Integrated analysis of wind and wave loading for complex support structures of Offshore Wind Turbines

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Integrated analysis with Flex 5 and ASAS(NL)

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- Structural modelling in Flex 5
- Integrated, sequential analysis with Flex 5 and ASAS(NL)
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- Examples
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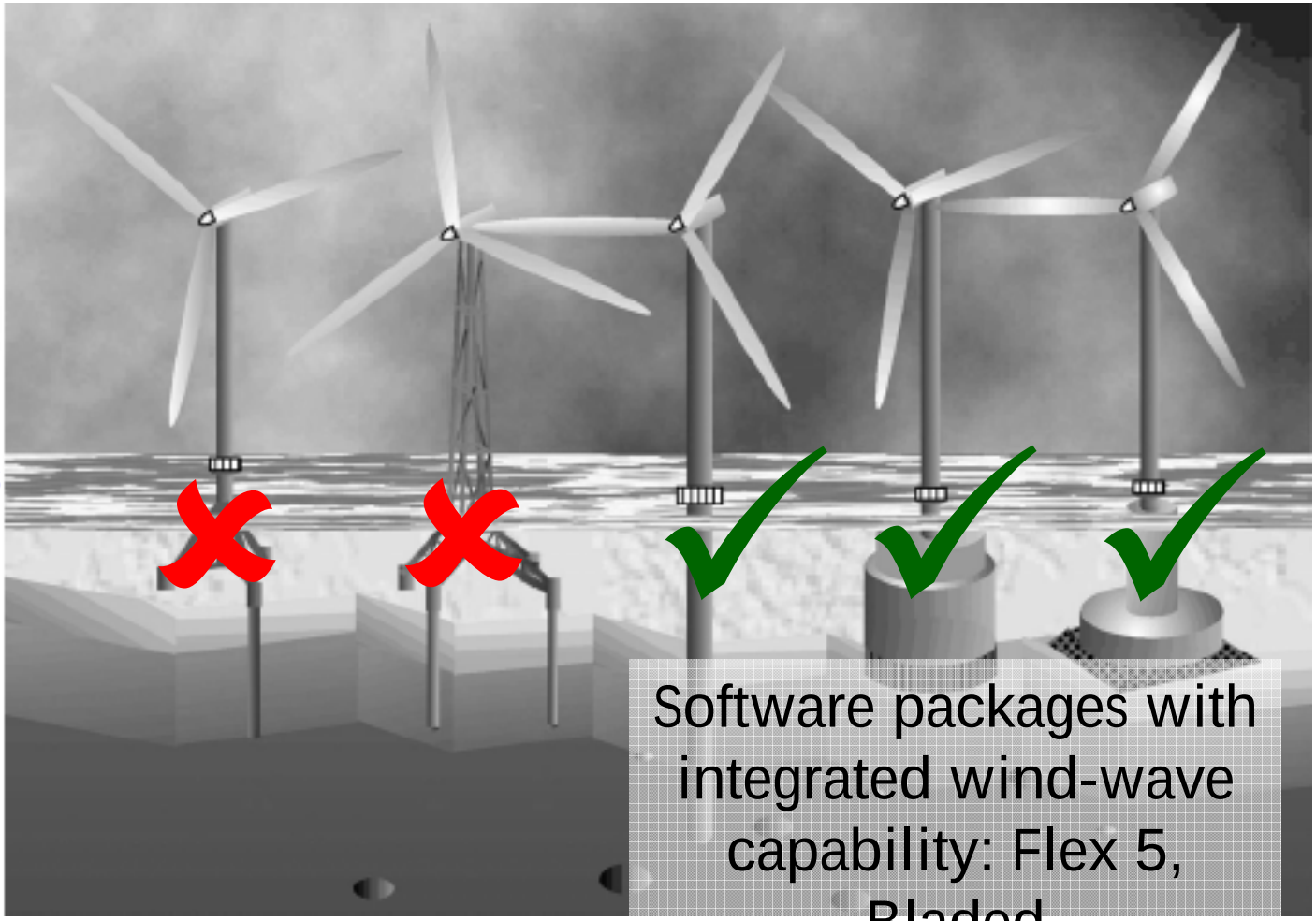

