Iranica Journal of Energy & Environment

Journal Homepage: www.ijee.net

IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

Technical Note

Crack Branching in Catastrophic Fractures of Metal Structures and Environmental Damages

A. A. Alexeev*, A. S. Syromyatnikova, K. N. Bolshev, A. M. Bolshakov, A. R. Ivanov

677891, Russian Federation, Yakutsk, 1, Oktyabrskaya str.
Larionov Institute of the Physical-Technical Problems of the North of the Siberian Branch of Russian Academy of Sciences

PAPER INFO

Paper history:
Received 28 December 2014
Accepted in revised form 15 Feburary 2015

Keywords:
Pipelines
High pressure tank
Fracture
Crack branching

ABSTRACT

In this article, fracturing in large-scale metal structures such as main gas pipelines, fuel and oil tanks operated in Arctic were investigated. It is shown that catastrophic accidents involved in large thin-walled metal structures in large diameter pipelines, tanks and pressure vessels. The fractures occurred not only due to stretch propagation of brittle or viscous fractures, but also followed branching that leads to fragmented fractures with simultaneous movement of many cracks. The character of the fracture depends on the level of the fracture strength. At high levels cracks propagated at a high speed by a mechanism of separation; as a result of crack branching fragment damage occurred. At low level, cracks propagate at a low speed by a cutting mechanism; that does not cause extensive fracturing. The cracks may cause structural and environmental damages.

***doi**: 10.5829/idosi.ijee.2015.06.02.04*

INTRODUCTION

Mechanical damages in pipelines transporting natural gas, oil and fuel may cause enviromental damages. One of the well known gas is natural gas which is one of the greenhouse gases, lead to global warming and changes in climate. According to present conduct studies cracking and leakage in pipelines is one of the most important reasons of releasing such gases into the atmosphere [1].

More over, oil and fuel contamination influence soil composition and as a result agricultural productivity decrease and biological ecosystem inside the soil can not be normally maintained [2]. Such environmental contamination may also influence on plants including: decreasing in respiration and transpiration rates and also inhibition in translocation [3]. According to these harmful effect of natural gas on atmosphere; the oil and fuel impact on soil, pipeline protections seems to be essential and necessay action has to be taken.

The problem of analyzing the causes of mechanical damage and fracture of structures remains valid for thousands of years and is particularly acute in our day because of the need for safe operation of the high risk potentially dangerous objects (or increased risk of industrial accidents) [4]. It is very critical to know that what consequences can lead to the fracturing of large-scale metal structures in terms of the propagation of fast cracks and their branching. In this paper, we analysed the case of the fracturing of large-scale metal structures; the main gas pipeline and oil tanks operated in the Arctic [5].

Fracture of the metal structures

The fracture of the main gas pipeline occurred in spring of 2003, by crack propagation along the pipeline on top with numerous branches (Figure 1). The fracture was of an explosive character without fire; the crack propagated by a mechanism of separation and on the ground cracks stopped passing onto the shift mechanism with plastic components.

* Corresponding author: Anisiy Anisievich Alexeev
Email: spinor03@gmail.com, Tel:+7 (4112) 390560, 390600

Please cite this article as: A. A. Alexeev, A. S. Syromyatnikova, K. N. Bolshev, A. M. Bolshakov, A. R. Ivanov , Crack Branching in Catastrophic Fractures of Metal Structures, Iranica Journal of Energy and Environment 6 (2): 98-102.

Figure 1. Fracture of the main gas pipeline

According to the act on technical investigation (TI) of accidents and incidents (here after referred as "Act TI") carried out by the expert organization [6], which was attended by the authors of this article. The main reason for the failure was the fatigue defects located on the inner side perpendicular to the mounting ring weld in the heat-affected zone at the junction of the base metal and the weld, having a sufficient length and evidencing long-term growth of the crack (Figure 2). In fact, the pipeline was built in 1970–1980; from steel pipes with a diameter of 5.3m and wall thickness of 7–8 mm. Spectral analysis revealed that the collapsed pipe materials comply with the following grades of steel: pipe №1 – 17G1S; pipe №2 – 09G2S. The greatest fracture occurred on the base material steel 17G1S.

