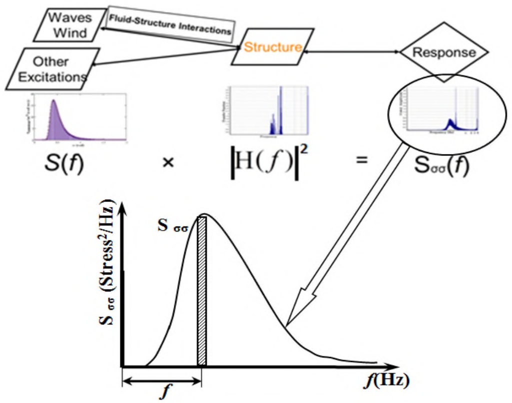
非线性动力学应用于结构疲劳分析与评估

贾军波

Aker Solutions

2020年6月16日



$$D_{j,q} = \frac{\tau(8\lambda_0)^{\frac{m}{2}}}{A} \cdot \sqrt{\frac{\lambda_2}{\lambda_0}} \cdot \Gamma(\frac{2+m}{2})$$

$$D_{total} = \sum_j \sum_q \left(\Psi_{j,q} \cdot D_{j,q}\right)$$

$$L_{total} = \frac{1}{D_{total}} \text{ years}$$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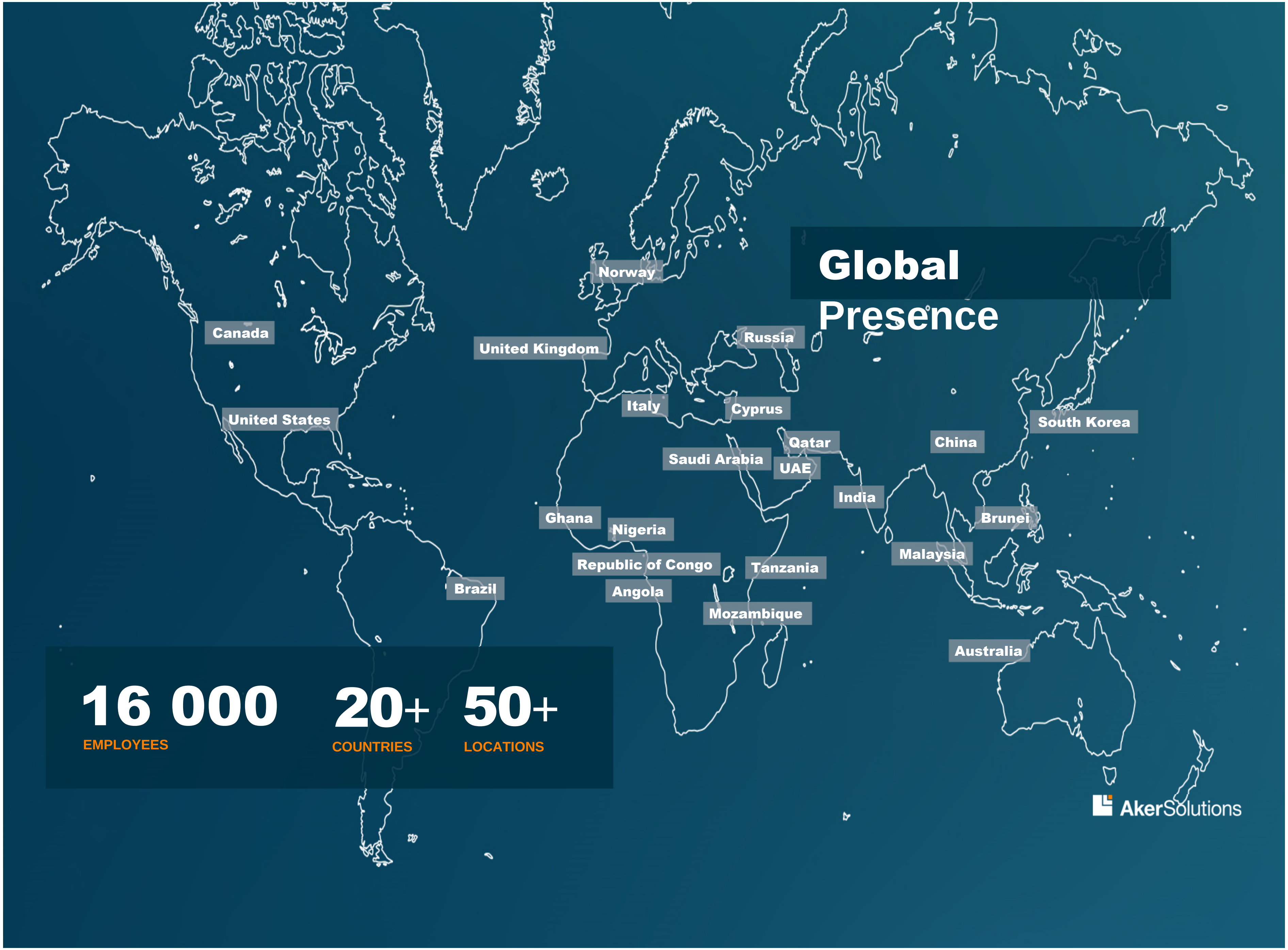
Concept
FEED
Detailed Design
Fabrication
Commissioning
Operations
Modifications
Late Life
Decommissioning

我们的愿景 Our Vision

打造为全球能源行业可持续发展的领导者

A leader in forging a sustainable future for the global energy industry and the world it serves


Global
Presence
Norway
Canada
United Kingdom
Russia
Italy
Cyprus
United States
Qatar
China
South Korea
Saudi Arabia
UAE
India
Ghana
Nigeria
Brunei
Malaysia
Republic of Congo
Tanzania
Brazil
Angola
Mozambique
Australia
16 000
EMPLOYEES
20+
COUNTRIES
50+
LOCATIONS
AkerSolutions

40多年的漂浮式基础设计经验

1972

37 × H3 Semis

1989

Veslefrikk

1991

Snorre TLP

1995

Heidrun TLP

1996

Genesis Spar

1997

Norne FPSO

1999

Laminaria

2000

Åsgard A

2001

Snorre B

2005

White Rose FPSO

2007

Blind Faith

2008

2 x Aker H6e

2010

Gjøa

2011

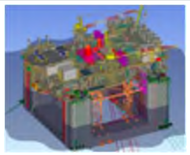
Skarv FPSO

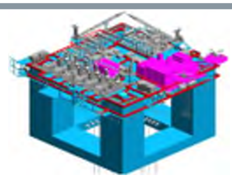
2012

Ichthys Semi & FPSO

2012

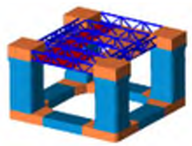
Aasta Hansteen SPAR

2012

Hadrian North Semi Concept

2013

Buckskin Semi Concept

2014

Castberg Semi/FPSO

2016-Ongoing

Jansz Compression

160+ 漂浮式基础

世界上60 %+ 半潜式基础

KBeFloater 设计软件 2005

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动态电缆工程实例 Dynamic Power Cables

GirRI (安哥拉)

- Water depth: 1500m
- Manufactured: Q2 2014
- Installed: Q1 2016
- Cables: 3x300mm^2 18/30kV
- Length: 12km single helix

Goliat (挪威)*

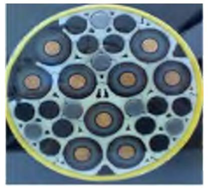
- Water depth: 370m
- Manufactured: Q3 2013
- Installed: Q2 2014
- Cables: 4x1600mm2 6/10(12)kV
- Length: 1750m

Ichthys (澳大利亚)*

- Water depth: 250m
- Manufactured: Q3 2014
- Installed: 2015
- Cables: 3x500mm^2 18/30kV
- Length: 5000m, dynamic in both ends

Cascade & Chinook (美国墨西哥湾)

- Water depth: 2700m
- Manufactured: 2010
- Installed: 2014
- Cables: 9x150mm^2 12/20kV
- Length: 3km



the design is tuned to meet a high weight to outer diameter ratio to avoid clashing with neighboring risers and are operating in **harsh environment with extreme wave and current conditions.*

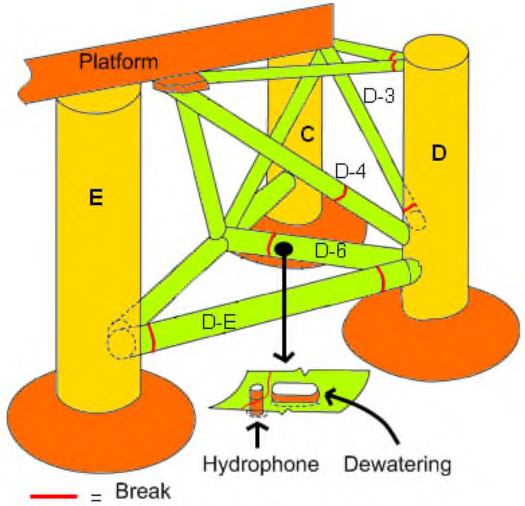
Plan for presentation

- Background
- Fatigue analysis procedure
- Structural and wave modelling for a prototype jacket structure
- Sensitivity analysis of the fatigue life influenced by the numerical and modelling parameters
- Statistical and frequency check of the structure’s response
- Recommendations and conclusions for modelling and analysis practice

