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PARAMETERS THAT RULE THE LOADS ON THE VERTICAL CONNECTION MODULES DURING SUBSEA DIRECT TIE-INS

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Abstract. The use of vertical connection module (VCM) has been the most conventional solution for direct lay-away connection between flowlines and subsea equipment offshore Brazil. A comprehensive study of the forces and moments exerted onto its gooseneck during the most critical phases of the connection is carried out herein, aiming at understanding their magnitude and sensibility to parameters such as pipe's bending stiffness. Finite-element techniques are employed in a quasi-static model comprising VCM and its rigid gooseneck, end-fitting, bend restrictor, flexible pipe and winch cables.

1 INTRODUCTION

In the subsea production systems using wet Christmas trees and flexible flowlines operating offshore Brazil, the use of guidelineless direct lay-away connection, with flowlines and subsea equipment interfaced by vertical connection modules (VCMs), has been the most common engineering choice since the last decade[3, 2] (see figure 1). Its convenience arises from the logistics concerned to subsea equipment and flowlines: they are usually manufactured by different suppliers and often require different offshore facilities to be installed, according to slightly different schedules. Furthermore, such tie-in method is compatible with tools and practices avaliable in most of the pipelay service vessels that can handle flexible pipes and has high success rate even for water depths exceeding 2,000 m. Some restraints indeed apply, because the flexible flowlines shall not exceed the curvature limit informed by its manufacturer, whereas the stress limits shall also be respected along the gooseneck. These limitations may affect the equipment design or the connection process.

The direct lay-away connection process comprises a few phases: (1) VCM lowering and approach to the equipment by winch payout; (2) VCM settlement onto the equipment and locking in position; (3) flowline release and settlement.

During the first phase, the dynamically-positioned pipelay vessel (PLSV) lowers the VCM and the flowline termination by paying the main winch cable out. In case of first-end connection, the flowline simultaneously is paid out, whereas the ancillary winch is paid out if second-end connection is used. The static equilibrium can be understood with the aid from a free-body diagram (see figure 2). During the final approach, the pulling forces and motions are controlled by the pipelay engineer in charge of the operation by paying out and retrieving the flowline and the winch cables, based on images acquired by remotely operated vehicle (ROV). By controlling the amount of pipe tension, the rigid-body rotation of the VCM can be driven, but any increase or decrease of it will likely make the VCM move laterally as side effect. The whole system is affected by vessel motions and there is a delay between the command and the action, thus the VCM positioning can become an interesting exercise of dynamic control.

The settlement phase comprises to align the module's bottom structure to the entry funnel or the mandrel in the subsea equipment. A deviation to the vertical direction is generally constrained not to exceed $\pm 1^\circ$, whereas the downmost section of the flowline termination (usually in the bend restrictor section) shall not touch the seabed. After the VCM is found to be in the due position, it is hydraulically locked. Then the gooseneck becomes a fixed end. End forces and moments arise at that connection point and, because of the vessel motions, an excess of curvature or load can be achieved if the flowline is held into the bent configuration too long. Therefore, the flowline or ancillary winch is released as fast as possible and the flowline is laid on the seabed, reducing the end loads and completing the operation.

The magnitudes of the shear force, the tension and the bend moments transmitted from the flowline termination assembly to the gooseneck flange depend on a number of factors. By varying the parameters and quantifying the trends, a study can help the subsea equipment designers to identify cases in which higher strength may be necessary to deal with increased stiffness (e.g.: insulated pipes), weight (e.g.: longer end fitting) or suspended length (e.g.: higher vertical position of the gooseneck flange) of the flowline termination assembly.

The influence from the non-linearity in the pipe's bending stiffness was already studied in LOPES[1], using static simulations and the software ORCAFLEX. The geometry, stiffness and

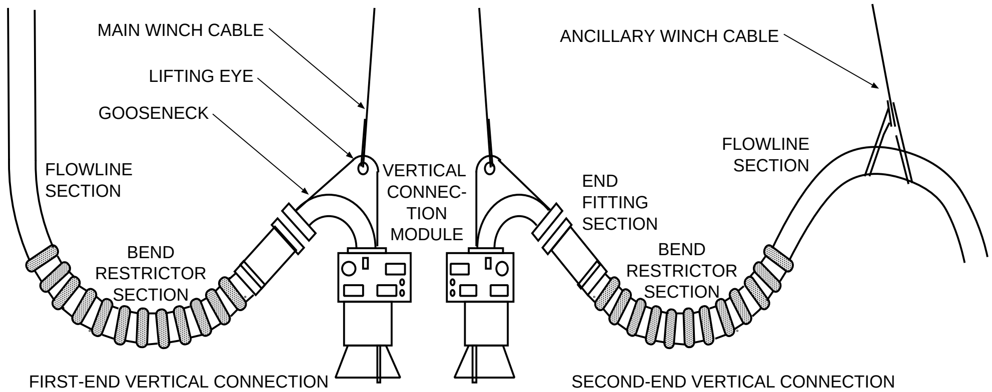

Figure 1: Vertical connection module and flowline termination assembly.

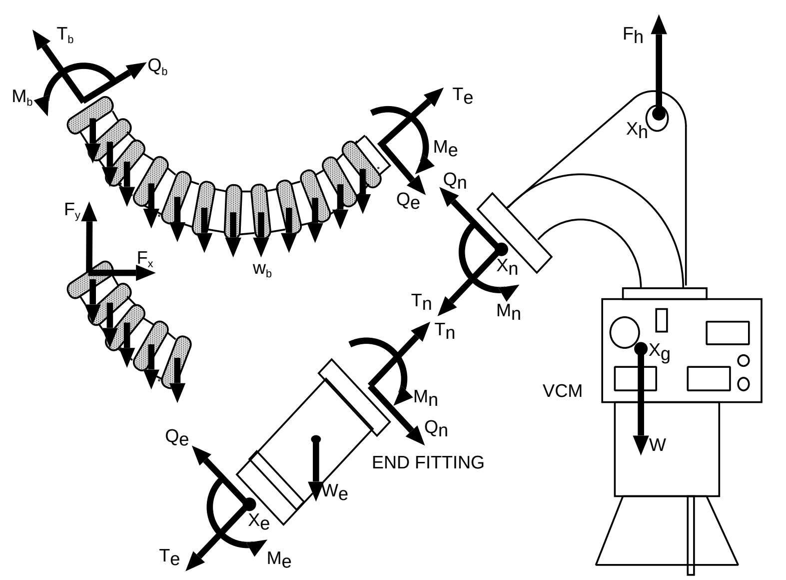

Figure 2: General forces in the VCM, end fitting and bend restrictor before connection.

mass parameters given in that study will be used as the base case herein. The authors' experience suggested that changing a few parameters in the system design or configuration may increase or diminish the loads very much, hence every project should be modelled in detail using ORCAFLEX or other FE package. This study also aims at finding general rules and trends on the magnitude of loads for varying gooseneck angle, pipe stiffness, curvature and pulling force, component weights and other parameters.

