

Effect of Casing Imperfection on the Casing Strength in Steam Injection Wells

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Abstract. In this study, effect of casing imperfection on the casing strength in thermal environment of steam injection wells was investigated. The imperfections were modelled in the form of casing pits which may represent local cavitation, wear or corrosion attacks. Several pits with various depths (C) relative to the casing thickness (t) and different casing diameter to thickness (D/t) ratios were considered in this study. For the purpose of investigation, 3D FE models consisting of defective casing-cement-formation system were developed. N80 casing with the casing length of 3.048 m is analyzed in the numerical study. In the analysis, the combined effects of cyclic thermal stress (from 25 °C to 360 °C), collapse pressure (from formation) and defects on casing were taken into account. From the numerical study, it is found that the casing imperfection greatly affected the casing strength in steam injection wells. The presence of pits markedly reduces the casing collapse strength in comparison to that of non-defective casing. For instance, the collapse strength of casing having 2 pits along its circumferential direction with depth $C = 0.5t$ reduced about 49% and 43% for $D/t = 22.09$ and $D/t = 17.26$, respectively. In addition, the combination of high temperature, imperfection factor and formation pressure induces severe deformation on casing, even at lower formation pressure.

1. Introduction

Casing integrity and its assessment have been always main concerns in the operational of wells in oil and gas industries. This is due to the fact that casing integrity is affecting the oil/gas production rate. In steam injection wells, some important factors related to the casing integrity need to be considered properly so that its assessment can be carried out accurately. They may include: (i) casing thermal expansion and cyclic thermal stress, due to well working temperature during steam injection, production and cooling phases [1, 2], (ii) surrounding formation pressure, due to non-uniform initial in-situ stresses in the rock salt formation, sanding induced cavities or rock flow [3], (iii) internal/burst pressure [4], and (iv) strength degradation of casing material (yield strength/ultimate strength), due to temperature dependent structural and thermal properties [5], such as modulus of elasticity (E), density



(ρ), Poisson ratio (μ) and coefficient of thermal expansion (α). All the factors could independently or in combination induce large deformations and stresses to cemented casing, causing strength degradation and integrity losses for the casing [6, 7].

In addition, another factor worth of consideration is imperfection. Imperfection factors may present in the forms of defect, ovality, eccentricity and residual stress. Among others, defect is an important factor that will reduce casing strength as it is thinning out the casing and acting as stress concentrator. Liu et al. [5] proposed a collapse strength formula to calculate the collapse strength of defective casings in steam injection wells. The formula improved the previous standards and formulations in ISO/TR 10400 [8] by taking into account the effect of temperature along with the presence of pits. It is shown that pit depth and pit circumferential spread are main factors affecting collapse strength of defective casing. In addition, Lin et al. [9] carried out casing integrity evaluation for the application of casing design by considering the effects of wear and corrosion on casing.

In this study, effect of casing imperfection on the casing collapse strength in thermal environment of steam injection wells was investigated. This paper extends the previous study by Hidayat et al. [10] in the sense that defective casing analysis is also related to the thermal cycle experienced by the casing. The imperfections were modelled in the form of casing pits which may represent local cavitation, wear or corrosion attacks. Several pits with various depths (C) relative to the casing thickness (t) and different casing diameter to thickness (D/t) ratios are considered in this study. For the purpose of investigation, 3D FE models consisting of defective casing-cement-formation system were developed. N80 casing with the casing length of 3.048 m is analyzed in the numerical study. In the analysis, the combined effects of cyclic thermal stress (from 25 °C to 360 °C), collapse pressure (from formation) and defects on casing are taken into account. In particular, stress and deformation of defective casing after certain thermal cycle are pointed out, in comparison to that of non-defective casing. It is shown that the combination of high temperature, imperfection factor and formation pressure induces severe deformation on casing, even at lower formation pressure.

2. Thermo-mechanical finite element analysis

Problem of cemented casing in steam injection wells can be represented by coupled thermo-mechanical analysis. Details of the thermo-mechanical analysis can be found in [10], and references therein. Readers are also directed to [11, 12] for further thermal formulation in media or structure.

