Lecture Notes in Networks and Systems 792

Nenad Mitrovic
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New Trends in Engineering Research

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Corrosion Damages of Pipelines Assessment by Using the Finite Element Method

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Abstract. In order to ensure pipeline safety during their service life, all relevant construction, testing and safety requirements must be met. Corrosion damage is a major hazard to the steel pipeline as a whole, and it is necessary to comply with inspections and adequate maintenance so that destruction with catastrophic consequences would be avoided. In this paper, the standard calculation for determining the maximum acceptable corrosion damage length according to the RSTRENG method is presented using the calculation of the corrosion-damaged structure of the ammonia (NH3) transfer pipeline. After that, the methodological approach to calculation using the finite element method (FEM) is presented in accordance with the methods defined by the new and general approach to standardization and technical harmonization for pressure equipment (Pressure Equipment Directive). The aim of the work was to present advanced modeling techniques of corroded surfaces based on FEM in order to develop a procedure for evaluating the residual strength of steel pipelines in the chemical industry.

Keywords: Pipeline · Corrosion damage · Corrosion assessment · FEM

1 Introduction

Corrosion damage, in which the load-bearing capacity of the section is reduced, greatly endangers the steel pipelines as a whole. Failure to perform required periodic and emergency inspections, as well as inadequate maintenance, can result in destruction with catastrophic consequences.

Improper maintenance of steel pipelines from the aspect of corrosion protection entails very expensive repairs, therefore it is necessary to thoroughly study the issues of protection, durability and maintenance of steel pipelines, as well as the possibility of monitoring corrosion aggression in operation. In this regard, it is necessary to assess the condition or the remaining strength of the steel pipeline subject to corrosion after long-term use, after which certain tests should be carried out using non-destructive methods to

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determine the actual degree of damage to the vital parts of the structure. Inspection and testing of the corroded zones of the supporting elements of the steel support structure of the pipelines by non-destructive methods must be accompanied by standard inspection calculations, as well as FME calculations, in order to evaluate the remaining strength of the steel pipelines; the inspection and testing must also include opinions and recommendations. In uncertain situations, the calculations must be confirmed by experimental analysis.

Prior to inspection and testing by non-destructive methods, the steel support structure of the pipelines must be cleaned (e.g., by sandblasting), and the necessary interventions in the form of modifications to critical elements must be immediately followed by corrosion protection.

Pipelines must be designed to be safe throughout their service life, taking into account all relevant influences, with special requirements for design, construction, testing and safety.

Allowable stresses must be limited by possible errors in operating conditions to fully eliminate uncertainties resulting from manufacturing, the calculation model, actual operating conditions, and the properties and behavior of the material.

Due to the risk of corrosion to which the steel support structure are exposed, a number of corrosion protection measures are prescribed during the construction phase:

- Use of clean and non-corroded sheet metal, profiles and binding material with corrosion protection.
- Protection of parts that need to be protected prior to installation against the effects of corrosive agents that may occur on site.
- During the construction phase, sensors and measuring tapes must be installed in order to monitor changes in the aggressiveness of the environment, stress and strain of the responsible supporting parts of the steel pipelines which are connected to a computer that processes the data and makes appropriate decisions.

After installation and prior to commissioning, steel pipelines are subject to inspection in order to obtain a work permit.

Despite numerous methods of protection, corrosion of steel pipelines is inevitable due to the harsh environmental conditions in the industry. It occurs in various forms, such as general corrosion with uniform loss of wall thickness or pitting corrosion associated with localized reduction of wall thickness. In practice, it happens that the steel embedded in the pipeline partially or completely corrodes, thus reducing the cross-section and thus the load-bearing capacity of the structure. In more severe cases, accidents with catastrophic consequences for production, facilities, production means, equipment and human lives can occur. Such accidents lead to pollution and harmful effects on flora and fauna, air, watercourses and groundwater.

Examples of corrosion of steel pipelines structures in the chemical industry are shown in Fig. 1.

Corrosion manifests itself as follows: appearance of cracks, loss of strength, swelling and loss of mass, corrosion spots and weakening of the cross-section. Visual signs of destruction are: erosion, flaking and crumbling, bruising, softening, cracking, crystallization, appearance of so-called "popcorn cracking". Point corrosion is especially dangerous on parts of the structure exposed to stresses. Due to the reduction in cross-section and high

Fig. 1. Examples of corrosion damage to steel support structures of pipelines [1, 2]

stress, occasional damage can lead to the formation of cracks and stress concentrations. [3, 4].

During operation, legally required inspections are performed to ensure safe and reliable operation of the steel pipelines. In addition to proper and timely maintenance, it is also necessary to monitor corrosion processes during operation. These processes can be monitored directly or indirectly. Direct monitoring involves checking the condition of the steel surface and the aggressiveness of the environment surrounding the pipeline steel support structure. In indirect monitoring, the corrosion effect is measured on samples made of the same material as the steel support structure of the pipeline.

Monitoring is very present in the world, especially monitoring the behavior of dynamically loaded structures, such as steel pipelines that operate in aggressive environments, especially those offered by the chemical industry. The value of the installed monitoring equipment is negligible compared to the value of the construction of steel pipelines or the value of rehabilitation works carried out after years of inadequate maintenance.

The direct and indirect costs caused by corrosion in the chemical industry are enormous. In the U.S., the total annual cost of corrosion is estimated at $1.7 billion, or about 8 percent of total capital costs [5]. The indirect costs of production stoppage due to failure or catastrophic destruction have not been calculated, but are estimated to be much higher.

The durability of steel for pipelines in the chemical industry depends on the properties of the corrosive environment and the ability to withstand internal and external influences, the character and intensity of which depend on the operating conditions of the steel pipelines. The internal influence is reflected by the purpose and type of fluid in the steel pipelines, which may be of different aggressiveness, toxicity and explosiveness, different pressures, temperatures and flows. The external influence depends on the type, composition and temperature of the exhaust gases and air surrounding the objects in question, the velocity, flow and pressure of the gases, as well as the powdery substances in the gas flow.

