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CRITICAL COMPRESSIVE STRAIN OF LINEPIPES RELATED TO WORKHARDENING PARAMETERS

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ABSTRACT

An approximate solution to predict a critical compressive strain at the peak load (the peak load strain hereinafter) of linepipes subjected to axial compression is proposed in this paper. The approximate solution is derived from the deformation theory applying the stress-strain relationship with non-linear hardening properties, which have not been taken into account in a number of current equations applied for pipeline design. The approximate solution proposed in this paper is a closed form equation, which is useful and effective for the practical application. The parameters in the Ramberg-Osgood representation expressing workhardenability of the linepipes are successfully introduced for the approximate solution. The effec-tiveness and accuracy of the approximate solution are verified comparing the critical compressive strains of several API 5L grade linepipes obtained by finite element analyses.

INTRODUCTION

The focus of this paper is to propose an closed form approximate equation to predict the peak load strain of a pipe subjected to axial compression, where the workhardenability of pipe materials can be assessed. Pipeline engineers have been concerned about pipeline buckling problems as buried pipelines may undergo large deformation and plastic deformation due to permanent ground deformation such as liquefaction-induced lateral spreading and fault movements (Zimmermann et al., 1995), (Suzuki, 1995), (JGA, 2000). Hence some semi-empirical equations can be referred in several current pipeline design codes to predict the peak load strain or the peak moment strain of the pipelines. However the semi-empirical equations are dependent only on the ratio of pipe wall thickness to diameter, t/D, so that a thicker wall shall be chosen when a larger critical compressive strain, the peak load strain and the peak moment strain, is necessary to ensure the pipeline integrity. And the required thick wall of the linepipes may consequently increase expenditure of pipeline construction such as freight, welding and so on.

It may be generally recognized that the potential deformability of the pipes to resist axial compression and bending moment can be improved without increasing the wall thickness, as the critical compressive strains of the pipes are dependent on the workhardening properties of pipe materials as well as the t/D ratio. Hence if it could be possible to express the critical compressive strain of the pipes in terms of the workhardening parameters, the potential deformability of the pipes depend on the workhardenability would be significantly focused and also reflected to the seismic improvement of the buried pipelines. Then the stress-strain curve control will be of great importance for the improvement of the deformability of the higher-grade linepipes, whose workhardenability is less than the lower-grade linepipes (Suzuki et al., 1999, 2000, 2001).

The approximate solution proposed in this paper in order to predict the peak load strain of a straight pipe without internal pressure and external pressure, which is subjected to only axial compression, is successfully represented in terms of three parameters defined in the R-O representation. The nonlinear fundamental equation derived by Gerard (1956) is used to express the approximate solution. Therefore the approximate solution is applicable to predict the peak load strain of a line pipe showing the arbitrary workhardening property. Accuracy of the approximate solution is verified comparing with numerically obtained exact solutions of the equation and finite element solutions. The approximate solution represented by the R-O parameters is precise and effective needless to define both a specific strain and a specific strain range to obtain the solutions, where the inconsistencies between the approximate solutions and the numerically obtained exact solutions are infinitesimally small, less than 0.5%.

BASIC EQUATION CONSIDERING WORKHARDENING PROPERTY

Peak Load Strain of a Pipe

The workhardening property of the pipe material can be taken into account by the deformation theory derived by Gerard (1956) in order to predict the peak load strain of the straight pipe. The peak load strain of the pipe can be expressed as Eq. (1) in terms of the Poisson's ratio (ν), the diameter to thickness ratio (*D/t*) and the ratio of the tangent modulus and the secant modulus (E_T/E_S).

$$\varepsilon_{cr} = C\sqrt{\frac{1-\nu^2}{1-\nu_p^2}}\sqrt{\frac{E_T}{E_S}}\frac{t}{D/2} \quad (1)$$

Substituting $\nu = 0.30$ and $\nu_p = 0.40$ into Eq. (1), we can obtain the peak load strain of the pipe as the following equation.

$$\varepsilon_{cr} = \frac{2}{3}\times 0.984\times\sqrt{\frac{E_T}{E_S}}\frac{t}{D/2} \approx \frac{4}{3}\sqrt{\frac{E_T}{E_S}}\frac{t}{D} \quad (2)$$

