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Development of an Integrity Evaluation Program for Corroded City Gas Pipelines

†D.J. Shim, K.O. Yun, J.B. Choi*, Y.J. Kim, W.S. Kim, and S.C. Choi

SAFE Research Center, Sungkyunkwan University, 300 Chunchun-dong Jangan-gu, Suwon, Kyonggi-do 440-746, KOREA

Pipelines have the highest capacity and are the safest and the least environmentally disruptive means for transmitting gas or oil. Recently, failures due to corrosion defects have become a major concern in maintaining pipeline integrity. A number of solutions have been developed for the assessment of remaining strength of corroded pipelines. In this paper, a Fitness-For-Purpose(FFP) type limit load solution for corroded city gas pipelines is proposed. For this purpose, a series of burst tests with various types of machined defects were performed. Finite element simulations were carried out to derive an appropriate failure criterion. Based on such solution along with existing solutions, an integrity evaluation program for corroded city gas pipeline, COPAP-CITY, has been developed.

Keywords *: corrosion defect, city gas pipeline, burst test, finite element analysis, integrity evaluation program*

1. Introduction

Since the 1950's, pipelines have been used as one of the most economical and safest ways of transmitting oil and gas, and a number of pipelines are still under construction all around the world. However, the number of accidents has also dramatically increased with the increasing number of operating pipelines.[1),2)] The integrity of these pipelines is of importance due to the explosive characteristic of gas and oil. Especially for city gas pipelines, which are mostly installed under highly populated district, integrity must be secured. For these reasons, intensive research efforts have been carried out on the assessment of structural integrity of gas pipelines.

Corrosion is known to be one of the major reasons causing pipeline failure. ASME B31G[3)] is one of the most widely accepted solutions for the assessment of corrosion defects. ASME B31G idealizes the complex geometry of a corrosion pit as an elliptical shape, and applies a bulging factor for the consideration of defect geometry. This solution has been modified by Kiefner and Vieth[4)] to enhance its accuracy. Vieth and Kiefner[5)] collected an extensive series of pipeline burst test results for deriving improved corrosion defect assessment procedures. The improvement was achieved by introducing a new bulging factor and the material flow stress, and a more detailed consideration of the defect shape using iterative calculations. This method has been implemented in a program known as RSTRENG.[6)]

ASME B31G and RSTRENG have been widely used for assessing the remaining strength of piping and pressure vessels due to its conservatism. However, it has been revealed that these criteria are excessively conservative when applied to defects in high strength pipelines.[7)-9)] In 1997, Stephens and Leis[10)] observed that the failure of corroded pipelines was controlled by ultimate strength rather than flow strength in mid-to high-strength steel pipelines. On the basis of experimental observations, Stephens et al.[11)] developed a specific finite element code, which is called PCORRC, and proposed a limit load solution for moderate- to high- toughness pipe based on an extensive series of finite element analyses. Recently, the corrosion defect assessment procedure has become more specific in terms of pipeline materials and defect geometries.[11)-13)] Therefore, it has been necessary develop a specific solution for an accurate assessment of corrosion defects especially in high strength pipeline steels.

In this paper, a limit load solution is developed for the assessment of corrosion defects in city gas pipelines, KS D3507 and KS D3631, by comparing experimental data with finite element analysis results. Based on such solution along with existing solutions, an integrity evaluation

†Corresponding author: boong33@skku.edu

program for corroded city gas pipeline, namely COPAP-CITY(COrroded Pipeline Assessment Program for CITY gas pipeline), has been developed.