External influences also include: the chemical effect of water - the environment and the substances dissolved in it, the changing effect of temperature changes (which leads to expansion changes of the steel), the changing humidification and drying of the steel, and the effect of dissolved salts in contaminated water. The emission of pollutants, which are almost always present in the ambient atmosphere of the chemical industry, has a great influence. It includes gases O_2, CO, CO_2, SO_2, NO, NO_2, NO_x, H_2S, water vapor, and particles of solids such as KCl, K_2SO_4, $(NH_4)_2SO_4$, $CO(NH_2)_2$ etc. The composition of exhaust gases and solids, their velocity, flow and increased concentration also affect the rate of corrosion and erosion of steel pipelines.

Pipes of appropriate diameter and wall thickness are used for the construction of steel pipelines, as well as various profiles in some qualities of general and fine-grained structural steel.

Steel pipelines made of steel elements require precision, great attention and trained and professional labor in their manufacture. They are made by welding or joining pipe flanges of suitable quality. They are equipped with suitable devices such as load cell, level gauges, safety valves, filling, draining and overflow valves, etc.

Depending on the aggressiveness of the transported fluid, steel pipelines are exposed to internal corrosion, depending on the environmental conditions and the effect of external corrosion.

The side of steel pipelines facing the sources of pollutant emissions, which is supported by airflow from that direction, is more exposed to corrosion due to the direct impact of pollutants on the structure of the steel pipeline. With poor air circulation, steel pipelines can be exposed to constant moisture, which, along with the emission of pollutants, can have disastrous consequences for the structure.

All defects, whether installed or created during the explosion, are investigated over a period of time, providing realistic insight into the potential damage progression, which in turn has a direct impact on reducing the number of failures, scheduling plant shutdowns, and significantly reduces overall costs.

To prevent defects and ensure safe operation, corrosion should be detected, measured and the remaining strength of the corroded surface of the element needs to be evaluated.

Inspections and tests should be documented with sketches and photographs to ensure the reproducibility of tests and updating the file, i.e. the "passport" of the steel pipeline.

In order to evaluate the residual strength of corroded elements of steel pipelines using any of the existing methods, the corrosion defect must be accurately measured. Currently, the ultrasonic method with associated equipment is the most commonly used method for testing corrosion damage to steel pipelines. The test and inspection results are processed manually or automatically with the help of computer programs. The programs can work in such a way that we provide them with data collected by the classic method of measuring the maximum corrosion depth (the minimum thickness of the pipe wall), or the program is integrated with a measuring instrument which scans the tested surface and compares the obtained results with the standard prescribed acceptance criteria. As a result, we obtain, by classical calculation or automatically, the remaining strength of the tested steel pipeline and on this basis determine the maximum allowable operating pressure.

2 Methods for Assessing Corrosion Damage to Steel Pipelines

There are several methods for evaluating the residual strength of corroded pipelines. Some of them are very simple and rely only on the length and depth of the fault, while others are much more complicated based on finite element modeling (FEM).

ASME B31G [3] is one of the most widely accepted solutions for evaluating corrosion damage in steel pipelines. The improvement of the method [6, 7] was achieved by introducing the damage factor, material loading and detailed consideration of the damage shape by calculations. This method is included in the program known as RSTRENG (Remaining Strength of Corroded Pipe). ASME B31G and RSTRENG have found wide application in the assessment of corrosion damage to steel pipelines in industry.

The presented methods allow the evaluation of longitudinal corrosion defects. The role of transversely oriented defects is usually denied. Kastner's standard for the drop-in plasticity at the defect location can be used for transversely oriented defects [8].

However, these criteria are too conservative when applied to damage in steel pipelines made of high-strength materials. Based on the experimental observations, a specific finite element framework called PCORRC has been developed, and solutions have been proposed for the evaluation of pipes made of medium- to high-strength steels, based on a large series of experiments and FEM calculations [9–25].

Corrosion defects are asymmetric defects that extend in any direction on the inner or outer surface of the pipeline. Therefore, in order to assess the remaining strength of the FEM and thus the service life, they should be modeled as realistically as possible.

The aim of this work is to present advanced modeling techniques of corroded surfaces based on FEM in order to develop a method for evaluating the residual strength of steel pipelines operating under the environmental conditions of the chemical industry.

2.1 Data for the Calculation of Corrosion Damage to the Steel Pipelines

The data required for the calculation of corrosion damage to pipelines, Fig. 2, using the RSTRENG method and FEM are:

- The nominal value of the outer diameter of the pipeline,$D = 125$ *mm*;
- Nominal wall thickness of the pipeline,$t = 5$ *mm*;
- Maximum depth of corrosion damage,$d = 2$ *mm*;
- Measured (longitudinal) length of the corrosion damage,$L_m = 70$ *mm*;

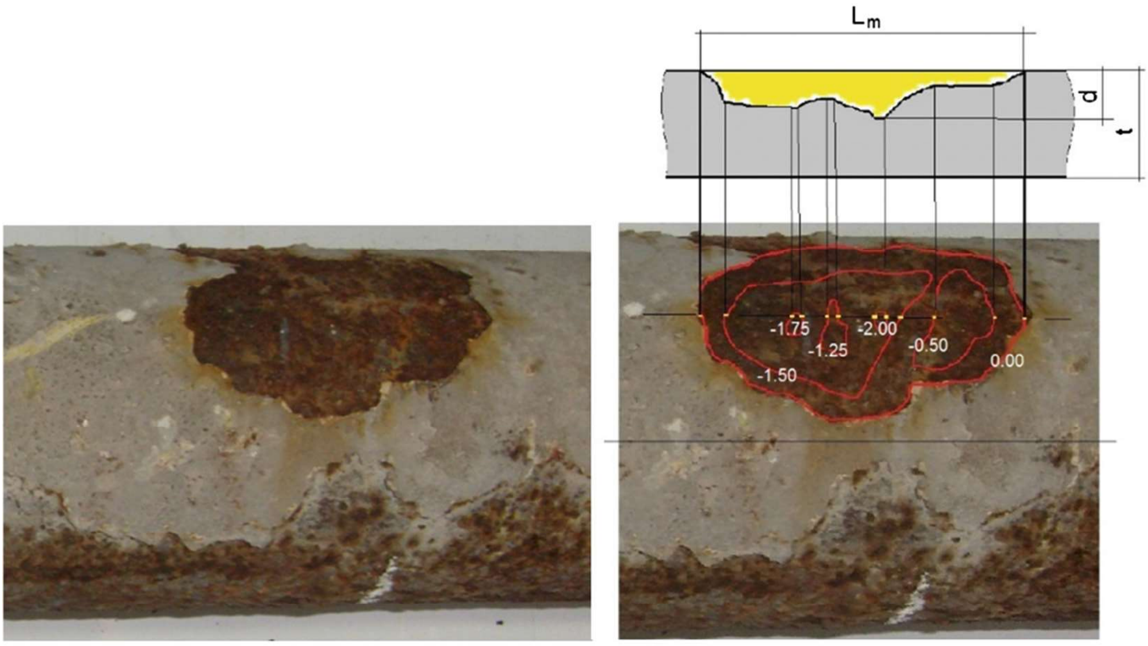
The pipeline is made of steel with the following mechanical properties, determined by experimental tests:

- Modulus of elasticity, $E = 211500$ *MPa*;
- Poisson's ratio, $\nu = 0.3$;
- Yield stress, $S_{eH} = 813.4$ *MPa*;
- Tensile strength, $S_M = 854.8$ *MPa*;
- The pipe is subjected to pressure during operation, $P = 60$ *MPa*.

Figure 3 shows the recommendations of the ASME B31G-Manual for Determining the Remaining Strength of Corroded Pipelines standard for evaluating corrosion damage.

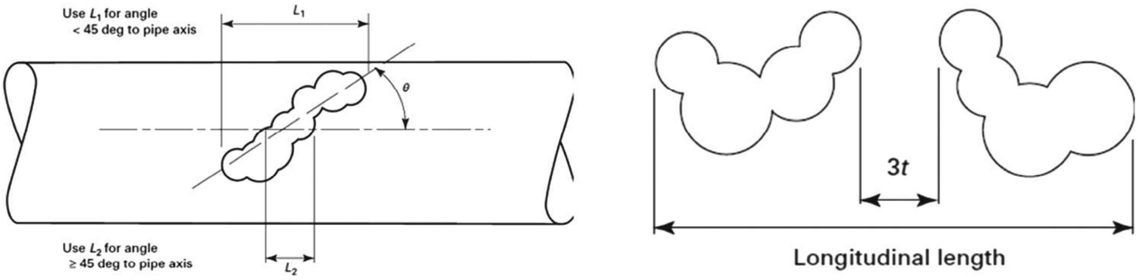
2.2 Determination of the Maximum Acceptable Length of Corrosion Damage Using the RSTRENG Method

The depth of corrosion damage can be expressed as a percentage of the nominal value of the pipeline wall thickness. If the depth of corrosion of the part is more than 10% or less



(a) *(b)*

Fig. 2. Corrosion-damaged pipeline (a), and measured values of the asymmetric corrosion damage to the pipeline (b)



(a) *(b)*

Fig. 3. Recommendations of standards for evaluation of corrosion damage, orientation of corrosion damage (a), and influence of mutual distance of corrosion damage (b) [3]

than 80% of the nominal value of the pipeline wall thickness, the length of corrosion damage shall not exceed the value determined by Eq. (1).

$$L = 1.12 \cdot B \cdot \sqrt{D \cdot t} \tag{1}$$

whereby:

- L - maximum allowable length of corrosion damage;
- B - value determined according to Eq. (2).

The maximum depth of corrosion damage is: d = 2 mm, 40% = 100·2/5.

$$B = \sqrt{\left(\frac{d/t}{1.1 \cdot \frac{d}{t} - 0.15}\right)^2 - 1} = \sqrt{\left(\frac{2/5}{1.1 \cdot \frac{2}{5} - 0.15}\right)^2 - 1} = 0,949998 \tag{2}$$

The maximum length of corrosion damage is:

$$L = 1.12 \cdot B \cdot \sqrt{D \cdot t} = 1.12 \cdot 0.949998 \cdot \sqrt{125 \cdot 5} = 26.6\boldsymbol{mm}$$

Figure 4 shows the relationship between corrosion damage and the criteria for accepting corrosion damage to pipelines. The criterion is that they must withstand a pressure equal to the lower yield strength SeL. The figure represents a parabolic section of the corroded part, where the y-axis shows the value of the maximum depth of the corrosion damage divided by the thickness of the pipeline wall, while the x-axis shows the length of the corrosion damage divided by the square root of the product of the pipe radius and the pipeline wall thickness.

$$\mathrm{d/t} = 0.400; \frac{L}{\sqrt{R \cdot t}} = \frac{26.6}{\sqrt{\frac{125}{2} \cdot 5}} = 1.505 \tag{3}$$

The coordinates of the point from Eq. (3) are exactly on the line of the diagram, Fig. 4. Considering that the actual measured length of the corrosion damage is L = 70 mm, the operating pressure should be reduced or the pipe with the corrosion damage should be replaced or repaired.

