Optimization of Offshore Wind Turbine Support Structures Using Analytical Gradient-Based Method

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Outline

- Background
- Optimal design problem
- Integrated optimization framework
- Case study: OC4 jacket substructure
- Conclusions & Future work

Background

- Optimization of offshore wind turbine support structures
  - Highly constrained
  - Non-convex
  - Non-linear
  - Dynamic problem
- Sensitivity analysis
  - Finite difference approximation
  - Inefficient & numerical error

Non-linear dynamic response constrained structural optimization

Optimal design problem

$$\text{Find } \mathbf{b}$$
$$\text{to minimize } f(\mathbf{b})$$
$$\text{subject to } g_i\left(\mathbf{b}, \mathbf{z}(t_j), \dot{\mathbf{z}}(t_j), \ddot{\mathbf{z}}(t_j), t_j\right) \le 0$$
$$\text{and } \mathbf{M}\ddot{\mathbf{z}}(t_j) + \mathbf{C}\dot{\mathbf{z}}(t_j) + \mathbf{K}\mathbf{z}(t_j) - \mathbf{f}(t_j) = 0$$
$$\text{where } i=1,\ldots,p,\ j=1,\ldots,q$$

Objective func

$$f = \sum_{n=1}^{N} \rho A_n L_n \text{ where } A_n = \pi(D_n t_n - t_n^2)$$

Sizing

$$g_1 = \mathbf{b}_{\min} \le \mathbf{b} \le \mathbf{b}_{\max} \qquad g_2 = \mathbf{A}_{ineq}\mathbf{b} - \mathbf{c}_{ineq} \le 0$$

Eigenfrequency

$$g_3 = 0.222 \text{ Hz} \le f_1 \le 0.311 \text{ Hz}$$

Tension, bending

$$g_{4a} = \left(N_{t,Sd}/N_{t,Rd}\right)^{1.75} + \left(M_{y,Sd}^2 + M_{z,Sd}^2\right)^{0.5} / M_{Rd} - 1.0 \le 0$$

Buckling

$$g_{5a} = N_{c,Sd}/N_{c,Rd} + \left\{\left[C_{my}M_{y,Sd}/\left(1 - N_{c,Sd}/N_{Ey}\right)\right]^2 + \left[C_{mz}M_{z,Sd}/\left(1 - N_{c,Sd}/N_{Ez}\right)\right]^2\right\}^{0.5} / M_{Rd} - 1.0 \le 0$$

Compression

$$g_{6a} = N_{c,Sd}/N_{cl,Rd} + \left(M_{y,Sd}^2 + M_{z,Sd}^2\right)^{0.5} / M_{Rd} - 1.0 \le 0$$

Extreme load (beam)

$$g_7 = \left(\sigma_{c,Sd} - 0.5 f_{he}/\gamma_m\right) / \left(f_{cle}/\gamma_m - 0.5 f_{he}/\gamma_m\right) + \left(\sigma_{p,Sd}\gamma_m / f_{he}\right)^2 - 1.0 \le 0$$

Shear, bending & torsion

$$g_{8a} = M_{Sd} / \left[M_{Red,Rd}\left(1.4 - V_{Sd}/V_{Rd}\right)^{0.5}\right] - 1.0 \le 0 \text{ for } V_{Sd}/V_{Rd} \ge 0.4$$

Hoop buckling

$$g_9 = \sigma_{p,Sd} / f_{h,Rd} - 1.0 \le 0$$

Extreme load (joint)

