International Journal of GEOMATE, Aug. 2019, Vol.17, Issue 60, pp.251-258
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2019.60.84652
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

SUBSEA PIPELINE PROTECTION DESIGN SUBJECTED TO DROPPED ANCHOR USING CONCRETE MATTRESS

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*Corresponding Author, Received: 18 Jan. 2019, Revised: 13 Feb. 2019, Accepted: 28 Feb. 2019

ABSTRACT: Out of the many potential hazards, certain critical possible hazards need to be assessed, and actions need to be taken to improve the probabilities and consequences to an acceptable degree. One of the major hazards commonly found in subsea pipeline operations is a dropped anchor, especially for pipelines located near jetties, where many ships are expected to move across the pipeline. One of the possible protection methods is the use of a concrete mattress. The dropped anchor hazard to a pipeline is characterized by the impact of energy, which will mostly be absorbed by the internal strain energy of the pipeline. The safety criteria for a pipeline subjected to a dropped anchor are given by DNV RP-F107 for the maximum dent depth and DNV OS-F101 for the maximum stress. A finite element analysis using ANSYS software was performed to obtain the maximum equivalent stress and dent depth for a pipeline. The effects of the length and height of a concrete mattress in redistributing the impact energy were obtained.

Keywords: Subsea pipeline, Concrete mattress, Dropped anchor, Finite element analysis

1. INTRODUCTION

Several subsea pipelines, especially those constructed before the current codes and regulations were developed, were laid un-trenched on the seabed, even in near-shore areas. Subsea pipelines that are located in areas of shipping movements or near jetties are susceptible to the effects of a dropped anchor. Dropping an anchor on a pipeline is one of the most serious accidents in the oil and gas industries. The environmental and economic consequences could be substantial if the risk is not carefully assessed. The safety and environmental risks from a dropped anchor are usually determined via a quantitative risk assessment.

This paper presents an assessment of the dropped anchor hazard to a pipeline protected by concrete mattresses. The main objective of this study was to determine how different dimensions for concrete mattresses affect the maximum equivalent stress and dent depth for a pipeline. The assessment was performed according to the common codes of practice. For example, DNV-RP-F107 gives damage classifications based on the dent depth, while DNV-RP-F101 lists classifications based on the maximum stress. The analysis was performed using a transient structural module of the general finite element analysis software ANSYS.

2. LITERATURE STUDY

The damage degree is different in each case, depending on the pipeline's unique properties, including the type and parameters of the vessel, characteristics of the anchor and anchor chain, water depth, and environmental conditions. Thus, more attention should be given to these factors, as well as ship traffic information [5]. Although vessels that move across a pipeline route usually know the exact location of the pipeline to avoid anchoring in that location, anchors might be dropped during emergencies or due to technical failures. Based on the results of the research conducted by [4], it was possible to determine the ships that pose threats to pipelines. The research on a pipeline subjected to a dragged anchor by [10] showed that strain-based criteria provide the optimum result for a dent in a pipeline. Thus, in this study, the stress and dent depth were considered in the analysis. A dropped anchor can rupture a pipeline, which would lead to the leakage of the gas or oil that it contains. This could lead to an emergency shutdown of the production system [7]. The leakage of the gas or oil inside a pipeline is unacceptable because of its effects on the economy, environment, and safety. Therefore, it is necessary to provide adequate protection for a pipeline subjected to the potential dropped anchor hazard corresponding to the largest vessel that is expected to move near the pipeline route. The research on the lateral buckling of a pipeline carried out by [9] showed that a certain point of the pipeline might be highly stressed as a result of the operating and support conditions. This kind of condition can amplify the combined damage effect of a dropped anchor and the operating condition.

