Numerical Analysis Techniques to Support the Reliability of Steel Tube and Pipe Products[†]

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Abstract:

Numerical analysis techniques currently utilized to establish the reliability of steel pipe products are introduced. High reliability is required for steel pipes used as mechanical and structural components, such as automobile parts and line pipes, to ensure the product safety. To quantify the rupture strength of pipelines and the deformation behavior of steel pipes for cars during the secondary forming, numerical analyses are performed along with selected experiments at JFE Steel. Calculated figures have a good correlation with experimental results.

1. Introduction

Steel pipes are used in a wide range of applications, as introduced in the special edition, and the characteristics required of them vary greatly accordingly. In particular, pipelines and oil country tubular goods for the energy industry and steel pipes for automobile parts must be highly reliable for keeping the safety. Safety must be verified through theoretical and experimental analyses of the fracture mechanism. However, it is difficult to conduct many experiments under various conditions of usage, so numerical analyses are used to complement the experiments. The iron and steel industry uses such techniques for iron- and steelmaking[1)], including thermal-fluid analysis and flow analysis in the iron and steel making processes, and the analysis of materials deformation behavior in the rolling process.

JFE Steel also uses numerical analyses for steel pipe manufacturing, such as:

· Deformation simulation during forming process of automobile parts;
· Deformation behavior of pipelines under ground deformation;
· Prediction of high-speed ductile fracture of pipelines[2)]; and
· Evaluation of sealability at joints of oil country tubular goods[3)].

For example, the deformation of pipelines resulting from ground movement, the expected fracture mode and the effect of material characteristics on the fracture can be quantitatively evaluated using numerical analyses.

With the progress of computers and the development of FEA in recent years, complex deformation behaviors of large structures can now be predicted by numerical simulations. In particular, JFE Steel, as a material manufacturer, quantitatively evaluates the deformation and fracture behavior of materials through both experimental fracture tests and numerical analyses, and conducts studies to verify safety and reliability. This paper describes the evaluation of the formability of steel pipes for automobiles and the safety of linepipes.

2. Numerical Analysis Techniques in Tube Forming

Regarding tube forming technology, for example, the shape of formed parts in tube hydroforming (THF) is often complex in three-dimensional mode, and these formed parts are subjected to preforming before THF such as bending and crushing. Accordingly, to quantitatively predict the shape, dimensions, and accuracy of the

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formed parts, actual forming tests are required.

Mold fabrication for THF is very expensive, whereas numerical simulation to predict the formability and mold shape can greatly reduce the cost. As the dynamic explicit method becomes increasingly used in finite element analysis (FEA) and as computing power becomes faster and cheaper, deformation analysis by numerical simulation of plastic forming for checking the formability and the mold-correction effect has recently become practical.

Currently, automobile and parts manufacturers generally use FEA as a core technology, and base material manufacturers use FEA for studying the effect of improvements in material characteristics on forming and for studying the defects in forming caused by the materials and forming technology.

A typical example of tube forming where FEA is effectively applied is the multi-stage FEM simulation for THF, which includes the preforming steps of bending and crushing as described above. **Figure 1** shows an example of FEA. The shape of the member is a model shape assuming subframe parts of an automobile. The THF experiment was conducted jointly with Aida Engineering, Ltd. A steel tube was bent, pressed, and subject to other preforming to create a shape resemble to the final product, which was then charged to a mold, where two kinds of working forces (axial pressing force and internal pressure) were applied to conduct expansion forming to obtain the intended mold shape[4,5]. In this process, it is important to investigate the portion of possible fracture caused by mass loss in THF and forming defects such as cracks and wrinkles which may occur during THF, using THF numerical analysis combined with the analytical results on strain variations during bending and crushing.

Figures 2 and **3** show the results of FEA and the experiments under the same forming condition varying the internal pressure and axial feeding force (loading path). Case 1 is an example of wrinkle generation, showing good agreement in the wrinkle shape between FEA and the experiment. Case 2 is an example of forming without generating wrinkles, showing that the maximum thinning ratio is almost equal between FEA and the experiment. For Case 1 and Case 2, the cause of presence or absence of wrinkles is the loading condition of internal pressure and axial feeding force. That is, the forming pressure at which to begin axial feeding in Case 1 is lower than that in Case 2.

Although the FEA program is commercially available, to attain higher analytical accuracy using FEA, it is important to reflect the material characteristics, mold condition, and forming conditions as the boundary conditions of FEA.

