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LOADS FROM WAVES AND CURRENT ON FLEXIBLE TARPS MARINE 2021

ARE JOHAN BERSTAD

Aquastructures
Kjøpmannsgata 21, 7013 Trondheim, Norway
e-mail: are@aquastructures.no, web page: http://www.aquastructures.no

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Abstract. This paper presents loads on flexible tarps. Tarpaulins have become popular in the Aquacultures industry to replace regular nets in parts of classic cages. Such systems respond in a highly hydro elastic manner. This need to be accounted for in a load response assessment. This paper outlines a formulation for the calculation of wave loads on flexible tarps, as well as a hybrid solution for calculating loads on tarps located in larger systems with stiffer parts included. Model tank testing has been carried out for a tube used in the aquaculture industry. Analysis and measurements are compared. Results shows good correspondence and are discussed for general applicability.

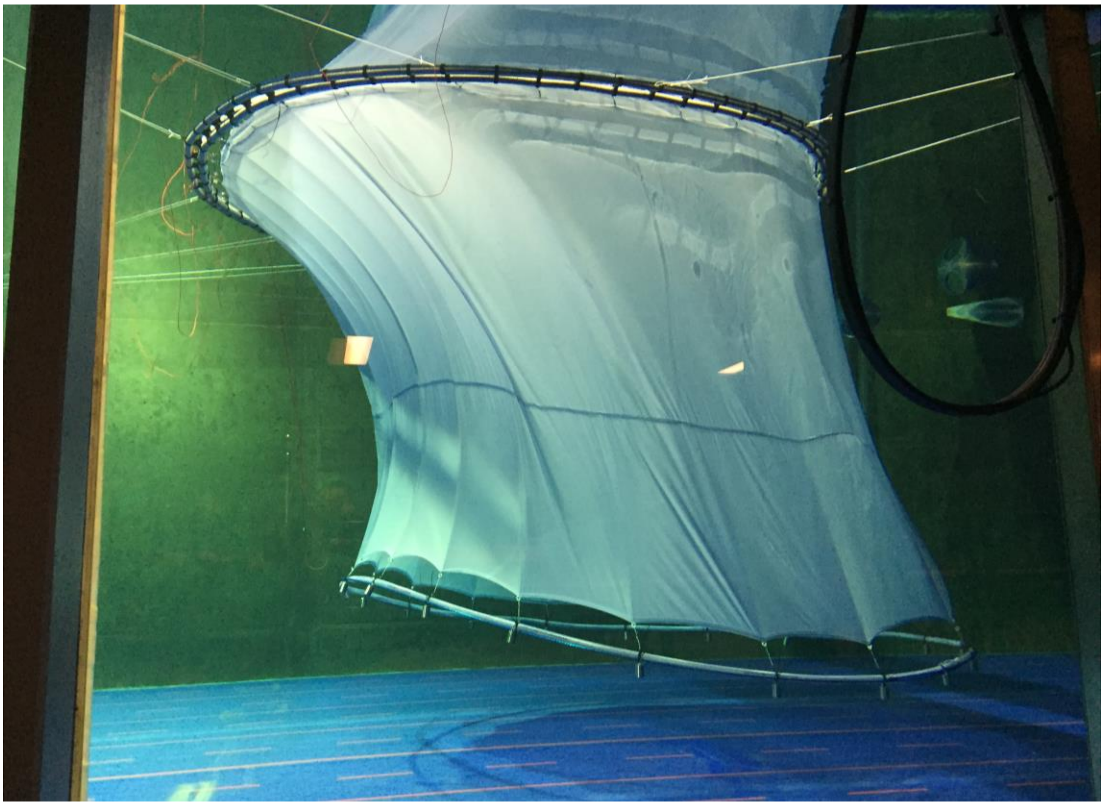

Figure 1 Tube in flume tank test facility [4]

1. INTRODUCTION

A tarp or tarpaulin is a large sheet of strong, flexible and water-resistant or waterproof material. The fabric is often cloth such as canvas or polyester coated with polyurethane or other polymers such as polyethylene. In the Aquaculture industry, the use of tarpaulins as lice skirts or tubes has been increasing recent years. Tarps are fitted into classic polyethylene aquaculture facilities with circular floating collars with tarpaulin as sidewalls (tubes) or parts of sidewalls (lice skirts) as seen in Figure 1 and Figure 4. At the bottom there is usually a polyethylene ring carrying weights as seen in Figure 5. The main load components for design verifications of such units are current and waves [5].

For stiff marine structures wave loads to enclosed objects is normally estimated by numerical diffraction theory (see e.g. [1]), or by analytical solutions in case such solutions can be fitted to the shape of the structure, for instance MacCamy & Fuchs theory [6].

This paper presents general theory for load application of both current loads and wave loads. Further, a new load model for application of wave loads on flexible tarps is presented. Analysis is compared to flume tank test results.