2.1 Impact Energy

The kinetic energy of a dropped anchor depends on its mass and velocity. The velocity of an object moving through water depends on the shape of the object and its mass in water. The terminal velocity is obtained when the object is in balance with respect to the gravitational forces, displaced volume, and flow resistance. When the object has reached this balance, it will move at a constant velocity, i.e., the terminal velocity, which can be expressed as the following equation [2]:

$$(\boldsymbol{m} - \boldsymbol{V} \cdot \boldsymbol{\rho_w}) \cdot \boldsymbol{g} = \frac{1}{2} \cdot \boldsymbol{\rho_w} \cdot \boldsymbol{C_D} \cdot \boldsymbol{A} \cdot \boldsymbol{v_T}^2 \qquad (1)$$

$$\boldsymbol{v_T} = \sqrt{\frac{2 \cdot (\boldsymbol{m} - \boldsymbol{V} \cdot \boldsymbol{\rho_w}) \cdot \boldsymbol{g}}{\boldsymbol{\rho_w} \cdot \boldsymbol{C_D} \cdot \boldsymbol{A}}} \qquad (2)$$

where

$\boldsymbol{m}$ = mass of the object (kg)
$\boldsymbol{g}$ = gravitational acceleration (9.81 m/s^2)
$\boldsymbol{V}$ = volume of the object (m^3)
$\boldsymbol{\rho_w}$ = density of seawater (1025 kg/m^3)
$\boldsymbol{C_D}$ = drag coefficient of the object
$\boldsymbol{A}$ = projected area of the object in the flow direction (m^3)
$\boldsymbol{v_T}$ = terminal velocity (m/s)

The kinetic energy of the dropped anchor at the terminal velocity is found as follows:

$$\boldsymbol{E_T} = \frac{1}{2} \cdot \boldsymbol{m} \cdot \boldsymbol{v_T}^2 \qquad (3)$$

In addition to the terminal energy, the impact energy ($\boldsymbol{E_E}$) also includes the energy of the added hydrodynamic mass ($\boldsymbol{E_A}$). The added mass ($\boldsymbol{m_a}$) can be obtained with an appropriate added mass coefficient value ($\boldsymbol{C_a}$) using $\boldsymbol{m_a} = \boldsymbol{\rho_w} \cdot \boldsymbol{C_a} \cdot \boldsymbol{V}$. The effective impact energy can be expressed as follows:

$$\boldsymbol{E_E} = \boldsymbol{E_T} + \boldsymbol{E_A} = \frac{1}{2} \cdot (\boldsymbol{m} + \boldsymbol{m_a}) \cdot \boldsymbol{v_T}^2 \qquad (4)$$

The drag and added mass coefficients are dependent on the geometry of the object. The drag coefficients will affect the terminal velocity of a dropped anchor. The values for the drag and added mass coefficients are given in Table 1.

Table 1 Drag and Added Mass Coefficients (DNV, 2010)

Drag and Added Mass Coefficients		
Shape	$\boldsymbol{C_d}$	$\boldsymbol{C_a}$
Slender	0.7–1.5	0.1–1.0
Box	1.2–1.3	0.6–1.5
Spherical to complex	0.6–2.0	1.0–2.0

2.2 Equivalent (Von Mises) Stress

The forces from a dropped anchor onto a subsea pipeline will induce large reaction forces in the pipeline. The behavior of the pipeline will be governed by elastic bending for smaller displacements. However, for a larger displacement of the pipeline, plastic behavioral characteristics, such as plastic bending and large axial membrane forces, are introduced [8]. The von Mises stress or equivalent stress is a measure used to determine whether a given material will yield or fracture. This type of stress is mostly used for ductile materials such as steels and other metals. The von Mises yield criterion states that if the von Mises stress of a material under load is equal to or greater than the yield limit of the same material under simple tension, then the material will yield.

2.3 DAMAGE CLASSIFICATION

The damage classification for a pipeline is given by DNV RP-F107 (Table 2) based on the dent depth and DNV OS-F101 (Table 3) based on the maximum stress. Based on DNV RP-F107, the material damage to a pipeline is classified using the following categories:

2.3.1 Minor damage (D1)

Damage neither requiring repair nor result in any release of hydrocarbons. Smaller dents in the steel pipe wall, e.g., up to 5% of the diameter, will not normally have any immediate influence on the operation of the line. This limit will vary and must be evaluated for each pipe. However, note that if damage occurs, inspections and technical evaluations should be performed to confirm the structural integrity. Minor damage includes damage to flexibles and umbilicals that does not require repair action. Any local damage to protective coatings or anodes will not normally require repair action.

