February 2013. Vol. 2, No.2 ISSN 2305-8269

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

WELLBORE INTEGRITY AND CEMENT FAILURE AT HPHT CONDITIONS

Catalin Teodoriu[1], Christian Kosinowski[2], Mahmood Amani[3], Jerome Schubert[4] , Arash Shadravan[5]

Clausthal University of Technology, Germany[1,2]
Texas A&M University, Qatar[3]
Texas A&M University, USA[4, 5]

Abstract

This paper presents the development and optimization process of a new high-pressure, high temperature experimental concept for testing wellbore cements on their behavior in cyclic loading situations.

The new specimens developed within this paper allow testing cement under wellbore conditions and geometry. For this, a ring like cement sample was designed. After a confining pressure is applied, the cement can be exposed to inner pressure cycles that simulate variable internal pressure. The failure behavior of the cement materials can be evaluated.

The failure mechanism and reasons for failure itself are also described and further ways for stress analysis are presented. An analytical and a finite element model were used to calculate the stresses in the cement sheath and to allow failure prediction and transfer of the results to theoretical models.

The integrity of wells is essential for their life time. This paper provides an overview of reasons for cement failure and additional methods and techniques to avoid the mentioned problems.

Keywords: Cementing Oil Wells, Cement Fatigue, Well Integrity, Cement Failure, HPHT, Drilling Oil Wells

Well Integrity Risk over the Life of the Well and the Connection to Cement

Well integrity means in this context the control of flow inside the wellbore (between different horizons), and the flow from the well (especially in the annulus behind the casing). The worst case of loss of wellbore integrity would be collapse of the well caused by failure of the construction material. The risk of uncontrolled flow of the well resulting from loss of integrity causes a potentially high risk in the end of a wells lifetime. In this period, corrosion and dissolution mechanism as well as stresses weaken the material (especially cementation and casing steel) of the well and might cause failure.

Figure 1 shows the potential risk for a wellbore failure compared to the projected risk (especially uncertainties due to unknown production parameters). It is shown that, especially in mature wells, higher risk of wellbore integrity failure is present. [5]

February 2013. Vol. 2, No.2 ISSN 2305-8269

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

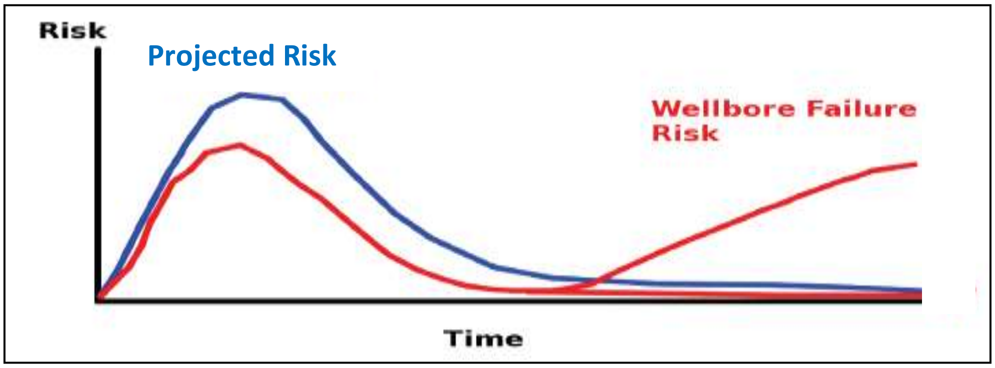

Figure 1: Project and Wellbore Integrety Risk over Time [5]

According to the following classification by Carey 2010 [5] there are several reasons for wellbore integrity issues. In his work two stages are classified, pre-production (mainly drilling) and the time of production itself. The list by Carey is printed italic; extra explanations by the author as standard text based on the references [6, 7, 8]:

Pre-Production Stage

- *Formation damage during drilling (caving)* ➔ Instable formations might show the trend to build caves. During the drilling process vibrations and pressure differences between formation and well might cause forces that end in formation failure.

- *Casing centralization (incomplete cementing)* ➔ In case of no proper centralization of the casing, the cement might not fully displace the mud from the annulus during the cementing operation. The cement rather flows in the wide opening of the well than in a narrow opening. This result in cement eccentricity and non-uniform cement thickness.
- *Non-adequate drilling mud removal* ➔ Drilling muds typically show the behavior of thixothropy which means that they build a gel-structure under low shear rates (low or no flow). This behavior is meant to prevent an accumulation of cuttings at the bottom of the well during periods without circulation. The gel structure has to be broken up and further the flow in the hole well has to be ensured. Mud pockets will compromise the entire well integrity.

- *Incomplete cement placements (pockets)*

- *Inadequate cement-formation / cement casing bond* ➔ Due to wrong composition of the cement slurry concerning the compatibility with the formation no good bond might be archived. Other reasons for this can be mud or grease residues on the casing or a deficit in the cement pumping strategy.

- *Cement shrinkage* ➔ Certain cement mixture show the behavior to shrink during the hydration process. This shrinkage can lead to pathways (e.g. micro annulus or channeling) and with this cause a bad cement bond quality and might induce pre-stresses in the cement sheath.

