for the fatigue assessment is even lower. For a detailed structural mesh with millions of elements, the number of elements selected for output along the weld line reduces to tens of thousands and to a few thousands for hot spots.



**FIGURE 5:** SYNTHESIS OF COUPLED POST-TREATMENT ENABLED BY EKIUM’S FRAMEWORK ON THE FLOATER CENTRAL NODE SCANTLING

The selective response printing algorithm embedded in TRUST software makes the fatigue assessment of FOW extremely efficient. Damage counting of 30K elements from 1-hour ILA simulation, with 0.1 sec time step, takes less than 10 minutes on a typical desktop computer. For the fatigue assessment with thousands of DLCs, the process can be run on a dedicated machine with enough CPUs and memory to perform the stress printing and damage counting with parallel operation. Fatigue assessment of 6,000 DLCs at 30K hotspots, for example, took less than 4 hours using 40 CPUs.

#### 4.2 Mooring system fatigue

FOWT station-keeping systems might seem similar to traditional permanent moorings, but experience reveals unique challenges.

- Potential very low-depth sites: Most floater concepts are designed for water depths starting from about 60 meters and deeper. In typical energetic oceanic sites, mooring loading regimes at the low end of this depth range can be intense and complex to design for.
- A typical vicious cycle encountered especially at low depth: reducing the extreme offset can require to increase pre-tension which itself increases fatigue.
- Time-domain methods: A frequency-domain approach is not always suitable even for initial screening, due to nonlinearities and turbine coupling.
- Cost constraints and series effects: In future commercial farms, cost optimization of each mooring component will be amplified across multiple lines and tens of units.
- Fatigue is often governing mooring line components (like chains); moreover vibrations coming from the turbine can propagate through the floater to the fairleads, dynamically exciting mooring lines. This must be identified early for a safe design process.
- Based on these observations, specific design methodologies were developed and integrated into Ekium’s time-domain calculation process, with a focus on enabling early and thorough assessment of fatigue, including the effects of turbine coupling.

## 5. CONCLUSION

In floating wind, the impact of fatigue in the design of floating substructures is quite significant, as it can dictate the amount of structural mass required, up to 30%, driving up costs likewise in the process.

Ekium's FOWT calculation chain will help tackling this challenge as it was designed with the following guidelines in mind:

- FOW requires a new mindset compared to oil&gas floating structures: the turbine dictates the design and so one must include its constraints early.
- Compute fatigue in the substructure from coupled simulations early in the project. Ensuring effective load propagation into structural details is crucial for identifying risks and optimizing costs.
- Facilitate early stages design convergence when the ILA computing budget is most constrained, and onward. This approach enhances engineering efficiency and boosts the likelihood of project success, including feasibility, optimal sizing, and timely delivery. Additionally, it reduces the risk of significant component redesigns midway through the project due to emerging fatigue issues.
- Maintain close control over the system's stiffness (and thus its frequency behavior) to prevent design divergence through negative feedback loops.
- Start with a certifiable or certified design basis from the outset.

Only under these conditions will one be able to optimise the substructures and reach the correct level of reliability quick enough, ensuring low-risk yet robust designs, which will be key to securing project costs and schedules.

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