Final Report : Fatigue Analysis of Permanent Bridge Plug

January 13, 2020

Abstract

In this work, the fatigue analyses of cement bridge plug under different oil-gas well conditions are performed. By using the state-of-the-art modelling framework by application of SolidWorks and ANSYS Workbench finite element softwares, the three-dimensional models of cement, bridge plug and casing with consideration of three different materials is explored and analyzed. The analysis shows that there are tensile stress concentrated in the area of connection between slips and cones of bridge plug. This finding in terms of safety factor reveals that considered bridge plug structures are safe against fatigue under most working conditions but it tends to fail when it comes to high pressure and high temperature (HPHT) condition as expected.

Executive Summary

As deeper and more complex well designs proliferate throughout oil and gas fields, well completion methods are challenged. Reliable and effective annular barriers continue to be crucial to well management for safety and performance[6]. The cementing has been the industry conventional means of creating these barriers and has improved significantly over the past few decades. The cement composition in the early days of the oil industry is similar to what is used today, but todays cement uses a number of additives that enhance the sealing of the cement in the wellbore. cement typically is used to create a seal between formations or to seal off the surface of the wellbore. Other materials which do not offer the same strength or durability as cement, including drilling mud, gel, and clay, are used to fill in the spaces between cement plugs. Additionally, the use of mechanical bridge plugs in lieu of a large cement plug since the bridge plug is extremely strong and nearly completely impermeable. However, mechanical plugs are susceptible to corrosion, and therefore the regulations typically require the bridge plugs to be capped by a specified amount of cement.

Based on these realistic consideration, the problem of fatigue analysis of bridge plug under different well conditions is of interest for oil-well operating companies, industrial practitioners and/or regulated state agencies who seek the insurance when it comes to possible emissions from the abandon wells.

Motivated by the above question in this work the state-of-the-art modelling framework of the well and cement plugging is considered by the application of the SolidWorks and ANSYS Workbench finite element methods. The plug is designed to be set in a wellbore and then have cement set on top to provide a complete seal of the reservoir below. In particular, the large scale 3D modelling of the relevant well size and cement bridge-plug geometry is considered in the simulation studies and reveals that bridge plug structures are safe against fatigue under most working conditions. It has been shown that bridge-plug degradable polymer content has a significant risk of failure in harsh downhole well environments. This is expected since polymer structure deteriorates over the time and changes as function of harsh environmental conditions (large fluctuations in the temper-

ature and/or pressure).
On the other hand, the study found that the mechanical bridge plugs usually have good compressive strength, corrosion resistance, and elastoplasticity [5]. In particular, after the stress is eliminated, the properties can be restored to its original state in a short time. The high strength characteristics of the cement plug can form a floor protection for the wellbore. Mechanical plugs are used in some wells to reduce the amount of cement required to plug a well or to provide additional protection from formation pressure in the well. Bridge plugs are typically made of cast iron with duel slips with a sealing element between the slips. Therefore, the main characteristics of using cement plugs and mechanical bridge plugs can not only improve the sealing quality, but also greatly improve the safety of the implementation of squeeze measures and achieve permanent well closure. By plugging wells correctly, future environmental issues, related to fluid or gas leakage, can be avoided and thereby preserve savings otherwise eroded by remediation or litigation costs.

Best Practices / Tangible Project Outcomes

The plugging and abandoning (P&A) of oil and gas wells that are no longer economically viable for production, or which have wellbore issues that require closure, has historically been conducted as an afterthought in the oil and gas production business. By plugging production wells that can no longer be used to prevent the oil and gas reservoir fluids from migrating uphole over time and possibly contaminating other formations and or freshwater aquifers. A well is plugged by setting mechanical or cement plugs in the wellbore at specific intervals to prevent fluid flow and provide a great environmental benefit by protecting the environment from potential contamination from oil and gas.
Abandoned wells generally have complex downhole technical conditions, and some wells cannot be implemented with conventional well closure methods. According to different downhole technical conditions, corresponding well closure treatment methods are used to implement well closure to ensure the permanent well closure effect. The sealing materials used for well plugging and abandonment must be adapted to the downhole condition changes that take place after well abandonment. Research has lagged on materials and methods for plugging wells although advances in technologies for drilling and completion should be applicable to practices in plugging and abandonment. As a result, many wells are poorly plugged and over time these poor plugging jobs may result in significant environmental problems. For instance, in the gas well area, the cementing of gas wells is a constant issue due to gas channeling. If operators plan poorly for the cementing of a gas well and try to cut costs by using cheaper materials and methods, those gas wells could potentially become a hazard due to gas leaking through the plugs. Actually, if the plug wells are located in a field for which pressure, thermal, and stress state are not in equilibrium at the beginning of abandonment, the downhole condition changes during abandonment can lead to plugging failure or micro-annulus formation inducing fluid leak-

age along the well.

