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Evaluating the Loading and Structural Response of an Offshore Platform Using Integrated Large and Small Scale Testing Combined With Diffraction and Finite Element Analysis and Offshore Measurements

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Abstract

After discussing the specific roles of model tests, simulations and offshore (full scale) measurements for the evaluation of offshore structures in general, the paper applies this integrated methodology to the investigation of the loading and structural response of the South Arne platform with the aim of extending the platform's capabilities. The South Arne platform deck is supported by a combination of a large volume concrete Gravity Based Structure (GBS) and a slender steel lattice structure. This resulted in a unique project, including the novel combination of small scale tests of the complete structure (GBS and lattice tower) with large scale component testing of parts of the lattice tower to limit and quantify scale effects on these slender members. The paper discusses the different phases (and scales) of model testing and also highlights the related Finite Element (FE) and diffraction calculations and offshore (full scale) measurements.

INTRODUCTION

In the process of evaluating an offshore structure during its design or while in operation, model tests, simulations and offshore (full scale) measurements all clearly complement one another (Figure 1). All three have their specific roles, strengths and limitations [1] which are summarised below.

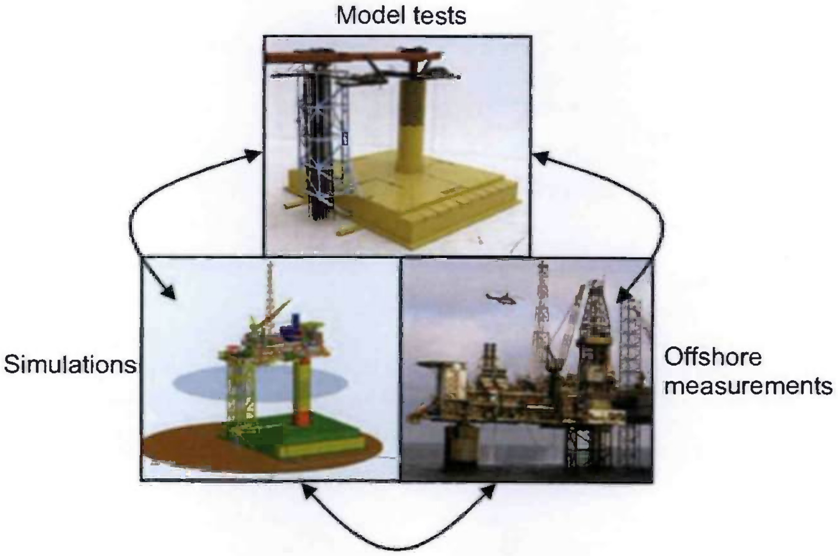


Figure 1 Combined model tests, simulations and offshore measurements to evaluate the South Arne Platform

The contribution of *model tests* is important because model tests:

a. Give reliable predictions of the loads on (and global motion response of) offshore structures.
b. Generate results for the validation of numerical tools and QA/QC of (complex) numerical models.
c. Provide a feasibility check for the system or operation.
d. Guarantee a complete modelling of the relevant physics (including all interactions).
e. Are carried out in a well-defined environmental input of wind, waves and current.
f. Allow the generation of limiting sea states, to see whether a structure is able to survive in the most difficult situations.

However, model tests need to be complemented by numerical simulations and full scale measurements because:

a. Structural elasticity and response is (generally) not modelled (in detail) or simplified for practical reasons.
b. Scale effects can play a role in some cases [2-4].
c. They are only carried out in a limited number of conditions for practical reasons.
d. Only a limited number of measurements are possible for model tests. It is also difficult to quantify fluid behaviour in detail at multiple points whereas this can be easily extracted from numerical simulations.
e. Model tests do not always explain 'why' things happen. Tests show the system behaviour in detail, but only when the physics behind certain behaviour can be described (in models); it is possible to understand why things happen.

Simulations on the other hand are important because they:

a. Allow the modelling of the detailed structural response of the structure.
b. Support the understanding of the complex hydrodynamics.
c. Are able to deliver relatively fast predictions of the behaviour of offshore structures and more readily permit extensive investigations into parametric sensitivities.
d. Allow a check of many different environmental and operational conditions. This can be used to define the critical conditions for the model tests, but also to define the responses and loads of structures as part of response based design methods.
e. Have (almost unlimited) visualisation and analysis capabilities. It is possible to show aspects that cannot easily be measured or visualised during tests.
f. Offer predictions such as fatigue lives, say.
g. Can model potential damage scenarios and their consequences.

However, numerical simulations cannot be used separately because:

a. Numerical models only include known effects. Where model tests and full scale measurements sometimes show real -but unexpected- physical behaviour, the behaviour of numerical models is always a result of physics that are known and described. The fact that something does (not) occur in a numerical simulation does not guarantee that it does (not) happen in reality.
b. Related to the above, it will be clear that each numerical model has its limitations. The important effects of viscosity cannot be described for instance in detail yet. Important parameters in the numerical simulations consequently need to be estimated or tuned with model tests.
c. Numerical simulations, with their impressive visualisation possibilities, sometimes give the impression of more reliability than is justified.
d. Numerical problems in the solution techniques can have a significant effect on the output, which sometimes cannot be detected easily.
e. QA/QC of increasingly more complex numerical modelling remains a significant challenge and an independent means of verification is required.

Finally the contribution of *full scale measurements offshore* is vital as they:

a. Offer exact prototype behaviour.
b. Allow a feedback to predictions from model tests and numerical simulations.
c. Give input to future projects.
d. Can be used for decision support during the present operation.

However, they cannot be used on their own because:

a. They cannot give predictions for the present project in the design stage, but can only give feedback.
b. At full scale the environment cannot be controlled, so that the structure cannot be tested in survival conditions such as a 100 year storm.
c. The input of wind, waves and current is sometimes not well defined, for instance as a result of the interference of the offshore structure itself with the measurement.
d. Only a limited number of measurements are possible because of costs and practical aspects (no measurements in critical working areas).
e. The accuracy and reliability of full-scale measurements can be influenced by the large size of the loads, the difficulty to take reference values (zero values, position reference) and external aspects (temperature, damage, etc).

Based on these points it will be clear that model tests, simulations and offshore measurements are complementary and need to be used in combination to come to a reliable evaluation of an offshore structure.