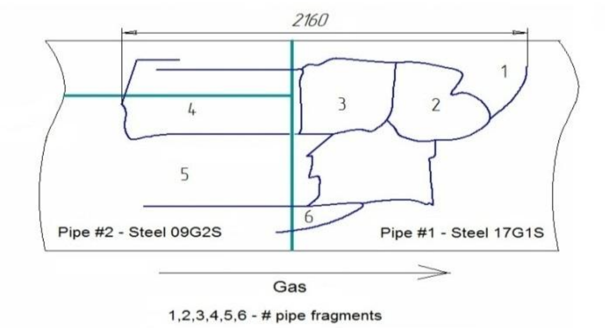

Figure 2. Schematic drawing of fracture: the main gas pipeline

Fracture of the vertical steel tank (RVS) №49 with a volume of 700 m^3 occurred in December 2007; when the outdoor temperature was −35 °C with a wind speed of 1–2 m/s in north-east direction. It was caused by the development of a crack on the base metal tank wall in the vertical direction on the heat-affected zone of weld connections (from the wall to bottom, from the wall to roof). As a result, the tank wall was torn from the bottom around the weld, cut off from the roof perimeter (30 m long), rolled and dropped 10 m in a southwest direction (Figures 3 and 4). The flooded crude oil quantity was approximately 422 tonnes. The oil spillage destroyed part of pasture green lands and caused serious environmental damages.

The vertical tank, RVS-700 №49 was built in year 1970; the tank height was 8.94m, tank diameter of 10.4m, with 6 zones and the stored product was crude oil. The tank wall was made by the wrapper method with assembled seam welded using lap manual welding. According to the results of spectral analysis, the approximate grade steel tank matches ST3PS (GOST 380-88).

According to the Act TI of expert organisation [6], the fracture was caused by a number of factors: the aging of the metal tank, which manifests itself in embrittled metal; lowering of the ambient temperature to −42°C; planar crack in the wall of the tank from the discontinuous metallurgical nature with location in the base metal, which had the character of fatigue during operation with direct access to the outer surface of the tank wall.

Damage to the vertical tank, RVS-700 №9 occurred in September 2008 in a positive-temperature environment as a result of a weld fracture in the horizontal direction. A flood of diesel fuel with the amount of 153 m^3 occurred; the tank originally held 712 m^3 of diesel fuel. The vertical tank RVS-700 №9 was built in year 1989. Labelling on the sheets and chemical analysis of the tank indicated that it was made of the steel ST3SP. The tank had dimensions of; tank height: 8.63 m, tank diameter: 10.3 mm with 6 zones and stored product was diesel fuel. The wall of the tank was made by assemblage of metal sheet; the assembly seam welded lap manual arc welding.

Figure 3. Fracture of the vertical tank RVS-700 №49 with capacity of 700 m^3.

According to the Act TI of expert organisation [6], the damage occurred due to the formation of a crack with a length of 17 cm leading to a 9 mm opening in the region with heat-affected zone of the weld of the bottom with the wall. The crack developed from the original welding defects such as welding undercut and corrosive wear, due to the combination of several factors: the presence of an invalid lap connection on the bottom sheets; deformation of the bottom; and unacceptable differential settlement of the tank.

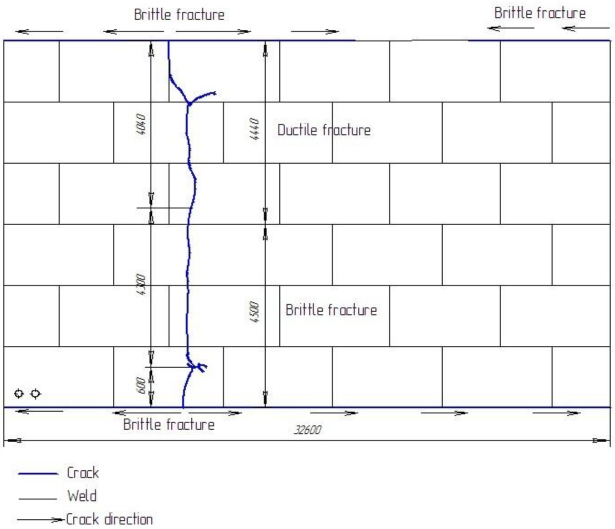

Figure 4. Schematic of the vertical tank fracture, RVS-700 №49

Also, it is worth to be mentioned as one of the factors that led to the fracture is the fact that the tanks were made of steel and ST3SP and ST3PS, with an estimated temperature toughness not corresponding to climatic conditions of the area of operation [6]. Based on the fact that the reasons for the fractures were due to nucleation stage and the start of a crack; this was investigated in detail via Acts TI. It is interesting to consider the stage of crack propagation in terms of the origin of the catastrophic fracture and initiation of critical modes of crack propagation. To estimate the critical modes of crack propagation, data on the speed of the crack, the stress-strain state of the structure or energy flow at the crack tip are needed [5]. Since the data were examined after fracture accidents [6], the data on speed, stress and energy are not available. To estimate these parameters the results of field tests of pipe-lines and vessels were required.