Here, the coupled thermal-mechanical FE equations are briefly described as follows:

$$^{i+1}[K_1]\{\Delta U\} - ^{i+1}[K_2]\{\Delta T\} = ^{i+1}\{R\} - ^i\{R\} \quad (1)$$

where:

$$[K_1] = \int_v [B]_T [D^{ep}] [B] dV \quad (2)$$

$$[K_1] = \int_v [B]^T [C^{th}] [M] dV \quad (3)$$

$$\{R\} = \int_s [N]^T \{p\} dS + \int [N]^T \{f\} dV \quad (4)$$

$$[D^{ep}] = [D^e] + [D^p] \quad (5)$$

$\{\Delta U\}$ and $\{\Delta T\}$ are the incremental of nodal displacements and temperature, respectively, $[B]$ is the matrix of strain-displacement, $[D^e]$ is the matrix of elastic stiffness, $[D^p]$ is the matrix of plastic stiffness, $[C]$ is the matrix of thermal stiffness, $[M]$ is the temperature shape function, $\{p\}$ is the vector of traction, $\{f\}$ is the vector of body force, i is the current step and $i+1$ is the next step of analysis.

The updated nodal displacements and stresses in the structure are respectively given as:

$$^{i+1}\{U\} = ^i\{U\} + \{\Delta U\} \quad (6)$$

$${}^{i+1}\{\sigma\} = {}^i\{\sigma\} + \{\Delta\sigma\} \quad (7)$$

$$\{\Delta\sigma\} = [D^{ep}] [B] \{\Delta U\} + [C] [M] \{\Delta T\} \quad (8)$$

$$\{R\} = \int_s [N]^T \{p\} dS + \int [N]^T \{f\} dV \quad (9)$$

$$[D^{ep}] = [D^e] + [D^p] \quad (10)$$

3. Collapse analysis of defective casing

3D FE models consisting of casing-cement-formation system were developed in ANSYS, as shown in Figure 1. Element contact with the Coulomb friction model are employed to model interaction between casing and cement as well as cement and formation. Geometrical data and material properties for the system of Grade N80 casing, cement and formation are given in Table 1. Length of the casing is 3.048 m. Imperfections are imposed to the 3D FE model in the form of pits.

Table 1. Geometrical data and material properties (at 25 °C) used in the numerical calculations.

Parameters and properties	Casing	Cement sheath	Rock
Dimension or OD (m)	0.1778	0.2238	1.572
Wall thickness (m)	0.0103	0.023	-
Young's modulus (E, GPa)	209	2.8	100
Poisson ratio (μ)	0.33	0.2	0.31
Density (ρ , kg/m ³)	7850	2400	2650
Thermal expansion (α , 1/°C)	1.69E-6	9E-6	5.4E-6

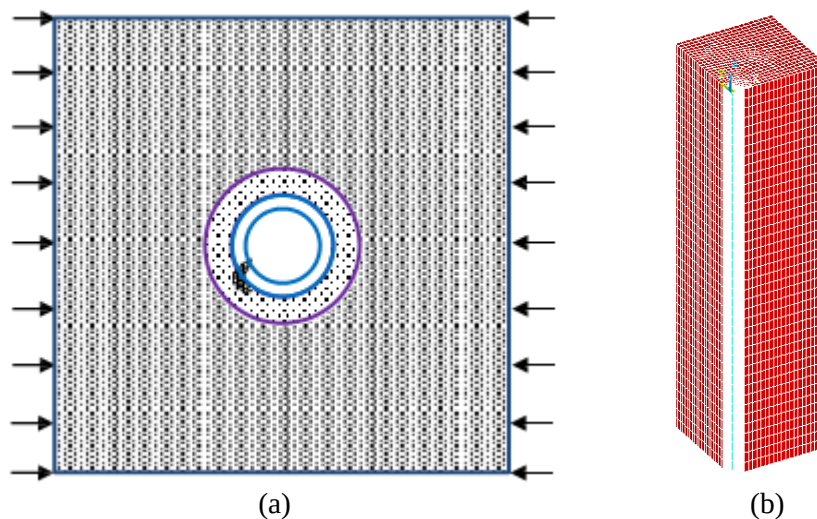


Figure 1. (a) Schematic of casing-cement-formation system under collapse pressure and (b) three-dimensional FE mesh (Hidayat et al., 2016).

4. Results and Discussion

Several pits with various depths (C) were considered i.e. $C = 0.20t$, $0.50t$ and $0.70t$, where t is the casing thickness. In addition, the values of $D/t = 17.26$ and 22.09 were examined. Here, lower D/t value associates with better collapse strength denoting increased casing capability to withstand external or formation pressure. Figure 2 shows defective casing with various pit depths and 2 pits.

In [10], the suitability of the 3D FE model is already shown that the simulation results obtained for non-defective casings are similar with those obtained in [5]. It was obtained previously that collapse strengths for non-defective casings at 25°C were 55 MPa and 71 MPa for the values of $D/t = 22.09$ and 17.26 , respectively.

