World Academy of Science, Engineering and Technology
International Journal of Geotechnical and Geological Engineering
Vol:18, No:11, 2024

Prediction Study of a Corroded Pressure Vessel Using Evaluation Measurements and Finite Element Analysis

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Open Science Index, Geotechnical and Geological Engineering Vol:18, No:11, 2024 publications.waset.org/10013907.pdf

Abstract**—**The steel structures of the Oyu-Tolgoi mining Concentrator plant are corroded during operation, which raises doubts about the continued use of some important structures of the plant, which is one of the problems facing the plant's regular operation. As a part of the main operation of the plant, the bottom part of the pressure vessel, which plays an important role in the reliable operation of the concentrate filter-drying unit, was heavily corroded, so it was necessary to study by engineering calculations, modeling, and simulation using modern advanced engineering programs and methods. The purpose of this research is to investigate whether the corroded part of the pressure vessel can be used normally in the future using advanced engineering software and to predetermine the remaining life of the time of the pressure vessel based on engineering calculations. When the thickness of the bottom part of the pressure vessel was thinned by 0.5 mm due to corrosion detected by non-destructive testing, finite element analysis using ANSYS WorkBench software was used to determine the mechanical stress, strain and safety factor in the wall and bottom of the pressure vessel operating under 2.2 MPa working pressure, made conclusions on whether it can be used in the future. According to the recommendations, by using sand-blast cleaning and anti-corrosion paint, the normal, continuous and reliable operation of the Concentrator plant can be ensured, such as ordering new pressure vessels and reducing the installation period. By completing this research work, it will be used as a benchmark for assessing the corrosion condition of steel parts of pressure vessels and other metallic and non-metallic structures operating under severe conditions of corrosion, static and dynamic loads, and other deformed steels to make analysis of the structures and make it possible to evaluate and control the integrity and reliable operation of the structures.

Keywords**—**Corrosion, non-destructive testing, finite element analysis, safety factor, structural reliability.

I. INTRODUCTION

SINCE its commissioning in 2011, the main building operation of the Concentrator plant have played an important role in the stable and reliable operation of the production. As shown in Fig. 1, the main structures of the Concentrator building can be broadly classified as: (a) Steel structure, (b) Concrete structure and (c) Other structure (Sandwich).

There are many steel structures and equipment that play an important role in the concentrator production process. Regular inspections and availability of spare parts are paid attention to fixed equipment and mobile equipment, but the main buildings and structures of the factory have not paid much attention to their integrity and reliable operation, which has led to serious corrosion, creep and crack growth of some steel structures, cracks and mechanical damage occur quite often in reality.

One of the main factors affecting corrosion is the regular water cleaning in the industrial environment, which is the main reason for the formation of corrosion in steel structures, which will adversely affect the aging process. Water cleaning is essential in the process of the Concentrator, so it is necessary to check the rate of corrosion of corroded metal structures and parts, to assess the age of steel structures due to corrosion in terms of strength and reliability, and further, the corroded metal structures and parts are needed to determine whether or not it can be performed, and response measures against damage, breakage, and collapse that may occur due to rusted parts based on measurements and calculations.

The concrete and other structures of the factory have been exposed to external overloads, and corrosion, damage, cracks, and leaks have appeared in some building structures, which negatively affects not only the productivity of the plant, but also our safety, normal and reliable operation of our equipment, creating conditions for major incidents. This study will show the solution and recommendation for above problems in detail.

Therefore, the important constructions of the factory include the main concrete and steel components such as columns, beams, foundation and supporting structures of the building, the foundation of the lifting equipment, high-pressure vessel and liquid storage tanks in devices, pipelines connecting them, working platforms including fasteners and connections.

II. MATERIALS AND METHODS

Selected as a research object the pressure vessel number 3820-REC-009 is used in the filtration system of the filter-drying section and also serves as a power source for air-powered equipment (Fig. 2).

