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Development of Evaluation and Prediction Technology for the Performances of Solid Expandable Tubular Pipe

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Abstract

Oil well construction utilizing tubular expansion technology is a revolutionary technology that allows for dramatic reductions in the cost of drilling. The major problem with expandable tubular pipe is its tendency to readily experience expansion fractures. In addition, development of expandable tubular material should be carried out by considering the difference in mechanical properties before and after expansion. In this study, evaluation and prediction technologies of expandability and collapse resistance were investigated by using the experiments and numerical simulations for high frequency electric resistance welding pipe. The results reveal the relevant combination of the pipe geometries and the material properties for preventing the expansion failure. Furthermore, collapse prediction technology which is capable of evaluating the post-expanded collapse was developed. This research work contributed to development of expandable tubular material with high reliability.

1. Introduction

The expandable tubular (EXP) is one type of casing that has been used in oil well construction over the last few years. The salient characteristic of EXP is that it is subjected to plastic working whereby its diameter is expanded after it is driven into the ground. **Figure 1** schematically shows a conventional oil well and an EXP oil well.

An examination of the structure of a conventional oil well (Fig. 1 (a)) shows that the diameter of the pipe near the earth's surface is much larger than that of the pipe deep in the ground. In the case of an EXP oil well, even if the EXP is damaged due to wear, corrosion or the like, it can be easily repaired by first inserting a steel pipe into the well and then expanding its diameter from the inside, as shown in Fig. 1 (b). In addition, as shown in Fig. 1 (c), EXP makes it possible for the entire well to be slimmer, thereby cutting drilling costs. For example, in a conventional oil well, a liner hanger must be used to suspend a pipe from the bottom end of the pipe that has already been driven into the ground, meaning that a mechanical device for pipe suspension is ordinarily required. With EXP, in contrast, it is possible to join the two pipes tightly by expanding the diameter of the appropriate pipe and securing the required bearing force with a suitable adhesive or the like. This makes it possible to omit the mechanical hanger, and to construct a slimmer well. There are now plans to use EXP to construct oil wells having a uniform diameter from top to bottom, as shown in Fig. 1 (d).[1)]

Conventional oil well pipes must have high strength and toughness, adequate collapse resistance against high ground pressure, and good sour resistance. In addition to these properties, an EXP oil well pipe is required to have sufficient deformability (expandability) so that it is free from fractures and excessive constriction while being expanded. In addition, since the mechanical properties and shape of the steel pipe when manufactured change significantly when the pipe diameter is expanded, it is necessary to accurately predict the working performance of the pipe after expansion.

To meet the needs of the EXP market while paying due attention to the above EXP characteristics, Nippon Steel & Sumitomo Metal Corporation has committed itself not only to the development of new materials for EXP but also to the establishment of techniques for evaluating and predicting EXP working performance, with the aim of enhancing product reliability.[2)] In the present study focusing

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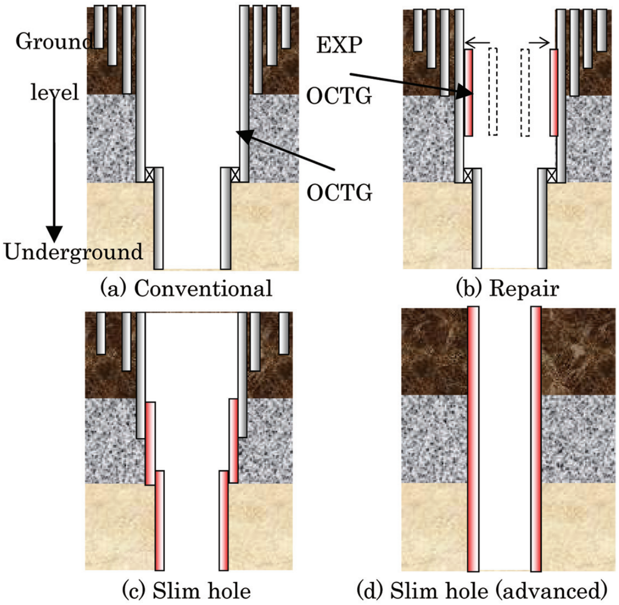

Fig. 1 Examples of EXP OCTG use

on EXP expandability and its collapse resistance after expansion, we carried out performance evaluation tests using actual EXP pipes, and clearly identified how their working performance was influenced by pipe expansion. We also developed a new numerical analysis technique that permits an accurate prediction of EXP collapse resistance after expansion.