Fatigue Accidents

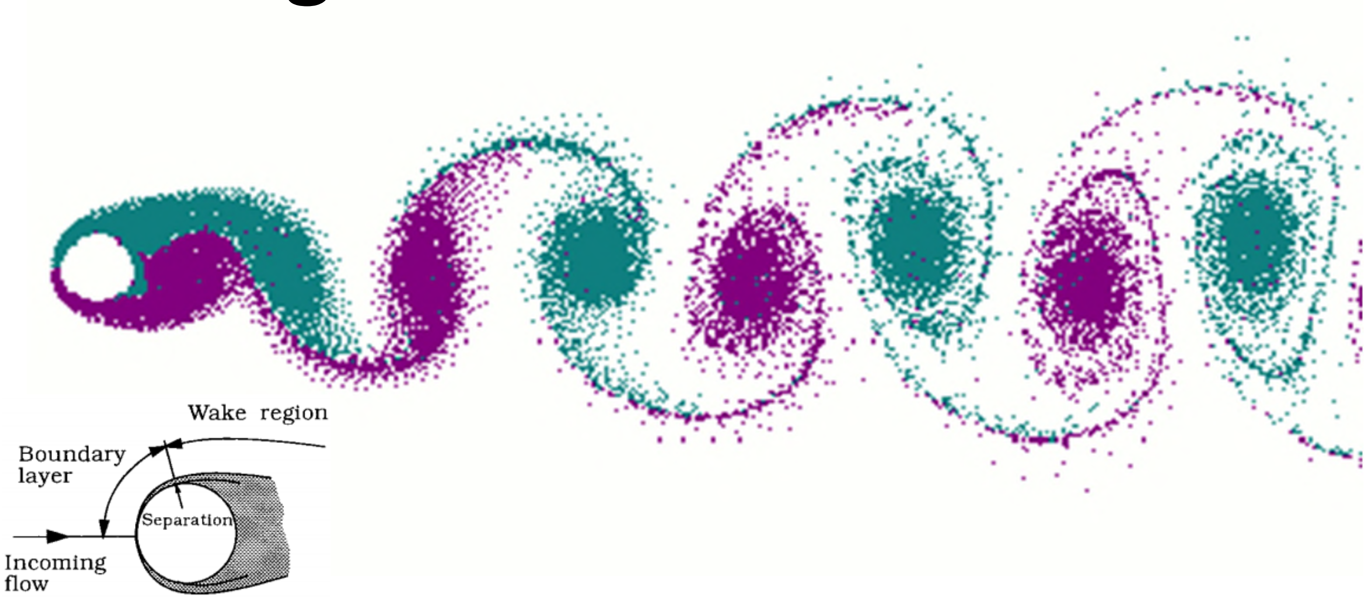
Eschede accident, 3rd of June 1998, speed before crash: 200 km/h, 102 dead, 88 injured, cracks in the wheel tire on the first middle car caused by vibrations

Capsizing of *Alexander Kielland* , 1980, 123 dead, fatigue of brace –> loss of column –> flooding into deck –> capsizing



Sinking of *MS Estonia* occurred on 28th of September 1994, 852 dead, fatigue of bow door visor locking devices due to repeated bow wave loadings

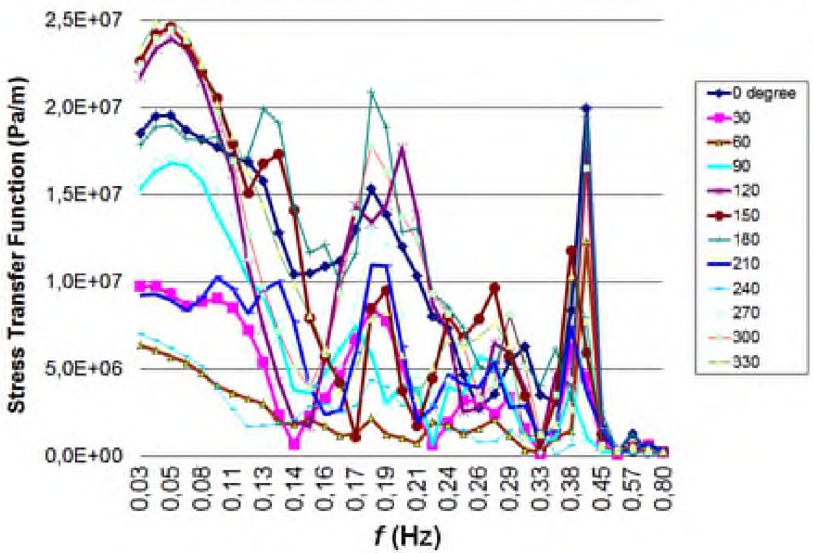
Fatigue due to Vortex Induced Vibration

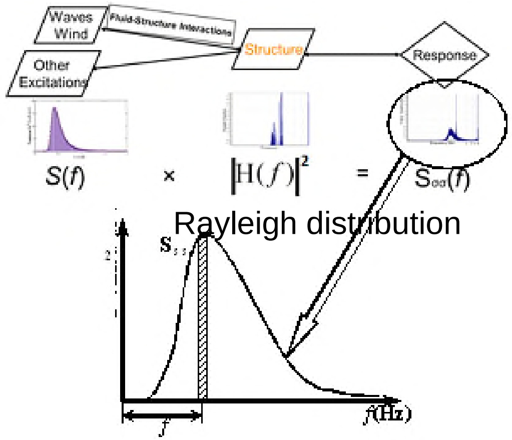


Severe vibrations have been reported on several flare booms in the North Sea - the actual vibration amplitude was up to 20 times higher than the one from the model testing of individual members

Stochastic Fatigue Analysis of Gullfaks C

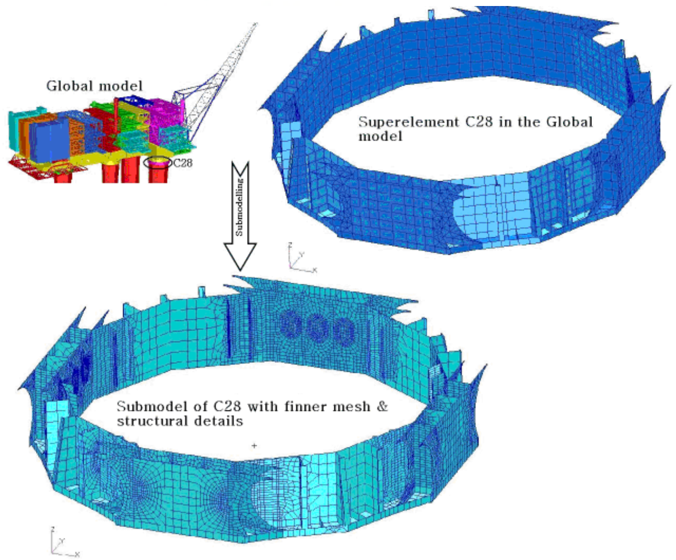
Modulus of principal stress transfer function at shell element surface



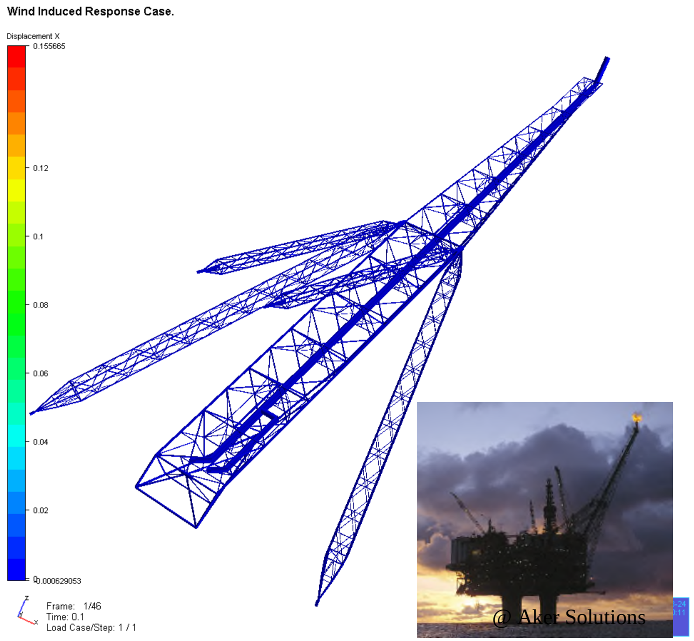


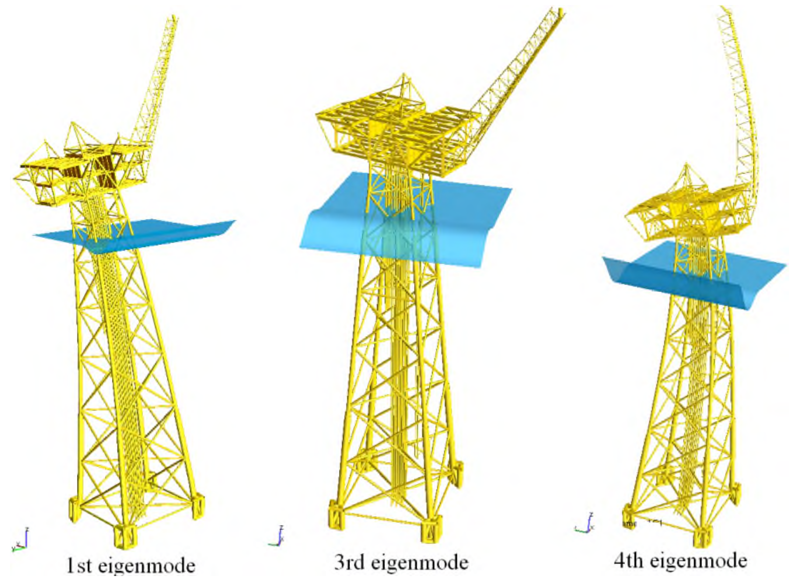
$$D_{j,q} = \frac{\tau(8\lambda_0)^{\frac{m}{2}}}{A}\cdot\sqrt{\frac{\lambda_2}{\lambda_0}}\cdot\Gamma\left(\frac{2+m}{2}\right)$$

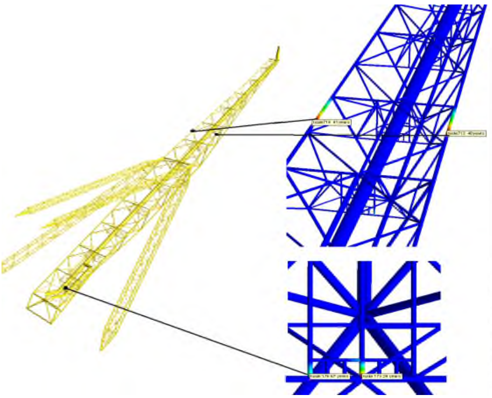
$$D_{total} = \sum_j \sum_q \left(\Psi_{j,q}\cdot D_{j,q}\right)$$

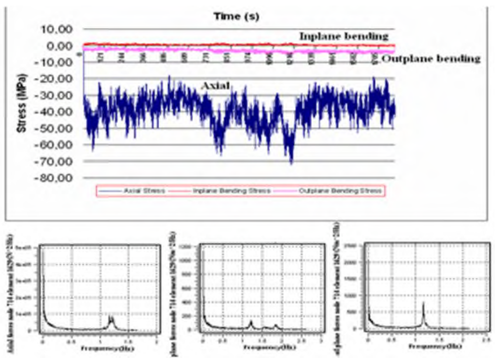


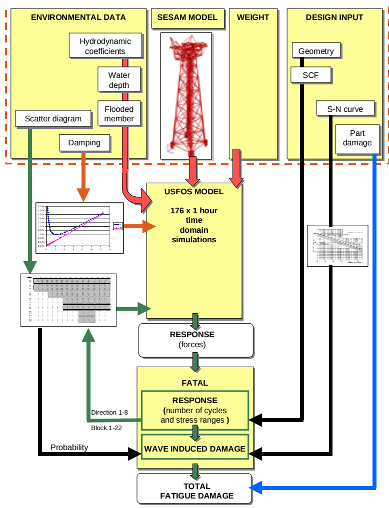
Wind and Wave Induced Fatigue – Nonlinear dynamics