- *Contamination of cement by mud or formation fluid* ➔ When mud or formation fluids (especially gas or water) mix into the cement slurry, they might change the cements properties and behavior (e.g. changes in the salt content cause a variation of the settling behavior). Gas might create channels in the cement and with create a flow path
- *Filtration of the cement slurry* ➔ Under suitable conditions (e.g. in case of a high pressure gradient from the wellbore to a

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

permeable formation horizon) fluid can be filtrated from the cement slurry. The lack of water during the hydration process will decrease the strength of the cement and further might cause intensified shrinking behavior with the results as mentioned before.

- *Fracture formation with cement* ➔ The cement slurry is typically the densest fluid used while drilling a well. As a result the danger of fracturing the formation during the cement job is high. For the integrity of the well this might have catastrophic outcomes and might even cause a blowout in the worst case. It will end in a bad cement job with possibility for bad or even no zonal isolation.

Production phase

- *Mechanical stress/strain* ➔ Mechanical stresses in the cement sheath are commonly induced by pressure and temperature changes in the wellbore due to production or workover operations. Pressure changes inside of the casing will induce forces to the cement that can cause a failure. Similar effects are caused by temperature changes that typically cause an expansion of the casing.

As a result the casing is set under compressive forces as it is restricted by cement on the outside. A fraction of the forces is conducted into the cement and causes stresses. Additionally buckling of the casing might occur if no sufficient pre-tensioning and wall thickness dimensioning was applied during the design phase. The results from the described process are the following outcomes.

  - *Formation of micro-annulus at casing/cement interface*
  - *Disruption of cement-formation bond*
  - *Cement failure due to mechanical or thermal induced stress*

- *Geochemical attack* ➔ During the life of the well it is exposed to an aggressive environment that attacks the construction materials. High temperatures and corrosive agents (e.g. H_2S or CO_2) deliver good conditions for corrosion of the casing and decarbonation or dissolution of the cement.
  - *Corrosion of casing*
  - *Degradation of cement (carbonation, sulfate, acid)*
- Cement Fatigue due to variable mechanical and or thermal stress/strain ➔ every production cycles will generate load cycles on the cement sheath, which may cause cracks and cement failure in time.

Overall most of the mentioned problems can be associated with cementing and/or cement stability problems, as shown inFigure 22.

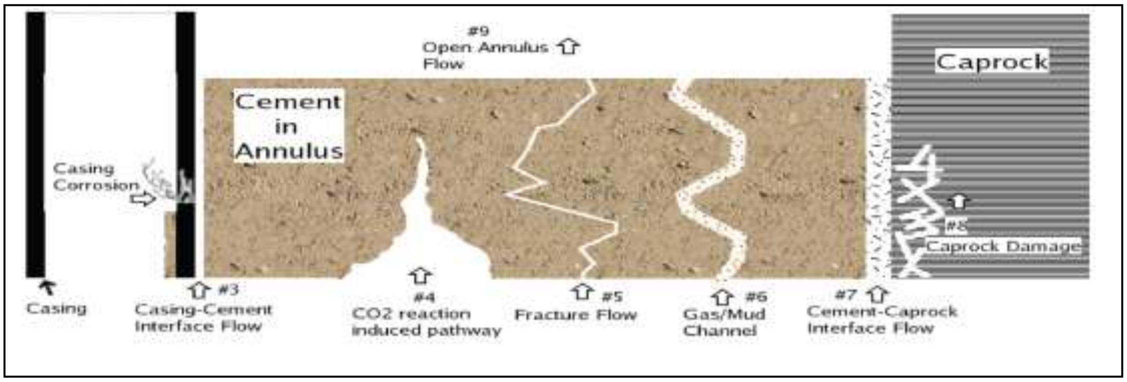

Figure 2: Cement Failure Modes Summary [5]

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

The aim of this paper is to present the development of a possible sample design that allow to investigate the mechanical failure of cement due to cyclic loading which is not yet fully recognized among petroleum engineering research facilities.

Mechanical Cement Failure

A wellbore integrity literature review showed that cement plays an important role in terms of wellbore stability. In what follow the mechanical failure types for cement based on the results from Wehling 2008 [9] are shown.

- Figure 3 a) Tensile failure: The cement is exposed to large internal pressure from the casing. This causes tensile stresses in the cement that lead to failure if the tensile strength is exceeded
- Figure 3 b) De-bonding between cement and casing: If internal casing pressure occurs, the casing might deform in a way that the contact between cement and casing is lost and a micro-annulus is created.
- Figure 3 c) Shear failure: in case of very high formation pressures (e.g. by creeping salt formations) the compressive strength of the cement might be exceeded and the material is crushed.

The stresses induced in wellbore cement are caused by the pressures acting from both sides of the sheath. On the outside is the formation with its pore pressure and on the inside the pressure transmitted from the inside of the casing. Figure 3 shows an overview of the most common failure types.