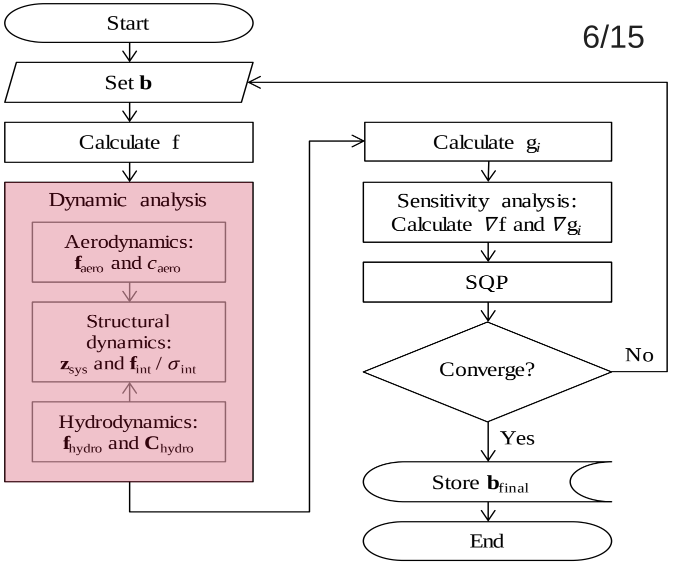
$$g_{10} = N_{Sd}/N_{Rdj} + \left(M_{y,Sd}/M_{y,Rdj}\right)^2 + M_{z,Sd}/M_{z,Rdj} - 1.0 \le 0$$

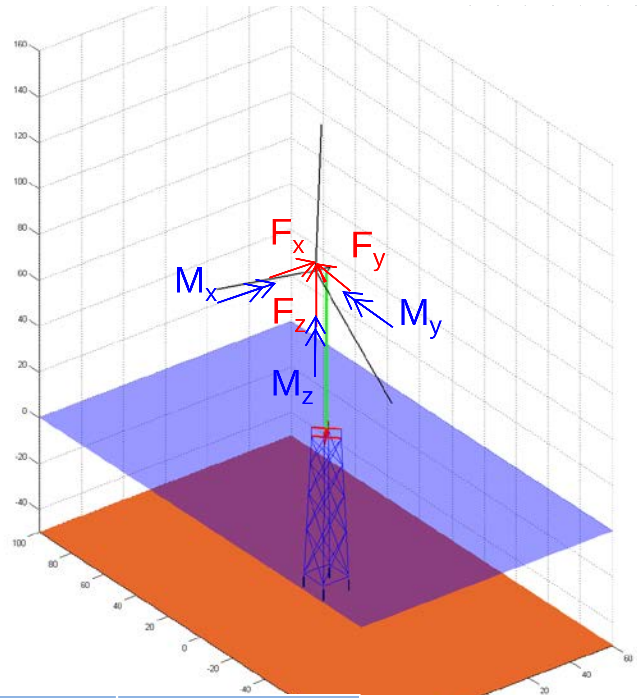
Fatigue load

$$g_{11} = \sum_{i=1}^{I} \frac{1}{\bar{a}\eta}\left(\frac{t}{t_{ref}}\right)^{mk} n_i \left(\Delta\sigma_{i,HSS}\right)^m - 1.0 \le 0$$

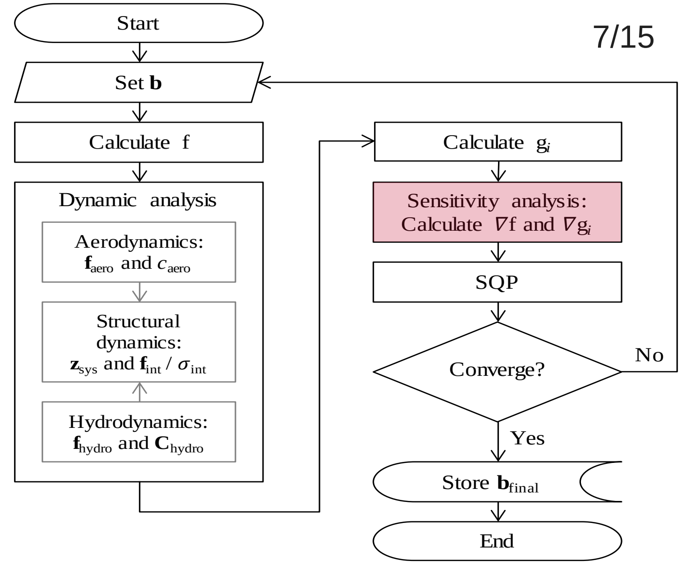
Optimization framework

- Time domain dynamic analysis
  - Structural dynamic
    - Euler-Bernoulli beam
    - Rayleigh damping
    - Newmark-beta integration
  - Hydrostatic & hydrodynamic
    - Buoyancy
    - Internal water mass; marine growth
    - Morison formula
  - Aerodynamic
    - Decoupled model
    - Aerodynamic external force
    - Aerodynamic damping