According to the requirements of laws and standards, external and internal inspection of the pressure vessel will be performed according to the “Pressure Vessel Inspection Code: In-Service Inspection, Rating, Repair, and Alteration” depending on the allowed working pressure of the pressure vessel [1], [2].

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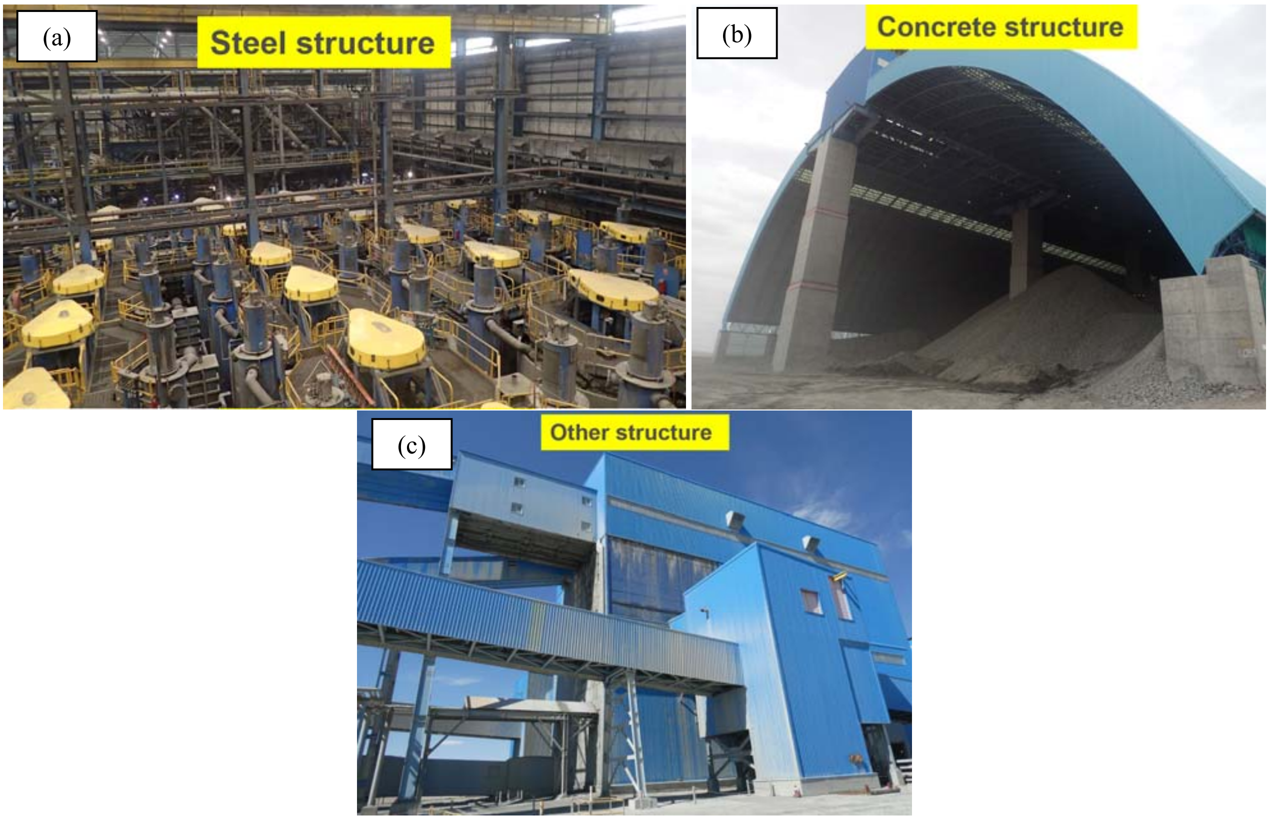


Fig. 1 Examples of Concentrator building structures

Fig. 2 Research object - 3820-REC-009 pressure vessel

The owner organization is required to carry out its own internal inspection once a year, and the regular full inspection shall be carried out by the competent authority once every four years. In the case of emergency situations, we will organize non-routine inspections and unscheduled inspections. In the event of serious damage to a pressure vessel registered in the state registry, or when carrying out major maintenance, improvement or modernization work, it is to be notified to the professional inspector.