2 BASIS

The structural system may be divided into two parts: the vertical connection module (VCM) itself and the flowline termination assembly – comprising end fitting, bend restrictor and the flowline sections. A third element, the main winch cable, becomes unimportant after the VCM is locked. Ancillary winch cable for second-end connection can be replaced by an equivalent force. In order to make a few hypothesis consistent, suppose that the connection occurs at depth above 1,000 m, thus the flowline and the winch cable are almost vertical in their top edge.

The pipeline termination assembly can be modeled as one section of rigid beam and two other sections of deformable beams under edge loads and distributed wet weight. Consider the end fitting section infinitely stiff, with length l_e and submerged weight w_e (full of fluid condition). Let w_b, l_b and EI_b be the distributed weight (submerged, full of fluid condition), length and bending stiffness of the bend restrictor section; and w, l, EI and κ_{adm} be the distributed weight (submerged, full of fluid condition), length and bending stiffness and allowable curvature of the flowline section.

The VCM is taken as a rigid body, whose relevant points are its centre of gravity, the lifting eye and the gooseneck's edge[1]. Let $\mathbf{X}_g \equiv (x_g, y_g)$, $\mathbf{X}_h \equiv (x_h, y_h)$ and $\mathbf{X}_n \equiv (x_n, y_n)$ be respectively the coordinates of the centre of gravity of the vertical connection module, of the lifting eye and of the edge of gooseneck. Let W, $\mathbf{F}_h$, $\mathbf{F}_n$ and M_n be respectively the VCM's weight (in vertical direction), lifting force, the resultant of forces applied by the flowline onto the edge of the gooseneck and the bending moment about the normal to the bending plane. The force $\mathbf{F}_n$ encompasses shear force Q_n and tension T_n at the gooseneck edge.

The main winch cable is linked to the VCM lifting eye, thus a force $\mathbf{F}_h$ supports the weight from VCM and part of the flowline termination assembly. Notice that flowline and the winch cable's downmost edges have to be connected to the VCM and that there is a distance between the winch and the pipe laying system on the vessel's main deck – sometimes they are located in opposite boards –, thus the pipe cannot be perfectly vertical, i.e.: the pipe declination at top $\vartheta_n(l)$ cannot be 90° and a horizontal component H_0 of the pipe tension will exist at top. If it is assumed that the distributed drag forces are negligible, the force H_0 is not expected to change along the flowline.

After the VCM settlement, the force $\mathbf{F}_h$ is not required to hold them up, as well as the VCM's weight W is balanced by contact forces over the bottom structure. In fact, dealing with $\mathbf{F}_h$ and W has no sense after that, thus the study gets limited to the magnitude of Q_n, T_n and M_n for different system parameters.

The end-fitting is taken as a rigid body in the analytical development, because its bending stiffness exceeds 20 times the flowline stiffness and it is linked to other rigid body (the VCM),

[1] Other point of usual attention is the downmost end of the gooseneck, because there is a weak link therein designed to break in case of excess of load, in order to protect the remaining structure.

so the computation of its end forces by finite element analysis is not very reliable. Make $W_e \equiv w_e\, l_e$ and the forces and bending moments at gooseneck end are then given by:

$$Q_n = Q_e - W_e \cos \overset{+}{\vartheta}_n \tag{1a}$$

$$T_n = T_e + W_e \sin \overset{+}{\vartheta}_n \tag{1b}$$

$$M_n = M_e + \frac{W_e\, l_e}{2} \cos \overset{+}{\vartheta}_n - Q_e\, l_e \tag{1c}$$

... where $\overset{+}{\vartheta}_n$= angle between gooseneck end axis and the horizon including any VCM rigid-body rotation $\delta\vartheta_g$, which is assumed to be small:

$$\overset{+}{\vartheta}_n = \overset{\circ}{\vartheta}_n + \delta\vartheta_g \tag{2}$$

By using the equations (1), the forces and moment at the gooseneck end after the VCM locking become functions of Q_e, T_e and M_e, which depend on the flowline and bend restrictor characteristics and configuration.

The bend restrictor section and the flowline sections are continuous beams under distributed weight and buoyancy loads, which are vertical loads. The tension and the shear force can be evaluated at any point along its length by:

$$T = -F_x \cos \overset{+}{\vartheta} + F_y \sin \overset{+}{\vartheta} \tag{3a}$$

$$Q = F_x \sin \overset{+}{\vartheta} + F_y \cos \overset{+}{\vartheta} \tag{3b}$$

... where: $F_x(s)$= horizontal force, which is nearly constant; $F_y(s)$= vertical force, which depends on the integration over length; $\overset{+}{\vartheta}(s)$= local angle with respect to the horizon.

Both beams can be analytically and numerically modelled. In benefit of standardization of the analysis herein, the case of free-hanging pipe is studied at first. The free-hanging pipe stands for a situation with no excess of tension in the downmost sections, but it is not the less challenging configuration in terms of curvature, because additional pipe length might be paid out in order to relieve the bending moment at the connection to the stiff edge.

