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# Theoretical Analysis on the Bending Springback of Flattened Oil and Gas Pipelines

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Oil and gas pipeline leakage incidents occur from time to time, causing environmental pollution, property damages and other serious consequences. Flattening the oil and gas pipelines to stop the flow can effectively reduce losses. The extrusion device can quickly arrive at the incident scene and flatten the pipeline within a short time using hydraulic power or mechanical force so as to stop the flow. However, due to the springback problem, a small amount of oil or gas will still leak. Therefore, studying the bending springback of flattened oil and gas pipelines is very essential to solving the oil or gas leakage problem. This paper analyzes the theories related to flattening and closure of oil and gas pipelines. Springback is an inevitable result of the elastic redistribution of the internal stress in a flattened pipeline. Regarding the bending springback problem of flattened steel pipelines, based on the assumptions of plane strain, this paper applies the plate bending theory and establishes a theoretical model for the bending springback process of flattened steel pipelines and obtains the factors affecting the bending springback of flattened pipelines. At the same time, it uses the model in conjunction with the experiment to analyze the relationship between the springback of a flattened pipeline and the closure efficiency.

## 1. Introduction

Modern transportation mainly includes railway, road, water, air and pipeline transportation (Li, 2015). Oil and natural gas are mainly transported through pipelines. Compared with other four means, pipeline transportation has such advantages as large transport capacity, low energy consumption, low transportation cost and long-term stable operation. With the advancement of science and technology and the social and economic development, more and more oil and natural gas are being consumed, and the construction of pipelines is also booming (Yan et al., 2017). However, due to human causes like improper management and irrational design as well as natural causes like corrosion, pipeline leakage incidents occur from time to time, resulting in environmental pollution, property damages and other adverse consequences (Yang, 2015; Feng et al., 1995; Zhang, 2014). To this end, experts at home and abroad not only think about what measures to take to prevent the occurrence of pipeline leakage incidents, but also commit themselves to making innovations on repair equipment and methods to deal with pipeline leakage. In many areas in China, pipelines are laid in undulate terrains with large elevation differences. When any leakage incident occurs to these pipelines, the emergency repair work can be very difficult. If the downhill section of an oil pipeline is greatly damaged or the leakage hole is large, the conventional repair and plugging methods may fail, and what is more, large repair equipment cannot reach the incident scene within a short period of time to complete pipe replacement and plugging operations (Yu, 2012; Qu et al., 2011; Wang and Sun, 2006; Wang, 2005;). In order to minimize economic losses and secondary hazards, before the arrival of large repair equipment, an extrusion device can be used near the leakage point as a temporary repair and plugging measure. The research team proposes a piping extrusion device (as shown in Figure 1), which utilizes hydraulic power or mechanical force to completely flatten the local section of a pipeline within a short time, which can effectively stop the pipeline flow and plug the leak. Wang (2009) obtained some patterns of pipeline extrusion deformation and the load-displacement curve through experiments. Zhang et al. (2012) analyzed the extrusion deformation principle of steel oil pipelines and established a model for the extrusion deformation of steel pipelines under the loads applied by

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upper and lower tools. Jiao et al., (2013) established a model for pipe extrusion deformation under uniform radial loads based on the theory of plastic deformation and the principle of virtual work. Through previous theoretical research and practice, the research team has found that, where the extrusion device is used to flatten a steel pipeline, a small amount of oil or gas will still leak as the pipeline will slightly spring back after the stress is unloaded (Ban, 2014). To mitigate or even solve this problem, this paper proposes bending the flattened pipelines and mainly performs theoretical analysis on the bending springback of flattened steel pipelines, hoping to provide basis for emergency repair of pipelines.

*Figure 1: Piping extrusion device*

## 2. Theoretical model for bending of flattened oil and gas pipelines Equations

The physical model for the bending springback of pipeline can be simplified as the mechanical model of a double-layer metal plate. Figure 2 is a schematic diagram of the bending deformation of a flattened oil/gas pipeline. The following assumptions are made for such deformation (Zhang et al., 2006):
(1) The pipe material is an ideal elastic-plastic hardening material;
(2) After the flattened oil/gas pipeline is plastically bent, the cross section of the bent area is still a plane;
(3) The deformation along the width of the sheet is negligible and in the plane strain state.
(4) The Bauschinger effect is ignored.