Optimization framework



- Analytical sensitivity analysis
  - Direct differentiation method

$$\nabla f = \frac{\partial f}{\partial \mathbf{b}} \qquad \nabla g_i = \frac{\partial g_i}{\partial \mathbf{b}} + \frac{\partial g_i}{\partial \mathbf{z}}\frac{d\mathbf{z}}{d\mathbf{b}}$$

  - Extreme load constraints

$$\frac{d\mathbf{z}_{sta}}{d\mathbf{b}} = \mathbf{K}^{-1}\left(\frac{d\mathbf{f}_{sta}}{d\mathbf{b}} - \frac{d\mathbf{K}}{d\mathbf{b}}\mathbf{z}_{sta}\right) \qquad \mathbf{M}\frac{d^2}{dt^2}\left(\frac{d\mathbf{z}_{dyn}}{d\mathbf{b}}\right) + \mathbf{C}\frac{d}{dt}\left(\frac{d\mathbf{z}_{dyn}}{d\mathbf{b}}\right) + \mathbf{K}\left(\frac{d\mathbf{z}_{dyn}}{d\mathbf{b}}\right) = \frac{d\mathbf{f}_{dyn}}{d\mathbf{b}} - \frac{d\mathbf{M}}{d\mathbf{b}}\ddot{\mathbf{z}}_{dyn} - \frac{d\mathbf{C}}{d\mathbf{b}}\dot{\mathbf{z}}_{dyn} - \frac{d\mathbf{K}}{d\mathbf{b}}\mathbf{z}_{dyn}$$

  - Fatigue load constraints

$$\nabla g_{11} = \sum_{i=1}^{I}\frac{mk}{\bar{a}\eta}\left(\frac{1}{t_{ref}}\right)^{mk} t^{mk-1}\frac{dt}{d\mathbf{b}} n_i\left(\Delta\sigma_{i,HSS}\right)^m + \sum_{i=1}^{I}\frac{m}{\bar{a}\eta}\left(\frac{t}{t_{ref}}\right)^{mk} n_i\left(\Delta\sigma_{i,HSS}\right)^{m-1}\frac{d\Delta\sigma_{i,HSS}}{d\mathbf{b}}$$

$$\frac{d\Delta\sigma_{i,HSS}}{d\mathbf{b}} = \begin{cases} \left.\frac{d\sigma_{i,HSS}}{d\mathbf{b}}\right|_{t_j=t_1} - \left.\frac{d\sigma_{i,HSS}}{d\mathbf{b}}\right|_{t_j=t_2} & \text{for } \sigma_{i,HSS}(t_1) > \sigma_{i,HSS}(t_2) \\ \left.\frac{d\sigma_{i,HSS}}{d\mathbf{b}}\right|_{t_j=t_2} - \left.\frac{d\sigma_{i,HSS}}{d\mathbf{b}}\right|_{t_j=t_1} & \text{for } \sigma_{i,HSS}(t_2) > \sigma_{i,HSS}(t_1) \end{cases}$$