2. LOADS INTRODUCED BY CURRENT AND WAVES

2.1. Loads from current

Consider flow around a cylinder like the case seen in Figure 1. Since the bottom of the tube is open the static pressure from water will be equal on the inside, and the outside. As outlined in [3] current loads to the system are calculated using drag by flow around a cylinder as basis for the calculation. Define a coordinate system where 0 degrees is in the opposite direction of the flow. By such there is a pressure coefficient, C_p, upstream that may be expressed as:

$$C_p = 1 - (C_l + 1)Sin^4\theta$$

Equation 1

For $\theta = 0 – 90$ degrees. C_l is the lift coefficient. Note that when Cl=3.0, this will correspond to the analytical solution for an inviscid flow. Then for the leeward side of the cylinder C_p can be approximated as:

$$C_p = \min(1 - (C_l + 1)\,Sin^4(90 + (\theta - 90) * 1.5), -C_{wake})$$

Equation 2

Where C_{wake} is found by matching the overall drag to the cylinder. C_d and C_l is set as input, then C_{wake} and C_p derived such that the total drag and lift fits. For the drag direction this means:

$$\int Cp \cdot \vec{n} = Cd \cdot A$$

Equation 3

Having found the pressure coefficient, Cp, as a function of the angle between the element in the horizontal plane and the current flow, the force acting into a net panel with an area, A, is found as:

$$F_N = \frac{\rho A C_p}{2} {U_c}^2$$

Equation 4

This solution is for two-dimensional flow around a circle. Generalizing to 3D, pressure is implemented normal to each surface and the crossflow principle is applied such that U_c is the part of the current velocity normal to the surface at the element fronting the current direction. In addition to the drag covered above, also frictional drag can be introduced. This is not introduced in the present work. For dynamic load and response, U_c is replaced by the relative velocity consisting of the fluid velocity caused by both waves and current as well as the velocity of the element. The velocity from wave particle motion is averaged over the object at the given vertical location.

2.2.Loads from waves

This section presents loads from water pressure to rigid structures and the new formulation applicable to flexible tarps. It starts with the pressure introduced by undisturbed waves, the Froud Krylov force.

2.2.1. Froude Krylov force

Let the wave elevation be described by Airy waves. The water particles will then move in a circular pattern at infinite depth and an elliptic pattern in finite depth. Wave elevation according to Airy wave theory can be expressed as:

$$\zeta = \zeta_a \sin(\omega t - kx)$$

Equation 5

For a wave propagating along the positive *x*- axis. Waves leads to a dynamic time dependent pressure component that for infinite water depth can be expressed by:

$$p_d = \rho g \zeta_a e^{kz} \sin(\omega t - kx)$$

Equation 6

where ρ is the density of the fluid. For finite water depth it can be expresses as:

$$p_d = \rho g \zeta_a \frac{\cosh(z+h)}{\cosh(kh)} \sin(\omega t - kx)$$

Equation 7

k is the wave number $k = \omega^2 / g$ for infinite depth and $k \tanh(kh) = \omega^2 / g$ for finite depth. The total pressure is the static pressure, plus dynamic pressure and can be formulated as:

$$p = p_d - \rho g z + p_{atm}$$

Equation 8

Forces from water to a submerged body will be the integral of the pressure around the body. We start out with integrating the pressure over the surface, then the Froude Krylov force, F_{FK} can be found as:

$$\vec{F}_{FK} = -\iint_{Sw} p\vec{n}ds$$

Equation 9

Where p is the pressure introduced by the undisturbed wave field, **n** is the unit vector normal to the wetted surface S_w.

2.2.2. Loads to a rigid object, diffraction

A fixed body introduces a perturbation on the flow field since the velocity normal to the body surface must be 0. This is normally stated in terms of a diffraction theory [1], [3], [7]. This perturbation leads to a modification of the pressure around the object and integrated to an additional force component normally stated as the diffraction force, F_D:

$$\vec{F}_D = -\iint_{Sw} p_D\vec{n}ds$$

Equation 10

Where Sw is the wetted area and p_D is the pressure introduced by the diffracted wave. The total force to the body is then found as:

$$\vec{F} = \vec{F}_{FK} + \vec{F}_D$$

Equation 11

2.2.3. Load model for a flexible tarp

Consider a case where the body follows the velocity of the incident fluid motion such that there will be no disturbance to the incident wave causing diffraction. The object in water is then assumed to follow the flow motion perfectly. This will be like a “free tarp” in water. Consider a tarp vertically in the water with the flat side normal to the wave direction. In this case let us apply the Froude Krylov pressure to the side of the flexible tarp facing the waves. The load to the panel will according to airy wave theory for deep water waves be expressed as:

$$\vec{F}_{FC} = \rho g \zeta_a e^{kz} \sin(\omega t - kx) \ \ \vec{n}A$$

Equation 12

Where $\vec{n}$ is a vector normal to the plane of the mesh plate, and A is the area of the (incremental) plate. As this is a harmonic motion, the dynamic response equation is applied such that the response can be derived by the following harmonic equation:

$$F = ku + c\dot{u} + m\ddot{u}$$

Equation 13

Where k is the stiffness, c is the damping term and m is the mass of the responding object. The wave elevation for an incident wave is expressed as:

$\zeta = \zeta_a \sin(\omega t - kx)$

Equation 14

The horizontal part of the velocity is expressed as:

$\dot{u}_{xw} = \zeta_a \omega e^{kz} \sin(\omega t - kx)$

Equation 15

Hence a solution where the response is derived with no mass og stiffness and damping

$c = \rho g / \omega$

Equation 16

will lead to horizontal motion of the (infinitesimal) vertical surface along with the particle motion of the fluid. This means that for a “free tarp” with a vertical side where the waves approach normal to the side, introducing Equation 16 as a damping term will lead to a response motion where the tarp follows the horizontal motions of the wave particles. Consider a tarp located in the horizontal plane. In case the vertical motion of a tarp perfectly following the incident wave

$u_z = \zeta_a e^{kz} \sin(\omega t - kx)$

Equation 17

$\dot{u}_z = \zeta_a e^{kz}\, \omega \cos(\omega t - kx)$

Equation 18

For response modelling it is convenient to apply the solution in Equation 16 also vertically. Introducing the vertical load with a 90 degree angle to the Froude Krylov force, as given in Equation 19:

$F_3 = \rho g \zeta_a e^{kz} \cos(\omega t - kx)\, A_z$

Equation 19

will mean the solution in Equation 16 is applicable also vertically. The flexible tarp solution is hence to apply damping from Equation 16 and along with Equation 12 applied as load in the horizontal direction and Equation 19 applied in the vertical direction. Note that for waves approaching oblique to the tarp, the part of the wave normal to the tarp is introduced as load whereas the tangential part is assumed to be neutral to both sides of the tarp. As seen by these equations there is no added mass associated with the flexible tarp solution.