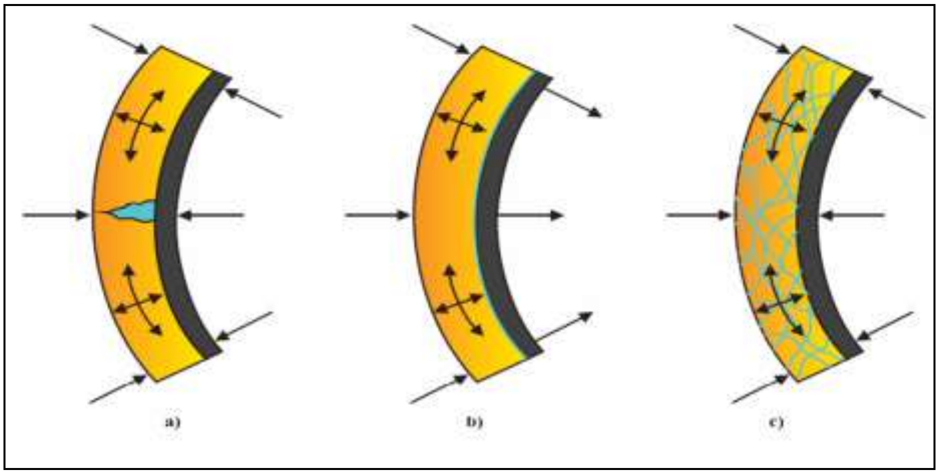

Figure 3: Types of Mechanical Cement Failure a) Radial Crack b) De-bonding c) Shear Failure, (Wehling 2008)

Stress Analysis

For development of models for cement fatigue analysis and other analyzing purposes (e.g. the comparison of comparability of experimental setup and reality) it is important to calculate the stresses induced in the cement sheath during the real and laboratory conditions.

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

Analytical Model

The basis of the analytical model presented in this chapter is based on the work of Ugwu 2008 [11], and Teodoriu et al 2010 [12]. They present an analytical model for determination of the stresses in wellbores, taking into account the mechanical properties of casing, cement and the formation as well. The basis of the calculations is the assumption that casing and cement can be treated as multi-cylinder-setup. By using stress analysis methods for thick and thin walled cylinders and basic stress-strain equations a way is derived to calculate all important stresses for the system. Figure 44 shows the basic assumptions and the geometry.

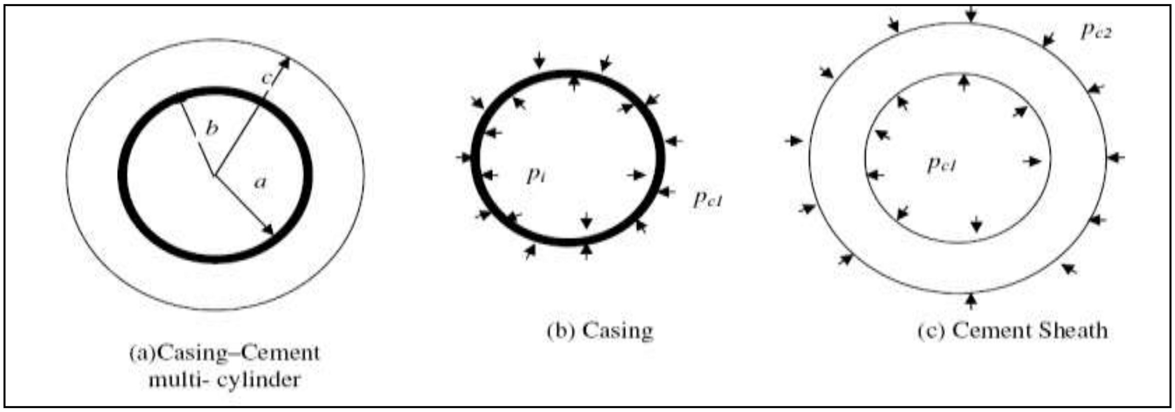

Figure 4: Geometry and Assumptions in the Analytical Model by Ugwu and Teodoriu [11, 12]

For the future experimental setup, the formation is replaced by hydraulic confining pressure, therefore the Ugwu model must be changed: the contact pressure to the formation (p_{c2}) equals the confining pressure and there is no restriction in the movement of the cement by the formation. The next step is to determine the contact pressure between casing and cement (p_{c1}) for calculation of the stress distribution.

