ABSTRACT

There is an ever-increasing demand for subsea transport of corrosive constituents which requires the use of corrosion resistant pipelines. This has generated interest in mechanically lined pipe (MLP) which consists of carbon steel pipe lined with a thin layer of corrosion resistant alloy (CRA), typically stainless steel. The CRA liner is adhered to the backing pipe by means of an interference fit.

MLPs have been traditionally installed subsea using low strain methods such as towing, S-lay or J-lay. More recently, the efficient reel-lay method, typically used for pipelines up to 18” (457.2 mm) in diameter, has also been considered. To prevent damage to the MLP during high strain bending (i.e. wrinkling of CRA the liner) and thus allow reel-lay installation, TechnipFMC has qualified reeling of MLPs at ambient and elevated pressures. The ambient reeling approach, where the liner thickness is increased to prevent wrinkling during reeling, is appropriate for smaller diameter MLPs. For larger pipelines, it is generally more cost-effective to pressurise the MLP during reeling.

Concerns have been expressed that liner imperfections such as small dents or wrinkles, introduced during manufacturing, installation or service, may compromise the integrity of the MLP subjected to high in-service cyclic loading. Therefore, this study was undertaken to examine the criticality of such flaws and determine the low cycle fatigue endurance of reeled MLPs with imperfections. First, a numerical study was undertaken to estimate in-service stress/strain ranges in the MLPs with liner flaws. Subsequently, small scale tests were carried out to quantify the fatigue performance of such MLPs. The obtained results confirmed that there is a negligible risk of failure of MLP flowlines due to crack initiation at liner imperfections and subsequent breach of the CRA layer, even for pipelines subjected to very severe in-service cyclic loading.

INTRODUCTION

Subsea transmission of corrosive petroleum fluids requires the use of pipelines with enhanced corrosion performance such as solid stainless steel or hot-roll bonded clad pipelines. Recently, mechanically lined pipes (MLP) have been used instead...
because they are generally more readily available and more cost effective than other corrosion resistant pipes.

MLP, illustrated in Fig. 1, is made of thin corrosion resistant alloy (CRA) liner adhered to backing carbon steel (CS) pipe by means of an interference fit. The MLP manufacturing process requires the liner (manufactured to API 5LC [1], for example) and the backing pipe (manufactured to API 5L [2], for instance). First, the liner is inserted into the host pipe and expanded by applying internal pressure until it contacts the host pipe. Then, expansion of both pipes continues until a target expansion level is achieved. Once pressure is released, the liner and the host pipe spring back so that grip (mechanical bond) develops between the two pipes. Subsequently, the liner ends are cut back to leave a required length of unlined CS pipe and clad overlay welding is carried out to seal the liner ends.

To enable insertion of the liner into the CS host pipe, a radial gap is required between the liner outer diameter (OD) and the host pipe inner diameter (ID). A large gap makes insertion easier but increases hoop strain in the liner during expansion which renders the liner seam weld prone to fracture. Since a small insertion gap is generally specified, some amount of liner scoring is inherent to the MLP manufacturing process. Light scoring, shown in Fig. 2(a), is typical of a well-controlled insertion process. Uncontrolled galling of the liner, shown in Fig. 2(b), may occur if: (i) the host pipe and the CRA liner are axially misaligned during liner insertion or (ii) the pipe diameter or straightness tolerances are too high. Liner galling may result in the build-up of CRA material (nugget) in the annulus between the liner and the host pipe, see Fig. 2(b). Those nuggets can indent the liner during expansion (see Fig. 3).

MLPs have been traditionally installed subsea using low-strain methods such as towing, S-lay or J-lay [3]. More recently, TechnipFMC has qualified MLP installation by the high strain reel-lay method. The reel-lay installation process involves four plastic bending events. First, the pipeline is spooled onto the reel. Then, the reel-lay vessel travels to the installation site where unreeling takes place. The pipeline is straightened in the free span between the reel and the aligner, passes over the aligner and is finally straightened in the straightener, see Fig. 4.