2.3.1 Moderate damage (D2)

Damage requiring repair, but not leading to the release of hydrocarbons. Dent sizes restricting an internal inspection (e.g., over 5% of the diameter for steel pipelines) will usually require repair. The ingress of seawater into flexibles and umbilicals can lead to corrosion failures. However, the repair may be deferred for some time, and the pipeline or umbilical may be operated provided that the structural integrity is confirmed.

Special consideration should be given to pipelines where frequent pigging is an operational requirement. For such pipelines, large dents will restrict pigging and lead to a stop in production. This damage should then be considered to be major (D3) rather than moderate (D2), even though no release is expected.

2.3.2 Major damage (D3)

Damage leading to the release of hydrocarbons or water, etc. If the pipe wall is punctured or the pipeline ruptures, the pipeline operator must be stopped immediately and the line repaired. The damaged section must be removed and replaced.

In the case of damage leading to a release (D3), the following classifications of releases are used.

2.3.3 No release (R0)

No release.

2.3.5 Small release (R1)

A release from small to medium holes in the pipe wall (<80 mm diameter). The pipeline may release small amounts of its content until detected either by a pressure drop or visually.

2.3.6 A major release (R2)

A release from a ruptured pipeline. A full rupture will lead to a total release of the volume of the pipeline and will continue until the pipeline is isolated.

Table 2 DNV RP-F107 Damage Classification [2]

Dent/Diameter (%)	Damage Description
<5	Minor damage
5–10	Leakage anticipated
10–15	Leakage and rupture
15–20	Leakage and rupture
>20	Rupture

Table 3 DNV OS-F101 Damage Classification [1]

Damage Description	Damage Criteria
No damage	$\sigma_{ym} < \sigma_{allow}$
Minor dent	$\sigma_{allow} < \sigma_{ym} < SMTS$
Minor leak	$SMTS < \sigma_{ym} < 1.1\ SMTS$
Rupture	$\sigma_{ym} > 1.1\ SMTS$

2.4 CONCRETE MATTRESS

Concrete mattresses are widely used in the offshore industry to protect subsea structures, pipelines, etc. Concrete mattresses are mostly used to stabilize subsea structures subjected to hydrodynamic loads, to prevent scouring of the seabed around the protected structure, and as the support for the construction of pipeline crossings [3]. However, a concrete mattress can also provide protection against anchor drop and drag hazards. This is because the force of any sharp object that hits the pipeline will be distributed across the area of the mattress in contact with the pipeline.

3. ANALYSIS AND RESULTS

3.1 Finite Element Model

The pipeline protection was modeled and analyzed using the transient structural modules in the ANSYS finite element analysis simulation software. The purpose of this simulation was to determine the maximum stress in the pipeline, as well as the maximum dent depth, which was assumed to be the parameters indicating the extent of pipeline damage.

The simulation model consisted of several parts, including the pipeline, concrete mattress, and impactor (idealized as a 30 cm × 30 cm × 30 cm cube). The width of the concrete mattress was assumed to be 50 cm. The mass of the impactor was made to be equivalent to the total impact mass of the anchor, including the added mass effect (0.2 times the displaced volume) and a drag coefficient of 0.7. The gravity acceleration of 9.81 m/s^2 was considered in the analyses. The pipeline was modeled to be 3 m longer than the concrete mattress. The finite element model is illustrated in Fig. 1 - Fig. 4 for pipelines without a coating, without a mattress, and with thicknesses of 15 cm and 30 cm for a 200 cm long concrete mattress, respectively.

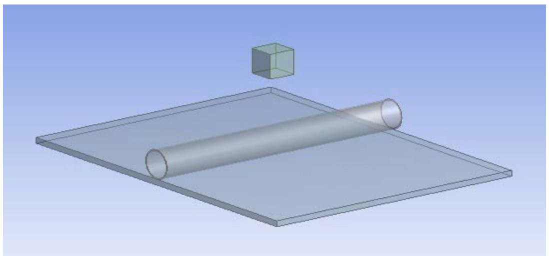

Fig. 1 Finite Element Model Illustration (Without Coating, Without Mattress)

