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Analytical model of stress concentration for the welded joints with angular distortion of thin-walled pipelines

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ABSTRACT

The paper concerns the analysis of stress distribution in the area of welded joints with angular distortion that may appear on the large welded pipelines or vessels. Authors present theoretical considerations leading to a simplified model which allows estimating stress concentrations occurring in this type of irregularities. Derived analytical formulas, fitting for stress calculation in both concave and convex angular distortions, provide an effective engineering tool that requires only a few geometrical parameters describing analyzed defects. This solution allows for quick estimation of the maximal stress concentration factor, which is a measure of the risk level posed by the defect in the thin-walled structures (pipelines, vessels). The correctness of the proposed solution is confirmed by the satisfactory agreement between the results of calculations and the results of strain gauge tests carried out for both types of analyzed imperfections, inventoried on two different hydropower penstocks.

1. Introduction

The problem of determining stress distribution in the thin-walled shells of large-scale pipelines is important for predicting their strength and service life. Ability to analyze the impact of different types of defects in such shells on increasing material strain allows to take appropriate action in order to increase the strength of these places.

Through years of research associated with operation of vessels, tanks, silos, pipelines, etc. a number of recommendations and standards concerning procedures in case of distortional damage or geometric imperfections of a thin-walled shells of such devices has been developed [1–4]. The main purpose of these is to determine the conditions in which it is necessary to repair defects or to estimate strength and fatigue life according to the characteristics of the deformed geometry, working conditions etc. The basis of the considerations in this regard is estimation of the maximum stress concentration and reduction of the fatigue limit of the shell in the area of defects. The subject of shell defects resulting from external forces (dents, bends, notches, corrosion) and their influence on strength reduction are quite well known and extensively described in the literature [5].

In addition to numerical analysis some analytical attempts to solve problems of stress distribution in deformed shells is also observed, as in the case [6] where analysis was conducted for dented cylindrical shell. In this work the results of the theoretical model were compared with the results of numerical calculations obtained using finite elements method (FEM) and satisfactory compliance has been obtained. In Ref. [7] a semi-analytical solution used for the determination of the stress concentration factor (*SCF*) in dented cylindrical shells has been presented. The calculation results were also compared with calculations obtained using FEM. It was pointed out that the *SCF* in such shells can reach very high values, and even small dents can cause stress concentrations that can threaten the safety of such shells.

The importance of the problem of imperfections of pipeline shells results from the fact that the reason of even 90% of pipeline failures occurring as a pipeline bursts are a consequence of stress concentration in the areas of pipeline shell deformations. Typically, such deformations are produced by external impacts (forces) and they are often focusing the attention of researchers. The study of such shells, theoretical and experimental, focuses also on the influence of the indentation depth on the burst pressure, eg. in Ref. [8]. The subject of research works in the area of bent cylindrical shells is often numerical studies analyzing e.g. the influence of internal pressure in the pipeline at the depth of the indentation caused by the force of given value [9] or the strength of the dented pipe shell assessed under internal pressure loading and external denting force [11].

In any case, the deformations of pipeline shells cause not only a reduction of the strength, but also decrease residual lifetime of the structure. In the paper [10] the new algorithm is proposed for assessing the fatigue life of dented pipelines. Particular attention is paid to the *SCF*s calculated using FEM for different dent geometries and taken them into account for assessing the fatigue life. The

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Nomenclature

D	diameter of a pipeline [m]
e	pipeline wall thickness [m]
E	elasticity modulus of the pipe wall material [Pa]
F	internal force [N]
h', h	depth (for concave distortions) or height (for convex distortions) [m]
L	length of imperfection [m]
M	bending moment [Nm]
N	internal force [N]
p	inner pressure in a pipeline [Pa]
R	radius of a pipeline [m]
S	tensile stresses [Pa]
SCF	stress concentration factor [dimentionless]
w	section modulus [m^3]
x	distance coordinate along pipeline axis [m]
α	angle between the tangent to the shell surface at the bottom point (concave) or peak point (convex) of a distortion (point 2) and an axis of a pipeline cross-section crossing this point – see Figs. 4–8 [deg]
β	angle between radius crossing the beginning of a distortion (point 1) and radius crossing point 2 – see Figs. 4–8 [deg]
ε	strain (dimensional deformation) [dimentionless]
ν	Poisson's ratio of the pipe wall material [dimentionless]

Subscripts concerns

int	internal, inner side of the shell
ext	external, outer side of the shell
o	circumferential
x	axial

authors also conducted fatigue tests of the dented pipe under cyclic internal pressure. Based on these studies the authors drew attention to the need for more appropriate S-n (stress-number of cycles) curve to use for such cases.