2. Method of Experimentation

Since every EXP oil well pipe is expanded at the well construction site, it is necessary to decide on the material design and pipe manufacturing conditions that impart adequate pipe deformability. In addition, in order to ensure safety at the planned oil well, it is important to accurately predict changes in pipe material properties caused by pipe expansion and the resulting working performance of the pipe. We therefore developed an expansion tester which simulates pipe expansion in an oil well to accurately evaluate the expandability of actual EXP products. In addition, using expanded steel pipes, we measured their working performance, specifically their collapse resistance.

2.1 Steel pipe tested

In the present study, the material used to evaluate the expandability of an EXP and its collapse resistance after expansion was a high-frequency electric resistance-welded steel pipe (ERW steel pipe) fabricated by welding the edges of a roll-formed steel plate. The steel pipe was 193.7 mm in outside diameter (D) and 9.53 mm in wall thickness (t). Ordinary ERW steel pipe shows a variance in strength circumferentially, which is ascribable to the roll forming process. In order to remove strength variation, we subjected the entire steel pipe to quenching and tempering. Round bars, each 6 mm in diameter, were cut circumferentially from the steel pipe and subjected to tensile tests. **Figure 2** shows stress-strain curves obtained from the tensile tests, while **Table 1** shows the mechanical properties of the steel pipe material.

2.2 Pipe expansion test

Figure 3 schematically shows the method of expansion of an EXP oil well pipe. Ordinarily, EXP pipe is put down into the well with an expansion plug which is fitted to one end of the pipe, and

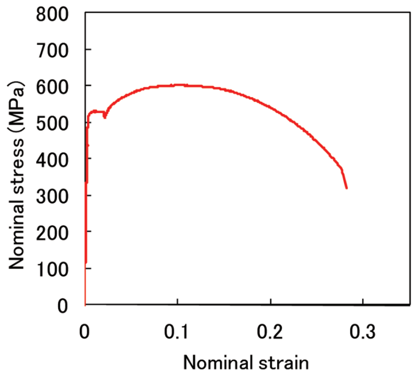

Fig. 2 Stress-strain curve of tested material

Table 1 Mechanical properties of tested material

Yield strength (MPa)	Tensile strength (MPa)	Uniform elongation (%)	Total elongation (%)
522	602	10.1	28.9

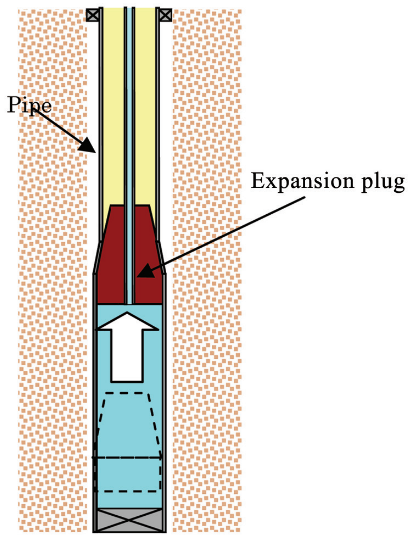

Fig. 3 Example of expansion method of EXP OCTG

which is larger in diameter than the EXP pipe. Then the expansion plug is driven into the pipe hydraulically or mechanically until the inside diameter of the pipe is expanded to the outside diameter of the plug. Generally speaking, overall pipe length decreases slightly as pipe diameter increases. However, if pipe deformation is significantly constrained by the surrounding strata, a tensile stress can occur in the pipe along its axis. Therefore, when it comes to evaluating the expandability of an EXP pipe, it is necessary to consider the condition of the surrounding strata as well.

Figure 4 schematically shows the expansion tester we developed, and the test piece subjected to the expansion test. The pipe was expanded by jetting high pressure water onto the back of the expansion plug to drive it into the pipe. In order to constrain axial pipe shrinkage that would occur in an actual oil well, the expansion tester was provided with a stopper which produced an axial force along the pipe axis when it was made to contact the tester frame.

Expansion test conditions are shown in **Table 2**. "Expansion ra-

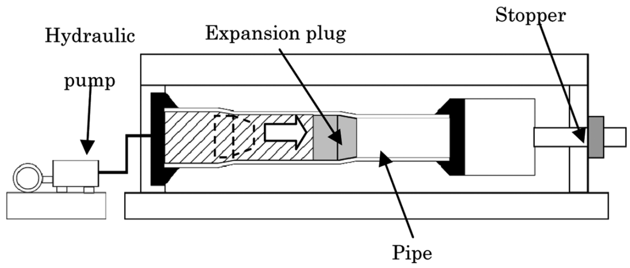

Fig. 4 Schematic drawings of expansion tester

Table 2 Full-scale test conditions

Expansion ratio (%)	Fixed/Free	Colapse test
17	Free	○
	Fixed	
23	Free	○
	Fixed	
28	Free	
	Fixed	

tio" was defined as (pipe ID after expansion – pipe ID before expansion)/(pipe ID before expansion) × 100 (%). Three different expansion ratios (17%, 23% and 28%) were tested. In addition, for each of the three expansion ratios, we decided to evaluate the influence of the constraining of pipe deformation on pipe expandability using expansion tests that assumed two different cases: a case ("Fixed") where a stopper is used to constrain pipe axial shrinkage, and a case ("Free") where a stopper is not used and pipe axial shrinkage is allowed to occur.