2. Full-scale pipe burst test

Full-scale pipe burst tests were performed by KOGAS using KS D3507 and KS D3631 pipes which are widely used for city gas transmission. A pipeline was cut into pieces with 2 *m* length, and both ends were capped by circumferential welding to accommodate high internal pressure. The geometrical configuration of the specimen tested is illustrated in Fig. 1, and dimensions of test specimens and resulting burst pressures, P_{test}, are summarized in Table 1. The corrosion defect was machined in a rectangular shape as shown in Fig. 1. The defect was machined to keep the same thickness at the bottom, and corner edges were rounded to avoid excessive stress concentration. For categorizing a corrosion defect, the depth (a), the width (c) and the length (l) are usually used. The rectangular shape corrosion pit is accepted since it can be assumed as the most critical shape with these three characterizing parameters. The test equipment is shown in Fig. 2(a).

All specimens showed bulging deformation around the defect area, and the final failure occurred at the bottom of defect area with a crack-like penetration in the longitudinal direction as shown in Fig. 2(b). The burst pressure was affected by the variation of defect depth and length as summarized in Table 1. The final failure was preceded by bubbling deformation around the defect area, which is typical for mid-to high-toughness pipeline material. The defect area shows a significant amount of thickness reduction along the penetration line, probably caused by local necking prior to final failure. For all specimens, failure was controlled by plastic collapse rather than fracture.

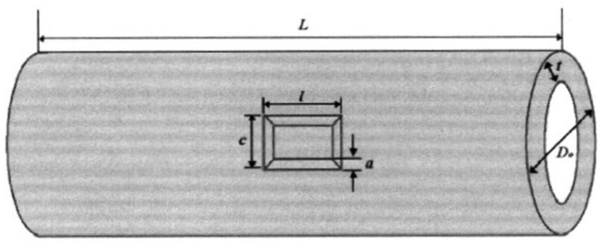


Fig. 1. A schematic illustration of burst test specimen

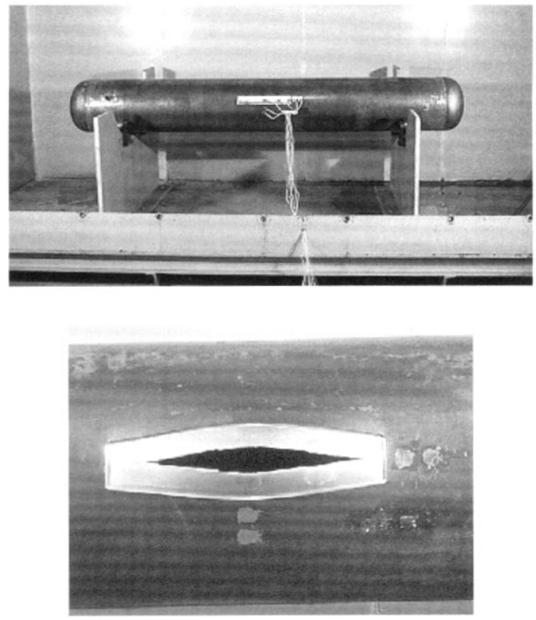


Fig. 2. Picture of (a) burst test equipment and (b) specimen 3631C after test

3. Finite element simulation of pipe burst test

In order to derive the failure criterion for corrosion defects, 3-D elastic-plastic finite element analyses simulating pipeline burst tests were performed using a com-

Table 1. Burst test pipe geometries and results

Test No.	Pipe Material	l (mm)	c (mm)	a (mm)	a/t	P_{test} (MPa)	P_{pre} (MPa)
3507A	KS D3507	100	50	3.5	0.55	14.07	14.20
3507B	KS D3507	200	50	3.5	0.55	12.12	11.72
3507C	KS D3507	300	50	3.5	0.55	10.76	10.64
3631A	KS D3631	100	50	3.4	0.53	13.84	13.69
3631B	KS D3631	200	50	3.7	0.58	11.64	10.32
3631C	KS D3631	300	50	3.5	0.55	10.77	9.75

