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ON THE DESIGN CONSIDERATIONS OF NEW OFFLOADING HOSE APPLIED ON A TURRET MOORED FPSO

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ABSTRACT

Offloading hoses are used to transfer crude oil or liquid petroleum products from a fixed offshore production platform/floating production, storage and offloading (FPSO) unit to shuttle tankers. The hoses are subjected to environmental loads that are mainly waves, current, and vessel motions from both FPSO and the shuttle tanker.

New offloading hoses were planned to be applied in a FPSO in harsh environment, and a design analysis was done in this connection.

Numerical simulations were performed on ultimate limit state (ULS), serviceability limit state (SLS) and accidental limit state (ALS) by using the software RIFLEX [2]. Critical responses such as curvature and axial forces are checked.

The following conditions are checked:

1. Normal operation condition with oil filled hose
2. Connect operation condition, floating gas filled hose
3. Emergency disconnect condition

A SIMA [3] workflow was established to calculate accumulated fatigue damage of all the elements of the offloading hose model.

For the new offloading hose, it is important to have a combined bending-tension loading capacity check. A utilization factor is proposed that possibly may be generalized.

The results show that the specified hose has ample capacity for the considered operating conditions for the shuttle tanker to stay in any position within the 2nd emergency shut down sector (ESD2).

INTRODUCTION

A loading system consists of a turret moored FPSO, a shuttle tanker (Tanker) and a loading hose, which connects the FPSO stern and the Tanker bow, as shown in **Figure 1**.

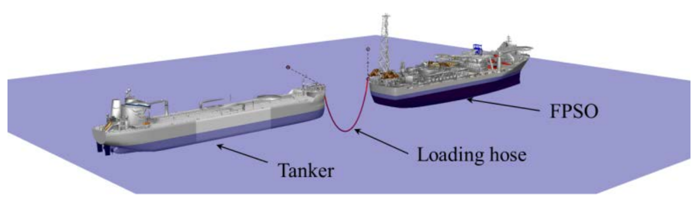

Figure 1 A typical offshore loading system.

The static loads on the hose are mainly due to gravitation and buoyancy. The dynamic loads are due to acceleration, hydrodynamic drag and inertia forces on submerged part of the hose. In this paper, the dynamic behavior of the loading hose is studied.

There are mainly two dynamic excitation sources: The first one is the motions of FPSO stern and Tanker bow. Here we only considered the wave frequency (WF) motions, while the low frequency (LF) motions are not included explicitly. The second source is the wave kinematics. The most important are wave velocity and acceleration normal to the hose axis.

The present study focuses on the hose curvature and on the axial forces. The hose capacity in terms of combined curvature and tension was provided and is compared with the calculated responses for a range of sea states and vessel positions. A key operational parameter in governing the hose dynamics is the distance between the ships which determines the sag depth and –tension, and also the hose inclination in the surface zone.

[1] Earlier MARINTEK, SINTEF Ocean from 1st January 2017 through a merger internally in the SINTEF Group

NOMENCLATURE

ALS	Accidental Limit State
ESD	Emergency Shut Down
FPSO	Floating, production, storage and offloading unit
LF	Low frequency
SLS	Serviceability Limit State
Tanker	Shuttle tanker
ULS	Ultimate Limit State
WF	Wave frequency
$b = \left(\frac{EI}{w}\right)^{1/3}$	Stiffness/load – parameter
w	Transverse load, submerged weight for horizontal sections
κ	Curvature
κ_J	Asymptotic J configuration curvature
κ_{max}	Maximum curvature
D_h	Hose distance
H_s	Significant wave height
K	Curvature
L_h	Hose length
T	Tension force
T_p	Peak wave period
R	Radius of curvature
T	Axial force (excluding hydrostatic pressures)
U_c	Current speed
θ_c	Current direction
θ_h	Hose direction
θ_T	Tanker heading
θ_w	Wave direction

OPERATIONAL PARAMETERS

Key operational parameters selected for this study are illustrated in **Figure 2**:

- Loading hose direction, θ_h. When the tanker is aligned with the FPSO at 90 m distance, $\theta_h = 194\ deg$. In addition a direction on the ESD sector limit is checked.
- Tanker heading, θ_T.
- Distance between FPSO stern and Tanker bow, D_h. Mean distance is 90 m, varied -25 m to + 45 m to cover the ESD2 limits.

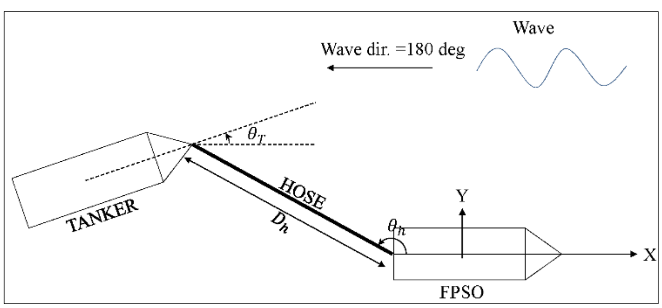

Figure 2 Operational parameters.

The operational sectors of the tanker bow position are shown in **Figure 3**. ESD1 crossing indicates preparation for closing and disconnecting. ESD2 indicates immediate disconnect.

Table 1 Specification of operational limits for the FPSO.