Stress-Strain Curve with Nonlinear Workhardening

A stress-strain relationship showing a continuous nonlinear workhardening characteristic can be represented by a power-law function as Eq. (3). Then the E_T/E_S ratio in Eq. (2) can be expressed by Eq. (4) and consequently the peak load strain of the pipe can be written as Eq. (5) (Kato et al., 1973).

$$\sigma = A\varepsilon^n \quad (3)$$

$$\frac{E_T}{E_S} = \frac{d\sigma/d\varepsilon}{\sigma_b/\varepsilon_b} = \frac{An\varepsilon_b^{n-1}}{A\varepsilon_b^{n-1}} = n \quad (4)$$

$$\varepsilon_{cr} = \frac{4}{3}\sqrt{n}\frac{t}{D} \quad (5)$$

The design formula proposed in the Seismic Design Codes for High Pressure Gas Pipelines (JGA, 2000) is based on Eq. (5) and represented as Eq. (6), where 0.11 for the workhardening exponent and 1.25 for the safety factor are applied.

$$\varepsilon_{cr} = \frac{1}{1.25}\frac{4}{3}\sqrt{0.11}\frac{t}{D} = \frac{44}{1.25}\frac{t}{D}(\%) = 35\frac{t}{D}(\%) \quad (6)$$

STRESS-STRAIN RELATIONSHIP WITH NONLINEAR WORKHARDNING : R-O MODEL

Peak Load Strain

Equation (7) represents the Ramberg-Osgood type stress-strain curve (Ramberg and Osgood, 1943) (R-O model hereinafter). And the E_T/E_S ratio can be written as Eq. (8).

$$\varepsilon = \frac{\sigma}{E} + \frac{\alpha\sigma_0}{E}\left(\frac{\sigma}{\sigma_0}\right)^N \quad (7)$$

$$\frac{E_T}{E_S} = \frac{E/\{1+\alpha N(\sigma_{cr}/\sigma_0)^{N-1}\}}{E/\{1+\alpha(\sigma_{cr}/\sigma_0)^{N-1}\}} = \frac{1+\alpha(\sigma_{cr}/\sigma_0)^{N-1}}{1+\alpha N(\sigma_{cr}/\sigma_0)^{N-1}} \quad (8)$$

Substituting Eq. (8) into Eq. (2), the peak load strain of the pipe can be obtained as the following equation. However the following equation includes the corresponding peak load stress in the right-hand side of the equation, so we cannot obtain a closed form solution. The peak load strain of the following equation can be solved numerically accompanied by Eq. (7).

$$\varepsilon_{cr} = \frac{4}{3}\sqrt{\frac{1+\alpha(\sigma_b/\sigma_0)^{N-1}}{1+\alpha N(\sigma_b/\sigma_0)^{N-1}}}\frac{t}{D} \quad (9)$$

Iterative Procedure for the Solution

Equating Eqs. (7) and (9), we can obtain the following nonlinear equation represented by S_{c0} which is the ratio of the yield stress and the peak load stress.

$$S_{c0} + \alpha S_{c0}^N - \frac{4E}{3\sigma_0}\sqrt{\frac{1+\alpha S_{c0}^{N-1}}{1+\alpha N S_{c0}^{N-1}}}\frac{t}{D} = 0 \quad (10)$$

Equation (10) can be transformed into Eq. (11), and Eq. (14) can be obtained setting the left-hand side term of Eq. (11) by Eq. (12) and the right-hand side term of Eq. (11) by Eq. (13).

$$(S_{c0} + \alpha S_{c0}^N)(S_{c0} + \alpha N S_{c0}^N) = \left(\frac{4}{3}\frac{E}{\sigma_0}\frac{t}{D}\right)^2 \quad (11)$$

$$X \equiv S_{c0} + \alpha S_{c0}^N \quad (12)$$

$$C = \left(\frac{4}{3}\frac{E}{\sigma_0}\frac{t}{D}\right)^2 \quad (13)$$

$$X\{NX - (N-1)S_{c0}\} = C \quad (14)$$

Equation (14) is a second order polynomial and can be rewritten as Eq. (15). Solving Eq. (15), we can obtain Eq. (16) as the solution of X. However we cannot obtain a solution X from Eq. (16) because X is dependent on S_{c0} as expressed by Eq. (12).