Consider a free-hanging pipe, whose rotation at the first edge at $s = 0$ is prescribed $\vartheta_{s=0} = \overset{+}{\vartheta}_n$ and that the horizontal force F_x is constant and equal to H_0 (i.e. no distributed force in horizontal direction exists). The results of rotation, curvature, tension, shear force and moment along the length of the free-hanging beam can be evaluated at any position s for a given end angle $\overset{+}{\vartheta}_n$ and horizontal force H_0. In fact, the computation of these components of displacement and force can be generalized by using non-dimensional parameters:

$$\tilde{T} = \frac{T}{EI}\left(\frac{EI}{w}\right)^{\frac{2}{3}}, \quad \tilde{Q} = \frac{Q}{EI}\left(\frac{EI}{w}\right)^{\frac{2}{3}}, \quad \tilde{H}_0 = \frac{H_0}{EI}\left(\frac{EI}{w}\right)^{\frac{2}{3}}, \quad \tilde{M} = \frac{M}{EI}\left(\frac{EI}{w}\right)^{\frac{1}{3}}, \tag{4a}$$

$$\tilde{w} = \frac{w}{w} \equiv 1, \quad \tilde{EI} = \frac{EI}{EI} \equiv 1, \quad \tilde{\kappa} = \kappa\left(\frac{EI}{w}\right)^{\frac{1}{3}}, \quad \tilde{s} = s\left(\frac{w}{EI}\right)^{\frac{1}{3}} \tag{4b}$$

The number of possible curves of internal forces or displacements versus length for each combination of $\overset{+}{\vartheta}_n$ and $\tilde{H}_0$ is infinite. A proper strategy shall be designed thus.

3 PRELIMINARY SYSTEM ANALYSIS

Firstly the curves for the free-hanging pipe with $\overset{+}{\vartheta}_n = \{45°, 60°\}$ and several values of $\tilde{H}_0$ are generated, because they can be applied to the study of the bend restrictor section[2]. The figures 3 and 4 show the rotation ϑ, the curvature[3] $\tilde{\kappa}$, the shear force $\tilde{Q}$ and tension $\tilde{T}$ along the length (in the abscissa) for a free-hanging pipe of constant stiffness, whose edge at $s = 0$ is constrained after a rotation of $\overset{+}{\vartheta}_n = 45°$. The figures 5 and 6 show the rotation ϑ, the curvature $\tilde{\kappa}$ shear force $\tilde{Q}$ and tension $\tilde{T}$ over a length $\tilde{\ell}$ (in the abscissa) for the pipe with $\overset{+}{\vartheta}_n = 60°$. The location where the local angle is null is the downmost position of the pipe, which shall not touch the seabed before it is released. When no horizontal force exists in the free-hanging pipe, that downmost point is found at $\tilde{s} \approx 0,65$; when horizontal force $\tilde{H}_0 = 1.0$, that point is found at $\tilde{s} \approx 0,75$.

The extreme curvature is found to occur at the pipe end for both situations. There is a slight trend on the rise of curvature when angle $\overset{+}{\vartheta}_n$ increases, but the graphs 3 and 5 cannot explain any further. In order to examine the correlation between the curvature and the angle, an additional FE model, in which the edge angle varied and the free-hanging condition is preserved, was run and its results are presented – with due correction of signal as applicable[4] – in the figure 7. Notice that the condition for null edge angle affords non-dimensional curvature around 1.1, which confirms the “natural bending radius” given in the technical literature of flexible pipes. The curvature is shown to increase when the gooseneck angle does. The horizontal force unfolds the pipe, thus it reduces the curvature. However, its effect in curvature reduction is lower than intuitively expected.

Paying out the pipe when the VCM is already locked in the position alleviates the curvature. This operation will have to be carried out soon after the VCM is seen to be locked. If done beforehand, however, it can make the pipe prematurely touch the seabed while a large amount of dynamic motion is still present or it can impose compression onto the pipe. In contrast, retrieving the pipe applies an additional pull that increases the curvature, which shall be avoided. However, it can be necessary if the pipe sagbend is too near the seabed. Suppose that an added vertical load $\tilde{V}_0$ is applied at the upmost edge of the hanging pipe. The figure 8 shows the effects of the added or removed pull (negative if the tension is reduced by payout) in the extreme curvature and the downmost position of the sagbend in relation to the pipe edge for the end angles of 45° and 60°. The curvature is shown to increase very much as the vertical force increases. It is minimum when the added vertical force $\tilde{V}_0$ is around -1.8. Paying additional pipe out from this minimum-curvature point will revert the curvature, which will rise again. The vertical distance between the sagbend section and the pipe end is shown to rise when the pipe is paid out, but retrieving it has little effect because the free-hanging condition ($\tilde{V}_0 = 0$) is already a condition of very bent pipe with short excess in length. By using the graph at right in figure 8, a pipeline engineer can also assess the vertical load when the pipe is released, since the vertical distance between the pipe end and the seabed is known.

[2] The angles of 45° and 60° are typical engineering choices for the gooseneck angles and, taken the end fitting as rigid, the angle at the bend restrictor end will be nearly the same. The uncertainty $\pm 1°$ is due to misallignment allowances.

[3] Notice that the $\tilde{M} = \tilde{\kappa}$.

[4] The postprocessing of FE model considers the motion from “neutral angle” equal to 90° to a negative value of the end angle.

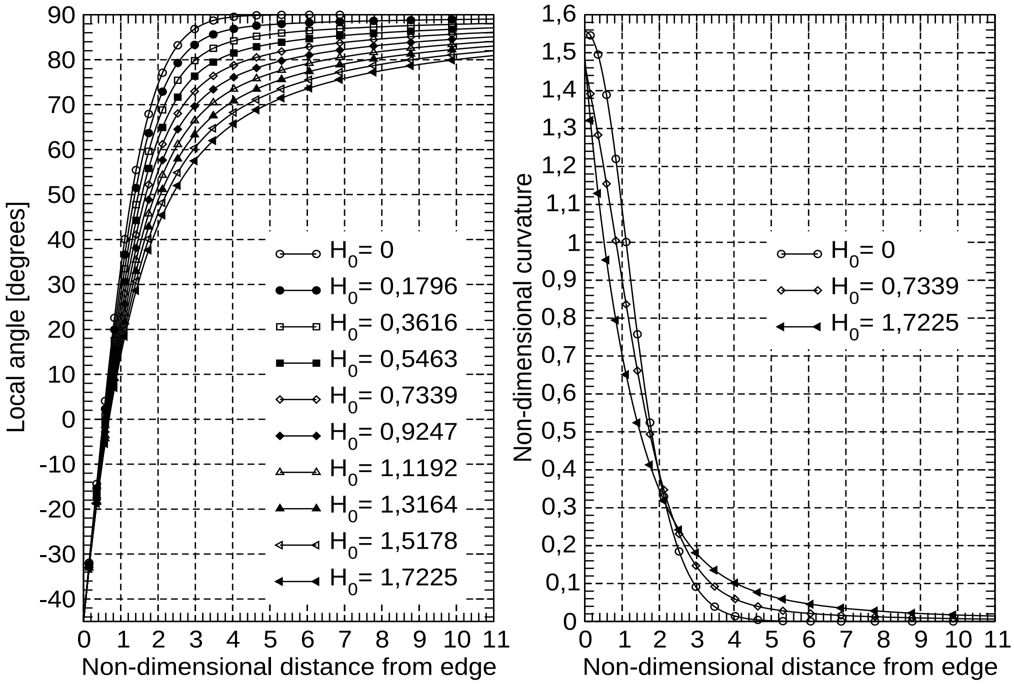

Figure 3: Angle and non-dimensional curvature for a free-hanging pipe with edge at 45°.

