PIPELINE STRUCTURAL INTEGRITY

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Summary

The process of fluid transportation using pipelines is nearly as old as human history, and transportation systems have always required maintenance to preserve their structural integrity. Today, managing pipeline structural integrity is done using sophisticated

pipeline risk-analyses and powerful and cost effective tools. A breach in pipeline structural integrity significantly impacts the environment and people, and often has a critical effect on business by bringing on economic losses due to disruption of delivery of the product, costs of cleanup efforts, etc.

Since common threats to pipeline structural integrity cannot be eliminated, they need to be evaluated and managed by means of a devised plan or program which is usually legislated (e.g. in USA, Canada, UK). Such a plan or program must be developed by professional engineers using recent expertise to analyse, detect, evaluate, mitigate or eliminate the risks to the pipeline operations.

It also needs to conform to the defined pipeline requirements such as standards, specifications, material orders, drawings, and documented maintenance philosophy. A good integrity management program must be supported by a competent workforce, regular inspections and appropriate training programs.

1. Pipeline Structural Integrity Definition

From an engineering standpoint, pipeline structural integrity can be defined as the preservation of both the individual parts as well as their mutual relation in an intact state. For this to occur, the stresses at all points and the deflections both local and overall must be kept within safe limits for the specific construction material.

In other words, the pipeline must be designed in such a way that it is able to safely withstand all the external and internal loads, including its own weight and all dynamic forces. In addition, the quality of all parts must be inspected at the time of installation. Then, the pipeline must be managed through proper operation, regular inspections, risk assessment and suitable improvements to maintain its safe condition.

Pipeline structural integrity, as other structural integrities, can be defined loosely within the framework of safety and financial terms. For example, Dr. Steve Roberts of Oxford University states that structural integrity is ***‘the science and technology of the margin between safety and disaster’*** [17]. Further Dr. James, in his paper [24], defines the major drivers for the structural integrity implementation which are primarily financial, involving the desire for operators and investors to maximize return on investment, the desire of insurers to have a pre-defined risk and the possibility of litigation in the event of failure.

An ‘industrial’ definition of structural pipeline integrity is to maintain the pipeline in as close to new condition as economically feasible.

Usually a breach in pipeline structural integrity leads to a failure which significantly impacts the environment and people and often has a critical effect on business. Apart from human aspects (death, injury, lawsuits) and regulatory restrictions (imposed new pipeline operation limits), a breach of structural integrity brings immediate economic losses due to disruption of delivery of the product, possible shutdown of manufacturing facilities, limitation of transportation services, cleaning up the area of spill, etc. To prevent failures and their consequences, a plan or program is usually developed which uses engineering expertise to analyse, detect, evaluate, mitigate or eliminate the risks to the pipeline operations. Such a program approach must conform to the defined pipeline requirements such as standards, specifications, material orders, drawings, and documented maintenance philosophy. These requirements along with the competent workforce ensure the effective operation of the pipeline.

2. Pipeline Structural Integrity throughout History and Today

The process of fluid transportation is nearly as old as human history. There are references to the Egyptians using copper pipe to transport water in 3000 BC. According to Advanced Water Distribution Modeling and Management, the first enclosed tubular pipes were constructed in the ancient city of Knossos on the island of Crete in 1500 BC.

From the early stages of civilization the developed societies transported first water and subsequently other liquids and gases for their utilization. Also, wastes were first primitively conveyed by means of ditches and later on, during Roman times, by complicated buried channel systems, see Figure 1.

The Romans developed water distribution systems, parts of which are used even today. There were eleven major aqueducts built in Rome between 312 B.C and 226 A.D, see Figures 2 and 3 [2], the longest of which was 59 miles long. These aqueducts, leading from the water intake in the hills to the distribution cisterns in Rome, consisted mostly of channels bored through the rock.

There was a gradient (less than 1/200) maintained throughout the length of the aqueduct, and vertical shafts were bored at intervals to provide ventilation and access. Only the final sections of the aqueducts were raised on arches, in order to give a sufficient head for water distribution. Up until the 6th century A.D., when the power of the Empire began to decline, the aqueduct system was constantly extended and repaired [1, 3]. Then, it was almost destroyed and remained inactive (except for the one aqueduct which ran entirely underground, *Aqua Virgo*, and a couple of others that were restored during the Middle Ages) until Renaissance times.

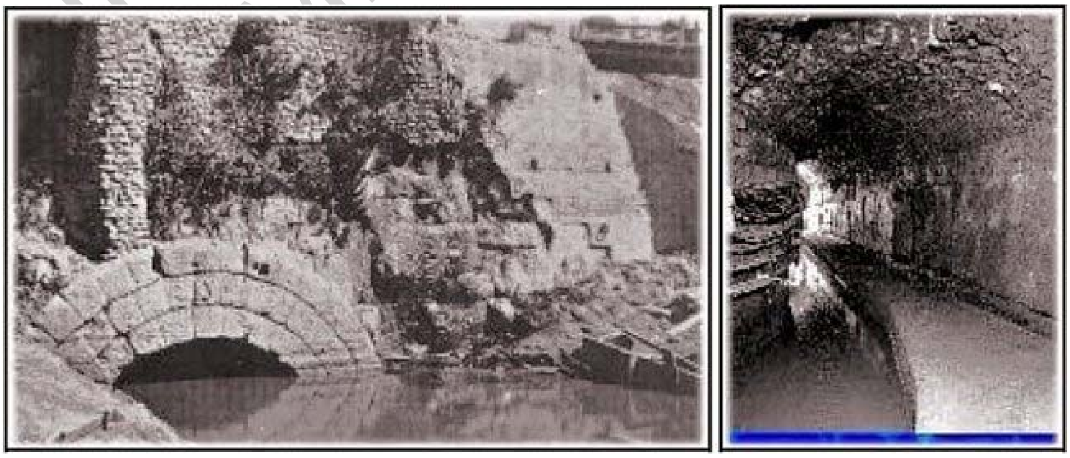

Figure 1: Roman sewer systems (photo courtesy of [4])

