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Reserves in axial shear strength of district heating pipes

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Abstract

Cost reduction for the installation of district heating pipes can be achieved through improved engineering strategies activating reserves of the system. This paper investigates experimentally the axial shear strength of the insulation of pre-insulated bonded district heating pipes. The standard design assumes a perfect bond. Conversely, the experimental investigation showed a shear displacement and reproducible conditions for small shear strain. Thus, a relative displacement of the service pipe within the pipe system seems to be possible without harming the bond. This relative displacement will relax the medium pipe from the highest axial stresses, representing a hidden reserve in the pre-insulated bonded pipe system. Using this reserve in static calculation may allow more economic pipe solutions.

Keywords: district heating pipes; axial shear strength; ageing; PUR foam; crack propagation

1. Introduction

District heating is characterized by the transport of heat in a pipe network from the generation unit to the customer. Due to the temperature in the system, the buried pipe network expands and interacts with the supports and the surrounding soil. The acting forces are, in many cases, quite large. Thus, a reliable design of the network is necessary for installation and operation. Currently, the standard case for Europe is a large scale district heating system with operating temperatures $T > 85$ °C and pre-insulated bonded district heating pipes according to EN 253 [1].

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These pipes consist of a steel medium pipe, a polyurethane insulation around the medium pipe and a protective polyethylene casing. However, small-scale networks are diffused significantly in rural areas. A characterization of small scale and large-scale district heating systems is given in [2].

Extensive displacements due to the temperature loads lead to unwanted high bending moments in the bows and branches of the network, which can be avoided when pipes and components are buried below surface. The skin friction activated around the perimeter of the pipeline constrains a part of the temperature induced displacements, which allows economic design of the pipe system. The interaction with the surrounding soil is only possible when thermal expansion of the medium pipe is transferred to the casing of the pipe by axial shear forces through the insulation and the casing. Because of this, the EN 253 requires minimum shear strength for the insulation and EN 13941 assumes a perfect bond between medium pipe and casing [3]. In reality, such a perfect bond does not exist, but, there is a hidden reserve in axial shear strength that was investigated here.

Nomenclature

a	thickness of the insulation
τ_{ax}	shear stress
F_{ax}	axial load
G	shear modulus
G_m	average shear modulus
L	length of the bond
D_s	outer diameter of the medium pipe
γ	shear strain
u, x, y	displacement, deflection
Φ	parameter
ρ^*	density of foam
ρ_s	density of solid cell walls
E_s	Young's modulus of solid cell walls

2. Methodology

Experimental tests were carried out in the laboratory of HafenCity University Hamburg on standard district heating pipes of the nominal diameter DN100. Herein, pipe samples with the geometry according to EN 253 and modified pipe samples were tested. Afterwards, the axial shear strength and the axial shear modulus were experimentally evaluated.

2.1. Test setup

The test setup was chosen according to EN 253. The bond is tested between service pipe and casing. Fig. 1 shows the test setup.

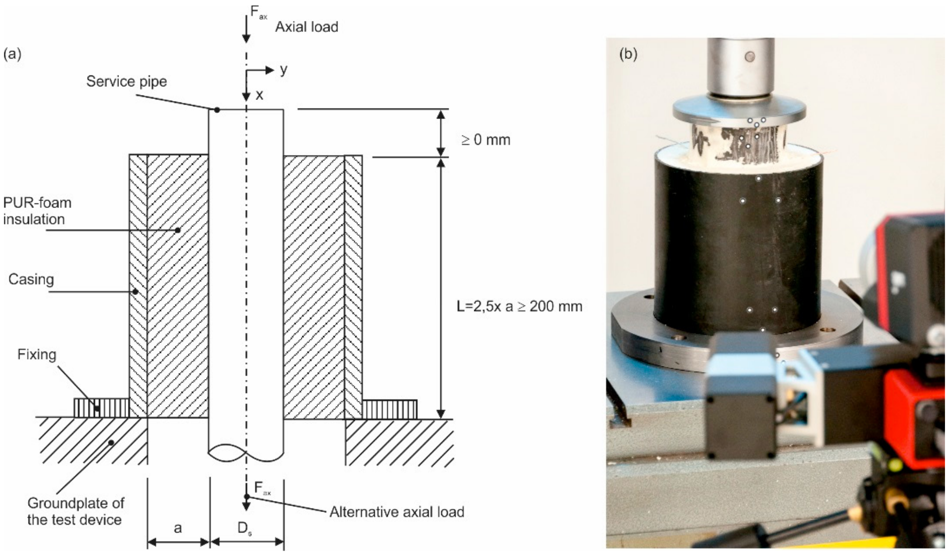

Fig. 1. (a) Test setup scheme; (b) test setup image.