2.3 Collapse test

Figure 5 schematically shows the collapse test procedure. First, the test piece (pipe) fitted with a watertight seal ring at each end is expanded. Water pressure is then applied to the pipe from the outside to cause it to collapse. In consideration of the influence of constraining of the pipe ends, the pipe length was decided to be at least 10 times the pipe outside diameter. As shown in Table 2, the collapse test was applied to a total of six steel pipes without constraining the deformation — three pipes expanded with an expansion ratio of 17%, and three pipes expanded with an expansion ratio of 23%. The collapse resistance of each pipe after expansion was compared with that before expansion.

2.4 Methods for measuring mechanical properties of the material and pipe shape

EXP oil well pipe expandability is significantly influenced by the material strength, deformability, and wall thickness distribution of the pipe before expansion. In addition, previous studies [3, 4] have reported that steel pipe collapse resistance is governed by a number of factors, such as the outside diameter to wall thickness ratio (D/t), circumferential compressive yield stress (C-YS), ovality, thickness unevenness, and residual stress. Therefore, to accurately evaluate expandability, collapse resistance, and other working performance factors of an expandable pipe, it is necessary to measure the mechanical properties of the pipe material and the shape of the pipe, using suitable methods. In the present study, the following methods were used.

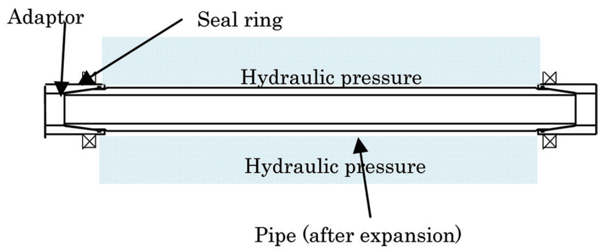

Fig. 5 Schematic drawings of collapse test

- Ovality and thickness unevenness

The outside diameter and inside diameter of each pipe were measured with a 3D noncontact-type profile meter, and the measurement data obtained was used to calculate ovality and thickness unevenness as follows.

Ovality (%) = (Max OD − Min OD) / Average OD × 100
Thickness unevenness (%) = Max wall thickness
− Min wall thickness) / Average wall thickness × 100

In the calculation of thickness unevenness, weld zones falling within 5 degrees from the seam were left out of consideration.

- C-YS

Cylindrical compression test pieces, each 6 mm in diameter and 12 mm in height, were collected circumferentially from steel pipes, and stress-strain curves obtained by subjecting the test pieces to compression tests were used to determine C-YS. Four test pieces were collected from the thickness center at intervals of 90° starting from the welding line as 0°. The average of 0.2% offset stresses at those four points was assumed to be C-YS.

- Residual stress

Residual stress was measured using the Crampton method. In this method, the steel pipe is given an axial slit and the residual stress in the steel pipe is calculated from the difference in the outside diameters before and after the pipe is slit.

3. Numerical Simulations

To evaluate the performance (expandability, and collapse resistance) of the EXP oil well pipe, it is necessary to conduct appropriate tests using actual EXP products. On the other hand, to quantify the influences of material properties on pipe performance and to reflect them appropriately in product design, it is effective to do susceptibility evaluations using numerical simulations. The present study used suitable models of pipe mechanical properties and shapes created on the basis of expandability and collapse test results, and conducted numerical simulations for evaluating EXP pipe expandability and collapse resistance.

3.1 Simulation of pipe expansion

To study how steel pipe expandability is influenced by the mechanical properties of pipe material and the constraining of pipe deformation, we created a model for the FEM simulation of pipe expansion. The model is shown in **Fig. 6**. With the steel pipe assumed as a 3D solid element and the expansion plug as a rigid body, the FEM analysis was carried out using the static implicit scheme. In addition, each steel pipe model was given a wall thickness distribution based on the results of the profile measurements of the pipe used in physical pipe tests. Details are shown in **Fig. 7**. The solid line indicates the wall thickness distribution of an actual steel pipe. It was simulated by a sine curve, with its amplitude Δt_p varied.