In contrast to shells with defects resulting from external forces, geometric imperfections of such shells resulting from improper installation or production errors is relatively poorly described. It is also because there is a fairly wide range of possible types of such defects. Overview of this type of shell defects and their impact on the stress distribution, as well as mechanisms of formation and development of such imperfections, can be found in Refs. [5,12].

One of these geometric imperfections have the form of welded joints with angular distortion (concave or convex), which are very difficult to avoid during the construction and assembly of large welded steel structures. These areas are characterized with an unfavorable stress distribution, which very often, due to the complex geometry, can be determined only numerically, mainly using the FEM. However, for practical reasons, it is expected to provide a simplified analytical method for predicting SCFs in such areas of pipeline shells.

The papers [13–15] greatly contribute to the understanding of the problem of stress concentration in concave and convex angular distortions in spherical pressure vessels. The authors of these works analyzes such kind of imperfections using both numerical and analytical calculation methods considering location, shape and size of these defects. They also point out that in order to properly determine the *SCF* in such shells it is necessary to define the geometric parameters of analyzed deformations in relation to the principal curvature of the shell. Unfortunately, validity of the proposed numerical and analytical solutions has not been confirmed experimentally.

In Figs. 1 and 2 examples of a cylindrical shell with imperfections analyzed in this paper are shown. The pictures show one of the hydropower plant penstock with a diameter of about 6 m. The construction of this pipeline is composed of 3.5 m long pipe segments made from bent steel plates welded with each other longitudinally. These segments are then joined together using circumferential welds. The operation of joining bent steel plates requires proper preparation of these plates-they should be evenly bent with a radius equal to the radius of the pipeline. Due to inaccuracies during bending of the steel plates the pipeline shell become deformed and the imperfections have the form of concave or convex angular distortions. Both types of imperfections may pose a significant threat to the safe operation of the penstock because of significant stress concentration in these areas.

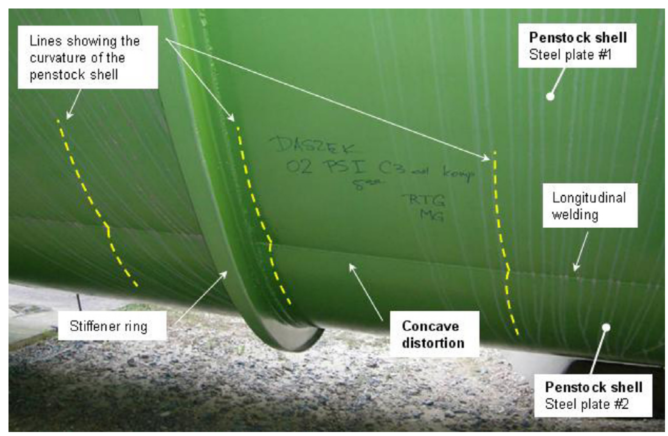

Fig. 1. View of a concave angular distortion of the steel penstock shell.

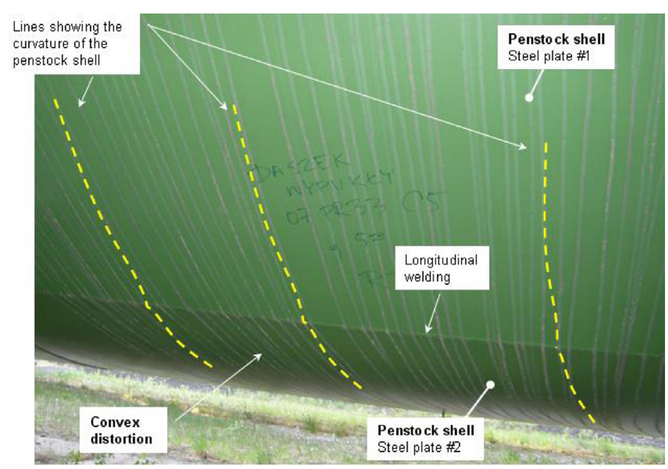

Fig. 2. View of a convex angular distortion of the steel penstock shell.

2. Simplified analytical method for calculating stress distribution in cylindrical shells with angular distortion (concave or convex) at welded joints

2.1. Simplifying assumptions

In the following considerations it is assumed that the pipeline is thin-walled, e.g. ratio between the pipeline wall thickness and