In Alberta, Companies must follow the Well Abandonment requirements in Directive 020 of Alberta Energy Regulator to ensure that the public and environment are protected. First of all, designing an abandonment program to identify any issues within the well that could lead to potential leaks (e.g., cracks) and to identify all oil or gas formations and all groundwater zones that the well passes through. In addition, the company must also evaluate the cement that holds the well in place to ensure that it remains strong and intact. Next, the company must clean the inside of the wellbore to remove any oil or gas that could cause it to corrode or could cause the cement plugs that will be inserted into the well to leak. Any issues identified with the wellbore during the planning phase must be repaired. In addition, all oil or gas formations must be isolated from one another with cement plugs, and any groundwater zones must be isolated from the wellbore to make sure that no oil, gas, or water can travel up the wellbore and contaminate soil or groundwater. The company must then fill the well with freshwater or other noncorrosive fluid and assess the well to ensure there are no leaks.

Combining the consideration of this work, the best practice outcomes for permanent abandon of oil & gas wells is to apply cement plugs and mechanical bridge plug and ensure that plugged well is not exposed to the high pressure and/or high-temperature variations which might induce the fatigue and plug failure. If normal operating conditions are ensured the cementing the well is recommended practice that provides certainty in ensuring the proper sealing of the well. In general, setting a permanent bridge plug within 15 m above the liner top and the cement top behind the casing extends above the top of the formation and the depth is below the BGWP. Once the bridge plug has been set, it must be pressure tested at a stabilized pressure of 7000 kPa for 10 minutes. The plug must be capped with either a minimum of 8 vertical meters of class G cement or with a minimum of 3 vertical meters of resin-based, low-permeability gypsum cement.

Contents

1 Background

With continuous well productions, the hydrocarbon potential of oil and gas wells decrease and become more difficult to exploit. It is estimated that over 6500 platforms exist today worldwide. The cost of decommissioning the 6500 offshore platforms worldwide alone is estimated to be from USD29 billion to USD 40 billion. Between 2000 and 2010 alone, offshore abandonment will encompass 27,000 wells on 4900 platforms worldwide[8]. Onshore tens of thousands wells will also be abandoned on top of that[1][2].

When there is no future economic use of a well (e.g. anon repairable well integrity issue, as necessary by regulations, or other reasons) the well's last stage within the life-cycle is plug and abandonment (P&A). P&A is process of permanently securing the well with cement plugs or other mechanical barriers in such a manner that ensures all fluids, hydrocarbons and water, are confined to their original indigenous strata[4].

In Alberta, the leakage occurrence rate is 0.5% of drilled and abandoned wells compared to 13% of cased abandoned wells[3]. Considering the harsh climate in Canada, the likelihood of leakage or even failure of plugs increases. With diverse and complicated geographical features, leakage may lead to freshwater pollution, other colossal losses and can quickly escalade to catastrophic damages. It is crucial to incorporate reliable and effective leak detection, condition monitoring, risk assessment and integrity management methods to guarantee hydraulic or gas (such as CO_2) isolation, tightness and safety[3].

2 Methodology

The purpose of the plugs is prevent any cross flow of fluids between fluid baring strata; as well as, prevent any fluid breaches at surface. The plugs in a well must also effectively segregate uncased and cased portions of the wellbore to prevent vertical movement of fluid within the wellbore.

Fatigue analysis and lifetime evaluation are very important in design procedures to assure the safety and reliability of abandoned well components. In this work, we conduct statistic and failure analysis for a permanent bridge plug using finite element analysis via ANSYS[13][15]. In particular, we consider three materials as the objective, including structural steel, fluororubber and the combination of them with cast iron, under two normal well conditions and an extreme well condition. Based on that, total deformation, von-mises stress and fatigue lifetime will be analyzed and predicted. A overview of all considered simulation cases can be found in Table 1.