In addition to assessing the condition of the pressure vessel, it is necessary to check regularly and confirm the normal operation of connection fittings, monitoring and protective devices.

Non-destructive testing shall be carried out in accordance with international and national standard requirements for that method.

Wall thickness measurements have been performed on pressure vessel steel structures by scheduled non-destructive testing using an ultrasonic instrument, Fig. 3, as per visual inspection report. By creating a unified database of measurements, it will be possible to prevent future risks, as well as monitor how the pressure vessel changes during operation.

A thickness measurement conducted and revealed that the thickness of the bottom part of the pressure vessel was originally 14 mm, as stated in the manufacturer's documentation, but it has been thinned by 0.5 mm. The wall thickness measuring instrument should be calibrated and verified, and the better results will be obtained by measuring as many points as possible on the measuring surface.

Some important parameters of the measured instrument are included in the report, which has the advantage of being able to view the instrument settings from the report for the next measurement, and this information can be used as a guideline and instruction for a new employee to measure. Time based measurement data are important for determining corrosion rates in the long-term duration [3], [4].

A. Determination the Corrosion Rate

Long-term and short-term corrosion rates can be determined using (1) and (2). In this case, the change in wall thickness and the time used are important (Fig. 4). As an example, the measurement report is shown in Fig. 5.

Fig. 3 Measurements with the DMS Go instrument used in non-destructive testing

Fig. 4 Pictures of the view during the measurement

The long-term (LT) corrosion rate shall be calculated from the following formula:

$$\text{Corrosion rate (LT)} = \frac{\text{t}\,initial - \text{t}\,actual}{\text{Time between } t\ initial\ and\ t\ actual(years)} \quad (1)$$

The short-term (ST) corrosion rate shall be calculated from the following formula:

$$\text{Corrosion rate (ST)} = \frac{\text{t}\,previous - \text{t}\,actual}{\text{Time between } t\ initial\ and\ t\ actual(year)} \quad (2)$$

where: t initial = the initial thickness, first thickness (mm); t actual = measured during the most recent inspection (mm); t previous = measured during a previous inspection (mm).

In 2011-2017 Corrosion rate (LT) $= \frac{\text{14mm} - \text{13.5mm}}{7\ (years)} = 0.07\ \frac{\text{mm}}{\text{year}}$

In 2021, 2022 Corrosion rate (ST) $= \frac{\text{14.9mm} - \text{14.9mm}}{2\ (year)} = 0\ \frac{\text{mm}}{\text{year}}$.

