Performance of operating district heating pipelines subjected to thermal aging and fatigue

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The service life of district heating (DH) pipelines depends on the level of operating temperature and the amount of cyclic loading, that influence thermal aging and fatigue of the system components. Fourth generation district heating networks (4GDH) integrate renewable volatile energy sources, like wind and solar thermal, operating at lower temperatures and greater fluctuation. These have asset management of the 4th generation district heating networks” funded by the International Energy Agency Technology (Wedlich et al., 2020). It discusses the influence of combined mechanical and thermal loading on the service life of pre-insulated bonded single pipes, representing the majority of currently operating DH pipelines, based on the 3rd generation technology (3GDH).

To minimize heat losses, these pipes have a composite cross-section with three different material layers, including the steel pipe for the water supply, the insulation foam of polyurethane (PUR), and an outer coating of High Density Polyethylene (HDPE), interacting with the surrounding soil. The stiffness of the PUR foam and its constant adhesion to the steel pipe are essential to properly transmit at the HDPE coating the friction stresses from the surrounding soil, counteracting pipeline thermal expansion (Banushi and Weidlich 2018; Nilsson 2016; Frederiksen and Werner 2013), as schematically illustrated in Figure 1.

Indeed, 3GDH pipes undergo large temperature variations, associated with significant cyclic loading at the soil-pipe interface, as well as within the pre-insulated DH pipe system, leading to accumulated material damage and ageing.

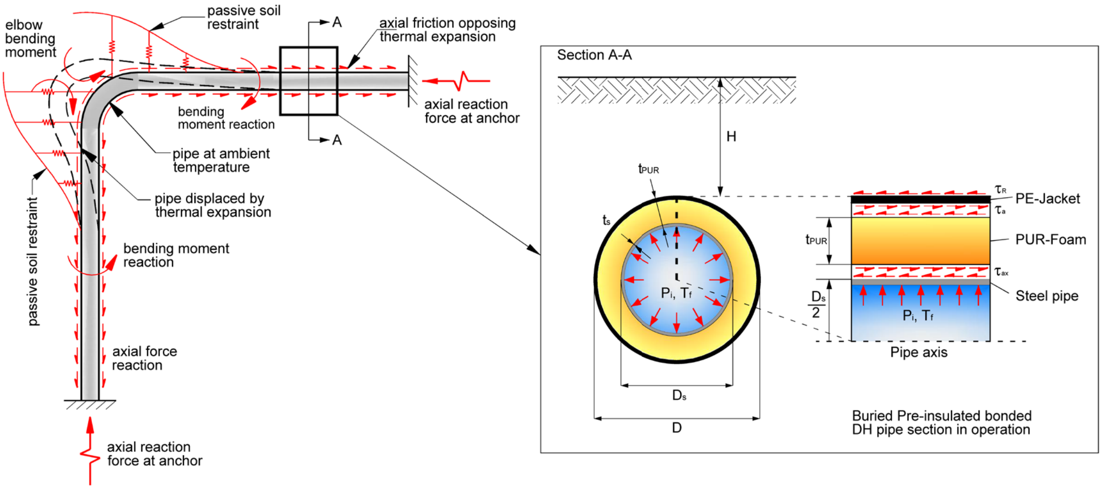

Fig. 1: Response of buried operating DH pipeline at the bend expansion zone (Banushi et al., 2021).

Conversely, 4th generation DH networks (4GDH) operate at lower temperatures, also integrating renewable energy sources, that are more volatile than the traditional 3GDH systems. The lower levels of operating temperature and the increased amount of cyclic loading influence ageing and the service life of 4GDH networks, requiring proper analysis of the system performance.

Moreover, current European standards (CEN 2009; 2019) do not address either the testing nor the design of 4GDH, highlighting the need to further investigate the combined effect of increased volatility, and decreased thermal loading associated with the integration of renewable energy sources in the DH network. Hence, it is fundamental to assess the combined effect of increased

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volatility and decreased thermal loading on the strength of the pipe components, including the fatigue resistance of the service pipe, the cohesion strength of the insulation, and the adhesion strength at their interface.