Software packages with integrated wind-wave capability: Flex 5, Bladed

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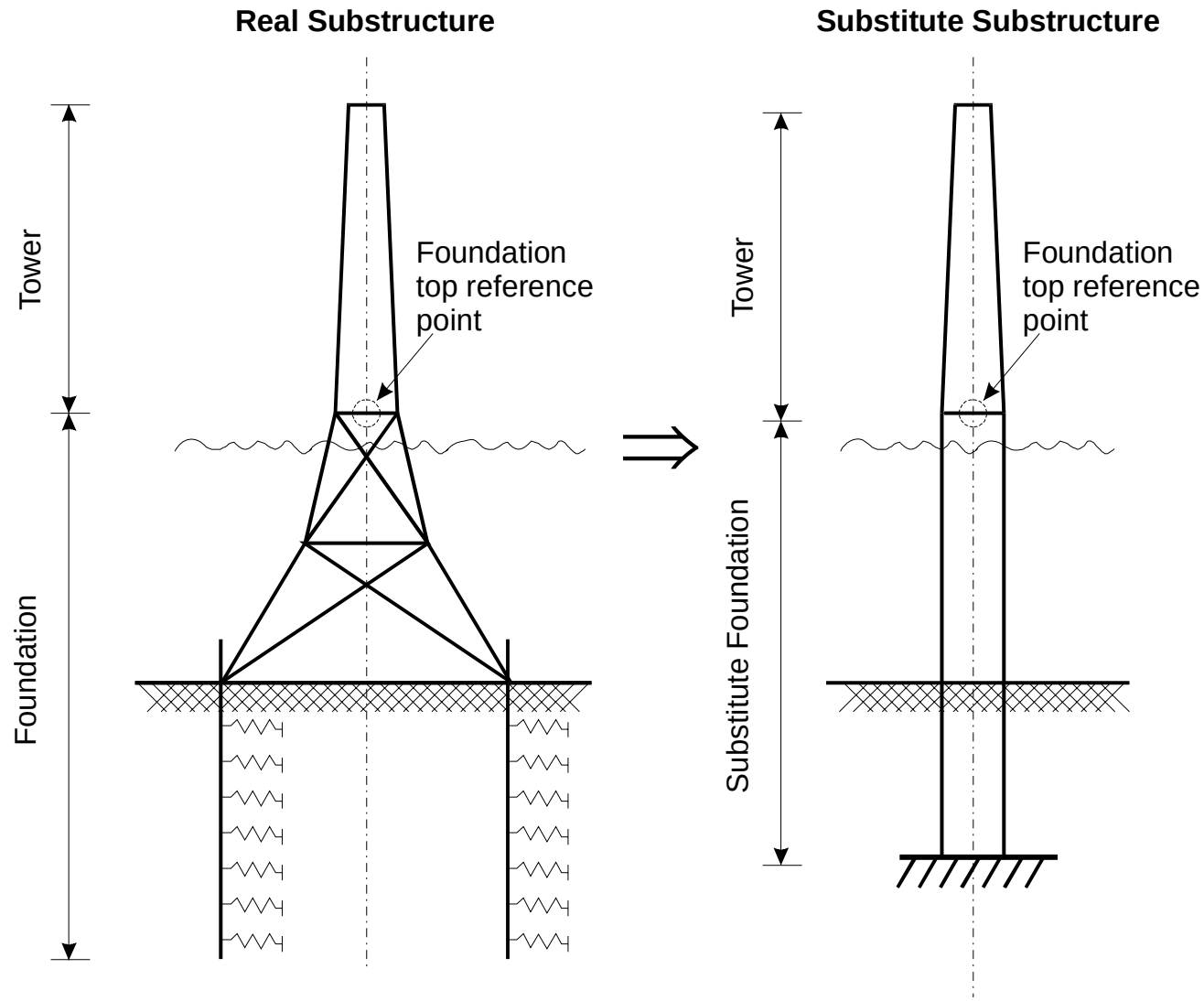

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Shortcomings of the "Substitute Monopile" approach are:

- Stiffness (as well as mass and damping) matrix can not be represented well for all substructures by a Monopile
- Superposition of wind and wave loads for the substructure can only be done statically with forces/moments applied at substructure top
- Wave loading is calculated for a single straight member only
- Two substructure models (full model and substitute Monopile) must be maintained, harmonized and checked!