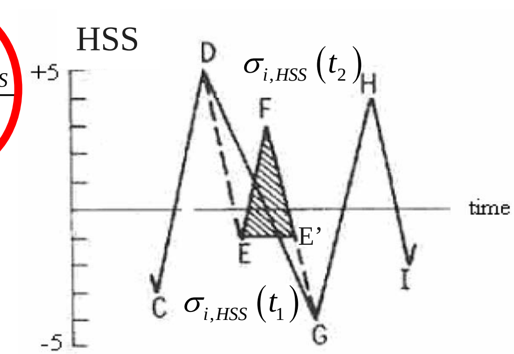
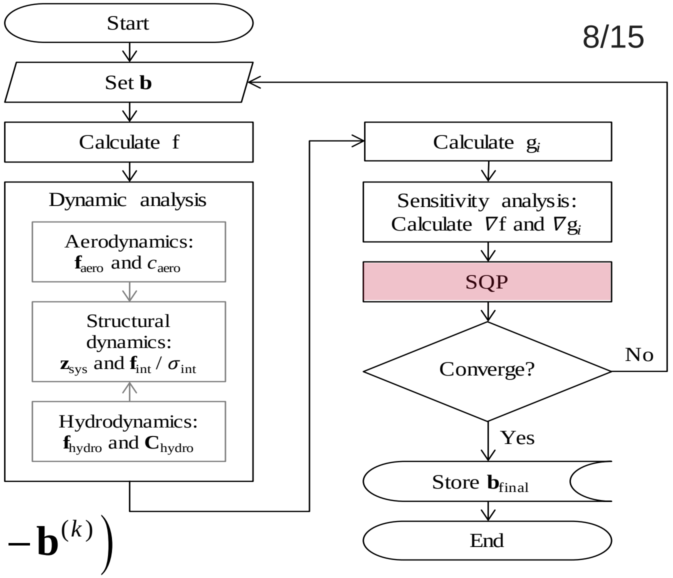


Fig. Rainflow counting

$$\frac{d\sigma_{i,HSS}}{d\mathbf{b}} = c_{Nx}\left(\frac{dSCF_{Nx}}{d\mathbf{b}}\sigma_{i,Nx} + \frac{d\sigma_{i,Nx}}{d\mathbf{b}}SCF_{Nx}\right) + c_{My}\left(\frac{dSCF_{My}}{d\mathbf{b}}\sigma_{i,My} + \frac{d\sigma_{i,My}}{d\mathbf{b}}SCF_{My}\right) + c_{Mz}\left(\frac{dSCF_{Mz}}{d\mathbf{b}}\sigma_{i,Mz} + \frac{d\sigma_{i,Mz}}{d\mathbf{b}}SCF_{Mz}\right)$$

Optimization framework



- Sequential Quadratic Programming (SQP)
  - Reformulate as QP subproblem

$$\min\ f\left(\mathbf{b}^{(k)}\right)+\left(\nabla f\left(\mathbf{b}^{(k)}\right)\right)^T\left(\mathbf{b}-\mathbf{b}^{(k)}\right)+\frac{1}{2}\left(\mathbf{b}-\mathbf{b}^{(k)}\right)^T\mathbf{H}\left(\mathbf{b}^{(k)}\right)\left(\mathbf{b}-\mathbf{b}^{(k)}\right)$$

$$\text{s.t. } g_i\left(\mathbf{b}^{(k)}\right)+\left(\nabla g_i\left(\mathbf{b}^{(k)}\right)\right)^T\left(\mathbf{b}-\mathbf{b}^{(k)}\right)\le 0,\ \ i=1,\ldots,p$$

  - Hessian $\mathbf{H}$ of Langragian function $L(\mathbf{b},\lambda)=f(\mathbf{b})+\sum_{i=1}^{m}\lambda_i g_i(\mathbf{b})$

$$\mathbf{H}^{(k+1)}=\mathbf{H}^{(k)}+\frac{\mathbf{q}^{(k)}\left(\mathbf{q}^{(k)}\right)^T}{\left(\mathbf{q}^{(k)}\right)^T\mathbf{s}^{(k)}}-\frac{\mathbf{H}^{(k)}\mathbf{s}^{(k)}\left(\mathbf{s}^{(k)}\right)^T\left(\mathbf{H}^{(k)}\right)^T}{\left(\mathbf{s}^{(k)}\right)^T\mathbf{H}^{(k)}\mathbf{s}^{(k)}}$$

where $\mathbf{s}^{(k)}=\mathbf{b}^{(k+1)}-\mathbf{b}^{(k)}$

$$\mathbf{q}^{(k)}=\nabla L(\mathbf{b}^{(k+1)},\lambda)-\nabla L(\mathbf{b}^{(k)},\lambda)$$