3 Data

Taking the Kappa bridge plug of Canadian Downhole Inc. as an example, it consists of the slips, cones, ratchet ring, mandrel, rubber and pump down spacer and rated 2,000-psi to 10,000-psi and 300F. The detail parameters and structure of Kappa bridge plug shown

Table 1: Evaluation parameters summary of under three well conditions

Materials of Bridge Plug	Evaluation Criteria	Case 1	Case 2	Case 3
		7MPa, 104F	2.8MPa,57C	103.4MPa,350F
structural steel	Total deformation mm(max)	0.018883	0.0075531	0.27892
	equivalent(von-mises)stress, MPa(max)	28.711	11.484	424.1
	fatigue life (cycles min)	1.00E+06	1.00E+06	2846.9
	Safety factor	5.0571	12.643	0.34236
fluororubber	Total deformation	2.67E+02	0.010698	0.39506
	equivalent(von-mises)stress	46.054	18.422	680
	fatigue life	1.75E+05	1.75E+05	121.74
	Safety factor	3.1526	7.8816	0.21343
fluororubber +cast iron + structural steel	Total deformation	0.326	0.01304	0.48154
	equivalent(von-mises)stress	46.326	18.53	684.29
	fatigue life	1.75E+05	1.75E+05	0
	Safety factor	2.4076	6.0191	0.16299

as Table 2 and Fig. 1.

Table 2: Parameters of Kappa bridge plug

CASING					PLUG		
Size IN(mm)	Weight LB/FT(kg/m)	Min.I.D. IN(mm)	Max.I.D. IN(mm)	Pressure Rating PSI(bar)	O.D. IN(mm)	Set force LB(daN)	Setting
5-1/2 (139.70)	13.0-23.0 (19.34-34.22)	4.580 (116.33)	5.044 (128.12)	10.000 (689.48)	4.312 (109.52)	33.000 (14.678)	00174656 (550DB10-B)

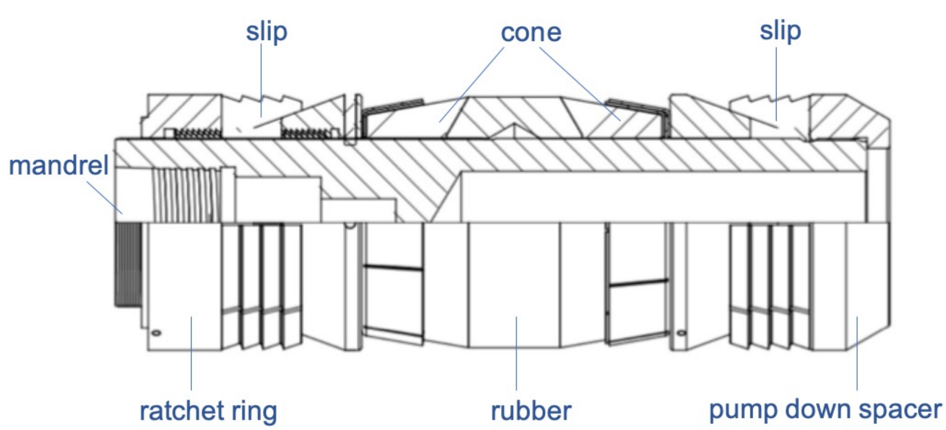

Figure 1: Kappa bridge plug of Canadian Downhole Inc.

3.1 SolidWorks model

The SolidWorks model can be established based on that, which shown as Fig. 2.

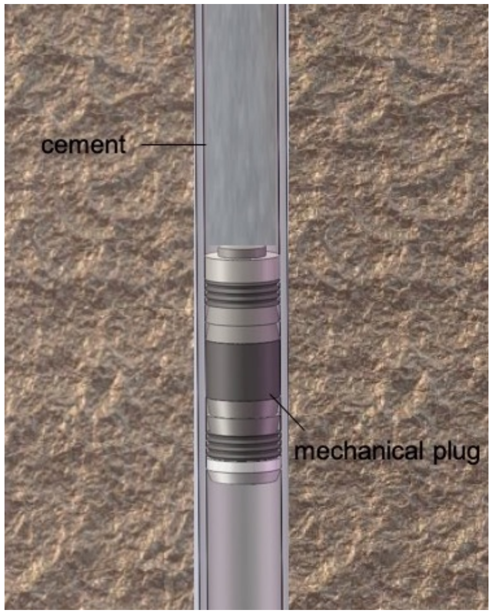

Figure 2: SolidWorks model of Kappa bridge plug

3.2 Material Properties

Based on the literature review, we have investigated three commonly used materials in petroleum engineering practice for mechanical plugs[11][10][12][7]. Three different materials, cast iron, fluororubber, and structural steel, for implant were used for the finite element analyses. Mechanical properties of these materials are shown in Table 3.

