

## Three dimensional finite element analysis of 4 inch smart flange on offshore pipeline

Ali Shaghaghi Moghaddam<sup>\*1</sup> and Saeid Mohammadnia<sup>2</sup>

<sup>1</sup>Young Researchers and Elite Club, Takestan Branch, Islamic Azad University, Takestan, Iran

<sup>2</sup>Pipeline Engineer, Iranian offshore and construction company (IOEC), Vila street, Tehran, Iran

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**Abstract.** Smart flanges are used for pipeline and riser repair in subsea. In a typical case in the gas export pipeline project, the end cap bolts of a 4inch smart flange were broken during operation, and in turn leakage occurred. This work presents the detail of three dimensional finite element analysis of the smart flange to support the observed end cap bolts failure. From finite element analysis it turns out that in the presence of external bending moment, an uneven contact distribution is present between seal and end cap, which in turn changes the uniform load distribution on bolts and threaten the integrity of bolts. On the other hand, 3D finite element analysis of interaction between pipeline and seabed is presented by means of Abaqus to explore the distribution of bending moment along the pipeline route. It is found that lateral buckling occurs in the pipeline which introduces large bending moment.

**Keywords:** smart flanges; subsea pipeline; end cap bolts; seabed topography; 3D finite element

### 1. Introduction

In shallow water offshore, the natural gas from wellhead jackets is transferred to onshore plant through export pipeline of different sizes, 24, 30, 32 inch. Export pipelines each with a piggy back line are used to transport raw material to onshore facilities. Due to presence of corrosive environment in sour services and probability of hydrate formation in the pipeline, mono-ethylene glycol (MEG) is introduced in the pipeline from offshore side. MEG is provided from onshore facility and exported to jacket through a 4inch line, piggy back line, which is secured to mainline through strapping (Yong 2001). In case of 3rd party activities such as trawl gear interference and anchoring, the 4inch line may be damaged and de-strapped from mainline (DNV-OS-F101, DNV-RP-F110) If any rupture in piggy back line is happened, emergence activity is required to correct the pipeline. In the meanwhile, MEG is transported to offshore facility through ships, which is too expensive. Consequently a fast remedial action is required. Among different techniques to mitigate the damaged section of pipeline, using smart flange is fast and applicable approach which is of interest for offshore industry. The product offers pipeline and riser repairs without the need for hyperbaric welding and can be installed in driverless applications. Available worldwide, the end connectors are stocked in a variety of sizes to accommodate from 2 inch up to

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\*Corresponding author, Assistant Professor, E-mail: [Shaghaghi@ioec.com](mailto:Shaghaghi@ioec.com)

24 inch pipeline diameters. It should be noted that subsea smart flange installation and pipeline repair is fast and easy, if performed right. The applications of smart flanges extend from pipelines and riser repair, valve and tee installation and pipeline abandonment. Parameters in selecting smart flanges include: Nominal Pipe Size (NPS), service condition (oil, natural gas, hydrocarbons, etc.), design pressure rating, hydrostatic test pressure rating, design temperature range and design Life. On the other hand, special cares have to be paid during installation and operation to put the integrity of pipeline in safe side.

Totally different modes of failure in flange connection have been studied. The influences of manufacture and operation conditions on crack initiation and propagation mechanisms in pressure vessel flanges are highlighted (Otegui *et al.* 2009). The test program on bolted flange plate connections used in circular tubular structures was presented in (Hoang *et al.* 2013). In the tested joints, the connected tubular elements are made of high strength steel (TS590) whilst normal steel grade (S355) is used for the flanges. The monotonic fracture behavior of two elastomer compounds (HNBR and FKM) was characterized (Major and Lang 2010). These elastomeric materials are frequently used in many oilfield applications (e.g., seals and hoses) and are exposed to a complex combination of mechanical, thermal and environmental loads. Failure analysis procedure of a cracked high pressure 321 SS RTJ flange in ISOMAX unit was studied in (Delavar *et al.* 2013). The dynamic structural response of piping systems is investigated and efficient analysis techniques are suggested to evaluate the influence of a bolted flange with an elastic gasket. It has been shown that the complex interaction between the flange and gasket has slight impact on the dynamic structural response of a piping system (William *et al.* 2006). Mathan and Prasad (2011) studied on gasketed flange joints under bending with anisotropic Hill plasticity model. By means of three dimensional finite element analysis and experiments the behavior of a gasketed flange joint under bending loads has been studied. The variations in bolt axial force of joints under bending load are predicted by the finite element analysis. 3D nonlinear finite element analysis (FEA) of a gasketed flange joint is carried out to study joint strength and sealing capacity under combined internal pressure and different steady-state thermal load (Muhammad 2006). A computational procedure is presented for the analysis of stress and deformation patterns in high-pressure vessel flanges (Bakker and Spaas 1977). Taking into consideration the nonlinearity of gasket material and the stiffness effect of the integrated part of the flange ring, gasket load drop caused by internal pressure at flange joints are analyzed (Nagy 1996). 3D finite element analysis of bolted flange joints has been carried out and it has been shown that the distribution of contact stress has a more dominant effect on sealing performance than the limit on flange rotation specified by ASME (Murali *et al.* 2007). The wave forces on the buried pipeline model is evaluated for a wide range of wave conditions, for different burial depths (Neelamani and Al-Bana 2013). The possibility of using the longitudinal strain on the surface of a pipe to determine the beginning of dangerous free spanning is investigated in (Ahmed *et al.* 2011).