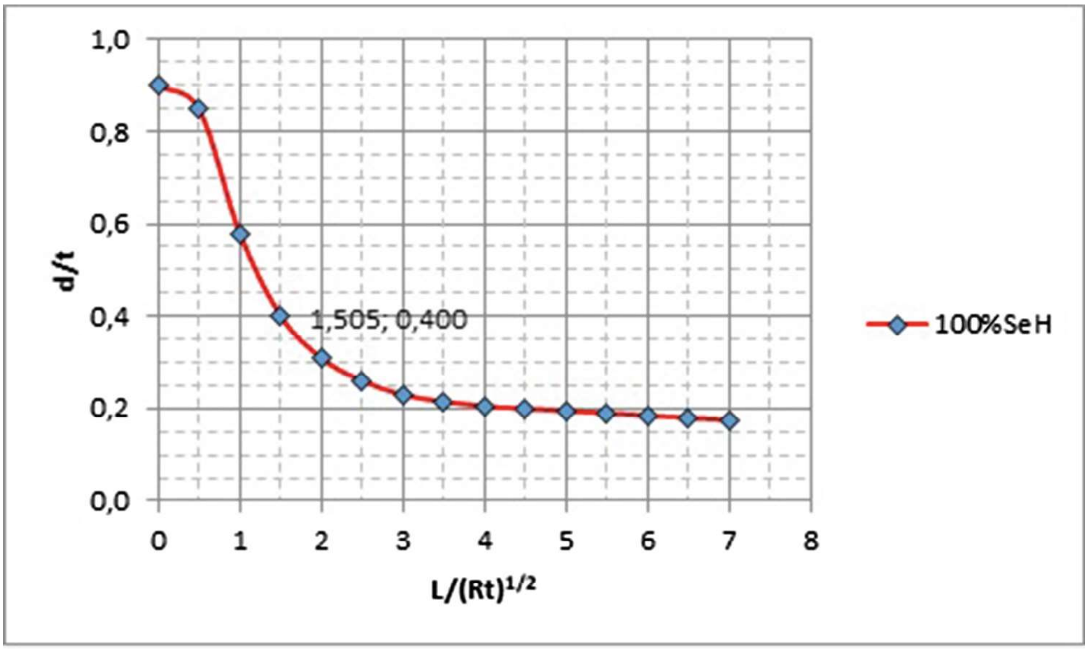


Fig. 4. Corrosion damage assessment diagram

If the maximum measured depth of corrosion damage is more than 10% of the nominal value of the pipe wall thickness and less than 80% of the nominal value of the pipeline wall thickness, and the measured length of corrosion damage is greater than the value determined according to Eq. 1, a calculation is required:

$$P\prime = 1.1 \cdot P\left[\frac{1 - \frac{2}{3} \cdot \left(\frac{d}{t}\right)}{1 - \frac{2}{3}\left(\frac{d}{t \cdot \sqrt{A^2+1}}\right)}\right] \tag{4}$$

whereby:

- P' - maximum allowable pressure for L_m and cannot be greater than P;
- P - determined pressure value in the pipe or:

$$P = 2 \cdot SeH \cdot t \cdot F \cdot \frac{T}{D} = 2 \cdot 813.4 \cdot 5 \cdot 1 \cdot \frac{1}{125} = 65.1\boldsymbol{MPa} \tag{5}$$

whereby:

- F - corresponding factor from ASME B31.4 [26], ASME B31.8 [27];
- T - corresponding temperature value based on B31 regulation (if not specified, T = 1).

$$A = 0.893\left(\frac{L_m}{\sqrt{Dt}}\right) = 0.893\left(\frac{70}{\sqrt{125 \cdot 5}}\right) = 2.50 \tag{6}$$

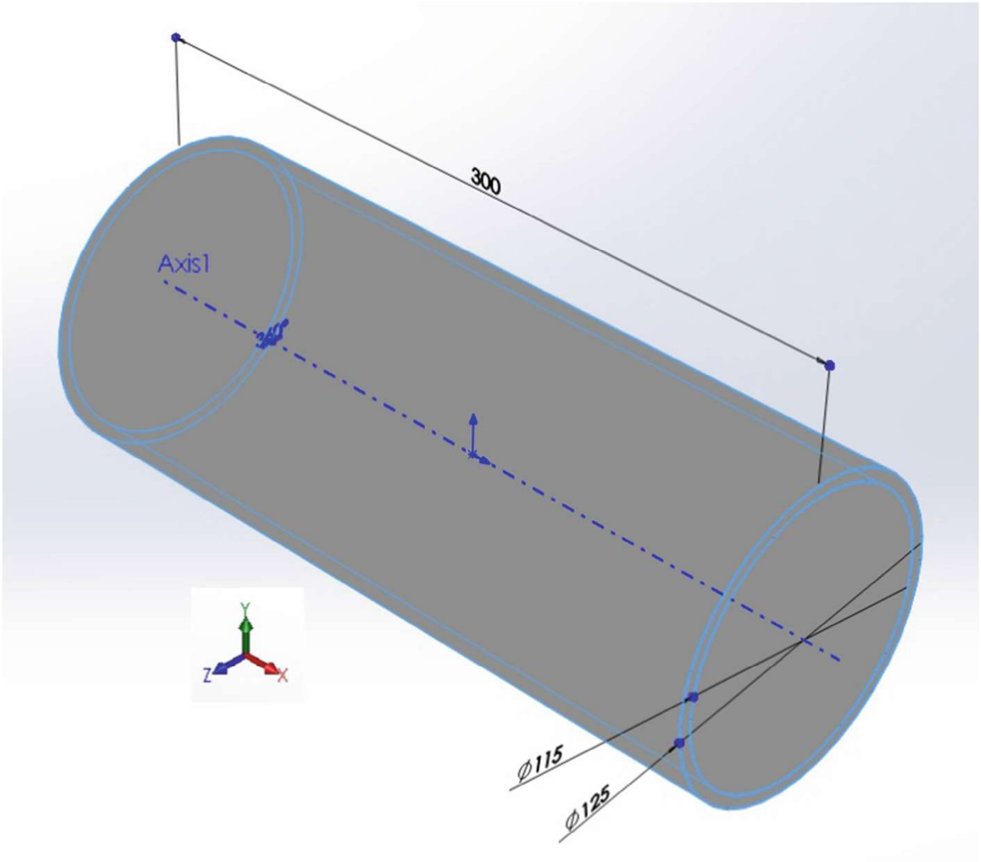
For a damage depth of 40% of the nominal thickness of the pipeline wall, the maximum allowable corrosion damage length of L = 26.6 mm was calculated. This corrosion damage length is smaller than the actual measured corrosion damage length of L = 70 mm, so it is necessary to calculate the maximum allowable pressure (P') of the corroded pipeline for this damage case, and it is:

$$P\prime = 1.1 \cdot P\left[\frac{1 - \frac{2}{3}\cdot\left(\frac{d}{t}\right)}{1 - \frac{2}{3}\left(\frac{d}{t\cdot\sqrt{A^2+1}}\right)}\right] = 1.1 \cdot 65.1\left[\frac{1 - \frac{2}{3}\left(\frac{2}{5}\right)}{1 - \frac{2}{3}\left(\frac{2}{2\sqrt{2.50^2+1}}\right)}\right] = 3.9\boldsymbol{MPa} \tag{7}$$