The calculation conditions used are shown in **Table 3**. The work hardening coefficient (n-value) was used as the index of pipe mate-

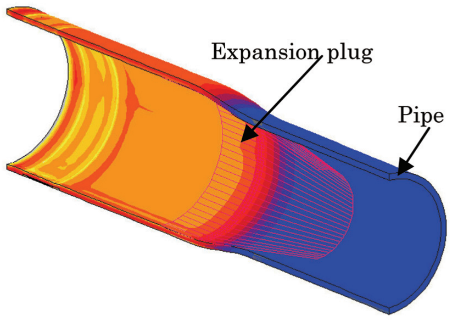

Fig. 6 FEM simulation of pipe expansion

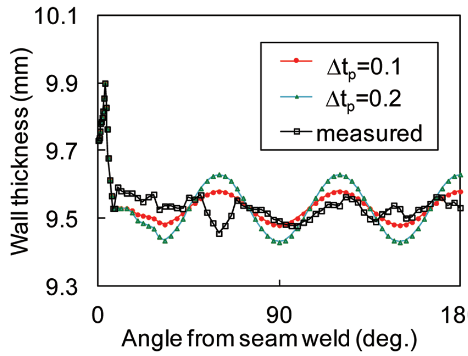

Fig. 7 Wall thickness distributions of expansion model

Table 3 Numerical conditions of expansion simulation

	Expansion ratio (%)	n-value	Δt_p (mm)	Fixed/Free
Case1	23	0.21	0	Free
Case2				Fixed
Case3	17	0.11	0.2	Fixed
Case4		0.13		
Case5		0.21		
Case6	23	0.11	0.2	
Case7		0.13		
Case8		0.21		
Case9	28	0.11	0.2	
Case10		0.13		
Case11		0.21		
Case12		0.17	0.05	
Case13			0.1	
Case14			0.2	
Case15			0.3	
Case16			0.4	

rial deformability, and the stress-strain curve obtained by varying the n-value from 0.11 to 0.21 was input as a mechanical characteristic. The value of Δt_p was varied from 0 to 0.4 (mm). By varying these parameters and the pipe constraining conditions during pipe expansion, we examined the condition of pipe deformation, the concentration of pipe plastic strain, and the wall thickness distribution before and after pipe expansion. In this way we were able to evaluate the influences of pipe material deformability and pipe wall thickness unevenness on pipe expandability.

3.2 Simulation of pipe collapse

We created FEM simulation models for predicting pipe collapse resistance after expansion. One of the models is schematically shown in **Fig. 8**. With the steel pipe assumed to be a 3D solid element, the compressive stress-strain curve in the pipe circumferential direction was input as the material mechanical characteristic. To simulate the steel pipe shape, one section of the pipe expanded after 3D measurement was axially expanded. The cross-section shape of the pipe in the axial direction was assumed to remain the same. In addition, the internal tensile stress/external compressive stress distribution (Distribution A in **Fig. 9**) obtained by linearly approximating a measured residual stress in the wall thickness direction was input to the model. The FEM analysis was conducted using the static implicit scheme, where the pressure on the pipe external surface was gradually increased until the convergent calculation could no longer be performed, and the critical pressure reached was assumed to be the collapse resistance of the pipe. For each pipe specimen subjected to the collapse test shown in Table 2, one model for FEM simulation was created, and the accuracy of prediction of the pipe collapse resistance after expansion was verified by comparing the measured and calculated collapse resistances.

In addition, to study the influence of residual stress on collapse resistance, we created two models, one having no residual stress (Distribution B in Fig. 9), and another having an internal compressive stress/external tensile stress distribution (Distribution C in Fig. 9) equivalent in terms of absolute value to a measured residual stress. Figure 9 schematically shows the concepts of residual stress distributions A-C.