Figure 2: Roman aqueduct circa 19 BC in southern France today- Pont du Gard (photo courtesy of [2])

Figure 3: Roman aqueduct Valens in Constantinople, Istambul Turkey today; (photo courtesy of [2])

Historically, all of the fluid and gas transportation systems required integrity management which particularly looked into the operation efficiency, cost effectiveness and the structural soundness of transmission systems.

Today's society is much more demanding and the pipeline transportation industry is focused on more than traditional factors. For example, the foreseeable costs of pipeline operation must include not only those related to possible bursts or leaks but also those which can result from loss of life and property, pollution, or civil and criminal liabilities.

Therefore, managing pipeline structural integrity presents a unique challenge, requiring sophisticated pipeline risk-analyses, know-how of technological advancements and powerful and cost effective tools. This necessitates employing numerous engineering disciplines, such as stress analysis, fatigue and creep analysis, fracture mechanics, metallurgy, corrosion control, non destructive testing, structural monitoring and instrumentation, failure analysis, vibration testing and analyses.

3. Overview of Potential Factors Leading to Structural Integrity Breach

3.1. Internal Pressure

Pipeline integrity requires that the pipeline is able to sustain the pressure load of the conveyed fluid. This requirement calls for evaluating: (i) the minimum necessary pipe wall thickness, and (ii) the pressure rating of the in-line components such as fitting, valves, metering devices and other instruments.

The following steps need to be followed during this process: First, based on the characteristics of the fluid and its service, a suitable piping material is chosen. The pipe diameter and its wall thickness are calculated. In addition, the corrosion, erosion and joint allowance are established as well as the pipe material strength and its mechanical features. Second, the determined pipe size and its wall thickness are compared to the prescribed code's requirements.

In the next step, the standard manufacturing tolerances are compared to the nominal wall thickness with expectation that the tolerance will not reduce the nominal pipe wall thickness to unacceptable values. Finally, the pressure rating based on material properties must be done for the in-line elements in such a way that it exceeds the line requirements. A mandatory non-destructive examination may be carried out for certain elements, e.g. valves, to qualify them for higher pressure rating than the nominal, prescribed by the vendor. This step is dictated for special-class elements and is described in ASME/ANSI B16.34 code.

3.2. Stresses within the Pipe Wall

Stress is defined as the load per unit area within the pipe wall. Piping leading to compressors, pumps, turbines, metering stations, pig launchers, valve stations, boilers, and other facilities must be analysed in order to ensure that

(i) The stress in piping and machine components meets the required codes
(ii) The equipment loads meet the specified vendors' allowable values

(iii) The position of loads on the piping and equipment supports is acceptable
(iv) The designed life span of structures under cycling loads is sufficient

Figure 4: Stress originated piping explosion; (photo courtesy of [16])

In addition, specific analyses are performed to determine stress in complex parts of equipment or sections of piping subjected to steady state or transient loads such as pressure, thermal displacements, flow excitations, acoustic loads, and vibration loads. Piping analyses are carried out assuming linear or non-linear material behaviour, depending on the studied system's requirements and its operating conditions. There are several failure modes which could damage the piping systems.

A failure mode is defined as the combination of a trigger mechanism and a failure mechanism where the trigger mechanism is an event which initiates the process leading to failure, see Figure 4. During static stress analysis, appropriate codes are used to define processes leading to a failure such as excessive plastic deformation, plastic instability, incremental collapse and high-strain low-cycle fatigue. Stress limits are then calculated according to different codes, which would prevent numerous failure modes.

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Biographical Sketch

Roman W. Motriuk is principal acoustics and structural dynamics engineer with Arcus Solutions Inc. For over 20 years, he has been involved in the oil and gas, power generation, chemical and aeronautic industries while employed by leading companies such as Beta Machinery, Nova Corporation of Alberta, TransCanada and AMEC. His assignments deal with design, troubleshooting and failure analysis of turbo- and reciprocating machinery, pipelines and its components.

He has extensive experience dealing with stress and fatigue failures, flow and pulsation induced vibration failures, dynamic system stability designs, fluid-solid interaction failures, environmental noise control and various flow metering problems.

Roman has a M.Sc. degree in Mechanical Engineering specializing in Drilling Machinery from the AGH University of Science and Technology, Cracow, and a M.Sc. degree in Applied Acoustics from the University of Calgary.

He actively participates in research and development projects, and has published over thirty scientific papers on vibration, dynamic stress, and turbo-machinery acoustics. For the past several years, he has been teaching courses on pipeline acoustics and compression systems at the University of Calgary.

He is a past chairman of the Calgary Technical Chapter of the ASME-PSD, a member of the international ASME-PSD Executive Committee, and a past co-chair of the International Pipeline Conference (IPC) 2004 Organizing Committee. In addition, he is a member of the Fluid Solid Interaction (FSI) ASME Committee.