In case any damage is occurred, the pipeline is surveyed with ROV, remote operated vehicle, to figure out the location of damaged section. In case local buckling or leakage is observed, the damaged section has to be replaced. The damaged section is cut underwater and upon completion the cutting, metrology is performed to find accurate coordinates of the two ends of pipelines for spool design. According to metrology data, the spool piece is designed and fabricated with weld neck flanges on two ends. Then it is lowered in seabed in its accurate position. Then with the help of smart flanges, the spool piece and pipeline are connected to each other in a very fast time. Typical procedure has to be followed up for safe installation of smart flanges. Hydro tight instruments are employed for bolt tensioning during flange installation. After the spool piece is

installed, hydrotest is conducted with pressure of 1.5 times the design pressure for about 24hrs, specified in the project specification, to assess the integrity of the pipeline, especially at the smart flanges locations. After successful hydrotesting, the pipeline is ready for commissioning. In Fig. 1 overall view of spool piece and smart flange connection is shown for subsea pipelines.

The route configuration of an export offshore pipeline is shown in Fig. 2. As a consequence of trawl gear interference, 4inch piggy back line was locally buckled and de-strapped about 1500 m from the mainline, as shown in Fig. 2. At the time, it was company policy to replace the damaged section with a new 4inch pipeline and use smart flanges to connect to the existing line. It is seen that the replaced 4inch line is composed of a 500-meter straight and 1000-meter curved section. In Fig. 3, smart flange connection on 4inch line is shown. The smart flange was installed according the procedure, and then the hydrotest was performed successfully and no pressure drop was recorded in the test period.