*For all pipe specimen: $L = 2$ m, $D_o = 300$ mm, $t = 6.4$ mm mercial finite element program, ABAQUS.[14] Symmetry conditions were fully utilized and only a quarter of a full pipe was modeled. The machined pit was modeled as a rectangular shape in accordance with the test specimen shown in Fig. 3. The model is designed with 20-node reduced integration elements, and the numbers of elements and nodes are 1,129 and 5,713, respectively. Since the final failure was observed from the defect area, the bottom of the defect area was modeled with sufficient number of elements determined by a preceding convergence analysis. The hydrostatic pressure was applied at the inner surface of the model. Since the test specimen was capped at both ends prior to the burst test, the corresponding axial stress was applied at the end of finite element model. The true stress-true strain curve was obtained from tensile test, which were performed for the same material as the burst test specimen. The full true stress-strain curve is shown in Fig. 4 for two materials considered in the test. Incremental plasticity with large deformation theory was applied for the entire finite element analysis to simulate local deformation at the defect area.

Since all test specimens showed local failure at the defect area, a failure criterion is proposed by considering the local stress at the defect area. The von Mises stress values at this area were monitored in comparison with experimental results using various reference stresses such as yield strength(σ_y), true ultimate strength($\sigma_{u,t}$), flow strength($\sigma_f = (\sigma_y + \sigma_u)/2$) and 90% of true ultimate strength($0.9\sigma_{u,t}$). Failure was then assumed to occur when the von Mises stress at the ligament reached the reference stress as shown in Fig. 5 and the corresponding internal pressure was determined as the burst pressure, P_{pre}. Results based on $0.9\sigma_{u,t}$ criterion showed good agreement with the actual burst pressure, P_{test}, as summarized in Table 1. Fig. 6 shows the comparison between the predicted burst pressure and actual burst pressure obtained from the test. The prediction provided conservative results and showed overall good agreement with the test results. Comparison shown in Table 1 and Fig. 6 provided sufficient confidence in the present finite element simulation.

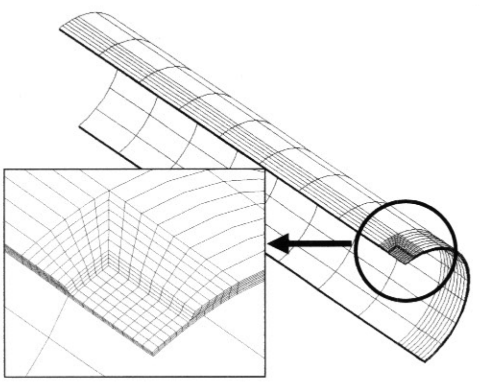


Fig. 3. A typical finite element mesh used for burst test simulation

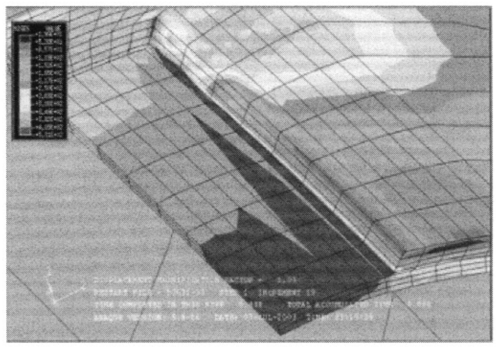


Fig. 5. Contour plot of von Mises stress at the corroded area

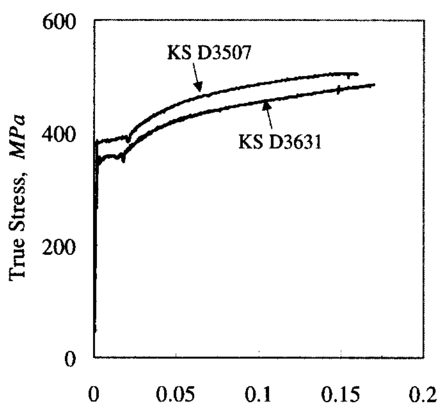


Fig. 4. True stress-strain curves for KS D3507 and KS D3631

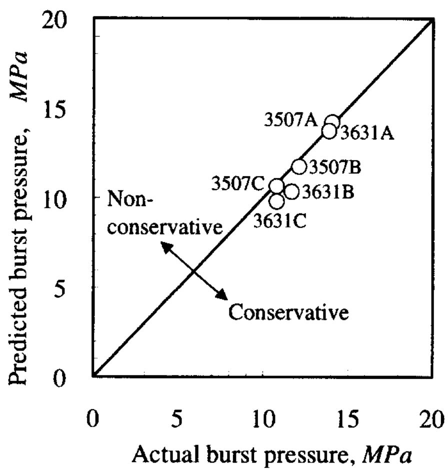


Fig. 6. Comparison between actual burst pressure and burst pressure predicted from finite element simulation