Wrinkling of the liner during plastic bending of the MLP is prevented by either increasing the liner thickness above a typical thickness of 2.5–3.0 mm [4–8] or pressurising the MLP [9]. Reeling of MLPs with increased liner thickness at ambient pressure is well-suited for pipelines up to 10.75”–14” (273.1–355.6 mm) in diameter. The first ever MLPs (7.625” (193.7 mm) OD flowlines and steel catenary risers), reeled at atmospheric pressure, were installed by TechnipFMC in the Gulf of Mexico in 2015. For larger MLPs, it is generally more economical to implement pressurised reeling due to a lower cost of the MLP with a nominal liner thickness of 2.5–3.0 mm. This approach was implemented offshore Brazil and in the Norwegian sector of the North Sea.

Concerns have been raised that liner imperfections introduced during manufacturing, installation or service may compromise the integrity of the MLP which is subjected to varying pressure, temperature and bending strain during operation. This study examines the criticality of such flaws. Finite-element (FE) analyses are carried out to determine cyclic stress/strain in liners containing wrinkles/dents, associated with in-service loading. Subsequently, it is shown that the liner stress/strain condition in the MLP under in-service loading can be replicated in a simple liner strip geometry subjected to cyclic axial loading. Finally, small scale fatigue testing on a liner with imperfections is undertaken. The fatigue endurance, defined as the number of high strain cycles applied before breach of the CRA liner occurs, is shown to be high enough to deem the risk of loss of the MLP integrity to be very low.

**NUMERICAL ANALYSIS**

**Approach**

Three MLPs, suitable for reel-lay installation at ambient pressure, are considered in this work: 8.625” (219.1 mm), 10.75” (273.1 mm), and 12.75” (323.9 mm) OD. The 8” and 12” CS pipes are lined with alloy 316L whereas the 10” pipe is lined with alloy 625. The average measured stress-strain curves for the CS (API 5L X65) and the liners (ASTM 316L and 625) are shown in Fig. 5.
First, a wrinkling parametric study is undertaken using small scale 3D FE models. Buckling of a standalone liner is simulated to generate eigenmodes, then radial displacements corresponding to a given mode are scaled and imposed to a perfect liner in an MLP. Subsequently, sensitivity analyses are carried out to determine which initial imperfection is appropriate to correctly predict liner wrinkling during bending of the MLP.

Then, the appropriate initial imperfection is introduced into a liner in a full scale 3D MLP model. Manufacturing, installation and operation of the MLP are simulated to produce large residual imperfections (dents/wrinkles) and determine the corresponding stress/strain ranges in the liner during subsea operation of the MLP. Liner wrinkles, up to 6 mm in height, are considered in this work in order to conservatively assess the fatigue endurance of MLPs with imperfections. Such wrinkles are unlikely to be caused by galling and denting of the liner during manufacturing. Equally, in practice it is not possible to introduce such wrinkles during ambient installation of reelable MLPs (i.e. those designed for reeling at atmospheric pressure). Therefore, bending of MLPs on a tight bending former is carried out experimentally and simulated in the FE analysis - the bending radius required to achieve the desired wrinkle height is much smaller than the reel hub radius of a typical reel-lay vessel.

Finally, a liner strip with a wrinkle, extracted from the full scale 3D FE model which accounts for the strain history, is subjected to cyclic axial loading. The applied axial cyclic loading is altered in an iterative manner until the stress/strain ranges in the strip FE model correspond to those in the full scale FE model where the MLP is subjected to in-service loading.

A standard kinematic hardening plasticity model (i.e. with no cyclic isotropic hardening/softening component) associated with the stress-strain behaviour illustrated in Fig. 5, is used throughout.