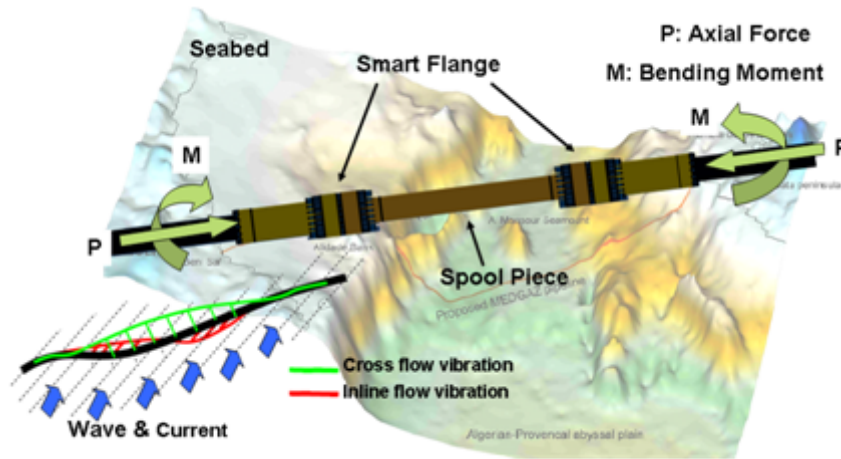


Fig. 1 Overall view of smart flange connection between spool piece and pipeline

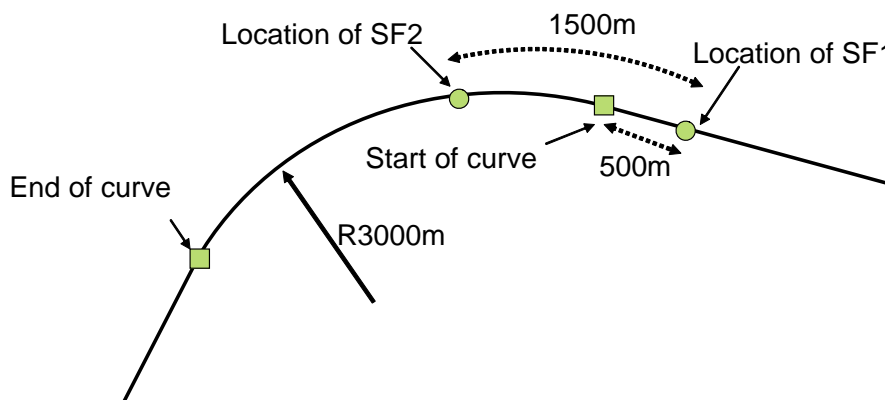


Fig. 2 Route configuration of an export offshore pipeline



Fig. 3 Smart flange connection to 4inch pipeline on seabed

However after commissioning the pipeline with MEG, a pressure drop was recorded. A survey was conducted to explore the leakage area. It was found that the smart flange had failed. The damaged smart flange was removed from the sealine, Fig. 4. It is seen that end cap bolts are broken and consequently the elastomeric seal is escaped from the main body.

The present work is intended to analyze the failure of end cap bolts shown in Fig. 4. At the beginning a brief description of smart flanges and the internal mechanism are discussed. General failure modes of smart flanges are studied in turn. Then a three dimensional finite element analysis by Abaqus is presented to study the interaction between pipeline and seabed to study the bending moment introduced in the pipeline during operating condition. The lateral buckling is analyzed and the critical bending moment in buckle crown is studied. The required data for finite element modeling are extracted from standard (DNV-RP-F113, DNV-RP-F109, ASME/ANSI B16.5, ASME/ANSI B16.47, API SPEC 6H, ANSI/API SPEC 5L), basic documents of the project and also survey data. To explore the failure of end cap bolts, a three dimensional finite element analysis of smart flange is presented. In turn, two cases of seal energizing and operating condition of smart flange are investigated. Subsequently the contribution of external bending moments on bolts failure is analyzed. Finally some engineering recommendations are discussed for safe operation of smart flanges in subsea application.



Fig. 4 Damaged smart flanged removed from the sealine

## 2. Internal mechanism of smart flanges

Before analyzing the failure mode, it is helpful to illustrate the internal mechanism of the smart flanges. The main parts of smart flanges are shown in Fig. 5(a). By tightening the flange stud bolts, the main body of the smart flange will be pulled toward the mating flange of the spool. At the first stage, the elastomeric seal is compressed to achieve the predefined percentage of compression adequate for the sealing. By design, this percentage of compression is limited by a combination of a ring and a groove in the main body of the connector, which prevent the seal to produce excessive reaction force. The body of the connector and the end cap are subjected to the reaction force of the seal due to the compression, Fig. 5(b). Since the seal is energized at the next stage the gripping parts which are entrapped between the piston and the limiting ring will be squeezed in order to hold the pipe firmly, Fig. 5(c). The position of the limiting ring is fixed by the groove in the body, therefore during the gripper system activation the parts of the connector which are stressed are main body, limiting ring, and the gripper part. None of the other parts are stressed in gripping activation. Installation completed, the smart flange is strongly connected to the existing pipe which makes any position change or slide over the pipe impossible, because it is restricted by the end lip of piston, gripping system, elastomer gasket and the mating spool. In fact, when a connector has fixed and bolted to the mating flange, it means all the internal component characteristics including sizes, tolerances and assembly are well verified.

To have more detail discussion on smart flanges failure, the most dominant modes of failure are discussed herein. Generally failure modes of smart flanges are categorized as product failure modes, installation failure modes and operation failure modes which briefly are described below:

- Fail to install on the pipe: When coupling has been pre activated and can not slide on pipe end.
- Activation causes damage to the pipe: When wall thickness of pipe is weaker than standard and can't stand gripping force.
- Fail to seal (leakage): When elastomeric gasket damage in compression or escape the sealing space. Also when gasket loose the sealing after some times.
- Fail to lock: When not sequential bolting, angel or applied force damage the cone slip assembly not to be able to ride on.
- Material/Fabrication Failure: When one or more materials have shown poor performance in test or operation
- Misalignment welding neck flange: When weld neck flange is not aligned with smart flange which cause the excessive force on internal mechanism.
- Pipeline Anchoring: When Pipeline in repair zone has allowance for displacement, bending and buckling.
- RTJ Leakage: Before mating weld neck flange with smart flange both groove should be clean, tightening stud bolts uniformly and in sequential order until final preload is reached and achieve approximate gap between the two flanges according to standard gap.
- Spool Size and placement: When spool length is shorter or longer than calculated tolerances or when placement of spool apply directional forces on joints.
- Installation equipments: Such as hydraulic tensioner, Pump, Gauges etc...should be calibrated.
- Smart flanges location: When location of repair is in high stress concentrated point, such as curve, free span and etc. which threaten the Smart flanges.
- Pressure excessive differentials  
Temperature shocks