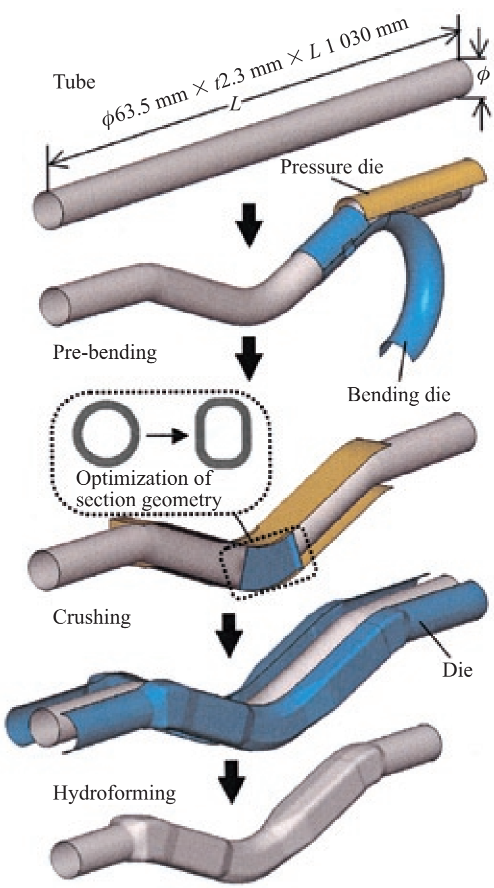

Fig. 1 Process of tube hydroforming

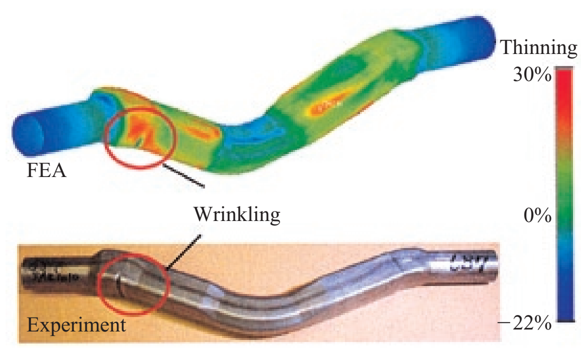

Fig. 2 Comparison of results between an FEA and an experiment (Case 1)

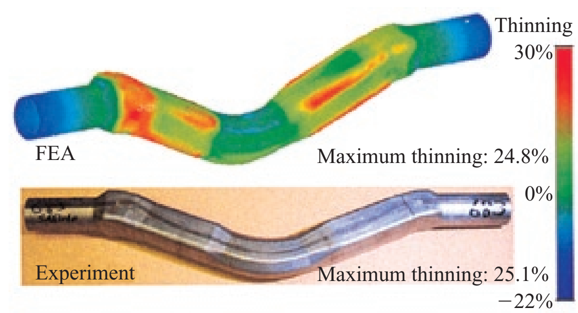

Fig. 3 Comparison of results between an FEA and an experiment (Case 2)

3. Numerical Analysis Techniques in Safety Evaluation of Linepipes

The distance that natural gas is transported between the site of production and consumption has increased in recent years, and so the pressure and the required strength of linepipes for transportation have increased. Long-distance natural gas pipelines are often laid in seismic regions, cold regions, and ice seas, so high-strength linepipes must have excellent deformation characteristics such as those of HIPER, or high strain capacity under bending.

The design formula for predicting the critical compressive strain of linepipes, given in existing design standards or design guidelines, is an empirical formula expressed as a function of D/t (D: pipe diameter, t: pipe wall thickness). The formula generally does not consider the influence of material characteristics and internal pressure. Furthermore, since the empirical formula is established within the range of strengths of conventional linepipes and transportation pressures, the formula cannot be applied to high-strength, high-pressure linepipes.

Although the critical compressive strain of high-strength linepipes must be derived by a compression experiment on an actual pipe, compression experiments using a large linepipe are expensive. So, it is common to conduct a minimum number of compression tests on actual pipes while applying FEA, taking into account material characteristics (work-hardening characteristics), geometrical initial imperfections (distribution in pipe diameter and pipe wall thickness), and internal pressure to accurately estimate the critical compressive strain. Furthermore, since FEA can adopt parameters which are restricted in an actual pipe experiment as arbitrary variables, much information can be acquired.

Figure 4 shows the comparison of wrinkles generated by bending moment between an actual pipe experiment and FEA. Since FEA considered the observed stress-strain curve, geometrical initial imperfection, and internal pressure, it can predict the critical compressive strain and buckling waveform with high accuracy. Regarding the critical compressive strain, the work-hardening characteristics are important variables in addition to D/t. However, it is difficult to quantitatively determine the influence of the work-hardening characteristics in an actual pipe experiment, for which FEA is the optimum means.