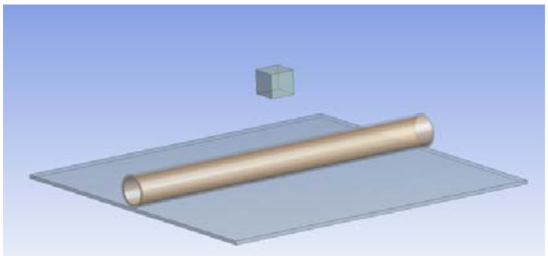

Fig. 2 Finite Element Model Illustration (Without Mattress)

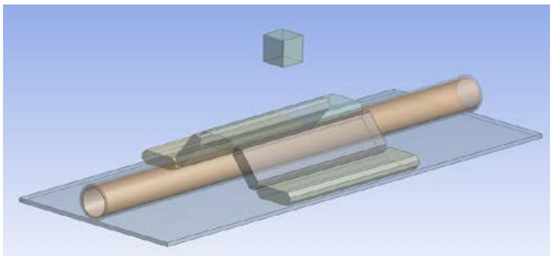

Fig. 3 Finite Element Model Illustration (15 cm Thick Concrete Mattress)

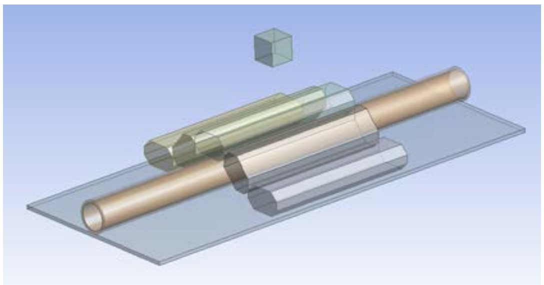

Fig. 4 Finite Element Model Illustration (30 cm Thick Concrete Mattress)

The model meshing of the aforementioned models is illustrated in Fig. 5 – Fig. 8.

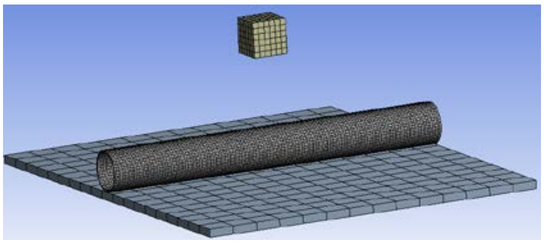

Fig. 5 Model Meshing Illustration (Without Coating, Without Mattress)

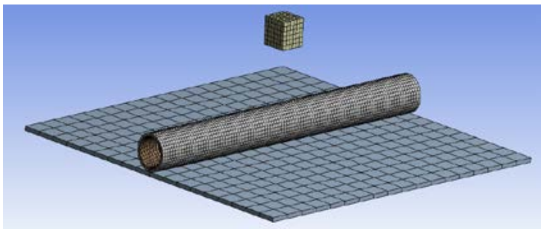

Fig. 6 Model Meshing Illustration (Without Mattress)

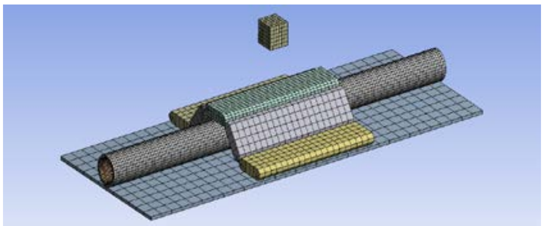

Fig. 7 Model Meshing Illustration (15 cm Thick Concrete Mattress)

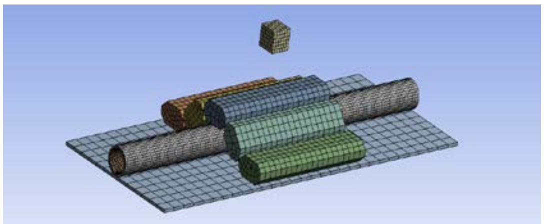

Fig. 8 Model Meshing Illustration (30 cm thick Concrete Mattress)

3.2 Pipeline Properties

The dimensional and material properties of the pipeline considered in this study are given in Table 4. The weight of the anchor, which was modeled as a cube, was based on the weight (3,700 kg) the anchor commonly used for a 15,000 DWT ship. The total impact energy was calculated to be 85.9 kJ using Eq. (4). The contact surface between the concrete mattress and pipeline was rough (no sliding), whereas the contact between the concrete mattress and seabed had no separation of the corner joint of the mattress with the seabed. The finite element analysis results in terms of maximum equivalent stress and dent/diameter ratio as presented in Table 5.