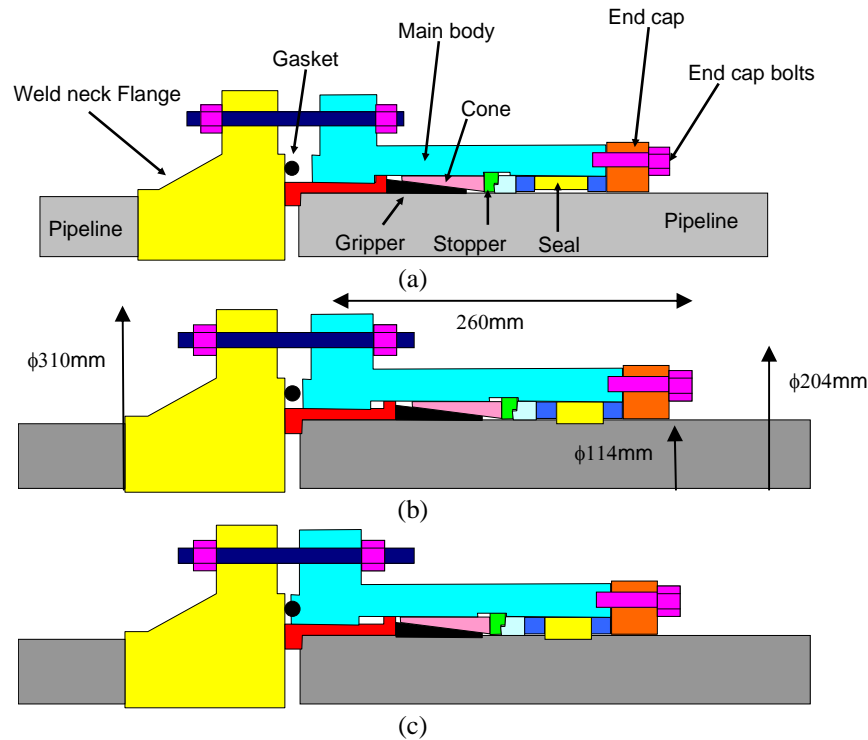


Fig. 5 (a) Internal mechanism of smart flange, (b) Sealing energized and (c) Gripping activated

### 3. Interaction between pipeline and seabed

In offshore pipeline design, it is of prime importance to study the contribution of external loads on the pipeline. Typically environmental and functional loads are exposed on the pipeline mainly due to presence of wave, current, internal pressure and temperature (DNV-OS-F101). The contribution of wave and current are emerged as hydrodynamic loads which produce drag and lift forces on the pipeline (Yong 2001, Ahmed *et al.* 2011). More significantly, the current flow across the pipeline excites cross flow and inline vortex induced vibration (VIV) which is the dominant mode for fatigue failure of pipelines girth welds. On the other hand, due to introducing hot content into the pipeline, consequently temperature difference between installation and operation, the pipeline tends to expand. However the expansion of pipeline is limited by soil friction with seabed (DNV-RP-F109). Due to presence of friction, some parts of pipelines are virtually anchored and some lengths are active length which experience expansion (DNV-RP-F110). As a result of soil friction, a compressive force and bending moment is introduced in the pipeline which increase the probability of occurrence of lateral buckling. Excessive axial strain and bending moments considerably threaten the integrity of pipeline and flanges, respectively. In case the axial strains and bending moments are out of acceptable range, remedial action is required. In the present work the finite element software Abaqus is employed for modeling pipeline and the interaction with seabed. The necessary information for pipeline, seabed and soil are obtained from survey data basis of design of the project.