2.2.4. Hybrid load model

The hybrid load model is an option which can be applicable for cases where one has stiff structure and flexible tarps integrated in systems. When the hybrid solution is used, loads are based on one part from the flexible tarp formulation and the other part from the MacCamy & Fuchs (MF) or numerical diffraction (NUM) solution.

Regardless of which load model is applied, at each timestep, the waterline is kept track of, so that wave pressure is only introduced to the wetted surface.

3. ANALYSIS COMPARED TO TANK TESTING

Analysis has been carried out by the analysis program AquaSim which is the leading analysis program applied in aquaculture for verification of cages, barges, nets, tarps, moorings and couples systems [8]. AquaSim is based on Finite Element Method and is developed for structural analysis of marine- and land-based structures. Calculations of response from environmental loads such as winds, current, waves and interaction in coupled systems makes AquaSim a viable tool for design verification. Time domain simulations are carried out calculating displacements, deformations, forces, and stresses acting onto- and within flexible and rigid structures.

3.1. Flume tank test arrangement

A flexible tarp, shaped as a tube, is tested in a flume tank see (Figure 1 and [7]). Analysis has been carried out in model scale. Table 1 presents the cross-sectional area of the tank compared to the cross-sectional area of the tube.

Table 1 Transverse area of tank and tube.

Transverse area tank [m^2]	21.60
Transverse area tube [m^2]	6.05
Transverse free flow area [m^2]	15.55

As seen from Table 1 the water flow velocity needs to increase the velocity by approximately 40 % to fulfil the continuous flow around or under the tank. As the tube deforms, the tube blocks a lower part of the transverse area. As an approximation, the test results are presented as a line where the left side is the nominal velocity and the right side is the velocity multiplied with 1.2, half of the possible increase.

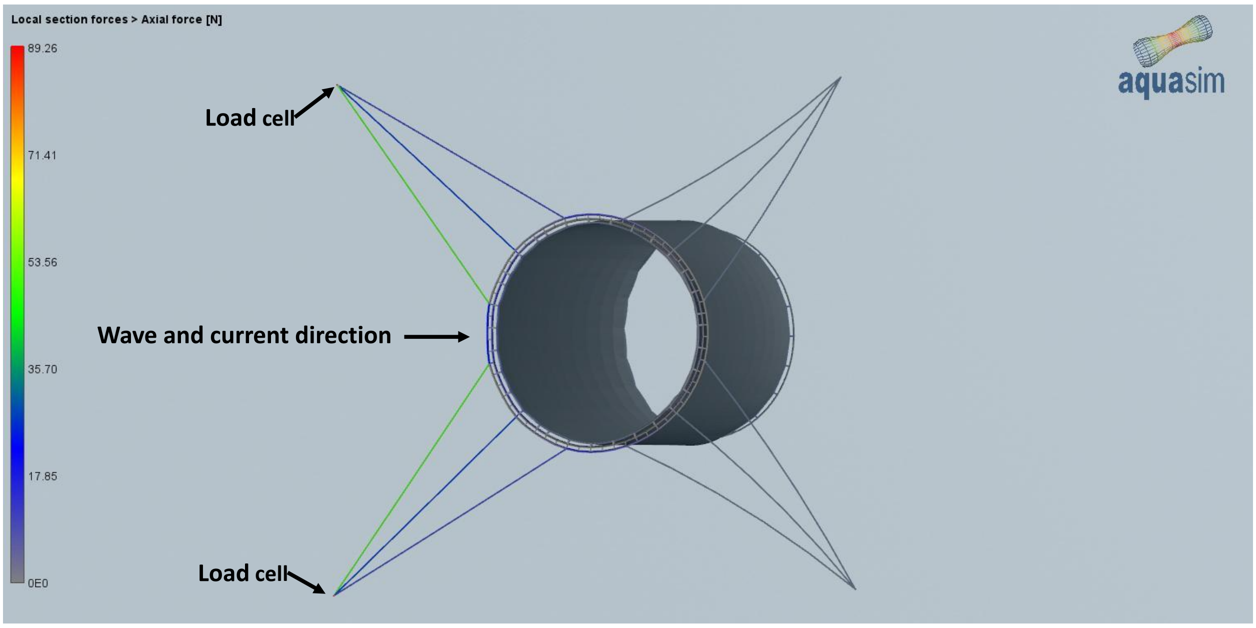

Figure 2 Location of load cells.

The load cells have been placed in each side of the upstream bridles as seen in Figure 2. The load cells measure all the forces in the three bridles. Loads are symmetric between the bridles.