Broyden-Fletcher-Goldfarb-Shanno (BFGS) approximation

  - Matlab optimization toolbox

Case study- *Problem formulation*

- Design variables
  - OC4 jacket substructure
  - 22 variables (diameter & thickness)
  - Sizing constraints
    - $\mathbf{b}_{\min} = 33\% * \mathbf{b}_{\text{initial}}$ $\mathbf{b}_{\max} = 300\% * \mathbf{b}_{\text{initial}}$
    - $20 \le D_{brace} / t_{brace} \le 120$
    - $20 \le D_{leg} / t_{leg} \le 64$
    - $0.2 \le D_{brace} / D_{leg} \le 1.0$
    - $0.2 \le t_{brace} / t_{leg} \le 1.0$
  - Extreme load constraints
    - 1248 (beam); 104 (joints)
  - Fatigue load constraints
    - 208

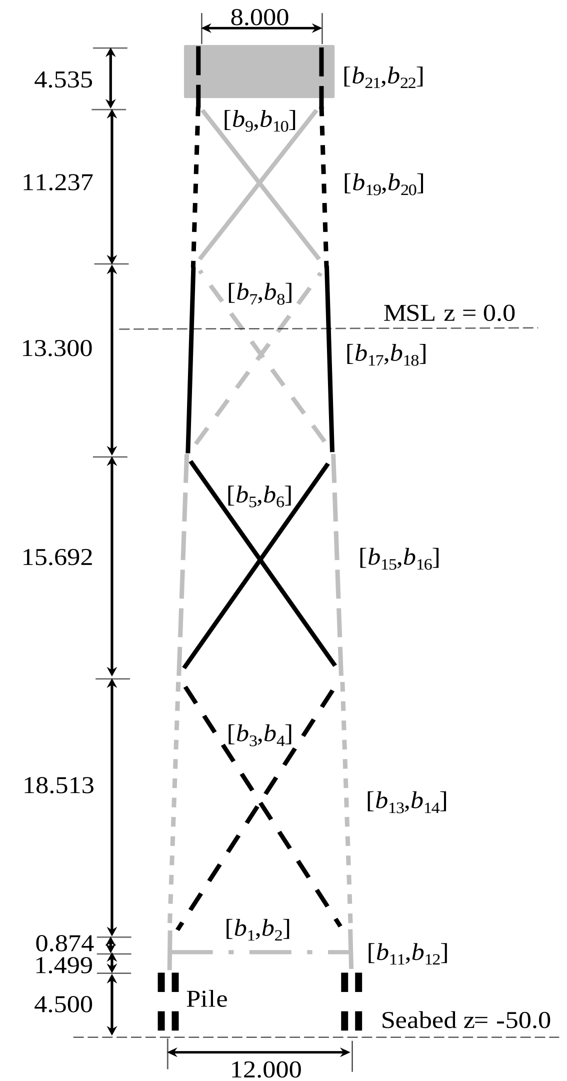


Fig. OC4 jacket substructure

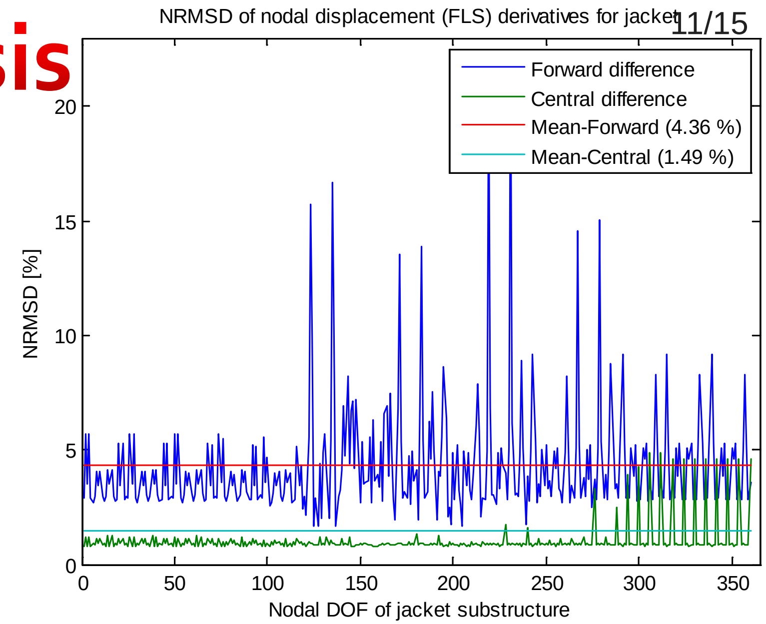
Case study- *Problem formulation*