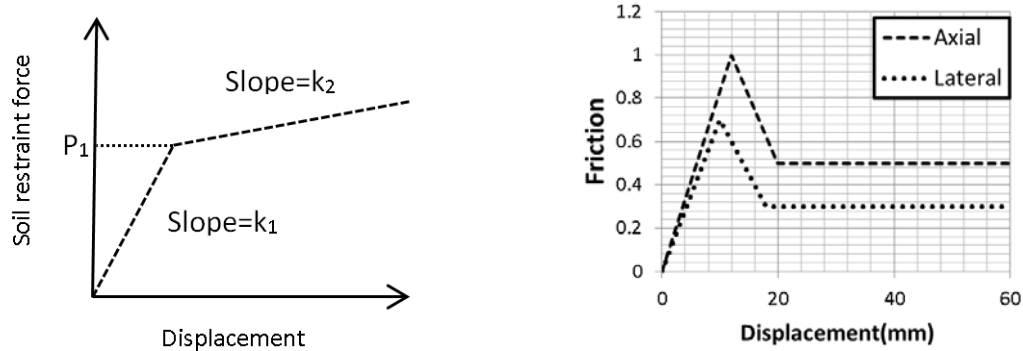


Fig. 6 Soil bearing capacity and coefficient of friction

The 3D configuration of the seabed is imported to finite analysis through Fledermous based on the survey data (Shaghghi and Mohammadnia 2013). The seabed type is three dimensional discrete rigid. However it should be noted that the soil properties have to be assigned to seabed mesh. The soil bearing capacity and coefficient of frictions are the most important factors that have to be included into the analysis. Soil vertical stiffness and coefficient of friction along the pipeline and transverse to the pipeline have to be considered. It should be noted that according to the field survey, the soil type and characteristic is extracted. Hence with respect to soil type, at any point along the pipeline, the soil properties are assigned. The soil stiffness in vertical direction is characterized as shown in Fig. 6, Which  $k_1$  (N/mm<sup>2</sup>),  $k_2$ (N/mm<sup>2</sup>) and  $p_1$ (N/mm) are soil parameters which are extracted from an in-house Mathcad sheet based on the soil survey report. After estimating the factors for vertical soil stiffness, they are assigned to the rigid discrete seabed through the contact property manager, normal behavior, in the Interaction module. In the next step, the coefficient of friction of soil has to be integrated in the finite element analysis. Similar to vertical soil stiffness, coefficient of friction is extracted from the MathCad sheet based on the soil survey report. Soil coefficient of friction is distinguished for axial and lateral direction. Where the axial direction is aligned along the normal to the pipe cross section and perpendicular to that is the lateral direction. As a consequence it is of main concern to employ anisotropic soil friction along the axial and lateral direction.

Commonly API materials grades are used for submarine pipeline, X52, X65 and etc. (DNV-OS-F101). Elastic-plastic material properties can be found (DNV-OS-F101). Pipeline nominal diameter is extracted from the hydraulic analysis report. An anti-corrosion coating is applied to pipeline outer diameter to protect from corrosive environment. For the finite element analysis 3-noded pipe element, PIPE32, is considered, which the element size is one OD.

Pipeline data are extracted from respective documents such as design basis, on bottom stability analysis, thermal buckling analysis and etc. Pipeline data are tabulated in Table 1. Fig. 2 depicts the route configuration which is considered in the finite element analysis. The interaction between pipeline and seabed is modeled in Abaqus. For the finite element analysis almost 6000 m of the 4inch pipeline are considered. Imposing the boundary condition, internal pressure and temperature the analysis is performed. Section bending moment along the route is shown in Fig. 7(a). As stated above, due to action of soil friction and its contribution on thermal expansion, lateral buckling is

likely to occur frequently along the pipeline between anchor points. A typical lateral buckling is shown in Fig. 7(b). From finite element analysis it is inferred that in the presence of lateral buckling, an excessive bending moment is introduced in the pipeline. Distribution of bending moment in the buckled section is shown in Fig. 8. It is seen that very large bending moment about 18kN.m is introduced in the buckle crown. In the next section the contribution of this bending moment on smart flange is investigated.

Table 1 Pipeline and route data

Pipe nominal diameter	4 inch
Pipe thickness	6 mm
Steel Grade	API 5L X-65
Steel density(kg/m <sup>3</sup> )	7800
Young's modulus(MPa)	210000
SMYS(MPa)	450
Anti Corrosion density(kg/m <sup>3</sup> )	1400
Soil type along the pipeline	Soft Clay
4inch Pipeline total length	140 km
Pipeline length under study	6000 m
Installation temperature	13C
Operating temperature	50C
Operating pressure	250bar