Ugwu 2008 [11] states the following relationship:

$$A \cdot p_{c1} + B \cdot p_{c2} = C \qquad \text{Equation 1}$$

with

$$A = \frac{b}{E_c}\left[\left(1 - v_c^2\right)\left[\frac{b^2 + c^2}{c^2 - b^2}\right] + \left(v_c + v_c^2\right)\right] + \frac{a}{E_s}\left[\frac{r_m}{t_s}\left(1 - v_s^2\right) + \left(v_s + v_s^2\right)\right] \qquad \text{Equation 2}$$

$$B = -\left[\frac{b}{E_c}\left(\frac{2c^2}{c^2 - b^2}\right)\left(1 - v_c^2\right)\right] \qquad \text{Equation 3}$$

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

$$C = \frac{p_i \cdot a}{E_s}\left[\frac{r_m}{t_s}\left(1-v_s^2\right)+\left(1+v_s-v_s^2\right)\right]+\left[\left(1+v_s\right)a\cdot\alpha_s\cdot\Delta T\right]-\left(1+v_c\right)b\cdot\alpha_c\cdot\Delta T \quad \text{Equation 4}$$

with the following factors included:

p_{c1}	Casing-cement contact pressure	E_c	Young's Modulus Cement
p_{c2}	Pressure at outer cement radius	E_s	Young's Modulus Steel
p_i	Internal casing pressure	r_m	Mean casing diameter
a	Internal casing radius	t_s	Casing wall thickness
b	Internal cement sheath radius	v_c	Poisson ration cement
c	Outer cement sheath radius	v_s	Poisson ration steel
α_c	Thermal expansion coefficient cement	ΔT	Temperature Difference
α_s	Thermal expansion coefficient steel		

When p_{c2} is known, p_{c1} can determined in the following equation which is derived from equation 1 by re-arranging.

$$p_{c1} = \frac{C - B\cdot p_{c2}}{A} \quad \text{Equation 5}$$

The following equations to determine the stresses in the cement sheath as function of the radius *r*, when the dimensions (inner radius *b*, outer radius *c*) and contact pressures (p_{c1} and p_{c2}) are known, can be used:

ISSN 2305-8269

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

Circumferential stress

$$\sigma_\theta(r) = p_{c1} \cdot \left(\frac{b^2}{c^2 - b^2}\right) \cdot \left(\frac{1 + c^2}{r^2}\right) - p_{c2} \cdot \left(\frac{c^2}{c^2 - b^2}\right) \cdot \left(\frac{1 + b^2}{r^2}\right) \qquad \text{Equation 6}$$

Radial stress

$$\sigma_r(r) = p_{c1} \cdot \left(\frac{b^2}{c^2 - b^2}\right) \cdot \left(1 - \frac{c^2}{r^2}\right) - p_{c2} \left(\frac{c^2}{c^2 - b^2}\right)\left(1 - \frac{b^2}{r^2}\right) \qquad \text{Equation 7}$$

Axial stress

$$\sigma_{axial} = \nu_c \cdot (\sigma_\theta + \sigma_r) \qquad \text{Equation 8}$$

The assumptions in the derivation process of the Equations 6, 7 and 8 consider the cement sheath as thick walled cylinder. We use for our samples a ratio between cement and “casing”-radius of 2 instead of 1.3 as it will result for most of the investigated wells, see figure 5.

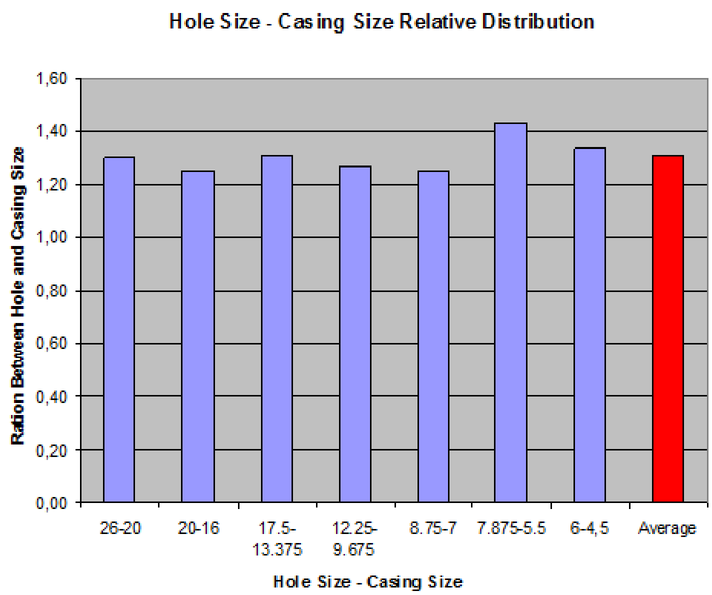

Figure 5. Ratio between hole and casing size, used to estimate the cement sheath behavior, using API recommended casing – hole size pairs [1]

ISSN 2305-8269

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

Figure 6. shows a set of circumferential stress distributions (the data-line names are based on "external pressure"–"internal pressure"). The shape of all curves show the expected behavior of curve with decreasing slope, but only high pressure differences from inside to outside deliver fully tensile stresses. In case of low difference only compressive forces appear. This may prove why normal loaded wells do not fail easily.