As an example of such integrated use, the present paper presents the overall methodology as it has been developed to investigate the loading and response of the South Arne platform (with Hess Denmark as Operator). The South Arne platform deck is supported by a combination of a large volume concrete Gravity Based Structure (GBS) and a slender steel lattice structure. It was installed in 1999 in the Danish sector in 60m water depth. A further analysis of the platform was initiated by Hess to verify the structural performance of the platform in its operational condition with the aim of extending the platform's capabilities which includes, *inter alia*, more reliable fatigue life predictions. The original structural behaviour was determined based on a Finite Element (FE) model including Morison wave loads with standard hydrodynamic coefficients. This method is widely used when designing fixed offshore structures. However, there is a need for a more accurate representation of the wave loading than those recommended in the standards. Therefore, model tests, simulations and offshore measurements are used in an integrated way to determine the reliability of the applied models with respect to the fluid loading and hydrodynamic shielding in particular. This resulted in a unique project, including the novel combination of small scale tests of the complete structure (GBS and lattice tower) with large scale component testing of parts of the lattice tower to limit scale effects on these small slender members.

Figure 2 South Arne Platform in the Danish sector at 60 m of water depth

The present paper presents the overall novel project methodology. It is currently intended that results of the overall investigation will be presented at a later stage.

OVERALL PROJECT METHODOLOGY

If we consider the South Arne Platform from a hydrodynamic loading and structural response point of view, we see the following combination of aspects:

- Non-linear high waves in moderate water depth (significant wave heights from 2.0m to 8.5m were investigated).
- Wave loads on a large-volume GBS (with concrete tower) in moderate water depth.
- Jacket-type lattice structure with slender members and risers/conductors (compared to the wave length), subject to Morison-type [2, 10] drag and inertia loads.
- Possible scale effects and interaction effects can play a role in the wave loading on the lattice structure (including marine growth and the effect of anodes).
- Effects of the large-volume GBS on the waves and wave kinematics at the lattice structure through diffraction and refraction effects.
- Structural response of a unique portal frame-like structure.

This combination of aspects requires and justifies a specific approach to the problem which uses model tests, simulations and offshore measurements.

Four series of model tests are carried out in this process:

- *Small scale tests of the GBS and lattice tower combined.* These give insight in overall wave loading and loading on specific parts of the structure in realistic waves, including the effects of wave diffraction around the column, wave refraction due to the base structure and interaction effects between the members in the lattice structure.
- *Small scale tests of the lattice tower only.* These excluded the effect of the GBS, which is in fact the conventional way the wave loads on the tower are considered in the Morison approach in the FE modelling.
- *Large scale tests of a section of the lattice tower.* These give insight into shielding effects in the loading (neglected in the FE modelling) and provide results of drag and added mass effects (C_D and C_M values) for selected parts of the lattice structure with minimum scale effects.
- *Small scale tests of the same section of the lattice tower.* These are used as a way to quantify the scale effects between the tests in general. They are a bridge between the small scale tests and the large scale tests.

The simulations carried out consist of two components:

- *Finite Element modelling.* FE modelling is carried out in a number of stages: from the overall structural evaluation of the complete platform to detailed analysis of the wave loads on specific parts that were used during the testing. This FE analysis provides detailed structural response and stresses, but does not include shielding, makes use of empirical drag and inertia coefficients and assumes a simplified (undisturbed) wave field.
- *Diffraction modelling.* Linear diffraction modelling of the GBS only is used to determine the disturbed wave field and wave kinematics.

Finally the extensive offshore (full scale) measurements give a confirmation of actual stresses at specific locations and the dynamic responses as a result of the (measured) waves, but no direct insight in the wave loading. In Table 1 the overall perspective of the key issues that are needed to evaluate fatigue lives, for example, are presented. These issues are:

- Insight in wave loading (excitation)
- Forces in the structure
- Influence of the GBS and the concrete tower
- Scale effects
- Effects of marine growth and anodes
- Structural response of the total platform
- (Local) stresses in the structure
- Final prediction of fatigue lives

Although there is some overlap, it is clear from Table 1 that a combination of all approaches is needed to evaluate the issues involved.

Key Issues	**Offshore measure-ments**	**Small Scale Tests**	**Small Scale Lattice only**	**Small Scale Section**	**Large Scale Section**	**FE analysis**	**Diffraction**
Wave loading	No	Realistic but scale effects	Realistic but scale effects	Oscillation and scale effects	Oscillation	Morison	Diffraction
Forces in structure	Limited local	Global & limited local	Global & limited local	Local section	Global & limited local	Global & Local	Only on GBS and tower
Influence of GBS and concrete tower	Yes	Yes	No	No	No	McCamy Fuchs and estimates	Yes
Scale effects	No	Yes	Yes	Yes	Limited	Empirical data	Limited
Marine Growth & Anodes	Yes	No	No	No	No / Yes	Empirical data	No
Structural response	Yes	No	No	No	No	Yes	No
Stresses in structure	Limited local	No	No	No	No	Yes	No
Prediction of fatigue life	No	No	No	No	No	Yes	No

Table 1 The different methods in light of the key issues that need investigation

In the rest of the paper an overview will be given of all the methods that are applied in this process.

MODEL TESTS

Small scale tests of the GBS and lattice tower combined

These (1:63.2 scale) tests give insight in the overall wave loading and loading on specific parts of the structure in realistic waves, including the effects of wave diffraction around the concrete tower, wave refraction due to the GBS base structure and interaction effects between the members in the lattice structure. Figure 3 gives a global overview of the model.