B. Engineering Calculation, CAD/CAE Modelling, FE Simulation Analysis

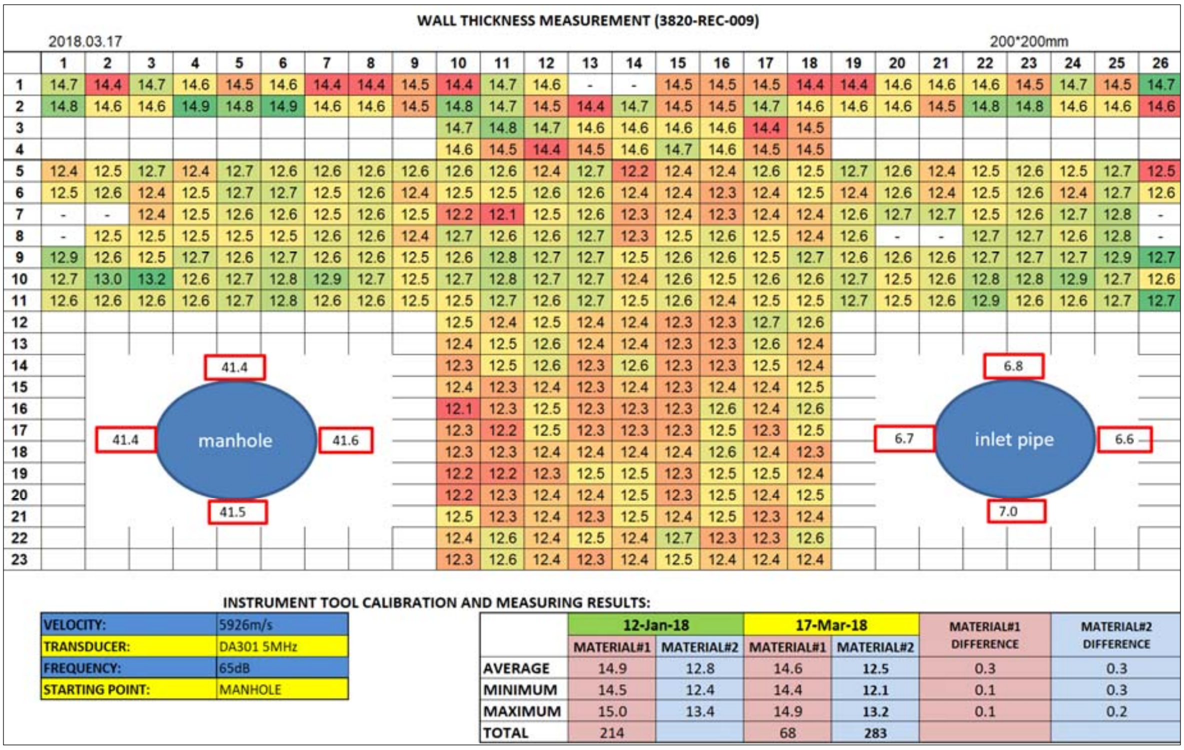
For CAD/CAE modelling and simulation of this pressure vessel, SOLIDWORKS software was used to build the CAD model, and how the thinning of the wall thickness of the pressure vessel caused by corrosion affects the reliable and safe operation of the structure, and the stress, strain and safety factor used to make conclusions about whether it can be used in the future. The parameters were converted to the ANSYS Workbench program and the 3D CAD model was created [5]. In the simulation, where the initial thickness of the bottom of the pressure vessel was 14 mm, the strength conditions and safety factor were checked for the calculation pressure vessel structure in the following 3 scenarios, Fig. 6:

(a) As original design or 14 mm thickness condition

(b) Maximum thinning (Corrosion) at that time is 0.5 mm
(c) In case of thinning of 1 mm

The pressure vessel is made of the special Q345R steel with material mechanical properties as:

- Allowable stress – 345 MPa
- Breaking stress – 510 MPa
- Poisson's ratio - 0.3



WALL THICKNESS MEASUREMENT (3820-REC-009)