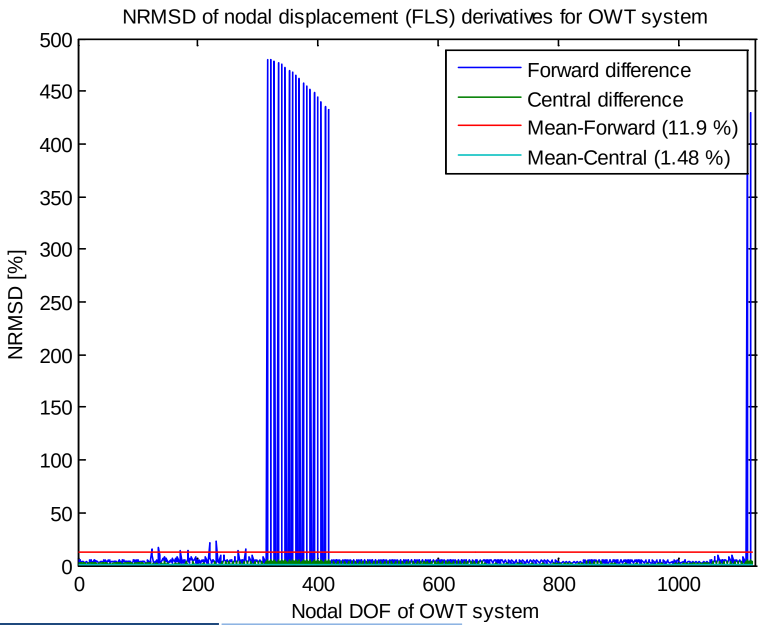
- Design load cases
  - Fatigue load case
  - Extreme load case

Load Case	Wind Conditions	Wave Conditions
FLS	NTM (Kaimal spectrum) V_{hub} = 8.00 m/s TI = 10.00 % α = 0.14	NSS (JONSWAP spectrum) H_s = 1.31 m T_p = 5.67 s γ = 1
ULS	EWM (Kaimal spectrum) V_{hub} = 42.73 m/s TI = 10.00 % α = 0.11	ESS (JONSWAP spectrum) H_s = 9.40 m T_p = 13.70 s γ = 3.3

Results- Sensitivity analysis

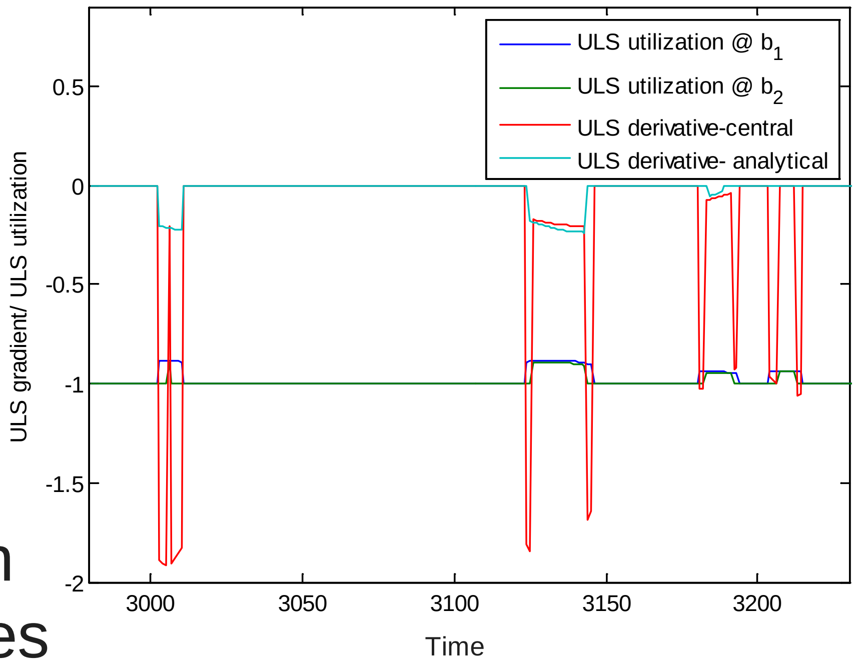
- Sensitivity analysis
  - *Central* vs *Forward* FD
  - Integration *time step* (0.01 s & 0.025 s)
  - Design *variables* (braces & legs)
- Displacement (ULS & FLS)
  - *Central & DDM*
    - 2.5 % NRMSD (jacket)
  - *Forward & DDM*
    - 6.0 % NRMSD (jacket)
    - Large deviation for entire OWT