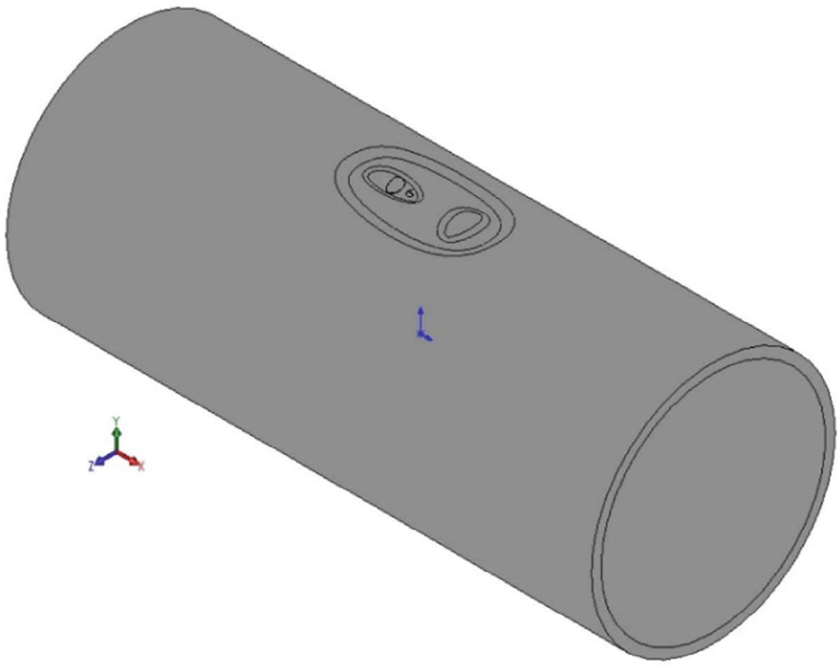
3 Evaluation of the Residual Strength of FEM Steel Pipelines

In order to evaluate the residual strength of steel pipelines FEM [2, 7], the processed test results can be implemented as a model in one of the commercial programs for FEM calculation, taking into account the PCORRC rules. Due to the asymmetry of the corrosion damage, a part of the corrosion damaged pipeline is modeled with an approximate shape to the actual shape. The model is created by connecting isoperimetric elements, where the number of elements depends on the size of the corrosion damage. It is necessary to represent the bottom of the damaged area with a sufficient number of elements determined by the analysis of the previous section. The inside of the model is exposed to the operating pressure, i.e. the test pressure. Symmetry planes are locations where boundary conditions are specified, i.e. motions in certain planes are constrained.

All numerical simulations in this work were performed using the Solid Works software package, which is based on FEM. The accuracy of the results depends on the precise modeling of the shape of the pipeline and the corrosion damage, as well as on the choice of the type and density of the final elements, so our task was to model the corrosion damage in Fig. 2 as realistically as possible. First, we created a model of a pipeline without corrosion damage, Fig. 5(a), and then a model of a pipeline with corrosion damage, Fig. 5(b).



(a)



(b)

Fig. 5. Appearance of the pipeline model without corrosion damage (a), and the pipeline model with corrosion damage (b)

The material properties were determined based on experiments, after which the data regarding the material and the boundary conditions were used in the calculation, Fig. 6. Then, a finite element mesh was generated for both the model without corrosion damage, Fig. 7(a), and the model with corrosion damage, Fig. 7(b).