Wrinkling Parametric Study

Buckling/wrinkling of tubes has been the subject of numerous studies over the past decades. Most studies focused on the behaviour of slender single skinned pipes under axial compression or bending, see [10–14] for example. More recently, liner wrinkling during monotonic bending of the MLP has been studied, see [15–19] for example. Buckling/wrinkling behaviour is strongly influenced by tube/liner imperfections. Most liner imperfections are introduced during manufacturing of the MLP when the liner conforms to the shape of the backing steel pipe ID. Seamless backing pipes are characterised by a spiral surface topology (visible on the pipe ID) which is introduced during the piercing process. This topology is transferred to the liner as shown in Fig. 3. In addition, any CRA material build-up may cause liner indentations during expansion, see Fig. 3. (It should be noted that shadows cast by backlit imperfections make them appear, in Fig. 3, larger than they actually are.)
Vasilikis and Karamanos, showed in [19], that applying liner imperfections from an eigenmode buckling analysis allows accurate prediction of wrinkle initiation and growth during bending. Later, Harrison et al. [20] established that idealised harmonic imperfections have a similar effect on liner wrinkling behaviour as those introduced by the seamless backing pipe. Therefore, imperfections derived from a buckling/wrinkling eigenmode analysis are applied to the liner in this study. The length of the liner model in the eigenmode analysis is equal to half of the wavelength of a liner wrinkle under axial compression [3].

\[
\lambda = \frac{\pi (rt)^{0.5}}{12(1-\nu^2))^{0.25}}
\]  

(1)

where \(t\), \(r\) and \(\nu\) are the thickness, the mid-wall radius and Poisson’s ratio of the liner. A quarter of the liner is modelled with first-order shell elements with reduced integration (S4R in ABAQUS [21]) and appropriate symmetry boundary conditions, see Fig. 6(a). A compression load mode is preferred over a bending load mode because it yields eigenmodes that are symmetrical with respect to the pipe axis. These are suitable for modelling reverse bending as experienced during the reeling process. Fig. 6(b) shows ten eigenmodes obtained from this analysis.
The FE model proposed in [18] is used to determine which imperfection shape (eigenmode in Fig. 6(b)) and height is appropriate to correctly predict liner wrinkling during bending of MLP. The model length is the same as that in the eigenmode analysis. Both the liner and the backing pipe are modelled with first-order shell elements with reduced integration (S4R in ABAQUS). A quarter of the MLP with appropriate symmetry boundary conditions is modelled. A finite-sliding contact formulation with Coulomb friction (friction coefficient of 0.1) is employed to model interaction between the liner and the backing pipe. A selected eigenmode is scaled so that the required initial imperfection height is seeded onto the liner. The nodes to the right hand side of the model in Fig. 7 are connected to a reference node through kinematic coupling. The MLP is bent by applying rotation to the reference node. The FE results, shown in Fig. 8, are expressed in terms of the liner separation from the host pipe normalised by the liner thickness versus the normalised bending curvature, $\kappa/\kappa_0$,

$$\frac{\kappa}{\kappa_0} = \kappa \times \frac{d^2}{t}$$  \hspace{1cm} (2)

where $d$ is the liner mid-wall diameter. Eigenmode 3 in Fig. 6(b) is the best suited imperfection shape, because it is symmetrical with respect to the neutral bending axis, and yields separation no lower than the other modes. Figure 9 shows the effect of the normalised imperfection height, $h/t$, on the liner separation at $\kappa/\kappa_0 = 1.5$. The predicted liner separation is very sensitive to the imperfection height for $h/t$ up to 5% only. Consequently, eigenmode 3 with $h/t = 5\%$ is adopted in the next section.