The axial force was applied until failure with a crosshead speed of v = 5 mm/min and logged automatically. The displacement was recorded by an optical non-contact measurement and the weight of the samples was respected. The tests were carried out at room temperature T = 23 ± 2 °C.

2.2. Test specimen

Six test specimens were prepared from a standard pre-insulated bonded district heating pipe with a nominal diameter DN 100. The specimens were cut out of the pipe perpendicularly to the pipe's axis. The axial length of the specimens was varied. According to EN 253, the required length should be 2.5 times the insulation thickness, with a minimum of 200 mm. Thus, three reference specimen were produced with a length L = 200 mm. Additionally, three specimens were prepared with a length L = 400 mm.

Table 1 shows the properties of the six pipe specimen. Tolerances of coaxiality according to EN 253 were fulfilled. The foam density of the insulation was determined according to EN 253, ranging between 75 to 77 kg/m³.

Table 1. Designation and properties of the samples.

Designation	Steel medium pipe, outer diameter, mm	Coating, outer diameter, mm	Axial length of insulation and coating, mm	Insulation thickness, mm	Weight, g
DN100_L200_1	114.5	203.4	200	41.05	3560
DN100_L200_2	114.4	202.7	200	40.65	3560
DN100_L200_3	114.5	202.6	200	40.55	3540
DN100_L400_1	114.5	202.7	400	40.7	6170
DN100_L400_2	114.5	202.9	400	40.7	6160
DN100_L400_3	114.4	202.7	400	40.65	6200

Fig. 2 shows the six test specimen. For the non-contact measurements, the specimen was signed with markings, visible as white dots on the black casing.

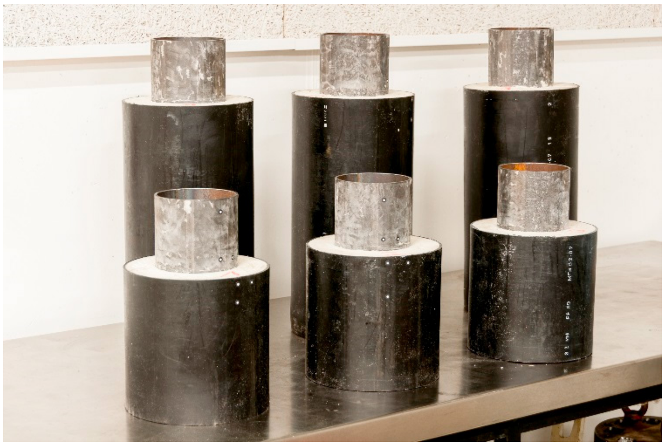

Fig. 2. Test specimen.

2.3. Shear strength

According to EN 253, the maximum axial shear stress is expected at the outer surface of the service pipe, and can be calculated through Eq. (1):

$$\tau_{ax} = \frac{F_{ax}}{L \cdot D_S \cdot \pi} \tag{1}$$

The shear stress is activated by a relative displacement u. Examples for test results from shear tests according to EN 253 are shown in Fig. 3 [4].

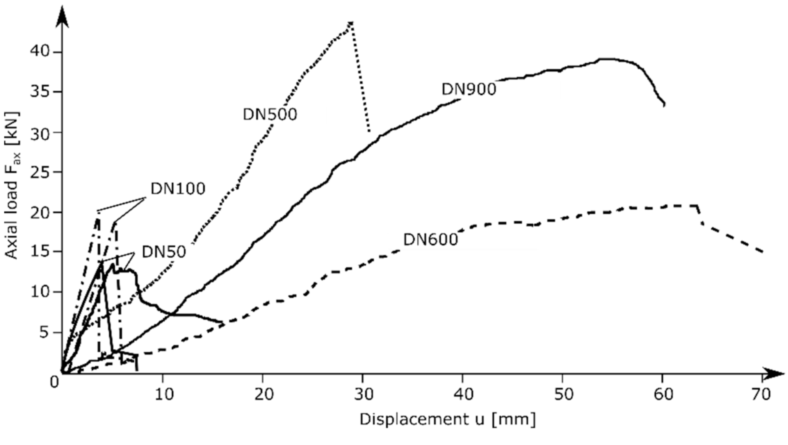

Fig. 3. Examples for shear test results according to EN253 [4].