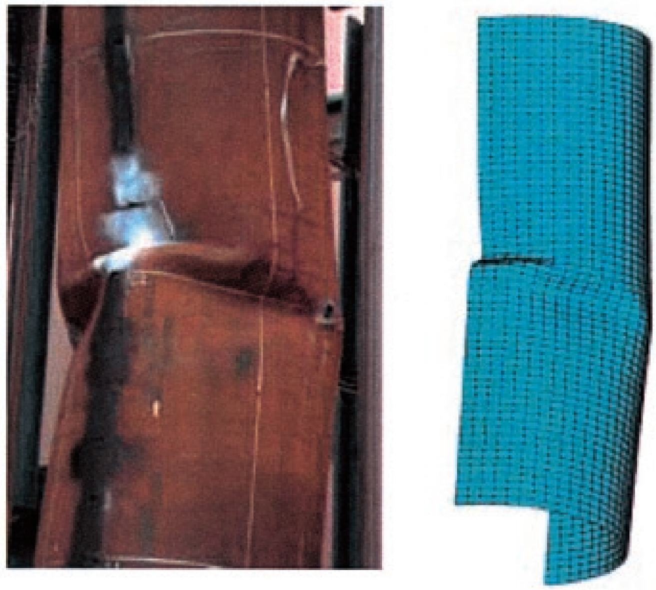

Fig. 4 Shell wrinkling due to bending

Referring to **Fig. 5** which shows a model experiment of a strike-slip fault (shear deformation), the influence of the work-hardening characteristics on the safety of pipelines is quantitatively described. The left figure of Fig. 5 shows a soil tank under shear deformation, and the right figure shows a state of excavated deformed underground pipeline (model). **Figure 6** shows the result of FEA on the total deformation of an underground pipeline (model). The bending deformation of the pipeline concentrated at a position slightly distant from the fault. **Figure 7** shows the axial strain distribution at a portion of concentrated bending deformation, for a fault displacement of 3 m. The upper figure of Fig. 7 shows the result of the estimated stress-strain curve in a conventional linepipe, while the lower figure shows that in

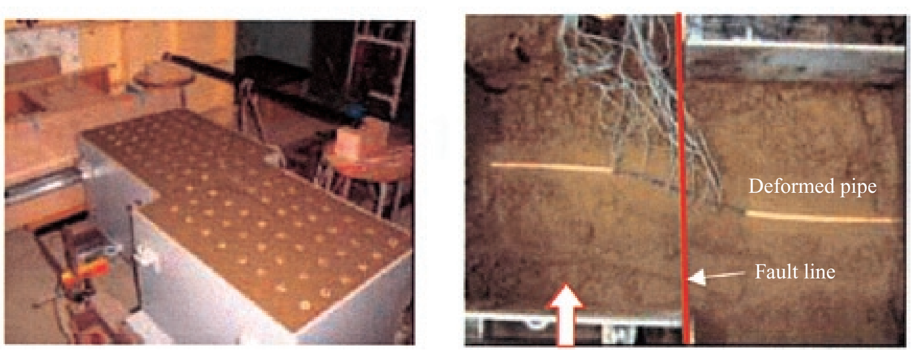

Fig. 5 Bending of a buried pipeline due to shear deformation

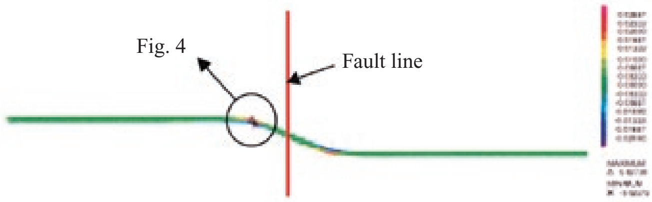

Fig. 6 Deformation of a buried pipeline (Fig. 2)

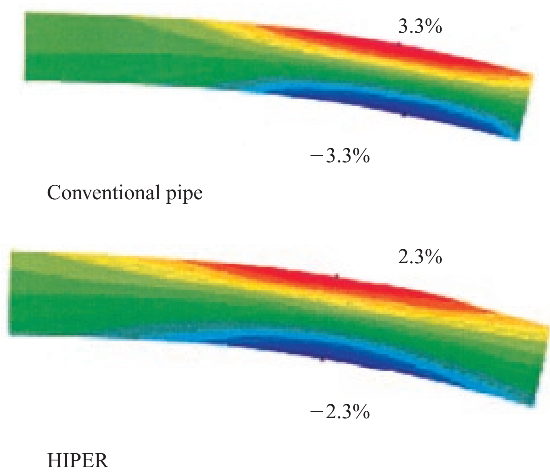

Fig. 7 Comparison of strain distribution of buried pipeline

HIPER.

Numbers in Fig. 7 show the calculation result for a fault displacement of 3 m. The figure shows the maximum compressive strain of 3.3% for conventional pipe, and 2.3% for HIPER. The maximum compressive strain of HIPER is thus about 60% that of conventional pipe, and the strain distribution of HIPER is wider. The critical compressive strain in HIPER is about 1.5 times that of conventional pipe. Consequently, HIPER is expected to be two or more times safer than conventional pipe under ground deformations occurring in seismic regions and cold regions.

Although a comparison between the actual pipe experiment and FEA and a comparison between the model experiment and FEA are not given here, the FEA with appropriate input data can predict the linepipe deformation characteristics and underground linepipe deformation with satisfactory accuracy.

4. Conclusion

Numerical analyses are highly effective for evaluating the behavior of materials under conditions that cannot be confirmed by experiments alone. JFE Steel not only supplies materials but also studies the technologies necessary for using the materials, and supplies information that customers require in order to use the materials.

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