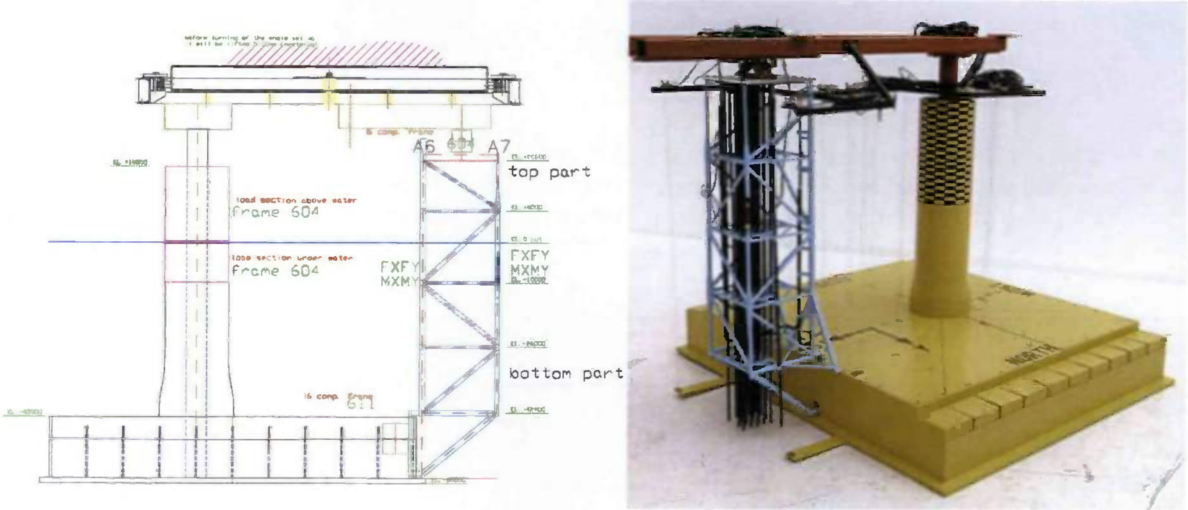


Figure 3 Small scale model of the GBS, concrete tower and lattice tower combined

The concrete tower is rigidly connected to the GBS and the carriage over the basin. Two segments in the concrete tower are instrumented with 6-component frames to measure local wave loads. One segment measures wave loads from -10m to water level. The other segment measures all above water level wave loads. The lattice tower is cut in half at water line level. Loads on the total lattice tower below and above water level are each measured with 6-component frames. Two individual leg member sections of the lattice tower are measured with 4 component force transducers.

The tests are performed in the Shallow Water Basin of MARIN (Figure 4). The Shallow Water Basin has a piston type wave maker at the short side of the basin. The opposite side of the basin is equipped with a beach to absorb the wave energy and minimize the wave reflection. The basin has dimensions of 220m x 15.8m and a maximum water depth of 1.1 m.

The wave board is equipped with a wave board driven by a linear motor for generating regular/monochromatic and irregular/random waves. The online computer facilities for wave board control, data acquisition, and data processing allow for direct control and computation of relevant wave characteristics. Wave energy spectra can be prescribed by using standard or non-standard spectral shape or specific of wave trains.

The shallow water basin has a piston-type wave board including 2nd order wave generation technique. This technique corrects for the differences between the oval shaped motions of the water and the linear motion of the wave board, which may cause unwanted free waves in the basin. The second order wave generation takes into account second order effects of the bound first higher and first lower harmonics of the wave field in the wave board motion.

Figure 4 Shallow Water Basin wave generator

The model is tested with irregular waves to provide the most realistic wave loading. From these irregular sea states also regular waves are derived with periods equal to the peak period of the irregular wave and wave amplitude equal to Hs of the irregular wave. As the objective in the first phase of tests was to focus on loadings relevant to fatigue predictions (i.e. not extreme loads) Hs is chosen instead of Hmax. Table 2 gives an overview of the irregular and regular waves used during the testing [5].

Wave	Hs [m]	Tz [s]	γ	H or Hmax [m]	T or Tp [s]	k	λ [m]
Irregular 1	2.5	5.0	3.3	4.65	6.44	0.097	64.7
Irregular 2	4.0	6.5	3.3	7.44	8.37	0.058	109.0
Irregular 3	2.5	5.5	3.3	4.65	7.08	0.080	78.2
Irregular 4	3.5	6.0	3.3	6.51	7.72	0.068	93.0
Irregular 5	4.5	7.0	3.3	8.37	9.01	0.050	126.1
Irregular 6	7.5	9.0	3.3	13.95	11.58	0.031	200.0
Regular 1				2.0	5.5	0.133	47.2
Regular 2				3.0	6.6	0.092	68.0
Regular 3				4.0	7.5	0.072	87.8
Regular 4				5.0	8.3	0.059	107.4
Regular 5				6.0	9.1	0.049	128.6
Regular 6				7.0	9.8	0.042	148.1
Regular 7				3.5	4.8	0.082	76.5

Table 2 Irregular and regular waves used

A total of 5 different wave directions from PL-E to PL-W are measured to derive the influence of shielding to the wave loading at the concrete tower and lattice tower, see Figure 5. In the basin these directions are achieved by rotating the model. A special rotation frame (with rotation point between lattice tower and concrete tower) was used for this rotation, see Figures 3 and 6.

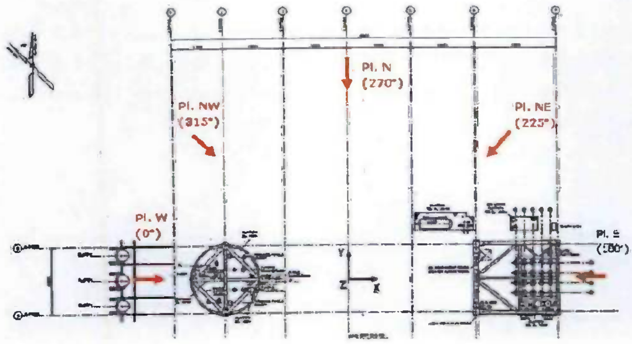


Figure 5 Wave directions tested

Figure 6 Small scale tests of the GBS and lattice tower combined in the basin

In the FE analysis prior to the testing it was found that the conductors have an important influence on the wave loading on the lattice tower. Further it was assumed that the close proximity of the conductors can induce shielding effects that are neglected in the application of Morison equation. Therefore, a number of conductor variations were investigated (see also Figure 7):

- 0 conductors
- 4 conductors (blue dots)
- 8 conductors (blue & red dots)
- 12 conductors
- 19 conductors (as is)
- 20 conductors and an additional riser

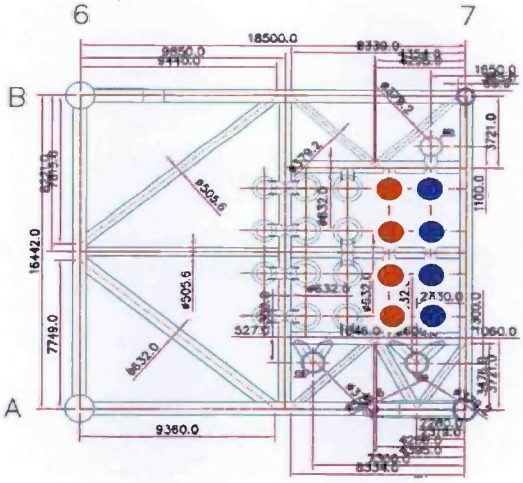


Figure 7 Tests with 4 or 8 conductors

Small scale tests of the lattice tower only

To separate the effect of the GBS and concrete tower from the undisturbed wave loading on the lattice tower, the GBS was removed from the basin at the end of the test program and the lattice tower only was tested (Figure 8). A number of waves were repeated, so that a direct comparison can be made of the wave loads with and without the presence of the GBS and concrete tower. As the situation without the presence of the GBS is in fact the way the wave loads on the lattice tower are considered in the Morison approach in the FE modelling, this insight helps to determine the differential load associated with the presence of the GBS.