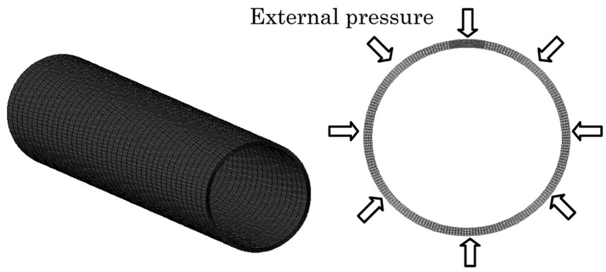

Fig. 8 Schematic drawings of collapse simulation

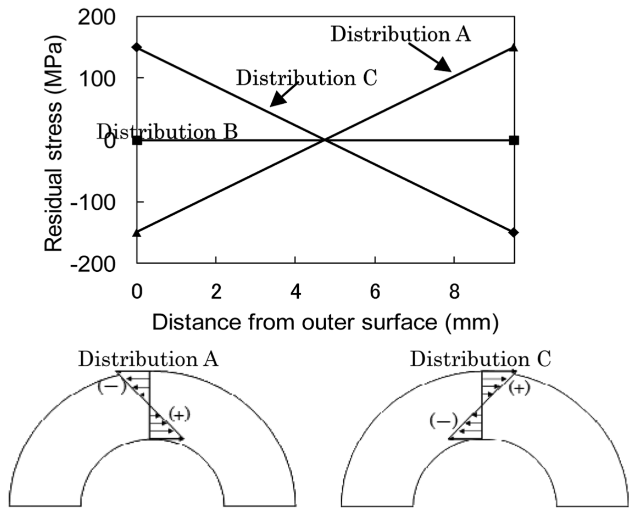

Fig. 9 Distributions of residual stress in collapse simulation

4. Results of Study on Pipe Expandability

4.1 Pipe expansion test results

Table 4 summarizes the results of our pipe expansion test. Under the "Free" condition, the pipes could be expanded to the end without being fractured. On the other hand, under the "Fixed" condition, pipes with an expansion ratio of 23% or more failed, although the pipe with an expansion ratio of 17% could successfully be expanded. **Figure 10** shows the relationship between the distance of movement of the expansion plug, the hydraulic pressure applied onto the plug back, and the axial tensile force produced in the pipe, obtained under the "Fixed" condition with expansion ratios of 17% and 23%. In either case, the hydraulic pressure required to drive the expansion plug remained nearly the same throughout the expansion test. With the expansion ratio of 17%, the axial tensile force began to increase sharply immediately after the start of constraining of pipe axial shrinkage. After that, the axial force leveled off at about 900kN. When the expansion ratio was 23%, the pipe fractured while the axial force was increasing. Thus, it was verified that the constraining of pipe axial shrinkage caused the pipe expandability to decline. **Figure 11** shows a fractured part of a steel pipe tested.

Figure 12 shows examples of circumferential wall thickness distributions measured before and after pipe expansion, in terms of the proportion to average wall thickness. In the figure, the difference between maximum and minimum values corresponds to the wall thickness unevenness. The 0° position on the horizontal axis indicates the weld seam. The wall thickness distribution before pipe expansion was nearly bilaterally symmetrical against 0° and the wall thickness unevenness was around 2%, with the exception of the weld having a thicker wall. On the other hand, wall thickness unevenness increased when the pipe was expanded. With the expansion ratio of 28%, some of the pipes tested showed a thickness unevenness exceeding 10%. Comparing the wall thickness distributions before and after pipe expansion, it can be seen that the parts which were smaller in wall thickness than the other parts before expansion decreased in wall thickness more as a result of pipe expansion, and hence the difference in wall thickness between them increased. The implication is that since thin-walled parts are structurally weak, they are subject to a concentration of plastic strain during pipe expansion, and hence their wall thickness unevenness deteriorates.

Table 4 Results of full-scale expansion test

Expansion ratio (%)	Fixed/Free	Result
17	Free	Not failed
	Fixed	Not failed
23	Free	Not failed
	Fixed	Failed
28	Free	Not failed
	Fixed	Failed

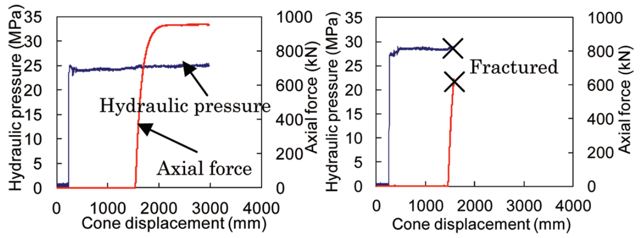

Fig. 10 Time histories of hydraulic pressure and axial force during expansion test

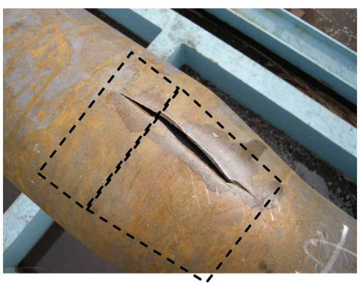

Fig. 11 Picture of expansion fracture

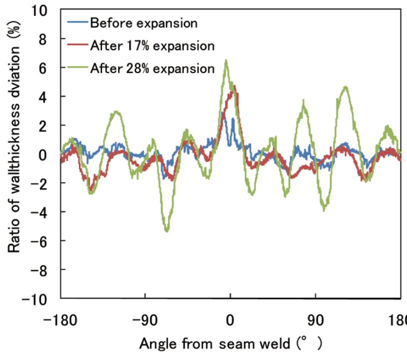

Fig. 12 Wall thickness distributions before and after expansion

4.2 Pipe expansion simulation results

Figure 13 shows circumferential strain distributions after pipe expansion in Cases 12 through 16 of Table 3. The strain caused by pipe expansion concentrated in thin-walled parts, such as the 90° and 150° positions from the weld seam. The larger the wall thickness unevenness before pipe expansion, the greater becomes the strain. Thus, it can be estimated that the larger the wall thickness unevenness of the base material of a pipe before expansion, the more easily pipe tends to fracture during expansion.