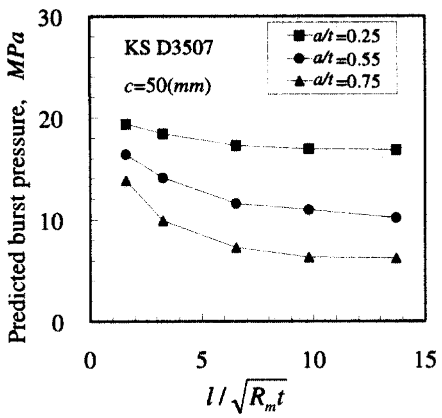


Fig. 7. Burst pressure predicted from finite element analysis for various defect shape

4. Limit load solution for city gas pipeline

In order to derive a general solution for defect assessment of city gas pipelines, extensive finite element analyses on various corrosion defects were performed. Two parameters, a/t and $l/\sqrt{Rt}$ were considered in the finite element analyses. The value of R/t was set to 22.94 considering the actual dimensions of a city gas pipeline. The values of a/t were set to 0.25, 0.55 and 0.75. Five different $l/\sqrt{Rt}$ values ranging from 1.63 to 13 were considered. The variation of c would not be significant since axial cracks are more critical than circumferential cracks for pressurized pipes and thus, c was fixed to 50 *mm* for the entire analysis matrix. Considering the material property, true stress-strain data for both KS D3507 and KS D3631 were used. Thus a total of 30 cases were analyzed.

For all cases, the maximum von Mises stress was observed at the deepest point of the defect. The failure, therefore, was assumed to occur when the von Mises stress in the defect ligament reached $0.9\sigma_{u,t}$ as determined in the previous section. The burst pressure was determined as the internal pressure when the failure criterion was satisfied. Fig. 7 shows the predicted burst pressures for KS D3507 pipe with various defect shapes.

By applying regression analysis on the finite element analysis results, a limit load solution is proposed as follows:

$$P_{max} = 0.9\times\frac{2t}{D_i}\sigma_u\left[C_2\left(\frac{l}{\sqrt{Rt}}\right)^2 + C_1\left(\frac{l}{\sqrt{Rt}}\right) + C_0\right] \quad \text{for} \quad \frac{l}{\sqrt{Rt}} \le 6 \qquad (1)$$

where

$$C_2 = 0.1163\left(\frac{a}{t}\right)^2 - 0.1053\left(\frac{a}{t}\right) + 0.0292$$
$$C_1 = -0.6913\left(\frac{a}{t}\right)^2 + 0.4548\left(\frac{a}{t}\right) - 0.1447$$
$$C_0 = 0.06\left(\frac{a}{t}\right)^2 - 0.1035\left(\frac{a}{t}\right) + 1.0 \qquad (2)$$

and

$$P_{max} = \frac{2t}{D_i}\sigma_u\left[C_1\left(\frac{l}{\sqrt{Rt}}\right) + C_0\right] \quad \text{for} \quad \frac{l}{\sqrt{Rt}} > 6 \qquad (3)$$

where

$$C_1 = 0.0071\left(\frac{a}{t}\right) - 0.0126$$
$$C_0 = -0.9847\left(\frac{a}{t}\right) + 1.1101 \qquad (4)$$