Operation status	Outer [m]	Inner [m]	Sector limit (deg)
ESD1	115	75	40
ESD2	125	65	50
Preferred distance	90	90	

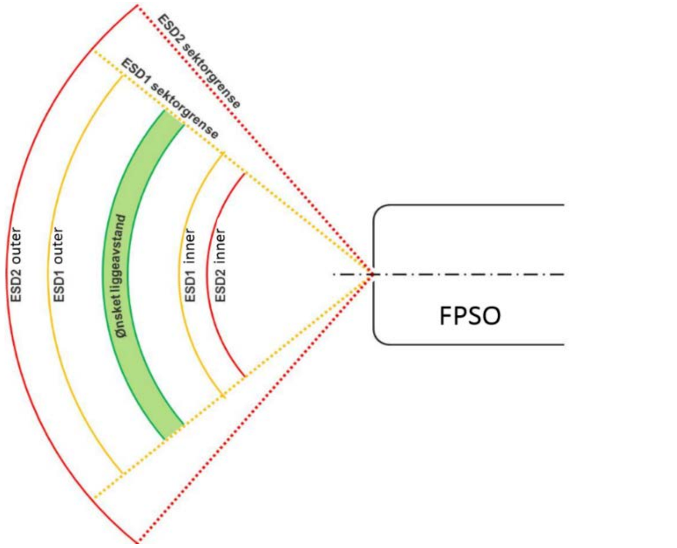

Figure 3 Specification of operational limits. Yellow: ESD1, Red: ESD2.

THE NEW HOSE

The hose is 152.4 m long and made up from 11 regular hose sections and 2 pieces of hose sections with strengthened ends. The 13 hose sections are coupled together with flanges.

ANALYSIS METHOD

A RIFLEX analysis model has been prepared by use of the SIMA workbench [2]. This involves a finite element model of the hose for the nonlinear FEM program RIFLEX and motion transfer functions of the two support vessels: FPSO and Tanker.

For the hose a beam element model was applied, using mass-, buoyancy- and stiffness properties in accordance with the specified input document. The hose is connected to both vessels with a ball joint component. In the parameter study both of the ball joints have been specified free-to-rotate around local Y- and Z-axes. In Z-rotation one is free and one is fixed. This model gives zero bending moment at the hose ends, zero torque, and the in-span curvature is obtained directly.

STATIC ANALYSIS

The static loads are governed by the hose weight, hose length, and the distance between the support points.

The static hose profile is shown in **Figure 4** for the target distance 90 m and 10 m and 20 m to each side. The sag depth ranges from 29 m to 45 m below the sea level. The sag bend radius is fairly close to the catenary radius, which means that the curvature is tension controlled, and that the bending stiffness plays a smaller role.

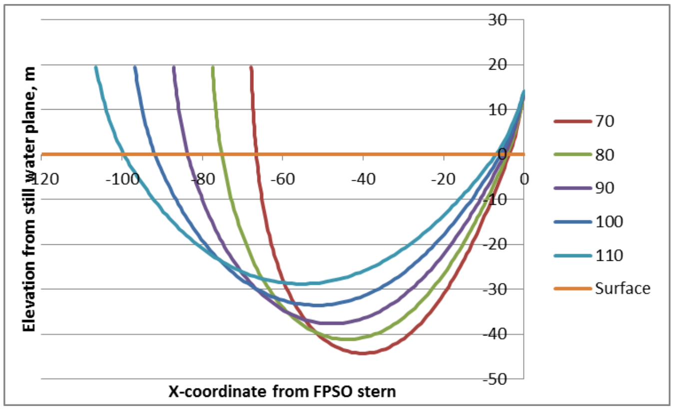

Figure 4 Static hose profile, the distance between the FPSO and Tanker varies from 70 m to 110 m. FPSO at right side, Tanker at left side.

A non-dimensional radius, r_b, may be defined as

$$r_b = R/b \quad \textbf{Eq. 1}$$

With a corresponding non-dimensional tension, t, as

$$t = T/(wb) \quad \textbf{Eq. 2}$$

where $b = \left(\frac{EI}{w}\right)^{1/3}$ is stiffness/load – parameter with dimension 'length'; w is transverse load, submerged weight for horizontal sections; R is radius of curvature; T is the axial force.

With zero bending stiffness the shape would be a catenary curve, with a radius $\mathrm{R_c} = \mathrm{T/w}$. A non-dimensional radius of the catenary is

$$\mathrm{r_c} = \mathrm{R}_c/b = \mathrm{T/(wb)} \quad \textbf{Eq. 3}$$

The relative importance of bending stiffness and tension in controlling the hose shape is evaluated from **Figure 5**. It shows that, when the tension force is approaching to zero, the radius is increasingly dominated by the bending stiffness effect. While as the tension increases, the 'gap' between the blue and red lines becomes smaller, which means the radius of the curvature is more controlled by the tension. The bending stiffness has small influence on the static configuration, provided that the non-dimensional tension and a non-dimensional radius of curvature are larger than about 2. For the present hose this corresponds to a radius of 10 m or more, and a horizontal tension of about 12 kN or more.

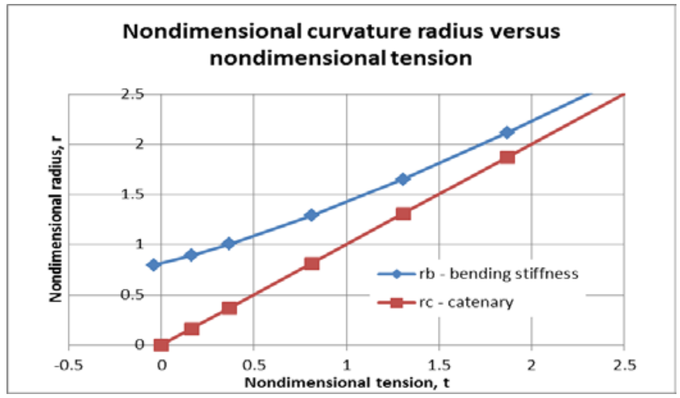

Figure 5 Relative importance of tension and bending stiffness in controlling curvature radius.