Structural Modelling in Flex 5

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Differential equations:

$$\underline{K} \cdot \underline{u}(t) + \underline{D} \cdot \underline{\dot{u}}(t) + \underline{M} \cdot \underline{\ddot{u}}(t) = \underline{p(t)}$$

Model characteristics in Flex 5:

- Limited number of DOFs
- Generalized DOFs for tower (modal generalization) and foundation (static generalization)

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Stiffness portion for foundation part with six generalized DOFs:

$$\underline{\boldsymbol{p}} = \underline{\boldsymbol{K}} \cdot \underline{\boldsymbol{u}} = \begin{pmatrix} \boldsymbol{K_{xx}} & K_{xy} & K_{xz} & K_{x\varphi_x} & \boldsymbol{K_{x\varphi_y}} & K_{x\varphi_z} \\ K_{yx} & \boldsymbol{K_{yy}} & K_{yz} & \boldsymbol{K_{y\varphi_x}} & K_{y\varphi_y} & K_{y\varphi_z} \\ K_{zx} & K_{zy} & \boldsymbol{K_{zz}} & K_{z\varphi_x} & K_{z\varphi_y} & K_{z\varphi_z} \\ K_{\varphi_x x} & \boldsymbol{K_{\varphi_x y}} & K_{\varphi_x z} & \boldsymbol{K_{\varphi_x \varphi_x}} & K_{\varphi_x \varphi_y} & K_{\varphi_x \varphi_z} \\ \boldsymbol{K_{\varphi_y x}} & K_{\varphi_y y} & K_{\varphi_y z} & K_{\varphi_y \varphi_x} & \boldsymbol{K_{\varphi_y \varphi_y}} & K_{\varphi_y \varphi_z} \\ K_{\varphi_z x} & K_{\varphi_z y} & K_{\varphi_z z} & K_{\varphi_z \varphi_x} & K_{\varphi_z \varphi_y} & \boldsymbol{K_{\varphi_z \varphi_z}} \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{x} \\ \boldsymbol{y} \\ \boldsymbol{z} \\ \boldsymbol{\varphi_x} \\ \boldsymbol{\varphi_y} \\ \boldsymbol{\varphi_z} \end{pmatrix}$$

Integrated Analysis with Flex 5 / ASAS(NL)

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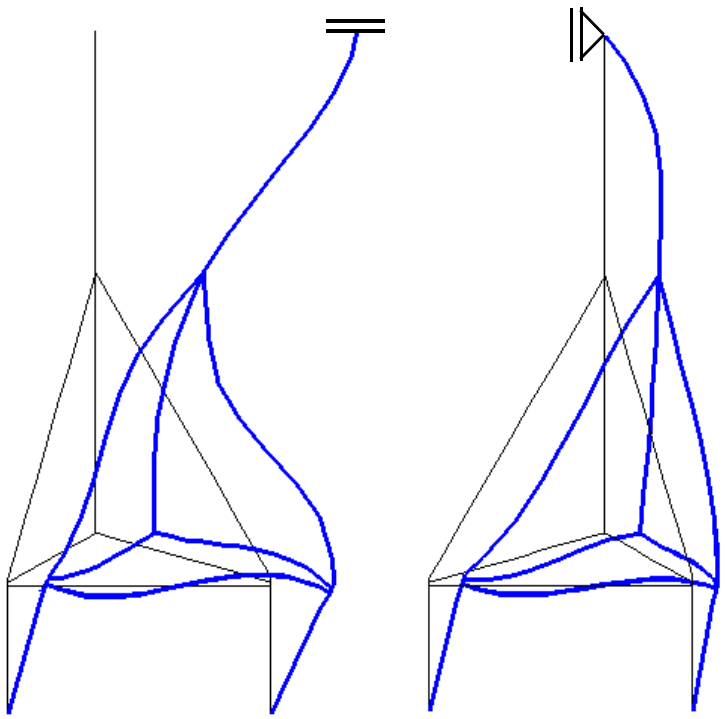
Substitution of Flex 5 Monopile module by ASAS(NL) routines

Generalized properties:

- Stiffness matrix
- Damping matrix
- Mass matrix
- Wave loading history (assuming fixed structure, i.e. no relative kinematics)

Deflection shapes for generalization:



⇒ Integrated, sequential calculation in Flex 5

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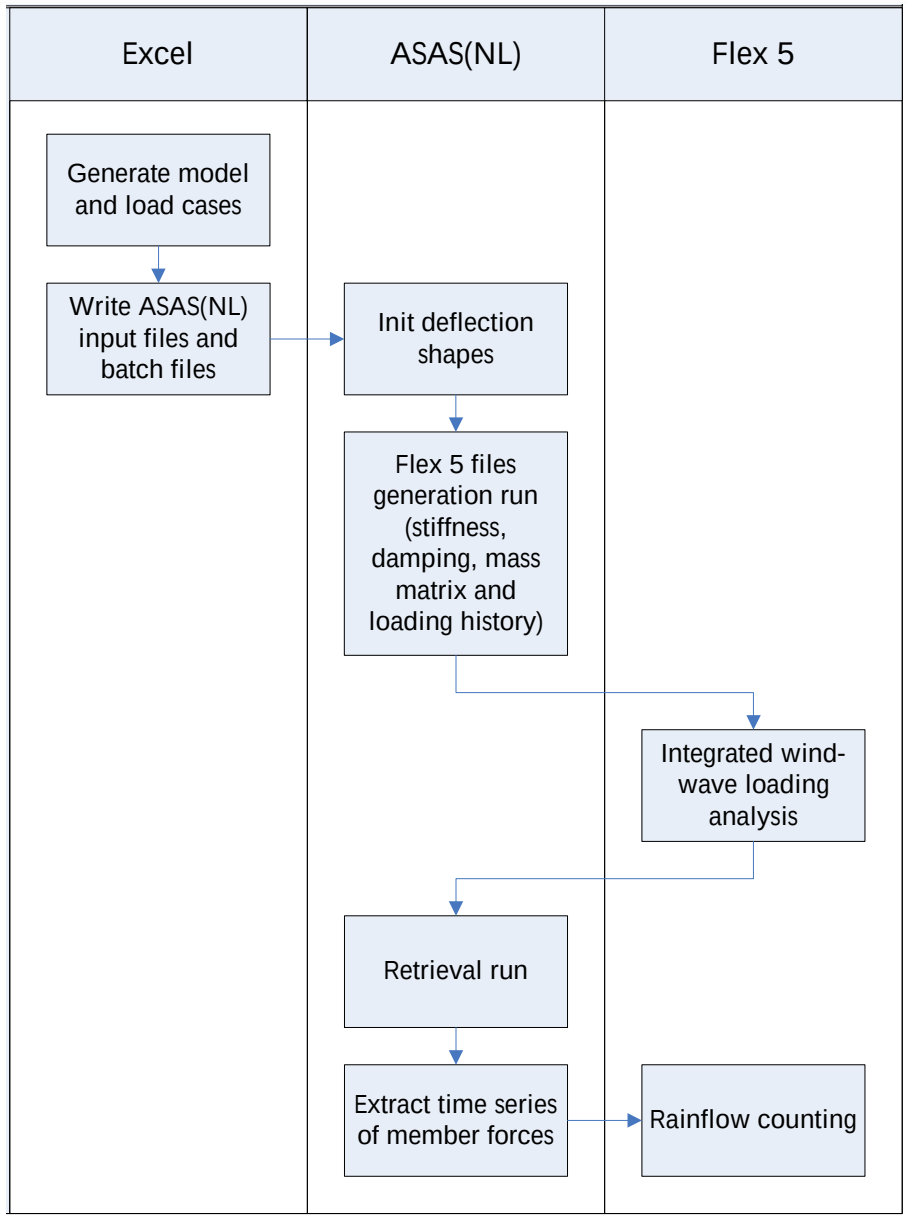

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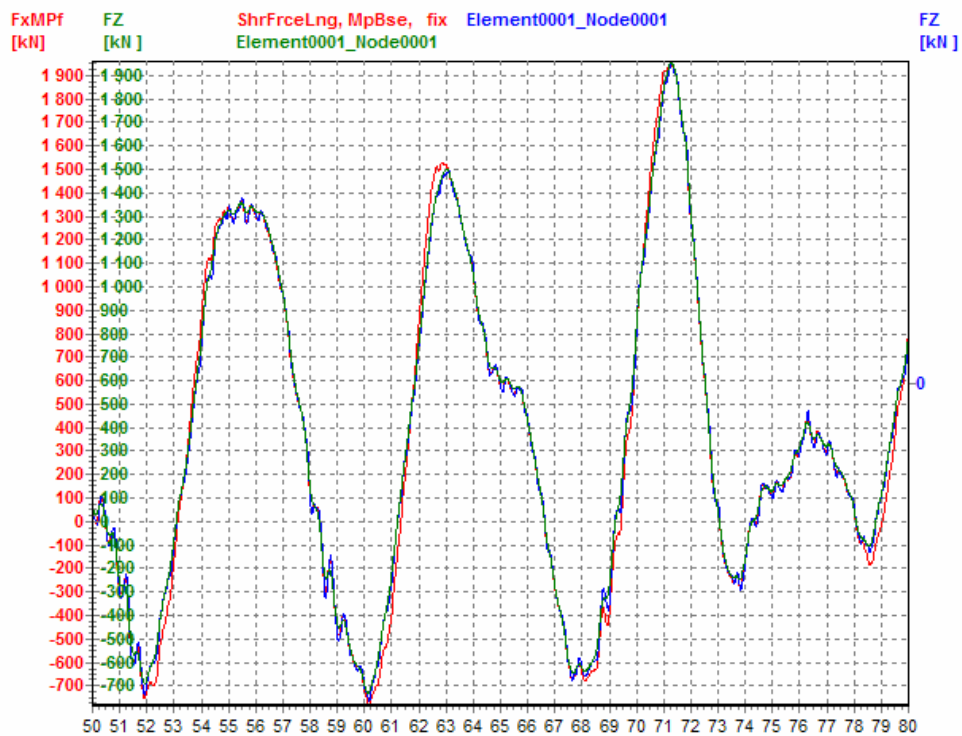
Complete validation with a Monopile example