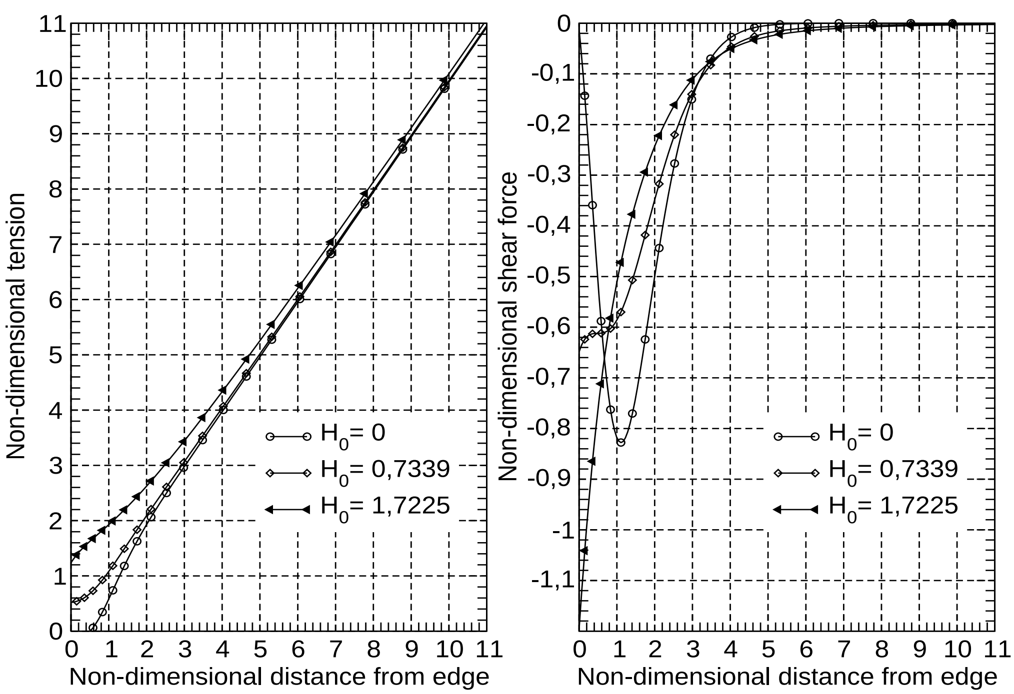

Figure 4: Non-dimensional tension and shear force for a free-hanging pipe with edge at 45°.

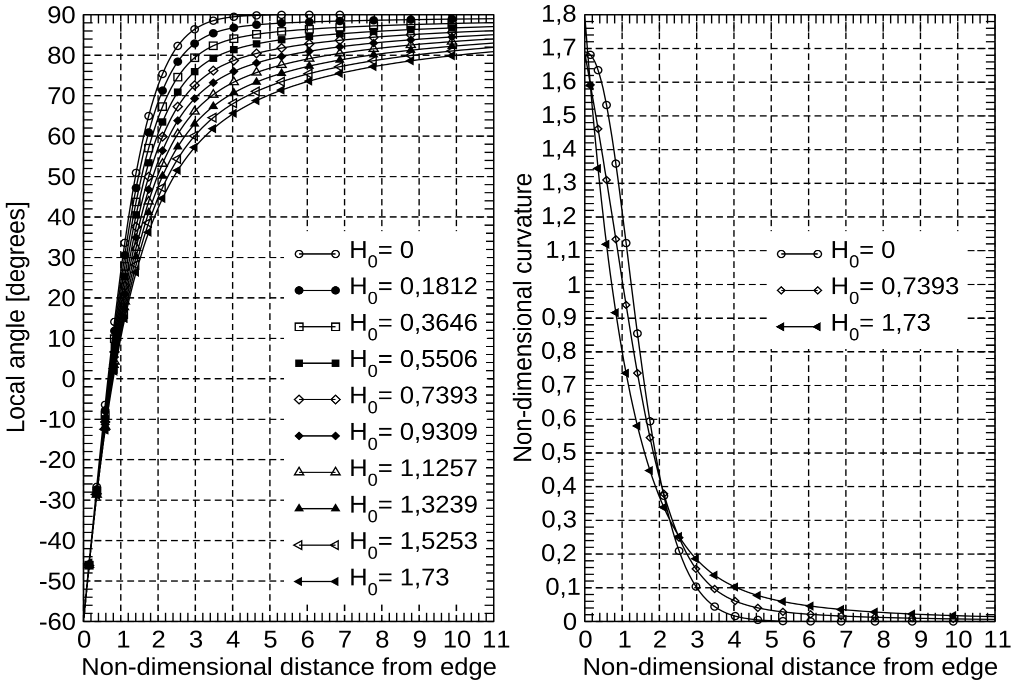

Figure 5: Angle and non-dimensional curvature for a free-hanging pipe whose downmost edge is restrained at 60°.