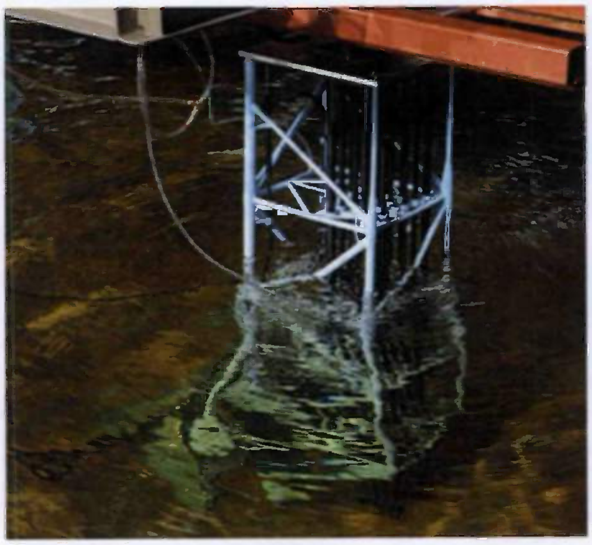


Figure 8 Small scale tests of lattice tower only

Large scale tests of a section of the lattice tower

Although the small scale tests give very important information about the overall loading on the platform and the interaction between the GBS and the lattice tower, there is always the issue of possible scale effects in the loading of slender bodies subjected to oscillating flows (drag and inertia loading) [2].

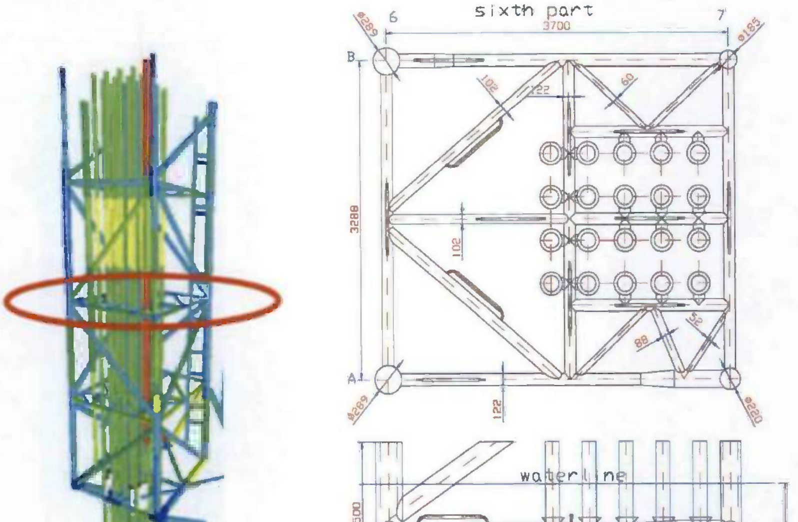


Figure 9 Frame at -10m selected for the large scale tests

The objectives of the large scale tests are therefore to determine drag and added mass effects (C_D and C_M values) for selected parts of the lattice structure, including possible shielding and interaction effects at appropriate Reynolds (Rn) and Keulegan Carpenter (KC) numbers (with limited scale effects).

For this purpose, a part of the lattice tower was selected that is subjected to sufficient wave action and contains both horizontal and vertical members. This was found on the -10m elevation horizontal frame with all vertical leg members and bracings attached, see Figure 9.

Also these tests are carried out in the Shallow Water Basin (at 1.1m of water depth). Above the waterline, the main structural components of the section are connected to a subcarriage of the basin that can be oscillated horizontally. The loads between the subcarriage and the section are measured to determine all inertia and hydrodynamic loads. To check the model and the set-up, the model is first oscillated in air without water in the basin. With this test the inertia forces of the model are measured. These forces are subtracted from the actual measurements in water to derive the actual hydrodynamic loads. Also some tests in current only are carried out to determine the C_D value with constant speed as a reference value.

The size of the model is chosen as large as possible at scale 1:5 to minimize scale effects. In the analysis of the scale effects, the experience in the field of large scale component testing [6-9] has been used.

To determine the required oscillation amplitudes/frequency and influence of scale effects, we will first look at the wave kinematics. The maximum oscillating velocities are determined with:

$$u = \zeta_a.\omega.\frac{\cosh k(h+z)}{\sinh kh}$$

$$w = \zeta_a.\omega.\frac{\sinh k(h+z)}{\sinh kh}$$

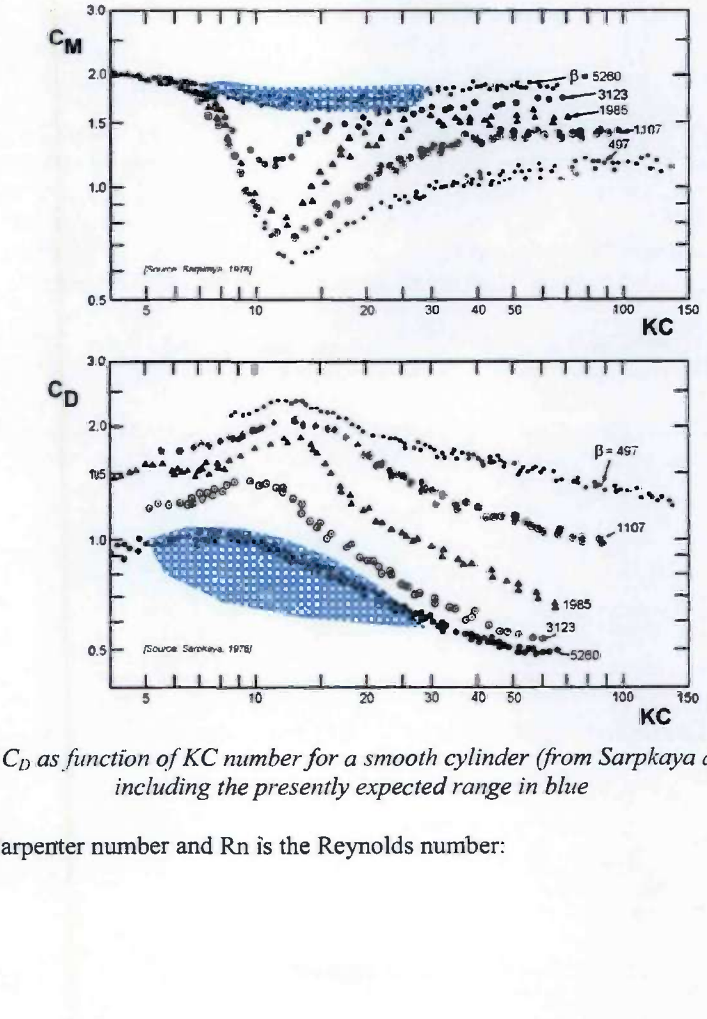
where:			
	u =	horizontal velocity	[m/s]
	w =	vertical velocity	[m/s]
	ζ_a =	wave amplitude	[m]
	ω =	wave frequency	[rad/s]
	k =	wave number	[rad/m]
	h =	water depth	[m]
	z =	vertical distance	[m]

In this formula z is replaced with 0 to calculate the maximum velocities.