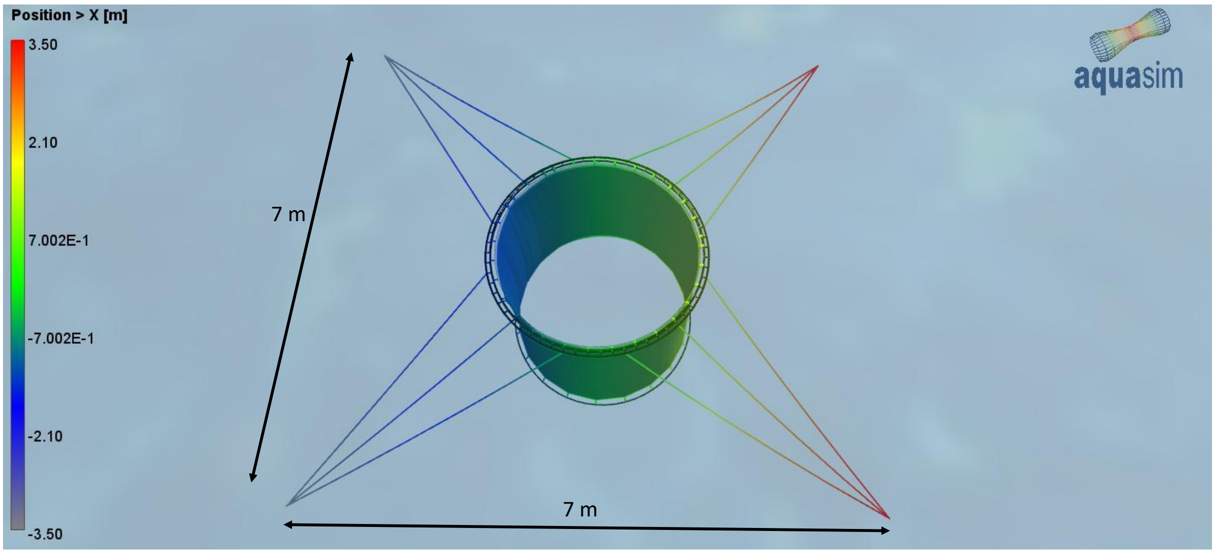

Figure 3 Size of test setup

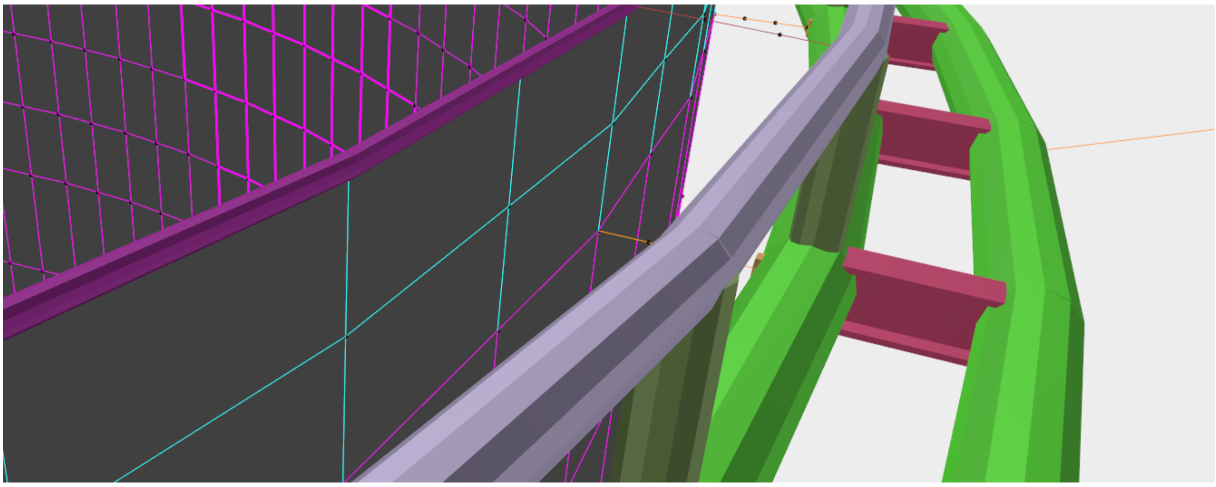

Figure 4 Floating collars, hand railing and connection to tube net. Analysis model.

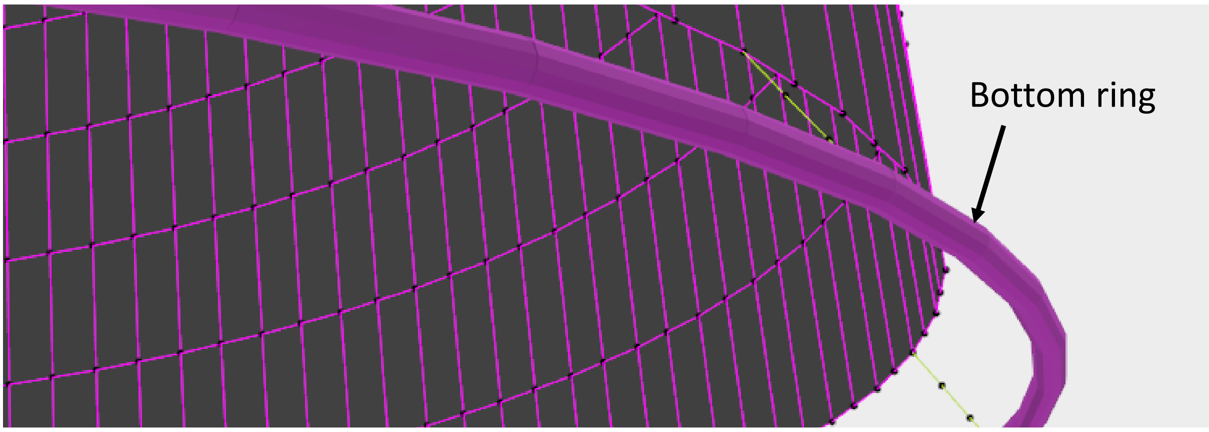

Figure 5 Analysis model. Bottom ring area with connection to tube net. Analysis model.