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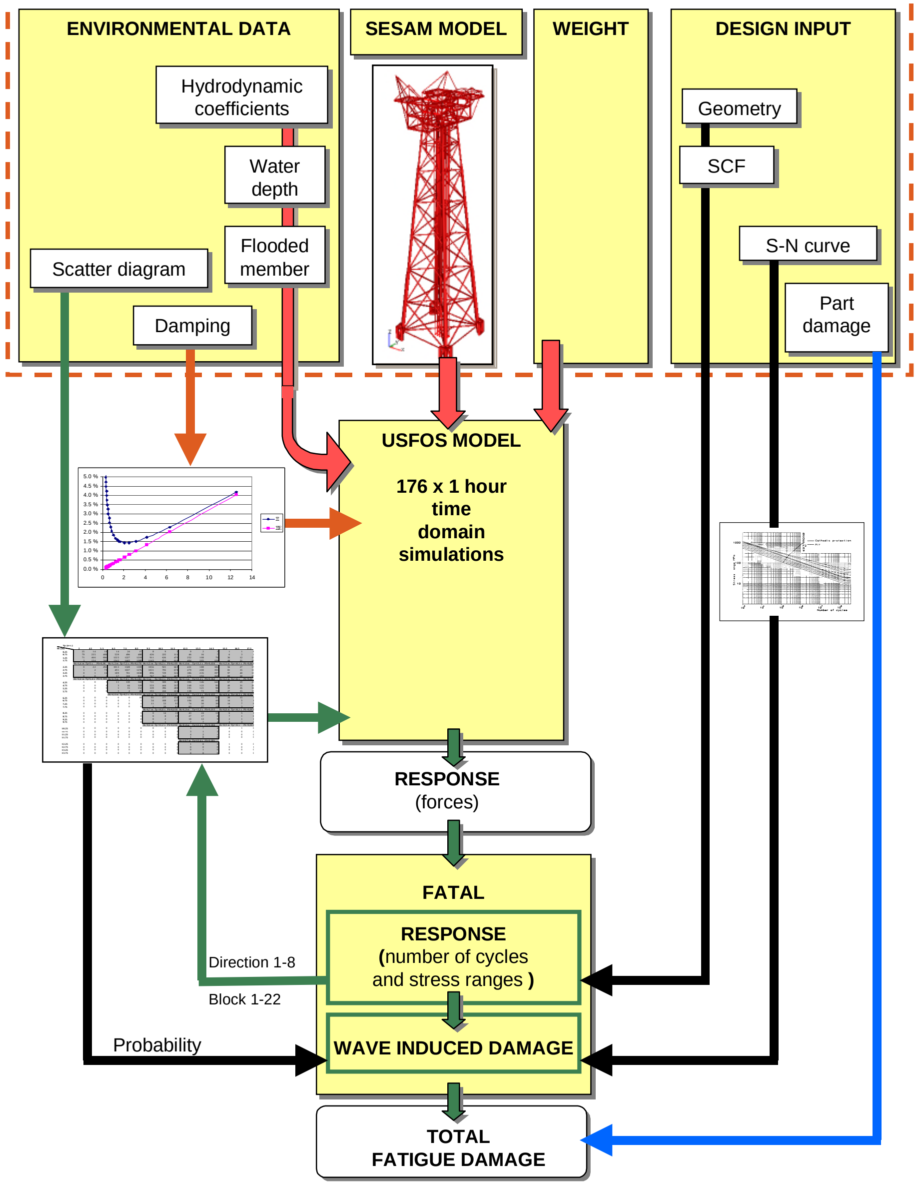
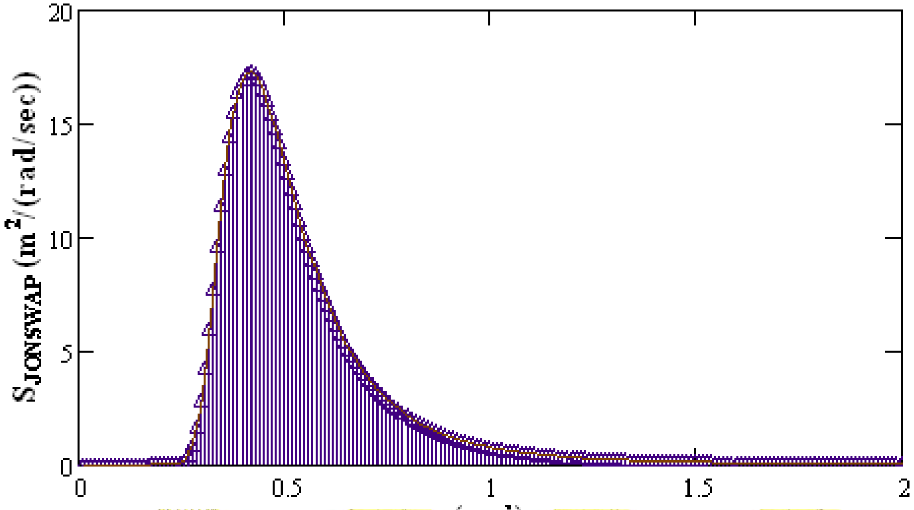
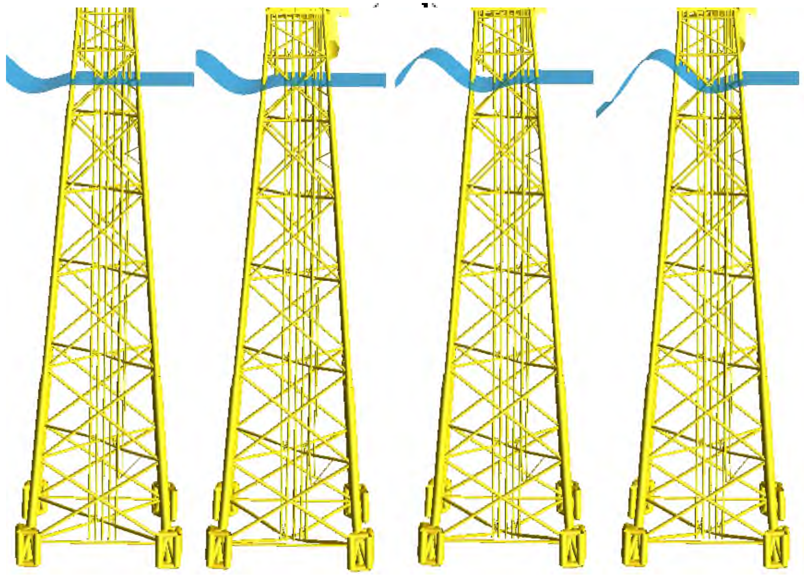
Analysis procedure



Wave descriptions



$$S_{JONSWAP}(\omega) = \frac{A}{\omega^5} e^{-\frac{D}{\omega^4}} \cdot \gamma^{\delta}$$



$$\xi(x,t) = \sum_{n=1}^{N} a_n \cos(k_n x - \omega_n t + \gamma_n)$$

$$a_n = \sqrt{2\Delta S(\omega_n)}$$

Wave statistics

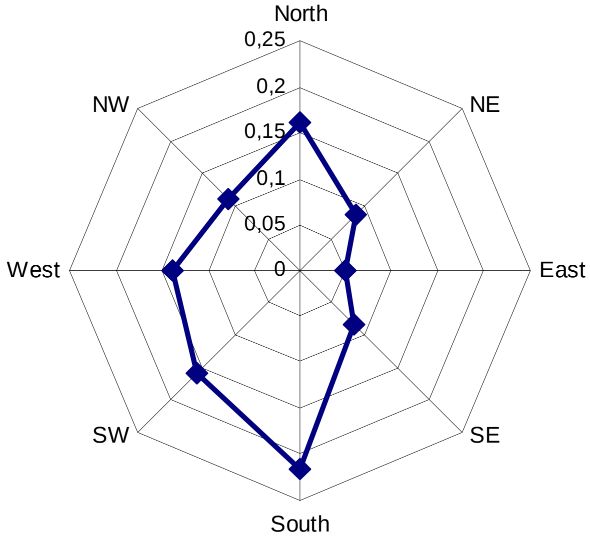
Table 2
Scatter diagram divided into 22 blocks (duration: 3 h)

H_s (m)	T_p (s) 2	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20>	
0.25	25	14	18	14	24	17	8	9	5	0	2	3	1	1	6	2	0	7	156
0.75	79	235	408	539	496	488	426	225	111	46	16	7	6	3	2	0	2	17	3106
1.25	71	466	896	1223	1227	1219	911	626	470	252	108	70	36	12	13	2	2	49	7653
1.75	3	134	768	1342	1443	1288	1143	854	618	404	205	129	44	21	10	3	4	21	8434
	H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b				
	1.4 m	5 s	0.06	1.5 m	7.5 s	0.178	1.5 m	10.3 s	0.103	1.6 m	13.1 s	0.024	1.5 m	16.1 s	0.003				
2.25	0	22	292	1013	1328	1359	1056	921	669	431	188	186	56	27	17	5	1	16	7587
2.75	1	2	79	491	1037	1276	1031	795	678	479	208	193	81	35	13	3	2	8	6412
3.25	0	1	16	189	701	1038	896	729	532	386	235	197	97	40	15	4	1	5	5082
3.75	0	0	3	57	318	814	767	562	447	371	193	168	89	50	17	3	0	3	3862
	H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b				
	2.4 m	5.4 s	0.008	2.9 m	7.8 s	0.184	3 m	10.3 s	0.173	3.1 m	13.2 s	0.062	3.2 m	16 s	0.01				
4.25	1	0	1	11	130	568	731	500	341	306	146	142	67	29	25	4	3	2	3007
4.75	0	0	0	3	44	329	533	444	337	248	122	95	40	31	20	2	4	1	2253
5.25	0	0	0	1	15	112	339	396	280	195	121	98	31	26	16	5	2	0	1637
5.75	0	0	0	1	4	46	193	244	224	138	73	70	27	15	15	3	0	1	1054
				H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b				
				4.6 m	8.3 s	0.024	4.9 m	10.4 s	0.087	4.9 m	13.2 s	0.033	4.9 m	16.2 s	0.007				
6.25	0	0	0	0	0	18	91	177	156	125	65	51	20	15	7	1	2	2	730
6.75	0	0	0	0	1	1	34	108	137	106	46	40	14	5	1	2	0	0	495
7.25	0	0	0	0	0	1	11	53	93	74	50	30	14	7	8	0	1	0	342
7.75	0	0	0	0	0	0	1	29	61	63	27	19	6	3	1	1	0	1	212
							H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b				
							6.7 m	10.8 s	0.018	6.9 m	13.2 s	0.013	6.8 m	16.1 s	0.002				
8.25	0	0	0	0	0	1	0	14	31	43	24	13	6	5	1	0	0	0	138
8.75	0	0	0	0	0	0	0	8	19	27	17	8	7	1	0	0	0	0	87
9.25	0	0	0	0	0	0	0	2	5	18	13	9	2	1	1	0	0	0	51
9.75	0	0	0	0	0	0	0	1	2	7	7	4	3	3	0	0	0	0	27
							H_s	T_p	P_b	H_s	T_p	P_b	H_s	T_p	P_b				
							8.6 m	11.2 s	0.002	8.8 m	13.2 s	0.004	8.9 m	16 s	0.001				
10.25	0	0	0	0	0	0	0	0	3	3	7	4	4	1	0	0	0	0	22
10.75	0	0	0	0	0	0	0	0	0	3	1	2	0	0	0	0	0	0	6
11.25	0	0	0	0	0	0	0	0	0	4	2	1	0	0	0	0	0	0	7
11.75	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
										H_s	T_p	P_b							
										10.7 m	13.4 s	0.001							
12.25	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	2
12.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
13.25	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
13.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
										H_s	T_p	P_b							
										12.8 m	13.0 s	0.00004							