- Comparison of integrated calculation with Flex 5 / WaveKin to Flex 5 / ASAS(NL)
- Example: Horizontal force at mudline



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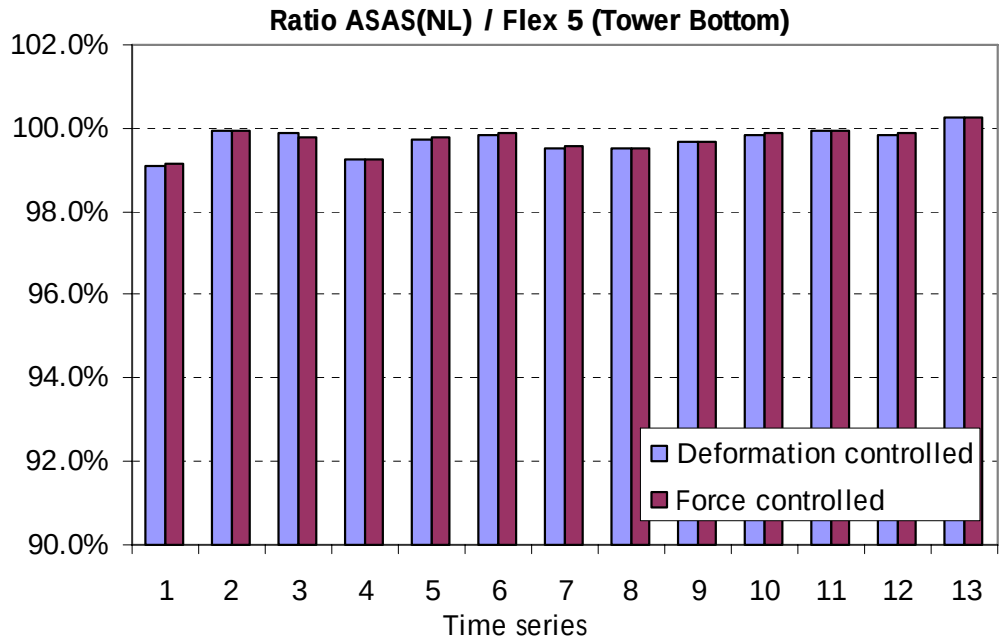
Fatigue loads at tower bottom



- Difference of 0.3% to Flex 5 due to different time steps
- “Force controlled” and “deformation controlled” are virtually identical

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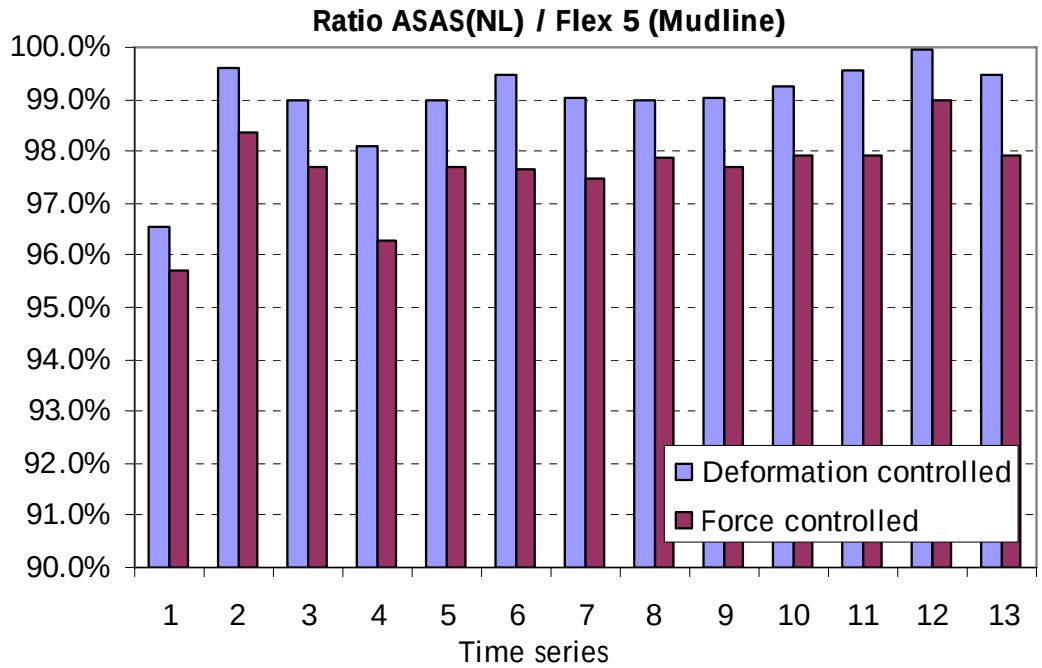
Fatigue loads at mudline:



- Ratio of "Deformation controlled" results to Flex 5 is 0.99 on average
- "Force controlled" slightly lower due to neglected inertia forces of the foundation

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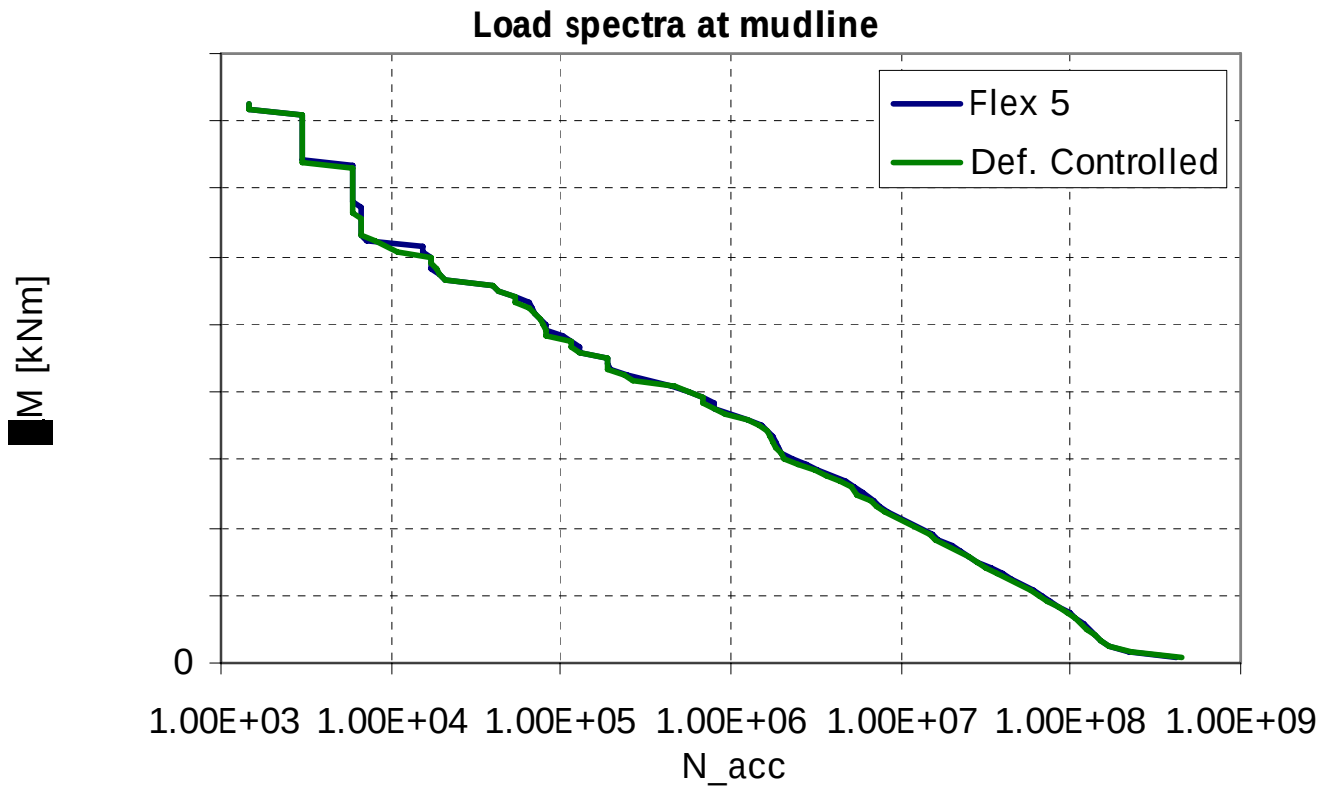
Fatigue loads at mudline:



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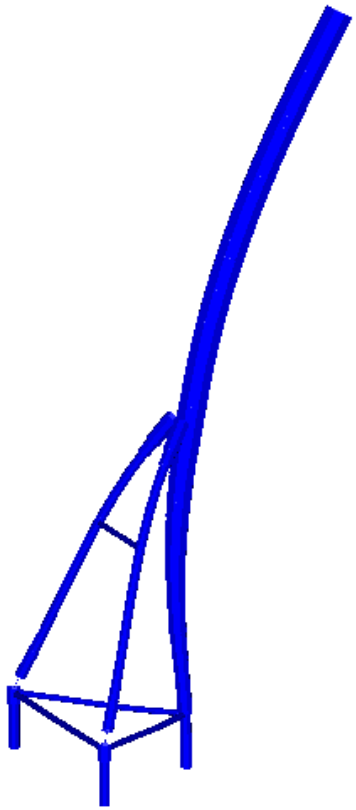
Mode shapes for Flat Face Tripod:



f_0 = 0.316 Hz
Flex 5: f_0 = 0.325 Hz

f_2 = 0.953 Hz
Flex 5: f_1 = 1.14 Hz

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Stiffness matrix analysis

1.19E+08	7.10E+06	-2.25E+08	2.39E+06	**-9.88E+07**	-3.36E+07
7.10E+06	**1.19E+08**	-2.25E+08	**9.89E+07**	-2.33E+06	3.36E+07
-2.25E+08	-2.25E+08	**2.05E+09**	6.26E+08	-6.26E+08	-7.98E+04
2.39E+06	**9.89E+07**	6.26E+08	**2.39E+10**	3.51E+08	1.31E+09
-9.88E+07	-2.33E+06	-6.26E+08	3.51E+08	**2.39E+10**	1.31E+09
-3.36E+07	3.36E+07	-7.98E+04	1.31E+09	1.31E+09	**3.31E+09**

Relative contribution per degree of freedom

100.00%	5.97%	-189.08%	2.01%	**-83.21%**	-28.28%
5.97%	**100.00%**	-189.08%	**83.27%**	-1.96%	28.31%
-10.96%	-10.96%	**100.00%**	30.54%	-30.55%	0.00%
0.01%	**0.41%**	2.62%	**100.00%**	1.47%	5.49%
-0.41%	-0.01%	-2.62%	1.47%	**100.00%**	5.49%
-1.02%	1.02%	0.00%	39.62%	39.62%	**100.00%**

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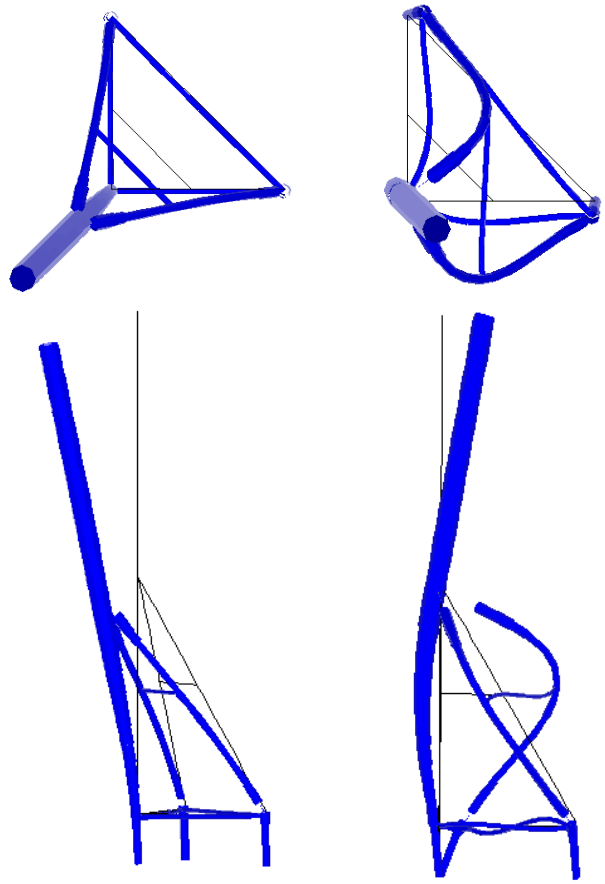
Visualisation of coupling between DOFs:



Deflection shapes for vertical force (left) and torsional moment (right) at hub height