Table 2 Main particular for the system

Main part	Parameter	Value
Tube	Diameter tube [m]	2.86
	Depth tube [m]	2.07
	Twine area per 5 cm with, each direction [mm2]	10
	Elastic modulus [Mpa]	100
	Diameter system at center outer floating collar [m]	3.12
Floating collar	Floating collar elastic modulus, E [MPa]	9000
	Diameter floating collar (local) [mm]	30
	Thickness	0.16
Bottom collar	Weight bottom collar [g/m]	1332
	Weight in water [g/m]	745
	Diameter bottom collar [mm]	23.4
Bridles	Lengt of centre bridle [m]	3.37
	Cross sectional area	3.14
	Elastic modulus [Mpa]	1000

3.1.Current

Response from current has been compared between tank test results and analysis with a variation of Cd and with a lift coefficient Cl = 2.4 and no tangential drag.

Figure 6 show a comparison of results between tank test and analysis. The following applies to this figure:

- The line labelled “Test” represents measurements in the tank. The nominal current velocity is the left end of each line, and the right end of the line is the velocity increased with 20% to adjust for the finite volume the water must pass around the tube. The lines are placed in the mean value for response from current as seen in the tank test results.
- The lines labelled “Analysis Cd =” represents analysis with the given drag coefficient.

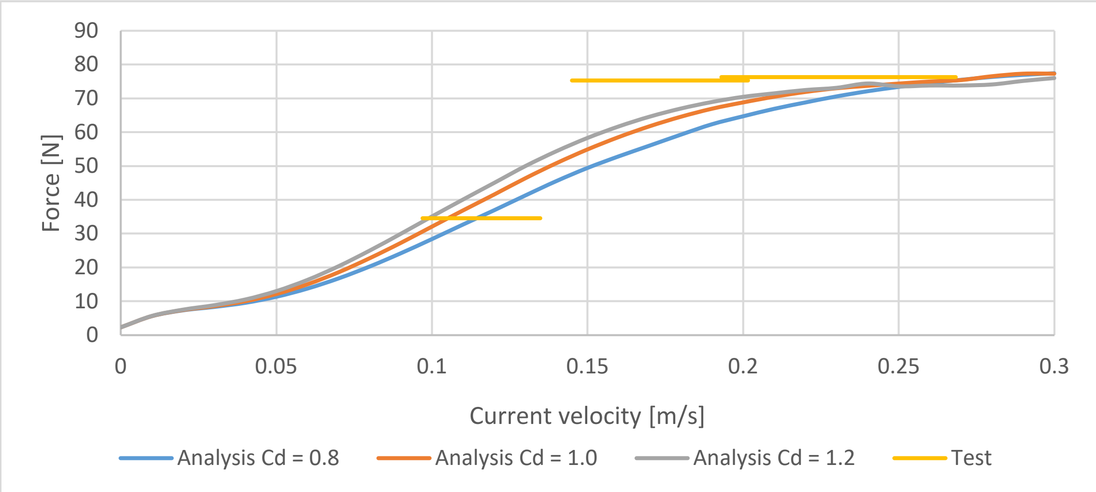

Figure 6 Analysis with a varying drag coefficient compared to test results (yellow).

As seen from Figure 6 , the analysis and testing does not compare fully, but the trend is similar. Figure 7 presents the deformations for the analysis and tank test, respectively.

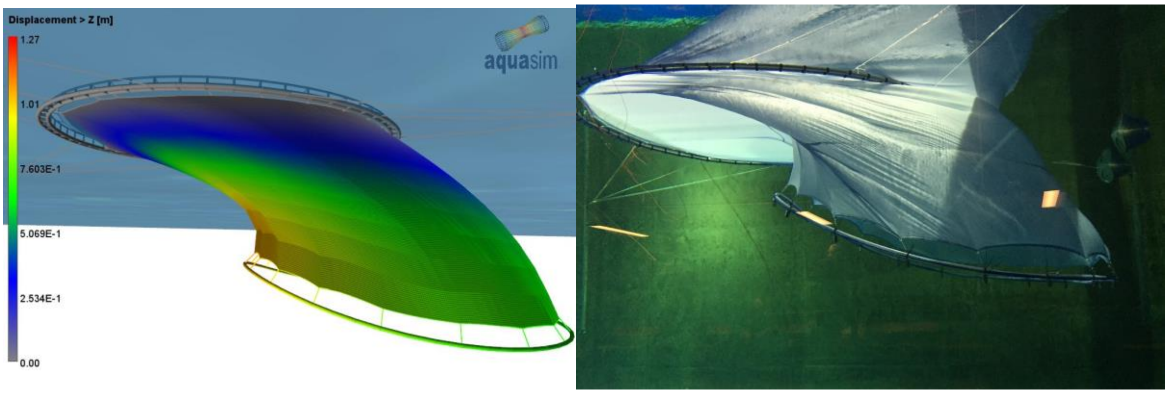

Figure 7 Analysis vs tank test at 0.193 m/s current velocity

As seen from Figure 7 the front of the tube deforms more in the tank test than in the analysis. This may be because as the front gets deformed other drag coefficients should be applied. In AquaSim there is an option for increasing the drag-coefficient in the front. This has not been applied, and it was chosen to use 1.0 as drag coefficient without any addition in the front for the analysis with waves and current.

3.2.Current and waves.

Three combinations of current and regular waves have been assessed. These are shown in Table 3.