$$NX^2 - (N-1)S_{c0}X - C = 0 \cdots\cdots\cdots\cdots\cdots\cdots\cdots (15)$$

$$X = (1-\frac{1}{N})\frac{S_{c0}}{2} + \sqrt{\left(1-\frac{1}{N}\right)^2\left(\frac{S_{c0}}{2}\right)^2 + \frac{C}{N}} \cdots\cdots\cdots (16)$$

After substituting Eq. (12) into Eq. (16), we can rewrite Eq. (16) as Eq. (17), which is a nonlinear equation with respect to S_{c0} and can be solved numerically by an iteration method such as the goal-seek solver.

$$S_{c0}^N = -\left(1+\frac{1}{N}\right)\frac{S_{c0}}{2\alpha} + \sqrt{\left(1-\frac{1}{N}\right)^2\left(\frac{S_{c0}}{2\alpha}\right)^2 + \frac{C}{\alpha^2 N}} \cdots (17)$$

Before discussing the method how to solve the above nonlinear equation, it should be mentioned that the notation S_{c0} is the ratio of the peak load stress and the yield stress, $\boldsymbol{\sigma}_{cr} / \boldsymbol{\sigma}_0$, and the local buckling may occur in the plastic deformation range. Then the peak load stress is higher than the yield stress and lower than the tensile strength. Therefore the minimum value of S_{c0} equals to 1.0 and the maximum value is the inverse of the Y/T ratio. Assuming the Y/T ratio to be 0.5, the maximum value of S_{c0} will be 2.0.

Instead of applying the goal-seek procedure to solve the nonlinear equation (17), we can introduce an iterative procedure as follows. Observing Eq. (17), $S_{c0}{}^N$ in the left-hand side of the equation can be calculated if we know the value of S_{c0} of the right-hand side of the equation. Therefore we can construct an iterative procedure as Eq. (18) successfully, where the iterative procedure should be repeated until the required convergence is satisfied.

$$S_{c0(i+1)}^N = -\left(1+\frac{1}{N}\right)\frac{S_{c0(i)}}{2\alpha} + \sqrt{\left(1-\frac{1}{N}\right)^2\left(\frac{S_{c0(i)}}{2\alpha}\right)^2 + \frac{C}{\alpha^2 N}} \cdots\cdots\cdots\cdots (18)$$

Convergence of the Iterative Solution

Verification and convergence of Eq. (18) were investigated using the API 5L grade linepipes ranging from X25 to X80 pipes, whose workhardening parameters are represented as Table 1 (Walker and Williams, 1995). Within the materials in the table, the X25, X42, X60 and X80 pipes were selected for the inves-tigation as illustrated in Fig. 2. The exact solutions of the peak load strain of the pipes and the corresponding S_{c0} were numerically obtained by solving the nonlinear simultaneous equation consists of Eqs. (7) and (9).

Table 1 Mechanical properties of API 5L grde pipes

API 5L Grade	σ_0 SMYS (MPa)	σ_u SMTS (MPa)	R-O parameters	
			α	N
X25	172	310	4.96	7.49
A	207	331	3.95	9.36
B	241	413	3.24	7.85
X42	279	413	2.55	12.03
X46	317	434	2.23	13.67
X52	358	455	1.86	17.99
X56	386	489	1.66	18.14
X60	413	517	1.48	18.99
X65	448	530	1.29	25.58
X70	482	565	1.13	27.13
X80	551	620	0.86	37.00

E：Young's modulus = 205GPa
SMYS corresponds to 0.5% strain

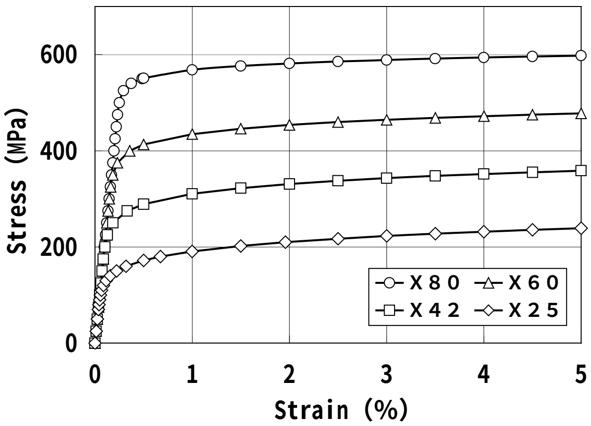

Figure 1 Stress-Strain curves of API materials

Figures 2, 3 and 4 show the convergence results calculated by Eq. (18), providing the initial value as $S_{c0(i=1)} = 1.0$. As shown in the figure, the convergence obtained by the first iteration is less than 0.1% for all the materials and the second iteration gives much better convergence less than 0.001%. The X80 pipe converged quickly compare with the other results, which is excellent and less than 0.01% after the first iteration. Consequently the convergence of Eq. (18) is very quick and stable, and the solutions obtained after the first iteration are sufficient enough to predict the peak load strain and stress.