The minimum curvature radius of U-shape (Zero horizontal force) and J-shape supported (horizontal touchdown with zero tension) hose (see **Figure 6**) are respectively:

$$R_U \approx 0.88\left(\frac{EI}{w}\right)^{\frac{1}{3}} \quad \textbf{Eq. 4}$$

$$R_J \approx 1.45\left(\frac{EI}{w}\right)^{\frac{1}{3}} \quad \textbf{Eq. 5}$$

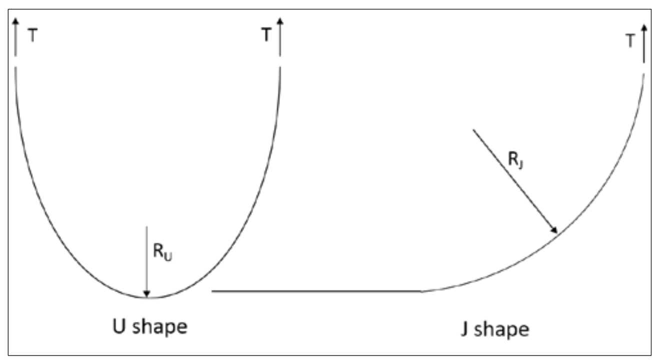

Figure 6 Illustration of U shape and J shape.

For combined tension-bending load the capacity check in terms of a utilization factor α, may be simplified to

$$\alpha^n = \left(\frac{T(t)}{T_{K=0}}\right)^n + \left(\frac{K(t)}{K_{T=0}}\right)^n \quad \textbf{Eq. 6}$$

$T_{K=0}$ and $K_{T=0}$ are taken as the largest values from hose capacity. α is a 'utilization factor' with a value less than 1.0. The inverse 1/α may be taken as a load factor (safety factor). In the subsequent analysis α is denoted utilization ratio, or and used as reference for design loads. N varies from 1.8 to 2.0 depending on the pressure of the hose.

DYNAMIC ANALYSIS

Important attributes related to hydrodynamic loading are the free fall acceleration and velocity of the hose section in water. If relative motions between support points and wave particle motions exceed these values, there will be compression in the sag bend. In oil filled condition the present hose has a free fall acceleration of 1.0 m/s^2 and a free fall speed of 1.4 m/s.

A time domain simulation of dynamic responses to irregular waves and consistant ship motions is carried out by means of the nonlinear FEM software RIFLEX. Irregular wave time series are generated and applied as time-dependent loading on the vessels and on the hose. Selected dynamic responses are stored and presented by means of the SIMA post processing module.

Sensitivity Study

Sensitivity studies were carried out on a 'base condition', in which the FPSO was in medium load condition, Tanker was in ballast condition, the offloading hose was with 'unpressurized' bending and axial stiffness, other settings for the base condition is shown in **Table 2**.

Table 2 Base condition for sensitivity study.

D_h (m)	θ_h (deg)	θ_T (deg)	H_s (m)	T_p (s)	θ_w (deg)	U_c (m/s)	θ_c (deg)
90	194	0	6	13.5	210	0.89	225

1) Sensitivity of simulation duration

A sensitivity study of simulation duration has been done, The results for the highest loaded element in each case are presented in **Figure 7** for combined tension and curvature. It appears that 2.3 hour duration is adequate for estimation of 3 h return period value from one sample (one seed number). The uncertainty is about 30 %.

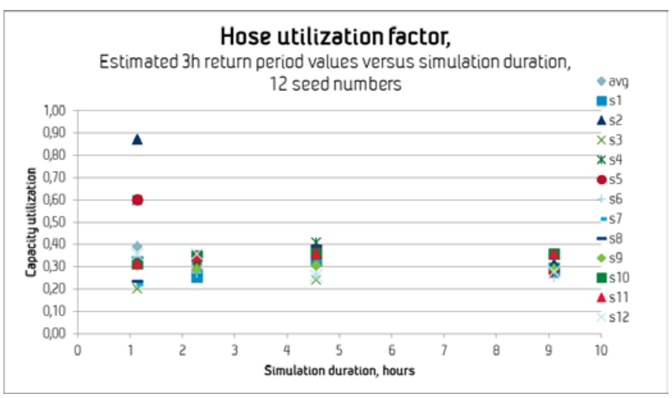

Figure 7 Estimates of hose utilization characterized by estimated 3 hour return period of utilization factor in combined tension and curvature loading.

2) Sensitivity of hose distance

The distance between the FPSO stern and Tanker bow varies as 60 m, 75 m, 90 m, 105 m, 120 m, and 135 m. The mean distance variation covers typical range of relative LF motions.

The tension sensitivity to distance is shown in **Figure 8**, and the curvature sensitivity is shown in **Figure 9**. Both the tension maxima and the curvature increases with distance but are within 36 % and 50% of the capacity up to 135 m distance.

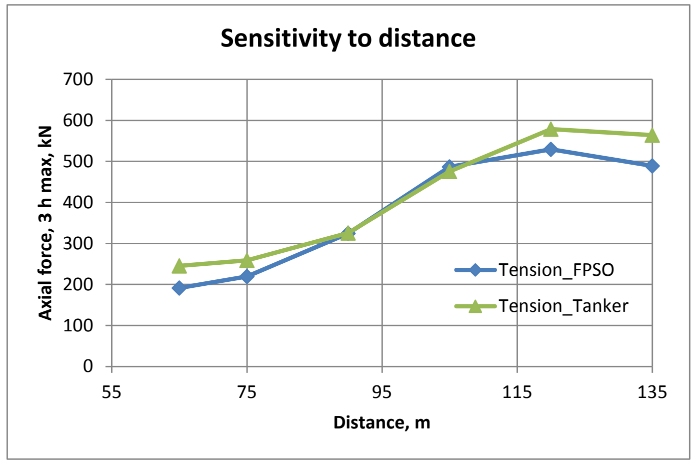

Figure 8 Hose tension sensitivity to distance.

