Full-scale thermal cycle testing of innovative high-temperature casing connections ("flexible couplings")

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ABSTRACT

Well integrity is key for efficient and sustainable utilization of deep geothermal resources. Over the lifetime of a geothermal well, the downhole construction must withstand thermal load changes caused by successive periods of operation and maintenance. Previous studies have shown that the single most occurring failure mechanism for high-temperature geothermal wells is mechanical overload of the casing string due to constrained thermal expansion. Mechanical overload can result in casing failures, e.g. collapse or tensile failure. In the internationally co-funded GEOTHERMICA project GeConnect, the function of an innovative casing connection, the Flexible Coupling, was demonstrated in a real working geothermal environment. Flexible couplings allow for a differential axial displacement between casing and cement which significantly lowers thermal straining of the casing material. The differential movement minimizes plastic deformation of the casing in the temperature range from 150-500 °C. An expert judgement exercise was performed to identify and evaluate potential risks and failures related to the functionality of the flexible coupling. It was found that the most crucial risk of failure relates to the manufacturing process and the construction of the well. Within the H2020 research projects GeoWell and DEEPEGS, full-scale prototypes of flexible couplings have previously been tested in laboratories at ambient temperatures. In a subsequent development phase, the flexible coupling was tested in a full-scale experiment in real working geothermal environment. The full-scale experiment comprised of two concentric casing joints cemented together while the inner casing was equipped with a flexible coupling. The setup was connected to a bypass of a production well in a high-temperature geothermal field in Iceland (up to 280°C). To simulate the extreme working conditions, the experimental construction was heated and cooled in several thermal cycles at moderate- (120°C) to high-temperature (280°C). An extensive analysis was made on the performance of the flexible coupling, the casing sliding behaviour, the cement sheath integrity and the cement-metal boundary. A custom-made monitoring suite was implemented to obtain high-precision real-time distributed temperature and strain information along the sliding part of the experimental setup. Additionally, piezoelectric pressure and acoustic sensors were used to characterize the dynamic sliding process in detail. The results of the field experiment serve as a foundation for the analysis of future flexible coupling field installations.

1. INTRODUCTION

Conventional technologies for the completion of geothermal wells offer only limited stability during cyclic thermal load changes. Over a lifetime, avoiding such load changes is in many cases impossible, or very difficult. In extreme cases, overloading of the casing can lead to subsequent tensile failure of the casing string (Figure 1). To allow axial thermal expansion and contraction of the casing during thermal load cycling, a concept for flexible casing connectors "Flexible Couplings" (FC) was developed and validated in the laboratory in the Horizon 2020 projects GeoWell and DEEPEGS. The FC prevents material yielding and plastic deformation at elevated temperatures (see Figure 2). This can significantly reduce the risk of damage to the casing, especially in high-temperature wells, and to the cement integrity in medium- and high-enthalpy wells. Consequential costs due to the repair of damage to the casing or the cemented annulus are avoided. Within the framework of GeConnect, the connectors were validated and demonstrated in an environment relevant for industry after successful laboratory testing. A summary of the project outcomes was recently published (Kaldal, et al. 2022).

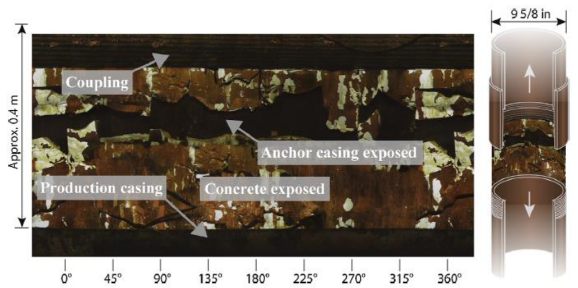

Figure 1: Coupling rupture in a high-temperature geothermal well. Picture compiled from a video log (Kaldal, et al. 2016)