5. Development of an integrity evaluation program

An integrity evaluation program for corroded city gas pipeline, namely COPAP-CITY(COrroded Pipeline Assessment Program for CITY gas pipeline), has been developed. COPAP-CITY is a Windows program based on 10 evaluation methods including the limit load solution proposed in the previous section. The evaluation methods implemented in COPAP-CITY are as follows:

- Limit load solution proposed in the present paper
- Classical effective area method
- ASME B31G criterion
- Modified B31G criterion
- Chell limit load criterion
- Kanninen shell Theory
- Sims pressure vessel criterion
- Ritchie and Last criterion
- PRCI/Battelle PCORRC criterion
- BG/DNV Level 1 criterion

5.1 Structure of COPAP-CITY

Fig. 8 shows the main window of COPAP-CITY, which consists of two analysis modules; single analysis module and parametric analysis module. Each module consists of four parts; data input part, calculation part, output display part and database part. Single analysis module can be used

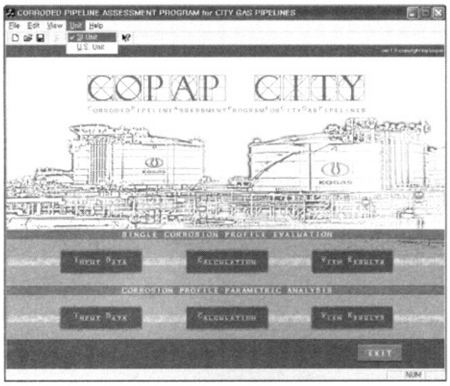
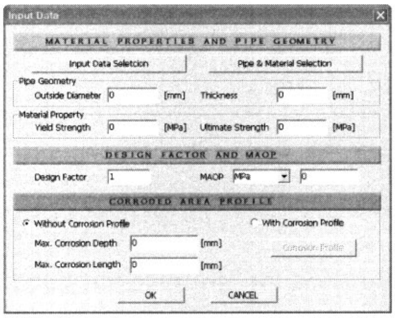
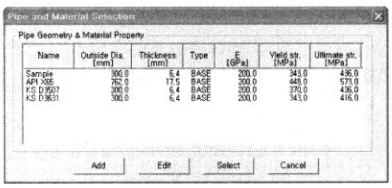


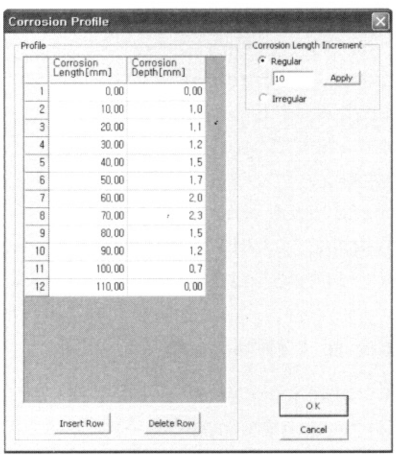
Fig. 8. The main window of COPAP-CITY



(a)



(b)



(c)

Fig. 9. Input data windows of COPAP-CITY

to evaluate a single corrosion profile. Parametric analysis module can be used to perform parametric study by ranging the corrosion profile.

5.2 Data input part

Fig. 9(a) shows the data input window of COPAP-CITY, which consists of 'material property and pipe geometry', 'design factor and MAOP' and 'corroded area profile'. Material property and pipe geometry can be either directly inputted or imported from the database as shown in Fig. 9(b). Corroded area profile can be simply inputted by giving the length and maximum depth of the corroded area or exact profile can be inputted in detail as shown in Fig. 9(c). For parametric analysis, range of the parameters, i.e. depth and length of corroded area, is given as an input.

5.3 Calculation part

In the calculation part of COPAP-CIYT, burst pressure of the corroded pipe is calculated based on the evaluation methods mentioned above. Also, the maximum safe pressure is calculated based on the predicted burst pressure and inputted design factor. For parametric analysis, the results are calculated for the minimum input value up to the maximum input value.