Crack branching in steel vessels and pipes

In field hydraulic tests of carbon steel pipes and vessels made by Duffy [7] shown that the mechanism of the fracture depends on the rate of crack propagation. A fast crack (450 m/s) fracture of objects occurs by the simultaneous propagation of several parallel cracks on the mechanism of separation. At an average speed of 275–450 m/s, a single crack branching was observed with separation as the main mechanism of fracture and the transition to the fracture of a cut in some areas. At low speeds (150–214 m/s), the propagation of a single longitudinal crack with the fracture mechanism of viscous cut occur.

In series of full-scale tests were conducted by Alexeev in Larionov Institute of the Physical-Technical Problems of the North, Yakutsk [8, 9]. He has applied internal pressure to cylindrical vessels with a diameter of 21.9 cm, length of 1.37 m, and wall thickness of 8 mm, made of air-hardened steel 45 with artificial applied surface stress raisers. The artificial defect in the form of a 2 mm deep and 2 mm wide longitudinal notch was made in the central area of the vessel surface; the notch lengths varied, with values of 50, 60, 70, and 90 mm. Internal pressure was applied to the vessel through the expansion of freezing water: a pressure vessel, filled with liquid and sealed, was cooled to sub-zero temperatures. When the internal hydrostatic pressure reached to the critical value, the vessel ruptured as the result of a crack initiated from the artificial defect.

A custom automated measuring system was developed in order to record the change in temperature, deformation, and pressure during rupture of the pressure vessel, allowing for real-time recording, processing, and analysis of experimental data obtained during testing stage. In the experimental rig, pressure sensors, thermocouples, strain gauges, and displacement sensors were used. Programs in Turbo Pascal 7, Delphi 7 were written for automatic data acquisition system for the entire course of the experiment and for its subsequent processing.

During vessel testing, crack propagation initiated from the notch in all cases (Figure 5). Depending on the notch length, the experiment lasted from 8 to 25 hours. According to strain gauge readings, elastic lateral deformation reached to 0.2% at pressures of 38, 32, 30, and 18 MPa for vessels with notches 50, 60, 70, and 90 mm long, respectively; further deformation was plastic. Longitudinal deformation remained within the elastic range until vessel fracture. According to thermocouple readings, the average temperatures were: ambient air: -20° C, vessel walls at fracture: -5° C, and inside vessel at fracture position: -3° C, which are comparable to the operating conditions for underground trunk lines in the permafrost zone.

The nominal fracture stress values σ for pressure vessels were calculated based on the empirical correlation proposed by Duffy [7] and Hahn [10] for thin-walled cylindrical steel vessels with defected surface stated as follows:

$$\sigma = \bar{\sigma}\left[\frac{\frac{t}{d}-1}{\frac{t}{d}-M_F}\right] \quad (1)$$

where M_F is the Folias correction; l is the notch length; t is the vessel wall thickness; d is the surface defect depth; and $\bar{\sigma}$ is the average plastic flow stress for the material, experimentally determined by means of yield strength $\sigma_{0.2}$ and ultimate strength σ_S.

Mechanical characteristics $\sigma_{0.2}$ and σ_S are experimentally determined in the course of standard tensile tests on flat samples using a Zwick Z600 universal testing machine at room temperature. In order to calculate $\bar{\sigma}$, the following regression equation was used [10]:

$$\bar{\sigma} = 0.5(\sigma_{0.2} + \sigma_S) \quad (2)$$

The process of vessel fracture with crack branching is accompanied by the formation of micro-branches of length λ, both before and after branching of the main crack, forming an angle α with the main crack. The values α, β, and λ take on the following values: α=8–10°, β=40–60°, and λ=2–130 mm, i.e. the maximum branching angles are significantly greater than microbranching angles.

The experimental and calculated data shows that crack propagation mode in vessels depends on the level of internal pressure P (fracture stress σ): at P<23 MPa (σ<422 MPa), crack propagation is rectilinear; at critical level of internal pressure P>31 MPa (critical level of fracture stress σ>444 MPa) crack propagation is observed along two branches, forming an angle (see Figure 6).