Wave statistics

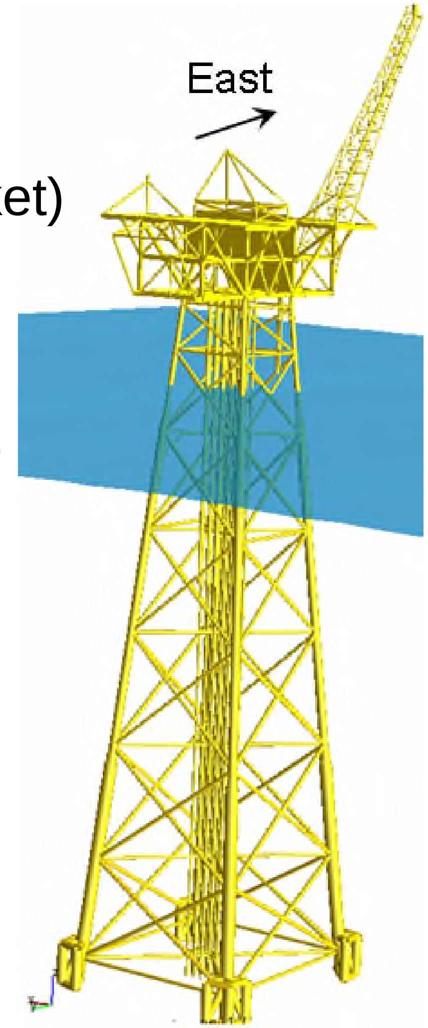
Block	H_s [m]	T_p [s]	P_b	Block	H_s [m]	T_p [s]	P_b
1	1.4	5.0	0.060	12	4.9	10.4	0.087
2	**1.5**	**7.5**	**0.178**	13	4.9	13.2	0.033
3	**1.5**	**10.3**	**0.103**	14	4.9	16.2	0.007
4	1.6	13.1	0.024	15	6.7	10.8	0.018
5	1.5	16.1	0.003	16	6.9	13.2	0.013
6	2.4	5.4	0.008	17	6.8	16.1	0.002
7	**2.9**	**7.8**	**0.184**	18	8.6	11.2	0.002
8	**3.0**	**10.3**	**0.173**	19	8.8	13.2	0.004
9	3.1	13.2	0.062	20	8.9	16.0	0.001
10	3.2	16.0	0.010	21	10.7	13.4	0.001
11	4.6	8.3	0.024	22	12.8	13.0	0.00004

The wave directional probability



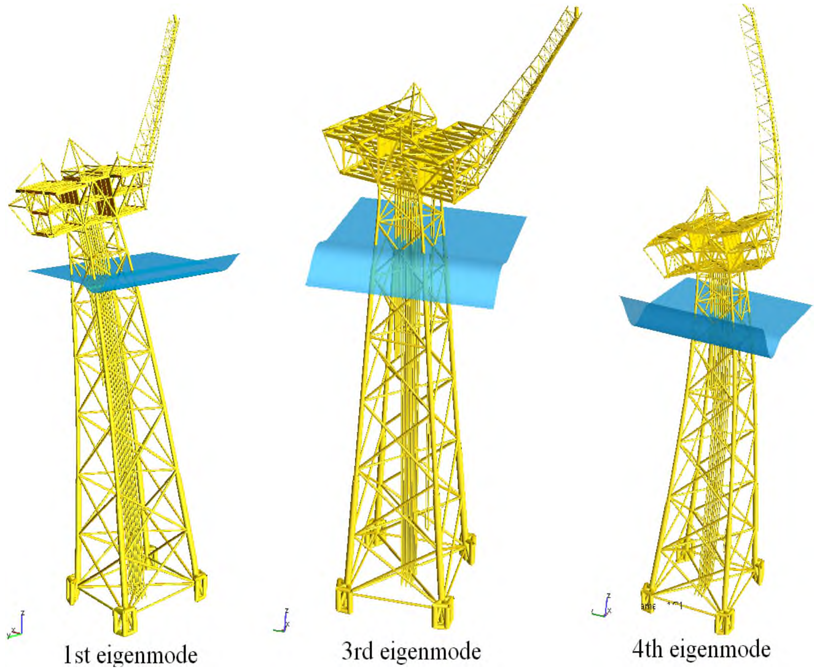
Jacket structure modelling

- Height (jacket part): 181 m
- Water depth: 157.35 m
- Weight: 12904 tonnes (topside) and 7100 tonnes(jacket)
- Material: steel
- 1789 beam elements model
- Structure-ground connections: linear springs (Norsok)
- Marine growth
- Splash zone
- Buoyance effects
- HHT-α method for time integration
- SCF: Efthymiou equations



Eigen-analysis

Mode number	*Eigen-period (s)*	*Remarks*
1	4.173	The first global flexural vibration along the east-west direction (Y).
2	4.115	The first global flexural vibration along the south-north direction (X).
3	2.454	The first global torsional vibration mode.
4	1.193	A global flexural vibration along the east-west direction.
5	1.189	A local vibration of centralizer on the topside.
6	1.091	A global flexural vibration along the south-north direction
7	1.018	A local vibration at the horizontal frames at EL -150 m.
8	0.990	A global flexural vibration along the south-north direction
9	0.940	A local vibration of centralizer
10	0.902	A global flexural vibration along the east-west direction



Parameters for investigation

1.

	γ	Directional wave effects	At the dominant wave direction
Eigen-analysis	2	Yes	N=**30**, 40, 60, 120, 240
			Time step length Δt=0.1 s, 0.2 s, **0.25 s,** 0.5 s, 0.75 s
			Significant wave height
			Modal wave period
	4.1	Yes	N=**30**