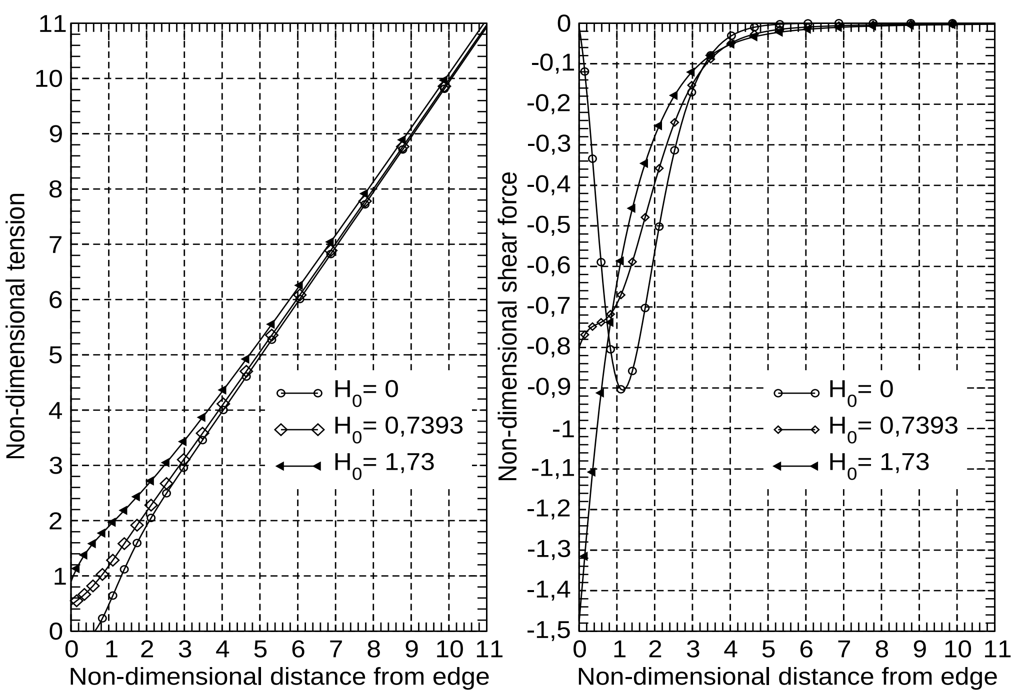

Figure 6: Non-dimensional tension and shear force for a free-hanging pipe with edge at 60°.

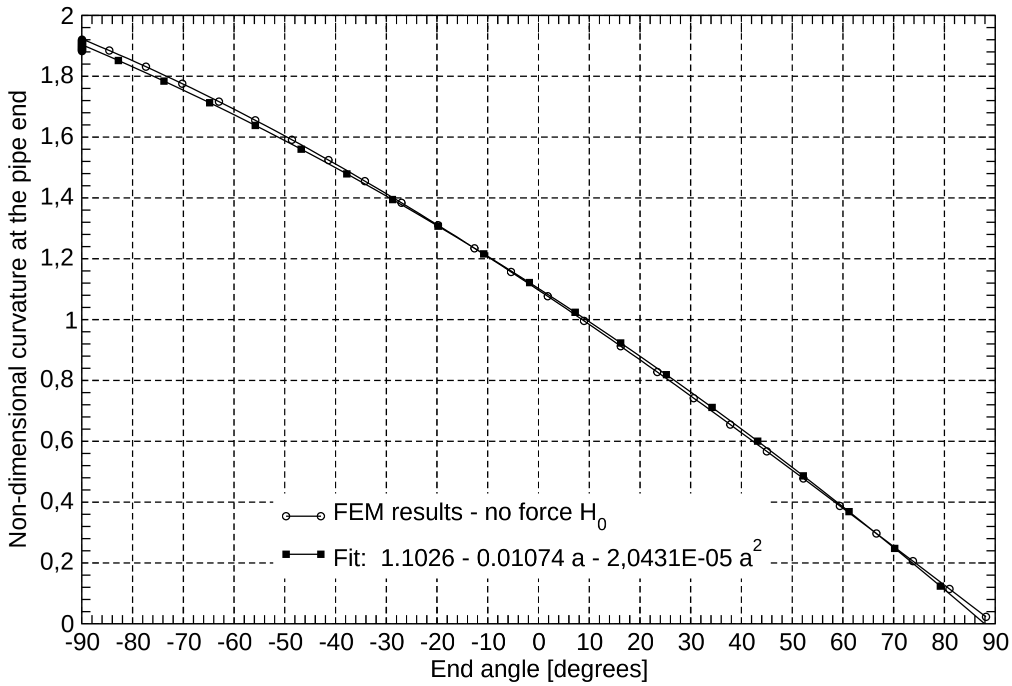

Figure 7: Non-dimensional curvature for free-hanging pipe with edge varying from -90 to 60°.

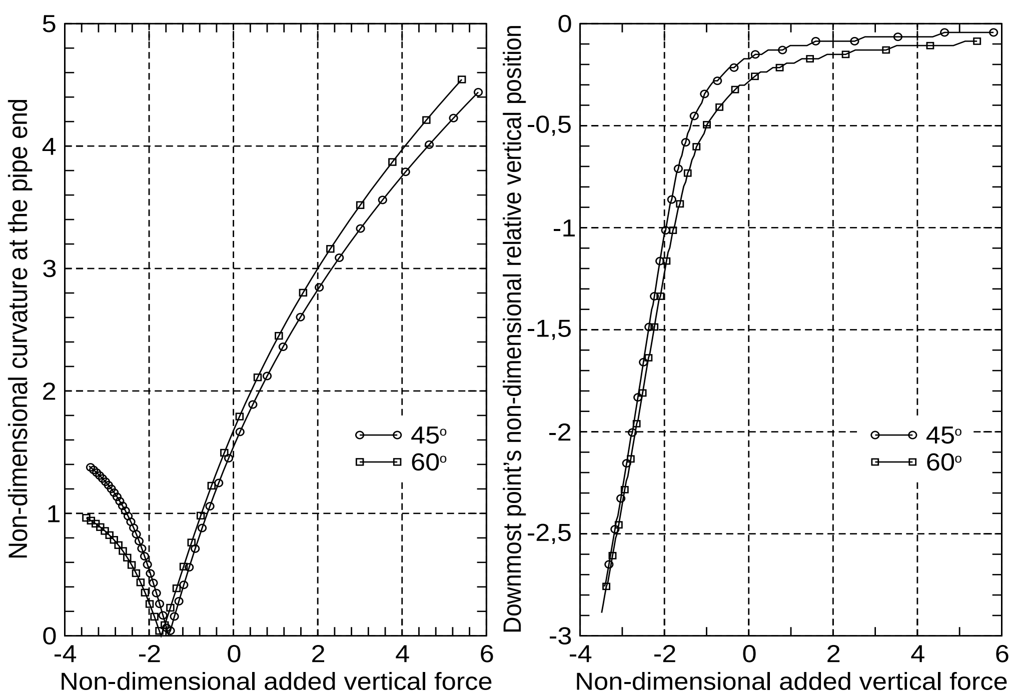

Figure 8: Effect from the pipe payout and retrieval on the non-dimensional curvature and relative height of the downmost section of the sagbend for edge angle of 45 and 60°.