The wave loads in the FE model are calculated based on the Morison equation [10]:

$$F(t) = \frac{\pi}{4} C_M.\rho.D^2.\dot{u}_t + \frac{1}{2} C_D.\rho.D.u_t.|u_t|$$

The C_M and C_D factors need to be determined with the model tests. Sarpkaya and Isaacson [2] performed numerous laboratory measurements on smooth cylinders, resulting in Figure 10:



[Source Sarpkaya, 1976]

Figure 10 C_M and C_D as function of KC number for a smooth cylinder (from Sarpkaya and Isaacson [2]), including the presently expected range in blue

where KC is the Keulegan-Carpenter number and Rn is the Reynolds number:

$$KC = \frac{u.T}{D}$$

$$Rn = \frac{u.D}{\nu}$$

Where: T = Wave or oscillation period [s]
D = Cylinder diameter [m]
ν = Kinematic viscosity [m^2/s]

β is calculated as the ratio between Rn and KC numbers:

$$\beta = \frac{Rn}{KC}$$

In Table 3 an overview is given for KC, Rn and β numbers at different scale factors for a typical lattice tower cylinder diameter of one metre and a typical wave condition (Regular wave 2: H=3m, T=6.6s). As can be seen from this Table, β values for the large scale model and the true scale South Arne platform are both well above 5000 and in this way outside the range of the results presented in the above figures from Sarpkaya and Isaacson.

scale	Full 1 : 1	Large 1: 5	Small 1 : 63.2
H	3.0	0.60	0.047
u	1.4	0.64	0.180
T	6.6	2.95	0.830
D	1.0	0.20	0.016
ν	1.19E-06	1.05E-06	1.05E-06
KC	9.4	9.4	9.4
Rn	1200034	121642	2707
b	127324	12907	287

Table 3 Hydrodynamic parameters for typical lattice tower cylinder at different scales for wave 2 (H=3.0m,T=6.6s)

Figure 10 shows that C_M is converging to 2.0 when β is increasing. Therefore it is expected that the large scale test model will predict C_M values quite well. The C_D values do not seem to converge for increasing β values at low KC numbers up to 10. A lower sensitivity for Rn (or β) is expected for the South Arne Lattice Structure than for a smooth pipe due to turbulence effects, shielding effects and roughness effects. This is confirmed by the results presented in Figure 11 using the MARIN's High Reynolds set-up as presented in [5-9]. The Figure presents C_D and C_M values for different smooth and rough pipes at higher Reynolds numbers. The C_M values confirm the convergence at higher β values. For the smooth/bare pipes low C_D values were found, but for rough cylinders the results are more in the range observed by Sarpkaya and Isaacson.

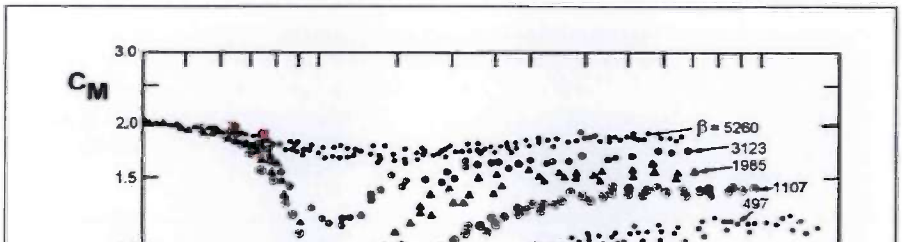


Figure 11 C_M and C_D values found for smooth and rough cylinders using the MARIN's High Reynolds set-up [5-9].

The present large scale tests are carried out to investigate and quantify this further:

- Measurements are carried out in the basin moving the carriage with the model at a constant speed through the still water at different speeds to determine the influence of Rn on the C_D value for the modelled section of the Lattice Structure.
- Oscillation tests are carried out over a range of KC and β (Rn) values.

Table 4 gives the set of oscillating conditions based on the regular waves from the small scale model test.

	Regular wave properties		Oscillating motions (full scale values)		
Wave	H	T	ω	x	u
	[m]	[s]	[rad/s]	[m]	[m/s]
Regular 1	2.0	5.5	1.142	1.000	1.142
Regular 2	3.0	6.6	0.952	1.500	1.428
Regular 3	4.0	7.5	0.838	2.001	1.676
Regular 4	5.0	8.3	0.757	2.504	1.896
Regular 5	6.0	9.1	0.690	3.017	2.083
Regular 6	7.0	9.8	0.641	3.543	2.272
Regular 7	4.8	7.0	0.898	2.400	2.154

Table 4 Oscillating conditions based on small scale regular wave properties (full scale values)

Table 5 shows the full set of oscillating parameters for the measured section of the large scale model (now at scale 1:5). Only the yellow lines (regular waves 2, 4 and 6) are used for the large scale model tests. These 3 regular waves cover almost the full range of wave periods of 6.6 to 9.8 seconds most relevant to fatigue loading. Furthermore 4 conditions are added (green lines) to be able to determine the influence of the KC value and Reynolds number on the measured forces and derived C_M and C_D values. Case 11 and 12 use the oscillating amplitude of regular wave 4 and have different oscillating periods (so only varying the Reynolds number). Case 13 and 14 use the oscillating period of regular wave 4 and have different oscillating amplitudes (so only varying the KC value).