2. Soil-structure flexibility

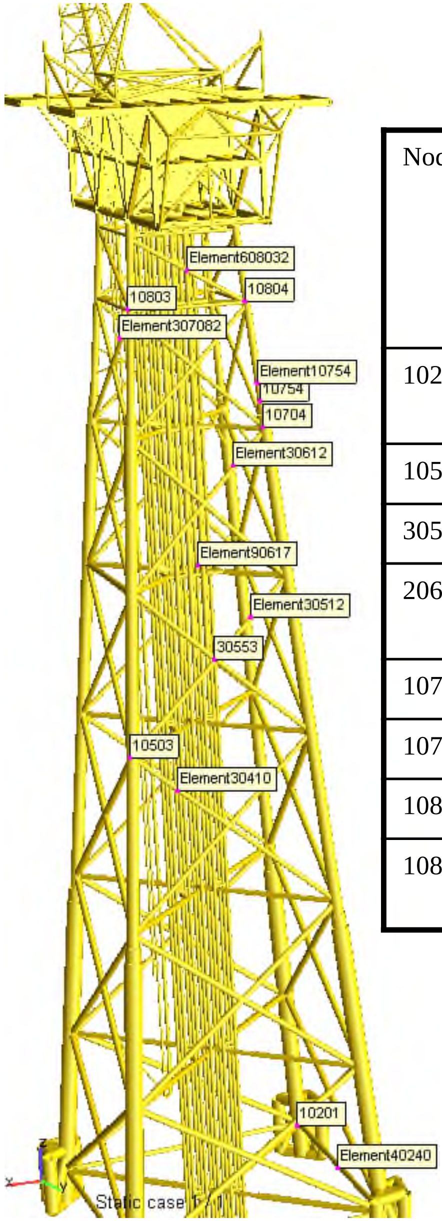
3. Structural inertia effects

4. Statistical and frequency check of the structural response

5. Gravity effects

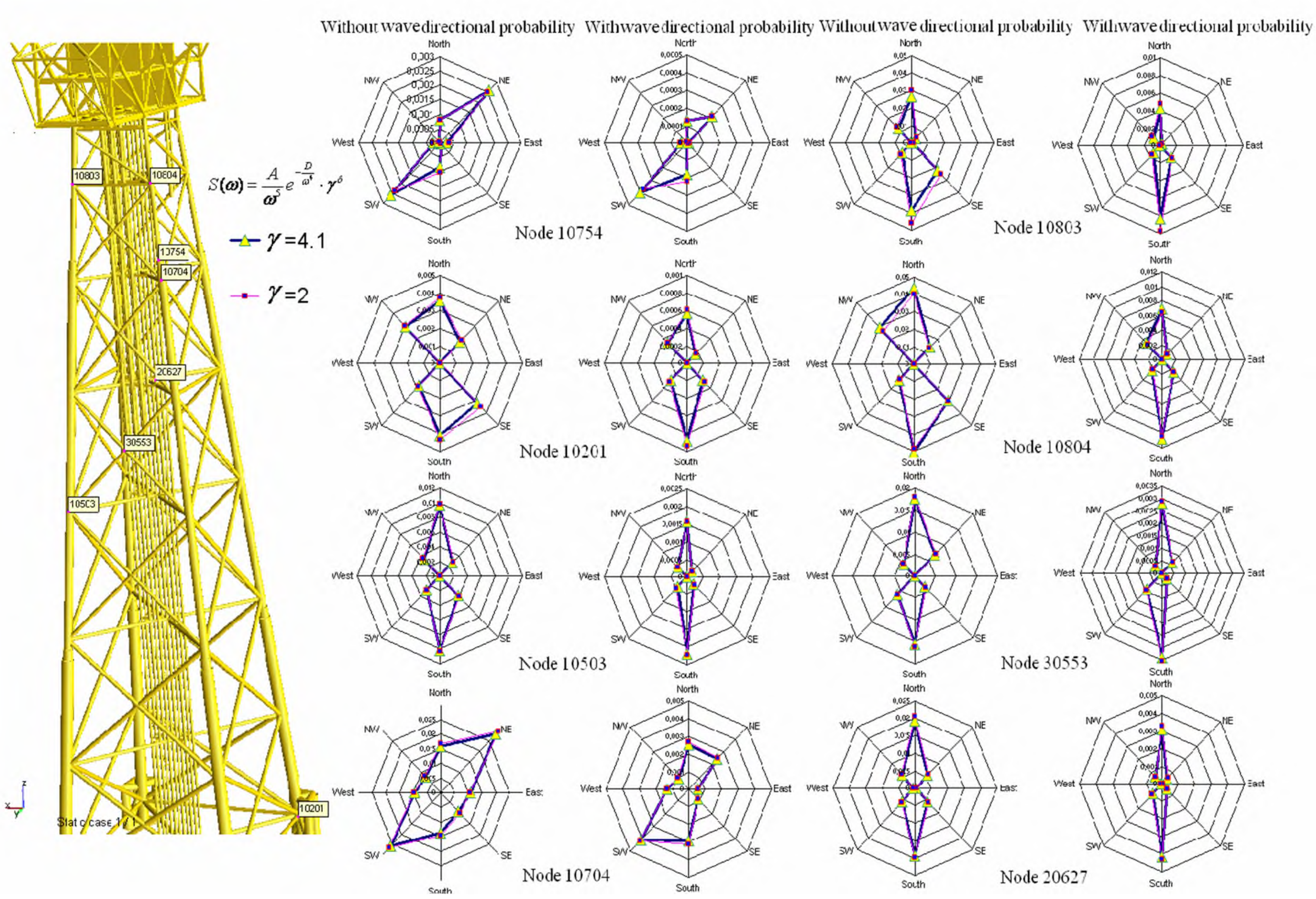
6. Natural period

The fatigue life calculations

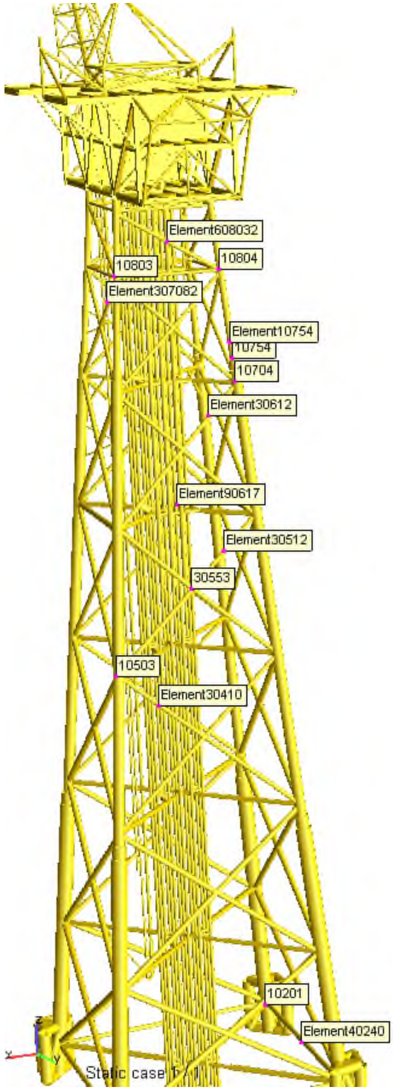


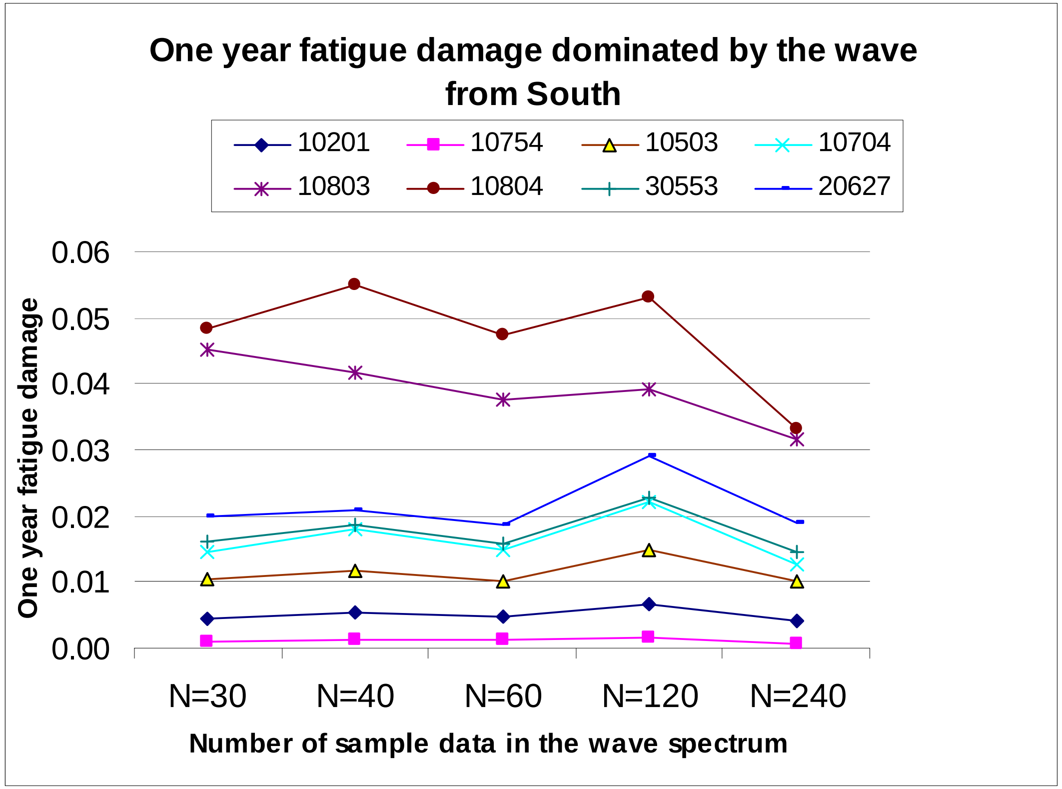
Node number	Brace (element number)	Elevation (m)	Position description	Fatigue life (years)	
				γ=2 (N=30, Δt=0.25 s)	γ= 4.1 (N=30, Δt=0.25 s)
10201	40240	- 150	A leg joint at the bottom	443	468
10503	30410	- 93	A leg joint	197	202
30553	30512	- 78	A face joint	115	119
20627	90617	- 63	conductor support	101	105
10704	30612	- 36	A leg joint	73	76
10754	10754	- 35	A leg joint	1031	1047
10803	307082	- 11	A leg joint	52	60
10804	608032	- 11	A leg joint	40	37

Influence from the wave enhancement and the wave directions



Influence from the number of sample inputs *N*

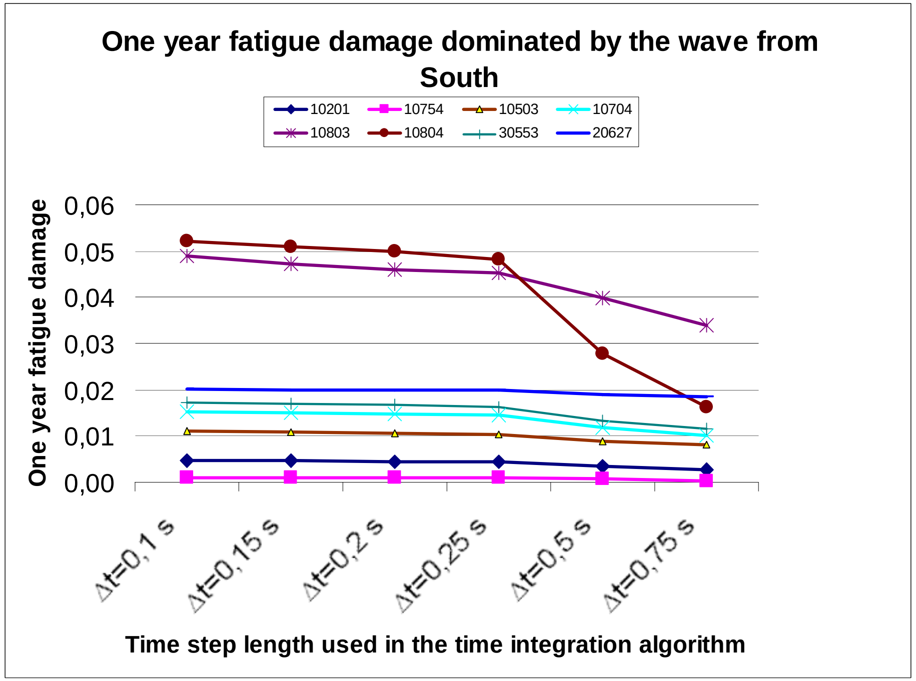




- The trend of the variation of the fatigue damage due to the variation of the sample inputs *N* can not be identified.