Manufacturing, Reeling and Operation

A simulation of liner expansion during manufacturing, reel-lay installation and in-service operation is performed with a half-symmetrical 3D FE model, shown in Fig. 10, to determine in-service cyclic loading in the liner. First-order shell elements with reduced integration and first-order pipe/beam elements (respectively S4R and PIPE31 in ABAQUS [21]) are used to model both the liner and the backing pipe. (It should be noted that beam elements are only used to extend the model length to a pipe joint, i.e. 12 m, at low computational cost.) The beam mesh is con-

FIGURE 10. 3D FE MODEL FOR SIMULATION OF MANUFACTURING AND REELING OF MLP
Connected to the shell mesh with kinematic couplings at either end of the model. The liner shell mesh has a refined central section where the eigenmode 3 imperfection (shown in Fig. 6) is seeded as detailed in the previous section. This central region is indented during simulated manufacturing with a rigid nugget to create a wrinkle/indent similar to those shown in Fig. 3. The end cap, which allows application of the end cap load in-service, is modelled using elastic shell elements (S3 in ABAQUS). Rigid bending formers are utilised to replicate the reel, the aligner, the straightener and the free span between the reel and the aligner. These formers are connected through their reference nodes to the beam mesh end nodes with kinematic couplings. The finite-sliding contact formulation and Coulomb friction model is again used to model the liner-to-host pipe and pipe-to-former interactions. Frictionless contact is assumed between the host pipe and the formers. Finite strain theory is assumed in the analysis.

The liner with a typical insertion gap of 3–4 mm is first subjected to internal pressure to simulate manufacturing of the MLP. This creates an interference fit between the liner and the host pipe while the liner is indented at its central section which is seeded with the eigenmode 3 imperfections, $0.05 \times t$ in height. After releasing the pressure, reel-lay installation is simulated by bending the pipe onto the reel, the “free span” former, the aligner and finally onto the straightener before the pipe is relaxed. The radius of the bending former is chosen so that the target wrinkle height (up to 6 mm in height) is obtained. On completion of the installation phase, all surfaces and elements, except from those shown in Fig. 11, are removed from the model in Fig. 10. After applying symmetry boundary conditions to the nodes on the left hand side of the model, shown in Fig. 11, subsea operation is simulated. The MLP is hydrotested to simulate pre-commissioning and bent to 1% strain to simulate a lateral bucking event. Then, the pipe is relaxed to 0.7% residual bending strain. Finally, a severe in-service loading sequence is simulated. The pipe is pressurised from 0 to a pressure corresponding to a hoop stress utilisation ratio of 0.8. Its temperature is increased by 150°C and the bending strain is increased from 0.7% to 1%. Subsequently, the pipe is depressurised, cooled to ambient and relaxed to 0.7% bending strain. The results in terms of operational stress/strain ranges at the crown of the wrinkle are used in the next section.
Fatigue Test Simulation

Figure 12 shows a half-symmetrical liner strip model extracted from the central section of the 3D FE model (Fig. 11) after simulated manufacturing, installation, and hydrotest (to account for the strain history). The size of the liner strip is representative of a dumbbell test specimen in a small scale fatigue test. Cyclic axial displacement is applied at the right end of the model, shown in Fig. 12, while the left end is fully constrained, to simulate a small scale fatigue test. The magnitude of displacement is altered in an iterative manner until the stress/strain range at the crown of the wrinkle in the strip FE analysis matches that obtained from the FE analysis of the MLP under operational cyclic loading.

Results of Numerical Study

Large and conservative wrinkle imperfections, up to 6 mm in height, are considered in this paper to assess the fatigue performance of MLPs. To achieve such imperfections in the FE analysis, a 2 mm high indent (double the height of the maximum allowable manufacturing imperfection for a project pipe), indicated with a short-dashed line in Fig. 13, is created during manufacturing and the MLP is bent on a very tight reeling former to maximise bending strain. The bending radius required to achieve the desired wrinkle height of 6 mm (indicated with a long-dashed line in Fig. 13) is smaller than the reel hub radius of a typical reel-lay vessel by the factor of 2. The residual wrinkle after hydrotest of just over 1 mm in height is indicated with a solid line in Fig. 13.

