Analytical Prediction and Numerical Validation for Interfacial Contact Pressure in Mechanically Lined Pipe Fabrication

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Abstract. Mechanically Lined Pipe (MLP) is a bi-metallic pipe consists of an external carbon steel pipe internally coated with a thin Corrosion Resistance Alloy (CRA) liner. This CRA layer acts against corrosive substance from the production fluid, while the carbon steel outer pipe bears the external loads. Continuous efforts have been undertaken to establish precise and dependable theoretical models for fabrication enhancement and subsequent installation and failure analyzes. Tresca criterion is regularly adopted for analysis associated with MLP fabrication given its mathematical simplicity. However, Tresca criterion is also known for its conservative approach in predicting metal yielding. The corresponding MLP analysis results is questionable. Therefore, MLP fabrication analytical model leverage infinitesimal strain theory and von Mises (vM) criterion is developed to increase accuracy. The maximum interfacial contact pressure and residual contact pressure are derived using compatibility relations in radial displacement and circumferential strain respectively. An axisymmetric Finite Element (FE) model is used to compare with the revised theoretical model in terms of interfacial contact pressure and allowable hydraulic expansion pressure range.

Keywords: Mechanically Lined Pipe, von Mises Criterion, Infinitesimal Strain Theory, Finite Element Method, Interfacial Contact Pressure.

1 Introduction

During offshore O&G development, caustic compositions compromise pipeline integrity. To safeguard the integrity, a bi-metallic structure is designed. It features a thick-walled carrier pipe (outer tube) of carbon steel, providing resistance to loads. The internal surface of carrier pipe is lined with a corrosion resistant alloy layer (inner tube). This double-walled pipe is generally produced through mechanical bonding. Thus, known as Mechanically Lined Pipe (MLP). The fabrication process of MLP can be generally divided into internal hydraulic expansion pressure loading and internal pressure unloading process. Given the mismatched properties at liner-carrier interface and elastic hoop strain rebounding. A lasting residual contact pressure is generated after hydraulic expansion unloading.

Reeling installation can cause liner separation from the carrier pipe due to repetitive plastic bending and compression. Excessive wrinkle and buckles hinder internal fluid flow. Liner wrinkling and buckling were studied numerically and experimentally by Vasilikis and Karamanos [1] and Yuan and Kyriakides [2], [3]. Conclusions show that residual contact pressure affects detachment. Residual contact pressure prediction and MLP fabrication analysis are critical for structural integrity during installation and following pipeline service.

To ascertain the residual contact pressure for subsequent engineering operation analysis, the manufacturing process is studied. Aydemir et al. [4] initially applied finite element analysis to investigate pipe hydraulic expansion and access loading path effects. Liu et al. [5] presented an analytical model predicting residual contact pressure for pure hydraulic expansion method, considering reverse yielding during unloading. Akisanya et al. [6] investigated hydraulic expansion of concentric pipes for O&G casing, developing a model linking hydraulic pressure, casing geometry and residual contact pressure using elasticity theory. Nonlinear FE analysis confirmed their findings, considering support conditions. Olabi and Alaswad [7] used ANSYS LS-DYNA to predict the optimal conditions for specific liner and carrier pipe combination. They claimed that hydroforming process achieved better formability when applying axial pushing after internal pressure. Yuan and Kyriakides [8] analyzed hydraulic expansion manufacturing, incorporating incremental plasticity and material hardening in a biaxial stress state model. Certain plastification of carrier pipe is found beneficial. A low yielding-stress liner with low hardening combining with high yielding-stress carrier pipe with high hardening enhances residual contact pressure. Gavriilidis and Karamanos [9] developed 3D FE model to simulate MLP bending. Liner prestressing during manufacturing suppressed wrinkling. Wei et al. [10] investigated the impact of partial plastification in carrier pipe made of linear-hardening material on residual contact pressure. Findings reveal that introducing plastification enhances residual contact pressure. Existing references shows that the derived analytical models regularly utilize the Tresca criterion due to the mathematical simplicity of elastoplastic analysis, which also introduces errors caused by conservatism. Another common source of error lies in assumption of omission of initial clearance and strain-hardening.

Given the above content, this technical research provides a theoretical estimate of residual contact pressure for open-ended MLPs manufactured by pure hydraulic expansion. The von Mises yielding criterion is employed against the conservatism of Tresca criterion. Theoretical modeling enables elastoplastic analysis for both pre- and post-fullplastification expansion. The residual contact pressure is determined by applying the hoop strain compatibility equation. Ultimately, the revised theoretical model is compared with an axisymmetric FE model in ABAQUS.