5.4 Output display part

Fig. 10 shows the output display part for single analysis module, which displays the corrosion profile in a graphical method. Also the predicted burst pressure and maximum safe pressure is shown as a bar graph. Results based on various evaluation methods are shown together for quick and simple comparison. From these results user can easily judge the state of the corroded city gas pipe. Fig. 11 shows the output display part for parametric analysis module. Fig.

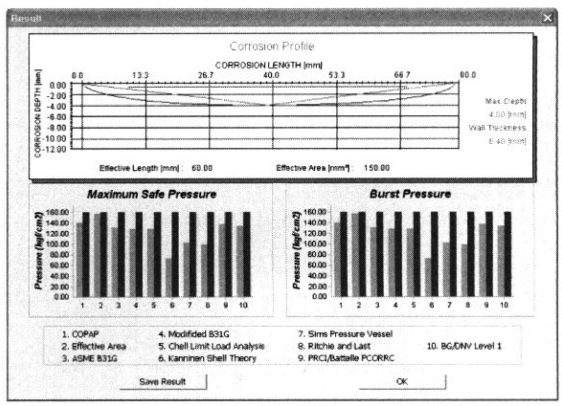
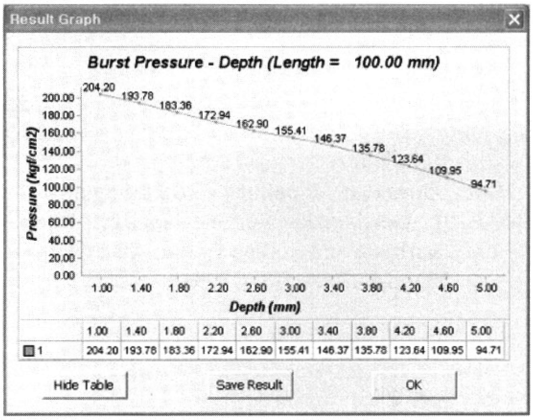
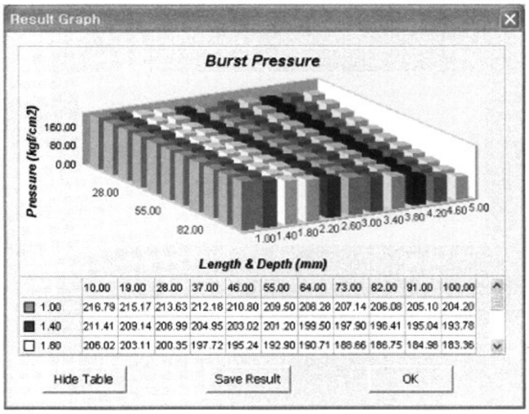


Fig. 10. Result window of COPAP-CITY showing predicted burst pressure



(a)



(b)

Fig. 11. Parametric analysis result of COPAP-CITY; Predicted burst pressure for (a) varying depth and (b) varying depth and length

11(a) shows the results for the case where the corroded length is fixed and the depth is set as a parameter. Fig. 11(b) shows the results for the case where both the corroded length and depth is set as a parameter.

5.5 Database part

The database of COPAP-CITY consists of both input database and output database. The input database includes material property, pipe geometry, input data for previously performed analyses. User can easily add, delete or edit the material property and pipe geometry. The output database includes all the results for the previously performed analyses. Based on this database COPAP-CITY provides an analysis report for the user, which contains all the input and output data of specific analysis.

6. Conclusions

In this paper, a systematic approach was followed to develop a limit load solution for the assessment of corrosion defects in a city gas pipelines, and based on such results an integrity evaluation program for city gas pipeline was developed. The resulting conclusions are as follows:

(1) Failure was predicted to occur when the von Mises stress reached 90% of the true ultimate strength across the entire ligament.

(2) A limit load solution for the assessment of corrosion defects in a city gas pipeline is proposed on the basis of finite element analysis results.

(3) By using the developed program, COPAP-CITY, it will be possible to perform quick and accurate assessment for corroded city gas pipeline.

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