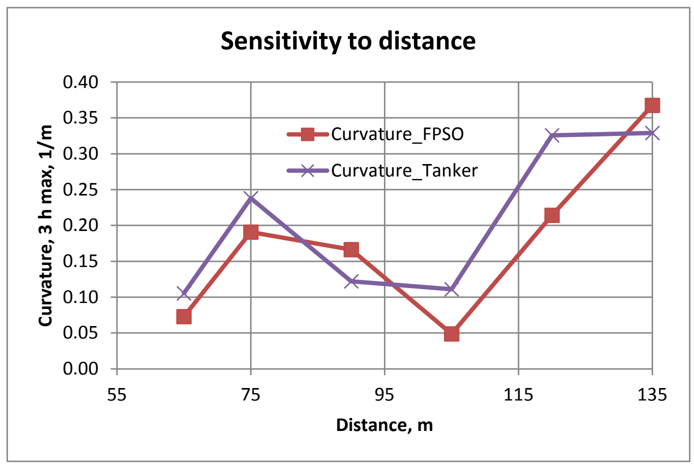

Figure 9 Hose curvature sensitivity to distance. Estimated 3 h maxima 24 m (2 sections) below the end section at each end.

3) Sensitivity of hose direction

The hose direction varies from 130 deg to 230 deg with 20 deg increment. The tension sensitivity to hose direction is shown in **Figure 10**, and curvature sensitivity is shown in **Figure 11**. The tension maxima tend to decrease when the hose is moved out of the center line. The curvature is increases to one side, but is within 30 % of the capacity.

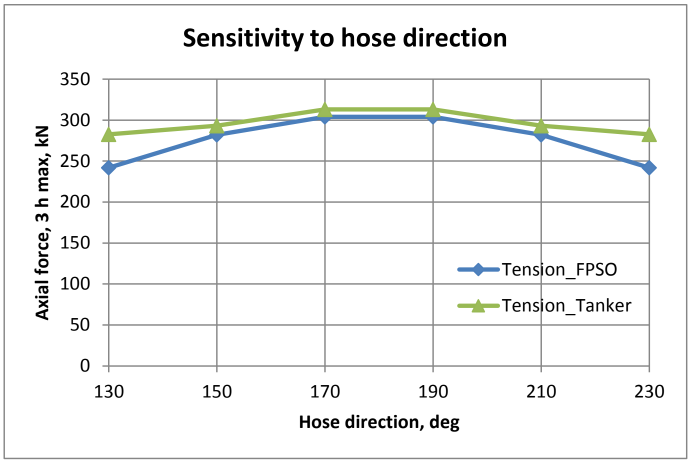

Figure 10 Sensitivity of tension to hose direction.

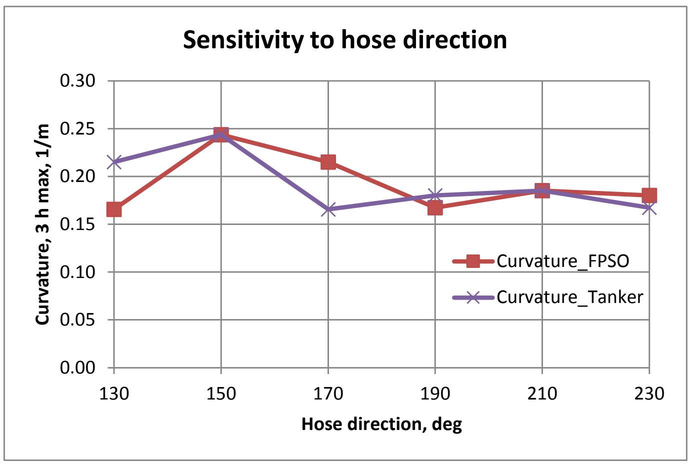

Figure 11 Sensitivity of curvature to hose direction.

4) Sensitivity of tanker heading

The tanker heading varies from 10 deg, 30 deg, and 50 deg from the mean position. The tension sensitivity to tanker heading direction is shown in **Figure 12**, and curvature sensitivity is shown in **Figure 13**.

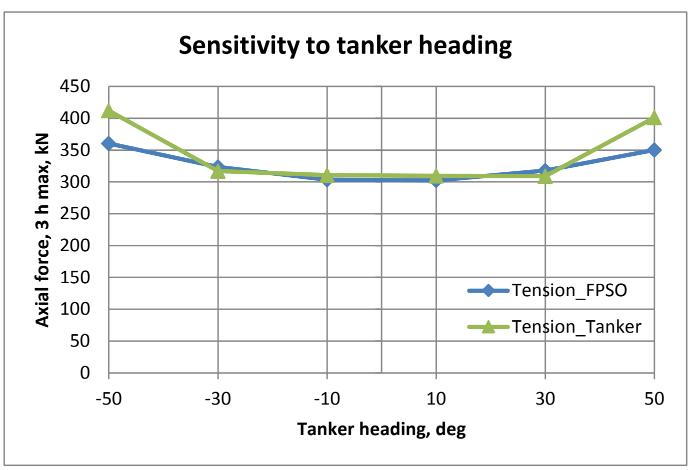

Figure 12 Sensitivity of tension to tanker heading direction. $D_h = 90$ m, $\theta_h = 194$ deg.