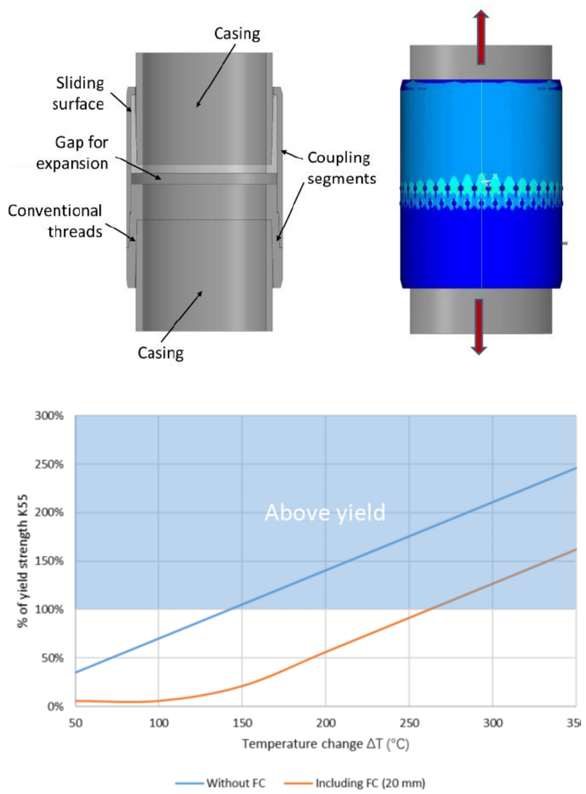

Figure 2: Schematic representation of the FC (top) and comparison of material thermal expansion with a casing string with FC and a conventional casing string (bottom) (Kaldal, et al. 2019)

2. TESTING OF MONITORING LINE

To monitor the thermal and mechanical behaviour of the field experiment in a highest possible detail, it was decided to design and implement a monitoring strategy based on distributed fiber-optic sensing and acoustic point measurements. Earlier experiments have shown that fiber-optic sensing technology can be used to measure temperatures up 300 °C and above (Reinsch und Henninges 2010). A setup was designed that allows to measure temperature and strain data in-situ along the casing over the entire temperature range up to 300 °C and deformations up to 0.5%, or 5000 microstrain. In order to pick up strain with a sensing fiber, a range of high-temperature adhesives were tested in the laboratory in a composite of sensing fiber – adhesive – metallic structure. Figure 3 shows a schematic sketch and a photo of the testing phase of three different high-temperature adhesives. The samples were heated in an oven in steps up to 300 °C and distributed fiber-optic data was acquired with a sensing technology based on Optical Frequency Domain Reflectometry (OFDR). An OFDR profile transmits information about temperature and strain changes along the sensing fiber (Soller, et al. 2005). To compensate for the effect of temperature, a reference thermometer (TH) is used. By doing so, a distributed strain profile was generated.

In a subsequent experimental phase, a full-scale (10 m long) fiber-optic testing length along a metallic structure was tested using multiple sensing technologies including distributed temperature sensing (DTS), fiber-bragg-grating (FBG), OFDR and piezo-electrical accelerometers.

With respect to the planned acoustic monitoring campaign and future implementation of the flexible coupling technology in boreholes, an in-situ borehole logging campaign was conducted in a geothermal well using distributed acoustic sensing (DAS) and DTS data (Lipus, et al. 2022).

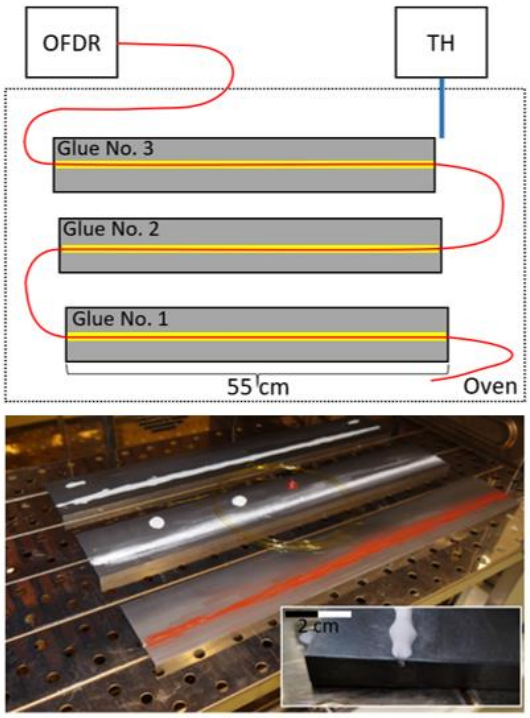

Figure 3: Experimental setup to test different adhesives in a "sensing fiber–adhesive–metallic structure" composite