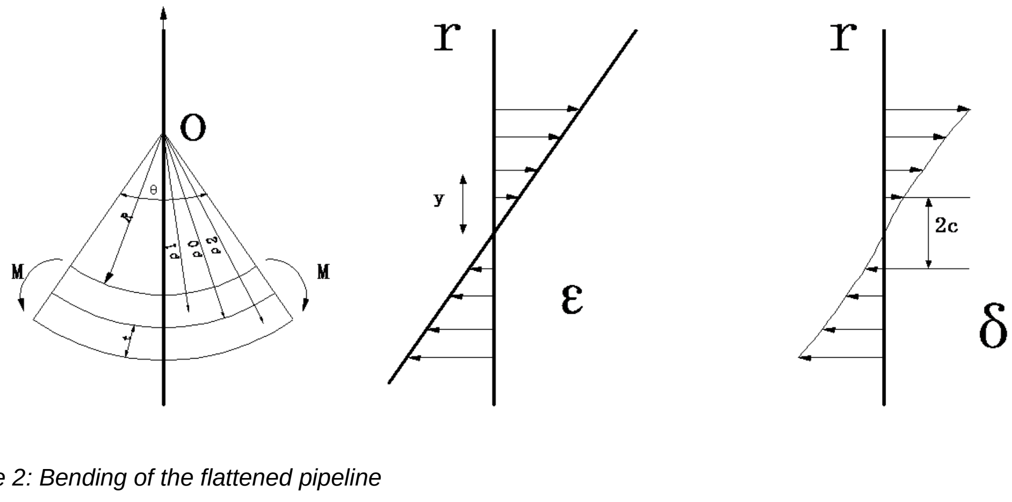


*Figure 2: Bending of the flattened pipeline*

Let the wall thickness of the pipe be t, the radius of curvature of the neutral layer in the flattened pipeline be $\rho_0$, the bending angle be α, and the radius of curvature of the inner surface layer be R. When the bending moment M is greater than the elastic ultimate bending moment Me, the material is in the elastic-plastic bending stage.

Let the distance between a mass point and the neutral layer be y, its tangential strain be $\varepsilon_\theta$, and its tangential stress be $\delta_\theta$:

$$\varepsilon_\theta = \ln\frac{(\rho_0+y)\alpha}{\rho_0\alpha} = \frac{y}{\rho_0} \tag{1}$$

Considering that the volume of the flattened oil/gas pipeline remains constant in the planar state, we have:

$$\varepsilon_\theta + \varepsilon_p + \varepsilon_b = 0 \tag{2}$$

From the Mises yield criterion (Li et al., 2016), it can be seen that:

$$\delta_\theta - \delta_p = \frac{2}{\sqrt{3}}\bar{\delta} \tag{3}$$

Equivalent stress

$$\bar{\delta} = \frac{\sqrt{3}}{2}(\delta_\theta - \delta_p) \tag{4}$$

Equivalent strain

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}}\varepsilon_\theta \tag{5}$$

The flattened pipeline obeys the exponential stress-strain hardening relationship in the plastic zone (Yu, 1992):

$$\bar{\delta} = B(\bar{\varepsilon})^n \tag{6}$$

Substitute formulas (4), (5) and (6) into formula (3), and there is:

$$\delta_\theta - \delta_p = \left(\frac{2}{\sqrt{3}}\right)^{n+1} B\left(\ln\frac{\rho}{\rho_0}\right)^n \tag{7}$$

Establish the equilibrium equation based on the microelement balance:

$$d\delta_p = (\delta_\theta - \delta_p)\frac{d\rho}{\rho} \tag{8}$$

By combining formulas (7) and (8), we can obtain the stress in the plastic zone:

$$\delta_\theta = \left(\frac{2}{\sqrt{3}}\right)^{n+1} B\left\{\frac{1}{n+1}\left[\left(\frac{\rho}{\rho_0}\right)^{n+1} - \left(\frac{R}{\rho_0}\right)^{n+1}\right] + \left(\frac{\rho}{\rho_0}\right)^n\right\} \tag{9}$$