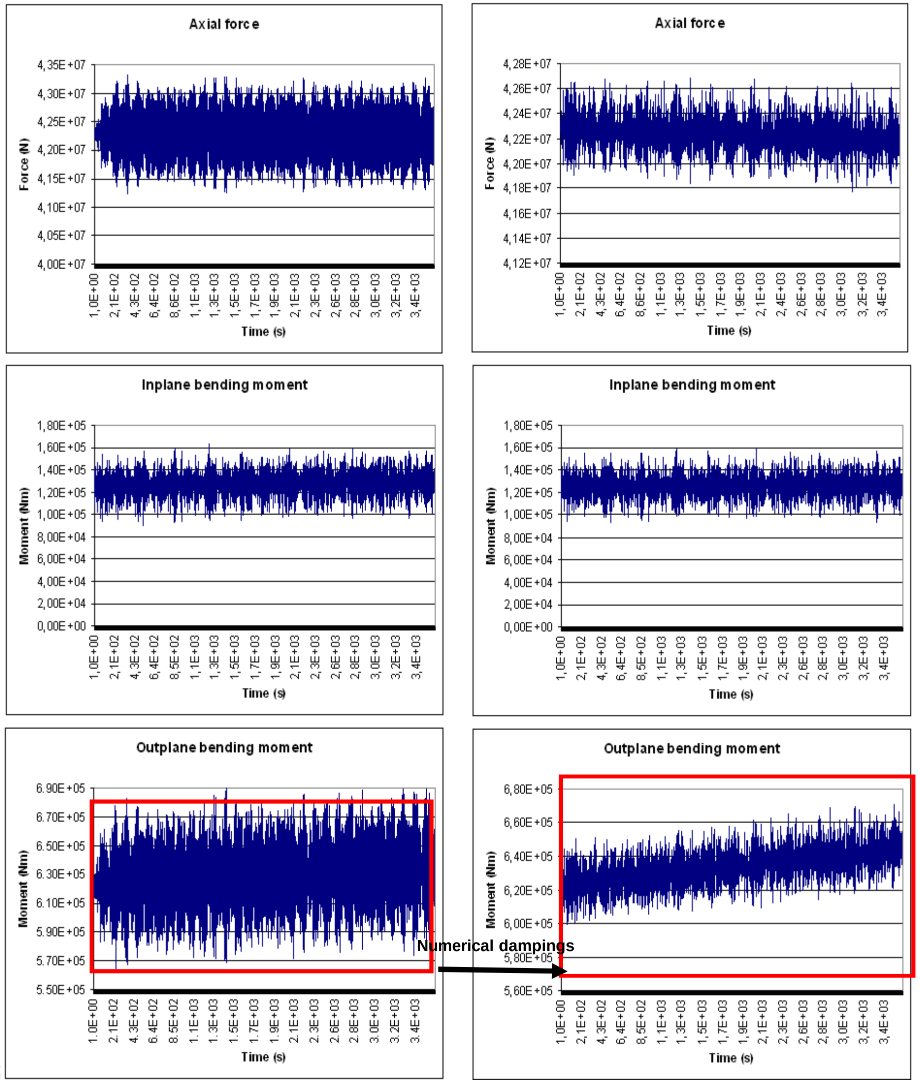
- The ratio of total computation time for *N*= 30, 40, 60, 120, and 240 is 1 : 1.07 : 1.18 : 1.47 : 2.09.

Influence from the time step length



Joint 10754, Hs=2.4 m *Tp*=5.4 s

Deltat = 0.25 s ***Deltat = 0.75 s***

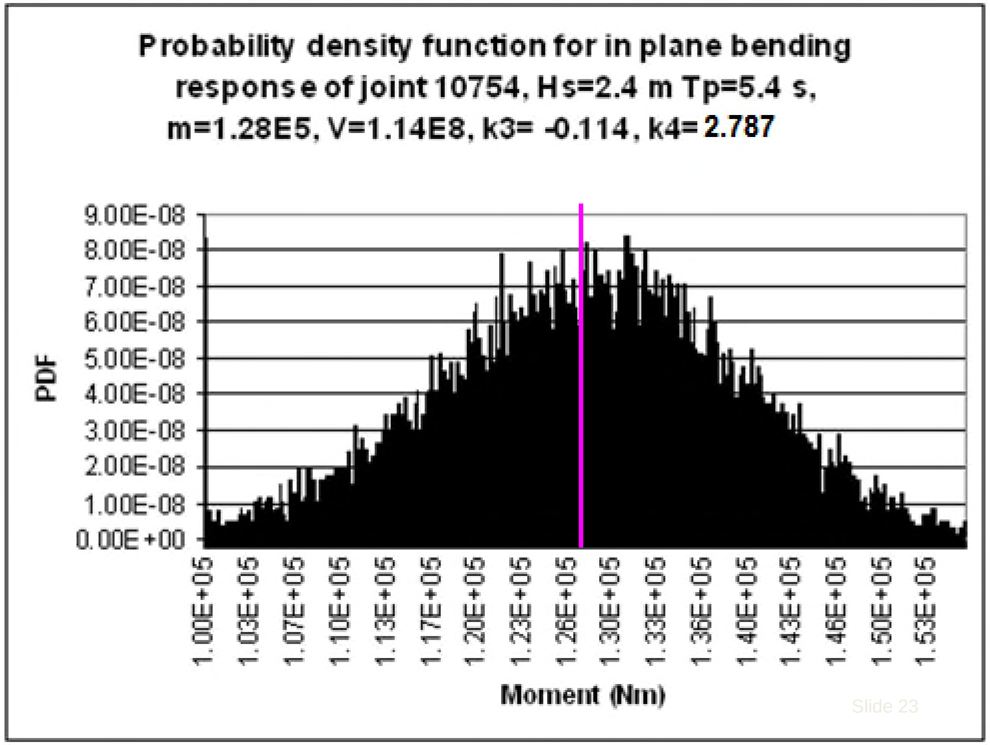


”Rule of thumb” for deciding time step:

Fixed offshore structures: 10% × min (T_{Sm},T_{Lm})

Statistical check of the structural response

	Hs=2.4 m T_p=5.4 s (block 6)			***Hs*=4.6 m T_p=8.3 s** (block 11)			*Hs*=6.7 m T_p=10.8 s (block 15)		
	Axial force	In plane bending	Outplane bending	Axial force	In plane bending	Outplane bending	Axial force	In plane bending	Outplane bending
V(resp)	2.00E+11	1.14E+08	5.73E+08	2.98E+11	6.50E+08	6.98E+08	1.67E+11	1.36E+09	6.69E+08
K3（偏度）	-0.00125	-0.1136	0.03366	-0.0158	-0,0493	0,044997	-0.14341	-0.17397	0.024856
K4(峰度)	1.88289	2.78655	2.10527	2.00316	3.944466	2.27622	*4.152773*	*4,223641*	*4.675471*

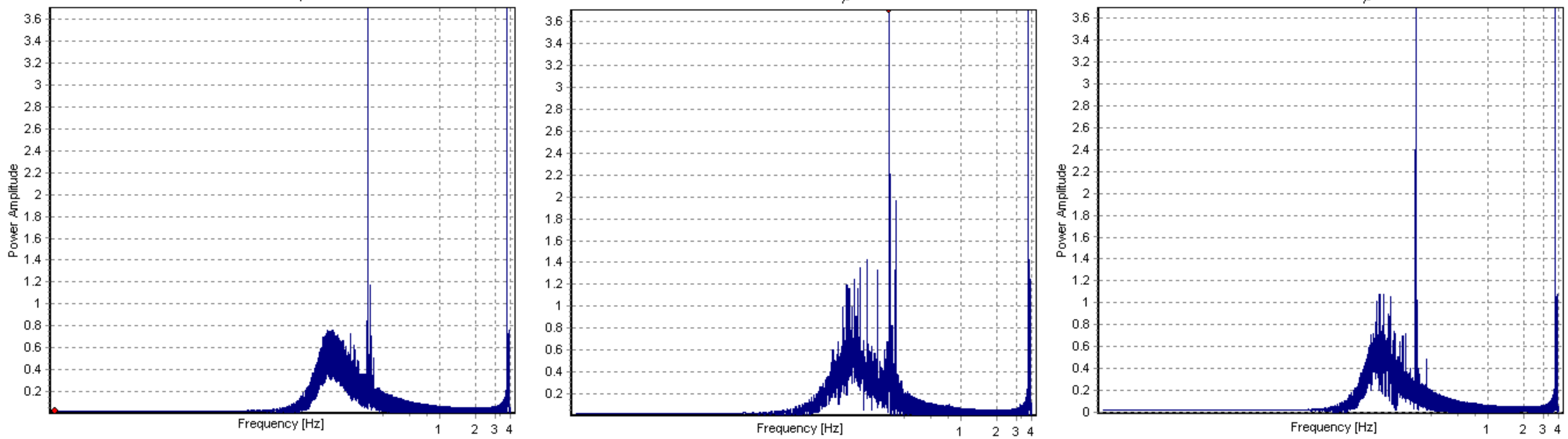


- Slight nonGaussian distribution is observed due to the nonlinear effects, dampings and numerical noises.
- The fatigue damage is directly related to the variance of the structural response.