2. THE SURFACE DEMONSTRATOR

A full-scale surface experiment was designed and constructed which allowed to test the FC in a real working environment by means of dimensions, temperatures and pressures. To mimic the downhole conditions, a 9 5/8" casing pipe was equipped with a FC and connected to a second casing pipe and placed horizontally in an experimental setup. The casing pipe was equipped with a tailor-made monitoring line to measure in-situ temperatures and deformations during the operational testing of the experiment. The 9 5/8" casing string was then placed in a 13 3/8" casing and cemented in. The entire setup was then mechanically confined with steel beams to form mechanical boundary conditions of the setup. Figure 8 shows pictures of the construction process and field testing of the experimental setup.

After construction, the final experimental setup was transported to Hellisheiði geothermal field (Iceland) in vicinity of a production well (64 bar at saturated steam temperature of 280 °C). A bypass was mounted to the outlet of the well and connected to the experimental setup. The experimental setup was heated in different phases: 1) first thermal cycle to moderate temperatures of 150 °C 2) cooling to ambient conditions, 3) heating to maximum temperatures (~ 260 °C), 4) cooling to ambient conditions, 5) 2nd heating to maximum temperatures (~260 °C). After a phase of maintenance, a 3rd heating phase to maximum temperatures was performed.

The experiment was monitored with a range of different sensors to achieve extensive information about the thermal and mechanical behaviour of the experimental construction during the heating and cooling phases. Temperature and pressure were monitored at the steam inlet and outlet of the experiment. A displacement sensor monitored the closure of the flexible FC. Piezo-electrical accelerometers were used to acquire acoustic data of the FC closure. A monitoring line fiber-optic distributed sensing technology was implemented to measure temperatures and absolute deformations along the 9 5/8" casing.

Furthermore, the possible implications and risks to the structural integrity and tightness of high temperature geothermal wells associated with the implementation of the novel FC technology were identified and evaluated. A finite element model was developed to simulate the behaviour of the flexible coupling, the annular cement and well material interfaces. A risk assessment approach based on the bowtie concept was performed to link possible causes (threats) with undesired events and the resulting consequences.

3. RESULTS AND DISCUSSION

First, results of the experimental testing of different high-temperature adhesives are shown and discussed. Then, results from the field testing of the flexible coupling are presented. Additionally, the results from the finite element analysis are shown.

Experimental results of the adhesive testing phase are shown in Figure 4. The upper subplot shows temperature corrected distributed strain data measured with the OFDR system. The grey profiles show the transient temperature increase from ambient conditions (20 °C) to 80 °C in time steps of 5 minutes. The blue line shows the steady-state profile at 80 °C. The grey dashed profiles show the expected analytical result (ΔT x thermal expansion coefficient of the specimen). The lower subplot shows the steady-state distributed strain profiles for different temperatures up to 250 °C. The measured data shows an increasing difference compared to the analytical solution. This is a result of the decoupling of the composite fiber-adhesive-metallic structure. This result shows the effect of adhesive types that are not optimal to pick up strain for the desired temperature range up to 300 °C. Subsequent tests with other adhesive materials have shown a clear strain profile up to the maximum temperature of 300 °C.