2018.03.17 — 200*200mm

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	14.7	14.4	14.7	14.6	14.5	14.6	14.4	14.4	14.5	14.4	14.7	14.6	-	-	14.5	14.5	14.5	14.4	14.4	14.6	14.6	14.6	14.5	14.7	14.5	14.7
2	14.8	14.6	14.6	14.9	14.8	14.9	14.6	14.6	14.5	14.8	14.7	14.5	14.4	14.7	14.5	14.5	14.7	14.6	14.6	14.6	14.5	14.8	14.8	14.6	14.6	14.6
3										14.7	14.8	14.7	14.6	14.6	14.6	14.6	14.4	14.5								
4										14.6	14.5	14.4	14.5	14.6	14.7	14.6	14.5	14.5								
5	12.4	12.5	12.7	12.4	12.7	12.6	12.6	12.6	12.6	12.6	12.6	12.4	12.7	12.2	12.4	12.4	12.6	12.5	12.7	12.6	12.4	12.5	12.6	12.5	12.7	12.5
6	12.5	12.6	12.4	12.5	12.7	12.7	12.5	12.6	12.4	12.5	12.5	12.6	12.6	12.4	12.4	12.3	12.4	12.5	12.4	12.6	12.4	12.5	12.6	12.4	12.7	12.6
7	-	-	12.4	12.5	12.6	12.6	12.5	12.6	12.5	12.2	12.1	12.5	12.6	12.3	12.4	12.3	12.4	12.4	12.6	12.7	12.7	12.5	12.6	12.7	12.8	-
8	-	12.5	12.5	12.5	12.5	12.5	12.6	12.6	12.4	12.7	12.6	12.6	12.7	12.3	12.5	12.6	12.5	12.4	12.6	-	-	12.7	12.7	12.6	12.8	-
9	12.9	12.6	12.5	12.7	12.6	12.7	12.6	12.6	12.5	12.6	12.8	12.7	12.7	12.5	12.6	12.6	12.5	12.7	12.6	12.6	12.6	12.7	12.7	12.7	12.9	12.7
10	12.7	13.0	13.2	12.6	12.7	12.8	12.9	12.7	12.5	12.7	12.8	12.7	12.7	12.4	12.6	12.5	12.6	12.6	12.7	12.5	12.6	12.8	12.8	12.9	12.7	12.6
11	12.6	12.6	12.6	12.6	12.7	12.8	12.6	12.6	12.5	12.5	12.7	12.6	12.7	12.5	12.6	12.4	12.5	12.5	12.7	12.5	12.6	12.9	12.6	12.6	12.7	12.7
12										12.5	12.4	12.5	12.4	12.4	12.3	12.3	12.7	12.6								
13										12.4	12.5	12.6	12.4	12.4	12.3	12.3	12.6	12.4								
14										12.3	12.5	12.6	12.3	12.6	12.3	12.3	12.5	12.4								
15										12.4	12.3	12.4	12.3	12.4	12.3	12.4	12.4	12.5								
16										12.1	12.3	12.5	12.3	12.3	12.3	12.6	12.4	12.6								
17										12.3	12.2	12.5	12.3	12.3	12.3	12.5	12.3	12.5								
18										12.3	12.3	12.4	12.4	12.4	12.4	12.6	12.4	12.3								
19										12.2	12.2	12.3	12.5	12.5	12.3	12.5	12.5	12.4								
20										12.2	12.3	12.4	12.4	12.5	12.3	12.5	12.4	12.5								
21										12.5	12.3	12.4	12.3	12.5	12.4	12.5	12.3	12.4								
22										12.4	12.6	12.4	12.5	12.4	12.7	12.3	12.3	12.6								
23										12.3	12.6	12.4	12.3	12.4	12.5	12.4	12.4	12.4								

INSTRUMENT TOOL CALIBRATION AND MEASURING RESULTS:

VELOCITY:	5926m/s
TRANSDUCER:	DA301 5MHz
FREQUENCY:	65dB
STARTING POINT:	MANHOLE

	12-Jan-18		17-Mar-18		MATERIAL#1 DIFFERENCE	MATERIAL#2 DIFFERENCE
	MATERIAL#1	MATERIAL#2	MATERIAL#1	MATERIAL#2		
AVERAGE	14.9	12.8	14.6	12.5	0.3	0.3
MINIMUM	14.5	12.4	14.4	12.1	0.1	0.3
MAXIMUM	15.0	13.4	14.9	13.2	0.1	0.2
TOTAL	214		68	283		

Fig. 5 Wall thickness measurement report

C. Loading Conditions and Constraints

It was assumed that the working pressure received in the industrial process of the pressure vessel is 2.2 MPa and the action of gravity is uniformly acting on the 3 legs of the foundation. The CAD/CAE models and load strain conditions are shown in Fig. 7.

III. Results

A. FEA Simulation Results of Stress: Stress Behaviour of the Initial Condition, without Any Losing of Wall Thickness

In the initial normal condition Stress and Strains are distributed uniformly through the whole tank except the supports. Maximum values Von-Mises Stress, Von-Mises Strain and Safety factory are 220 MPa, 0.1% and 1.5 respectively. The most stressed locations are in the supports, especially in the junction areas of connection of supports and bottom spherical part of the vessel.