Table 3 Cases of combined waves and current

	Case 1	Case 2	Case 3
Current velocity [m/s]	0.097	0.145	0.193
Wave amplitude [m]	0.0988	0.0988	0.0988
Wave period, nominal [s]	1.217	1.244	1.271
Wave period earth fixed [s]	1.158	1.158	1.158

Further parameters for the analysis are given in Table 4. The labels in Table 4 and succeeding figures and tables indicates the following:

- Num diffraction: Wave loads calculated by numerical diffraction theory, such that the pressure to the outside of the tube is derived from diffraction theory and the water line inside the tube is still.
- Flexible tarp: Loads are calculated by the flexible tarp theory as outlined above.
- Hybrid 0.25. This means the loads are summarized by 75% from the flexible tarp load model and 25% from the numerical diffraction load model.

Note that damping has been set equal for all three cases and added mass is as specified evenly distributed to the tube. No additional damping or added mass found by numerical diffraction theory has been introduced.

Table 4 Model parameters for analysis in waves

Load application formularion	Flexible tarp	Hybrid 0.25	Num. diffraction
Added mass [mH2O]*	0	0.29	0.29
Damping coefficient *ω/ρg	1	1	1
Part diffraction	0	0.25	1

**The unit mH2O is "Meters of water".*

3.2.1. Case 1

Figure 8 shows measured forces in the load cells for Case 1.

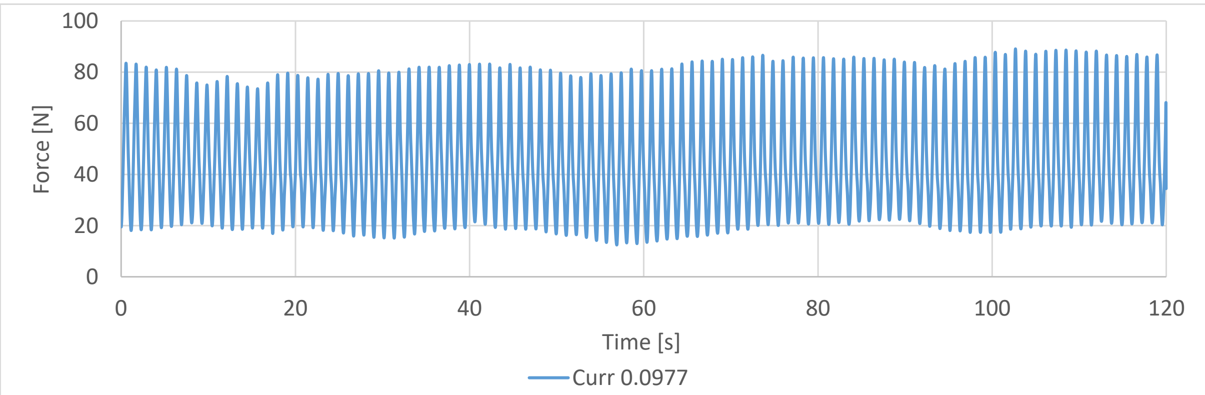

Figure 8 Case 1, tank test data.

Figure 9 shows analysis compared with tank test results. Statistical parameters for test and analysis are given in Table 5.

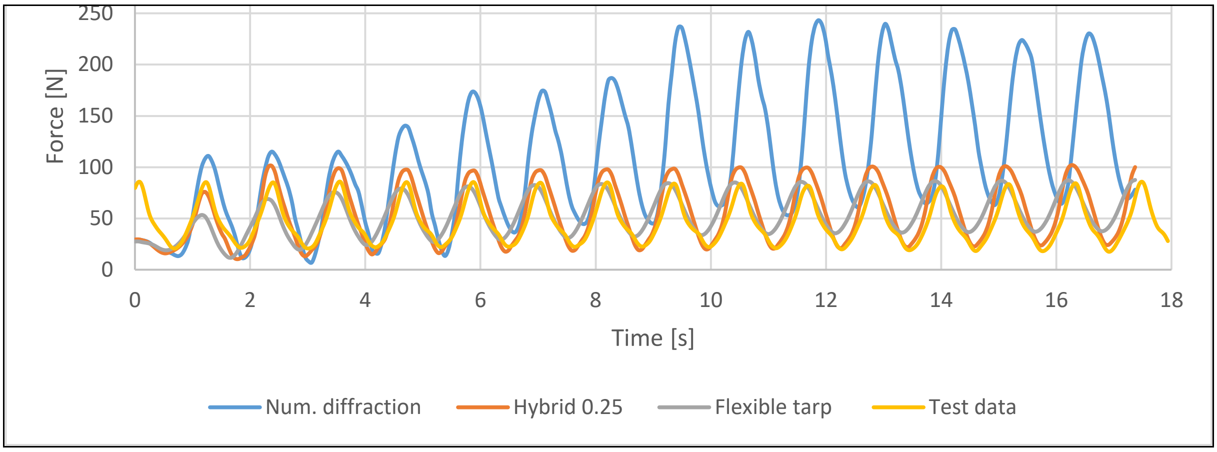

Figure 9 Analysis compared to excerpt of test data. Test case 1. Labels are explained in Table 4.

Table 5 Statistical parameters load case 1.

	Test data	Num. diffraction	Hybrid 0.25	Flexible tarp
Max	89.17	243.16	102.10	87.58
Min	12.52	7.21	13.08	19.79
Average	45.48	108.84	54.32	53.46
St. dev.	20.62	62.92	28.28	18.52

In Table 5 “Max” denotes the maximum found in test/analysis. “Min” is the minimum value seen. “Average” is the average value and “St. dev” is the standard deviation. As seen by comparing analysis and tank test, the results compare much better for the hybrid and flexible tarp load model than for the analysis with diffraction theory.