Results- Sensitivity analysis

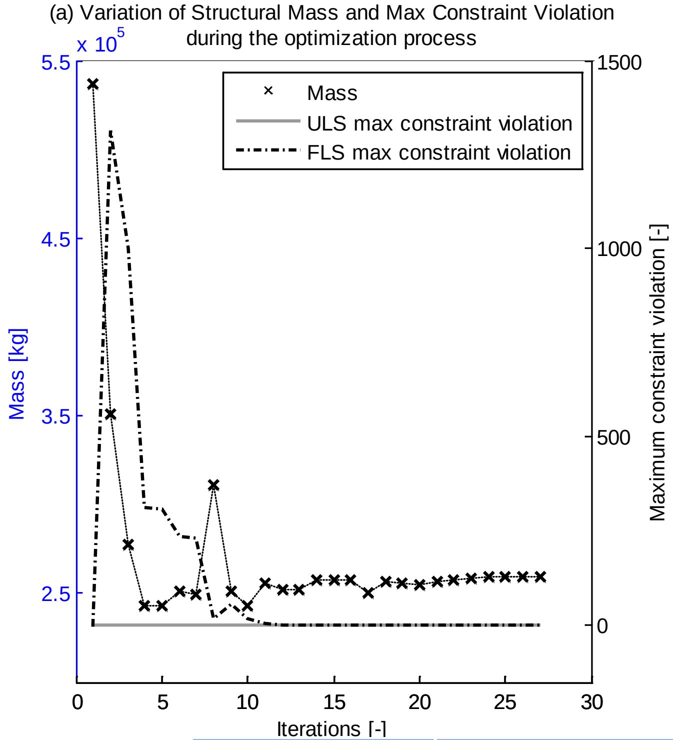
Comparison of ULS derivatives against b_{15} for beams between central difference and analytical



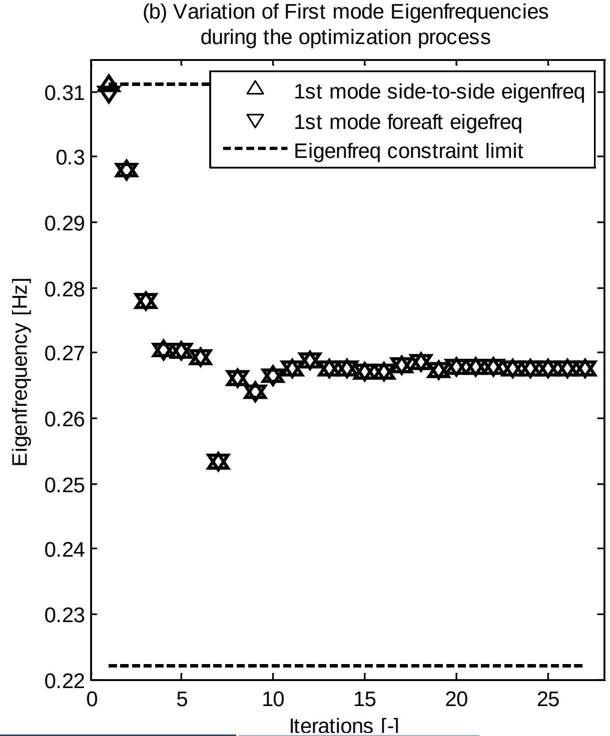
- Eigenfrequency
  - Small NRMSD
- Extreme load (beam)
  - Large NRMSD~ 22 %
  - Numerical artifacts in FD
  - Discontinuity due to switch in compression & tension modes
- Extreme load constraints (joints)
  - Central & DDM: 2.5 %; Forward & DDM: 6 %
- Fatigue load constraints
  - Central & DDM: 5 %; Forward & DDM: 7 %
  - Influenced by other derivatives, e.g. SCF