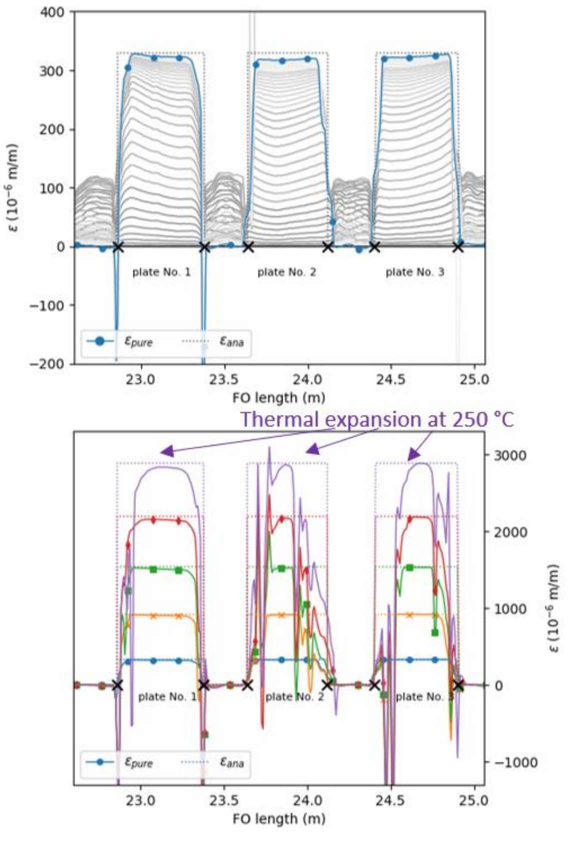

Figure 4 Top: Distributed strain sensing profiles (after temperature correction) measured with a glass fiber for the transient temperature increase from 20 °C to 80 °C for experimental testing of different high-temperature adhesive materials. Bottom: strain profiles up to a maximum temperature of 250 °C with a maximum strain of 2800 microstrain, or 0.28%. The dashed boxes mark the analytical result.

Figure 5 shows temperature data measured at the inlet, outlet and the outer surface of the external casing casing of the experimental setup during the first three thermal cycles in the field test. The heating of the experiment was controlled by a number of valves that regulated the rate of flow of steam. The two-phase steam was at saturation conditions with very little water ratio and the temperature was regulated by controlling the pressure within the casing. The temperature at in- and outlet reached equilibrium after about 10 minutes after opening the valves. The temperature increase at the outer casing was slower due to the insulating cement sheath between casings and was still in the transient phase until the end of each experimental run.

The data of the displacement sensor is shown in Figure 6 for each thermal cycle. The full opening of the flexible coupling is displayed at *D1 max* = 0 mm and the maximum closure of the flexible coupling is at *D1 max* = 20 mm. After each thermal cycle, the closure of the flexible coupling is shown by *D1 cold*. At the 1st thermal cycle up to 140 °C, the flexible coupling only showed a small displacement of less than 2 mm. At the 2nd thermal cycle (1st cycle to 260 °C), the flexible coupling reached almost full closure. The 3rd cycle was interrupted by a failure in the test frame at an early stage of heating and it was still in the transient heating phase. After repairs, during the 4th and 5th cycle, the flexible coupling showed full closure. During cooling, the gap of the flexible coupling does not completely open to initial conditions.

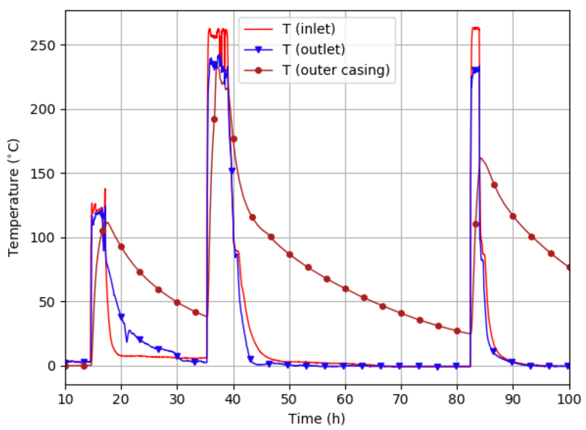

Figure 5: Temperature recordings from the field experiment at the steam inlet, the steam outlet and at the outer surface of the external casing