To evaluate the material strength of traditional and 4GDH pipelines, we have investigated the behaviour of the service steel pipe, the insulation foam, and their adhesive interaction, adopting an innovative analytical and experimental approach, as schematically illustrated in Figure 2.

First, the steel pipe material accumulated damage is estimated through the Palmgren–Miner rule, evaluating the number of equivalent full temperature cycles (CEN 2019), regarding temperature history data collected from operating DH pipelines in Germany, Sweden, Norway, and South Korea. Then, the response of the insulation foam is investigated experimentally, through shear tests on DH supply and return pipe samples, subjected to natural and accelerated aging under the combined effect of thermal aging and cyclic mechanical loading.

The fatigue performance, in terms of number of equivalent full temperature cycles for each gathered temperature history data has been assessed using the rain flow cycle counting algorithm, according to the ASTM E1049 standard, implemented in MATLAB (Mathworks 2018), as shown in Figure 2(a). These results are compared with the design criteria indicated in EN 13941 (CEN 2019), recommending that the number of full temperature cycles, equivalent to 30 years operation at the reference temperature 110°C, for transmission, distribution, and house connection pipelines should be within the range 100–250, 250–500, and 1,000–2,500, respectively.

The accelerated aging tests, performed at RISE (Research Institutes of Sweden), investigated whether the deterioration rate in the pipe in the expansion zone, subjected to thermal and mechanical loads, is greater than in the rest of the system, as schematically illustrated in Figure 1. Specifically, five DN 50=160 mm pipes were tested, with service pipe nominal diameter DN 50, outer casing diameter 160 mm, and pipe length of 3.4 m. While one pipe was kept at room temperature as a reference, four pipes were connected to the electrical installation for thermal aging, and two of them were additionally connected to the axial loading equipment during thermal aging.

The selected aging temperatures are 130°C and 140°C, whereas the cyclic axial load was applied through the piston, connected to the electrical cylinders, with a range 20 kN, and time period of 1 h. All pipes were tested for mechanical adhesive strength using the plug method [Figure 2(b)], and some of the obtained PUR samples were analyzed using Fourier transform infrared (FTIR) technique (Banushi et al. 2021, Vega et al. 2020; 2021, Weidlich et al. 2020).
Finally, we examined the material deterioration of naturally aged DH pipes, gathered from four DH branches of KDHC (Korea District Heating Corporation) in South Korea [Figure 2(c)]. The minimum length of collected pipe specimens is 1,000 mm, to obtain at least three specimens (SPMs) for axial shear test, and one SPM for gas analysis. The shear strength tests were performed according to EN 253 (CEN 2009), where the pipe samples were cut to 200 mm length. In total, 36 SPMs were analyzed for axial shear test, and one SPM for gas analysis. Thereafter, the plug testing method and FTIR analysis was performed on naturally aged DH pipe samples, and the results were further compared with those from accelerated aging tests.

The fatigue analysis results indicated that the lifetime of 4GDH pipelines is expected to increase, compared to conventional DH, because of the lower operating temperature, and the diminished impact of thermal loading volatility in the network. To accurately estimate the fatigue damage, the measuring time interval in the temperature data should be sufficiently small, requiring proper data logging.

The performed artificial ageing tests revealed a greater material damage at the interface between the steel pipe and the PUR foam, undergoing larger strains and greater chemical changes. Clearly, the combined effect of mechanical loading and thermal ageing accelerates the rate of chemical degradation of the PUR foam, leading to a faster material deterioration, that should be properly considered in current design standards for lifetime assessment.