For the fatigue properties of materials, it can be defined as the number of cycles to break a specimen into two pieces at a particular stress for stress-controlled, or at a particular strain for strain-controlled, tests. Traditionally, the fatigue characteristics of materials, including rubbers, were determined by a ?Wohler? curve, also known as S-N curve (S denotes the applied dynamic stress σ for a stress-controlled test or, alternatively, strain ε for a strain-controlled test, and N is the number of cycles to failure)[16]. Fig. 3 known as S-N curves shows fatigue properties of cast iron, fluororubber, and structural steel.

3.3 Loads and Supports

According to the bridge plug was coverd by cement, we takes the top of bridge plug as a whole part with cement, which support fixed and apply pressure from the bottom. It

Table 3: Properties of materials

Materials	Cast Iron	Fluororubber	Structural Steel
Density(kg/m^3)	7300	1.84	7850
Young's Modules (MPa)	1.65E+05	12	2E+05
Poisson's Ratio	0.26	0.47	0.3
Tensile Ultimate Strength (MPa)	310	18.547	460

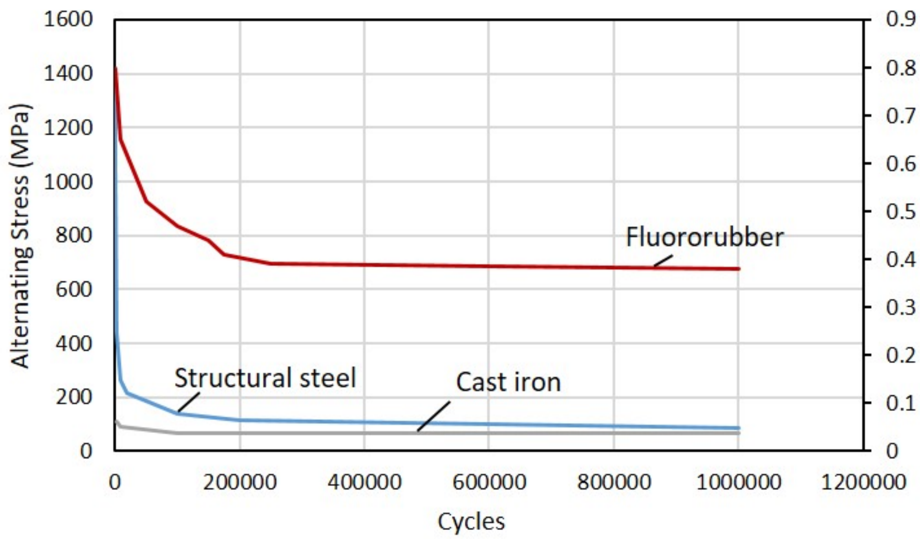

Figure 3: Fatigue curves (S-N curve) for cast iron, fluororubber, and structural steel

shown as Fig. 4 . Considering the different environment condition of wells, three sets of temperatures and pressures seem as conditions.

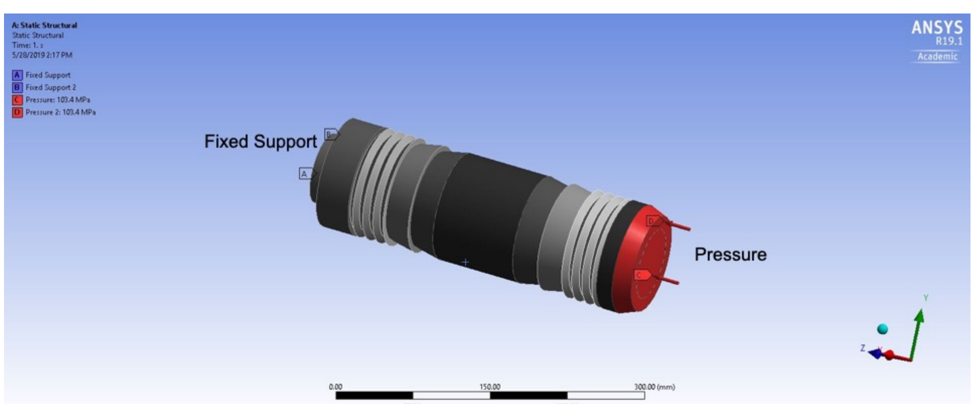

Figure 4: Loads and Supports of bridge plug

In order to fully reflect the stress and strain of the bridge plug under different well conditions, the load applied in the Ansys Workbench is divided into three cases: The first is to apply 2.8MPa in the Z-axis direction, and the surface temperature is 57 °C. The second is to apply 7MPa in the Z-axis direction, and the surface temperature is 40 °C. The third is to apply 103.4MPa in the Z-axis direction, and the surface temperature is 176 °C. These four states basically reflect the working conditions of the bridge plug.