Contour plots are depicted in Fig. 9 - Fig. 11 for the four cases illustrated in Fig. 1 - Fig. 4. Plots of the results are depicted in Fig. 13 - Fig. 14 for the dent depth and maximum stress in the pipeline, respectively.

Table 4 Pipeline Properties

Property	Values	Unit
Structural Steel Density (ρ)	7850	kg/m^3
Concrete Density (ρ)	2300	kg/m^3
Structural Steel Elasticity Modulus (E)	200000	Mpa
Concrete Elasticity Modulus (E)	30000	Mpa
Structural Steel Yield Strength (Fy)	317.1589	Mpa
Structural Steel Ultimate Strength (Fu)	434.3698	MPa
Concrete Compressive Ultimate Strength (Fu)	41	MPa
Concrete Tensile Ultimate Strength (Fu)	5	MPa
Concrete Poisson's Ratio	0.18	-
Structural Steel Poisson's Ratio	0.3	-
Pipeline Diameter	35.56	cm
Pipeline Wall Thickness	1.27	cm
Concrete Coating Thickness	2.54	cm

Table 5 Finite Element Analysis Results

No.	Case	Stress (Mpa)	Dent/ Diameter
1.	No Coating, No Mattress	419	38.2%
2.	Concrete Coating, No Mattress	393	14.8%
3.	Concrete Coating, 15 cm Thick & 40 cm Long Mattress	363	11%
4.	Concrete Coating, 15 cm Thick & 120 cm Long Mattress	333	6.2%
5.	Concrete Coating, 15 cm Thick & 200 cm Long Mattress	325	4.6%
6.	Concrete Coating, 15 cm Thick & 280 cm Long Mattress	318	3.46%
7.	Concrete Coating, 15 cm Thick & 400 cm Long Mattress	314	2.8%
8.	Concrete Coating, 15 cm Thick & 600 cm Long Mattress	287	2.25%
9.	Concrete Coating, 30 cm Thick & 40 cm Long Mattress	360	11%
10.	Concrete Coating, 30 cm Thick & 200 cm Long Mattress	323	4.6%