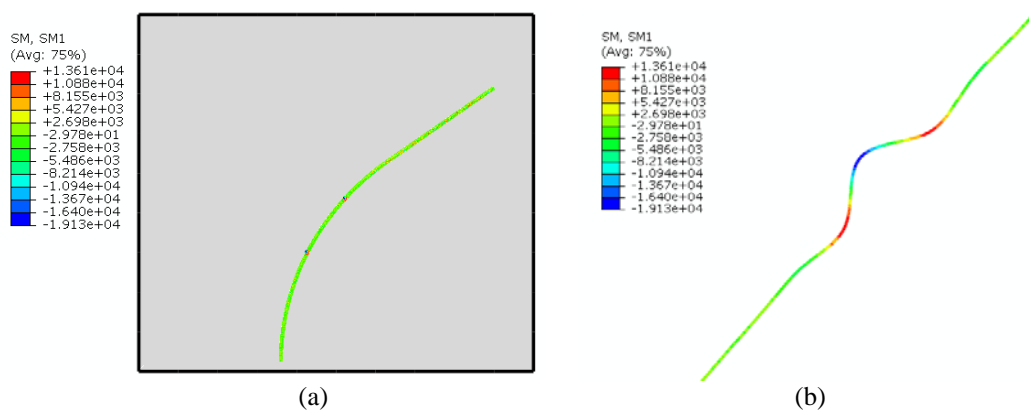


Fig. 7 (a) Section bending moment distribution along the route (b) local lateral buckling along the route



#### 4. Finite element analysis of smart flange

Based on the discussion on internal mechanism of the smart flange, it is aimed to analyze the failure of smart flange imposed to external bending moment. From Fig. 4 it is figured out that failure is happened from end cap. Typically end cap bolts are broken and subsequently the elastomeric seal escaped and leakage occurred. Also it is understood that the rupture of the bolts has happened in un-symmetric pattern and the observed gap between end cap and main body is un-symmetric. The bolts failure show that excessive axial force has contributed to failure. This helps us to figure out that un-symmetric load condition contributed to bolt rupture. Details of end cap bolts are tabulated in Table 2.

From Fig. 5(b) it is seen that during energizing of elastomeric seal the reactive is transferred to the end cap bolts. This compressing force plus the required force to energize the gripping system is produced by the flange stud bolts using some stud tensioner tools. At the design stage, the end cap bolts should be designed to ensure having appropriate strength against this reaction force. From practical point, it was observed that during installation and hydrotest no failure has occurred. As a consequence, the sealing reactive force during energizing has got no contribution to bolts failure. Material specification of smart flange components is tabulated in Table 3. To analyze the bolts failure, a detail three dimensional finite element analysis of smart flange is performed hereafter.