4 STUDY OF FIRST-END VERTICAL CONNECTION AND EFFECTS FROM STIFFNESS VARIATION

Suppose a case in which the conventional installation had always been performed using pipes within a certain range of values of stiffness and weight for each diameter, so the VCM's structure might have been standardized to accelerate its procurement. However, the connection of large-diameter, heavily insulated flowlines is foreseen, so the engineers have to revise the VCM's structural design. It is necessary to assess the load uprise for significant increases in pipe bending stiffness, weight and subsea Christmas-tree's height.

The base case consists of VCM, conventional 6"-ID production flowline and its accessories (bend restrictor and end fitting). The VCM's gooseneck centreline ends at 2.00 m above the seabed with angle of 45° and the coordinates of that end are $\mathbf{X_n} = (0.74, 2.00)$. The lifting eye is located at $X_h = (-0.142, 2.9)$. The coordinates of the VCM's centre of gravity are $\mathbf{X_g} = (0.132, 1.15)$. For the flowline, bend restrictor and end fitting, the following parameter apply:

$$
\begin{aligned}
EI &= 23.4\ \text{kNm}^2, \quad w = 34.81\ \text{kgf/m (empty)}, 53.41\text{kgf/m (full)}, \quad l = 1200\ \text{m},\\
EI_b &= 23.4\ \text{kNm}^2, \quad w_b = 44.8\ \text{kgf/m (empty)}, 63.4\ \text{kgf/m (full)}, \quad l_b = 2.5\ \text{m},\\
EI_e &= \infty, \quad w_e = 390.0\ \text{kgf/m}, \quad l_e = 1.5\ \text{m}, \quad \kappa_{adm} = 0.704\ \text{m}^{-1}.
\end{aligned}
$$

The analysis was carried out using the FE package ABAQUS/Standard version 6.8. The model uses B21 elements for pipes and winch cables and rigid elements RB2D2 for the VCM's body and its gooseneck (see figure 9). The mesh of the VCM's body consists of simple connections between nodes where relevant forces are applied, it has no further physical aim. The end fitting's mesh consists of 25 very stiff beam elements[5]; the bend restrictor is made of 60 elements and the flowline is made of 114 elements, whose lengths increase as more distant they are from the connection. The seabed is a rigid analytical surface. Three load steps are used:

- Catenary and VCM lowering (time ranging from 0 to 1): the pipe is made initially straight (zero-moment condition), so it is bent within this load step by applying weight and edge motions. Instead of the free-hanging condition focused on the previous section, the main interest here will be the minimum-bending radius (MBR) condition, at which the bend restrictor impedes further curvature to avoid pipe damage. During this step, the contact between the pipe and the seabed is not verified.

- VCM rotation (time ranging from 1 to 2): by paying out and retrieving the pipe, the VCM rotation is controlled. The corresponding internal forces and curvatures can be studied then, simulating the approach and alignment before the VCM is in position. Again, the contact between the pipe and the seabed is ignored. At the end of this step, the VCM is in position and can be locked. If required, misalignment ($\pm 1°$) can be obtained for the next phase.

- Payout (time ranging from 2 to 11): by releasing the vertical motion of the upper edge of the pipe while an horizontal velocity – simulating the PLSV motion – is allowed, the flowline settlement onto the seabed is numerically simulated. If the total friction force

[5] The refined mesh in end fitting section was motivated by trials to reduce the errors in the calculation of shear force within it.

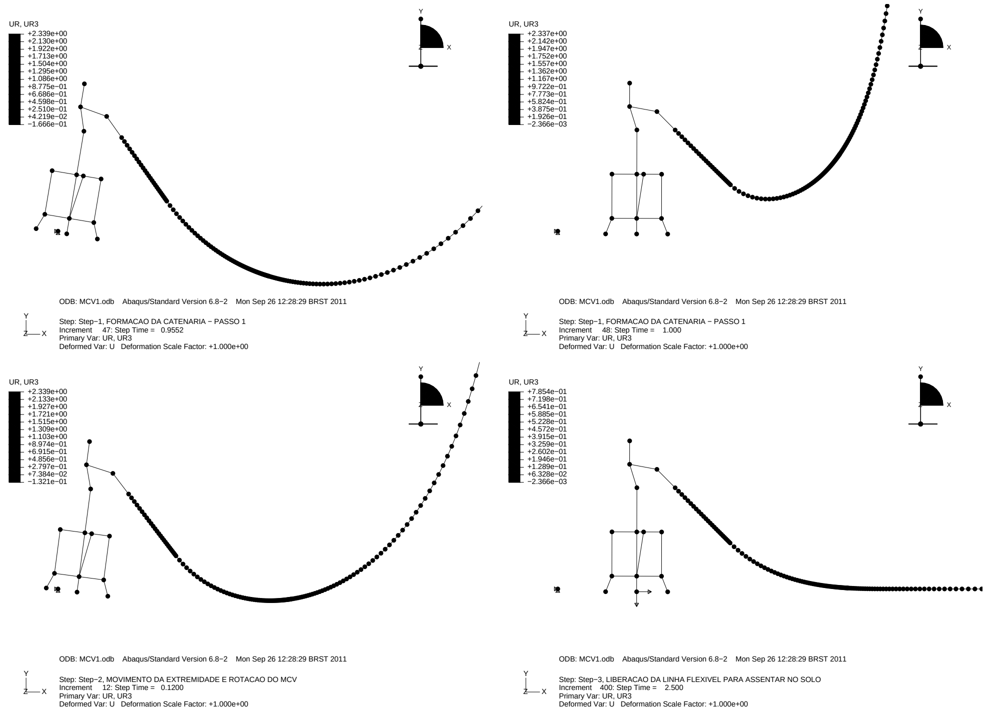

Figure 9: Finite-element analysis of VCM during approach, connection and release.

between the seabed and the laid flowline is insufficient, the forces and curvatures along the flowline and in the gooseneck's neighbourhood will depend on the PLSV motion.

The adjust of the steady VCM position is manually done, by increasing or decreasing the magnitude of the vertical motions of the winch cable's and of the flowline's top node during the first load step. Though some automatization may be achieved by using FORTRAN subroutines in ABAQUS to perform such control, it was not completed by the end of this investigation and several runs were necessary to get the VCM to the right location and rotation within $\pm 1^\circ$ from vertical direction.

The results for the base case are shown in the graphs of the figures 10 and 11. Results after step time 3 (continuation of pipelay on the seabed) are disregarded because their significance is minor.