Observe the stress distribution of the elastic zone in the flattened pipeline. Assuming that the thickness of the elastic zone is 2c, based on Hooke's law, we have:

$$\delta_\theta = \frac{E}{1-v^2}\varepsilon_\theta = E_1\frac{y}{\rho_0} \qquad y \le c$$

In the above formula, $E$ and $E_1$ are the elastic modulus of the flattened pipeline and the elastic modulus of the flattened pipeline under plane strain condition.

$$E_1 = \frac{E}{1-v^2}$$

The bending moment of the flattened pipeline in the longitudinal plane consists of the bending moment in the elastic zone and the bending moment in the plastic zone:

$$M = M_e + M_p \tag{10}$$

where, the bending moment of the elastic zone is:

$$M_e = 2\int_0^c \delta_\theta\, y dy = \frac{2E_1}{3\rho_0}c^3 \tag{11}$$

And the bending moment of the plastic zone is:

$$M_p = 2\int_c^t \delta_\theta y dy$$

$$=2\int_c^t \left(\frac{2}{\sqrt{3}}\right)^{n+1} B\left\{\frac{1}{n+1}\left[\left(\frac{\rho}{\rho_0}\right)^{n+1} - \left(\frac{R}{\rho_0}\right)^{n+1}\right] + \left(\frac{\rho}{\rho_0}\right)^{n}\right\}\rho d\rho$$

$$= \frac{B(t^{n+3}-c^{n+3})}{(n+1)(n+3){\rho_0}^{n+1}} - \frac{BR(t^2-c^2)}{2(n+1)} + \frac{B(t^{n+2}-c^{n+2})}{{\rho_0}^{n}(n+2)} \tag{12}$$

## 3. Calculation of the springback of the flattened oil and gas pipeline

During the unloading process, the internal stress of the flattened oil/gas pipeline is redistributed, and the elastic parts in the elastic and plastic deformation zones are partially elastically recovered. After unloading, the bending radius of the flattened steel pipeline is greater than that under load. The change caused by the unloading bending moment is equivalent to the elastic stress generated by a reverse bending moment M applied to the flattened steel pipeline (Zhen, 2016).

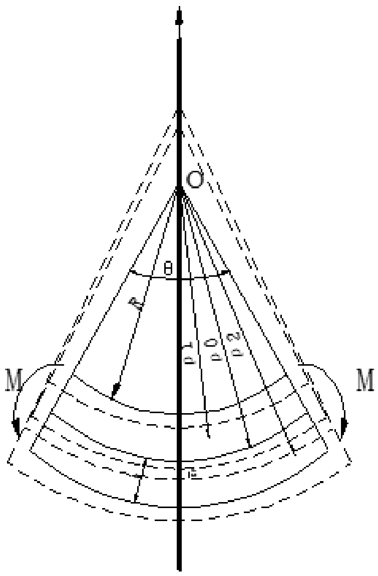


*Figure 3: Springback of the flattened pipeline*

According to the unloading theorem, the change rate of the curvature radius of the flattened steel pipeline after unloading is:

$$\frac{1}{\Delta\rho} = \frac{1}{\rho_0} - \frac{1}{\rho_0{}'} = \frac{M}{EI} \tag{13}$$

where, $\rho_0{}'$ is the radius of curvature of the flattened pipeline after springback and I is the inertia moment of the cross section along the unit width ($I = \frac{t^3}{12}$).

$$\frac{1}{\rho_1} - \frac{1}{\rho_1{}'} = \frac{M_1}{EI_1} \tag{14}$$

$$\frac{1}{\rho_2} - \frac{1}{\rho_2{}'} = \frac{M_2}{EI_2} \tag{15}$$

From Figure 3, we know

$$\rho_2 = \rho_1 + t \tag{16}$$

Combine formulas (14), (15) and (16), and we have:

$$\rho_2{}' - \rho_1{}' = \frac{\rho_2 EI}{EI - M\rho_2} - \frac{\rho_1 EI}{EI - M\rho_1} \tag{17}$$

Considering that the longitudinal length of the neutral plane remains constant during the bending and springback of the flattened pipeline, we have:

$\rho_1\theta_1 = \rho_1'\theta_1'$
$\rho_2\theta_2 = \rho_2'\theta_2'$
By combining the above formulas, we can obtain the angles $\theta_1'$ and $\theta_2'$ of the flattened pipeline after springback;
From the figure 3, it can be seen that the clearance of the flattened pipeline after bending and springback is:

$$\Delta X = \rho_2' - \rho_1' - t \quad (18)$$

From this, it can be seen that, the greater $\Delta X$, the better the closure effect; and vice versa.