Oscillation	ω	x	u	$\dot{u}$	KC	Rn	β
	[rad/s]	[m]	[m/s]	[m/s^2]	[-]	[-]	[-]
1	2.554	0.200	0.511	1.305	6.3	97313	15488
2	2.129	0.300	0.639	1.359	9.4	121642	12907
3	1.873	0.400	0.749	1.404	12.6	142726	11358
4	1.693	0.500	0.846	1.433	15.7	161212	10263
5	1.544	0.600	0.926	1.430	18.8	176447	9361
6	1.434	0.700	1.004	1.439	22.0	191151	8692
7	2.007	0.480	0.963	1.934	15.1	183505	12169
11	2.129	0.500	1.064	2.266	15.7	202736	12907
12	1.434	0.500	0.717	1.028	15.7	136537	8692
13	2.781	0.300	0.834	2.321	9.4	158929	16863
14	1.220	0.700	0.854	1.043	22.0	162717	7399

Table 5 Oscillating conditions for the large scale tests (at scale 1:5)

This component-type of large scale test is now performed for a series of configurations in a systematic way to maximise the insight we can derive from the results. The most important ones are given in Figure 12:

- Configuration A only consists of the horizontal frame and the vertical legs and is the base case configuration. It is connected with a 6 component force and moment frame to the oscillating carriage of the basin. This series of tests can be used as base case as the interference between the different members is limited.
- In Configuration B also the members and guides in the horizontal frame are added, giving important insight in the interactions in this plane.
- In Configuration C the vertical bracings are added.
- In Configuration D (which has more variations) the number of conductors is varied to get optimum insight in the

interaction between the different conductors. For this purpose the separate loads on 3 different conductors is measured, besides the overall loading.

By comparison of the different configurations the contributions of the different components can be studied. Besides the configuration variations, also the effect of marine growth and the influence of anodes are investigated.

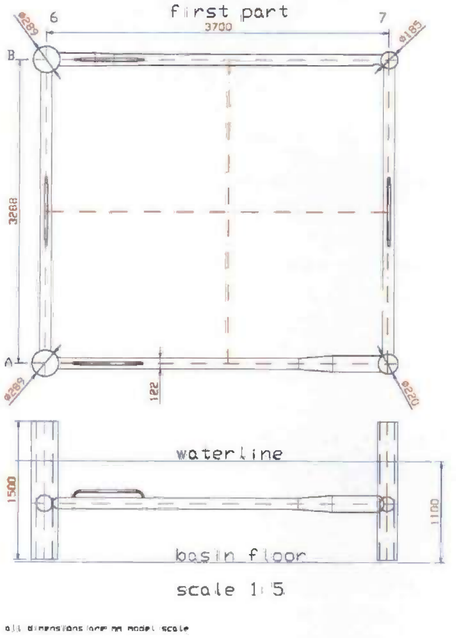
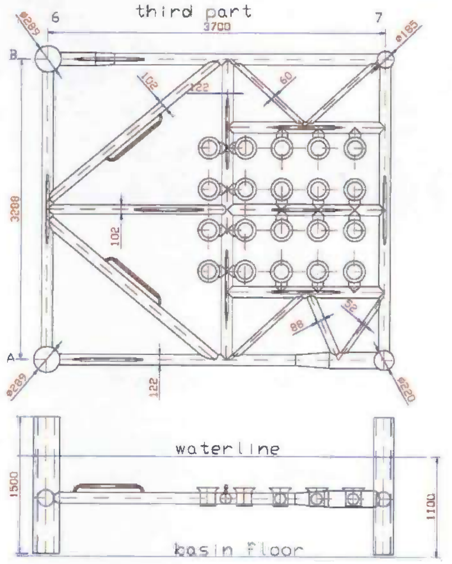
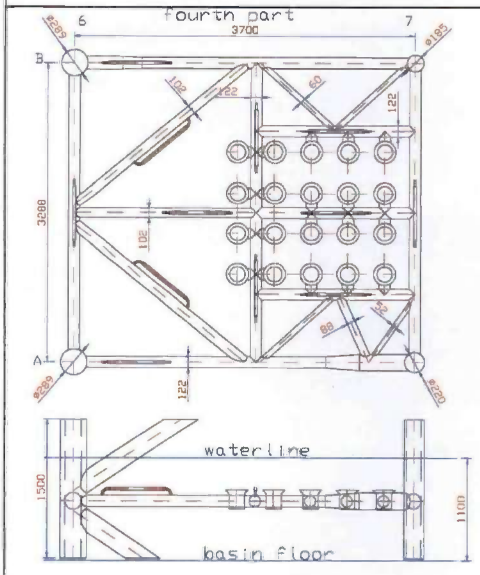
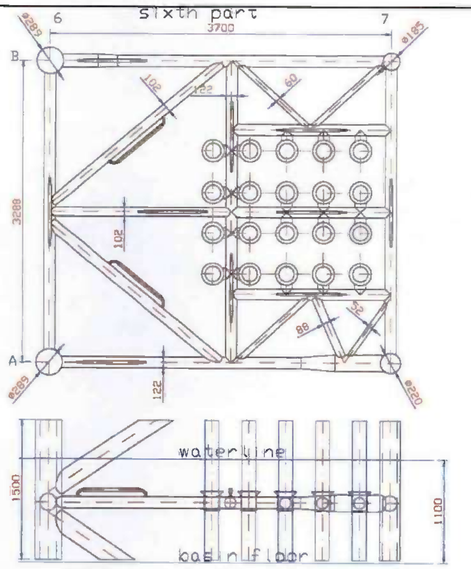
Configuration A Main Structure of 4 vertical legs + horizontal frame.	Configuration B Horizontal frame including conductor guides added
	