The shapes of the curves are different, since the activated shear stress depends on sample dimensions, foam density, foam homogeneity and foam age. Thus, comparability and interpretation are influenced by the available datasets for the samples. Instead of the displacement u, the shear strain γ will be used in the following. For the presented test setup according to Fig. 1, this leads for small strains to Eq. (2):

$$\gamma \approx \frac{u}{a} \tag{2}$$

2.4. Shear modulus

The shear modulus is given by the ratio between shear stress and shear strain according to Eq. (3):

$$G = \frac{\tau_{ax}}{\gamma} \tag{3}$$

Huang and Gibson reported the dependency of the shear modulus to the polyurethane foam density [5]. For a density of 64 kg/m³, the evaluated shear modulus is G = 6.79 MPa. Furthermore, Gibson and Ashby distinguished open cells foams from closed cells foams, proposing Eq. (4) to estimate of the shear modulus in closed cells foams.

$$G \approx \frac{3}{8}\left(\phi^2\left(\frac{\rho^*}{\rho_S}\right)^2 + (1-\phi)\frac{\rho^*}{\rho_S}\right)\cdot E_S \tag{4}$$

Eq. (4) relates the shear modulus to the Young's modulus E_s and the density ρ_s of the solid cell walls. Empirical values for rigid polyurethane foams are E_s = 1.600 MPa, ρ_s = 1.200 kg/m³ and the parameter Φ equals to 0.8.

For pre-insulated bonded district heating pipes and the test setup according to EN 253, the shear modulus was not investigated beforehand. Higher values are expected, because the casing and the service pipe hinder lateral expansion. Furthermore, the shear stress distribution through the insulation is not constant. Assuming at least a linear decrease from the surface of the service pipe to the surface of the inner coating, an average modified shear modulus G_m applies according to Eq. (5):

$$G_m = \frac{\tau_m}{\gamma} = \frac{\tau_{ax}\cdot\left(\frac{1}{2}+\frac{D_s}{2(D_s+2a)}\right)}{\gamma} \tag{5}$$

3. Results

Fig. 4 shows the obtained τ_{ax}-γ curves from the six shear tests.

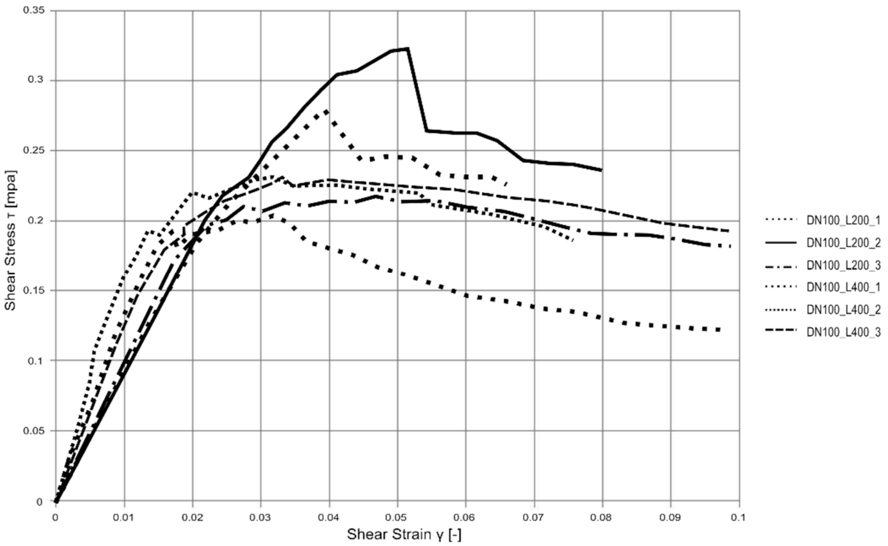

Fig. 4. Obtained curves from the tests.

3.1. Shear strength

The maximum shear stress was determined for all pipe samples. The influence of the specimen's dead weight to the results was investigated and excluded. The observed deviation was in the range of 0.2 % for the samples with length L = 200 m and 0.2–0.3 % for the samples with length L = 400 mm. According to EN 253, the minimum axial shear stress is $\tau_{ax,min}$ = 0.12 MPa for room temperature. The required displacement to reach the maximum shear stress was logged. Table 2 shows the achieved values. Similar values were reported in [6–8]. Clearly, the shear stress observed for L = 200 mm is higher than for L = 400 mm.

3.2. Shear modulus

The curves of Fig. 4 show a significant linear similarity for γ = 0 to 0.014. Thus, the shear modulus G was determined in this range as a tangent modulus according to Eq. (3) and Eq. (5) The obtained values for all pipe samples are given in Table 2.