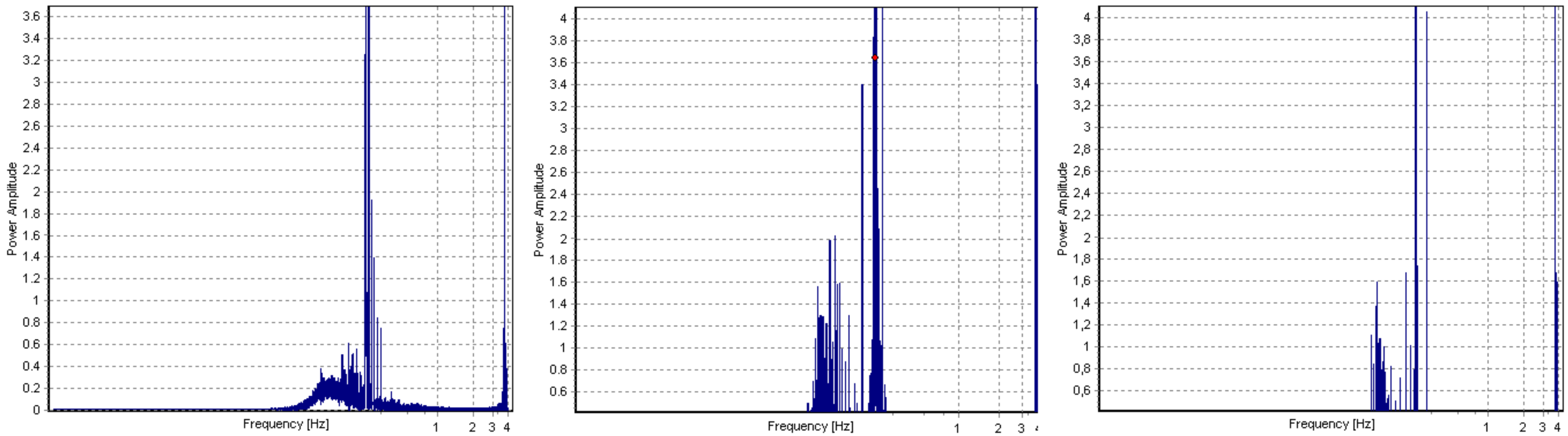
Check in the frequency windows

Node 10754

Hs=2.4 m T_p=5.4 s Hs=6.7 m T_p=10.8 s Hs=4.6 m T_p=8.3 s

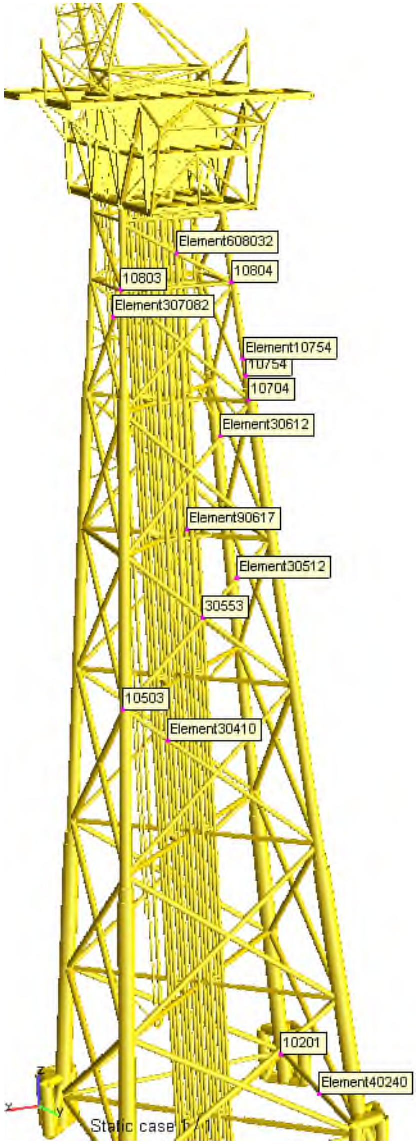


Axial force



Outplane bending moment

Influence from the soil-structure flexibility and the inertia effects



Joint number	Elevation (m)	Fatigue life (years)		
		Consider both the soil-structure flexibility and the inertia effects	The bottom of the jacket is fully fixed	Ignoring the inertia effects of the structure
10201	- 150	711	NA	3849
10503	- 93	283	335	554
30553	- 78	162	178	392
20627	- 63	155	166	187
10704	- 36	94	94	131
10754	- 35	2335	1540	2.47×10^{6}
10803	- 11	55	56	74
10804	- 11	65	42	119947

- For a first estimation, the structure-soil connection can be modelled as rigid for soft jacket structures

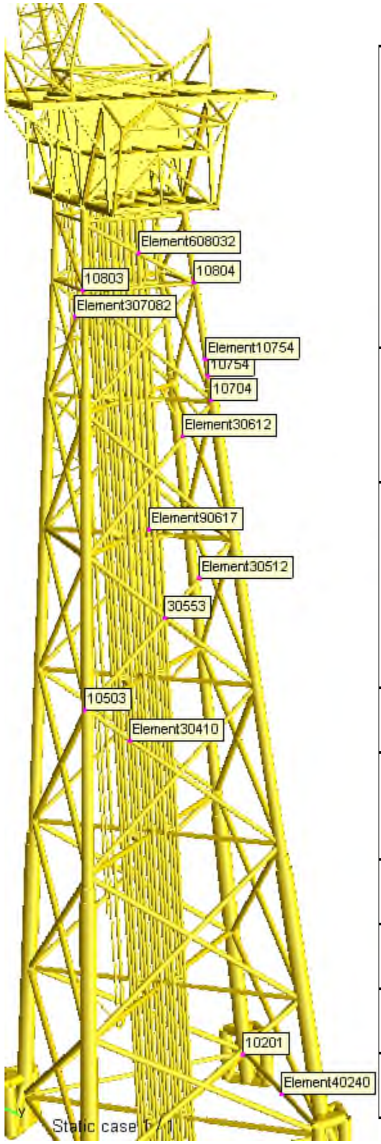
- The inertia effects are significant on the fatigue damage

Influence from the selfweigtht induced load – calculated eigenfrequency

- Stress stiffening effects

Mode number	Eigenperiod (s)		
	With gravity	Without gravity	Diff. (%)
1	4.173	4.120	1.3
2	4.115	4.065	1.2
3	2.453	2.442	0.4
4	1.203	1.194	0.7
5	1.193	1.187	0.5
	NA	1.152	NA
6	1.090	1.086	0.4
7	1.014	NA	NA
8	0.990	0.987	0.3
9	0.914	0.939	2.7
10	0.902	0.901	0.1

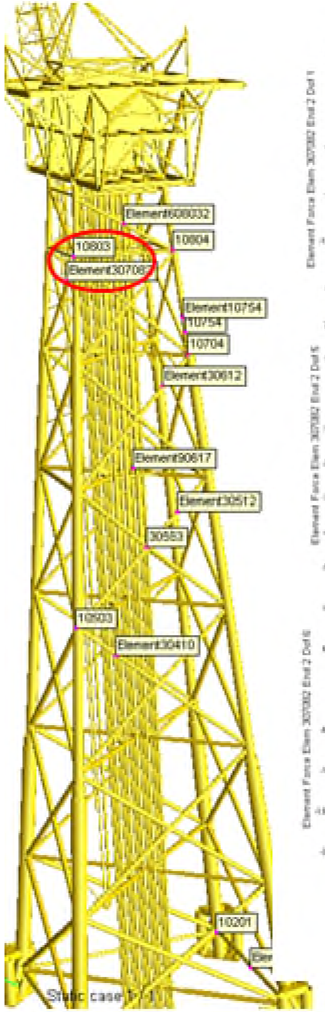
Influence from the gravity – results



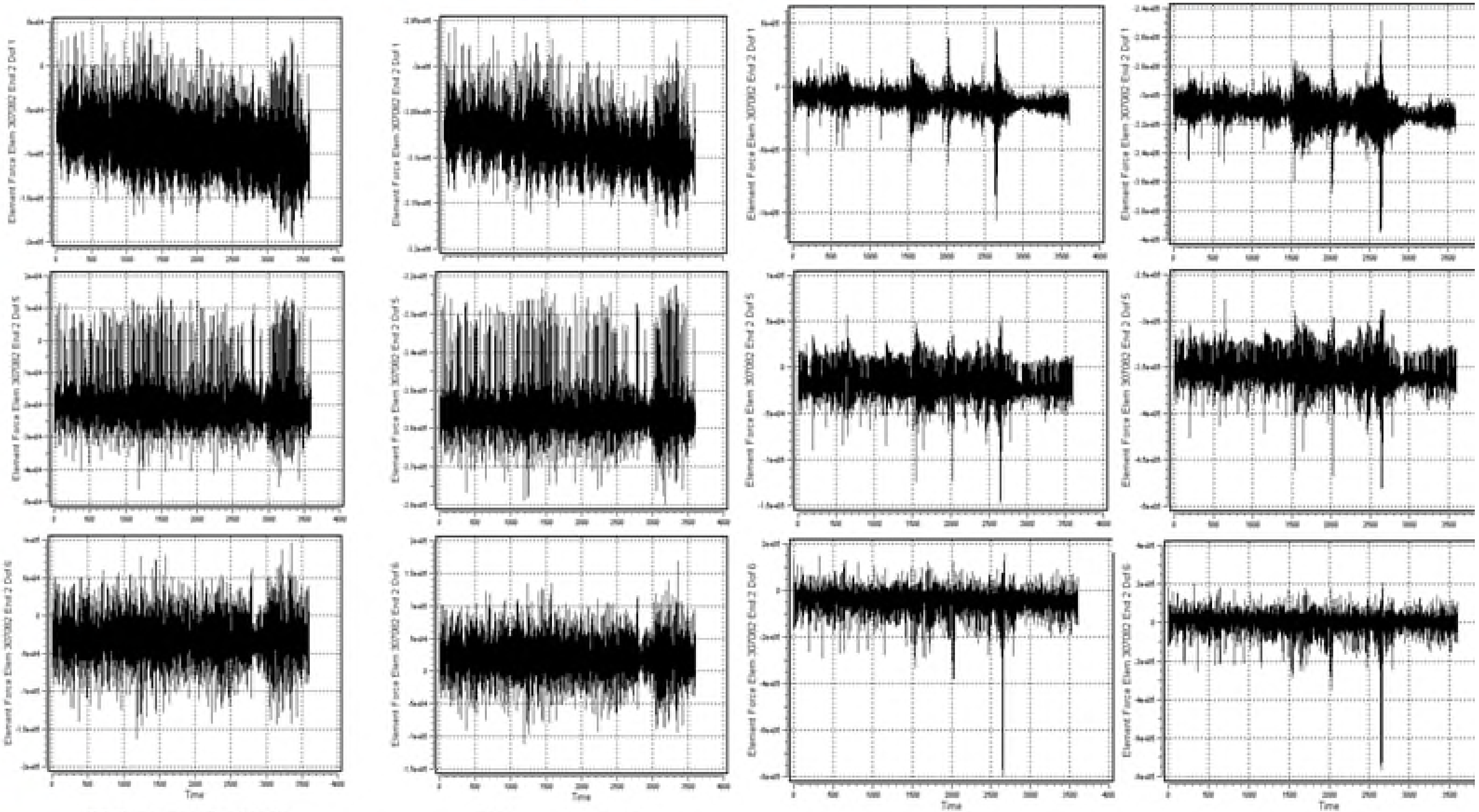
Node number	Position description	Fatigue life (years)		
		With selfweight	Without Selfweight	Error
10201	A leg joint at the bottom	443	525	19%
10503	A leg joint	197	185	-6%
30553	A face joint	115	110	-4%
20627	A conductor support	101	117	16%
10704	A leg joint	73	70	-4%
10754	A leg joint	1031	1015	-2%
10803	A leg joint	52	58.3	12%
10804	A leg joint	40	41	3%

- The ignorance of the platform’s selfweight is likely to underestimate the the fatigue damage to some extent.