In the first of them, the rotation of the VCM (rigid-body motion) and of the node between the bend restrictor and the flowline sections are given in the downmost section, the curvatures of the bend restrictor in the vicinity of the end fitting and of the flowline sections are given in the intermediate section and the vertical distance between the downmost point of the bend restrictor or the flowline, as well as the motions of a point 5-m away for the bend restrictor's end are given in the the upmost section[6].

The rigid body rotation of the vertical connection module was driven by the pipe retrieval. The amount of pipe retrieval was about 6.55 m, which sufficed to make the VCM lay 90°. The curvature is made extreme by excessive pull. The PLSV's velocity is not shown to disturb the

[6]The purpose of the verification of the displacements at the position 5-m away from the bend restrictor's end is to confirm that the vessel motion is not transmiting displacements and forces to the connection systems.

equilibrium, because the motions of the node located at 5-m away from flowline end are held constant as the pipelay operation goes on.

The tensile and shear forces, as well as the bending moments, are shown in the figure 11. Tension is shown to be very sensitive to pipe retrieval. The magnitudes of forces at the gooseneck are roughly confirmed[7] to meet the equation (1), but the precision is affected to some extend by numerical precision of the computation of the nodal displacements and rotations, which is impared by the fact that the end fitting is much stiffer than any other deformable structure in the FE model.

Stiffer flowlines, longer or heavier accessories may impede the VCM to be connected while complying with the separation between the flowline and the seabed. For the abovementioned system, considering the allowable tolerance, the bend restrictor section will inevitably touch the seabed if, holding the remaining parameters constant, the flowline stiffness exceeds 112 kNm^2. Increasing the vertical distance between the gooseneck flange and the seabed is the recommended workaround. The graph in figure 8 can give directions in this process.

For this study, the alternative flowline's bending stiffness is multiplied by a factor of 4, hence $EI_b = 100$ kNm^2. The results of such change are shown in the figures 12 and 13.

By applying 6.55 m of pipe retrieval, the stiffer structure was expected to make the VCM rotate as much as in the base case (around 90°), however the VCM rotates less than 40°. It is explained by increased horizontal force to keep the distance between the pipe and the winch cable, additionally folding the catenary. The entire system moves laterally (in the direction opposite to the flowline route) and the winch cable – in which a large tension exists – gets declined to balance that horizontal force. Therefore, the flowline connected to the gooseneck tends to rotate the VCM, whilst the winch cable opposes to that motion. The final equilibrium configuration will indeed depend upon very specific characteristics of this system, such as the distances between application points and the magnitude of the loads, which cannot be extrapolated to other connection systems.

Despite the large stiffness variation, the magnitude of internal forces and moments during the VCM rotation phase is reduced. One of the factors of the reduction is that the magnitudes of tension along the pipe and its accessories are reduced by the superposition of the compressive forces due to the abovementioned catenary folding process. In the actual application, the flowline stiffness and its weight are slightly proportional, hence the forces and moments will usually rise as the pipe gets stiffer.

5 CONCLUDING NOTES

A comprehensive discussion on the kynematics and modelling of vertical connection was carried out. The loads exerted on the flowline end were studied by combining finite-element techniques and dimensional analysis. The results are useful for preliminary design of vertical connection modules (VCMs), as well as for planning of the operations of vertical connection between flowlines and subsea equipment.

[7] Largest computation error is around 12%.

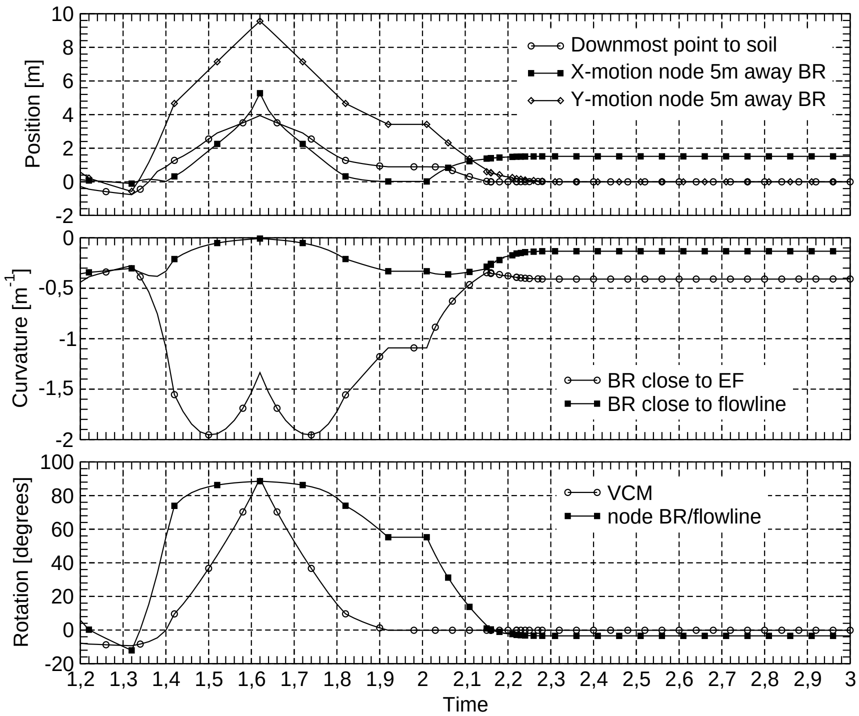

Figure 10: Rotation, curvatures and distances applicable to several points in the VCM and flowline system (base case).