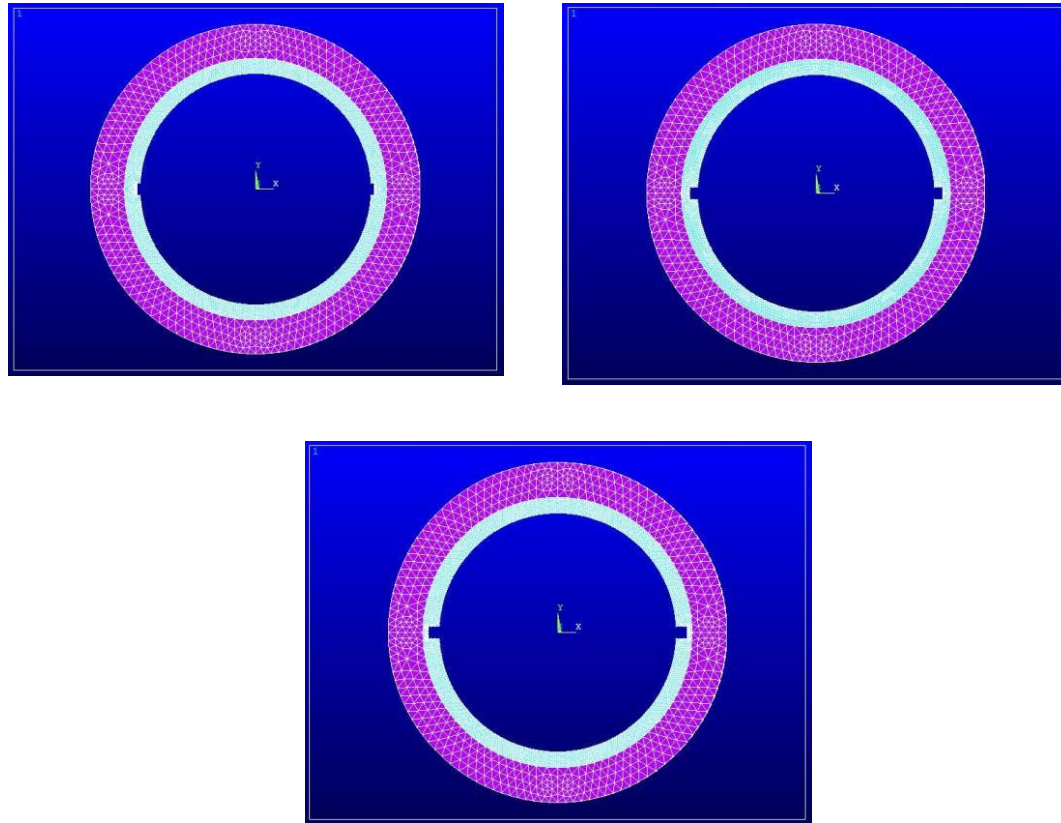


Figure 2. Defective casing with various pit depths of (a) $C = 0.20t$, (b) $C = 0.50t$ and (c) $C = 0.70t$.

Table 2 presents the simulation results of defective casing collapse strength with respect to various pit depths and D/t ratios. Note that the results are corresponding with 2 pits shown in Figure 2.

Table 2. Defective casing collapse strength for different D/t ratios (at 25 °C).

$D/t = 22.09$			$D/t = 17.26$		
Collapse strength of non-defective casing is 55 MPa	C	Collapse strength (MPa)	Collapse strength of non-defective casing is 71 MPa	C	Collapse strength (MPa)
	$0.2t$	43.4		$0.2t$	57.6
	$0.5t$	28.2		$0.5t$	40.5
	$0.7t$	19.1		$0.7t$	27.2

It can be seen that the presence of pits affects the casing collapse strength markedly in comparison to that of non-defective casing as given in Table 2. For instance, for $C = 0.5t$ the casing collapse strength reduced about 49% and 43% for $D/t = 22.09$ and $D/t = 17.26$, respectively.

Further, the analysis for the defective casing is expanded here i.e. deformation of defective casings is also related to the thermal cycle experienced by the casing. This aspect has not still been considered in the previous studies. For clarity, deformations of non-defective casing (under pressure of 17.2 MPa) and

some defective casings ($C = 0.20t$) with various number of pits and different external pressure values are shown in Figure 3.