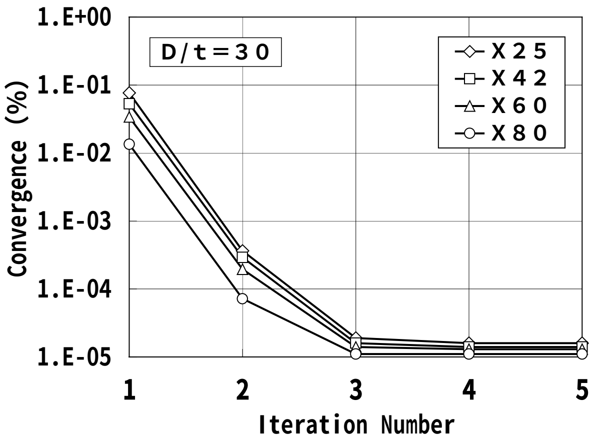

Figure 2 Convergence of the iterative solution

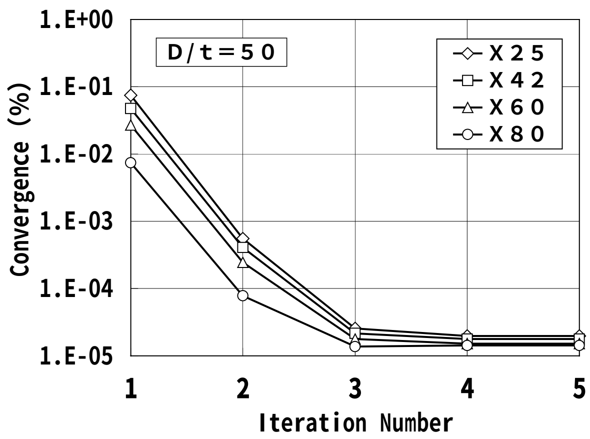

Figure 3 Convergence of the iterative solution

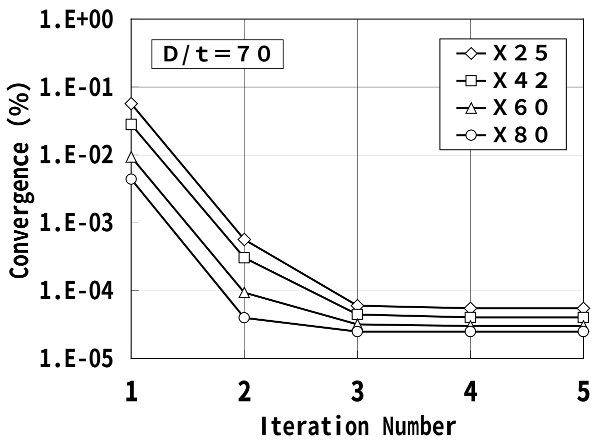

Figure 4 Convergence of the iterative solution

Closed Form Approximate Solution

As mentioned above, we can provide $S_{c0(i=1)}$=1.0 and rewrite $S_{c0}{}^{N}{}_{(i=1)}$ as $S_{c0}{}^{N}$, then a closed form solution can be obtained as Eq. (19), which turns to be an accurate approximate solution.

$$S_{c0}^{N}=\left(\frac{\sigma_{cr}}{\sigma_{0}}\right)^{N}=-\frac{1}{2\alpha}\left(1+\frac{1}{N}\right)+\frac{1}{2\alpha}\left(1-\frac{1}{N}\right)\sqrt{1+\frac{4N}{(N-1)^{2}}\left(\frac{4Et}{3\sigma_{0}D}\right)^{2}} \quad (19)$$

Where S_{c0} expresses the stress ratio, σ_{cr}/σ_{0}, we can obtain the peak load strain as the following equation.

$$\varepsilon_{cr}=\frac{\sigma_{cr}}{E}+\frac{\alpha\sigma_{0}}{E}\left(\frac{\sigma_{cr}}{\sigma_{0}}\right)^{N}=\frac{\sigma_{0}}{E}\left(\frac{\sigma_{cr}}{\sigma_{0}}\right)+\frac{\alpha\sigma_{0}}{E}\left(\frac{\sigma_{cr}}{\sigma_{0}}\right)^{N} \cdot (20)$$