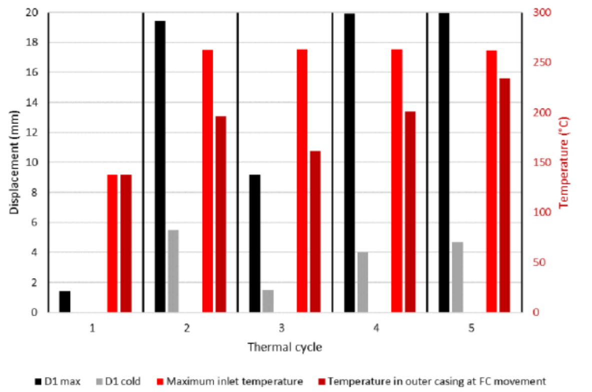

Figure 6: Overview of displacement of the flexible coupling (with 20 mm capacity) and temperatures for each experimental cycle (Kaldal, et al. 2022). In the 3rd cycle the test frame malfunctioned and was repaired for continuation.

Numerical results showed that the flexible couplings are already activated at 100°C and casing yielding does not occur at low temperatures (100°C). However, the results depend heavily on defined input parameters of steel/cement bond strength. For a steel/cement bond strength of 0.2 MPa which showed to be representative of the Flexible Coupling’s functionality, yielding of the casing occurred at higher temperature (460°C) with the Flexible Coupling accommodating casing displacement of total 20 mm at lower temperatures. Choosing a relevant gap for expected temperature change is therefore of importance to avoid yield at elevated temperatures and to ensure that a low residual compressive stress remains in the casing once the FC has reached full closure.

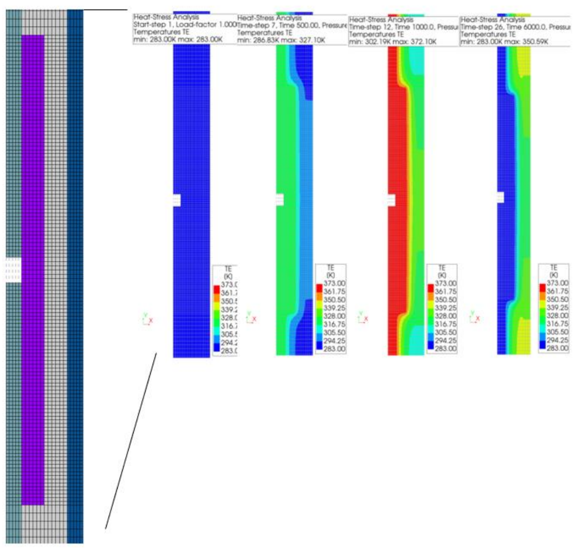

Figure 7: Finite element analysis (Schreppers, Gert-Jan, 2021)