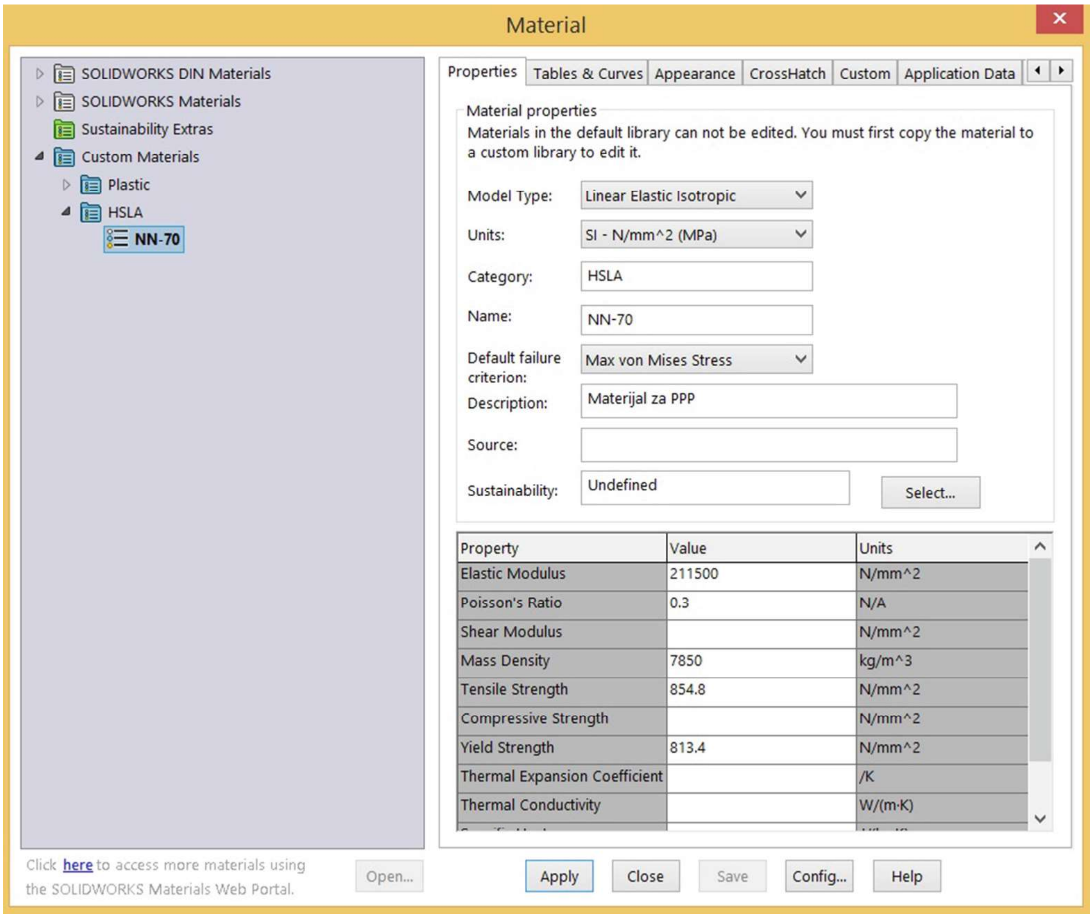
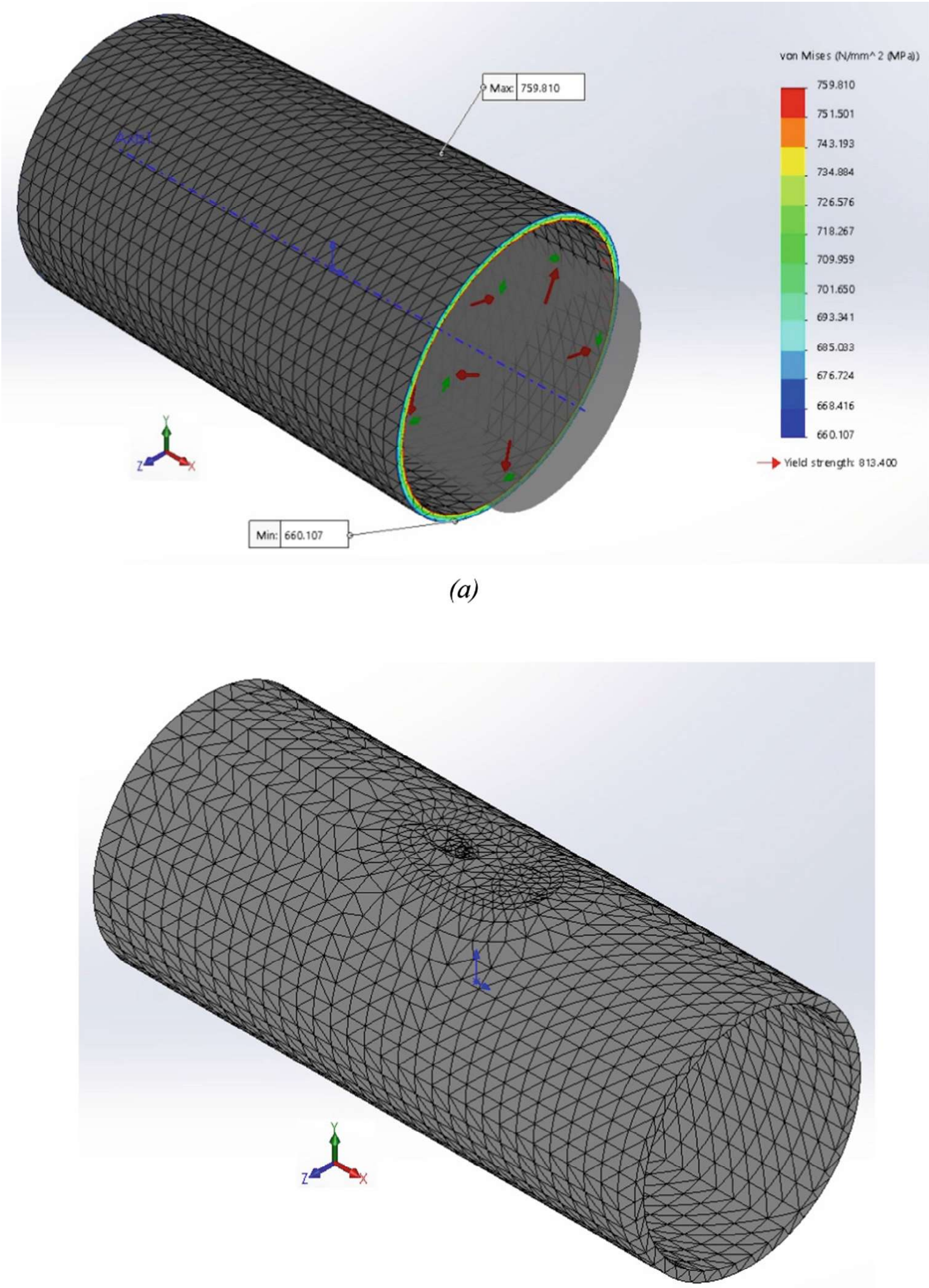


Fig. 6. Pipeline material properties and boundary conditions

In the finite element mesh of pipeline with corrosion damage, Fig. 7(b), the size of the elements varied depending on their location. Smaller elements were used at locations where corrosion damage occurred, while larger elements were used at locations far from the critical locations to keep the number of nodes as small as possible so that the calculation would be simplified to some extent.

Figures 8, 9, 10 and 11 show the calculation results of pipeline with asymmetric corrosion damage. The calculation was performed for the operating pressure of the undamaged pipe 60 MPa, the pressure calculated according to ASME B31.G of 3 MPa and the pressure 22 MPa, which ensures the operation of the pipeline with $\nu = 1$, which means that the pressure in the pipe must not exceed this value.