B. FEA Simulation Results of Stress: Stress Behaviour of the Vessel in Corroded Condition, with Thinning of the Wall Thickness by 0.5 mm

In corroded case, with thinning of the wall thickness by 0.5 mm, Stress and Strains are distributed uniformly through the whole tank except the supports. The most stressed locations are in the supports, especially in the junction areas of connection of supports and bottom spherical part of the vessel. Maximum values Von-Mises stress, Von-Mises Strain and Safety factor are 237 MPa, 0.12% and 1.36 respectively.

C. FEA Simulation Results of Stress: Stress Behaviour of the Vessel in Corroded Condition, with Thinning of the Wall Thickness by 1.0 mm

In corroded case, with thinning of the wall thickness by 1.0 mm, Stress and Strains are distributed uniformly through the whole tank except the supports. The most stressed locations are in the supports, especially in the junction areas of connection of supports and bottom spherical part of the tank. Maximum values Von-Mises stress, Von-Mises Strain and Safety factory are 330.8 MPa, 0.16% and 0.97 respectively.

Results of simulations with the Von-Mises criteria the stress and strain, and safety factor distributions of the spherical bottom part of the vessel are shown in Table I.

TABLE I
COMPARISON OF SIMULATION RESULTS

Parameters	Normal Condition	Corroded by 0.5 mm	Corroded by 1.0 mm
Von-mises Stress	107 MPa	182 MPa	187 MPa
Von-mises Strain	0.06%	0.09%	0.09%
Safety Factor	3.35	1.75	1.71