Results- Optimization

- Optimization
  - 52 % mass reduction
  - 27 iterations
  - Active constraints



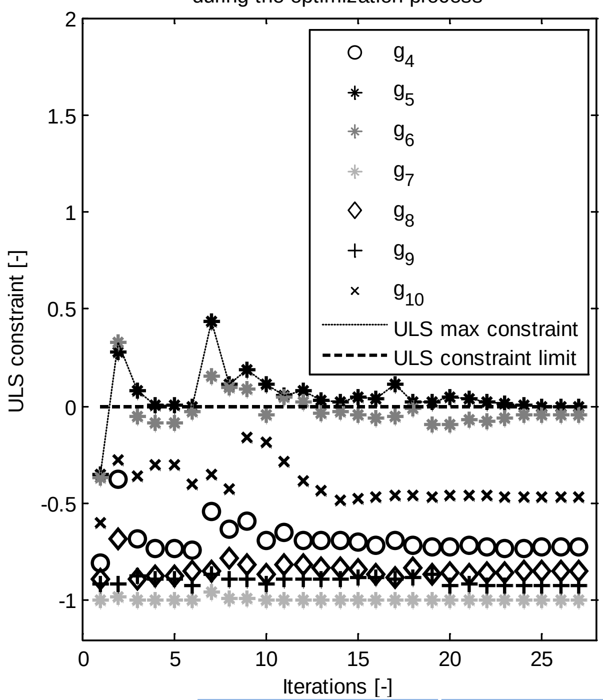
- Eigen-frequency
  - Variation pattern
  - Converged to center of constraint limit



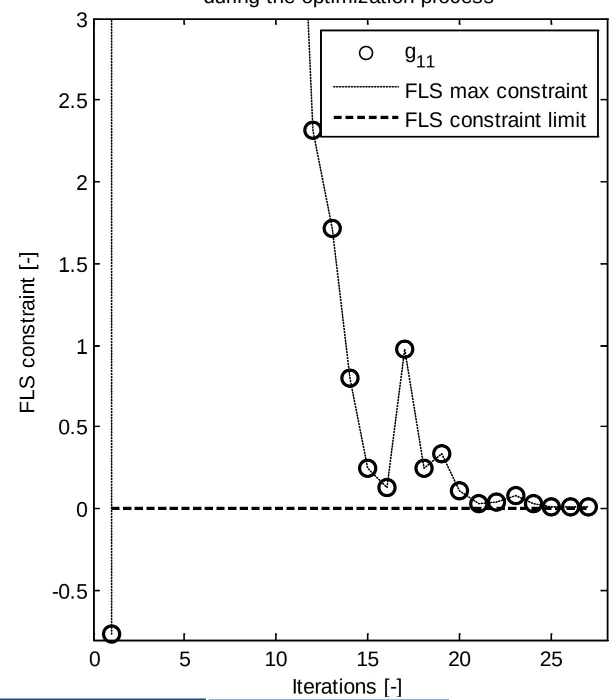
Results- Optimization

- Extreme load constraints
  - Buckling & compression
  - Others remained inactive
- Fatigue load constraints
  - Critical constraint

(c) Variation of Extreme Load Constraints during the optimization process



(d) Variation of Fatigue Load Constraints during the optimization process



Conclusions & Future work

- Successful key implementations:
  - Optimization in **time** domain, s.t. comprehensive **constraints**
  - Sensitivity analysis using **analytical DDM**
- Sensitivity analysis results
  - **Central** difference **matches well** with **DDM**
  - DDM is **twice more efficient**
  - DDM can **avoid numerical artifacts**
- Optimization results
  - Optimal design converges in **27 iterations**
  - Both **FLS & ULS** influence optimal design
  - **Buckling** & **compression** constraints are active
- Future work
  - Optimization s.t. complete fatigue load cases
  - Include geometrical/ topological variation

Thank you
Questions and Answers