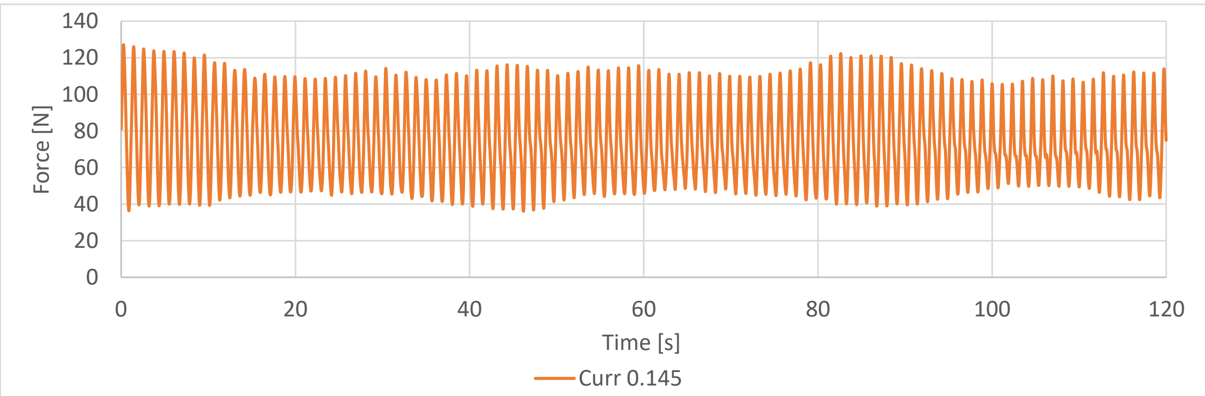

Figure 10 Case 2, tank test data.

3.2.1. Case 2

Figure 10 shows measured forces in the load cells for Case 2. Figure 11 shows analysis compared with tank test results. Statistical parameters for test and analysis are given in Table 6.

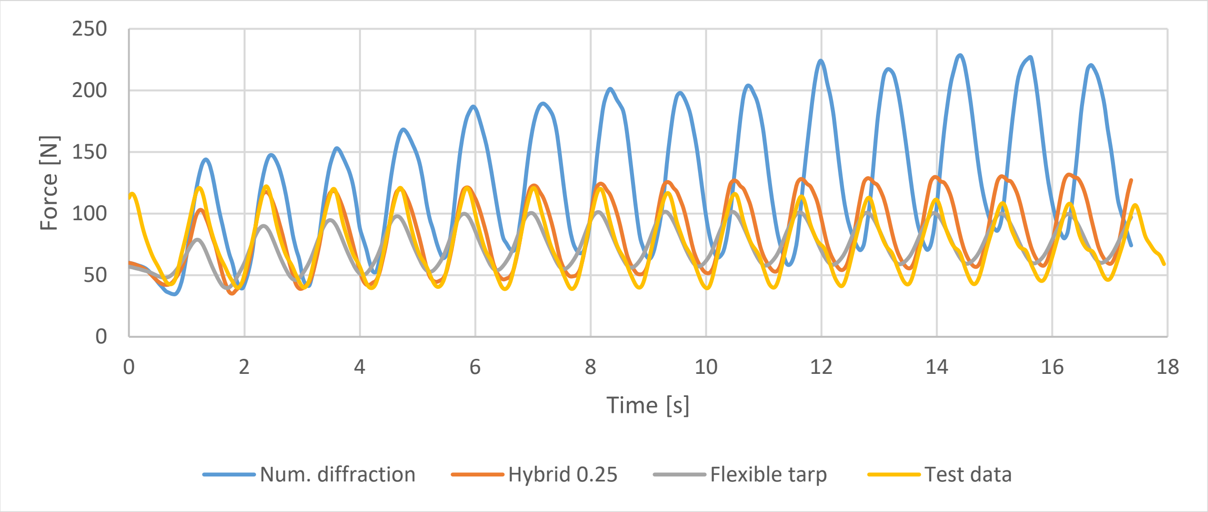

Figure 11 Analysis compared to excerpt of test data. Load Case 2. Labels are explained in Table 4.

Table 6 Statistical parameters load Case 2

	Test data	Num. diffraction	Hybrid 0.25	Flexible tarp
Max	127.14	228.43	131.32	101.29
Min	36.09	41.73	39.12	46.11
Average	74.84	124.99	83.81	74.00
St. Dev.	22.45	50.86	28.05	15.62

As seen by comparing analysis and tank test results, also for this case the hybrid and flexible tarp load model fits much better. Note that in this case, the flexible tarp model underpredicts both max value and standard deviation.