Influence from the selfweight induced load – response time series



Mild sea state: H_S=2.9m, T_p=7.8s   High sea state: H_S=8.8m, T_p=13.2s



Without gravity loads   With gravity loads

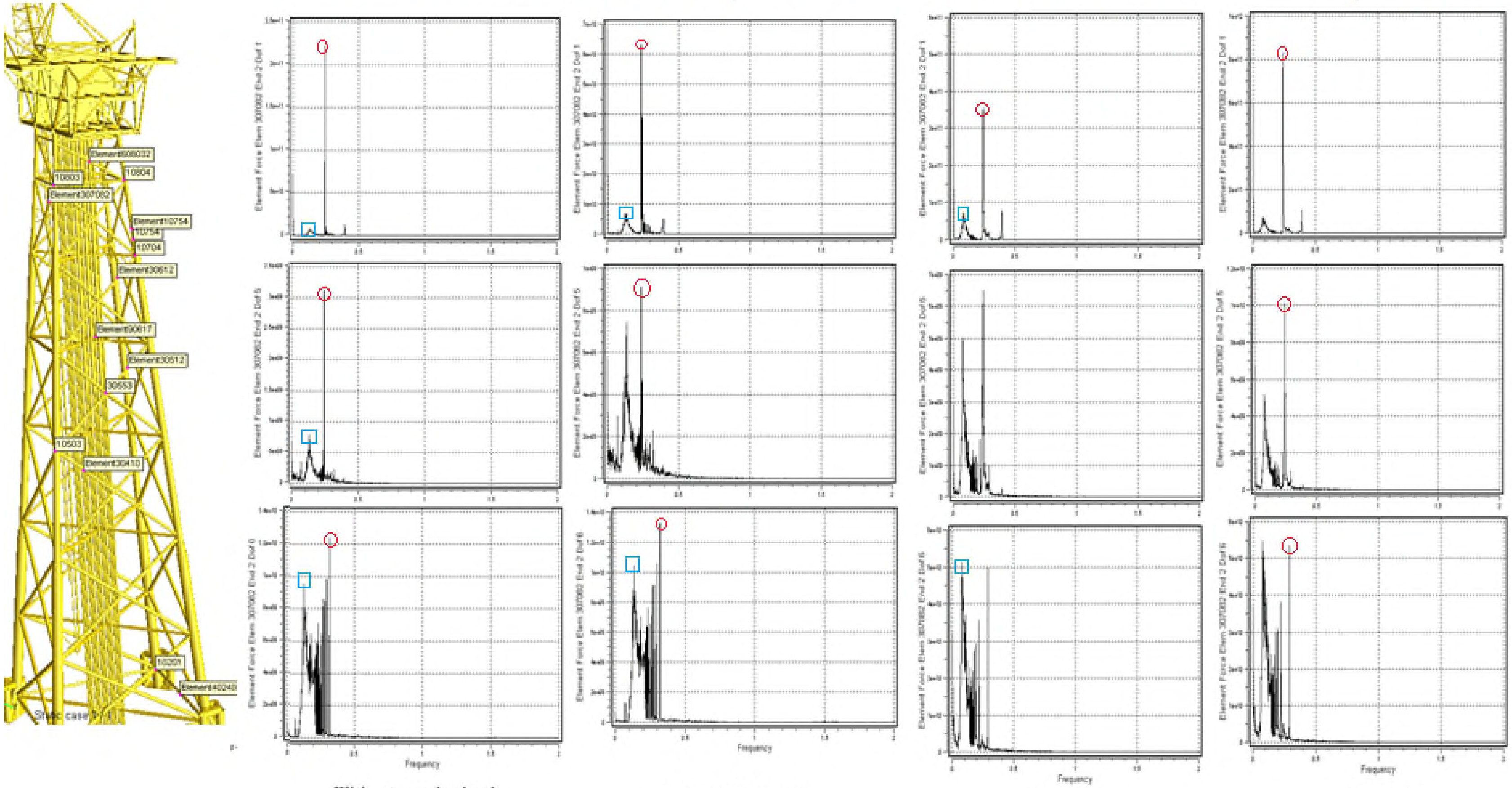
for sea state block 7 (Hs=2.9m, Tp=7.8s)

Without gravity loads   With gravity loads

for sea state block 19 (Hs=8.8m, Tp=13.2s)

Influence from the selfweight induced load – responses in frequency domain (joint 10803)

Mild sea state: H_s=2.9m, T_p=7.8s   High sea state: H_s=8.8m, T_p=13.2s



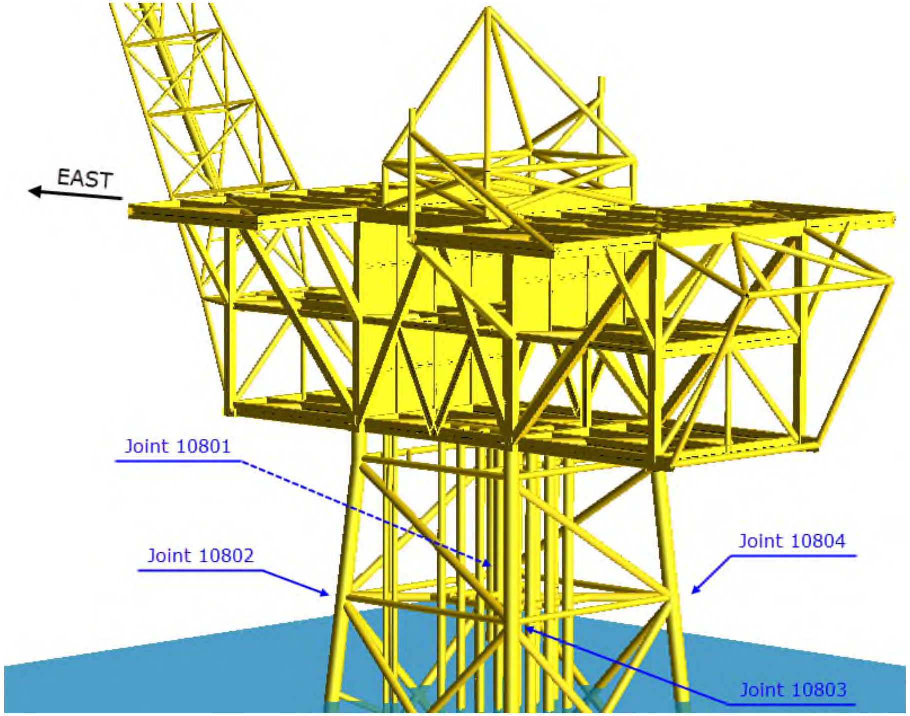
Without gravity loads   With gravity loads   Without Selfweight   With Selfweight

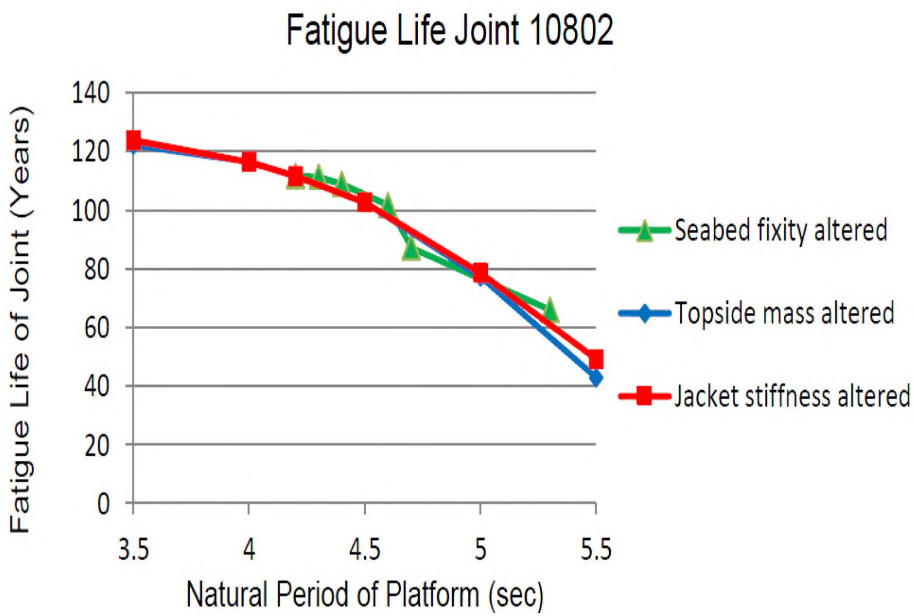
Gravity loads effects	Low Sea state	High Sea State
Axial force	Decrease	Significantly increase
In-plane bending	Decrease	Significantly increase
Out-of-plean bening	Increase	Slightly increase

Influence from the selfweight induced load – responses statistics

Joint 10803		With gravity load			Without gravity load		
Sea State	Items	Axial force (N)	In plane bending (N·m)	Outplane Bending (N·m)	Axial force (N)	In plane bending (N·m)	Outplane Bending (N·m)
Hs=2.9m, Tp=7.8s	m	-3.08E+06	-3.55E+05	2.03E+04	-8.35E+04	-1.89E+04	-3.18E+04
	k2	8.35E+08	5.89E+07	8.75E+08	1.22E+09	6.92E+07	8.17E+08
	k3	3.90E-01	1.35E+00	-2.08E-01	2.46E-01	1.28E+00	-2.70E-01
	k4	7.41E-01	5.89E+00	9.49E-01	2.95E+00	5.37E+00	9.63E-01
Hs=8.8m, Tp=13.2s	m	-3.11E+06	-3.53E+05	-1.16E+03	-1.05E+05	-1.55E+04	-4.81E+04
	k2	9.18E+09	3.33E+08	3.59E+09	7.58E+09	3.11E+08	3.37E+09
	k3	-5.59E-01	-1.77E-01	-2.24E+00	-7.76E-01	-2.08E-01	-2.33E+00
	k_4	8.47E+00	4.60E+00	4.49E+01	11.44E+00	4.72E+00	4.59E+01

Wave Induced Fatigue – Trend of fatigue life estimate varying with natural frequency





Source: Aker Solutions and City University, London

Contributions and conclusions

- Present a practical procedure for calculating fatigue: capable of capaturing nonlinear and non-Gaussian phenomenon.
- Wave spectrum inputs are efficient: fatigue damage is not sensitive to the number of sample frequency points *N*.
- Fatigue damage is not sensitive to the variation of wave peak enhancement.
- Suggestions on how to decide a decent time step length.
- Slight non-Gaussian response is observed for even inertia dominated response.
- Self-vibration may in a lot of case contribute to the fatigue significantly.
- For fixed offshore structures: fatigue damage is highly influenced by the waves with low modal period.
- Hydrodynamic coefficients defined in Norsok 2007 leads to significant higher fatigue life for inertia dominated offshore structures.
- Variation of drag force coefficient has less influence on the fatigue damage than the inertia coefficient.
- Soil-structure flexibility variation does not significantly influence the critical fatigue damage for the target structure.
- The structural inertia effects are rather significant.
- Ignoring the selfweight of the platform is unconservative to some extent.

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