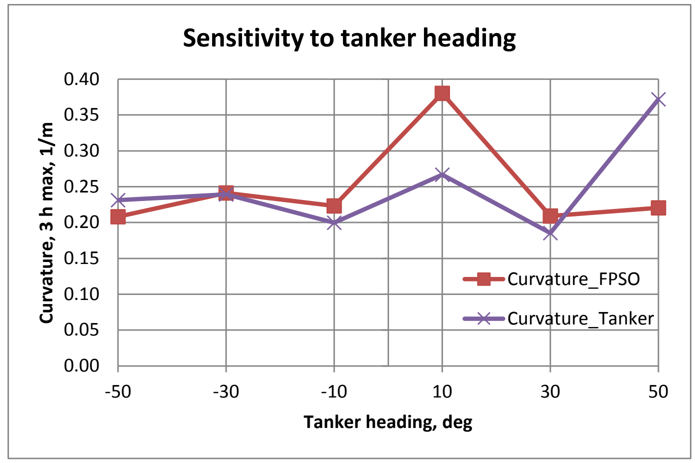

Figure 13 Sensitivity of curvature to tanker heading direction. $D_h = 90\ m,\ \ \theta_h = 194\ deg.$

The tension maxima tend to increase when the heading is moved out of the center line but is within 25 % of the capacity. The curvature is increases to one side, but is within 50 % of the capacity.

The sensitivity to tanker heading direction is also checked at the outermost port corner of the ESD2 sector (see **Figure 3**). The results are shown in **Figure 14** for tension, and in **Figure 15** for curvature.

Tanker heading -50 deg is in-line with the hose direction. Turning the bow port 50 deg to head into the waves gives a slight tension increase and curvature increase. Turning further 50 deg, 100 deg to the hose direction gives a maximum tension of 505 kN, and a maximum curvature of 0.37 m^{-1}, about 30 % of tension capacity and 50 % of curvature capacity. The hose has comfortably capacity for the tanker to stay anywhere within the ESD2 sector in this wave condition.

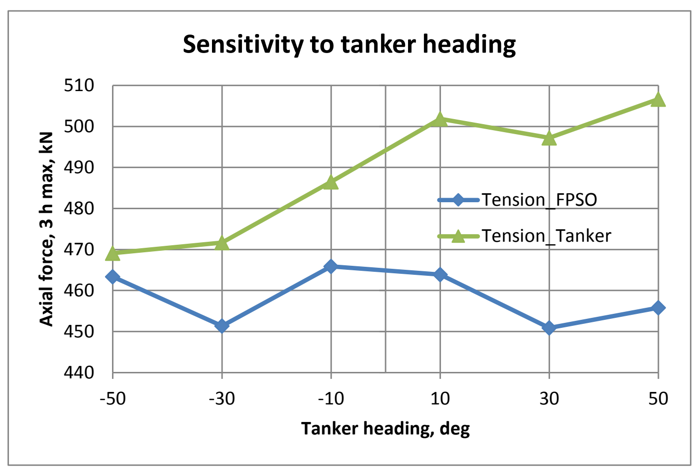

Figure 14 Sensitivity of axial force to tanker heading direction. $D_h = 125\ m,\ \ \theta_h = 130\ deg.$

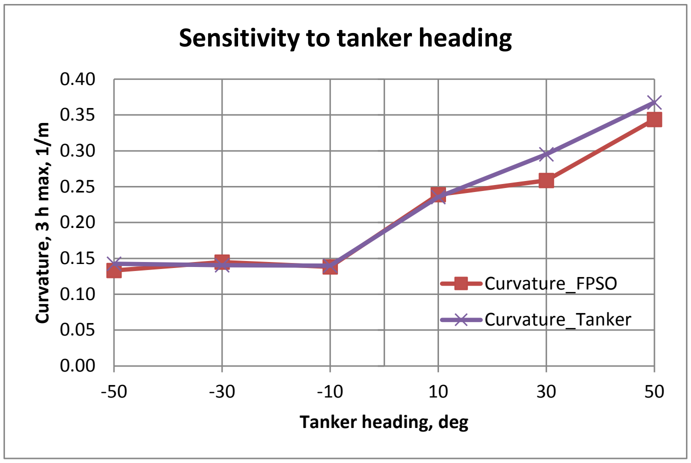

Figure 15 Sensitivity of hose curvature to tanker heading direction. $D_h = 125\ m,\ \theta_h = 130\ deg.$

Ultimate Limit State (ULS) analysis

The specification and general environmental condition for ULS analysis is shown in **Table 3**.

Table 3 General ULS condition.

D_h (m)	L_h (m)	θ_h (deg)	θ_T (deg)	H_s (m)	T_p (s)	U_c (m/s)
90	152.48	194	0	6	13.5	0.89

The 4 cases shown in **Table 4**, representing different load conditions and different environment directions have been checked.

Table 4 Loading condition and weather direction for ULS analysis.

No.	FPSO	Tanker	θ_w (deg)	θ_c (deg)
1	Ballast	Loaded	180	180
2	Ballast	Loaded	210	225
3	Loaded	Ballast	180	180
4	Loaded	Ballast	210	225

When the new hose at maximum pressure (21 bar) is in operation condition, the maximum allowable curvature is 1.3 m^{-1}, and the maximum allowable tension is 1155 kN.

The estimated 3 hours return period hose loads in terms of maximum tension and maximum curvature at the FPSO end and at the Tanker end are shown in **Table 5**. The highest curvature utilization is 17 % (at Tanker end, Case 4) and the highest tension capacity utilization is 27 % (at Tanker end, Case 3).