2 Mechanically Lined Pipe Manufacturing Process

MLP manufacturing involves hydraulic pressure loading and unloading. Liner experiences elastic, elastoplastic and post-fullplastification expansion until the target pressure is reached. Carrier pipe starts elastic expansion after contacting with liner, and it remains elastic within fabrication. During the unloading, both liner and carrier pipe shrink inward. The elastic rebounding at liner-carrier interface in circumferential direction are identical. The residual contact pressure comes from the unmatching between the radial expansion and elastic strain rebounding. The following content provides a more detailed description of fabrication model derivation.

3 Stress-Strain Analysis of MLP Fabrication

To determine the relationship between internal hydraulic expansion pressure p_i and residual contact pressure p^* requires the application of hoop strain compatibility. When MLP is fully loaded, reaching the target expansion pressure p_i^t, the hoop strains at the outer surface of liner and inner surface of carrier pipe are denoted as $(\varepsilon_\theta)_{io}^t$ and $(\varepsilon_\theta)_{oi}^t$ respectively. Similarly, at the end of unloading with the residual contact pressure p^*, the hoop strains are $(\varepsilon_\theta)_{io}^*$ and $(\varepsilon_\theta)_{oi}^*$. The compatibility equation, expressed as Eq. (1), asserts that, during the unloading, the elastic hoop strain rebounding at the contact interface of the liner and carrier pipe is identical.

$$(\varepsilon_\theta)_{io}^t - (\varepsilon_\theta)_{io}^* = (\varepsilon_\theta)_{oi}^t - (\varepsilon_\theta)_{oi}^* \tag{1}$$

To facilitate the derivation, we adopt the subsequent assumptions: (1) homogeneity and incompressibility; (2) isotropic hardening; (3) infinitesimal strain theory; (4) no body force act; (5) power-law constitutive model. (6) utilize Hencky deformation theory and vM criterion, Bauschinger effect is not considered; (7) open-ended boundary conditions.

Give the Lamé equation is a widely-recognized solution of single cylinder elastic expansion problem. Its derivation is folded here. The analysis for pre-fullplastification expansion of single cylinder is referred to the work by Gao [11]. The fundamental equations for the extended model derivation includes: power law constitutive model, stress equilibrium of internally-pressurized open-ended cylinder, equivalent vM stress, strain compatibility. (for detail, please see Eq. 5-10 in Gao [11]). Wei et al. [12] further extended the model of Gao for the cases of post-fullplastification expansion without/with external contact.

The key to the solution of the stress-strain state in plastic region is the auxiliary variable method. Considering stress components as basic unknowns, an auxiliary variable $\phi = \phi(r)$ is introduced, and letting:

$$\sigma_\theta = \frac{2}{\sqrt{3}}\sigma_i \sin\left(\phi - \frac{\pi}{6}\right) \quad \sigma_r = -\frac{2}{\sqrt{3}}\sigma_i \cos(\phi) \tag{2}$$

The difference between extended models with pre-fullplastification model is the boundary conditions. The BCs for post-fullplastification are listed in Eq. (3). Associating fundamental equations with BCs forms boundary-value determinant problem. The solution for the post-fullplastification expansion without external contact is Eq. (4):

$$\begin{cases} \sigma_r|_{r=r_a} = -\alpha p_i^{100} \\ \sigma_r|_{r=r_b} = 0 \\ \sigma_i|_{r=r_b} = \beta\sigma_{yi} \end{cases} \begin{cases} \sigma_r|_{r=r_a} = -\alpha p_i^{100} \quad \alpha \geq \alpha_c \\ \sigma_r|_{r=r_b} = -p_{int} \\ \sigma_i|_{r=r_b} = \beta\sigma_{yi} \quad \beta \geq \beta_c = \alpha_c \end{cases} \tag{3}$$

$$\begin{cases} \phi_n = arccos\dfrac{\sqrt{3}n}{\sqrt{3n^2+1}} \\ \dfrac{r_b}{r_a} = \sqrt{\dfrac{sin\left(\phi_a + \frac{\pi}{6}\right)}{sin\left(\phi_b + \frac{\pi}{6}\right)}}\left|\dfrac{cos(\phi_b+\phi_n)}{cos(\phi_a+\phi_n)}\right|^{\frac{2n}{3n^2+1}} exp\left[\dfrac{\sqrt{3}}{2}\dfrac{1-n^2}{3n^2+1}(\phi_b - \phi_a)\right] \\ \dfrac{\alpha p_i^{100}}{\beta\sigma_{yi}} = \dfrac{2}{\sqrt{3}}\left|\dfrac{cos(\phi_b+\phi_n)}{cos(\phi_a+\phi_n)}\right|^{\frac{3n^2+n}{3n^2+1}} exp\left[\dfrac{\sqrt{3}n(n-1)}{3n^2+1}(\phi_a - \phi_b)\right] cos(\phi_a) \end{cases} \tag{4}$$