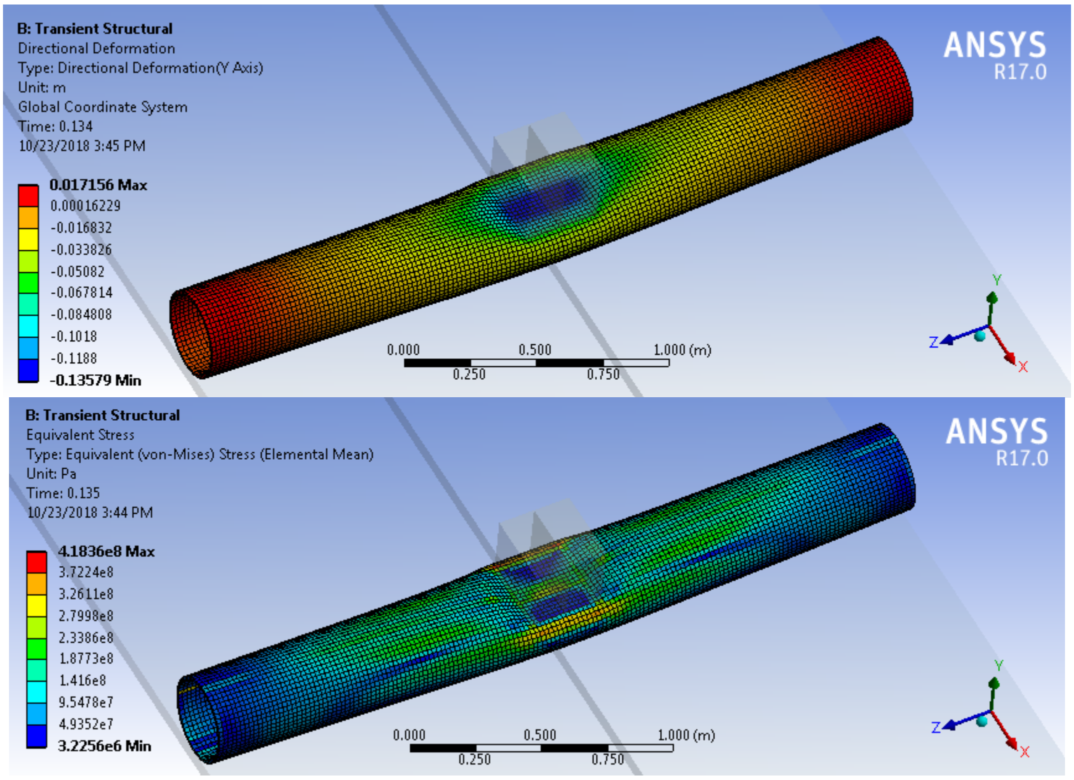

Fig. 9 Finite Element Results (Without Coating, Without Mattress) for Dent Depth (Top) and Maximum Stress (Bottom)

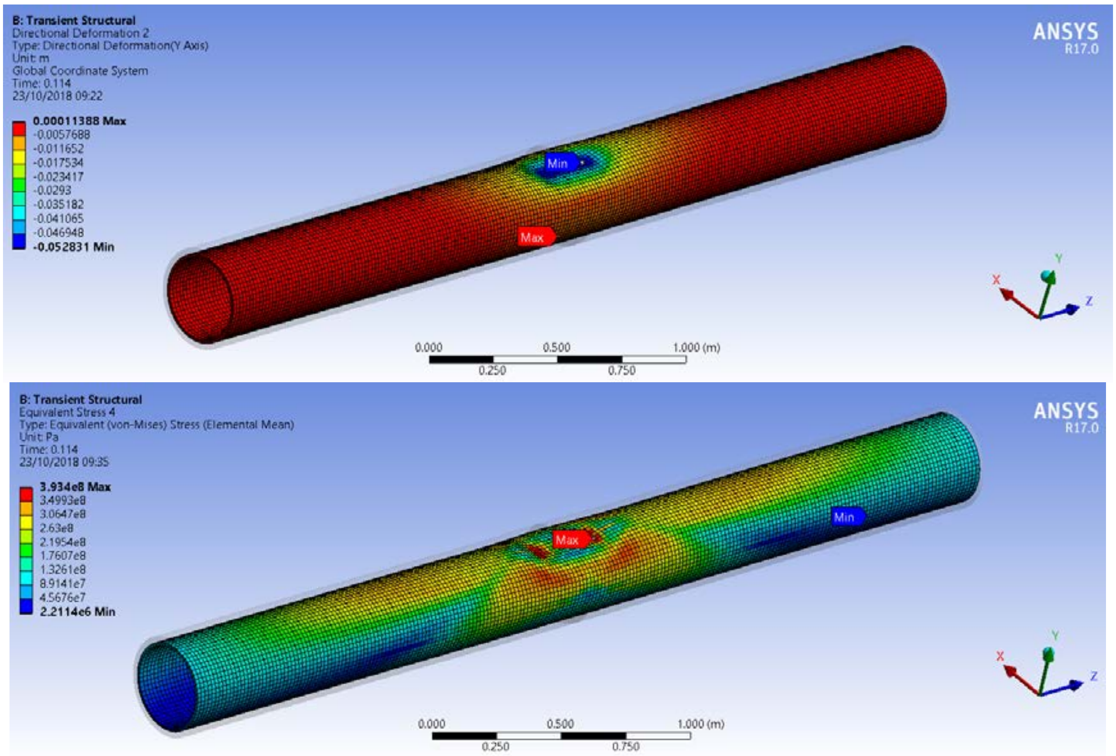

Fig. 10 Finite Element Results (With Coating, Without Mattress) for Dent Depth (Top) and Maximum Stress (Bottom)