Table 5 Estimated maximum tension and curvature with 3 hours return period.

	T (kN)		κ (1/m)	
Case	FPSO	Tanker	FPSO	Tanker
1	305	262	0.06	0.18
2	298	252	0.07	0.21
3	277	312	0.06	0.19
4	276	301	0.17	0.22

The maximum tension will occur at the upper end of the hose, where the curvature is either zero, with articulated support, or constant, equal to the guide curvature, in the case of launching over a curved chute. Maximum curvature will always occur in the wave zone at times when the local hose tension is close to zero, or negative. Therefore, in evaluating extreme loads, it is not necessary to consider interaction between tension and curvature, unless compression has a detrimental effect on the curvature capacity.

Accidental Limit State (ALS) analysis

1) Floating Hose

When the offloading hose is in the connecting phase, the hose is gas filled and floating on the sea surface. The density of the gas content is assumed to be 1.5 kg/m^3. A transverse current is assumed with $U_c = 0.25\ m/s$, in order to obtain a well-defined geometry. An element load model with partially submerged cross section is used. In RIFLEX, only regular wave loading is allowed in this case.

The static analysis has been done with varying D_h from 85 m to 135 m, and the results are shown in **Figure 16**. The maximum curvature κ_{max} is close to the asymptotic J configuration curvature value κ_J for horizontal touch down, see Eq. 5 and **Figure 6**.

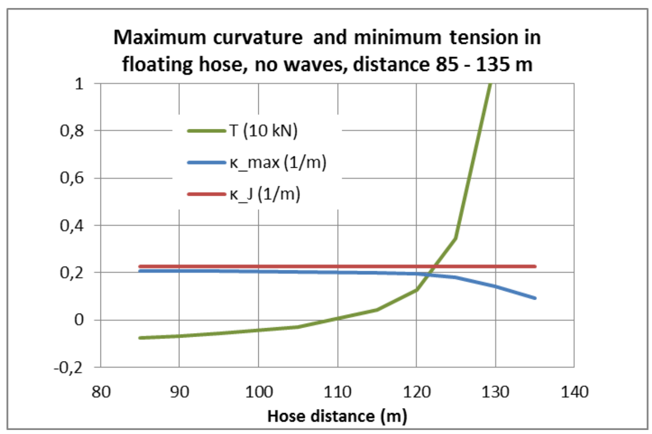

Figure 16 Maximum curvature and minimum tension at a calm water 'touch down' vs. hose distance.'

Dynamic responses in regular waves from 1 to 6 m height with a moderate steepness ($H/L = 1/20$) and with a high steepness ($H/L = 1/7$) level are shown in **Figure 17**. The wave profile curvature shown in the figure, is of little relevance. Since the largest curvatures, in the transition zone from near-vertically suspended to floating, are governed by the vertical motions of wave and of the support points.

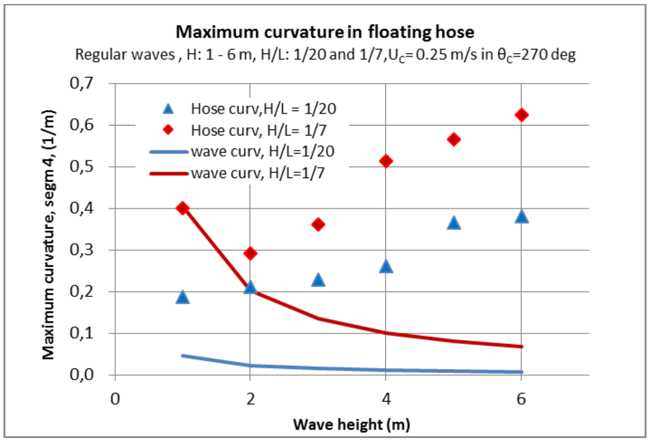

Figure 17 Maximum hose curvature and wave profile curvature for moderate and high values of wave steepness.

The maximum curvature of selected cases is summarized in **Table 6**. The largest curvature occurs below the tanker bow, see **Figure 18** for example.

Table 6 Maximum curvature of selected floating hose cases.

Condition	κ_{max} (1/m)
$H = 6\,m,\ T = 9\,s,\ H/L = 1/20$	0.38
$H = 6\,m,\ T = 5.18\,s,\ H/L = 1/7$	0.65
$H = 6\,m,\ T = 3.66\,s,\ H/L = 1/7$	0.36

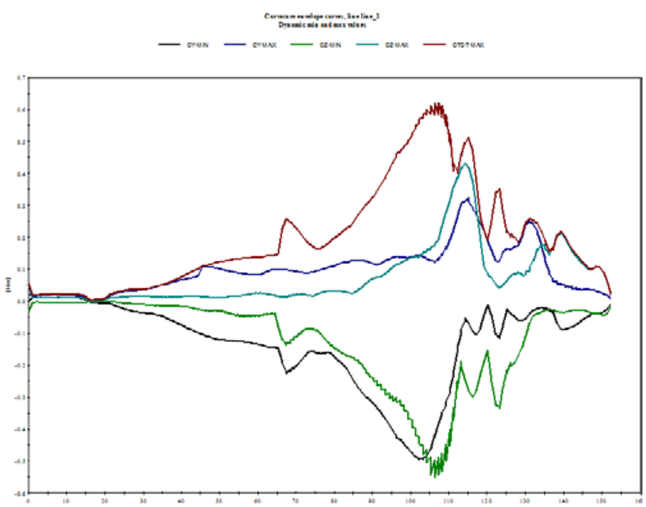

Figure 18 Curvature envelope, left: FPSO stern; right: Tanker bow. H=6 m T=5.18 s, H/L=1/7.