## 4. Analysis of closure effects

The research team carried out pipeline rupture experiments on the pipelines with a diameter of 150mm, 256mm, and 510mm, respectively. The team first flattened the pipeline and then performed bending springback. Let the pressure inside the pipeline be 3MPa, the flow rate 1.5m/s, the density 850Kg/m3 and the wall thickness 5mm.
The closure efficiency ω is defined as follows:

$$\omega = \frac{Q_1 - Q_2}{Q_1};$$

where, $Q_1$ is the flow rate when the pipeline leakage is not stopped, and $Q_2$ is the flow rate after the pipeline undergoes flattening and bending springback following the leak.

*Table 1: Changes in the closure rate*

| Pipe diameter/mm | Closure rate | Closure rate | Closure rate | Closure rate | Closure rate | Closure rate | Closure rate | Closure rate | Closure rate |
|---|---|---|---|---|---|---|---|---|---|
| 150 | 0.987 | 0.974 | 0.961 | 0.948 | 0.935 | 0.922 | 0.909 | 0.897 | 0.884 |
| 256 | 0.992 | 0.985 | 0.977 | 0.970 | 0.962 | 0.955 | 0.947 | 0.939 | 0.932 |
| 510 | 0996. | 0.992 | 0.989 | 0.985 | 0.981 | 0.977 | 0.973 | 0.970 | 0.966 |

Based on Table 1, the closure efficiency graph is prepared, as shown in Figure 4 According to the analysis of the relationships between the bending springbacks of the flattened pipelines with different diameters and the closure efficiency, for flattened pipelines with the same diameter, with the increase of the springback, the closure efficiency decreases; and for pipelines with different diameters, when the springback is the same, the greater the diameter, the higher the closure efficiency.

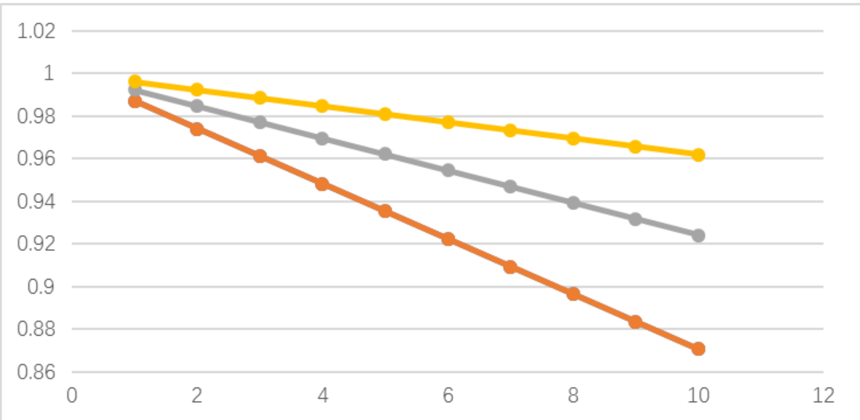


*Figure 4: Closure efficiency*

## 5. Conclusions

The bending springback of flattened oil and gas pipelines is a very important problem in the emergency repair of pipelines and the treatment of oil and gas leakage, but no research has been done on this aspect either at home or abroad. Considering this problem, based on the assumptions of plane strain, this paper theoretically analyzes the bending springback process of a flattened pipeline, establishes a mechanical model for the bending process of the flattened pipeline, calculates its springback and discusses the relationship between springback and closure efficiency through some experiments. The research results show that, the springback of a flattened pipeline has something to do with the pipe wall thickness, pipe material and die size, and that with the increase of the springback, the closure efficiency becomes lower.

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