Finite element model required in FE analysis is created by discretizing the geometric models shown in Fig. 2 into smaller and simpler elements, which shown in Fig. 5. The discretization was performed in ANSYS environment. The solid model assembly of slips, rubber, cone and mandrel was transferred to ANSYS Workbench by direct interface. ANSYS Workbench automatically recognizes the contacts existing between each part and establishes the contact conditions for corresponding contact surfaces. The finite element model of bridge plug consisted of around 61,920 elements and 207,743 nodes. In addition, the slips, byte in the casing wells, has been meshing refined.

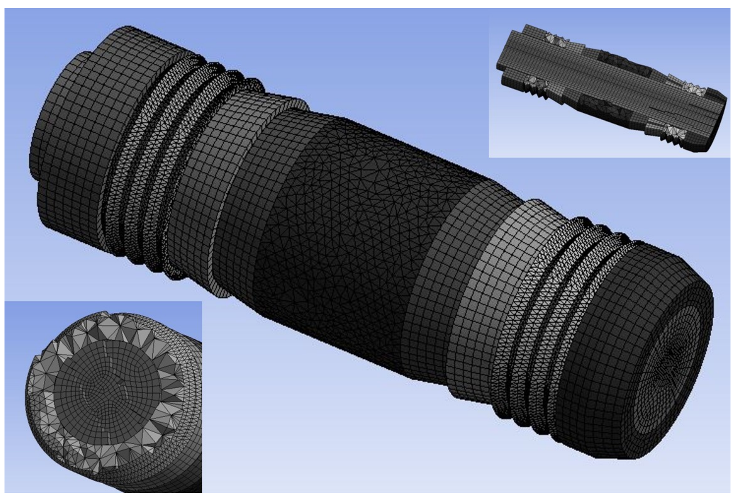

Figure 5: Finite element model of bridge plug

4 Results

Fig. 6 and Fig. 7 shows equivalent von Mises stress distribution and total deformation provided from the FE analysis. Results showed that there are tensile stress concentrated the area of connection between slips and cones. The calculated maximum von-Mises stress is σ_{max}= 18.422 MPa, 46.426MPa, 684.29MPa, respectively; Comparing with the Tensile Yield Strength of cast iron (204MPa), we can calculate that they account for 9%, 22.8%, 335% of the yielding point of material, respectively. This means that bridge plug satisfies the safety conditions for maximum loading under normal well conditions if it is exerted statically, but it will fatigue under extreme well condition.

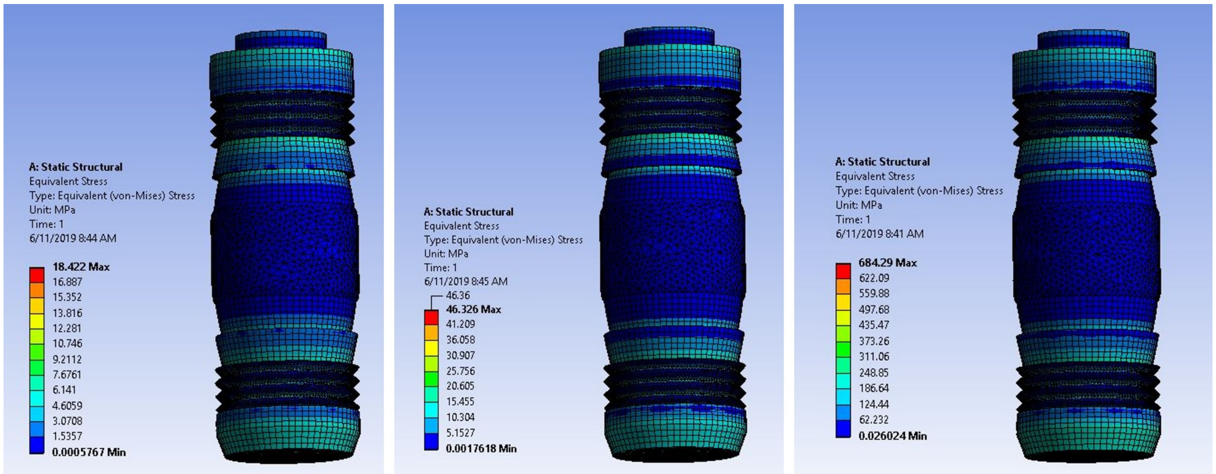

Figure 6: Equivalent von-Mises stress (2.8MPa, 57°C/7MPa,40°C/103.4MPa,176°C)