Configuration C Added bracings on vertical legs	Configuration D With conductors
	

Figure 12 Different configurations of the large scale component tests

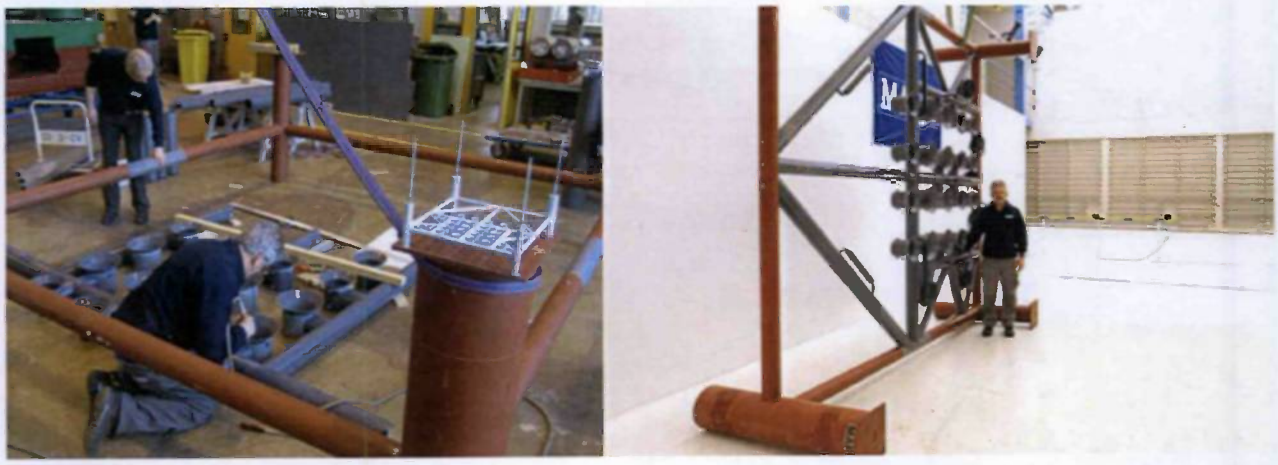


Figure 13 Large scale section (1:5) during preparation and after completion, small scale section (1:63.2) is on one of the corners during preparation

Small scale tests of the same section of the lattice tower

This small scale section model is an exact copy of the large scale model. The scale factor of the model is chosen equal to the small scale model testing with the GBS, scale 1: 63.2. The main objective of this model test is to link the small scale test results to the large scale test results.

To optimise the comparison between the large scale and small scale section testing, the model is not tested in the Shallow Water Basin itself, but in a scale 1:12.64 model of this facility. A scale 1:5 model in the scale 1:12.64 facility results in an overall scale of 1:63.2, which is the same as the initial small scale model.

Also in the model of the model basin an oscillator is used to generate harmonic motions. The small scale section model and the model of the Shallow Water Basin are shown in Figure 14.

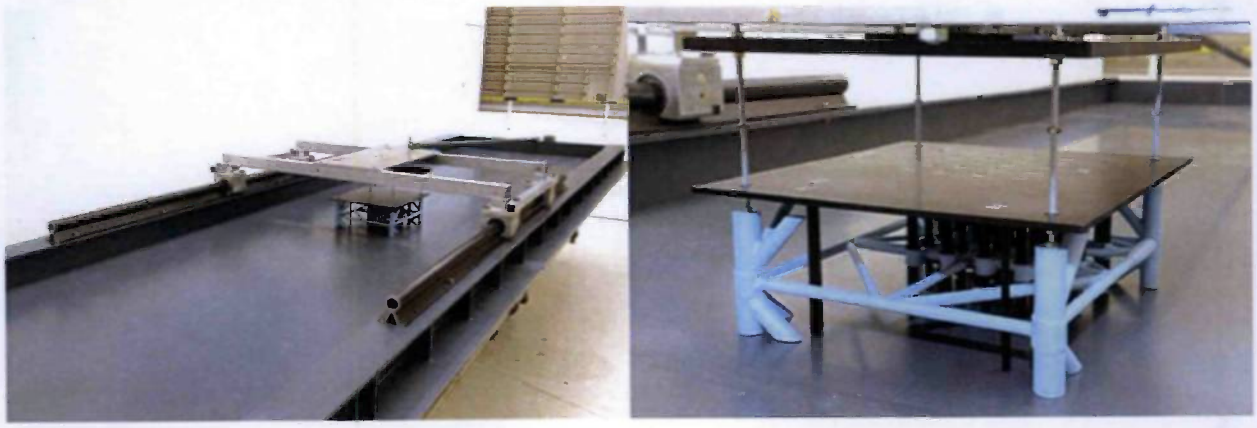


Figure 14 Model of the Shallow Water Basin (left) at scale 1:12.64 and the small scale section model (right) at scale 1:63.2

These small scale section tests are the bridge between the large scale oscillation tests and the small scale tests (with and without the GBS). There are two differences between this model and the small scale lattice tower only testing:

1. Only a section of the Lattice Structure is modelled opposed to the full lattice tower.
2. The section model uses an oscillator to apply hydrodynamic loads opposed to true wave loading of the Full Lattice Structure.

SIMULATIONS

Finite Element (FE) Modelling

The Ramboll Offshore Structural Analysis (ROSA) software is used for the FE modelling of the South Arne structure. In ROSA the structure geometry is defined, beam properties, appurtenances, loads and load combinations. The output from ROSA is sectional forces for numerous cross sections throughout the structure, node displacements and rotations, wave load summaries and spring forces (e.g. link elements or other spring connections). These results can be post-processed in one of several programmes designed for specific purposes (e.g. fatigue prediction, stress check according to specified standards, tubular joint checks, etc.). The ROSA model in a 50-year extreme wave is presented in Figure 15.

The lattice tower, the concrete tower and the topsides are treated as one integrated structure because of the complex load pattern. The two towers are impacted by wave loads, but they are not in phase as the large diameter concrete tower is dominated by inertial forces and the steel lattice tower is also influenced by drag forces. The portal frame arrangement with members of different equivalent stiffnesses makes the South Arne platform unique in terms of its structural design and this feature results in a more complex structural response.

Figure 15 South Arne ROSA model

ROSA is a powerful tool for analysing fixed offshore structures, but as in all other numerical programs, the results are no better than the mathematical models used to represent the various details. The behaviour of the steel tubulars, for instance, is expected to be well described within ROSA as steel is a predictable material following simple mathematical rules and the as-built geometry is known in great detail. However, some aspects of structural modelling do not follow simple rules and some are too complex to apply in a computer model (it is a well known challenge of FE models that a complex geometry can require numerous iterations to reach a solution and this can make some dynamic models almost impractical). Wave loading of complex structures like South Arne and modelling the dynamic behaviour of pretensioned and reinforced concrete are examples of challenging numerical models.

To improve the reliability of the numerical structural model, the more uncertain elements need to be determined in greater detail. In the first instance, these are as follows:

- *Wave Loads* are determined from the model tests and the ROSA model is calibrated against the tests in terms of calibrated Cd/Cm factors for all structural members.
- *Structural Responses* measured offshore will help clarify the natural frequences and other responses and thus the overall stiffness and mass distribution can be calibrated. Individual member stresses can also be verified.

A numerical model that is calibrated against verified measurements (improved input) will generate more reliable results (improved output) that can only practically be investigated with a computer model, e.g. fatigue life predictions or extreme events. (It should be noted that fatigue life predictions also require the calculation of hot spot stresses which is a subject outside the scope of this paper.)