Furthermore, considering the R-O parameters listed in Table 2, the first term in a square root of Eq. (19) is negligibly small compare with the second term. Therefore, Eq. (19) can be deduced into the following equation.

$$\left(\frac{\sigma_{cr}}{\sigma_{0}}\right)^{N}=-\frac{1}{2\alpha}\left(1+\frac{1}{N}\right)+\frac{4}{3\alpha\sqrt{N}}\frac{E}{\sigma_{0}}\frac{t}{D}\cdots\cdots\cdots(21)$$

The above equation is a closed form approximate solution newly proposed in this paper, which includes the three parameters of the R-O formula and needs no iterative procedure. By using this equation we can evaluate the peak load strain of a linepipe and the effects of the workhardening property on the peak load strain.

DISCUSSION OF THE APPROXIMATE SOLUTIONS

Verification of the Approximate Solution

Peak Load Strain Obtained by the Approximate Solution

Figure 5 shows the peak load strains of the four materials evaluated by the newly developed approximate solution, Eqs. (20) and (21). The horizontal and the vertical axes represent the D/t ratio and the peak load strain, respectively.

As shown in Fig. 5, the peak load strains of the linepipes decrease gradually in accordance with the increase of the D/t ratio. Comparing the peak load strains of the four linepipes, the strains of the X25 pipe are greatest and the strains of the X80 pipe are the smallest. The peak load strains of the X25 pipe are approximately two times larger than the X80 pipe. Based on these data we can recognize afresh that the peak load strains of the high-grade linepipes are less than the low-grade linepipes.

And this tendency implies that the workhardening property of the low-grade linepipes is preferable to endow the high-grade linepipes with sufficient deformability to resist external forces or endure the permanent ground deformation.

By using the approximate solution we can predict the peak load strain and peak load stress of the linepipes subjected to axial compression in terms of the stress-strain relationship or the workhardening property of the materials. This is the verification of the approximate solution being capable of taking the work-hardening property of the materials into account.

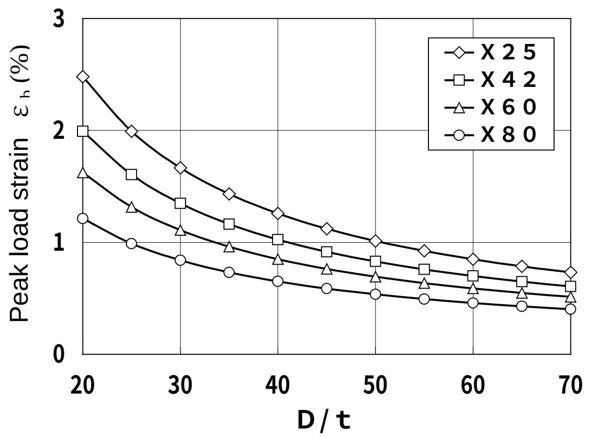

Figure 5 Critical compressive strain considering the R-O parameters

Workhardening Properties of the Linepipes

The accuracy of the approximate solution is described after comparing the finite element solution. Besides the FEA, the basic equation (5) derived by Gerard and expressed in terms of exponent n is taken for the comparison in order to know the accuracy of the basic equation of the design equation.

The value of n applied to the design equation of the seismic design codes is assumed to be constant as shown in Eq. (6), however, we can evaluate the exponent dependent on the pipe grades or the warkhardening properties of the pipe materials. Then we can also predict the peak load strain of the linepipes using Eq. (5) and the n-values. The n-values in Table 2 are evaluated using the stress-strain relationship between 1% and 4% strains where the exponents are approximately constant. And the R-O parameters shown in the table are the same data as in Table 1.

Table 2 Workhardening parameters of the API pipes

API 5L Grade	n 1-4%	R-O parameters	
		α	N
X25	0.141	4.96	7.49
X42	0.090	2.55	12.03
X60	0.059	1.48	18.99
X80	0.032	0.86	37.00

Comparison of the Peak Load Strain

Table 3 shows the comparison of the peak load strains of the line pipes predicted by finite element analyses and the design equation and newly proposed approximate solution. The D/t ratios of the linepipes are provided to be 30, 50 and 70. The finite element analyses were performed using axi-symmetric shell elements. The peak load strains of the design equation were obtained from Eq. (5) and the approximate solutions were calculated from Eq. (21). The ratios of the predicted strains and the finite element solutions are also presented in the table.