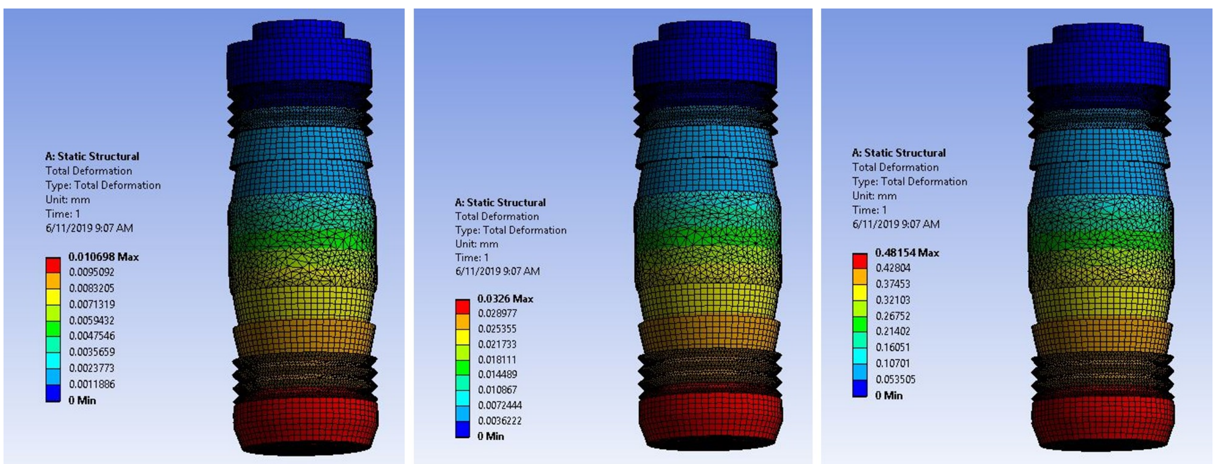

Figure 7: Total deformation(2.8MPa, 57°C/7MPa,40°C/103.4MPa,176°C)

5 Discussion

Fig.8 is a virtual fatigue profile based on the S-N curve shown in Fig. 3. By predicting the fatigue life of the three materials via Ansys Fatigue Tool, it shows that the safety factor of the three materials is more than 1 under normal conditions.. However, under extreme conditions, their safety factor is less than 1. In conclusion, the bridge plug are safe against fatigue but the results of fatigue simulations predicts that it failed on HPHT condition (Fig. 9).