2) Disconnected Hose

An emergency disconnect from the tanker is simulated by a boundary change of the 'tanker hose' supernode at a specified time.

A series of snapshots following release at 100 m distance, in Hs 6 m waves at time 100 s is shown in **Figure 19**.

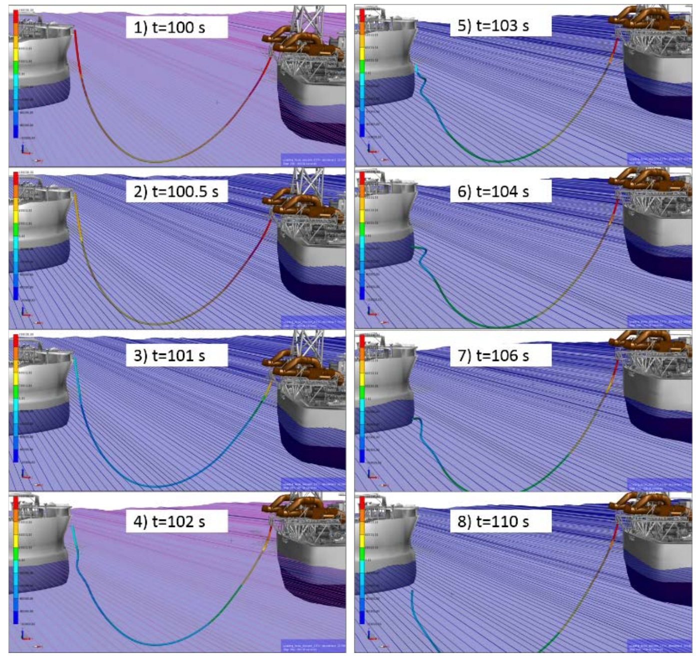

Figure 19 Snapshots of disconnecting process, $D_h = 110\,m$, H_s = 6 m.

The maximum curvature is 0.48 m^{-1} and occurs about 11 m from the hose end at the tanker side, see **Figure 20**. The maximum curvature is well within the capacity of the pressurized and unpressurized hose.

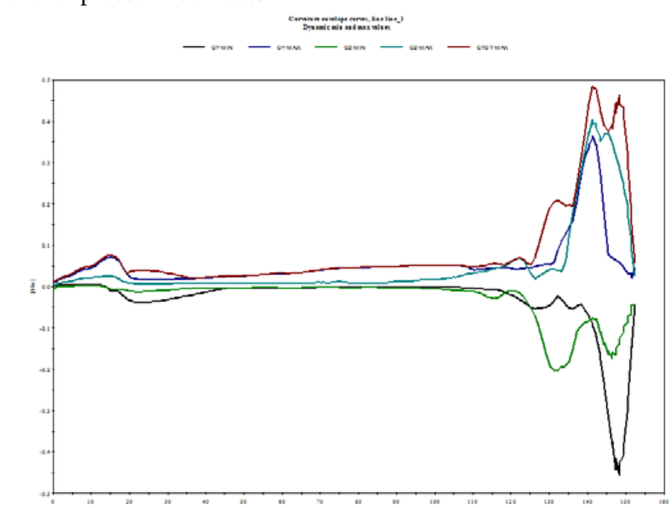

Figure 20 Maximum curvature along the hose. Left: FPSO stern; Right: Tanker bow.

The maximum compression (minimum tension) is ca 118 kN and occurs 9 m below the Tanker bow, 20 m from the end, see **Figure 21**.

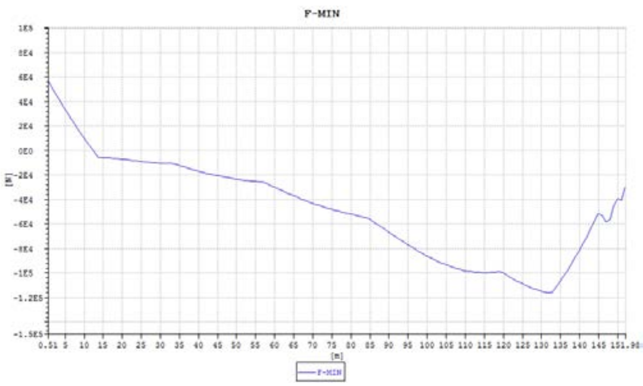

Figure 21 Maximum compression force along the hose. Left: FPSO stern; Right: Tanker bow.

The time series of tension at 3 locations are shown in Figure 22.

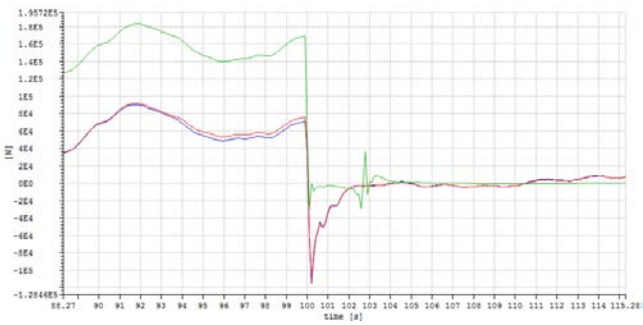

Figure 22 Time series of axial force in elements 2 and 3 of segment 4, ca 15 m below the tanker bow connection (red and blue), and in element 9 of segment 5, at the end of the hose (green).

Fatigue Limit State (FLS) analysis

The different components of the typic offloading hose can be categorized into three groups, see **Table 7**.