Figure 5. The crack branching in steel pressure vessel

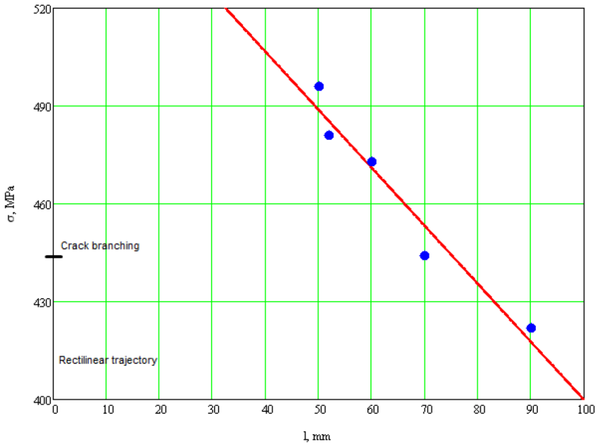

Figure 6. Dependence of a fracture stress σ on the notch length l

RESULTS AND DISCUSSION

From the testing of pipe-lines and vessels results, it was found that the fracture depends on the fracture stress. At low rates cracks propagate in a straight line in the plane perpendicular to the direction of maximum tensile stress; while at high fracture stress cracks go through the following stages: a curved path extends without forming micro-branches; micro-branches from the main crack start forming; the crack separates into two branches, wherein the fracture process is accompanied by the formation of micro-branches both before and after the branching of the main crack.

From the analysis of accidents, we found that the fracture of the main gas pipeline and the vertical tank, RVS-700 №49 occurred by brittle fracture with a straight crack propagation by the mechanism of separation. At the fracture crack branches in the pipe body of the №1 pipeline and tank led to the fragmentation of the structure. As a result of the branching structure being completely destroyed, the full streaming of the stored product occurred, resulting in material losses and environmental damage due to the release of natural gas and oil.

Damage to the vertical tank RVS-700 №9 occurred as a result of straight crack propagation with little length by the viscous mechanism, without branching. Despite a result of damage to the tank it was not destroyed, fuel leak led to a flood of 22% of the stored reservoir oil. As a result of the crack stopping, there was no large-scale structural fracture, and after repair work operation of the tank may resume, with limited environmental damage.

CONCLUSIONS

To summarise, the analysis of fractures and damage to large-scale metal structures due to their long-term use in Arctic reveals the following:

-Catastrophic fractures of large-scale structures occur in the propagation of cracks with branching, which leads to fragmented fractures with simultaneous movement of many cracks;

-The character of each fracture depends on the level of the fracture stress: at high rates cracks propagate at a high speed by a mechanism of separation and as a result of crack branching fragment damage occurring; at low rates cracks propagate at a low speed by a cutting mechanism and do not cause extensive fractures. The crack stops causing damage to the object.

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Persian Abstract

DOI: 10.5829/idosi.ijee.2015.06.02.04

چکیده

در این مقاله، شکستگی در سازه‌های فلزی با مقیاس بزرگ نظیر خطوط لوله اصلی گاز، مخازن سوخت و نفت فعال در نواحی شمالی سیبری مورد بررسی قرار گرفته است. همچنین نشان داده شده است که مصیبت‌های فاجعه‌انگیز در ساختمان‌های فلزی با ضخامت دیواره کم در قطر بزرگی از خطوط لوله، تانک‌ها و مخازن تحت فشار رخ می‌دهد. شکست‌ها نه‌تنها به دلیل کش آمدن بر اثر گسترش شکست‌های شکننده یا ویسکوز بلکه به علت متابعت از شاخه‌دار شدن اتفاق می‌افتد که به شکستگی‌های تکه‌تکه با حرکت هم‌آهنگ و هم‌زمان ترک‌ها، هدایت می‌شود. خصوصیت شکست به درجه استحکام آن بستگی دارد. در سطوح بالا، ترک‌ها در سرعت زیاد به‌وسیله یکی از مکانیسم‌های جداسازی گسترش می‌یابد؛ لذا به دلیل انشعاب یافتن ترک‌ها، پدیده آسیب قطعات خردشده اتفاق می‌افتد. در سطوح پایین نیز، شکاف‌ها در سرعت کم به‌وسیله مکانیسم برش گسترش می‌یابد که این امر باعث شکستگی وسیع نمی‌گردد. شکاف‌ها ممکن است باعث بروز صدمات ساختاری گردند.