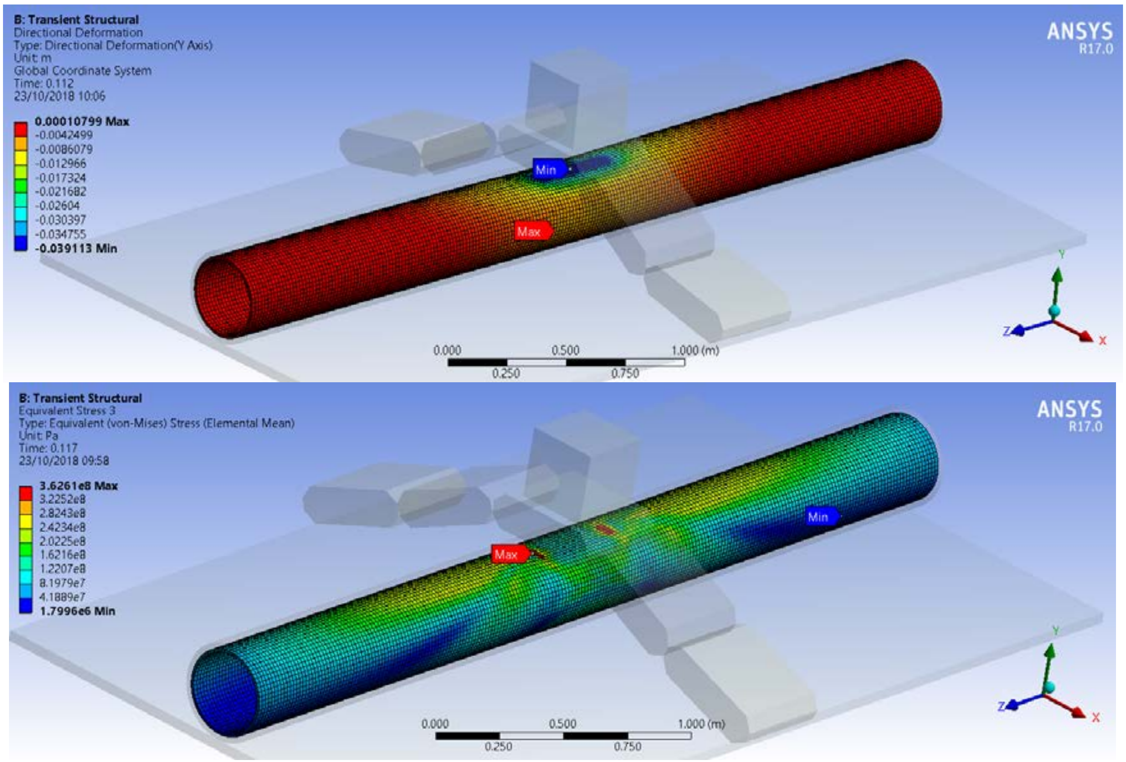

Fig. 11Finite Element Results (With Coating, 15 cm Thick Mattress) for Dent Depth (Top) and Maximum Stress (Bottom)