Table 7 Different components of typical offloading hoses.

Metallic components	Hybrid polymer layer	Elastomer
• Fitting welds • Binding wire • Embed wire	• Lining – body • Lining- fitting interface • Cover	

The fatigue damage/life of each component are considered separately. A SIMA workflow is established for the fatigue analysis, see **Figure 23**. A workflow in SIMA administrates RIFLEX analysis and post-processes the axial force and curvature along the hose.

In this paper the fatigue calculation of metallic components will be presented. Fatigue analyses of hybrid polymer layer and elastomer have been done in a similar way, but will not be further mentioned.

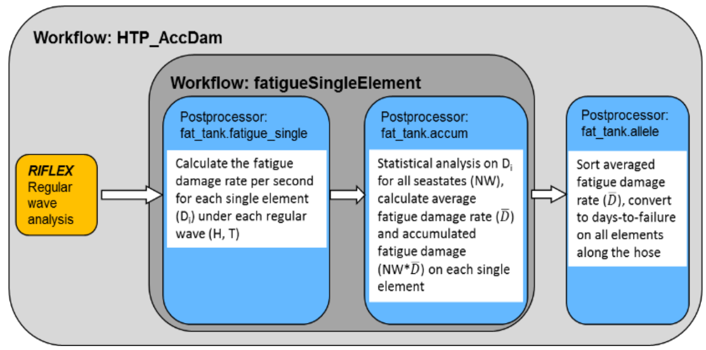

Figure 23 Established SIMA workflow to do fatigue analysis of offloading hose.

The means and ranges of axial force and curvature are converted to either stress or strain using rate independent transfer functions. Linear superposition is assumed on the stresses or strains due to axial force, bending and pressure. At present, all stresses or strains are assumed to be in-phase, so that the total stresses or strains are obtained by directly adding three contributions together. **Figure 24** is a flowchart of calculation of fatigue damage rate of a single metallic component element due to one single regular wave sea-state.

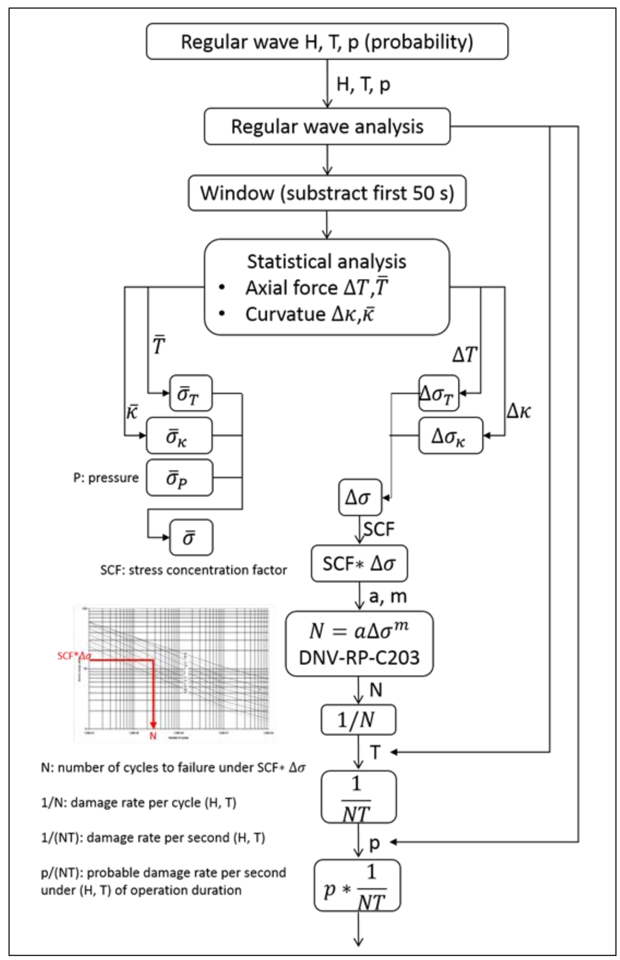

Figure 24 Metallic component single element fatigue damage calculation procedure under one regular wave.

CONCLUSION

A model for calculating dynamic responses in a new loading hose to be installed at a turret moored FPSO has been prepared by means of SIMA. A nonlinear RIFLEX model with excitation from irregular waves, current and forced motions of both end support points is used. Irregular motions of the end supports are pregenerated from the wave pattern using specified motion transfer functions of the two vessels.

Both tension and curvatures are well within the nominal capacities of the hose for the range of operational and environmental parameters covered in this study.

A position sensitivity study on the FPSO has been done on the hose end distance, the hose direction from the FPSO and the tanker heading from the FPSO heading. The results show that the hose has capacity to allow the shuttle tanker to stay anywhere within the ESD2 zone with a heading tolerance of ±45 deg from the FPSO heading.

Emergency disconnect condition and a condition with gas filled, floating hose, are simulated. The results indicate that the tension force and curvature are both well within the hose capacity.

A SIMA workflow is established to calculate accumulated fatigue damage of all the elements along the offloading hose. Damage accumulation models have been specified by the hose supplier. Damage rates are based on stress and strain ranges from dynamic response analysis in regular waves. Realistic model parameters are required in order to perform a numerical testing of the model.

This procedure could be generalized to other offloading hose types and different applications.

FUTURE WORK

It's of interest to compare numerical simulation with model test results if available.

Vortex-induced vibrations due to vessel motions have been observed from previous model tests carried by SINTEF Ocean, and other literatures. The main concern might be increased drag load and potential fatigue damage caused by VIV. This subject has been popular for decades, and could be a part of offloading hose study in the future.

ACKNOWLEDGMENTS

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