As shown in Table 3, the predictions performed by Eq. (5) are fairly good for the D/t ratios where the peak load strains obtained by the FEA are close to or greater than 1.0% strain. This is because the n-values substituted into the design equation were determined in the strain range of 1 to 4%. And the tendency is recognized to be independent of the linepipe grade as shown in the table. Therefore we can evaluate the accuracy of the design equation knowing the peak load strain.

On the other hand, the predictions performed by the approximate solution, Eq. (21), show excellent coincidences with the solutions obtained by the FEA for all of the D/t ratios presented in the table. These preferable results were brought by the R-O parameters being introduced in the approximate solution, which parameters cover the entire strain range represented in Fig. 1.

Table 3 Comparison of the peak load strain

Case		Peak load strain (%)		
		FEA	*Prediction／FEA*	
Grade	D/t		n Eq.(5)	R-O Eq.(21)
X25	30	1.613	1.669 *1.03*	1.645 *1.02*
	50	0.996	1.001 *1.00*	1.001 *1.00*
	70	0.732	0.715 *0.98*	0.724 *0.99*
X42	30	1.290	1.333 *1.03*	1.336 *1.04*
	50	0.830	0.800 *0.96*	0.826 *1.00*
	70	0.589	0.571 *0.97*	0.606 *1.03*
X60	30	1.028	1.080 *1.05*	1.107 *1.08*
	50	0.703	0.648 *0.92*	0.701 *1.00*
	70	0.505	0.463 *0.92*	0.525 *1.04*
X80	30	0.827	0.795 *0.96*	0.854 *1.03*
	50	0.519	0.477 *0.92*	0.562 *1.08*
	70	0.426	0.341 *0.80*	0.435 *1.02*

Therefore we can conclude that the high accuracy of the prediction can be performed applying the workhardening parameters independent of a specific strain or a specific strain range of the stress-strain relationships.

The ratio of the tangent modulus and the secant modulus, E_T/E_S, can be represented by Eq. (8). Figure 6 shows changes of the E_T/E_S ratios of the four API linepipes. As shown in the figure, the E_T/E_S ratios decrease quickly at small strains less than 0.5%. However the E_T/E_S ratios gradually decrease and become to be constant at strains greater than 1.0%. It should be mentioned in the figure that the E_T/E_S ratios of the high-grade linepipes are smaller than the low-grade linepipes and due to this property the peak strain of the high-grade linepipes are comparatively small.

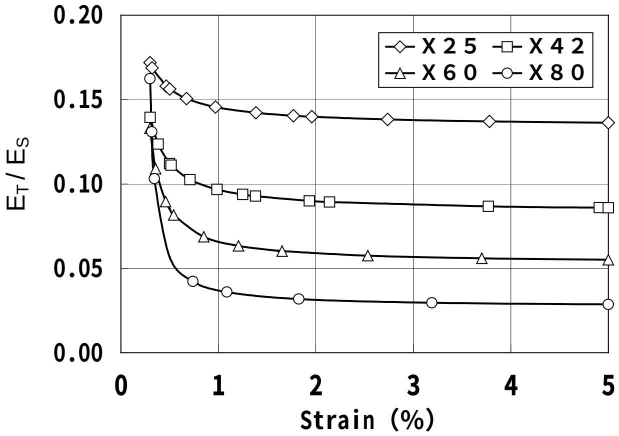

Figure 6 E_T/E_S of the R-O formula (Eq. (8))

Parametric Study to Investigate Effects of Workhardening Property of the X80 Pipes

Stress-Strain Curves

Three hypothetical stress-strain curves of the X80 pipes, A, B and C, shown in Fig. 7 are provided to investigate the effect of the workhardening property on the peak load strain. In the figure the X80-SM pipe coincides with the X80 pipe defined in Tables 1 and 3. The Y/T ratios of the X80-SM, A, B and C pipes are 0.93, 0.85, 0.78 and 0.70, respectively. The yield stress and the tensile stress correspond to the stresses at 0.5% strain and 8% strain in this case. The exponent *n*-values and R-O parameters are listed in Table 4. The *n*-values in Table 4 were calculated as same as data represented in Table 2.