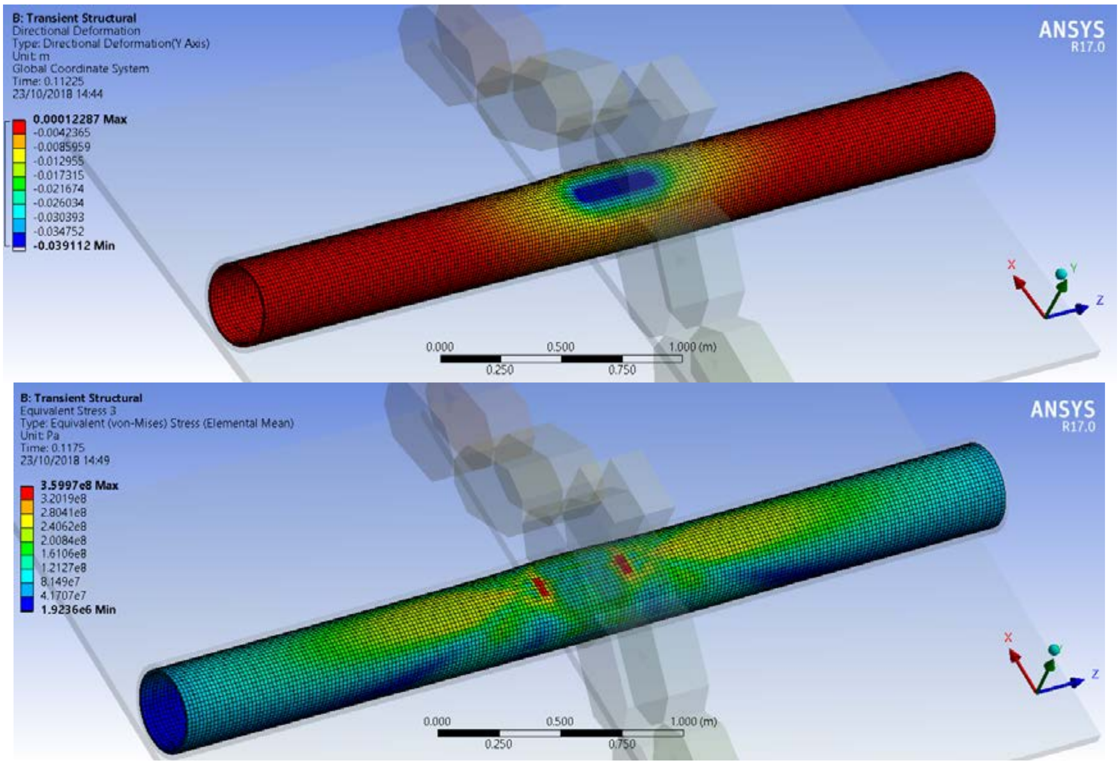

Fig. 12 Finite Element Results (With Coating, 30 cm Thick Mattress) for Dent Depth (Top) and Maximum Stress (Bottom)

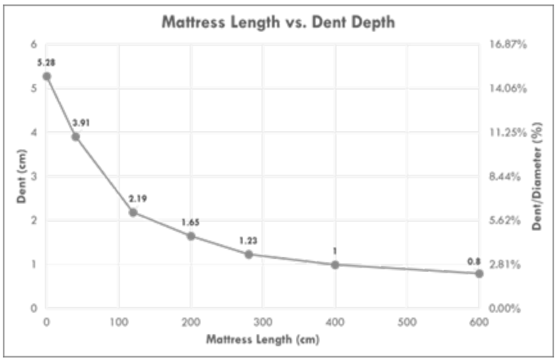

Fig. 13 Plot of Results for Dent Depth and Mattress Length

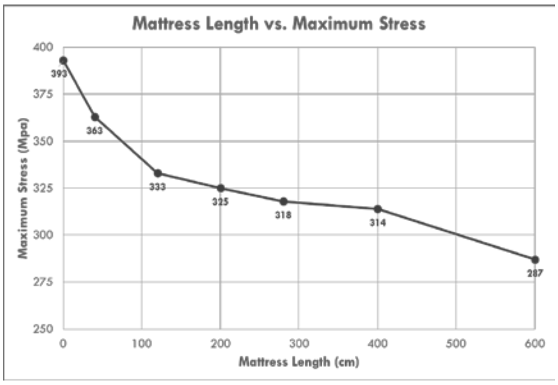

Fig. 14 Plot of Results for Maximum Stress and Mattress Length

3.3 CONCLUSIONS

Based on the results of the simulation of an anchor dropped on a pipeline protected by a concrete mattress, several observations can be made as follows.

1. A concrete mattress can be used for subsea pipeline protection against a dropped anchor, which will significantly reduce the maximum stress and dent depth for the subsea pipeline. The maximum stress without concrete mattress is 393 MPa and with concrete mattress is 287 MPa. The dent depth without concrete mattress is 14.8% and with concrete mattress is 2.25%.
2. It was found that increasing the length of the concrete mattress decreased the dent depth and maximum stress of a subsea pipeline produced by a dropped anchor more effectively than increasing the thickness of the concrete mattress. The maximum stress with 40 cm long concrete mattress is 363 MPa and with 600 cm long concrete mattress is 287 MPa. The dent depth with 40 cm long concrete mattress is 11% and with 600 cm long concrete mattress is 2.25%.

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