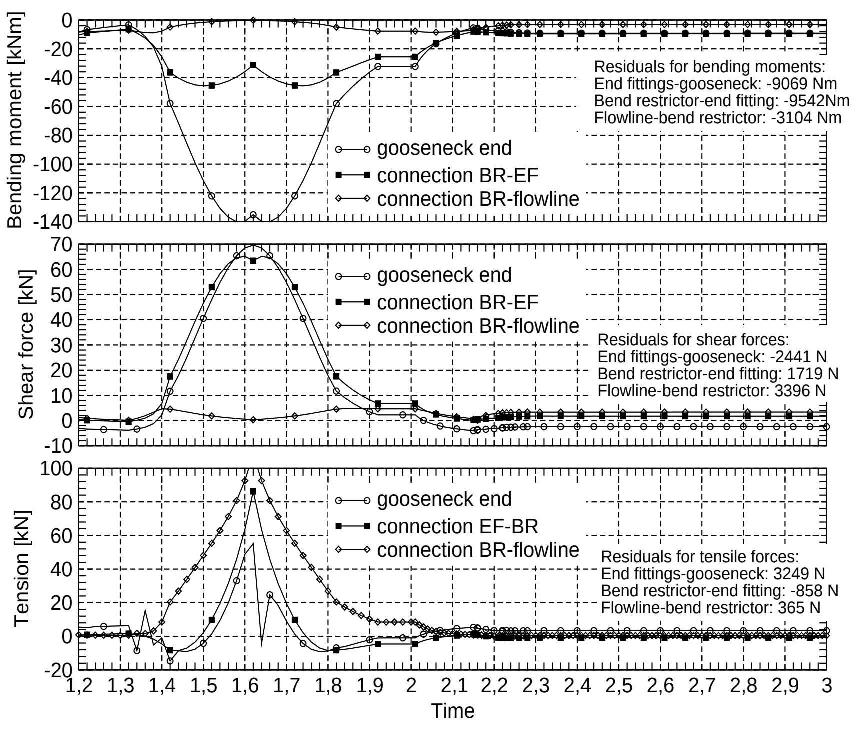

Figure 11: Forces and bending moments at relevant points in the VCM and flowline system (base case).

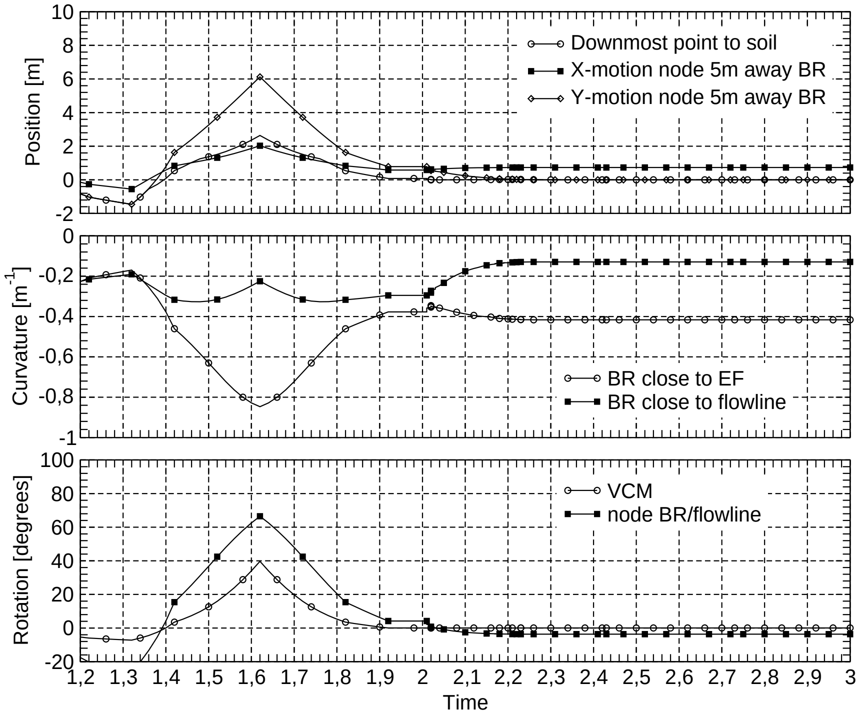

Figure 12: Rotation, curvatures and distances applicable to several points in the VCM and flowline system (stiffer flowline).

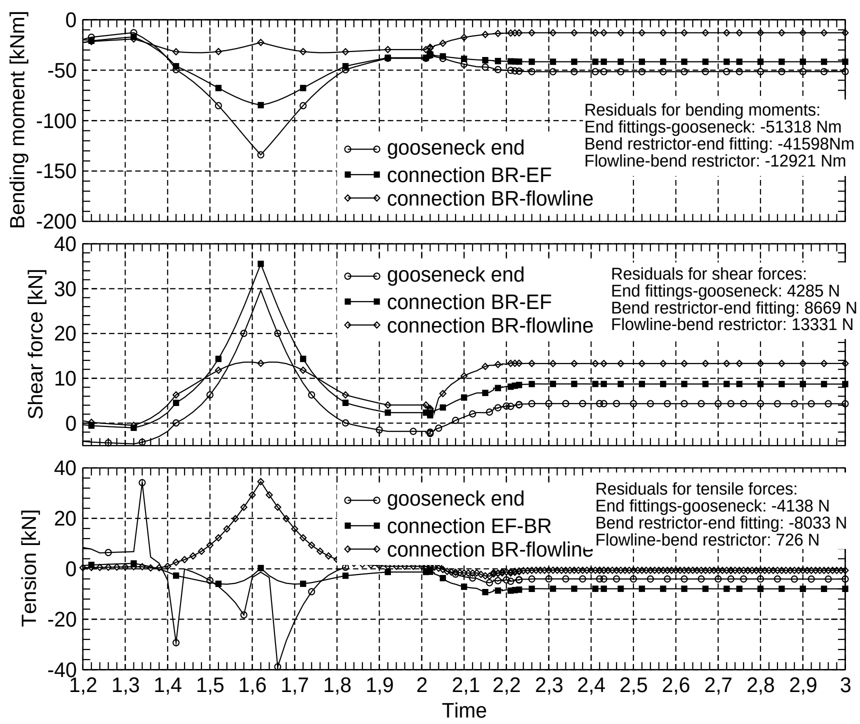

Figure 13: Forces and bending moments at relevant points in the VCM and flowline system (stiffer flowline).

REFERENCES

[1] V.S. LOPES. Influência da rigidez à flexão de duto flexível na instalação de módulos de conexão vertical em àguas profundas. Master's thesis, COPPE/Universidade Federal do Rio de Janeiro, Rio de Janeiro, maio 2005.

[2] J.R. Moreira, M.B. Cerqueira, G.J. Rosa e Silva, and F. Nagle. Further advances in deepwater flowline connection technology. In *Annual Offshore Technology Conference*, volume 4, pages 785–798. Offshore Technology Conference, 1996.

[3] F.J.M. Nagle, J.E. Mendonça da Silva, L.A.G. Costa, and R.W. Capllonch. Vertical connection system for flexible pipes: Offshore tests and pioneer installation. In *Annual Offshore Technology Conference*, number 7260-MS. Offshore Technology Conference, 1993.