Figure 14 compares the circumferential (C), longitudinal (L), and radial (R) plastic strains in pipe with and without deformation constraint in Cases 1 and 2 of Table 3. Without constraint, the pipe increases in diameter as it is expanded. At the same time, the pipe

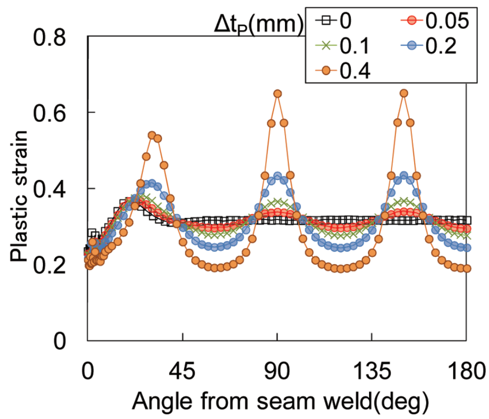

Fig. 13 Strain concentration after expansion on FEM simulations

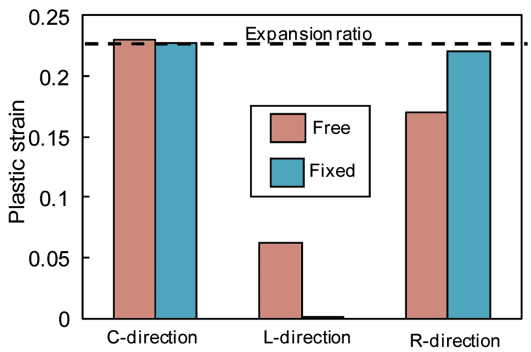

Fig. 14 Plastic strain in L, C, and R direction after expansion

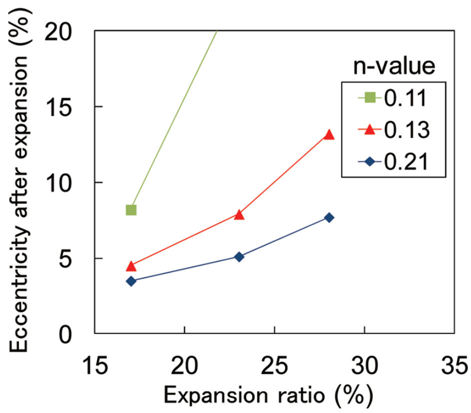

Fig. 15 Relationship between n-value, eccentricity and expansion ratio

decreases in length and wall thickness. Therefore, the C strain becomes equal to the pipe expansion ratio, and the sum of the L and R strains becomes nearly equal to the C strain. The ratio of L strain to R strain was about 7:3. On the other hand, when pipe shrinkage in the L direction is constrained, L strain is minimal, whereas R strain increases. Since R strain has a correlation with the decrease in wall thickness, it is considered that constraining pipe shrinkage promotes a reduction in wall thickness by pipe expansion, making it easy for the pipe to fracture.

Figure 15 shows the relationships between the expansion ratio, the wall thickness unevenness after expansion, and the n-value, obtained from the analysis results in Cases 3 through 11 of Table 3. With an increase in expansion ratio, the wall thickness unevenness after pipe expansion increases. On the other hand, the larger the n-value, the less conspicuous becomes the increase in wall thickness unevenness. Thus, it can be seen that the larger the n-value of pipe material, the greater becomes the tolerance for wall thickness unevenness, which means that the pipe becomes less likely to fracture with higher expansion ratios.

On the basis of the above analysis results, we created a design map for implementing the optimum material design to allow for even critical pipe expansions required by users. **Figure 16** shows the relationship between pipe wall thickness unevenness and the material n-value required for pipe expansion when pipe circumferential strength was made uniform by heat treatment, and when the tolerable wall thickness unevenness after expansion was assumed to be 12.5%. By applying this technique, we could show the direction of more reliable material design to achieve the desired working performance of ERW steel pipe for EXP tubular.