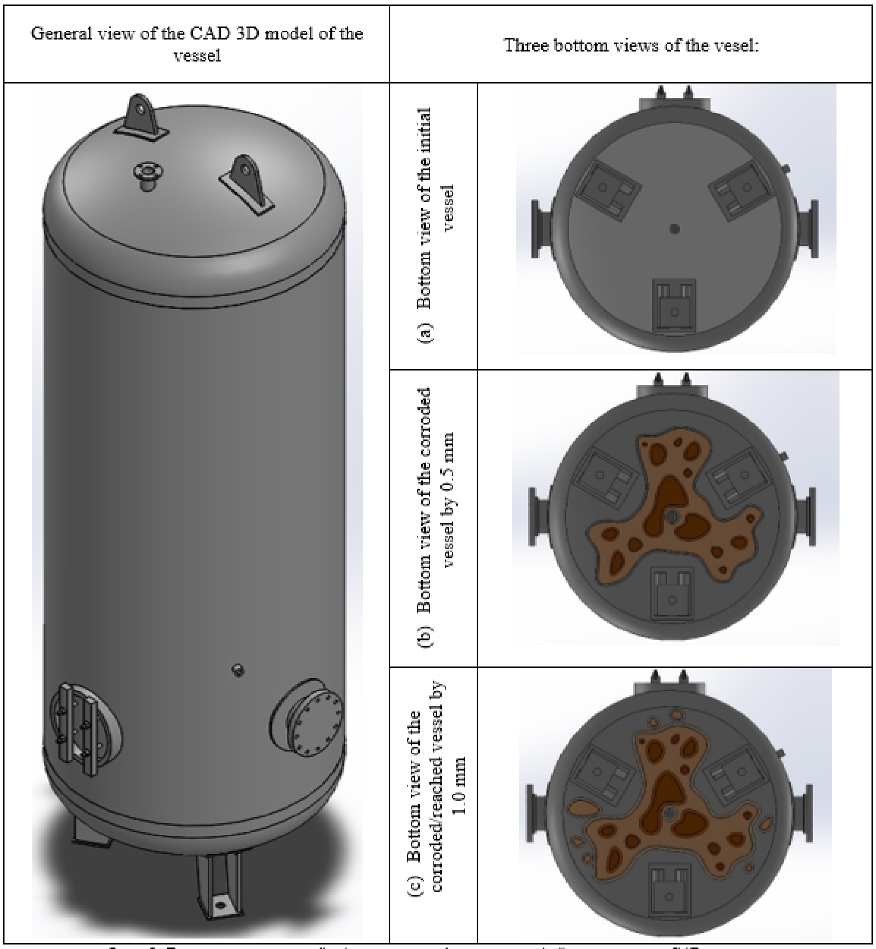


Fig. 6 CAD model of normal and corroded parts of a pressure vessel

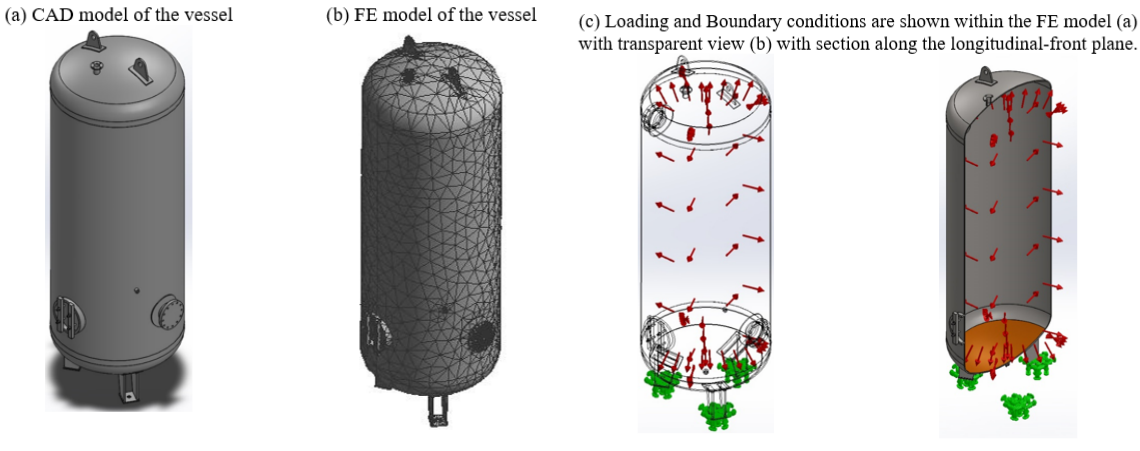


Fig. 7 CAD/CAE modelling and loads, constraints

IV. Discussions and Conclusions

Due to regular water cleaning in the area where the pressure vessel was located, the entire steel structure of that area was affected by corrosion. The protective coatings and paint of some steel structures have been deteriorated by rust and are no longer able to perform their primary functions and insufficient air circulation in that area, the humidity level was high compared to other areas. The safety relief valve located at the top of the pressure vessel was heavily corroded. It can be seen by visual inspection that the inlet and outlet air pipelines of the pressure vessel were heavily corroded.

Conclusions below are based on the evaluation on Stress-Strain Behavior and Safety Factor in the pressure vessel under working pressure of 2.2 MPa, by ANSYS WorkBench Software:

1. In corroded two cases, at the spherical bottom part, excluding junction areas of connection of supports and bottom spherical part of the tank there is no sufficient differences between the results of the conditions either reduced the wall thickness by 0.5 mm or by 1.0 mm. The safe working process still could be kept with the corrosion deepness reaching up to 1.0 mm, but not more than this.
2. Current condition of reduced wall thickness of the bottom part of the tank which corroded by 0.5 mm is still retains enough safety factor (SF = 1.36) during working process of the vessel.
3. The prediction results, with the scenario of the bottom part of the tank corroded to 1.0 mm, has shown low value of the safety factor (SF = 0.97) and can possibly cause the failure at the most stressed locations- in the supports, especially in the junction areas of connection of supports and bottom spherical part of the vessel.
4. According to the simulation, the corrosion rate of the vessel is acceptable, but it is necessary to improve the current corroded condition and to re-paint the bottom side of vessel by anti-corrosion paint.

ACKNOWLEDGMENT

This study was conducted within the framework of the Research Grant Program of "OYU-TOLGOI" LLC, MUST and "Rio Tinto Mongolia", contract No2022/03.

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