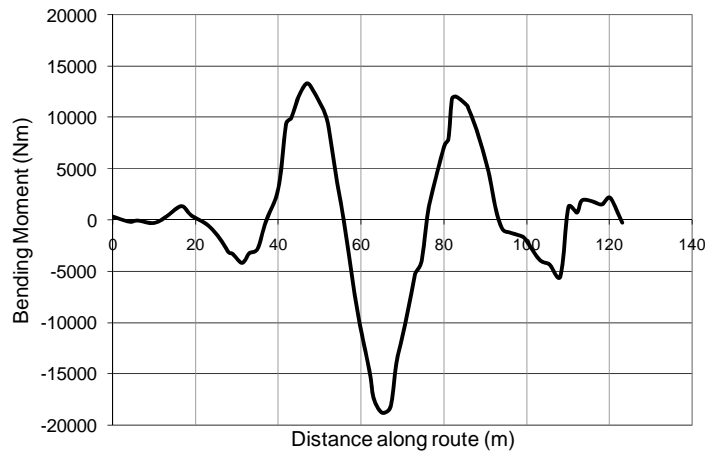


Fig. 8 Distribution of bending moment in the buckled area

Table 2 Details of end cap bolts

Size of end cap bolts	M12
Material grade	10.9
Number of bolts	16
Proof load	70kN

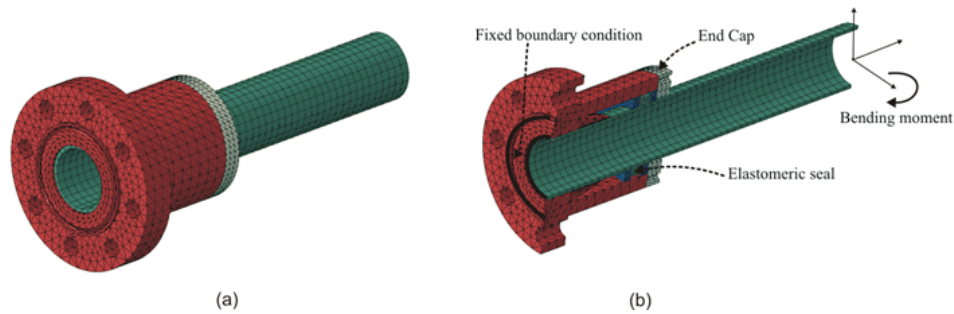


Fig. 9 (a) 3D finite element of smart flange (b) cross sectional view of mesh

Three dimensional finite element mesh of the smart flange is shown in Fig. 9(a). Details of cross section of smart flange are shown in Fig. 9(b). For elastomeric seal, hyperelastic material is defined and hybrid elements, C3D8H; 8-node linear brick hybrid element, is associated in the finite element model. For the rest of components, 8-node linear brick element is considered. The interaction between elastomeric seal and mating components such as pipeline, metal rings, main body and end cap are defined by means of finite sliding surface to surface interaction scheme. Nonlinear effect is included in steps definitions to account for the nonlinearity due to material properties and contact interaction. In the finite element model the flange face and pipeline end is gripped. Two load steps are considered: 1) elastomeric seal energizing and 2) operating condition in the presence of external bending moment. In the first load step the elastomeric seal is compressed and the reactive force is transferred to the end cap bolts. Then functional loads are imposed for the second load step. To impose the bending moment, a reference point is defined on the pipe end. Then in the interaction module the reference point is constrained to the pipe section by constraint type “coupling”. All the degrees of freedom are constrained. In the load module, the bending moment is imposed to the reference point. In the present finite element analysis it is aimed to study the contact stress distribution on elastomeric seal for different load conditions. The contact between elastomeric seal and metal ring is transferred to end cap and dictates the load on end cap bolts. The von mises stress distribution on flange components for two load steps are shown in Fig. 10. In the energizing load step the problem serves as axi-symmetric due to symmetry of geometry and boundary condition. However in the presence of external bending moment, stress distribution is not symmetric.

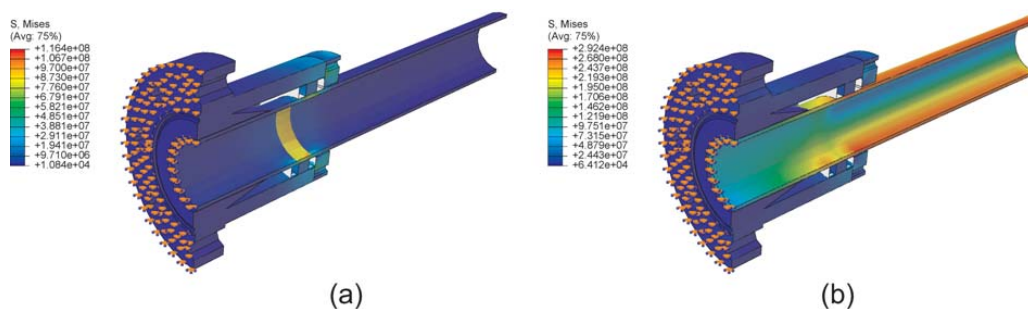


Fig. 10 Von mises stress distribution on flange components for (a) seal energizing and (b) operating conditions

For the first load step the contact stress distribution on elastomeric seal is shown in Fig. 11(a). Axi-symmetric contact stress distribution is observed. Through thickness non-uniform contact stress distribution observed in Fig. 11(a) is dictated by the influence of friction between seal and mating parts. Von mises stress distributions on end cap are shown in Fig. 11(b). It is inferred that all bolts are in similar conditions. As stated above, the reactive force of seal energizing is sustained by end cap bolts. To evaluate load pattern on end cap bolts, reference points are tied to bolt cross sections. Imposing boundary condition to each reference points, the reactive force on bolts can be obtained. The reactive force on each bolts are now extracted from finite element analysis. The results for typical bolts are shown in Fig. 11(c) which is 25 kN for all bolts and still well below the proof load of bolt materials.

As seen from Fig. 10(a) and Fig. 11 it is concluded that during seal energizing the stress distribution is uniform and axisymmetric and load on end cap bolts are equal and below the proof load. Now the contribution of external bending moment is investigated. Based on Fig. 8 the external bending moment of 18 kN.m is imposed on the pipeline. Von mises stress distribution of smart flange component is shown in Fig. 10(b). It is seen that stress distribution is not symmetric. Contact stress distribution on elastomeric seal is shown in Fig. 12(a).