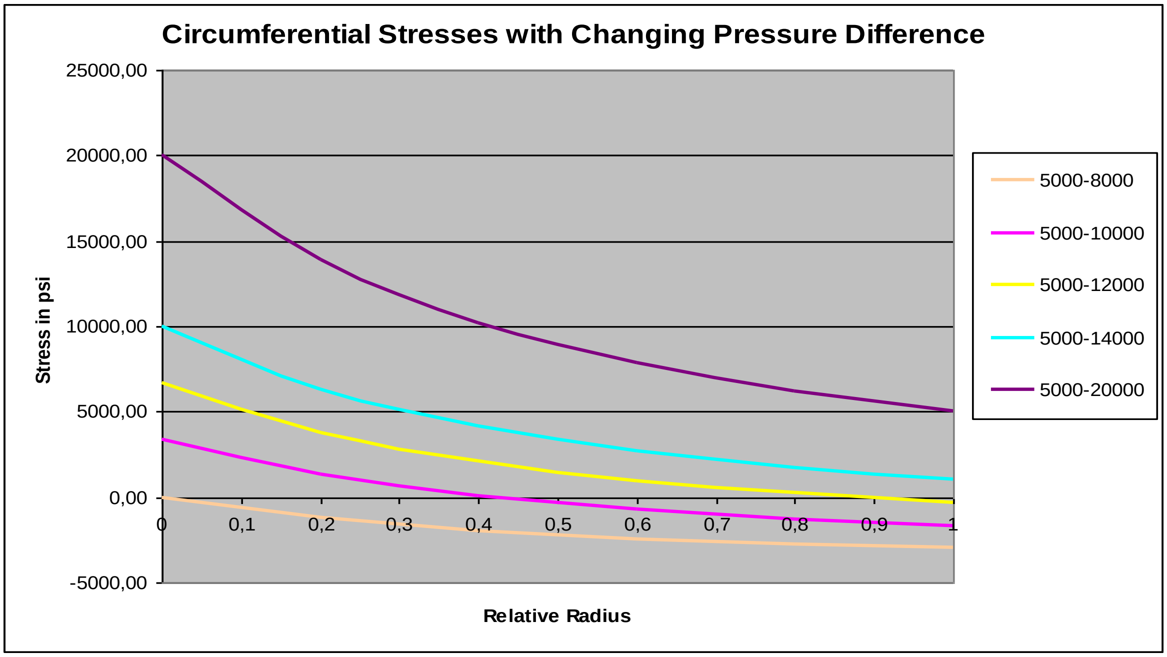

Figure 6: Cement Stress Distributions

The FEM model

The FEM simulation was performed to better reproduce the final stress distribution in the proposed sample.

Based on the real model, the specimen was recalculated so that the ballooning effect of the real casing can be mimicked under laboratory conditions, as shown in figure 7.

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

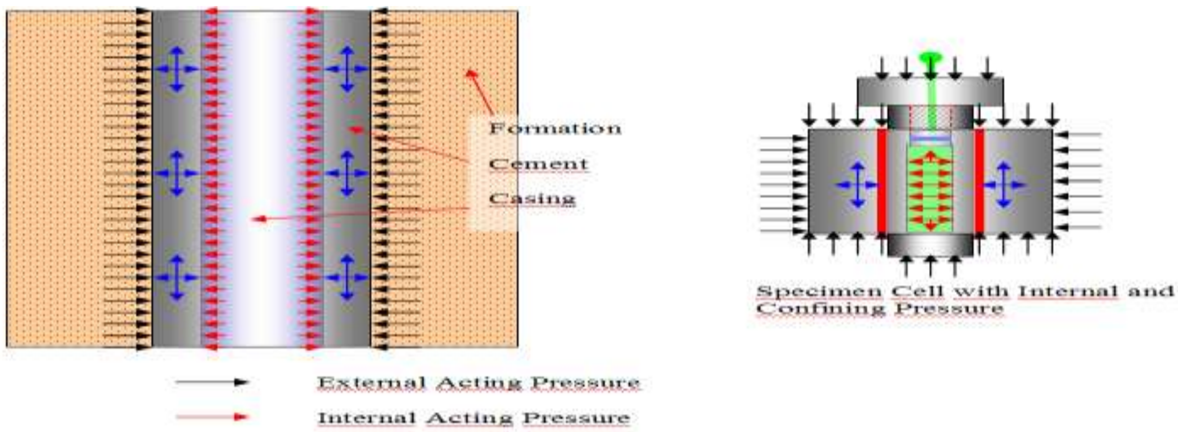

Figure 7. Real versus Laboratory loads on a cement sample

The simulation was used to understand the stress induced into the cement sheath when the inner capped end pipe is exposed to internal pressure. The simulation was further performed, by varying stress and geometry until a match to a full scale situation was obtained.