(a)

(b)

Fig. 7. Representation of the finite element mesh on the pipeline without corrosion damage (a), and on the pipeline with corrosion damage (b)

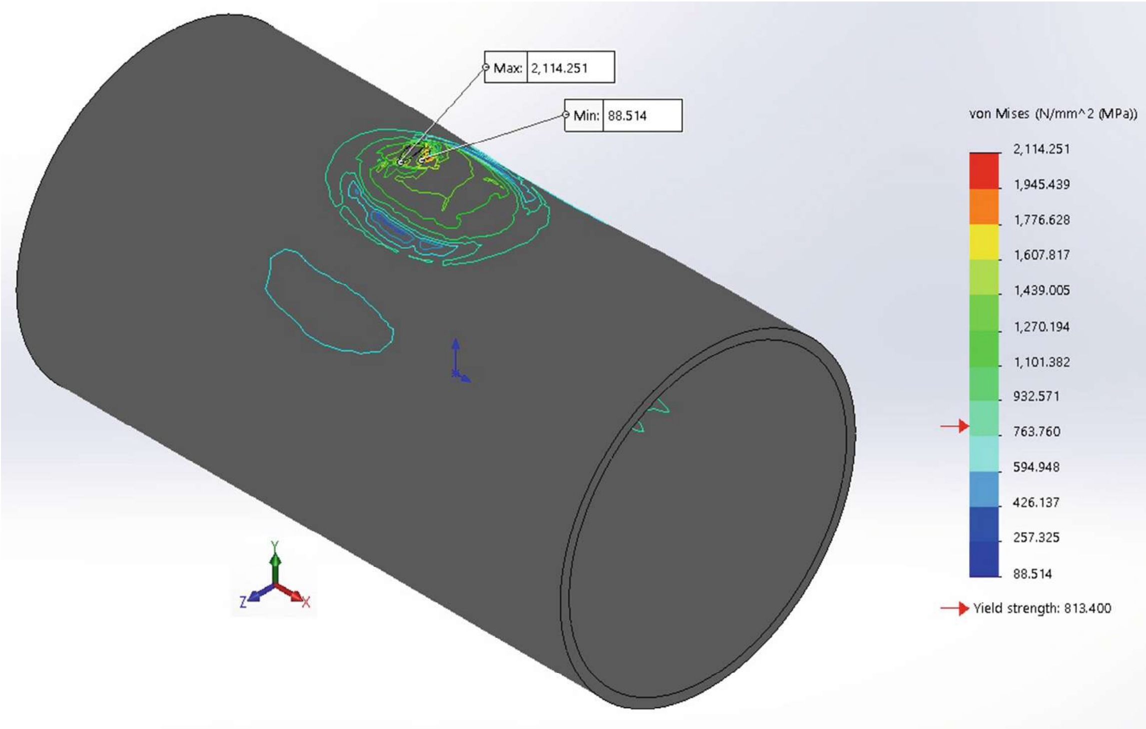


Fig. 8. Distribution and stress values on pipeline with corrosion damage for a pressure 60 MPa

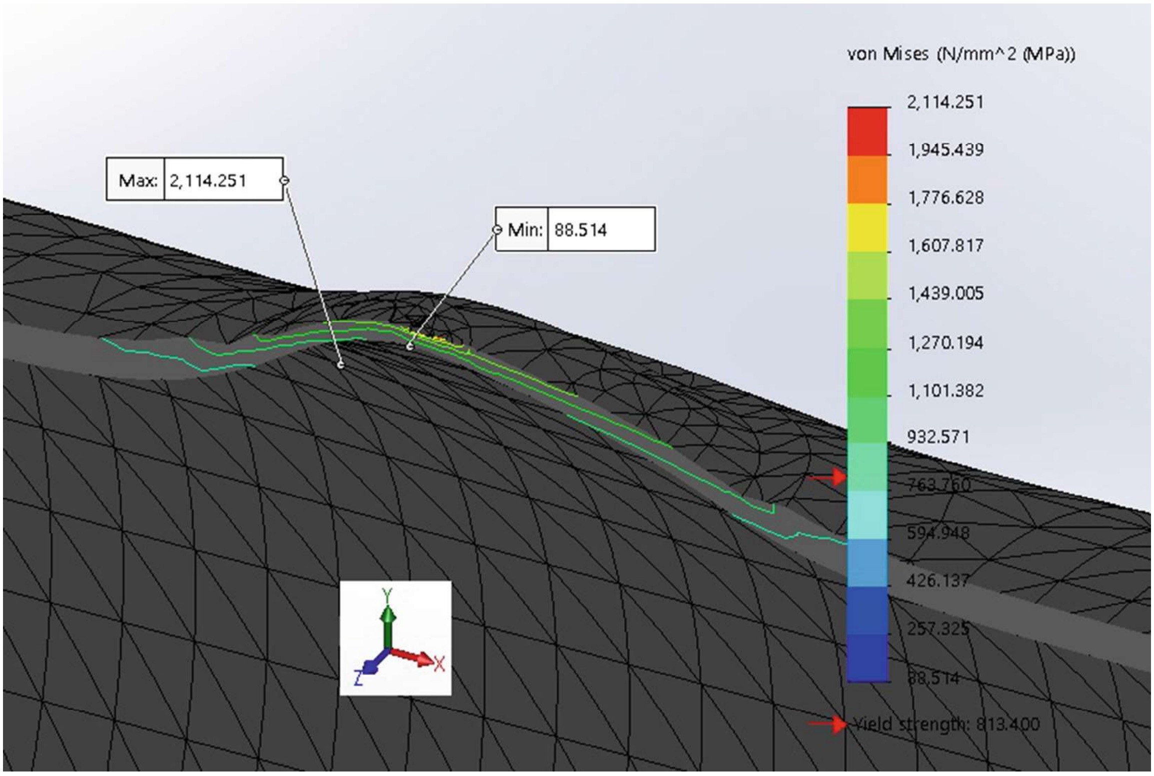


Fig. 9. Section through a model of corrosion damage to a pipeline that has been subjected to a pressure 60MPa