Diffraction analysis

Diffraction calculations were performed with MARIN's linear diffraction code DIFFRAC. DIFFRAC solves the linearised velocity potential problem using a three-dimensional source distribution technique. The mean wetted part of the structure is approximated by a large number of panel elements. The distribution of source singularities on these panels forms the velocity potential describing the fluid flow and wave pattern around the structure. The pressure distribution on the structure is calculated from the velocity potential. The wave forces are then determined from the pressure distribution. All these calculations in DIFFRAC are carried out in the frequency domain. The element distribution of the GBS with concrete tower is presented in Figure 16.

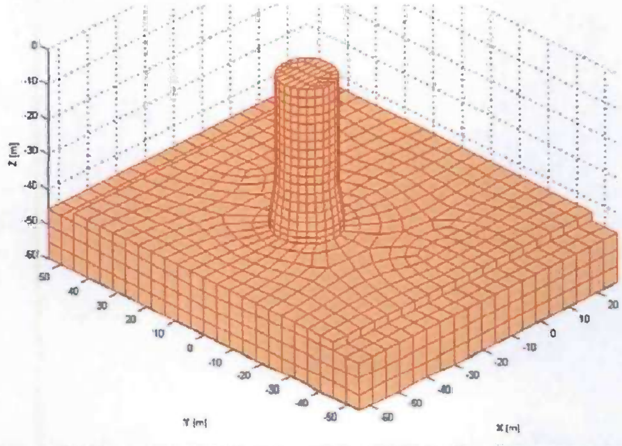


Figure 16 Element distribution of the GBS in the diffraction analysis

With these results is it possible to determine the wave diffraction (reflection) of the GBS (mainly the concrete tower) as well as the wave refraction (mainly due to the base structure). Figure 17 shows an example of the disturbed wave field, including the clear radiating waves away from the tower. These waves (and resulting kinematics) can be used to derive the local kinematics at the location of the lattice tower.

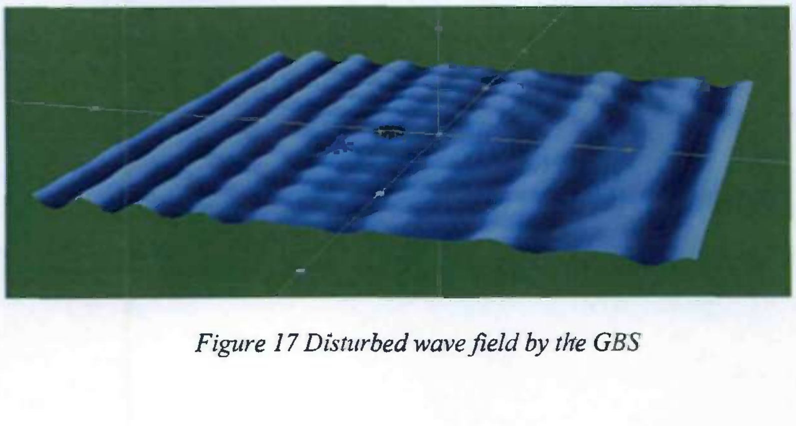


Figure 17 Disturbed wave field by the GBS

OFFSHORE MEASUREMENTS

The Structural Monitoring System (SMS) for the South Arne platform was provided by Fugro Structural Monitoring. The purpose of the Structural Monitoring System (SMS) is to monitor the topside displacements and rotations, the strains in selected parts of the lattice tower, and the wave height.The SMS consists of a PC based data acquisition system, signal conditioning and sensors as follows: 10 triaxial accelerometers, 32 strain gauges, 4 strain transducers, 4 displacement sensors, 5 Rosemount wave radars and 1 Gill ultrasonic anemometer. These sensors provide the raw data channels. Derived data channels include displacements and rotations, the axial force and bending moments of the concrete shaft, the axial force and bending moments of each lattice tower member at a common elevation above the mean water level and the corresponding lattice tower global axial force and bending moments. Raw and derived data channels are used to create statistical results. The wave radars located on each of the four lattice tower legs are used to derive the wave directionality.

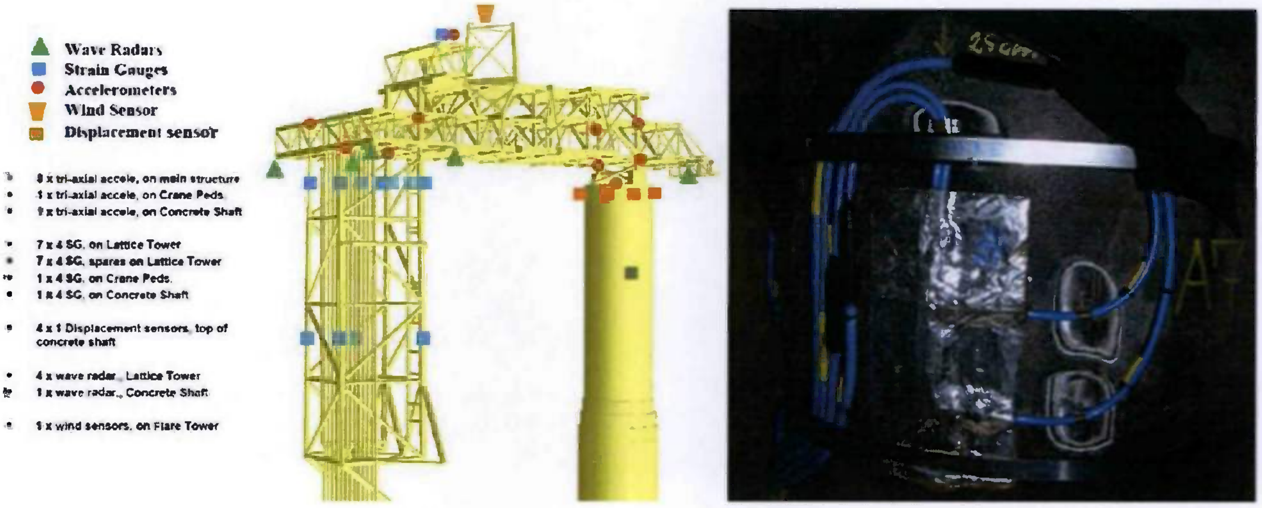


Figure 18 Overview of the Structural Monitoring System (left) and strain gauge on lattice structure (right)

CONCLUSIONS

This paper presents an integrated methodology for the evaluation of the loading and structural response of a fixed offshore platform where model tests, simulations and offshore (full scale) measurements all have their specific and important roles. This integrated methodology is illustrated by application to the South Arne platform with its unique portal frame-like configuration.

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