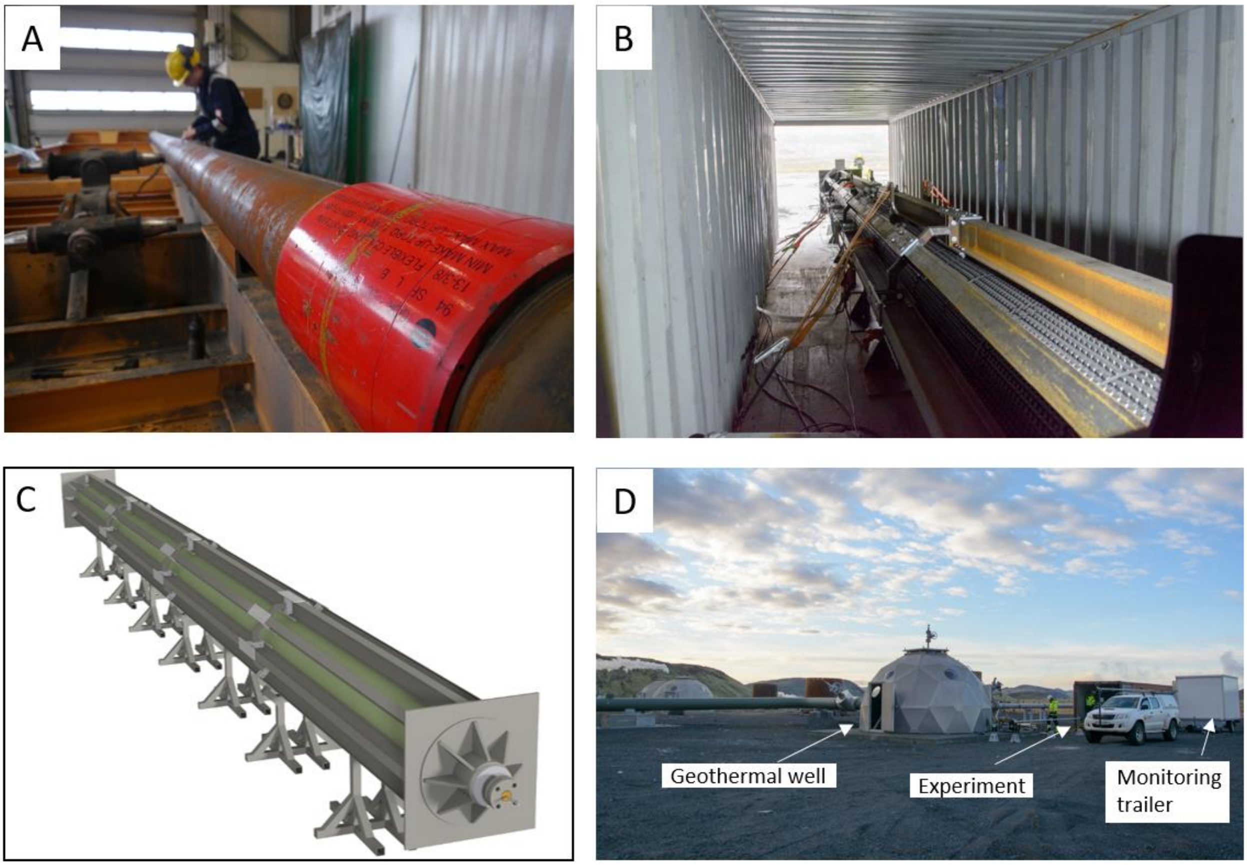

Figure 8: Construction phases of the field demonstrator. A) 9 5/8" casing string with mounted flexible coupling (red). B) final experimental assembly in measurement container in the geothermal field. C) 3-D model of the final assembly. D) Photo of the experimental site during testing

3. CONCLUSIONS

For the first time, the function of novel casing connections, Flexible Couplings, has been shown and confirmed in relevant environment at steam pressure of 57,8 bar-g and temperature of 262°C. The test was conducted during 8 November to 17 December 2021 at the geothermal field Hverahlíð which is a part of the Hellisheiði power plant (303 MW electricity and 133 MWt of hot water) operated by ON Power a subsidiary of Reykjavik Energy.

REFERENCES

Kaldal, G. S., et al. "Full-scale surface experiment of cemented-in casing connections designed for thermal stress mitigation." *European Geothermal Congress 2019 Den Haag, The Netherlands, 11-14 June 2019*, 2019.

Kaldal, Gunnar S., et al. ""Tight geothermal casing connections for axial stress mitigation - GeConnect" Final Report, Summary of Project Outcomes." GEOTHERMICA public report, 2022.

Kaldal, Gunnar Skulason, Magnus T. Jonsson, Halldor Palsson, and Sigrun N. Karlsdottir. "Structural modeling of the casings in the IDDP-1 well: Load history analysis." *Geothermics 62*, 2016: 1-11.

Lipus, Martin P., et al. "Dynamic motion monitoring of a 3.6 km long steel rod in a borehole during cold-water injection with distributed fiber-optic sensing." *Solid Earth*, 2022.

Reinsch, T., and J. Henninges. "Temperature-dependent characterization of optical fibres for distributed temperature sensing in hot geothermal wells." *Measurement Science and Technology 21*, 2010.

Soller, B. J., D. K. Gifford, M. S. Wolfe, and M. E. Froggatt. "High resolution optical frequency domain reflectometry for characterization of components and assemblies." *OPTICS EXPRESS 666*, 2005.

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