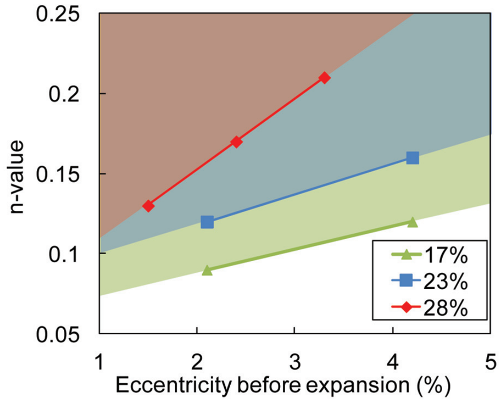

Fig. 16 Required eccentricity and n-value for pipe expansion

On the basis of the above results, we developed new products that can be expanded with the 15%-20% expansion ratio targeted by many users, with consideration given to pipe shrinkage during expansion. It has become possible to manufacture EXP oil well pipe on a stable basis by properly determining the chemical composition of the pipe material, the manufacturing conditions for hot-rolled steel plate as the raw material for ERW pipe, and the range of control of heat treatment conditions for the pipe manufactured in order to secure the optimum n-value for the aimed expansion ratio.

5. Results of Study of Collapse Resistance

5.1 Collapse test results

Table 5 summarizes the collapse test results and the values of C-YS, ovality, thickness unevenness, and residual stress obtained under various test conditions. Comparing pipe collapse resistances before and after pipe expansion, it can be seen that the collapse resistance after 23% expansion is approximately 30% of that before expansion. This is due mainly to the following two factors.

(1) Increase of D/t (increase in outside diameter and decrease in wall thickness)

Expanding a pipe increases the outside diameter and decreases the wall thickness. Since the increase in outside diameter increases the pipe surface area that is subject to external pressures, the external force that acts upon the pipe increases. On the other hand, the wall thickness that is required to withstand the external force decreases. As a result, collapse resistance declines.

(2) Decrease of C-YS

Figure 17 shows the compressive stress-strain curves obtained before pipe expansion and after 23% expansion. The stress-strain

Table 5 Collapse test results and properties after expansion

Expansion ratio (%)	D/t	Collapse (experiment) (MPa)	C-YS (MPa)	Ovality (%)	Eccientricity (%)	Residual stress (MPa)
Before expansion	20.3	51.7	627	0.31	1.8	0
17	26.1	19.5	521	0.36	5.7	206
	26.1	19.7	524	0.36	5.6	200
	26.2	19.3	520	0.22	6.6	196
23	28.6	16.1	528	0.47	6.0	110
	28.7	16.2	527	0.39	8.8	108
	28.7	15.5	522	0.51	8.2	102

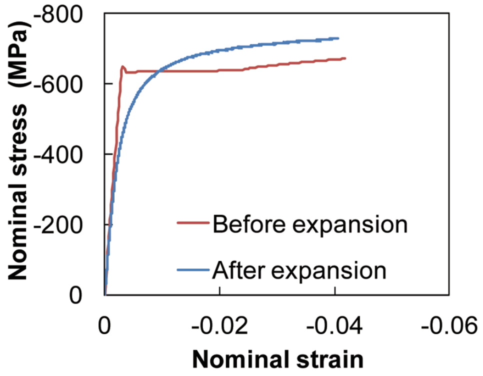

Fig. 17 Compressive stress-strain curve before and after expansion

curve before expansion reveals a yield elongation, whereas the stress-strain curve after expansion appears round in form and yield strength deteriorates. This is considered due to the Bauschinger effect which is produced when a pipe is compressed peripherally after it is subjected to a circumferential tensile stress as a result of expansion.

Among factors that influence pipe collapse resistance, ovality did not change markedly after pipe expansion. The residual stress before expansion was negligibly small since it was relieved by heat treatment during the manufacturing process. After expansion, however, the pipe showed a residual stress due to plastic deformation. Table 5 shows the absolute values of residual stress. The stress distribution was tensile for the inside of pipe and compressive for the outside of pipe.

5.2 Collapse simulation results

Table 6 summarizes the collapse test results after pipe expansion and the difference between collapse resistances predicted using an FEM simulation model, and measured collapse resistances. The shape and mechanical properties of the steel pipes tested were properly reflected in the FEM model. In addition, the same residual stress distribution (Distribution A) as obtained with actual pipe — tensile for the inside of pipe and compressive for the outside of pipe — was used in the simulation. As a result, it was possible to accurately predict pipe collapse resistance after expansion (error within 5%). Thus, it has become possible to quantify the factors that govern steel pipe collapse resistance after expansion.