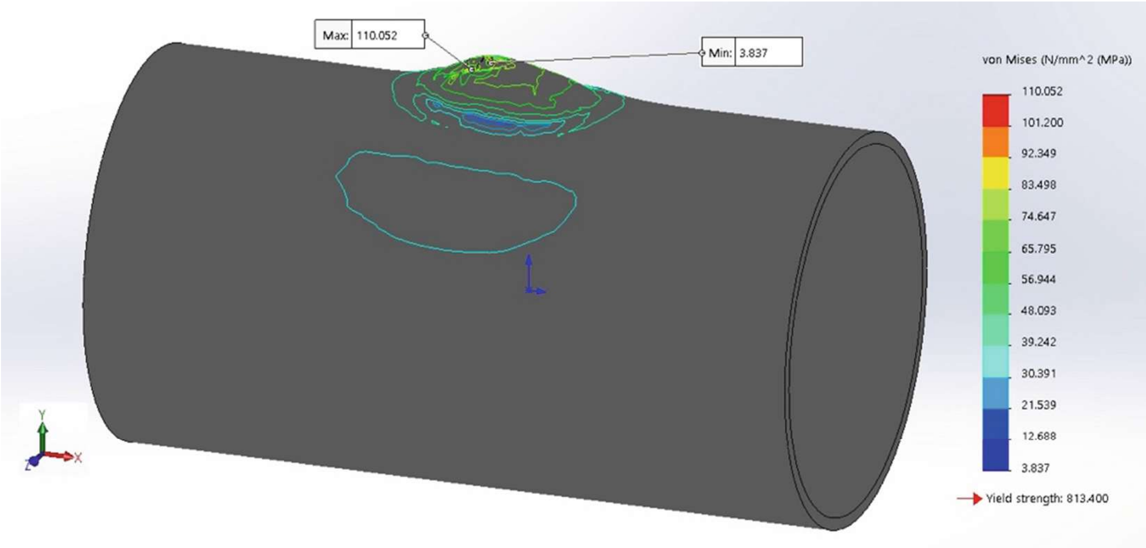


Fig. 10. Distribution and stress values on pipeline with corrosion damage for a pressure 3MPa

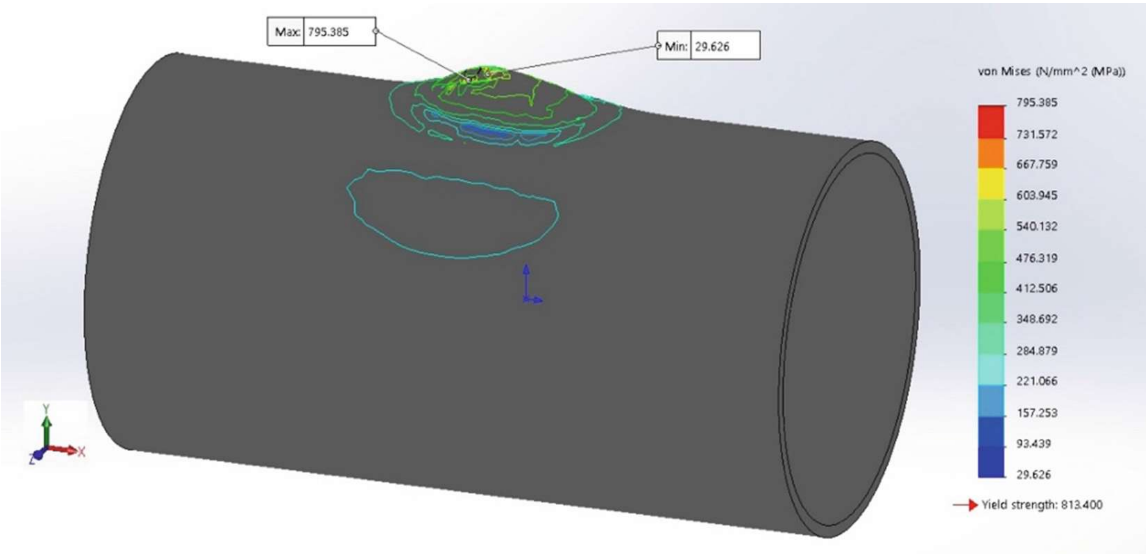


Fig. 11. Distribution and stress values on pipeline with corrosion damage for a pressure 22MPa

4 Results and Discussion

The standard calculation for determining the maximum acceptable length of corrosion damage using the RSTRENG method resulted in an operating pressure of an undamaged pipeline of 65.1 MPa, while the pressure of a damaged corroded pipeline calculated according to ASME B31.G is 3.9 MPa.

A finite element method calculation was performed in Solid Works, and Table 1 shows the maximum and minimum stress values on pipeline with corrosion damage for different operating pressures - for the operating pressure of an undamaged pipeline of 60 MPa and for the pressure of 3 MPa calculated according to ASME B31.G.

As evident in Table 1, the maximum stress value for the working pressure of the undamaged pipeline 60 MPa is 2144.5 MPa, which is much higher than the yield stress

Table 1. Stress values on pipeline with corrosion damage

Stress, MPa	FEM (von Mises stress)	
	σ_{min}, MPa	σ_{max}, MPa
60	2144.5	187.9
3	110.0	3.8
22	795.3	29.6

813.4 MPa, while for the calculated ASME B31.G pressure 3 MPa, the maximum stress value is 110.0 MPa, which again is much lower than what the corroded pipeline can withstand. This is due to the fact that the standard calculation is quite conservative. For this reason, through calculations with FEM, we have shown that this type of corrosion damage can withstand a pressure of 22 MPa when the pipeline would work with $\nu = 1$, and the maximum stress in this case is 795.3 MPa.

5 Conclusion

Corrosion damages the steel pipelines. It is therefore important to carry out regular and extraordinary inspections and adequately maintain the steel pipelines to avoid destruction with catastrophic consequences. The inspection by nondestructive testing of the corroded zones of the supporting elements of the steel pipelines constructions must be followed by inspection calculations using standard methods and FEM to assess the remaining strength of the steel pipeline.

In this paper, advanced modeling techniques for corroded surfaces based on FEM were presented with the aim of developing a procedure to evaluate the residual strength of steel pipelines operating in the environmental conditions of the chemical industry.

By analyzing the stress distribution on the corrosion-damaged pipeline for the operating pressure of the undamaged pipeline 60 *MPa*, the pressure 3 *MPa* calculated according to ASME B31G and the pressure 22 *MPa*, which ensures the operation of the pipeline with $\nu = 1$. After the FEM calculation, a completely different picture of the stress distribution can be seen, which is to be expected, and it tells us that for a complete understanding of the behavior of a corroded pipeline for the purpose of control calculation, the FEM calculation is mandatory on a model where all significant corrosion damage is modeled as realistically as possible.

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