For the case of single cylinder post-fullplastification with external contact, one more condition named "radial displacement compatibility" is added, which is expressed as Eq. (5). This complementary condition implies that the liner-carrier interface generate the same radial displacement after contacting during loading process.

$$\begin{aligned} & r_b \sqrt[n]{\frac{\beta\sigma_{yi}}{A}} sin\left[arccos\left(\frac{\sqrt{3}p_{int}}{2\beta\sigma_{yi}}\right)\right] - g_0 \\ & = p_{int}R_a^2(1-\mu_o)\left(R_b^2 - 2\mu_o R_a^2 + R_a^2\right)/E_o R_a\left(R_b^2 - R_a^2\right) \end{aligned} \tag{5}$$

In Eq. (3)-(5), r_a, r_b and r_c stands for internal, external radii and elastoplastic boundary. α and β are amplification factors, p_{int} means the interfacial contact pressure, p_i^{100} is the internal pressure to just induce full plastification of liner. R refers to the relevant parameters of carrier pipe. μ_o means the Poisson ratio of carrier pipe. p_c is the absolute value of radial stress at $r = r_c$.

Therefore, the stress distribution within liner can be determined. Observing that the elastic hoop strain equation for plane stress problem is $\varepsilon_\theta^e = 1/E\,(\sigma_\theta - \mu\sigma_r)$ and the Lamé equation is applicable for carrier pipe. Combining the general elastic hoop strain equation and inserting the hoop and radial stress state at the liner-carrier interface into Eq. (1). The maximum internal pressure p_i^t and residual contact pressure p^* corresponding to p_{int} can be predicted.

4 Finite Element Modelling

An axisymmetric FE model is developed in ABAQUS for numerical simulation of MLP fabrication. The interfacial contact pressure at the fully loaded and unloaded moments are recorded to verify the consistency with the prediction of target interfacial contact pressure P_{int}^t and residual contact pressure p^*. The cross-sections of liner and carrier pipe are represented by 2 coaxial axisymmetric deformable rectangular shell parts. The lengths of liner and carrier pipe are set as more than 2 times of the internal radius of liner to ascertain the contact pressure uniformity. The material properties and FE model configuration are shown in Fig.1 and Tab.1. The internal pressure is applied on the internal surface of liner. One end of MLP is set as free boundary to represent the open-ended BC, and the order end is set as symmetric BC. The liner surface is set as "slave" given its relatively lower Young's modulus than carrier pipe. CAX4R is adopted for meshing. Through the wall-thickness, there are 20 elements assigned on both liner and carrier pipe. There are respectively 2000 and 500 elements assigned on liner and carrier pipe in the longitudinal direction. To perform the simulation, the P_{int}^t is firstly assumed, then the corresponding p_i^t and p^* are determined theoretically. The predicted p_i^t is applied to the FE model, the target interfacial contact pressure and residual contact pressure are extracted from the contacting surface at the fully loaded and unloaded moment.

Table 1: Material and geometric parameters of liner and carrier pipe

Properties	E (GPa)	μ (Poisson)	σ_y (MPa)	ID (mm)	OD (mm)	n
Liner	193	0.3	215.62	287.64	293.64	0.088
Carrier Pipe	205	0.3	464.92	296.10	324.70	0.231

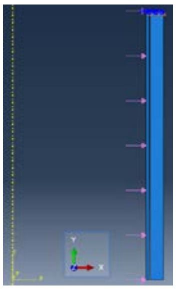

Figure 1: Axisymmetric FE model configuration.

5 Results Discussion and Conclusion

The comparison between the analytical prediction and FE model simulation in terms of the target interfacial contact pressure and residual contact pressure has been demonstrated in Fig.2. Under the same target internal expansion pressure p_i^t, a good correlation of target interfacial contact pressure can be found between the derived analytical model and numerical method. There is a constant difference in terms of residual contact pressure between the FE model and analytical prediction. The analytical model tends to underestimate the mechanical bonding. Consequently, the theoretical model overestimates the minimum hydraulic expansion pressure.

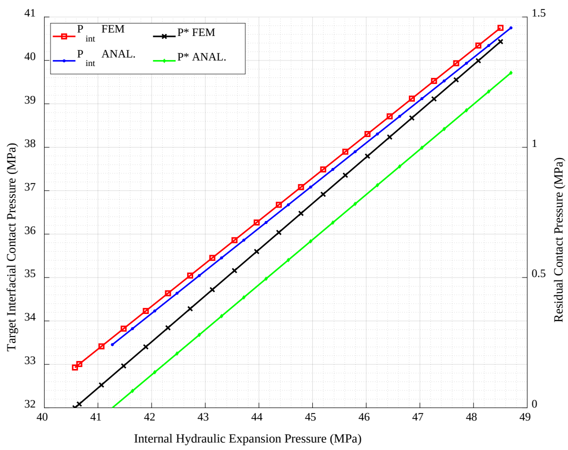

Figure 2: Axisymmetric FE model configuration.