Figure 8 shows the deformation of model of the cement specimen, please note that the deformation scale was exaggerated in order to show the effect of the pipe ends. The data used for cement properties was taken after Teodoriu et al. 2012 [10] and consists of simulation for low and high curing time of the cement

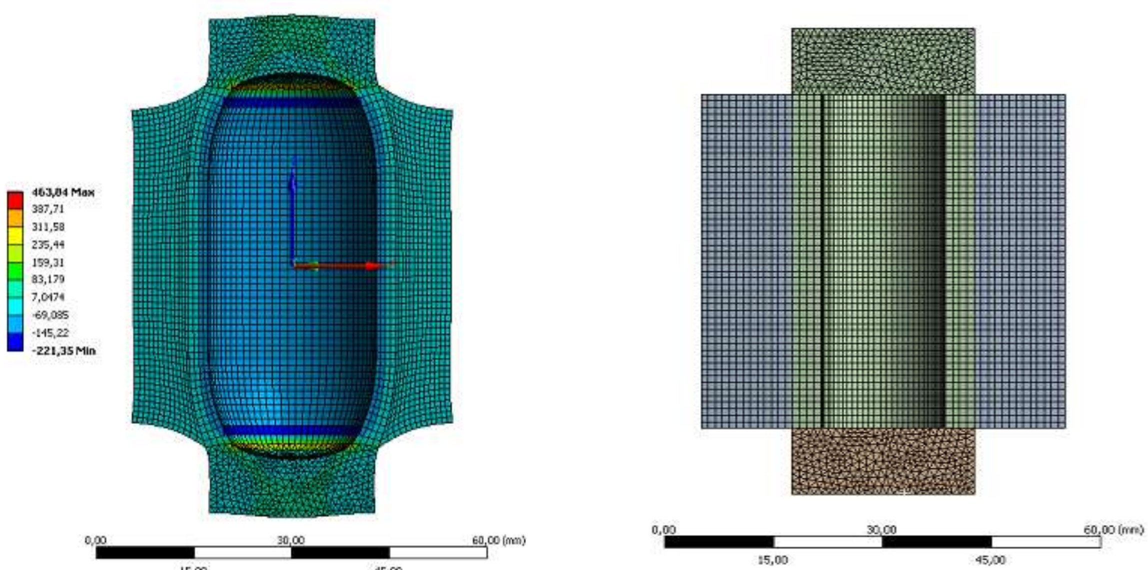

Figure 8. The deformed shape of the specimen (left) versus its original shape (right)

ISSN 2305-8269

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

Discussions

A review of the cement failure mechanism is provided for future analysis. The description and definition of cement failure is essential to allow importance between experimental series executed from different persons. When new laboratory setups are developed, the comparability of results is always crucial.

The main result obtained with the first specimens was that cyclic loading under confining pressure is visible as it was predicted in the design phase. The cement samples failed if the pressure difference between specimen and outer cell reached a certain level. How the samples fail and which mechanism in lead to failure is discussed as follow.

Detecting the failure of the cement samples is one of the most critical steps in the complete testing procedure. The reason for the stresses induced in the cement is caused by the pressure difference between the specimen and outer cell. In case the pressure in the specimen cell is the larger one this will result in ballooning of the specimen cell body as it can be seen in Figure 9.

Ballooning means that the diameter of the cell increases and it shortens (typical effect for production tubular). If a cement sheath is around the cell, this will prevent the ballooning to happen and as explained in the stress analysis this will induce stresses in the cement. The stresses can lead to failure of the cement sheath in case the forces overcome the cement strength. The ballooning and stress distribution is influenced by boundary effects (i.e. pipe ends). The massive bottom and cap of the specimen cells prevent this effect, therefore the rounded shape shown in figure 8.

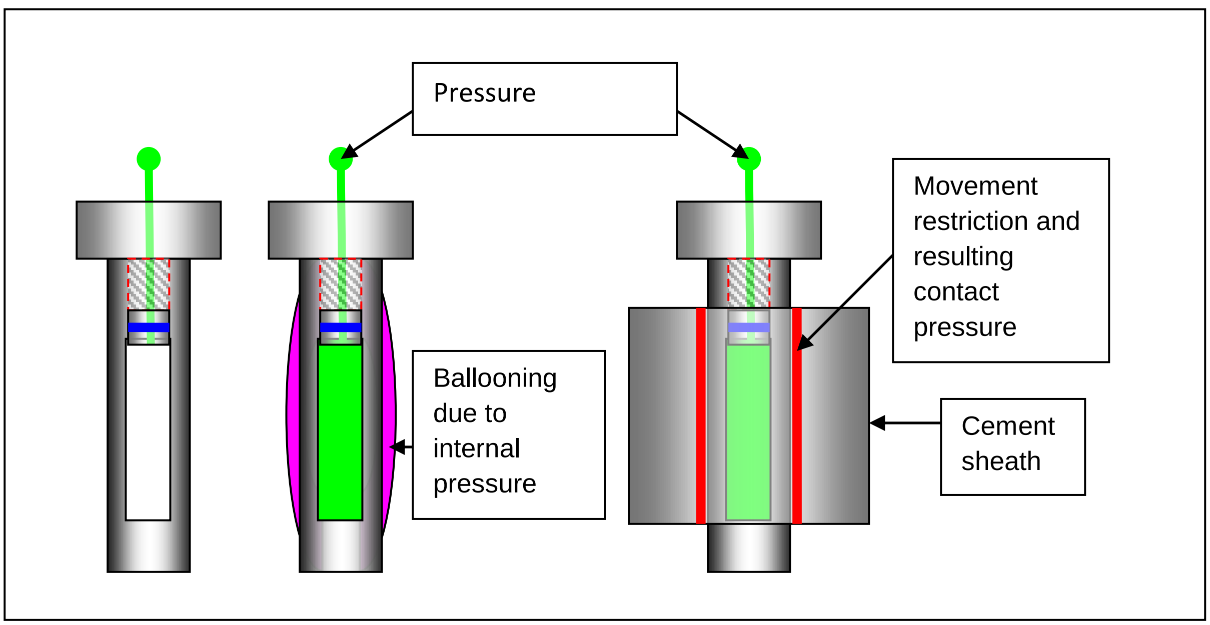

Figure 9: Ballooning Effect as Reason for the Stresses in the Cement

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

The observed sample failure during the test conducted in the course of the optimization phase showed the following results:

Cracking of the cement sheath was the first type of failure. We also observed that cement which was cured for only a few days and still showed a rather plastic behavior did not crack over the complete length (see Figure 10).

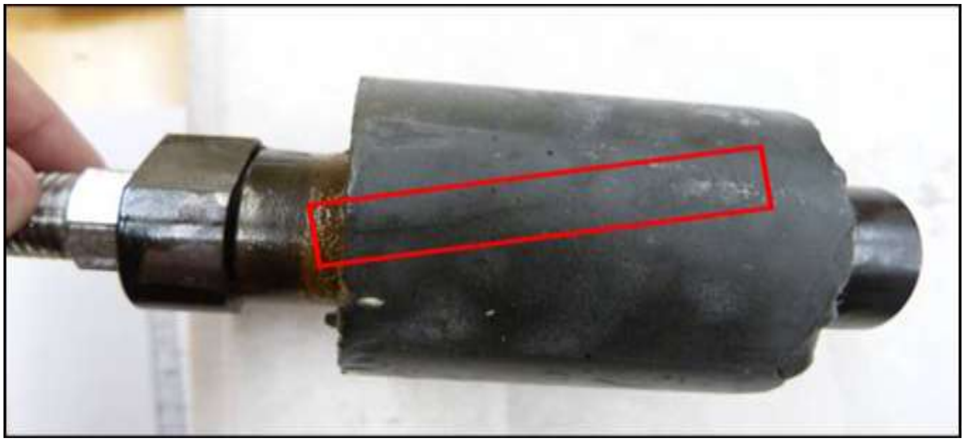

Figure 10: Cement Failure with Low Curing Time

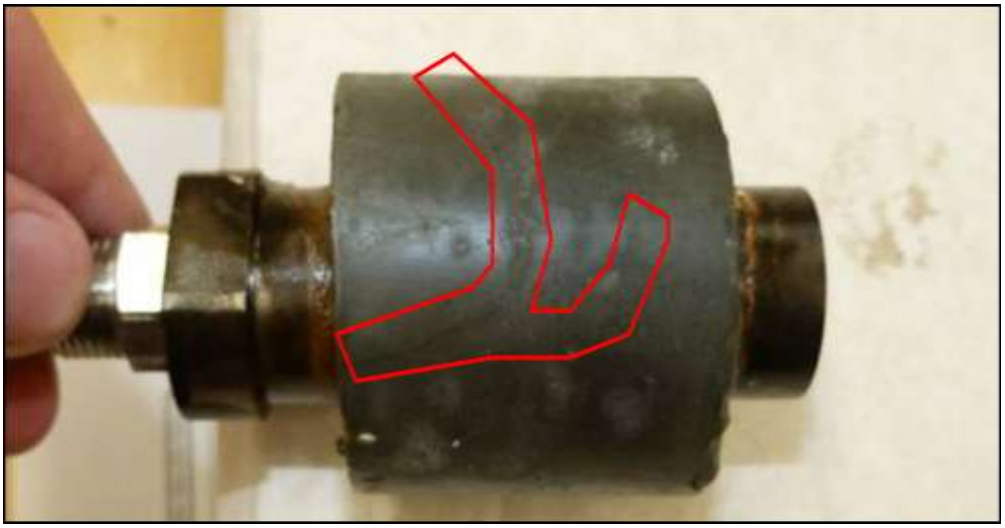

Figure 11: Cement Failure as Network from Initial Crack

 ISSN 2305-8269

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

Once a failure in form of a crack occurred, this initial crack typically grew into a network of cracks (see figure 11). The initial crack was radial before an axial failure was observed. After one radial failure occurred, this crack continued to grow until the complete sample is disintegrated.

Additionally to the failure by cracks, it was observed that the cell-cement-bond was broken up. Unloaded samples showed a really good steel-cement bond. It was even so good that the cement removal needed a lot of efforts, sometimes even close to damaging the specimen cells material. The cement sheath from tested samples was compared to this completely loosened. It was possible to remove it without tools with a twist of the hand.