Figure 14 shows the evolution of axial stress at the wrinkle crown during operation, obtained from the model illustrated in Fig. 11. It may be seen that it takes approximately 7 cycles for the stress range to stabilise although peak stresses continue to rise slightly. The maximum stress range, $\Delta \sigma = 600$ MPa, is predicted to occur at the liner intrados, see Fig. 14. The three contributors to stress variations, bending, pressure and temperature, are denoted in this figure by “B”, “P” and “T”, respectively. The sign “+” in Fig. 14 indicates that bending strain, pressure or temperature increases while the opposite is indicated with the sign “–”. It can be seen that temperature variations have the largest effect on the stress range at the liner intrados. Figure 15 shows the evolution of the corresponding axial strain at the liner intrados. It also takes approximately 7 cycles for the strain range to stabilise. The maximum (stable) strain range is $\Delta \varepsilon = 0.5\%$. It is to be noted that the mean axial strain also slowly increases with the number of cycles due to ratcheting.

Figures 16 and 17 compare the results, in terms of axial stress and strain at the liner intrados, obtained from the 3D MLP model (indicated by a dashed line) and the simple strip model (indicated by a solid line). It can be seen that the applied cyclic displacement in the strip FE model can be selected so that the stress/strain range in the MLP is conservatively reproduced. This demonstrates that the complex behaviour of the MLP in-service can be well captured in a small scale displacement-controlled fatigue test.
It may be noted that a strain range, on the order of twice that predicted with the full scale MLP model, is applied to the strip model to achieve similar stress range in both models. Higher strain range must be applied in the strip model to compensate for biaxial loading (and to some extent plastic deformation due to lateral buckling) in the MLP model.

The results presented in this section are for the 8” MLP. Similar results are obtained for the 10” and 12” pipes.

EXPERIMENTAL WORK

Approach

The 8”, 10” and 12” MLPs, detailed in the previous section, were manufactured and bent in a rig, shown in Fig. 18, to simulate reel-lay installation. The MLP is then bent on an increasingly tight former until the required wrinkle height is achieved.

Following hydrotest, the pipes are sectioned to remove the liner. Subsequently, dumbbell specimens are extracted from the liner so that the wrinkle is located centrally along the specimen. Finally, small scale tests are carried out to assess the low cycle fatigue performance of MLPs with imperfect liners. The cyclic axial displacement is selected from the numerical results presented in the previous section.

Bending Trials and Hydrotest

The MLP test strings are conservatively subjected to five reverse bending cycles (i.e. 2.5 times a standard reel-lay installation cycle). The pipe is mounted in the rig, shown in Fig. 18, and bent onto an 8.23 m radius reeling former. After relaxing, it is rotated through 180° while the reeling former is replaced with the straightening former with a 34 m radius. The pipe is then bent onto the straightening former, the load is removed and the pipe turned 180°. This process continues until a total of five reverse bending cycles is applied. Visual inspection carried out during the bending trial revealed no wrinkles after simulated reeling. Therefore, the MLPs are subjected to bending on an increasingly tight former (down to 0.5 of the original bending radius) until a wrinkle height of 3–6 mm is achieved. The height of wrinkles drops to 1–2 mm following hydrotest (at a pressure of 64 MPa). After hydrotesting, the test strings are sectioned to remove the liner and fabricate specimens for small scale fatigue testing.
Small Scale Fatigue Tests

Dumbbell test specimens (Fig. 19) are machined from the corrosion resistant alloy 316L and 625 liners which are removed from the 8" 10" and 12" MLPs after simulated reeling and hydrotest. Before fatigue testing, the specimens are buckled in the test machine, shown in Fig. 20, to increase the wrinkle height back to 3–6 mm. Subsequently, the samples are instrumented with biaxial strain gauges. A transverse gauge is used to compensate for temperature effects. After mounting the specimen in the test machine and installing the cooling system, an extensometer with a 12.5 mm gauge length is affixed to the specimen around the crown of the wrinkle (see Fig. 20). The extensometer is used to control the cross-head displacement of the test machine so that the gauge length is subjected to a global strain range of +/-0.5%. This is conservative and results in a higher strain range at the wrinkle crown compared to that reported in Fig. 17.