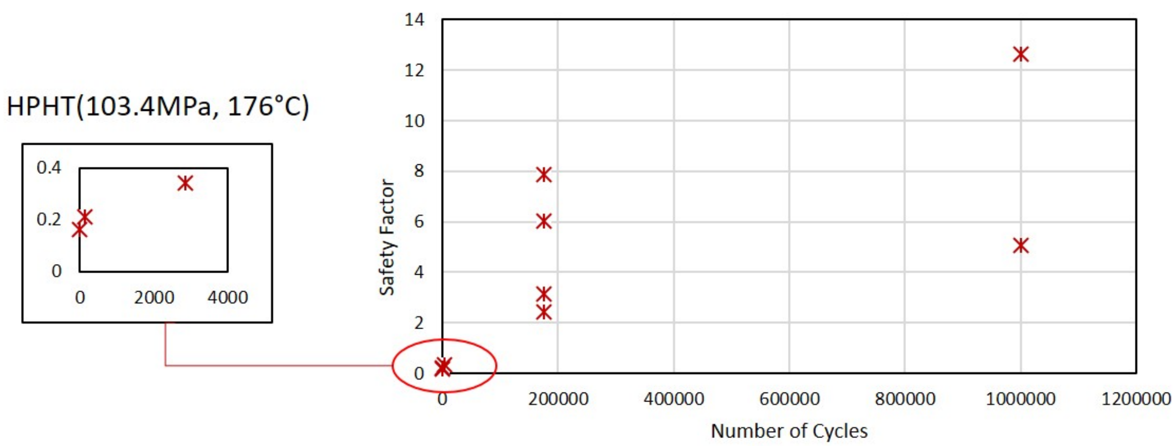

Figure 8: Fatigue life profile of the bridge plug

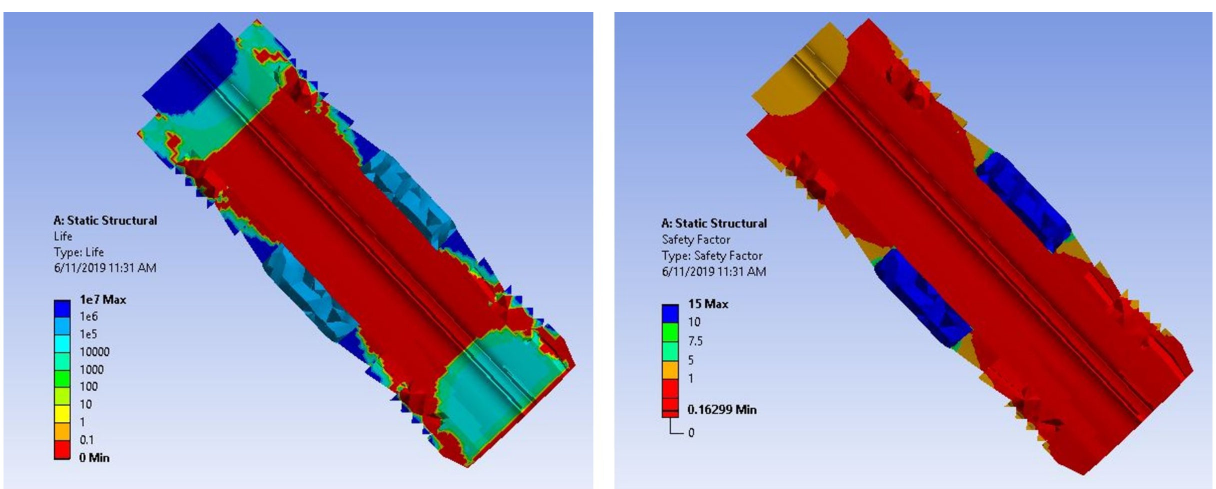

Figure 9: Fatigue life and Safety factor under 103.4MPa,176°C

As an important indicator for the remaining useful life, the remaining life cycles are calculated under these considered conditions (with respect to different combinations of pressure and temperature). To obtain an actual timeframe, the fluctuation period of pressure (compressive and tensile stresses) needs to be provided, by which the actual remaining useful timeframe can be subsequently computed by using the calculated remaining life cycles. In addition, based on the S-N diagram of the considered materials, we calculate the remaining life cycles and the structural safe factor under the pre-described working conditions by using the Ansys Fatigue Tool, as shown in Fig.8 and Table 1. Thus, this work provides a two-layer approach to evaluate whether a plug has failed. First of all, we expect a mechanical plug to fail if the calculated safe factor is less than or close to 1. If not, we move to the second layer. Based on the calculated remaining life cycles and the actual data oscillation frequency (or period) obtained from the monitoring data (such as the reservoir gas cap pressure, temperature and etc.), the actual remaining timeframe can be determined [14].

6 Conclusions

The mechanical plugs often operate at environments with high temperature and pressure from oil and/or gas reservoirs, which poses a significant challenge to monitor and predict remain useful life of the corresponding key components such as sealing rubber rings and/or gaskets[9]. In this work, the behaviour of bridge plug with commonly utilized materials subjected to different thermal and pressure loadings was investigated by using advanced finite-element analysis.

For the extreme high pressure high temperature working condition, the structural safe factors are small than 1. For other normal working conditions, three considered permanent bridge plugs behave well, and the corresponding remaining life cycles are calculated accordingly. Specifically, for the considered plug with fluororubber, cast iron and structural steel, the remaining life cycles are 1.75×10^5, which tend not to be failed considering the low evolution of the reservoir gas gap pressure.

7 Recommendations

Although this report analysis some parameters of mechanical plugs in P&A applications there still remains several issues that should be investigated further.

- **Well and plug information integration**
  To address in-service mechanical plug longevity prediction, the specific well and plug information needs to be integrated to the proposed ANSYS analysis for accurate evaluation. More specifically, the static information (well/reservoir type and characterization, plug structure data, materials and etc.) and dynamic monitoring data (subjected working conditions, pressure, temperature historical and online monitoring datasets and so on). By integrating the specific well and plug information with the ANSYS-based simulation studies, a personalized fatigue prognosis analysis can be provided for the targeted well and plug of interest.

- **Hybrid methods exploration for bridge plug integrity management in a entire life cycle**
  Regarding different life stages, various techniques are encouraged to be exploited for plug integrity managements. For instance, in the design process, first-principle models and numerical simulations can be used for structure optimization and material selection. In the early age of a bridge plug, numerical simulation studies can

be carried for bridge plug mechanical behaviour analysis and prediction. In the late period, with the accumulation of the monitoring data, some data-driven regression models can be built and incorporated in the simulations for an overall comprehensive analysis.

8 Application

structure optimization, material selection, mechanical behaviour (failure) analysis, structure enhancement, prediction The conducted study and the proposed methodology provide the engineers and operators several potential applications as follows.