Convergence of the Peak Load Strain

Figure 8 represents the convergence of the approximate solution, Eq. (19), where the R-O parameters are introduced. The tendency of the convergence is almost the same as Fig. 3 and the worst results after the first iteration can be observed for the X80-C pipe, however, which is less than 0.5% and sufficient enough for the prediction of the peak load strain.

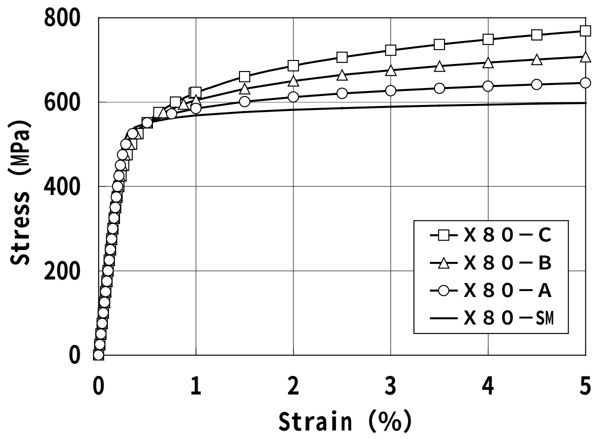

Figure 7 S-S curves of X80 pipes

Table 4 Workhardening property of the X80 pipes

API 5L	*n* 1-4%	R-O parameters	
		α	N
X80-SM	0.031	0.86	37.00
X80-A	0.058	0.86	19.00
X80-B	0.098	0.86	12.00
X80-C	0.131	0.86	9.00

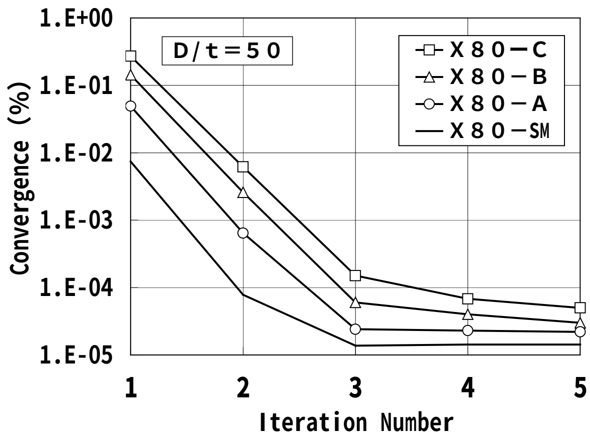

Figure 8 Convergence of the approximate solution

Comparison of the Peak Load Strain

Figure 9 shows the peak load strains of the X80 pipes calculated by the approximate solution. As shown in the figure the lowest peak load strain is the X80-SM pipe and the highest is the X80-C pipe. And the peak load strains of the X80-A, B and C pipes are similar to the results of the X60, X42 and X25 pipes, respectively. Therefore the X80-SM pipe, whose peak load strain is the smallest among the X80 pipes, can be increased as high as the X25 pipe. Then we can conclude that the peak load strain of the X80 pipe can be improved by controlling the workhardening property and/or the shape of the stress-strain curve.