In the present study, we examined the influence of residual stress distribution in steel pipes on pipe collapse resistance. Ordinarily, ERW steel pipe has a compressive residual stress in the inner surface and a tensile residual stress in the outer surface. It has been known that these residual stresses cause pipe collapse resistance to decline.[3] However, with regard to residual stresses occurring in pipes after expansion, their influence on pipe collapse resistance was unclear. We, therefore, clarified it using the FEM model created in the present study.

The residual stress distributions, A-C, shown in Fig. 9 were used in the simulation. It was found that when Distribution A and C were applied, pipe collapse resistance was lower than when Distribution B was applied, although there was little difference between A and C. Thus, it can be seen that under the analytical conditions used in the present study, steel pipe residual stress causes pipe collapse resistance to decline regardless of stress distribution. **Figure 18** shows the strain distributions right before the collapse of pipe simulated using the FEM model. Although residual stress distributions A and C influence collapse resistance almost equally, there is a marked difference between the maximum strains they produce at the time of pipe collapse. Namely, maximum strain is located in the outer surface of pipe with Distribution A, and in the inner surface of pipe with Distribution C. Thus, steel pipe collapse resistance can be considered to be unaffected by a difference in residual stress distribution, although the starting point of collapse differs according to residual stress distribution.

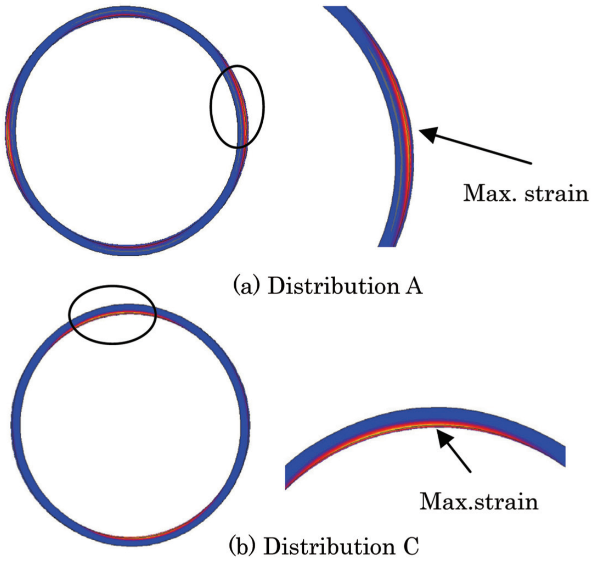

Fig. 18 Relationship between residual stress distribution and the location with max. strain in collapse simulation

Table 6 Accuracy of collapse simulation model

Expansion ratio (%)	Collapse resistance: Experiment (MPa)	FEM Distribution A Prediction (MPa)	Error (%)	FEM Distribution B Prediction (MPa)	Error (%)	FEM Distribution C Prediction (MPa)	Error (%)
17	19.5	20.0	2.6	20.8	6.7	20.9	5.6
	19.7	20.5	4.1	21.2	7.6	20.4	3.6
	19.3	20.0	3.6	20.5	6.2	19.9	3.1
23	16.1	16.1	0.0	16.2	0.6	16.1	0.0
	16.2	16.5	1.9	16.8	3.7	16.6	2.5
	15.5	15.6	0.6	15.9	2.6	15.8	1.9

6. Conclusion

In addition to the requirements of conventional oil well pipes, high deformability is required of EXP oil well pipe. In addition, EXP tubular pipe working performance is influenced by an expansion-induced change in factors such as material mechanical properties and pipe shape. For the realization of a new EXP tubular pipe, therefore, we developed a high-precision performance evaluation technique in order to secure high product reliability, based on a susceptibility evaluation, and implemented optimum material design, based on a performance evaluation. Our new EXP tubular pipe has led to the successful commercialization of Nippon Steel & Sumitomo Metal's EXP tubular pipe, which is now applicable in actual oil fields.

Major achievements of the present study are summarized below.

(1) Establishment of a new pipe expansion test method that per-

mits selecting whether to constrain pipe axial shrinkage during expansion, considering actual use of the pipe, and a new collapse test method that permits evaluating pipe collapse resistance after expansion.

(2) Establishment of a design map for optimum material design appropriate to the required expansion ratio, based on steel pipe expandability, expressed in terms of the relationship between wall thickness unevenness of pipe and the n-value of pipe material.

(3) Development of a numerical simulation model that permits accurately prediction of steel pipe collapse resistance after expansion.

(4) Performance of a susceptibility evaluation based on numerical analysis to quantify the influence of residual stress distribution in steel pipe after expansion on the collapse resistance of the expanded steel pipe.

(5) Development of methods for evaluating/predicting the working performance of steel pipe that helps enhance tubular products quality, on the basis of a combination of experimentation and numerical simulation techniques.

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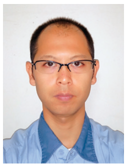

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