Eighteen dumbbell specimens, six for each pipe size, are fatigue tested at a frequency of 2 Hz to determine the fatigue endurance of MLPs with imperfect liners. Although the maximum service temperature can be high (100–150°C or above), testing is conveniently undertaken at room temperature as fatigue cracks generally grow slower at elevated temperature [22].

Results and Discussions

Figure 21 shows an example of the maximum load-life line for the alloy 316L sample tested in this programme. At the beginning of the fatigue test, a rapid decrease in peak load is observed but after a few hundred cycles the rate of load decrease stabilises at a constant low value, most likely due to ratcheting. When cracking initiates, at ca. 7600 cycles in Fig. 21, the load decreases rapidly again. Fatigue failure is deemed to occur when the applied load reduces by 10%, as indicated by the blue line in Fig. 21, which can be considered as crack initiation.

The test results for the 8″/316L, 10″/625 and 12″/316L MLPs (indicated respectively by the triangles, circles and squares in Fig. 22) are compared in Fig. 22 to the BS 7608 class C mean curve [23]. It can be seen that all test results exceed the BS7608 class C mean curve. Furthermore, fatigue life of the alloy 625 liner is higher than that of the alloy 316L liner. This is in line with other studies, where it has been shown that crack initiation and growth is slower in alloy 625 than in alloy 316L [22].
CONCLUSIONS

Deep scoring of the liner, when its insertion into the backing pipe during MLP manufacturing process is not well controlled, may result in the build-up of the CRA material in the annulus between the liner and the host pipe. Consequently, the liner may be indented when it is expanded during manufacturing. Furthermore, imperfections such as wrinkles may be introduced during installation or service. As flowlines are often subjected in-service to high pressure and temperature fluctuations and cyclic bending strain, concerns have been expressed that the presence of liner wrinkles/indents may reduce the fatigue performance of MLPs.

A numerical study was undertaken to quantify the stress/strain ranges associated with imperfect liners when MLPs are subjected to onerous in-service loading. It was found that the axial strain range in the liner does not exceed 1% for a pressure range equal to a hoop stress utilisation ratio of 0.8, a temperature range of 150°C and a bending strain range of 0.3%. It was further demonstrated that the stress/strain range in the liner subjected to in-service loading can be reproduced in a strip geometry under cyclic axial displacement. Therefore, a simple small scale test set-up can be used in place of expensive and time consuming large scale testing to determine the fatigue endurance of the MLP in-service.

Liner dumbbell specimens were extracted from the 8", 10" and 12" MLP strings which underwent simulated reeling (bending on the former) and pre-commissioning (hydrotest). The liner specimens had wrinkles, up to 6 mm in height, introduced halfway along their length prior to fatigue testing. The fatigue life obtained from these specimens was between 4,000 and 22,000 cycles, and was significantly higher for alloy 625 (13,000 to 22,000 cycles) compared to that for alloy 316L (4,000 to 10,000 cycles). The predicted life for MLPs with large imperfections and subjected to high cyclic loading is well in excess of 3000 cycles, which corresponds to one shut-down cycle every month, for 25 years with a safety factor of 10. This demonstrates that liner imperfections (indents/wrinkles) in the range considered in this work (up to 6 mm in height) are not detrimental to the in-service integrity of MLP flowlines.

ACKNOWLEDGMENT

The authors wish to thank Gilles Maitres from A2MI, and Ludovic Krauss, Daniil Vasilikis and Paul Sicsic from Tech-nipFMC for their valuable contribution.

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