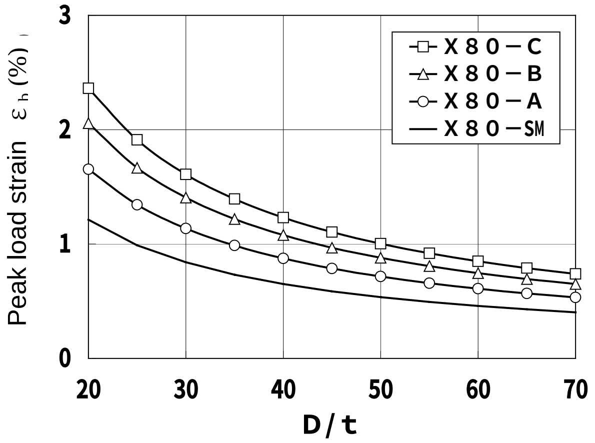

Figure 9 Peak load strain of X80 pipes

Table 6 Comparison of the peak load strain

Case		Peak load strain (%)		
		FEA	*Prediction／FEA*	
Pipe	D/t		*n* Eq.(5)	R-O Eq.(21)
X80-SM	30	0.827	0.795 *0.96*	0.854 *1.03*
	50	0.519	0.477 *0.92*	0.562 *1.08*
	70	0.426	0.341 *0.80*	0.435 *1.02*
X80-A	30	1.116	1.070 *0.96*	1.146 *1.03*
	50	0.689	0.642 *0.93*	0.737 *1.07*
	70	0.529	0.459 *0.87*	0.559 *1.06*
X80-B	30	1.327	1.391 *1.05*	1.419 *1.07*
	50	0.858	0.835 *0.97*	0.901 *1.05*
	70	0.679	0.596 *0.88*	0.674 *0.99*
X80-C	30	1.522	1.609 *1.06*	1.629 *1.07*
	50	0.997	0.965 *0.97*	1.027 *1.03*
	70	0.778	0.689 *0.89*	0.764 *0.98*

Figure 10 shows variation of the E_T/E_S ratios of the X80 pipes mentioned above. As shown in the figure, the n-value of C is almost four times larger than the X80-SM pipe. The n-values of the X80-A and B pipes are between them. The variations of the exponents shown in Fig. 10 are similar to the exponents concerning to the X25, X42, X60 and X80 pipes shown in Fig. 6. The similarity can be explained on the ground that the Y/T ratios of the corresponding pipe materials are almost the same.

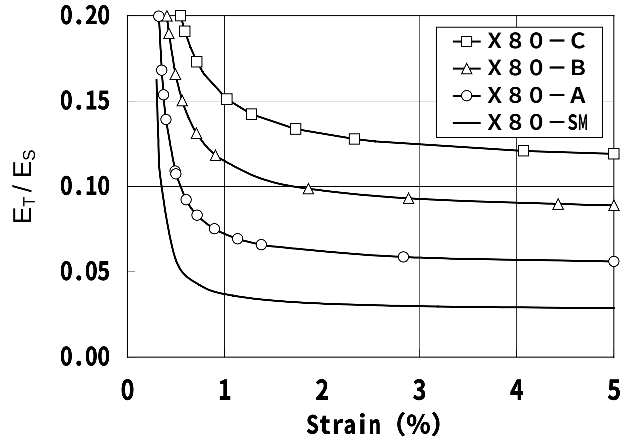

Figure 10 E_T/E_S of X80 grade pipes

CONCLUSIONS

An effective approximate solution, represented in a closed form equation, is proposed in order to predict the peak load strain of a linepipe, where workhardenability of pipe materials can be taken into account. As mentioned before, the semi-empirical equations, some of which have been adapted to the current pipeline design codes, are defined to cover the minimum peak load strains or the peak moment strain obtained by experiments and finite element analyses. And the semi-empirical equations are represented only by the t/D ratio, from which we cannot evaluate the effect of the workhardening properties of the pipe materials on the peak load strain.

The workhardenability of the materials will be able to be taken into consideration to predict the peak load strain of the line pipes by the proposed approximate solutions in this paper. The best way to predict the peak load strain is to apply the solution formulated with the R-O parameters, which solution can be adapted for the prediction needless to consider a specific strain or a specific strain range. However, the design equation should be applied considering the strain or the strain range to be applied for the calculation. And then the material design aspect will be focused in lieu of the structural design aspect associated with the wall thickness adjustment to increase the deformability of the linepipes.

Finally we would like describe the necessity of the following issues to be discussed in order to develop approximate solutions applicable to take into account the workhardenability of the materials and to ensure the integrity of the buried pipelines, which may undergo large deformation due to liquefaction-induced permanent ground deformation and fault movements and so on.

(1) Effect of internal pressure on the peak load strain,
(2) Fomulation of the peak moment strain of the linepipes,
(3) Effect of internal pressure and external pressure to the peak moment strain of the linepipes.

NOMENCLATURE

A : constant
C $=1/\{3(1-\nu_p^{\ 2})\}^{0.5}$
D : pipe diameter
E : Young's modulus
E_T : tangent modulus
E_S : secant modulus
m : workhardening coefficient $(=E_T/E)$
n : workhardening exponent
t : wall thickness
α, N : Ramberg-Osgood parameters
ε : nominal strain
ε_{cr} : critical compressive strain at peak load
ε_y : yield strain
ε_{LE} : strain at end of Luders elongation
ν : Poisson's ratio, elastic
ν_p : Poisson's ratio, plastic
σ : nominal stress
σ_0 : stress at 0.5% strain
σ_y : yield stress

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