Clearly, the shear modulus values of the short samples (L = 200 mm) fit very well with G = 9.0 MPa, obtained through Eq. (4), for the given foam parameters. Conversely, the values for the longer samples are approximately 30 % higher.

Table 2. Results from the shear tests.

Designation	Maximum shear stress $\tau_{ax,max}$, MPa	Displacement u at $\tau_{ax,max}$, mm	Shear modulus G, MPa	Average shear modulus G_m, MPa
DN100_L200_1	0.278	1.613	9.27	7.33
DN100_L200_2	0.321	2.095	9.46	7.50
DN100_L200_3	0.216	1.899	9.93	7.87
DN100_L400_1	0.203	1.280	12.24	9.70
DN100_L400_2	0.231	1.278	14.01	11.10
DN100_L400_3	0.229	1.684	11.63	9.22

3.3. Crack analysis

All six pipe samples were tested until failure and cracking of the foam. The analysis of the cracks showed random crack propagation. Fig. 5 illustrates the different cracks observed at the bottom of the samples.

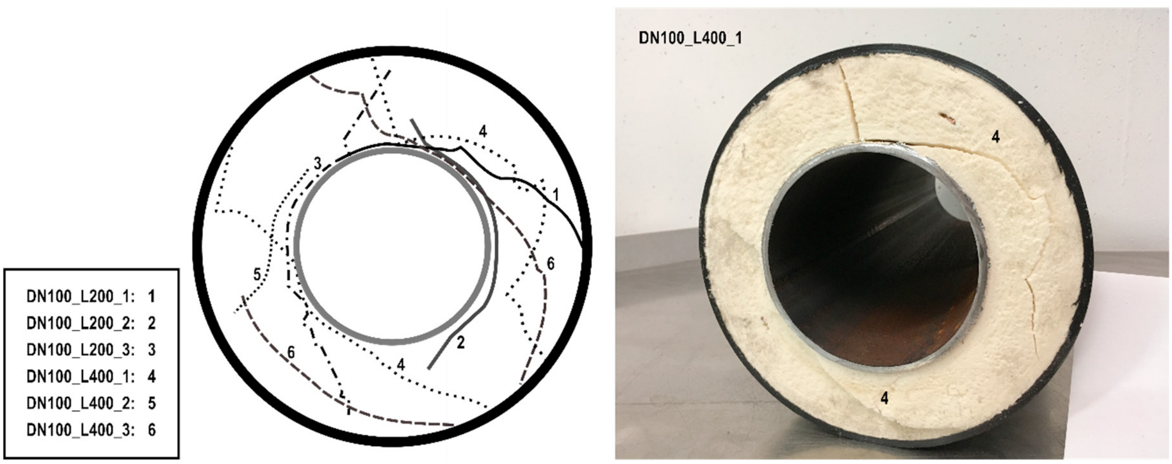

Fig. 5. Observed cracks at the bottom of the samples.

However, the cracks seem to start at the service pipe region, associated with higher shear stress. Subsequently, the shear plane propagates through the insulation in different unpredictable ways.

3.4. Analysis of results and test conditions

A good similarity of the curves resulted in the initial range of shear deflection, for $\gamma = 0$ to 0.014. For greater deformation $\gamma > 0.028$, the curves deviated strongly, due to the different behavior of the samples at failure. Surprisingly, lower maximum values were observed for the longer pipe samples L = 400 mm. These samples underwent local buckling of the coating close to the support. The coating in the longer samples could not withstand the stress concentration associated with the higher axial load required to fail the bond. A stress concentration for longer samples was also observed within the finite element analysis reported in [8].

Fig. 6. Local buckling of the coating (DN100_L400_2).

Thus, the failure of the bond in the tests with longer samples was overlaid by local buckling. This suggests that, to avoid buckling, longer samples have to be supported along the complete skin of the pipe casing. Evidently, the axial support at the bottom of the pipe casing, is sufficient only for short samples.

4. Conclusions

The investigation showed reproducible and similar curves for small shear strain in shear tests according to EN 253. Thus, a small relative displacement of the medium pipe within the pipe system seems to be possible without harming the bond. This relative displacement will relax the medium pipe from the highest axial stresses, which is a hidden reserve in the pre-insulated bonded pipe system. Using this reserve in static calculation might allow more economic pipe solutions.

Moreover, only the axial support at the bottom of the pipe casing recommended in EN 253, is not sufficient for longer pipe samples, needing additional support along the whole pipe casing, in order to avoid local buckling.

Lastly, it would be interesting to evaluate the behavior of the buried operating DH pipeline through accurate numerical models, validated using the present experimental results.

Acknowledgements

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