Based on the above content, several points are concluded:

(1) The derived analytical model presents a very good match in terms of target interfacial contact pressure with the axisymmetric FE model. and linear relationships between p_i^t, P_{int}^t and p^* are found.
(2) Compared with FE model, the proposed theoretical model tends to underestimate the residual contact pressure. Thus, a higher minimum hydraulic expansion pressure is determined analytically. The error may lie in the incompatibility between the infinitesimal strain theory adopted by analytical model and the geometry nonlinearity (finite strain theory) from the FE model. Further improvement in terms of geometry nonlinearity is still needed.
(3) The revised theoretical model successfully includes the influences of initial gap and strain-hardening. Relevant parametric studies can provide conceptual guidance for material combination and dimension design for MLP fabrication.

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References

[1] D. Vasilikis and S. A. Karamanos, “Mechanical behavior and wrinkling of lined pipes,” Int J Solids Struct, vol. 49, no. 23–24, pp. 3432–3446, Nov. 2012, doi: 10.1016/j.ijsolstr.2012.07.023.

[2] L. Yuan and S. Kyriakides, “Liner buckling during reeling of lined pipe,” Int J Solids Struct, vol. 185–186, pp. 1–13, Mar. 2020, doi: 10.1016/j.ijsolstr.2019.08.017.

[3] L. Yuan and S. Kyriakides, “Liner wrinkling and collapse of bi-material pipe under bending,” Int J Solids Struct, vol. 51, no. 3–4, pp. 599–611, Feb. 2014, doi: 10.1016/j.ijsolstr.2013.10.026.

[4] A. Aydemir, J. H. P. De Vree, W. A. M. Brekelmans, M. G. D. Geers, W. H. Sillekens, and R. J. Werkhoven, “An adaptive simulation approach designed for tube hydroforming processes,” J Mater Process Technol, vol. 159, no. 3, pp. 303–310, 2005, doi: 10.1016/j.jmatprotec.2004.05.018.

[5] F. Liu, J. Zheng, P. Xu, M. Xu, and G. Zhu, “Forming mechanism of double-layered tubes by internal hydraulic expansion,” International Journal of Pressure Vessels and Piping, vol. 81, no. 7, pp. 625–633, 2004, doi: 10.1016/j.ijpvp.2004.03.014.

[6] A. R. Akisanya, F. U. Khan, W. F. Deans, and P. Wood, “Cold hydraulic expansion of oil well tubulars,” International Journal of Pressure Vessels and Piping, vol. 88, no. 11–12, pp. 465–472, Dec. 2011, doi: 10.1016/j.ijpvp.2011.08.003.

[7] A. G. Olabi and A. Alaswad, “Experimental and finite element investigation of formability and failures in bi-layered tube hydroforming,” Advances in Engineering Software, vol. 42, no. 10, pp. 815–820, 2011, doi: 10.1016/j.advengsoft.2011.05.022.

[8] L. Yuan and S. Kyriakides, “Hydraulic expansion of lined pipe for offshore pipeline applications,” Applied Ocean Research, vol. 108, Mar. 2021, doi: 10.1016/j.apor.2020.102523.

[9] I. Gavriilidis and S. A. Karamanos, “Effect of Manufacturing Process on Lined Pipe Bending Response,” Journal of Offshore Mechanics and Arctic Engineering, vol. 142, no. 5, Oct. 2020, doi: 10.1115/1.4046566.

[10]R. Wei, M. A. Vaz, and X. Hu, “Residual contact pressure for mechanically lined pipe hydroforming with carrier pipe plastification,” International Journal of Pressure Vessels and Piping, vol. 206, p. 105076, Dec. 2023, doi: 10.1016/j.ijpvp.2023.105076.

[11]X. Gao, “An exact elasto-plastic solution for an open-ended thick-walled cylinder of a strain-hardening material,” International Journal of Pressure Vessels and Piping, vol. 52, no. 1, pp. 129–144, Jan. 1992, doi: 10.1016/0308-0161(92)90064-M.

[12]R. Wei, M. A. Vaz, and X. Hu, “Theoretical analysis on mechanically lined pipe fabrication”. Proceedings of the ASME 2024 43nd International Conference on Ocean, Offshore and Arctic Engineering.