- Structure optimization and material optimal selection of bridge plugs
  By simulating bridge plugs with different structures and materials in ANSYS, one can obtain the important indicators, including deformation, stress and strain contours and distributions. Additionally, we can also account for the effects of different working conditions to get the optimized structure and materials through a comprehensive comparison analysis.

- Failure analysis of bridge plugs
  From the perspective of safe factor and maximum stress points, one can infer whether there is a fault (such as crack or leak) occurred in a bridge plug. For a faulty bridge plug, we can study the mechanical methods to enhance the reliability. For instance, adding a mechanical ring at the weaken spot for a retrievable bridge plug.

- Longevity prediction of bridge plugs
  Many industries have records of failure data for components and systems over long time spans. With such historical data, statistical methods such as maximum likelihood estimation (MLE) can be used to estimate the corresponding lifetime distribution and the corresponding failure probability, either for a component and specific failure modes, or at the system level. For the assessment of lifetime distributions or the longevity of failure probabilities of bridge plugs, the historical available data of abandoned fields is needed. Then, when the censored data are available, a Bayesian approach is feasible for the assessment of a lifetime distribution.

Bibliography

[1] Øystein Arild, Hans Petter Lohne, Mohammad Mansouri Majoumerd, Eric P Ford, Fatemeh Moeinikia, et al. Establishment of a quantitative risk-based approach for evaluation of containment performance in the context of permanently plugged and abandoned petroleum wells. In *Offshore Technology Conference*. Offshore Technology Conference, 2017.

[2] Øystein Arild, Hans Petter Lohne, Hans Joakim Skadsem, Eric Patrick Ford, and Jon Tømmerås Selvik. Time-to-failure estimation of barrier systems in permanently plugged and abandoned wells. In *ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers Digital Collection, 2019.

[3] T Benedictus, MDC van der Kuip, RA Kronimus, JN Huibregtse, F Yavuz, G Remmelts, and JC Stam. Long term integrity of co2 storagewell abandonment. *IEA Greenhouse Gas R&D Programme*, 2009.

[4] L Dahmani, L Hynes, et al. Enhancing well construction for more efficient well abandonment. In *SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition*. Society of Petroleum Engineers, 2017.

[5] YUAN Dayong, XUE Zhanfeng, WU Jinxia, HUANG Yong, and MA Shankun. Study on mechanical properties of expansion sleeve of bridge plug.

[6] Daniel Eshraghi. P&a-status on regulations and technology, and identification of potential improvements. Master's thesis, University of Stavanger, Norway, 2013.

[7] Jeff M Fulks et al. 20,000 psi frac applications using composite bridge plugs. In *Offshore Technology Conference*. Offshore Technology Conference, 2004.

[8] D Liversidge, S Taoutaou, S Agarwal, et al. Permanent plug and abandonment solution for the north sea. In *SPE Asia Pacific Oil & Gas Conference and Exhibition*. Society of Petroleum Engineers, 2006.

[9] M Mainguy, P Longuemare, A Audibert, and E Lécolier. Analyzing the risk of well plug failure after abandonment. *Oil & Gas Science and Technology-Revue de l'IFP*, 62(3):311–324, 2007.

[10] Robin McGowan et al. New innovation improves performance and reliability of downhole plugs. In *Abu Dhabi International Petroleum Exhibition and Conference*. Society of Petroleum Engineers, 2015.

[11] Luis Mendez, James Goodson, Yusheng Yuan, Martin Coronado, and Rocky Turley. Composite inflatable downhole packer or bridge plug, November 4 2004. US Patent App. 10/770,790.

[12] Frank Rattray, Alex Annandale, Robert Forbes Grassick, et al. Milling of cast-iron bridge plug with electric-line-conveyed technology. In *SPE/ICoTA Coiled Tubing and Well Intervention Conference and Exhibition*. Society of Petroleum Engineers, 2008.

[13] Tadeusz Stolarski, Yuji Nakasone, and Shigeka Yoshimoto. *Engineering analysis with ANSYS software*. Butterworth-Heinemann, 2018.

[14] Anastasios P Vassilopoulos. *Fatigue life prediction of composites and composite structures*. Woodhead publishing, 2019.

[15] Olgierd Cecil Zienkiewicz, Robert L Taylor, Perumal Nithiarasu, and JZ Zhu. *The finite element method*, volume 3. McGraw-hill London, 1977.

[16] Mark D Zoback. *Reservoir geomechanics*. Cambridge University Press, 2010.