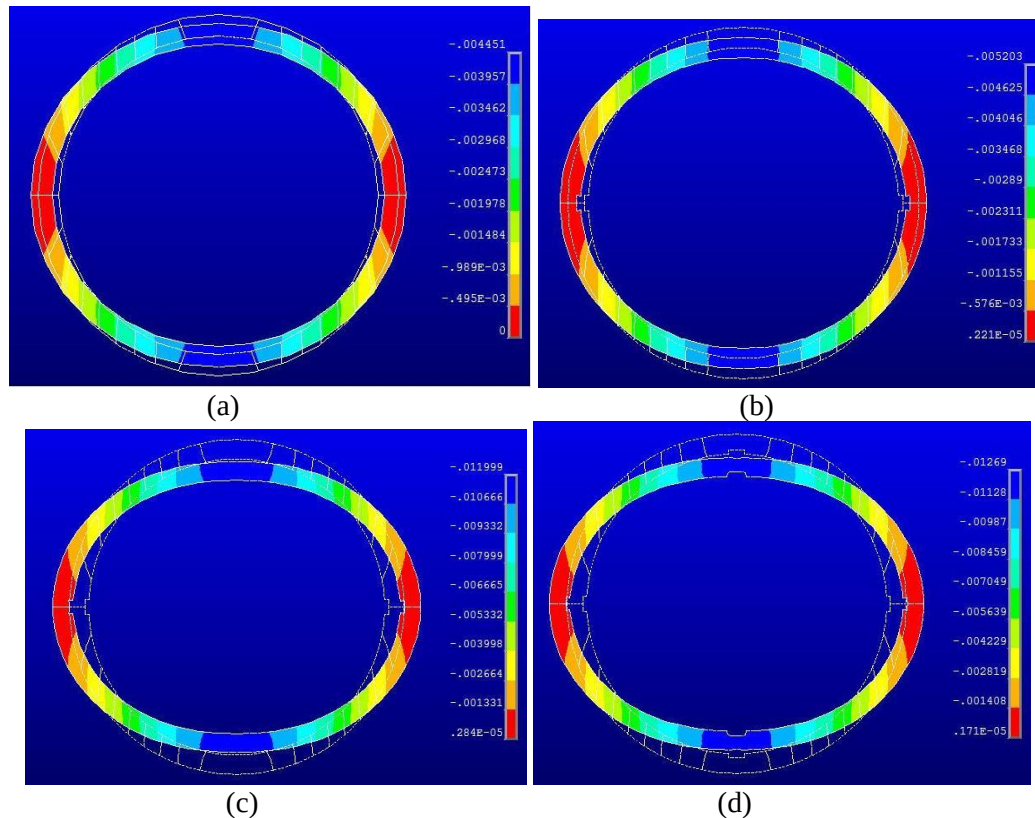


Figure 3. Deformation of (a) non-defective casing (under pressure of 17.2 MPa), and defective casing $C = 0.20t$ with various number of pits (b) 2 pits under pressure of 17.2 MPa, (c) 2 pits under pressure of 33 MPa, and (d) 4 pits under pressure of 33 MPa.

From the results, it was obtained that defective casing deformation after one thermal cycle was greater than that of non-defective casing after six thermal cycles. For instances: a defective casing with $C = 0.20t$ and 2 pits under 17.2 MPa deformed 5.2 mm after one cycle (Figure 3(b)), while that of non-defective casing under the same pressure was 4.5 mm after six cycles (Figure 3(a)). In addition, defective casings with $C = 0.20t$ and 2 pits and $C = 0.20t$ and 4 pits deformed 12 mm and 13 mm, respectively, after one cycle under 33 MPa (Figures 3(c) and 3(d)), while that of non-defective casing under the same pressure was 10.9 mm after six cycles. Hence, it is clear that the casing imperfection greatly affects the casing strength and casing strength degradation. It is also obvious that the combination of high temperature, imperfection factor and formation pressure induces severe deformation on casing, even at lower formation pressure. It is noted that steady external pressure between 10 and 40 MPa could be experienced by casing due to rock flow caused by creep formation [13].

5. Conclusions

In this study, effect of casing imperfection on the casing strength in thermal environment of steam injection wells has been investigated. The imperfections were modelled in the form of casing pits which may represent local cavitation, wear or corrosion attacks. Several pits with various depths along with different D/t ratios were considered in this study. Deformation of defective casings is also related to the thermal cycle experienced by the casing. It was found that the casing imperfection greatly affected the casing strength in steam injection wells. In addition, the combination of high

temperature, imperfection factor and formation pressure induces severe deformation on casing, even at lower formation pressure.

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