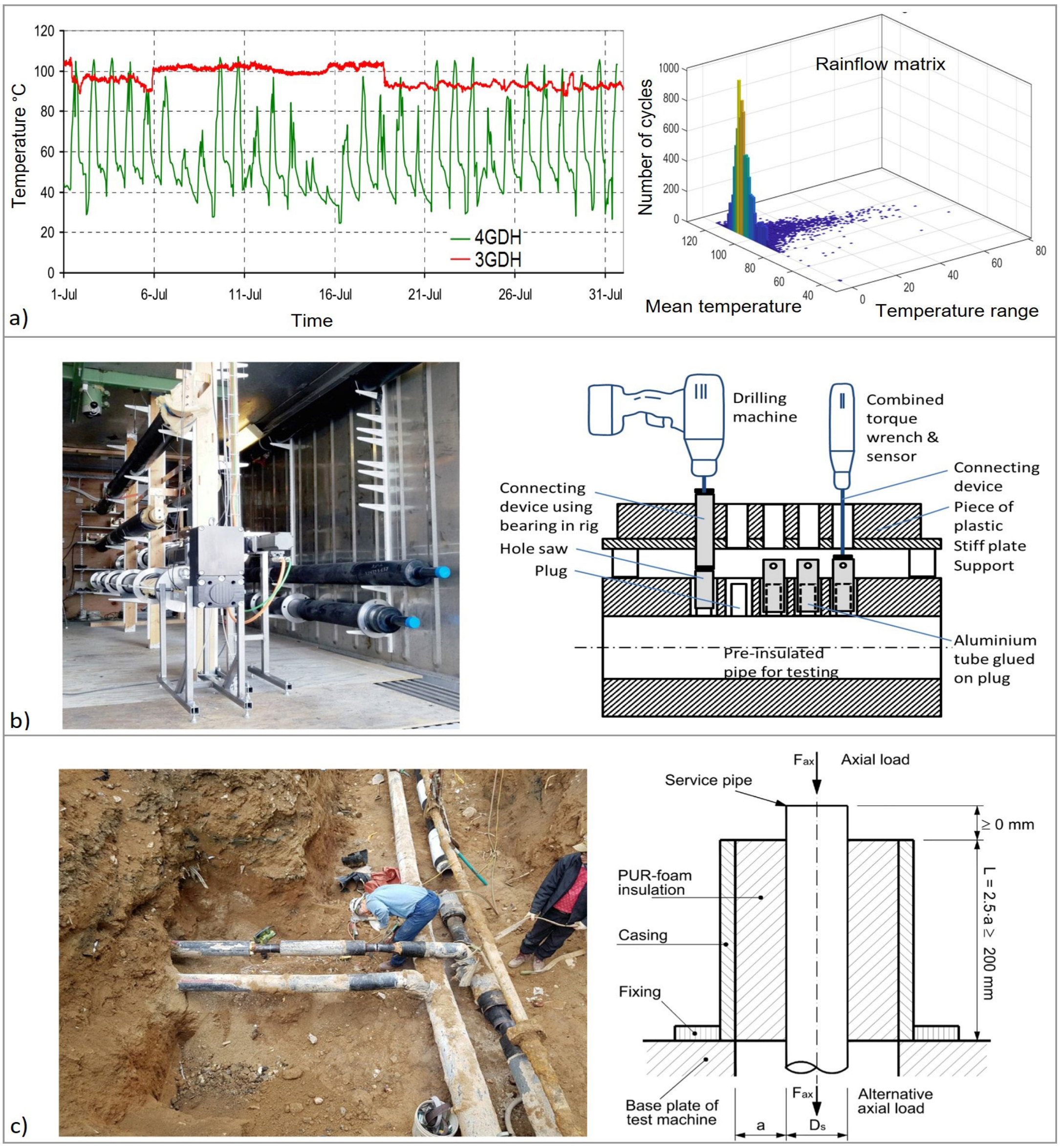

Fig. 2: Schematic representation of (a) fatigue analysis for the gathered temperature history data, using the rain flow cycle counting algorithm (ASTM 2017); (b) view of the electrical and mechanical test installation, and schematic representation of the mechanical testing using the plug method; (c) Sampling for the field test and schematic representation shear strength test set-up according to EN 253 (CEN 2009).

The analysis of the shear strength data from naturally aged pipes showed that thermal loading, as well as pipe material and geometric properties significantly influence the pipe shear strength, requiring detailed information, and monitoring of the system characteristics throughout the operational lifetime. Therefore, it is recommended to document the operating temperature history and the most important properties of the pipe system before installation, as well as during operation, contributing to better predictive maintenance, and subsequent reduction of economic risks for replacement and repair.

In conclusion, the obtained results allow a better understanding of 4GDH and traditional DH pipeline response, suggesting important recommendations for a more effective asset management since installation, and throughout the operational lifetime, contributing to a more energy efficient infrastructure.

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