Although the cracks shown in figures 10 and 11 are hardly visible, there was a large similarity in the crack-structure from other samples compared to the way the cement samples failure was described by Kosinowski and Teodoriu in [3, 4]:

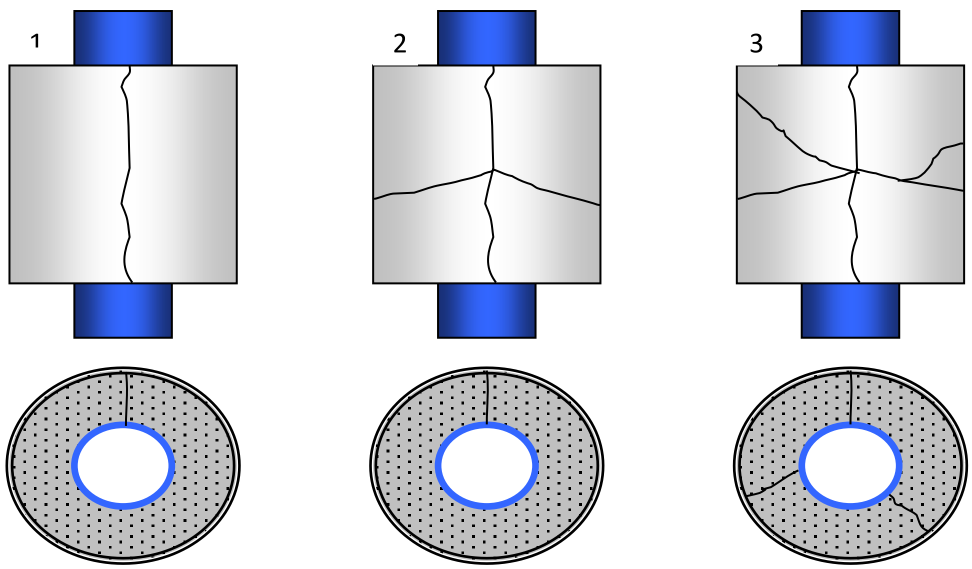

Figure 12: Phases of Cement Failure [4, 13]

The tests described by Kosinowski [4] where conducted under atmospheric conditions using transparent setup that allow direct observation of the crack growth. The initial HPHT samples were tested without direct visualization of the crack initialization, but overall the crack sequence and form are similar.

Based on the existing results a new laboratory setup and methodology is under development. We believe that the specimens we developed herein and presented in this paper will allow the scientist to obtain comparable results independent of the testing apparatus and environment.

Conclusions and recommendations

Recent developments in the area of drilling and production expose wellbores to cyclic loading situations.

This paper shows the performed stress analysis using an analytical approach and a finite element solution to create a new cement specimen that can be representative for HPHT conditions.

The theoretical and preliminary tests showed that tensile failure of the cement occurs in all testing situations.

We also found that cracks may occur after several loading cycles which are an indicator for damage accumulation.

International Journal of Engineering and Applied Sciences

www.eaas-journal.org

The next step is to build a standard experimental setup and conclude the proposed series of tests, which completely describes the cement fatigue under HPHT conditions.

Acknowledgment

This publication was made possible by the NPRP award [NPRP 09-489-2-182] from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors.

References

[1] API Bit Selection Chart.

[2] W. Gusler, M. Pless, J. Maxey, "A New Extreme HP/HT Viscometer for New Drilling-Fluid Challenges", SPE Paper No. 99009 (2006)

[3] C. Kosinowski, C., Teodoriu, "Study of Class G Cement Fatigue using Experimental Investigations", EAGE European Unconventional Resources Conference and Exhibition held in Vienna, Austria, 20-22, March 2012.

[4] C. Kosinowski, "Low Cycle Fatigue of Class G Well Cement" Bachelor's Thesis, TU-Clausthal (2011)

[5] B. Carey, "Wellbore Integrity and CO_2 Sequestration", http://www.ieaghg.org/docs/General_Docs/Summer_School/CAREY%20Wellbore%20Integrity_Tues_secured.pdf , Los Alamos National Laboratory (2010)

[6] Bourgoyne, "Applied Drilling Engineering", Society of Petroleum Engineering (1991)

[7] Lyons, "Handbook of Petroleum and Natural Gas Engineering", Gulf Publishing Company (1996)

[8] C. Teodoriu, K. M. Reinicke, C. Fichter, P. Wehling, "Investigations on Casing-Cement Interaction with Application to Gas and CO2 Storage Wells", SPE 131336, 2010 EAGE/SPE EUROPEC, 14-17 June 2010, Barcelona, Spain

[9] Wehling, "Wellbore Cement Integrity Testing", Master's Thesis, TU-Clausthal, (2008)]

[10] C. Teodoriu, Z. Yuan, J. Schubert, M. Amani, "Experimental Measurements of Mechanical Parameters of Class G Cements", SPE-Paper 153007, 2012

[11] Ugwu, "Cement Fatigue and HPHT Well Integrity with Application to Life of Well Prediction" Master's Thesis, Texas A&M University (2008)

[12] C. Teodoriu, I. Ugwu, J. Schubert, "Estimation of Casing-Cement-Formation Interaction using a new Analytical Model", SPE131335, 2010 EAGE/SPE EUROPEC, 14-17 June 2010, Barcelona, Spain.