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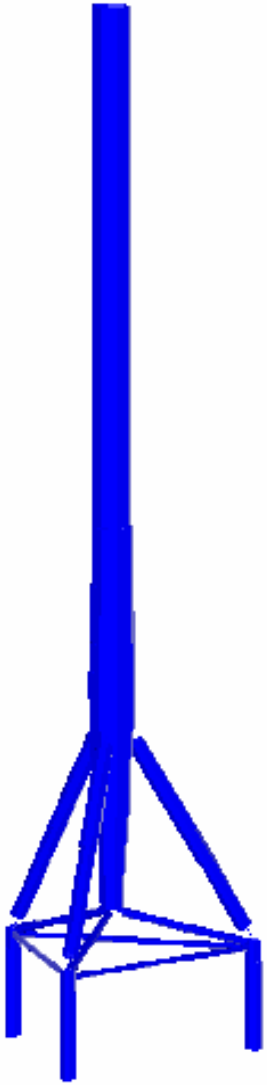
Center Column Tripod (Stiffness matrix):

7.96E+07	5.94E+03	-6.67E+04	8.48E+04	**-1.29E+09**	-8.35E+03
5.94E+03	**7.96E+07**	4.81E+04	**1.29E+09**	-6.72E+04	4.24E+04
-6.67E+04	4.81E+04	**1.92E+09**	7.31E+05	1.12E+06	-1.22E+05
8.48E+04	**1.29E+09**	7.31E+05	**3.91E+10**	-9.62E+05	4.45E+05
-1.29E+09	-6.72E+04	1.12E+06	-9.62E+05	**3.91E+10**	9.84E+04
-8.35E+03	4.24E+04	-1.22E+05	4.45E+05	9.84E+04	**6.15E+09**

Relative contribution per degree of freedom

6.18%	0.00%	0.01%	0.01%	**100.00%**	0.00%
0.00%	**6.18%**	0.00%	**100.00%**	0.01%	0.00%
0.00%	0.00%	**100.00%**	0.04%	0.06%	0.01%
0.00%	**3.29%**	0.00%	**100.00%**	0.00%	0.00%
3.29%	0.00%	0.00%	0.00%	**100.00%**	0.00%
0.00%	0.00%	0.00%	0.01%	0.00%	**100.00%**

No coupling between the generalized degrees of freedom!



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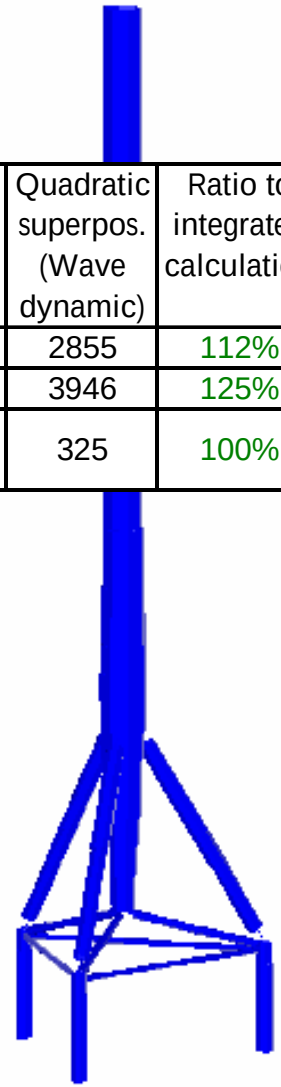
Center Column Tripod (Fatigue results):

	Wind only (Flex 5 / ASAS)	Wind & Wave (Flex 5 / ASAS)	Wave static (ASAS)	Wave dynamic (ASAS)	Quadratic superpos. (Wave static)	Ratio to integrated calculation	Quadratic superpos. (Wave dynamic)	Ratio to integrated calculation
Fx (axial)	1180	2550	2170	2600	2470	97%	2855	112%
Mz (IPB)	2300	3164	1904	3206	2986	94%	3946	125%
Mx (torsion)	325	325	0	0	325	100%	325	100%

Integrated analysis shows significant benefit compared to quadratic superposition of wind and wave loads (dynamic simulation)!



Summary and perspective

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Summary:

- An integrated, sequential approach with Flex 5 and ASAS(NL) has been developed
- The Monopile module from Flex 5 is completely substituted by a detailed substructure model in ASAS(NL)
- Approach to use generalized DOFs in Flex 5 is maintained (fast calculation time, ease of implementation)
- Reliability and robustness of integrated response to wind and wave loading significantly improved to achieve economic design