It is inferred that uneven contact stress distribution is present on seal material. Then contact stress between seal and metal ring is transferred to the end cap. The von mises stress distribution on end cap due to uneven contact stress on seal material is shown in Fig. 12(b). Accordingly the load on end cap bolts can be found as reactive force on reference points associated to each bolt cross section. Bolt forces are shown in Fig. 12(c) which shows that the load pattern on end cap bolts are not symmetric and at the critical bolt on the lower side of end cap, the force is more than the proof load. Upon breaking the critical bolt, loads are redistributed among the rest of bolts and breaking is occurred in critical bolts. Consequently the elastomeric seal is escaped from the main body.

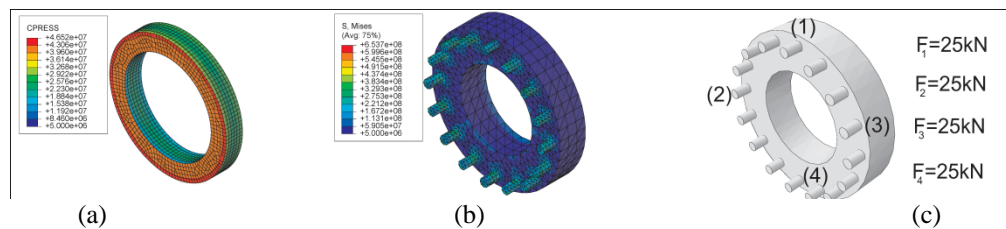


Fig. 11 (a) Contact stress distribution on elastomeric seal (b) Von mises stress distributions on end cap and (c) load patterns on end cap bolts for energizing load step

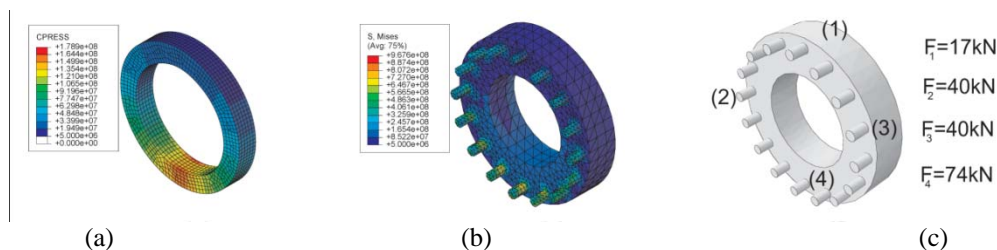


Fig. 12 (a) Contact stress distribution on elastomeric seal (b) Von mises stress distributions on end cap and (c) load patterns on end cap bolts in the presence of bending moment

It is seen that external bending moment has considerable influence on contact stress distribution. As a consequence, the reactive force on end cap bolts may endanger the integrity of smart flange. Normally, the extend of bending moment in pipeline is not critical, however in the presence of lateral buckling or free span and etc. an excessive bending moment presents.

## 5. Conclusions

In the present work failure of end cap bolts in smart flanges were analyzed. A 3D finite element analysis was performed to model interaction between pipeline and seabed. It was seen that lateral buckling is likely to happen in the pipeline. In the presence of lateral buckling, excessive bending moment is introduced in buckle crown. Then the contribution of bending moment on failure of smart flange was studied. To this aim a full 3D finite element of smart flange was studied. Two load cases of seal energizing and bending moment were considered in the finite element analysis. it was seen that during seal energizing a uniform contact stress distribution is developed in the elastomeric seal. Consequently the reactive loads on end cap bolts were identical and below the proof load of bolts. However, in the presence of bending moment, the contact stress distribution is not uniform and subsequently, the load pattern on end cap bolts were not uniform. At the critical location, the bolt load was higher than the proof load of bolt and consequently bolt is broken. Base on the finite element analysis it is figured out that external bending moment endanger the load condition on end cap bolts and may threaten the integrity of smart flange. As a consequence special care has to be taken during installation of smart flange. For installation of smart flange, the same procedure provided by manufacturer has to be followed up. The location of smart flange on seabed has to be surveyed for any possible free span, debris, rock and etc. In case of uneven seabed, it is recommended that at smart flange location mattress or grout bag is used. It is also noticed that the smart flange has to be secured and has got no degree of freedom to displace. Mattress can be employed on pipeline near the smart flange to fix the section from any excessive movement. Flange protector can be employed to protect the smart flange from any third party such as dropped objects and etc.

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