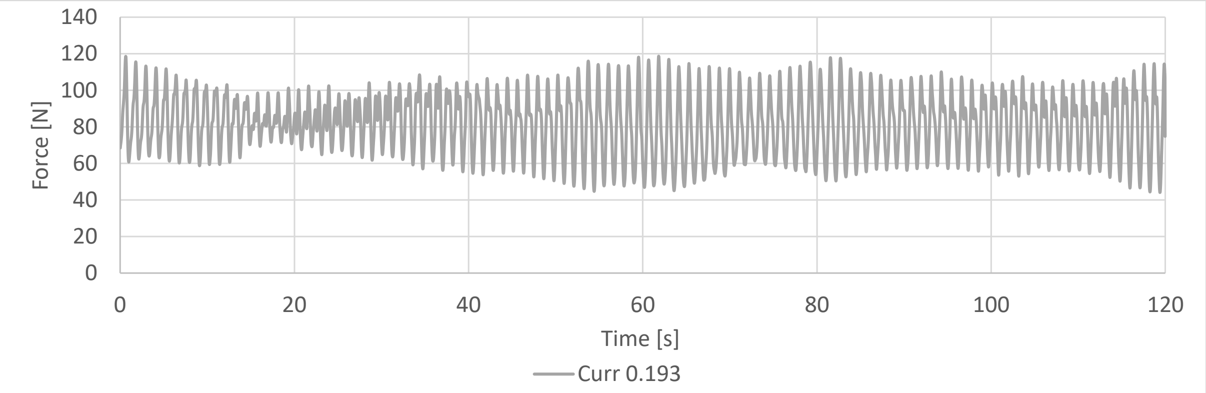

Figure 12 Case 3, tank test data.

3.2.1. Case 3

Figure 12 shows measured forces in the load cells for Case 3. Figure 13 shows the three load versions of analysis given in Table 4 analysis compared to an excerpt of the response time series in the test. Statistical parameters for test and analysis are given in Table 7.

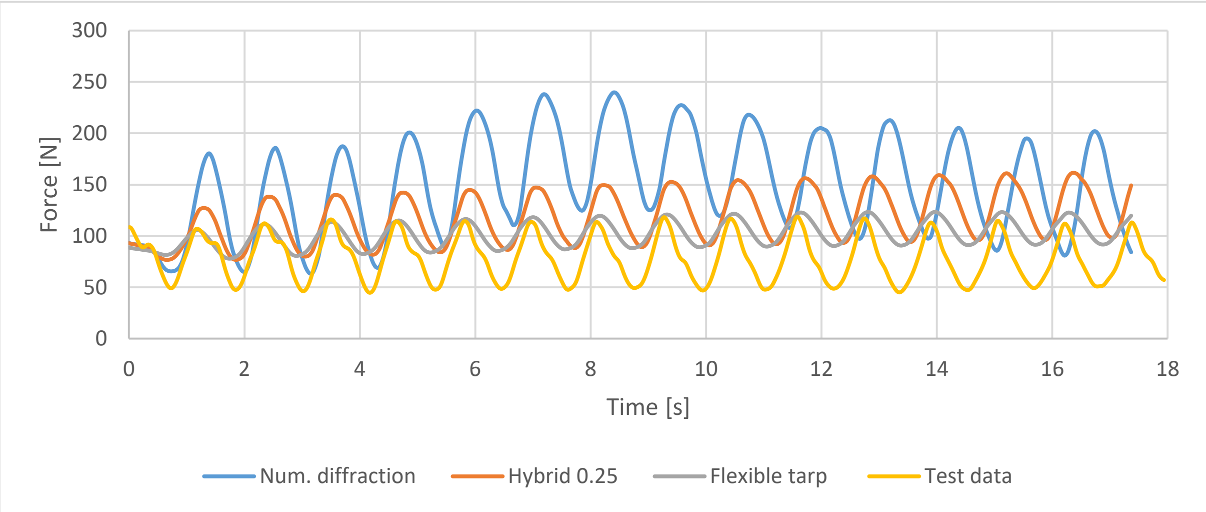

Figure 13 Analysis compared to excerpt of test data. Test case 3. Labels are explained in Table 4.

Table 7 Statistical parameters load case 3

	Test data	Num. diffraction	Hybrid 0.25	Flexible tarp
Max	118.75	239.65	161.57	123.48
Min	44.20	63.71	80.10	80.63
Average	81.75	148.54	117.87	101.28
St. Dev.	16.82	44.69	23.31	11.96

As seen by comparing analysis and tank test results, also the hybrid and flexible tarp load model fits much better. Note that in this case, the flexible tarp model underpredicts both max value and standard deviation. Mean values and average are overpredicted for all analysis options.

4. CONCLUSIONS

This paper compare analysis with tank test results of a flexible tarp system. A new load formulation for wave loads to flexible tarps is presented. The new load formulation may be applied alone or may be used in combination with diffraction theory as a hybrid load formulation. Results shows that applying the load model for flexible tarp theory as well as a hybrid load formulation compare well with flume tank testing. Applying diffraction theory does not compare well. This shows that the flexible tarp load formulation can be utilized as a practical load formulation for flexible systems such as the considered tube and lice skirts.

4.1.Discussion

The flexible tarp load model did in general introduce less loads than diffraction theory. Diffraction theory will lead to an opposite wave assumed in the front leading to additional forces. For the flexible tarp load model there are no additional forces by diffraction introduced, and the method has a lot of damping associated with it. This means the load model should be used carefully for systems that is not validated with flume tank testing. The stiffer the system is, the more the hybrid model should lean towards diffraction theory. For the case considered in this paper a hybrid model including 25% diffraction showed to give good correspondence with testing and lean towards the conservative side.

4.2.Recommendations for further studies

It is strongly recommended both to do more model testing of such systems and to carry out more sensitivity studies. In this work it was noted that results showed sensitivity on several parameters such like the stiffness of the bridle lines, and weight of bottom ring. Here, base values from [4] was used. In further studies a systematic variation in parameters should be carried out. With respect to more tank testing such tank testing may test simple models, but care should be taken to document all relevant parameters.

Also note that parameters such as drag and lift coefficients as well as added mass depends strongly on the condition, and even assuming the validity of a response description by using them is an approximation. This means one cannot assume to choose these values and have good fits for all components. This should be included in a sensitivity assessment.

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